The Tectonic Evolution of the German offshore area, as part of the Trans-European Suture Zone (North and East of Rügen Island).

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„Ferne Kunde bringt Dir der schwankende Fels–Deute die Zeichen“ EMIL WIECHERT

Content

I Index of figures III

II Index of tables XI

III List of abbreviations XIII

Abstract 1

Kurzfassung 3

1. Introduction 5

2. Outline of previous work 9

3. Geological framework 19
   - 3.1 Regional setting of the working area 19
   - 3.2 Plate tectonic and sedimentary evolution at the southwestern margin of the East-European Craton since the Neoproterozoic 22
   - 3.3 Special tectonic features in the working area 45
     - 3.3.1 The buried Caledonian Suture Zone between Baltica and Avalonia – the problem of terminology, appearance and reactivation phases 47
     - 3.3.2 Tornquist Fan and Tornquist Zone 51
     - 3.3.3 The Wiek Fault and other deep-rooted Palaeozoic faults, block-faulted Rügen and vicinity 55
     - 3.3.4 The North German Basin as part of the Central European Basin System 58

4. Data base and methods 61
   - 4.1 Seismic and well data 61
   - 4.2 Reflection seismic data - measurement and processing 63
   - 4.3 Data analyses and seismic interpretation 65
   - 4.4 Restoration of seismic sections with MOVE™ 69

5. Results 71
   - 5.1 Stratigraphic units 71
     - 5.1.1 Proterozoic basement and Neoproterozoic to Cambro-Ordovician cover 73
     - 5.1.2 Silurian cover 75
     - 5.1.3 Deformed Ordovician of the accretionary wedge 77
     - 5.1.4 Devonian 79
     - 5.1.5 Carboniferous 81
     - 5.1.6 Permian 84
       - 5.1.6.1 Rotliegend 84
       - 5.1.6.2 Zechstein 86
     - 5.1.7 Triassic 88
       - 5.1.7.1 Buntsandstein 89
       - 5.1.7.2 Muschelkalk 92
       - 5.1.7.3 Keuper 94
     - 5.1.8 Jurassic 98
     - 5.1.9 Cretaceous 100
   - 5.2 Major tectonic structures of the Arkona, Wolin and Gryfice blocks 103
     - 5.2.1 Structures of the Arkona Block 106

5.2.1.1 Jütland-Møn Fault Zone 106
5.2.1.2 Skurup Fault and Gat Fault 106
5.2.1.3 Hiddensee Fault 107
5.2.1.4 Arkona Fault 108
5.2.1.5 Agricola-Svedala Fault 109
5.2.1.6 Caledonian Deformation Front (CDF) 109
5.2.1.7 Velocity pull down patches 110
5.2.2 Tectonic situation of the Wolin Block 111
5.2.2.1 Wiek Fault System and other faults 111
5.2.2.2 Kinematic analysis of the Wiek Fault System 116
5.2.3 Tectonic situation of the Gryfice Block 120
5.2.3.1 Adler-Kamień Fault Zone 121
5.2.3.2 Gryfice Fault Zone 122
5.2.3.3 Kinematic analysis of the Adler-Kamień Fault Zone 123

6. Interpretation and discussion of the structural features along the Arkona, Wolin and Gryfice blocks 125
6.1 Time structure maps and morphological implications 125
6.2 Structural evidence at the different blocks 130
6.2.1 Arkona Block 130
6.2.1.1 Caledonian accretionary wedge, Variscan remains and younger displacements 131
6.2.1.2 Degassing structures or Quaternary channels? 134
6.2.2 Middle Rügen and Wolin blocks – The Wiek Fault System: Characterisation and formation, relationship with other Palaeozoic faults and the WPFS 137
6.2.3 Gryfice Block – Evolution along the Adler-Kamień Fault Zone and the contemporary formation of the Gryfice Fault Zone 141

7. Summary and Conclusions 145
7.1 Overview of the geological development 145
7.2 Main results of this thesis 151

8. Perspective for future work 155

9. References 157

Appendix
A Supplementary chapters
a. Working with the SeisWare™
b. MOVE™ Workflows
c. The ArcGIS Project
B Petrobaltic Field Parameters
C Seismostratigraphic horizons of the Petrobaltic and SASO working groups
D Time structure maps and Time thickness maps (all in TWT)
E Comprehensive table characterising faults and flexures north and east of Rügen
F Supplementary material

Acknowledgements

Declaration of independence

List of publications, talks and posters

I Index of figures

Fig. 2-1: One of the first tectonic maps by DEECKE (1906). 9

Fig. 2-2: Working area of the Petrobaltic (based on REMPEL 1992*b*). 11

Fig. 2-3: Profile density of the Petrobaltic CDP seismic data in the German sector (based on REMPEL 1992*a*). 11

Fig. 2-4: The drilling platform "Petrobaltic" in Poland as an example for all other offshore wells erected and used by Petrobaltic (photos provided by the Erdölmuseum Reinkenhagen). 12

Fig. 2-5: Overview of some EUROPROBE projects (modified after GEE & ARTEMIEVA 2000). 13

Fig. 2-6: Overview of the SASO, DEKORP-Basin'96 and VPSS research areas (based on BABEL WORKING GROUP 1993, KRAWCZYK et al. 1999, KRAUSS & MAYER 2004). 14

Fig. 2-7: Focused areas of the Millennium Atlas and SPBA (modified according to DOORNENBAL et al. 2010). 15

Fig. 2-8: Example of a 3D model with the relief view of the top Zechstein (modified after SCHECK & BAYER 1999). Abbreviations used: AH-Altmark High, EL-Elbe Fault system, FH-Flechtlingen High, GH-Grimmen High, ST-Sub-Hercynian Trough, PTB-Permo-Triassic Basin, PPD-Pre-Permian Depression, RL-Rheinsberg Lineament, the red rectangle marks the location of Rügen, and therefore the working area of USO. 16

Fig. 3-1: : Research areas of USO West (yellow) and USO East (orange) in the southern Baltic Sea; Bathymetry: TAUBER (2012*a*-*i*). 19

Fig. 3-2: Sea bottom relief and bathymetry of the southern Baltic Sea, around Rügen (Bathymetry: TAUBER 2012*a*-*i*). 20

Fig. 3-3: Position of the USO research area (indicated by the red box) within the Tornquist Fan and at the border of the Central European Basin System (CEBS) in yellow. AH–Arkona High, CG–Central Graben, CDF–Caledonian Deformation Front, DB–Danish Basin, EL–Elbe Line, GG–Glückstadt Graben, HG–Horn Graben, MH–Møn High, MPT–Mid Polish Trough, NGB–North German Basin, RFH–Ringkøbing-Fyn High, STZ–Sorgenfrei-Tornquist Zone, TEF–Trans-European Fault, TTZ–Teisseyre-Tornquist Zone (adjusted from SEIDEL et al. 2018 and citations therein). 21

Fig. 3-4: Palaeogeographic maps of the Neoproterozoic (modified after PHARAOH et al. 2010). AO–Aegir Ocean, ATA–Amorican Terrane Assemblage, AV–Avalonia, B–Baltica, G–Gondwana, IO–Iapetus Ocean, L–Laurentia, S–Siberia, PO–Panthalassic Ocean. 22

Fig. 3-5: Palaeogeographic maps of the Late Ordovician (PHARAOH et al. 2010). For Legend see Fig. 3-4. AO–Aegir Ocean, ATA–Amorican Terrane Assemblage, AV–Avalonia, B–Baltica, IO–Iapetus Ocean, L–Laurentia, S–Siberia, RO–Rheic Ocean, TS–Tornquist Sea. 22

Fig. 3-6: Active continental margin of Avalonia (according to BEIER et al. 2000, modified). 23

Fig. 3-7: Caledonian Orogeny (DE VOS et al. 2010, according to BEIER 2001). 24

Fig. 3-8: Palaeogeographic map of the Silurian (PHARAOH et al. 2010; for legend see Fig. 3-4). ATA–American Terrane Assemblage, Bal–Balonia, RO–Rheic Ocean. 24

Fig. 3-9: Location of the Middle Rügen Depression (modified after AEHNELT & KATZUNG 2009). AKFZ–Adler-Kamień Fault Zone. 25

Fig. 3-10: Palaeogeographic map of the Late Devonian (PHARAOH et al. 2010, see Fig. 3-4 for legend). ATA–Amorican Terrane Assemblage, G–Gondwana, LR–Laurussia, PTO–Palaeotethys Ocean. 26

Fig. 3-11: Palaeogeographic map during the Early and Late Carboniferous, working area marked in red (MESCHEDE & WARR 2019, modified). LBM–London-Brabant Massif, MCZ–Mid-German Crystalline Zone, Mo–Moldanubian, Rh–Rhenohercynian, Sa–Saxothuringian. 27

Fig. 3-12: Stratigraphic overview of the Upper Carboniferous and Permian in the North German Basin (GEIßLER et al. 2008, modified). 28

Fig. 3-13: Volcanic and sedimentary rocks of the Rotliegend of the Northern and Southern Permian Basins with the Mecklenburg-Vorpommern (MVSP), East Brandenburg (EBSP)and Flechtlingen-Altmark sub-provinces (FASP) (BREITKREUZ et al. 2008, modified). The working area marked in red. 29

Fig. 3-14: Facies distribution of the Upper Elbe Sub-group (compiled by STOLLHOFEN et al. 2008). 30

Fig. 3-15: Palaeogeographic map during the Zechstein (PHARAOH et al. 2010). 31

Fig. 3-16: Stratigraphic table of the Triassic with main successions in Mecklenburg-Western Pomerania, as they have been used in the well descriptions, and its prominent discordances within the NGB (compiled after BEUTLER 2004, LUNG 2004, STOLLHOFEN et al. 2008, STG 2016). 32

Fig. 3-17: Global plate-tectonic situation during the Late Triassic (MESCHEDE & WARR 2019). Ap–Apulian Plate, G–Germany. 33

Fig. 3-18: Palaeogeographic map of the Lower Triassic (MESCHEDE & WARR 2019, modified). 33

Fig. 3-19: Palaeogeographic map of the Muschelkalk (MESCHEDE & WARR 2019, modified). The red rectangle marks the research area of this thesis. 35

Fig. 3-20: Palaeogeographic map of the Keuper (MESCHEDE & WARR 2019, modified). The red rectangle marks the research area of this thesis. AM–Armorican Massif, BM–Bohemian Massif, CM–Central Massif, LBM–London-Brabant Massif, VL–Vindelician Land. 36

Fig. 3-21: The Schilfsandstein Formation in the eastern part of the NGB (FÖRSTER et al. 2010). 37

Fig. 3-22: Palaeogeographic map of the Lias (MESCHEDE & WARR 2019, modified). The red rectangle marks the research area of this thesis. 38

Fig. 3-23: Palaeogeographic map of the Malm (MESCHEDE & WARR 2019, modified). The red rectangle marks the research area of this thesis. 39

Fig. 3-24: Palaeogeographic map of the Lower Cretaceous (MESCHEDE & WARR 2019, modified). The red rectangle marks the research area of this thesis. AA–Austroalpine, AM–Armorican Massif, Br–Briançonnais, Ca–Carpathians, CM–Central Massif, Di–Dinarides, Hel–Hellenides, NP–North Penninic Ocean, PO–Pyrenees Ocean, RBM–Rhenish-Bohemian Massif, SA–South Alpine. 40

Fig. 3-25: Palaeogeographic map of the Upper Cretaceous (MESCHEDE & WARR 2019, modified). The red rectangle marks the research area of this thesis. AA–Austroalpine, AM–Armorican Massif, Br–Briançonnais, Ca–Carpathians, CM–Central Massif, Di–Dinarides, Hel–Hellenides, NP–North Penninic Ocean, PO–Pyrenees Ocean, RBM–Rhenish-Bohemian Massif, SA–South Alpine. 41

Fig. 3-26: Palaeogeographic map of the Eocene (MESCHEDE & WARR 2019, modified). The red rectangle marks the research area of this thesis. 42

Fig. 3-27: Palaeogeographic map of the Miocene (MESCHEDE & WARR 2019, modified). The red rectangle marks the research area of this thesis. 43

Fig. 3-28: Recent vertical displacements of the crust along the southern Baltic Sea (HARFF & MEYER 2011, modified). The working area is marked by the red rectangle. 44

Fig. 3-29: Tectonic situation of the southeastern Baltic Sea (modified after DEUTSCHMANN et al. 2018, Seidel et al. 2018 and citations therein): CDF–Caledonian Deformation Front, TESZ–Trans-European Suture Zone, TTZ–Teisseyre-Tornquist Zone, STZ–Sorgenfrei-Tornquist Zone. Fault zones (FZ) of the WPFS: I–Werre FZ, II–Prerow FZ, III–Agricola FZ, IV–Reinberg FZ, V–Samtens FZ, VI–Greifswald-Poseritz FZ, VII–Freest FZ, VIII–Moeckow-Dargibell FZ and IX–Usedom FZ. Bh–Bornholm; Ds–Darss Peninsula; Fa–Falster Island, M–Møn Island, Rn–Rügen Island; Ud–Usedom Island; Wl–Wolin Island. 45

Fig. 3-30: Overview of the tectonic evolution of Europe (modified after FRISCH & MESCHEDE 2013; PHARAOH et al. 2010, MESCHEDE 2018). 46

Fig. 3-31: Left– Structural map by BERTHELSEN (1998, modified) with the Thor Suture (marked by red arrows) north of Rügen. 47

Fig. 3-32: Avalonia - Baltica docking and counter-clockwise rotation (TORSVIK & RENSTRÖM 2003, modified). 48

Fig. 3-33: Location of the PQ-, BABEL A-, DSB-9, and BASIN96-seismic lines (KRAWCZYK et al. 2002). 48

Fig. 3-34: DEKORP-Basin '96 seismic line crossing the Trans-European Suture Zone (MCCANN & KRAWCZYK 2001, modified): a - reflections in the mantle which were previously interpreted as Caledonian structure (BABEL WORKING GROUP 1993), b - SW dipping reflectors within the accretionary wedge, c - surface of the Caledonian suture, often labelled as O-horizon, d - SW-dipping reflectors related with later thrusting. For line location see Fig. 3-33. 49

Fig. 3-35: Interpreted reflection seismic line of the BASIN96-transect (GUTERCH et al. 2010, modified). See Fig. 3-33 for location of the lines BASIN9601, PQ2-9.1 and PQ2-5. 49

Fig. 3-36: The tectonic units of the Tornquist Fan (compiled by THYBO 2000, modified): BBB–Blekinge Bornholm Block, BF–Børglum Fault, BG–Brande Graben, BMF–Bamble Fault, CDF–Caledonian Deformation Front, EL–Elbe Lineament, FBZ–Fennoscandian Border Zone, FF–Fjerritslev Fault, GA–Grimmen Axis, GT–Glückstadt Trough, HG–Horn Graben, MH–Møn High, MNS–Mid North Sea High, MZ–Mylonite Zone, OG–Oslo Graben, RFH–Ring-købing-Fyn High, RFZ–Rømø Fault Zone, RG–Rønne Graben, SG–Skagerrak Graben, SNF–Sveconorwegian Front, STZ–Sorgenfrei-Tornquist Zone, TEF–Trans-European Fault, TIB–TransScandinavian Igneous Belt, TTZ–Teisseyre-Tornquist Zone, VFZ–Vinding Fault Zone. The working area is marked in red. 51

Fig. 3-37: Comparison of the different illustrations of the Tornquist Zone. According to PHARAOH (1999), THYBO (2000) but also SCHLÜTER et al. (1997*a,b*) and others, the up to 80 km broad Tornquist Zone is terminated by the Adler-Kamień Fault Zone (AKFZ) and the Koszalin Fault (KF) and included the Gryfice (GB) and Kołobrzeg (KB) blocks. KOSSOW et al. (2000) restricted the southern branch of the up to 40 km broad TTZ to the northern KB, between the Trzebiatow Fault (TF) and the KF. A southeastern prolongation is assumed. According to NARKIEWICZ et al. (2011), MAZUR et al. (2018) and others, the Tornquist Zone comprises an approximately 20 km thick band, which parallels the northern border of the KB. Thus, the TTZ runs close to the KF (Bh–Bornholm, Rn–Rügen, STZ–Sorgenfrei-Tornquist Zone, TTZ–Teisseyre-Tornquist Zone). 53

Fig. 3-38: Comparison of different tectonic maps with a varying Wiek Fault, marked as a thick black line, compiled by SEIDEL et al. (2018) and recently modified. The single figures are based on: A–MAYER et al. (1994), B–SCHLÜTER et al. (1997b), C–ERLSTRÖM et al. (1997), D–KRAUSS & MAYER (2004). AKFZ–Adler-Kamień Fault Zone, NJF–Nord Jasmund Fault, Rn–Rügen, SFZ–Samtens Fault Zone, WF–Wiek Fault. 55

Fig. 3-39: Structural map of Rügen according to KURRAT (1974). I–sub-block of Glowe, II–sub-block of Neuenkirchen, III–sub-block of Trent, IV–sub-block of Putbus. 56

Fig. 3-40: Recent structural map of Rügen and research wells (modified after FRANKE 2018). 57

Fig. 3-41: Cross-section through the Caledonian- and Variscan-deformed succession with the location of major faults (modified from MAYER et al. 1994 and PISKE et al. 1994). CDF–Caledonian Deformation Front. 58

Fig. 3-42: The Central European Basin System (CEBS). CG–Central Graben, GG–Glückstadt Graben, HG–Horn Graben, STZ–Sorgenfrei-Tornquist Zone, TTZ–Teisseyre-Tornquist Zone (SCHECK-WENDEROTH & LAMARCHE 2005, slightly modified). 59

Fig. 4-1: Working area with seismic lines of different sources, and wells (green dots: German research wells; red dots: offshore wells of Petrobaltic and the Danish geological survey – GEUS. For more information see Tab. 4–2 or Section 5.1). 61

Fig. 4-2: Offshore reflection seismic method (HÜBSCHER & GOHL 2014). 63

Fig. 4-3: Data reprocessing during the SASO-project. For more information see SCHEID et al. (1995) and ARNDT et al. (1996). 64

Fig. 4-4: Stratigraphic Table according to STG 2016, comparing the selected main horizons with those of the Petrobaltic (PB) and SASO working groups. 65

Fig. 4-5: Well ties of the four offshore wells east of Rügen with an extract of the seismic section, the synthetic and physical well logs and the lithology. For legend of the horizons see Fig. 4-4. 67

Fig. 4-6: Typical reflection patterns of the seismic lines; left: schematic, right: original seismic sections (subdivision based on MITCHUM et al. 1977 and VON HARTMANN et al. 2015). 68

Fig. 4-7: Workflow for the restoration of seismic lines. 70

Fig. 5-1: Fault inventory within the area of USO East. The single fault planes have been mapped and illustrated by former projects (Chapter 5.2); AB – Arkona Block, GB – Gryfice Block, MRB – Middle Rügen Block, NJF – Nord Jasmund Fault, RB – Rønne Block, SB – Skurup Block, SRB – South Rügen Block, TTZ–Teisseyre-Tornquist Zone, WB – Wolin Block (SEIDEL et al. 2018 and references therein, modified). 71

Fig. 5-2: Location of presented seismic sections marked in red. Grey lines indicate previously known faults (e.g. THOMAS et al. 1993, MAYER et al. 1994). 72

Fig. 5-3: Time-structure map of the Top Proterozoic (EEC/Baltica) within the area of USO East. 73

Fig. 5-4: Time-structure map of the Top Silurian (cover of the EEC) within the area of USO East. 75

Fig. 5-5: Interpreted section regarding well log G14 1/86, for location see Fig. 5-2. (Vertical exaggeration-VE≈5.5, assuming an average velocity of 3000 m/s). 76

Fig. 5-6: Time-structure map of the Top Ordovician (accretionary wedge) within the area of USO East. 77

Fig. 5-7: Time-structure map of the Top Devonian within the area of USO East. 79

Fig. 5-8: Seismic section showing the block faulted Palaeozoic successions which are subhorizontal covered by Mesozoic deposits. Moreover the projected location of the well H9 1/87 is shown (for location see Fig. 5-2). (VE≈3, assuming an average velocity of 3000 m/s). 80

Fig. 5-9: Time-structure map of the Top Carboniferous within the area of USO East. 81

Fig. 5-10: Seismic line crossing the Wolin Block southeastward. Black lines indicating the internal differential dipping reflections and the angular unconformity between the Middle Devonian and the Carboniferous (for location see Fig. 5-2). (VE≈2.5, assuming an average velocity of 3000 m/s) 82

Fig. 5-11: Time-structure map of the Top effusive Rotliegend within the area of USO East. 84

Fig. 5-12: Time-structure map of the Top Zechstein within the area of USO East. 86

Fig. 5-14: Velocity depth distribution along a profile west of Rügen in the Mecklenburg Bay (NOACK et al. 2018), illustrating a varying velocity of the Zechstein strata with a general velocity decrease towards the Base of Zechstein successions (Pre-Zechstein is not calculated) VE≈4. 87

Fig. 5-13: Well tie of the well H2 1/88 and a seismic section (for location see Fig. 5-2). VE≈1, assuming an average velocity of 3000 m/s, positive amplitudes are brown (peaks), negative amplitudes are blue (troughs). 87

Fig. 5-15: Small salt accumulations (marked with red arrows), about 100 m exaggerated, at the Wolin Block.(For location see Fig. 5-2). (VE≈3, assuming an average velocity of 3000 m/s). 88

Fig. 5-16: Time-structure map of the Top Buntsandstein within the area of USO East. 89

Fig. 5-17: Time-structure map of the Top Muschelkalk within the area of USO East. 92

Fig. 5-18: Time-structure map of the Top Triassic/ Top Keuper within the area of USO East. The northern extension of the top Muschelkalk and top Buntsandstein is marked by the dotted lines. 94

Fig. 5-19: 3D view on the surface of the Grabfeld Formation. Its morphology indicates an elongated depression, SW of the NJF (grey, transparent plane). 97

Fig. 5-20: Seismic section crossing the internal Keuper channel (for location see Fig. 5-2; according to FRANZ et al. 2018b). (VE≈2.5, assuming an average velocity of 3000 m/s) 97

Fig. 5-21: Time-structure map of the Top Lower Jurassic within the area of USO East. 98

Fig. 5-22: Time-structure map of the Base Cretaceous within the area of USO East. 100

Fig. 5-23: Fault inventory within the area of USO East. The single fault planes have been mapped and summarised as Fault zones and systems. Therefore each fault plane was defined (cursive labels; see Appendix D,E) and characterised. 103

Fig. 5-24: Location of the presented seismic sections (marked red) showing the individual fault planes (see Fig. 5-23). 104

Fig. 5-25: Seismic section crossing the Arkona Block and visualizing the Caledonian Deformation Front (CDF), Velocity Pulldown Patches (VPP), the basement faults, such as the Jütland-Møn Faults (JMF), and the Palaeozoic to Mesozoic faults such as the Arkona Fault (AF). For location see Fig. 5-24 (VE≈4, assuming an average velocity of 3000 m/s). 106

Fig. 5-26: Seismic sections crossing the SF (a) west of the Gat Fault and (b) east of the Gat Fault (for location see Fig. 5-24). (VE≈2, assuming an average velocity of 3000 m/s). 107

Fig. 5-27: Section of the Line D014 crossing the NNE striking Hiddensee Fault (abbreviations: VPP – Velocity pull down patches, see Section 5.2.1.7; for location see Fig. 5 24). VE≈4, assuming an average velocity of 3000 m/s). 108

Fig. 5-28: Cross sections along the Arkona Fault (red line), displacing the deformed Ordovician and its Permo-Triassic cover. East of the Arkona Block (A) a syncline is terminated to the south, West of the Block (B) the top of the Ordovician is normal faulted, leaving an exaggerated southwestern part. Orange lines indicates fault traces of the Jütland-Møn Fault Zone (for location see Fig. 5-24, VE≈3.5, assuming an average velocity of 3000 m/s). 108

Fig. 5-29: Section of a shallow seismic line, crossing the Agricola-Svedala Fault (for location see Fig. 5- 24, VE≈2.5, assuming an average velocity of 3000 m/s). 109

Fig. 5-30: Seismic section crossing the CDF, for location see Fig. 5-24. (VE≈2.5, assuming an average velocity of 3000 m/s) 109

Fig. 5-32: Seismic section (near offset single channel) of crossing velocity pull down patches (for location see Fig. 5-24 or Fig. 5-31, VE≈4.5, assuming an average velocity of 3000 m/s). 110

Fig. 5-31: Map of the distribution of velocity pull down patches (orange circles), shown in the seismic. The light green line shows the location of Fig. 5-32, faults are differentially coloured (see Fig. 5-23). The CDF is marked as black line. 110

Fig. 5-33: 3D view of seismic sections crossing the Wolin Block and faults and flexures of the WFS. The faults in the NW concentrate on the Palaeozoic successions (as they are coloured in a dark green and orange). Further to the SE, faults and flexures appear in the Mesozoic (purple, blue and light green) successions. The thick black line marks the fault trace of the NJF, and the thick green line, the trace of the WF. 111

Fig. 5-34: Seismic sections crossing the WFS (for location see Fig. 5-24). (VE≈2.5, assuming an average velocity of 3000 m/s). 114

Fig. 5-35: Palaeozoic faults (PZ1-5) indicating strike slip displacements south in the Wolin Block (for location see Fig. 5-24). (VE≈2, assuming an average velocity of 3000 m/s). 115

Fig. 5-36: Seismic section crossing an anticline structure south in the Wolin Block and is bordered by a major fault – red line (for location see Fig. 5-24, VE≈2.5, assuming an average velocity of 3000 m/s). 115

Fig. 5-37: Restoration results of a seismic section, crossing the WFS in the north (Seidel et al. 2018, modified). For location see Fig. 5-24 or Fig. 5-33, line 2, and for legend see Fig. 5-38. (VE≈2, assuming an average velocity of 3000 m/s). 116

Fig. 5-38: Restoration results of a seismic section, crossing the WFS in the south. For location see Fig. 5-24 or Fig. 5-33, line 5 (Seidel et al. 2018, modified). (VE≈2, assuming an average velocity of 3000 m/s). 117

Fig. 5-39: Seismic section crossing the Faults of the WFS, the AKFZ and the Gryfice Fault Zone (for location see Fig. 5-24). (VE≈3, assuming an average velocity of 3000 m/s). 120

Fig. 5-40: 3D view of several NE striking seismic sections, crossing the Fault planes of the AKFZ (blue) and the Gryfice Fault Zone (green). 121

Fig. 5-42: Seismic sections, crossing the Gryfice Fault Zone, for location see Fig. 5-41. (VE≈2.5, assuming an average velocity of 3000 m/s). 122

Fig. 5-41: Detailed map of the Gryfice Fault Zone. Thick red lines mark the location of the seismic sections, shown in Fig. 5 42. 122

Fig. 5-43: Restoration of a seismic section, crossing the AKFZ in its central part from SW to NE. For location see Fig. 5-24 (Seidel et al. 2016, VE≈2.5, assuming an average velocity of 3000 m/s). GFZ-Gryfice Fault Zone (see Fig. 41 & 42). 123

Fig. 6-1: Compilation of time structure and thickness maps (all in TWT [ms]). Time structure maps: A–Top of Proterozoic (basement of Baltica); B–Top of the deformed Ordovician as part of the accretionary wedge, which is down-faulted south of the Arkona Block and reflects the base of the Middle Devonian Old Red Rügen Basin; C–Top of Triassic, showing the major inverted areas as anticlines south of the Wolin Block, NE of the NJF and AKFZ; E–Base of Cretaceous, indicating the northward deepening of the Cretaceous depression. Time thickness maps (note the flipped colour scale, with thin successions in blue, and thick deposits in red to white): D–thickness of the Palaeozoic to Mesozoic cover above the accretionary wedge, including successions between the Top of the deformed Ordovician and the base of Cretaceous; F–

Thickness of the Cretaceous and post Cretaceous successions, indicating a general thickening towards the NE (see also Appendix D). 126

Fig. 6-2: Major faults and unconformities on (A), Rügen with depth in m (FRANKE 2018, modified), compared with (B) an interpreted seismic section crossing the Arkona and Wolin blocks east of Rügen, with depth in ms. The location of well H9 1/87 is projected (for location see Fig. 5–2,corresponds to Fig. 5–8). NJF-Nord-Jasmund Fault, SF-Schaabe Fault, WF-Wiek Fault. VE≈3, assuming an average velocity of 3000 m/s. 127

Fig. 6-3: Compilation of seismic sections crossing the anticlines from SW to NE. As can be seen, all anticlines are restricted to inverted faults. AKFZ–Adler-Kamień Fault Zone, BF–Bergen Fault, KB–Kołobrzeg Block, NJF–Nord Jasmund Fault, SF–Strelasund Fault, SmF–Samtens Fault, TF–Trzebiatow Fault. VE≈3, assuming an average velocity of 3000 m/s. 129

Fig. 6-4: Schematic sketch of the Arkona Block with the bordering Wiek Fault (WF) and Skurup Fault (SK), such as the block crossing Jütland-Møn Fault Zone (JMF) and the Arkona Fault (AF). Shown stratigraphic successions are the Proterozoic Basement of Baltica (PB) with a Neoproterozoic to Ordovician sedimentary cover (C-O), Silurian successions covering Baltica (S), the folded Ordovician within the accretionary wedge (O), the Devonian to Carboniferous successions along the Wolin Block (D-C), the Permo-Jurassic strata thickening towards the centre of the NGB (P-J) and the Cretaceous to Quaternary successions (C). The undulating line marks the Pre-Permian (Asturian or Sudetian) Discordance. 130

Fig. 6-5: Comparison of various depictions of the CDF with the findings of this thesis. 131

Fig. 6-6: Results of the analysed faults in comparison with previous published fault patterns (grey solid lines – Palaeozoic faults according to THOMAS et al. 1993; MAYER et al. 1994; grey dashed lines – Mesozoic faults according to KRAUSS & MAYER 2004) crossing northern Germany (SEIDEL et al. 2018, modified). Faults at the Arkona Block are separated into deep faults, displacing the basement (brown coloured) and shallow faults, displacing the Ordovician, Permo-Triassic and Cretaceous successions (red coloured). Moreover, the Gat Fault is coloured light blue, WFS–green, AKFZ – light blue, and the Gryfice Fault Zone –dark blue. The dark red fault south of the Wolin Block is not assigned jet, but might be a prolongation of the Strelasund Fault. AB–Arkona Block, MRB–Middle Rügen Block, NJF–Nord Jasmund Fault, SF–Schaabe Fault, SRB–South Rügen Block, TTZ–Teisseyre-Tornquist Zone, UFZ–Usedom Fault Zone, WF–Wiek Fault. 133

Fig. 6-7: Distribution of Velocity Pull Down Patches (orange) mapped in the USO East area, compared with areas without a significant sea floor relief but filled channel structures as mapped by SCHLÜTER et al. 1998 (green) and the superior valley system as mapped by FLODÉN et al. 1995 (grey). Bathymetry by TAUBER (2012*a*-*i*). 136

Fig. 6-8: Schematic sketch of a relay ramp between overlapping faults and antithetic faults crossing the ramp, marking the sinistral strike direction along a strike slip fault (modified after PEACOCK & SANDERSON 1995). 137

Fig. 6-9: Possible tectonic phases triggering a sinistral strike-slip activity along the Palaeozoic deep faults (NJF-Nord Jasmund Fault, WF-Wiek Fault), which subsequently displaced the NNW striking Adler-Kamień Fault Zone (AKFZ). Scheme A shows a possible sinistral displacement during the Variscan foreland basin formation, while a N-S extension was active. Note the deformation ellipse. Scheme B illustrates the situation during the Late Carboniferous to Early Permian compression. A pure NE-SW orientated compression (as delineated by the deformation ellipse) would have forced reverse faulting along the NW-SE trending faults. The clockwise rotation of the Variscan orogenic complex (indicated by the yellow arrow) may have been transferred to Laurussia and in particularly on the TESZ. The resulting transpression may have led to a decreasing southeastward motion of the southern and northern Wolin Block (WB) and the Arkona Block (AB), and a relative sinistral displacement along the block-terminating faults (NJF, WF). 138

Fig. 6-10: Location of the purple Binz-Hamrane Fault (according to SEIFERT et al. 1993) and the dark red Pernille Fault (according to GRAVERSEN 2004). The green section 1 is based on results of GRAVERSEN (2004) and is compared with the actual results of a seismic section crossing the AKFZ (green section 2). 141

Fig. 6-11: Interpreted seismic section crossing the Rønne Graben, which is terminated by the Gat Fault (GF) to the west and by the Rønne Fault (RF) to the east, such as being cross-cut by the Pernille Fault (PF); AB-Arnager Block, LC-Lower Cretaceous, MJ-Middle Jurassic, SB-Surup Block; for location see Fig. 6 9, section 1 (GRAVERSEN 2004, modified). 142

Fig. 6-12: Seismic section crossing the Adler-Kamień master fault (blue) and the Pernille Fault (yellow). For location see Fig. 6 9, section 2. 142

Fig. 6-13: Burial history curve of well K 1/86 at the Gryfice Block with coloured thermal maturity zones (KOSAKOWSKIE et al. 2010, modified), Pr–Precambrian, Cm–Cambrian, O–Ordovician, S–Silurian, D–Devonian, C–Carboniferous, P–Permian, T–Triassic, J–Jurassic, Cr–Cretaceous, N–Neogene, Q–Quaternary. 144

Fig. 7-1: Overview of the Proterozoic to Cenozoic lithology, based on the STG 2016, illustrated for the three blocks: AB–Arkona Block, GB–Gryfice Block, WB–Wolin Block; and compared with the mapped horizons (for abbreviations see Fig. 4–4). The wells are represented in grey and discordances cursive. The main orogenic cycles and tectonic events are shown and set against the tectonic evolution along the TESZ–Trans-European Suture Zone and the TTZ–Teisseyre-Tornquist Zone (SEIDEL et al. 2018 & citations therein, modified). AKFZ–Adler-Kamień Fault Zone, CDF–Caledonian Deformation Front, NGB–North German Basin, TZ–Tornquist Zone, WPFS–Western Pomeranian Fault System. Numbers labelling the tectonic phases are described in the text. 145

Fig. 7-2: Main phases of the Post-Caledonian tectonic evolution along the TESZ and the Gryfice Graben, as part of the Tornquist Zone. 147

II Index of tables

Tab. 2-1: Summary of the previous exploration projects since the 20th century. 17

Tab. 4-1: Reflection seismic data used for USO East. 61

Tab. 4-2: Overview of the four German offshore wells (DIENER et al. 1988, 1989, LÜCK et al. 1987, PUPUNYN et al. 1990, REMPEL 1992*a*). 62

Tab. 5-1: Borehole information for the Proterozoic and its Neoproterozoic to Palaeozoic cover, based on HOTH al. (1993) for the onshore wells and on the original well description tables (DIENER et al. 1988, 1989, LÜCK et al. 1987, PUPUNYN et al. 1990) for the offshore wells. 73

Tab. 5-2: Borehole information for the Silurian cover, based on HOTH et al. (1993) for the onshore wells and on the original well description tables (DIENER et al. 1988, 1989, LÜCK et al. 1987, PUPUNYN et al. 1990) for the offshore wells. 75

Tab. 5-3: Borehole information for the deformed Ordovician, based on HOTH et al. (1993) for the onshore wells and on the original well description tables (DIENER et al. 1988, 1989, LÜCK et al. 1987, PUPUNYN et al. 1990) for the offshore wells. 77

Tab. 5-4: Borehole information for the Devonian, based on HOTH et al. (1993) for the onshore wells and on the original well description tables (DIENER et al. 1988, 1989, LÜCK et al. 1987, PUPUNYN et al. 1990) for the offshore wells. 79

Tab. 5-5: Borehole information for the Carboniferous, based on HOTH et al. (1993) for the onshore wells and on the original well description tables (DIENER et al. 1988, 1989, LÜCK et al. 1987, PUPUNYN et al. 1990) for the offshore wells. 81

Tab. 5-6: Borehole information for the Rotliegend, based on HOTH et al. (1993) for the onshore wells and on the original well description tables (DIENER et al. 1988, 1989, LÜCK et al. 1987, PUPUNYN et al. 1990) for the offshore wells. 84

Tab. 5-7: Borehole information for the Zechstein based on HOTH et al. (1993) for the onshore wells and on the original well description tables (DIENER et al. 1988, 1989, LÜCK et al. 1987, PUPUNYN et al. 1990) for the offshore wells. 86

Tab. 5-8: Borehole information for the Buntsandstein based on HOTH et al. (1993) for the onshore wells and on the original well description tables (DIENER et al. 1988, 1989, LÜCK et al. 1987, PUPUNYN et al. 1990) for the offshore wells. 89

Tab. 5-9: Borehole information for the Muschelkalk based on HOTH et al. (1993) for the onshore wells and on the original well description tables (DIENER et al. 1988, 1989, LÜCK et al. 1987, PUPUNYN et al. 1990) for the offshore wells, in this case without further stratigraphic informations. 92

Tab. 5-10: Borehole information for the Keuper based on HOTH et al. (1993) for the onshore wells and on the original well description tables (DIENER et al. 1988, 1989, LÜCK et al. 1987, PUPUNYN et al. 1990) for the offshore wells. 94

Tab. 5-11: Borehole information for the Jurassic based on HOTH et al. (1993) for the onshore wells and on the original well description tables (DIENER et al. 1988, 1989, LÜCK et al. 1987, PUPUNYN et al. 1990) for the offshore wells. 98

II Index of tables

Tab. 5-12: Borehole information for the Cretaceous based on HOTH et al. (1993) for the onshore wells and on the original well description tables (DIENER et al. 1988, 1989, LÜCK et al. 1987, PUPUNYN et al. 1990), for the offshore wells. 100

Tab. 5-13: References for single tectonic elements in the working area and its vicinity. 105

III List of abbreviations

Tectonic structures

AB	Arkona Block
AKFZ	Adler-Kamień Fault Zone
AH	Arkona High
ATA	Amorican Terran Assablage
CDF	Caledonian Deformation Front
CEBS	Central European Basin System
DB	Danish Basin
EEC	East European Craton
GB	Gryfice Block
MPT	Mid-Polish Trough
NGB	North German Basin
NJF	Nord Jasmund Fault
RFH	Ringkøbing-Fyn High
SF	Schaabe Fault
STZ	Sorgenfrei-Tornquist Zone
TESZ	Trans-European Suture Zone
TTZ	Tornquist-Teisseyre-Zone
UF	Usedom Fault
VDF	Variscan Deformation Front
WB	Wolin Block
WEP	West European Platform
WF	Wiek Fault
WFS	Wiek Fault System
WPFS	Western Pomeranian Fault System (German: Vorpommern Störungssystem **VPSS**)

Institutions

BGR	Bundesanstalt für Geowissenschaften und Rohstoffe / Federal Institute for Geosciences and Natural Resources
CEP	Central European Petroleum Ltd.
LUNG M-V	Landesamt für Umwelt Naturschutz und Geologie Mecklenburg Vorpommern / Geological Survey of Mecklenburg-Western Pomerania

Others

asl	above sea level
bsl	below sea level
GDR	German DemokraticRepublic
Ma	Million years
Pkm	Profile Kilometer
s/ms	seconds/milliseconds
TWT	Two way traveltime
USO	Project: Untergrundmodell südliche Ostsee
VE	Vertical exaggeration

Abstract

The southern Baltic Sea embodies an incomparable geological archive of the tectonic evolution of the 450 Ma old Trans-European Suture Zone (**TESZ**). This WNW to NW trending suture formed during the collision of Baltica and Avalonia and has accommodated the repeatedly changing stress regimes since then, as evidenced by numerous fault zones and systems. The German offshore part in the vicinity of Rügen Island is strongly block-faulted, with each block showing a specific geological pattern, enabling the reconstruction of the structural evolution of the area.

The work of this thesis is part of the USO working group of the University of Greifswald and the Geological Survey of Mecklenburg-Western Pomerania, which aims to build a unified three-dimensional tectonic model of the southern Baltic Sea area. This thesis presents the results of new structural investigations of the Arkona, Wolin and Gryfice blocks north and east of Rügen. Especially, conflicting structural analyses in the previous work are united into a consistent model.

The integrated interpretation of 144 reprocessed seismic vintage lines (original Petrobaltic data) and 23 high resolution academic seismic sections (from the Universities of Hamburg and Bremen), with additional consideration of on- and offshore wells, revealed 19 seismostratigraphic horizons that subdivide the succession between the Proterozoic basement and the Upper Cretaceous. Up to 100 faults of superior fault zones and systems control the tectonic situation. Besides NW trending deep faults formed during the Palaeozoic, for instance the Wiek and Nord Jasmund faults, and NNW trending Mesozoic faults and flexures that belong to the Western Pomeranian Fault System, other major faults such as the Adler-Kamień Fault Zone document the polyphase evolution of this area.

The restoration of selected seismic sections support the evaluation of separately generated faults and their reactivation, leading to a subdivision of the tectonic evolution of the area into six stages:

(1) The Caledonian Orogeny (Ordovician/Silurian) was accompanied by a NE-SW compression, resulting in the formation of the TESZ and an accretionary wedge within the upper crust. **(2)** The following S to SW trending extension of the Variscan Foreland (Devonian/Carboniferous) triggered the evolution of the Middle Devonian Old Red Rügen Basin south of the Wiek Fault. Further WNW to NW trending faults (e.g. Nord Jasmund Fault) subdivided the basin. **(3)** The advancing Variscan Orogeny (Late Carboniferous) caused an increasing NE-SW orientated compression and subsequently reactivated faults and tilted blocks (e.g. Lohme Sub-block). **(4)** The North German Basin and Mid Polish Trough formed by thermic subsidence in the S to SE of the research area during the Permo-Carboniferous. Simultaneously, the evolution of the Gryfice Graben as part of the Teisseyre-Tornquist Zone commenced. **(5)** Due to the Arctic-North Atlantic Rifting an E-W trending extension increased. Consequently, grabens such as the Gryfice Graben continued their subsidence. As the stress system rotated counter-clockwise, the shear strength increased along the NE trending faults. The Western Pomeranian Fault System developed due to intense transtension during the Keuper and Jurassic, and is characterised by pull-apart structures. **(6)** In the Upper Cretaceous, a NE-SW compression, forced by the Africa-Iberia-Europe convergence, triggered the reactivation of faults and flexures as reverse ones, the inversion of grabens (e.g. Gryfice Graben), and the formation of anticlines, for instance at the Wolin Block.

This thesis combines the calculation of gridded time structure maps and a detailed fault pattern analysis, and represents the base for a velocity- and subsequently depth-based 3D modelling.

Kurzfassung

Im Untergrund des deutsch-polnischen Ostseegebiets verbirgt sich ein unvergleichbares geologisches Archiv, welches Informationen zur tektonischen Entwicklung der 450 Ma alten Trans-Europäischen Sutur Zone bereithält. Diese WNW bis NW streichende Sutur entstand während der Kollision Baltikas und Avalonias und kompensiert seither die sich stetig verändernden regionalen Spannungsimpulse, was wiederum von diversen Störungszonen und -systemen belegt wird. Das Arbeitsgebiet im deutschen offshore Bereich, im Umkreis der Insel Rügen, ist tektonisch stark gestört und in separate Blöcke unterteilt. Jeder dieser Blöcke weist eigene geologische Besonderheiten auf und trägt damit zur Rekonstruktion der strukturgeologischen Entwicklungsgeschichte bei.

Die USO ("Untergrundmodell Südliche Ostsee") Arbeitsgruppe stellt eine Kooperation zwischen der Universität Greifswald und dem Landesamt für Umwelt, Naturschutz und Geologie Mecklenburg-Vorpommerns dar und hat sich die Erstellung eines dreidimensionalen tektonischen Modells der südlichen Ostsee zum Ziel gesetzt. Die vorliegende Arbeit zeigt die Ergebnisse der strukturgeologischen Untersuchung im Bereich der Arkona, Wolin und Gryfice Blöcke (nördlich und östlich Rügens), wobei die bisher kontrovers diskutierten Strukturen im Fokus liegen.

Durch die umfangreiche Interpretation von 144 reprozessierten seismischen Vintage-Profilen (Petrobaltic-Daten) und 23 hochauflösenden seismischen Profilen (der Universitäten Hamburg und Bremen) unter Berücksichtigung von on- und offshore Bohrungen, konnten 19 seimostratigraphische Horizonte zwischen dem Proterozoischen Grundgebirge und der Oberen Kreide kartiert werden. Etwa 100 Störungen, die übergeordneten Störungszonen und -systemen angehören, bestimmen die lokale tektonische Situation. Neben NW streichenden Paläozoischen Tiefenstörungen (wie z.B. der Wiek oder Nord Jasmund Störung), sowie NNW streichenden Mesozoischen Störungen und Flexuren des Vorpommern-Störungssystems, dokumentiert die Adler-Kamień Störungszone die mehrphasige Entwicklung dieses Gebietes.

Die Rückabwicklung einzelner ausgewählter Profile stützt die zeitliche Einordnung der Entstehung und Reaktivierung dieser Störungen. Final konnten sechs tektonische Phasen unterschieden werden:

(1) Die Kaledonische Orogenese (Ordovizium/Silur) wurde von einer NE-SW gerichteten Kompression begleitet, die zur Entwicklung der TESZ und eines Akkretionskeils innerhalb der oberen Kruste führte. **(2)** Durch die anschließende S bis SW gerichtete Dehnung des Variszischen Vorlandes (Devon/Karbon) entstand das Mitteldevonische Old Red Rügen Becken südlich der Wiek Störung und wurde von weiteren WNW bis NW streichenden Störungen (z.B. Nord Jasmund Störung) untergliedert. **(3)** Die fortschreitende Variszische Orogenese (Spätes Karbon) bewirkte eine zunehmende NE-SW gerichtete Kompression und die daraus resultierende Reaktivierung von Störungen und Verkippung einzelner Blöcke (z.B. Lohme Block). **(4)** Während des Permo-Karbons entwickeln sich infolge einer großräumigen thermischen Subsidenz das Norddeutsche Becken sowie der Polnische Trog im S-SE des Arbeitsgebietes. Dabei setzte auch die Absenkung des Gryfice Grabens, als Teil der Teisseyre-Tornquist Zone, ein. **(5)** Die Arktisch-Nord Atlantischen Riftprozesse verstärkten die E-W gerichtete Dehnung während der Trias, wodurch Gräben, wie z.B. der Gryfice Graben weiterhin subsidierten. Das Spannungssystem rotiert nachfolgend entgegen dem Uhrzeigersinn und verstärkt die Scherkomponente entlang der NW streichenden Störungen. Aufgrund der resultierenden Transtension entwickelt sich das, durch pull-apart Strukturen gekennzeichnete Vorpommern-Störungssystem im Keuper und Jura. **(6)** Während der Späten Kreide bewirkte die Afrika-Iberia-Europa Konvergenz die NE-SW gerichtete Kompression. Daraufhin wurden Störungen und Flexuren als Auf- oder Überschiebungen reaktiviert, Gräben, wie der Gryfice Graben invertiert und Antiklinalen z.B. entlang des Wolin Blocks ausgebildet.

Diese Arbeit vereint die Erarbeitung von Zeitstrukturkarten ausgewählter seismostratigraphischer Horizonte, mit einer detaillierten Strukturgeologischen Erkundung und dient somit als Grundlage für die Erstellung eines Geschwindigkeits- und anschließend Tiefen-basierten 3D Untergrundstruktur-modells.

1 Introduction

The southern Baltic Sea, and especially northern Germany and Poland, constitute a key geological locality for several reasons. Not only does this area embody the 450 Ma old Trans-European Suture Zone (TESZ), a remainder of the Caledonian collision of Baltica and Avalonia, located just below the water column, but it also comprises a late Palaeozoic to Mesozoic succession at the north-eastern margin of the North German Basin, and an inverted graben structure in prolongation of the Mid-Polish Trough. Given that the suture zone is located offshore, an unusually dense marine-geophysical measuring network of seismic profiles was established since the 1970s, with a much higher vertical and horizontal resolution of structures compared to onshore explorations.

The offshore area thus provides unique conditions for studying the suture zone and its polyphase reactivation in detail. By interpreting reprocessed seismic data with additional data from offshore and onshore wells, this thesis aims to analyse the structural inventory and reconstruct the evolution of the German offshore area north and east of Rügen Island. Moreover it attempts to resolve some of the existing controversial interpretations of the tectonic situation of this area.

The 2000 km long Trans-European Suture Zone crosses Europe from the North Sea along Poland until Romania, and forms the welded seam between the Proterozoic East European Craton and the Palaeozoic West European Platform (GUTERCH et al. 2010). In the area of the southern Baltic Sea it terminates the crust of Baltica and Avalonia, and was formed during the Caledonian Orogeny (e.g. BERTHELSEN 1992*a,b,* THYBO 2000). The polyphase reactivation of the area is evidenced by faults and flexures of different ages, separating or crossing the three main blocks of Arkona, Wolin and Gryfice. Therefore, the key locality around Rügen includes the: (1) Caledonian collisional phase, (2) post-Caledonian extensional phase, (3) Variscan collisional phase, (4) Permian to Mesozoic phase of basin subsidence, basin reorganisation and salt mobilisation, and (5) Upper Cretaceous–Tertiary compressive inversion phase (e.g. ZIEGLER 1990*a,b,* PHARAOH 1999, KRAWCZYK et al. 2002).

This thesis is integrated into the **USO** Project that establish a 3D model of subsurface structures in the southern Baltic Sea. The project is a cooperation between the University of Greifswald and the Geological Survey of Mecklenburg-Western Pomerania (LUNG M-V), and focuses on the structural inventory of the German Baltic Sea area between Fischland-Darß-Zingst Peninsula and Usedom Island. The research area is divided into two parts: **USO West** investigates the offshore area west of Rügen (DEUTSCHMANN et al. 2018), while **USO East** examines the offshore area north and east of Rügen, and is the research area of this thesis.

Studies of the sub-surface tectonics on the Island of Rügen can be traced back to the beginning of the 20th century, when DEECKE (1906) published a first structural map and block model. His proposed major faults were supported by later studies, such as the first geomagnetic measurements by VON BUBNOFF (1937/38 *in* KURRAT 1974), and seismic studies by VEB Geophysik Leipzig (later: GmbH Geophysik Leipzig; REINHARDT 1993*a,b*). Due to increasing interest in oil- and gas-bearing sediments in the 1960s, offshore seismic measurements were implemented and later improved within the former German Democratic Republic (GDR) (SEIFERT et al. 1993, KRAUSS & MAYER 2004, FÖRDERVEREIN "ERDÖL & HEIMAT E.V." REINKENHAGEN 2009). The organisation Petrobaltic, founded in 1975, explored the oil and gas prospects across the southern and south-eastern Baltic shelf area of the former GDR, Poland and the Soviet Union (REMPEL 2011). The Petrobaltic hydrocarbon exploration used deep reflection seismic technology (some kilometres' penetration depth) from 1978/79 until 1989 in the East German sector, between Fischland-Darss Peninsula and Usedom Island (SCHLÜTER et al. 1997*a*). For political reasons, the results were initially kept confidential, but after the fall of the iron curtain and the political shift in 1989, they became accessible for research and publication (REINHARDT 1993*a,b*, SEIFERT et al. 1993, SCHLÜTER et al. 1997*a*,*b*, DEKORP-BASIN RESEARCH GROUP 1999, GUTERCH et al. 1999, MAYER et al. 2000). The deep seismic Petrobaltic data were used by the research projects SASO (SCHLÜTER et al. 1997*a*) of the Federal Institute for Geoscience and Natural Resources (BGR), and SASO II (MAYER et al. 1998) of the University of Greifswald to enhance the geological, tectonic, and sedimentary analyses of the offshore area, especially around Rügen.

Several further research projects aimed to analyse the stratigraphic and tectonic situation of the North German Basin as part of the Central European Basin System (CEBS) (see **Chapter 2)**. International projects, such as BABEL and EUROPROBE (GEE & ARTEMIEVA 2000, BABEL WORKING GROUP 1993), and national projects, such as DEKORP-BASIN'96 (BLEIBINHAUS et al. 1999, DEKORP-BASIN RESEARCH GROUP 1999, KRAWCZYK et al. 1999; see **Chapter 2**), focused on the deeper crust by far deep (wide angle) seismic measurements with tens of kilometres' penetration depth. Their main interest was the Caledonian collisional zone between Baltica and Avalonia, thus between the top of the Palaeozoic successions and the inner mantle reflections (BLEIBINHAUS et al. 1999, DEKORP-BASIN RESEARCH GROUP 1999, KRAWCZYK et al. 1999). Since 2000, subsequent projects of the Western Pomeranian Fault System VPSS I & II have been initiated to close the gap between seismic offshore and onshore lines (MAYER et al. 2000, MAYER et al. 2001*a*). Moreover, detailed studies of the TESZ and the Caledonian accretionary wedge have been undertaken (MAYER et al. 2000, MAYER et al. 2001*a,b*, KRAUSS & MAYER 2004).

Since 1998, academic studies of the Baltseis and NeoBaltic projects (e.g. HÜBSCHER et al. 2004, 2010, HANSEN et al. 2007, AL HSEINAT et al. 2016, AL HSEINAT & HÜBSCHER 2017) of the Universities of Hamburg and Aarhus (Denmark) and of the Baltic Gas project (e.g. JØRGENSEN & FOSSING 2011, TÓTH 2013) have completed new geophysical surveys, such as single-beam echo sounding and shallow seismic data with tens to hundreds of meters' penetration depth, along the southern and central Baltic Sea (**Chapter 2**).

These previous research projects have investigated different tectonic features along the transition from the East European Craton towards the West European Platform, such as the Mid-European Caledonian Orogen, the North German Basin, or the Western Pomeranian Fault System. Depending on their research targets, they used various geophysical methods and different horizontal and vertical scales. Consequently, as discussed in **Section 3.3**, certain structures, such as the Nord Jasmund Fault, have received contradicting interpretations and terminology has been used in a number of different ways. Moreover, the traceability of the research outcomes, especially of the old projects, was impeded due to an incomplete appendix (such as missing interpreted seismic sections). In addition, major technical developments in seismic measurement but also in processing and interpretation techniques have been achieved during this time span of over 100 years of exploration. This means that a consistent model of the subsurface including the seismostratigraphic horizons, and especially a detailed structural investigation of the appearance, character and evolution of individual tectonic features, are missing.

This thesis aims to resolve the conflicting existing analyses, bring together the results of the previous work, and answer the following research questions:

- What are the major seismostratigraphic horizons known from onshore wells that can be detected and traced offshore north and east of Rügen?
- The accuracy and completeness of the displayed fault pattern in the vicinity of Rügen varies in the literature. Which faults and flexures can be mapped and classified in the research area? What are their main characteristics, e.g. their strike- and dip-direction, fault classes and segmentation? Which faults can be associated with fault zones or systems and do they interact with each other? Which lithostratigraphic horizons are displaced and what can be inferred about their origin and reactivation phases in relation to the changing regional palaeostress system?
- Special structural features have been documented along the Arkona Block. The Caledonian Deformation Front is agreed to terminate the accretionary wedge towards the north, but its course is presented in a number of different ways. Is it possible to trace this lineament by the seismic sections? What does the accretionary wedge look like? Moreover, several syncline structures have been documented within single seismic sections, which are indications for fluid flow or Quaternary channels. This thesis aims to describe and clarify their character and extension.

To address these questions, three different sets of seismic sections were simultaneously interpreted using the software SeisWare™ and its 3D application: (i) vintage data of the Petrobaltic dataset, which was reprocessed by the SASO Project and provided by the BGR; (ii) state-of-the-art reprocessed Petrobaltic data, provided by Central European Petroleum Ltd (CEP); and (iii) recently measured and processed shallow seismic sections from the Universities of Hamburg (courtesy C. Hübscher) and Bremen (courtesy V. Spieß). The results presented in this thesis are time structure maps of the main seismostratigraphic horizons showing the distribution, morphology, and vertical variation (in TWT) of major lithostratigraphic units. Moreover, detailed information is given about tectonic elements, such as horst and graben structures, and fault zones and systems, while examining their evolution by an individual restoration workflow, using the software of MOVE™ (Midland Valley). A detailed outline of this thesis is provided below.

1 Introduction

This thesis is organised as follows.

Chapter 1 outlines the background, main goals and structure of this work.

Chapter 2 gives an overview of the previous work since the beginning of the 20th century and summarises the main surveys and accompanying literature.

Chapter 3 represents the geological framework and is subdivided into three sections. First, the regional geographical and geological setting is described, then the geological evolution is discussed, and finally, the various different tectonic terms used in the literature are introduced.

Chapter 4 introduces the dataset used in this thesis and summarises the measurement and processing of the seismic data in the previous projects. Moreover, the data analysis and interpretation with the software SeisWare™ are presented, as well as the data restoration using MOVE™.

Chapter 5 presents the results of this thesis. It is subdivided into a presentation of the mapped and gridded horizons between the top of Proterozoic until the base of Cretaceous in Section 5.1, and a description of structural features, such as faults and flexures in the three main blocks Arkona, Wolin and Gryfice, in Section 5.2. This second part shows also the results of the kinematic analysis (restoration).

Chapter 6 includes the interpretation and discussion of the results. Section 6.1 discusses the results of the mapped horizons, whereas Section 6.2 concentrates on the detected faults and other structural features in the Arkona, Wolin and Gryfice blocks.

Chapter 7 summarises the polyphase evolution of the working area with regard to the structural inventory and the kinematic analysis at the three single blocks. Furthermore, the raised questions in Chapter 1 will be answered.

Chapter 8 provides an outlook for further work and mentions arisen questions.

Final Remarks:

The author is not allowed to transmit the raw data of this thesis to third parties. Therefore, these data (seismic lines and well logs) cannot be provided on an accompanying data disc, but are archived and managed at the Geological Survey of Mecklenburg-Western Pomerania, such as the Universities of Hamburg and Bremen.

Furthermore, the shot or CDP numbers are not visible in the seismic section presented in Chapters 5 to 7. However, a vertical and horizontal scale is always added.

2 Outline of previous work

The tectonic and stratigraphic situation of Rügen Island and its surroundings have been a focus of scientific interest since the beginning of the 20th century. One of the first structural maps was published by DEECKE (1906) (**Fig. 2-1**) in the "Proceedings of the Royal Prussian Academy of Sciences" ("Sitzungsbericht der Königlich Preussischen Akademie der Wissenschaften"). Deecke's elaborate studies were based on shallow wells containing Cretaceous, Tertiary, and Quaternary strata. He analysed NW-SE (Hercynian) striking faults by mapping, such as the regional occurrence of brine springs and other evidence of deformation, and he discovered the prominent Strelasund Fault between Stralsund and Rügen. Moreover, Deecke developed the first block model with the uplifted blocks of "Jasmund", "Bergen", and "Poseritz", where these horst structures were separated by NE and SW dipping normal faults that bordered small graben structures in the Upper Cretaceous, typically filled with Tertiary sediments. Later works, such as the first geomagnetic measurements by BUBNOFF (1937/38 *in* KURRAT 1974), confirmed the position and character of the faults (KURRAT 1974).

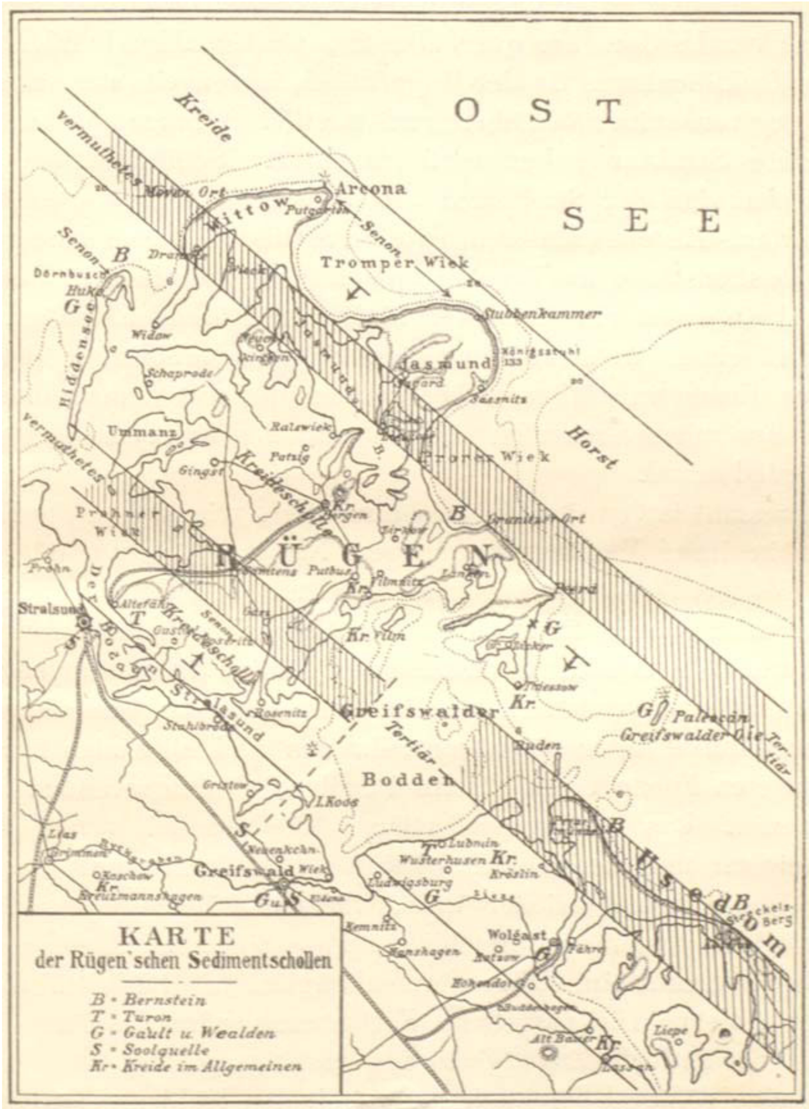


Fig. 2-1: One of the first tectonic maps by DEECKE (1906).

According to REINHARDT (1993*a*, and references therein), the first reflection seismic studies in the former German Democratic Republic (GDR) started in 1951 and were run by **VEB Geophysik Leipzig** (later: Geophysik GmbH Leipzig). Since 1968, they have compiled a reflection seismic atlas (with scales of 1:100000 to 1:500000) covering the whole GDR, which was updated every one to three years. The first maps were published by REINHARDT (1993*a*).

Drilling the first well Reinkenhagen 2a in March 1961 led to the discovery of an oil reservoir which significantly increased the geological and geophysical interest in hydrocarbon-bearing fluids and gases of the Upper Carboniferous and Permian sediments around Rügen (SEIFERT et al. 1993,

KRAUSS & MAYER 2004, FÖRDERVEREIN "ERDÖL & HEIMAT E.V." REINKENHAGEN 2009). As a result, the tectonic and stratigraphic history of the area of northern Germany received more interest in the 1980s.

Detailed information about investigations by the former East German company “VEB Geophysik Leipzig” between 1962 and 1987 is given by SEIFERT et al. (1993), who lists their extensive geophysical work, including gravimetric, magnetic, and seismic surveys. A dense network of 2D seismic profiles, partly conducted by research vessels, was implemented between 1962 and 1969 (SEIFERT et al. 1993):

1962/63 Using the vessel *Geophysica,* the Baltic Sea shelf area was explored by a 4x4 km network of magnetic profiles (result: ΔT-map with a scale of 1:200000 and an isonormal distance of 20 nT) and first sea-seismic test-profiles (seismics with the Two-Ship-Technology, explosions as trigger and analogue recording on photo paper)

1962 11 reflection seismic and two refraction seismic profiles were measured in the offshore area between Warnemünde and the Pomeranian Bay ("Oderbucht") with the Soviet research vessel *Wladimir Obrutschew*

1964/66 The Soviet seismic vessel *Juri Godin* was employed in addition to the research vessel *Geophysica* (using magnetic tape recording since 1964), which sank on 6 May 1966, near Sassnitz

1967 Gravimetric recording along the Southern Baltic Sea by *Geophysica* with a point density of 1 point per 4 km² (result: Bouguer gravity map of 1:100000 scale with 1 mGal isogram distance). The research vessel *Georgius Agricola* started with a one-ship technology for seismic data acquisition. The trigger worked with three or five groups, covering two times the setup length from 400 to 1200 m and 24 to 48 traces, measuring additional CDP test profiles covering up to 12 times

1969 Sea seismic measurements were terminated, although the research operations were not yet finished; the scientists worked on seismic trigger methods without explosives

1970 *Georgius Agricola* was handed over to the Institute for Baltic Sea Research (Institut für Ostseeforschung Warnemünde - IOW) and renamed *Alexander von Humboldt*

1971 Shallow-water seismics were terminated in the sensitive fish farming areas, such as the surroundings of Rügen Island, Hiddensee Island, and in the restricted shallow-water areas (bodden areas) of Western Pomerania

Within this time frame, the sea seismic technology and applied methods were significantly improved, and the analogue processing steps were enhanced, especially by the development of algorithms for the frequency and wave number filters. Thus, the interfering waves which are typical for sea seismics could be reduced (SEIFERT et al. 1993).

In 1975, the ***Petrobaltic***, a joint research group of the former GDR, the Soviet Union, and Poland, was founded (REMPEL 1992*a,b,* 2011). Consequently, the investigations along the Baltic Shelf were separated from the formerly INTERMORGEO program and became the working area of Petrobaltic (SEIFERT et al. 1993). The research vessel *Kopernik* took over the seismic and magnetic explorations along the East German and North Polish Shelf. For the shallower areas of less than 12 m depth, shallow water CDP seismics were generated up to 6 m bsl, with 10,200 profile km until 1987 by VEB Geophysik Leipzig with the container river boat *Impuls* (SEIFERT et al. 1993).

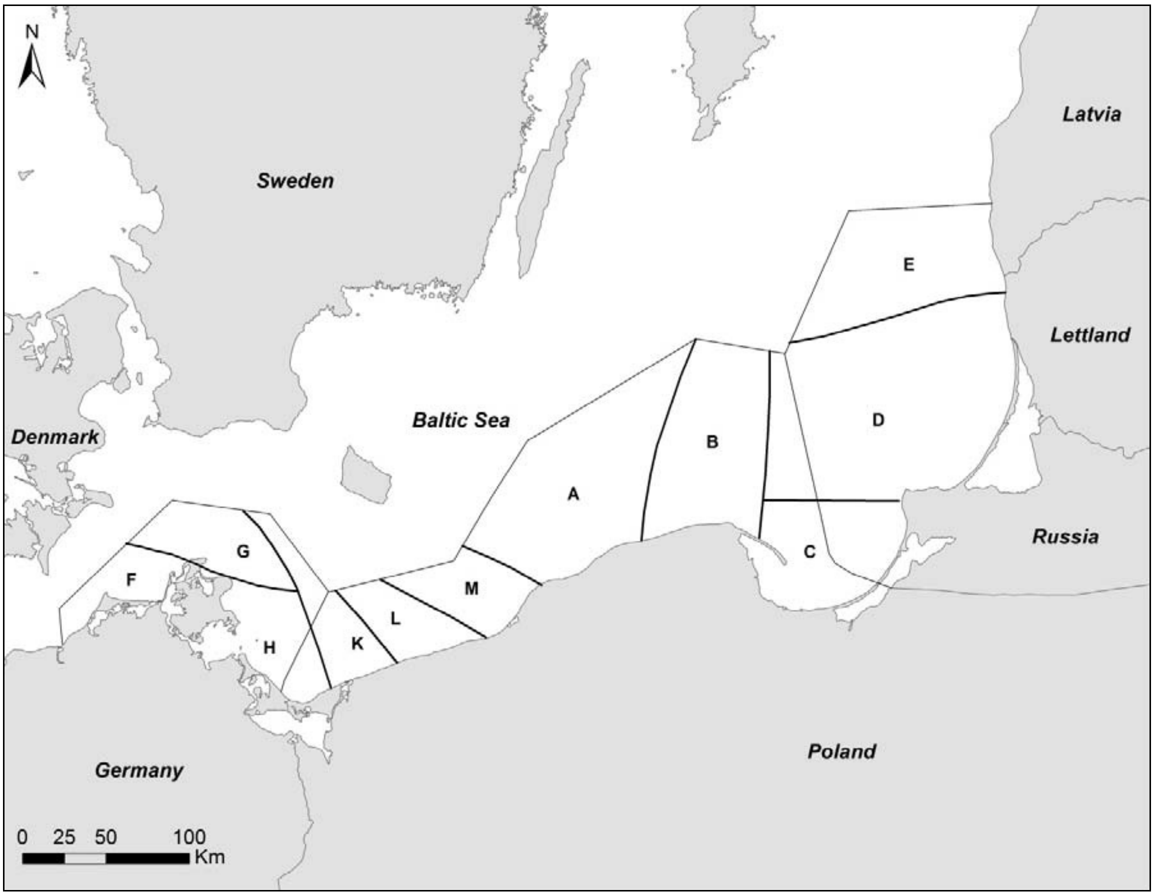


Fig. 2-2: Working area of the Petrobaltic (based on REMPEL 1992*b*)

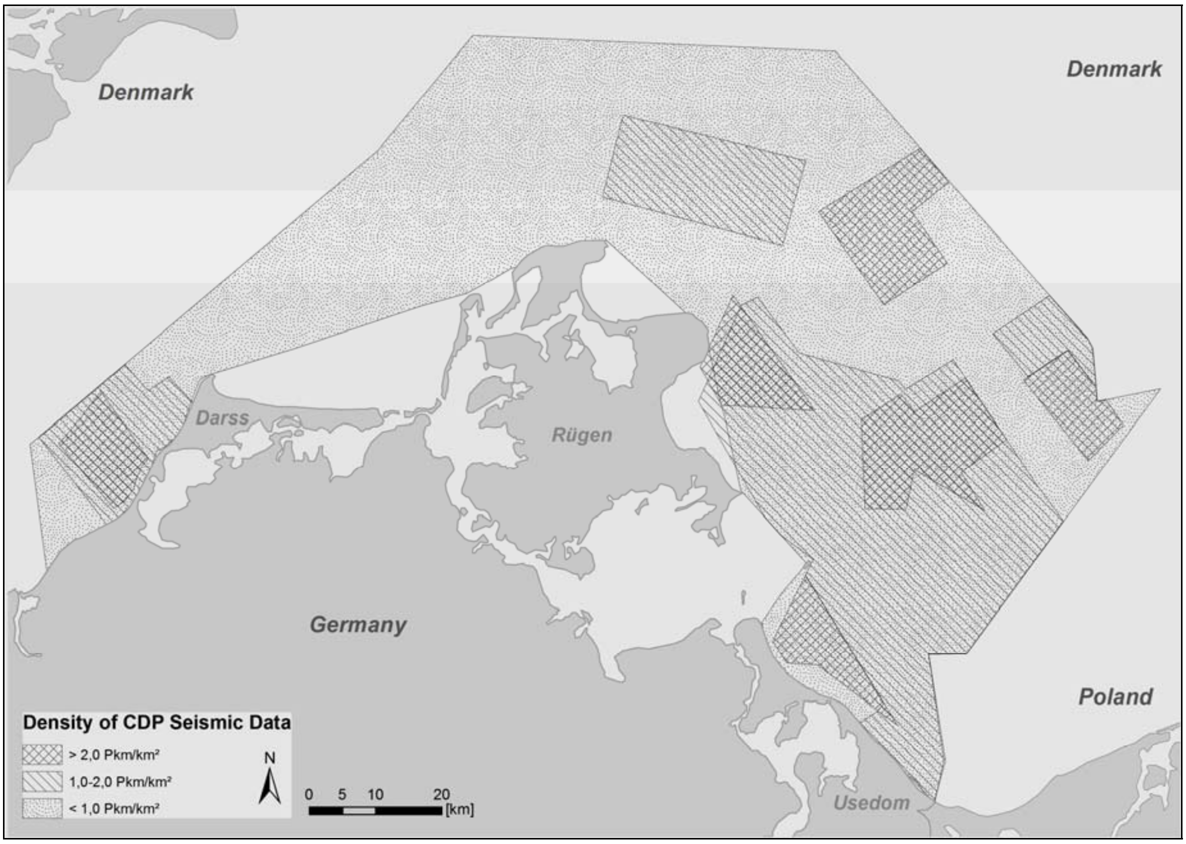


Fig. 2-3: Profile density of the Petrobaltic CDP seismic data in the German sector (based on REMPEL 1992*a*).

Fig. 2-4: The drilling platform "Petrobaltic" in Poland as an example for all other offshore wells erected and used by Petrobaltic (photos provided by the Erdölmuseum Reinkenhagen).

The first "modern" reflection seismic investigations of Petrobaltic started in 1978/79 in the GDR (SCHLÜTER et al. 1997*a*). The aim of these investigations, which comprised the offshore areas of East-Germany, Poland, and the former Soviet Union, was the exploration of hydrocarbon-bearing fluids and gases. In particular, the German sub-region extended from the Darss to the German-Polish border on Usedom. The research area of Petrobaltic was subdivided into several blocks (A-M, **Fig. 2-2**), whereas the blocks F, G, and H were located in the eastern offshore part of the GDR. The explored German shelf area has a size of 6644.5 km². The investigation phase was divided into three parts: for the regional measurements, a profile grid of 2x4 km was used with 5952 km profile length; for the prospecting investigations, a 2x1 km grid with 4749 km; and for the detail measurements, a 1x1 km grid with 1579 km (REMPEL 1992*a*). **Fig. 2-3** shows the varying profile density within the German working area. Between 1986 and 1990, four German offshore wells were drilled by Petrobaltic at the eastern and northeastern side of Rügen (G14 1/86, H9 1/87, K5 1/88 and H2 1/90). The photos of the "Petrobaltic" well in Poland (**Fig. 2-4**), which was installed at the same time, give an impression of the offshore wells within the Baltic Sea. These wells were extensively petrologically investigated and the occurrence of macro- and microfossils were studied. Moreover, different geophysical logs were measured, such as sonic logs (as acoustic logs or vertical seismic profiling - VSP), as well as gamma ray and resistivity logs (SCHLÜTER et al. 1997*a*).

At the same time the "VEB Erdöl-Erdgas Gommern" (EEG) explored the western part of East Germany, between Rostock and Wismar (SCHLÜTER et al. 1997*a*). The results had to remain confidential until the reunification of Germany in 1990. Then, the data were published (e.g. FRANKE 1990, HOFFMANN 1990, REINHARDT 1993*b*, SEIFERT et al. 1993, SCHLÜTER et al. 1997*a,b*, DEKORP-BASIN RESEARCH GROUP 1999, GUTERCH et al. 1999, MAYER et al. 2000, KRAUSS & MAYER 2004) and were allowed to be reused.

Simultaneous with the Petrobaltic efforts during the 1970s to 80s, the Swedish and Danish parts of the Baltic Sea were explored by several companies with industrial seismic surveys for oil and gas purposes. ***Oljiprospektering AB*** (***OPAB***, now Svenska Petroleum) explored the Swedish offshore area in detail and acquired about 33000 km of 2D seismic sections with changing acquisition parameters (SOPHER & JUHLIN 2013). After the data became available for scientific use, SOPHER & JUHLIN (2013) presented a reprocessing workflow, which also improved the interpretation of the area north of the Tornquist Zone. The Danish offshore area, especially around Bornholm, was surveyed by ***Jebco Seismic Ltd.*** and Western Geophysical, and the seismic data were used for later scientific research (THOMAS & DEEKS 1994, GRAVERSEN 2004). During the 1990s, the database was extended by first wide angle seismic sections of the scientific ***BABEL*** project, focussing on the structure of the lithosphere along the transition from the Baltic Shield towards the Caledonides, crossing northern Germany. Thus, the Tornquist Zone and in particular its northern branch, the Sorgenfrei-Tornquist Zone, was seismically visualized for the first time (BABEL WORKING GROUP 1993).

The research project “Structural Atlas of the Southern Baltic Sea” ("Strukturatlas südliche Ostsee", ***SASO***, SCHLÜTER et al. 1997*a*) of the Federal Institute for Geoscience and Natural Resources (BGR Hannover) carried out a revision of the Petrobaltic data. While Petrobaltic used the high-quality results exclusively for hydrocarbon explorations, the SASO project aimed to reconstruct the geological, tectonic, sedimentological, and facial history of the area north and east of Rügen. The reprocessing of some seismic profiles, primarily consisting of Permian and Mesozoic layers, improved the resolution of the main horizons between 250 and 2500 ms (SCHLÜTER et al. 1997*b*). The original SASO project, founded in 1993, was operated by the Federal Institute for Geosciences and Natural Resources (BGR, Bundesanstalt für Geowissenschaften und Rohstoffe) and focused on the structural geological interpretation of the profiles along the border between the Baltic Plate and the Caledonian Basin north and east of Rügen. An additional project named *SASO II* was implemented by a research group at the Ernst-Moritz-Arndt-University of Greifswald, and concentrated on the pre-Quaternary structural patterns of the shallow water areas such as the Greifswalder Bodden southeast of Rügen (MAYER et al. 1998). Both projects were completed in 1997/98.

Between 1992 and 2000, the Lithosphere Dynamics Program ***EUROPROBE*** (GEE & ARTEMIEVA 2000) investigated the origin and evolution of the continent. Nine multi-disciplinary projects, including the **EUROBRIDGE** and **Trans-European Suture Zone (TESZ)** projects, investigated lithospheric structures along different suture zones of Europe **(Fig. 2-5).** The focus of the **EUROBRIDGE** project was the Palaeoproterozoic accretion of Sarmartia and Fennoscandia (GEE & ARTEMIEVA 2000), for which a 1700 km long seismic profile (deep seismic survey) was acquired. It intersected a major boundary of the EEC, which transects the Baltic Fennoscandian Shield to the Ukrainian

Fig. 2-5: Overview of some EUROPROBE projects (modified after GEE & ARTEMIEVA 2000).

Shield (Archean core of Sarmatia/Ukraine). The **TESZ** project studied the Phanerozoic accretion and the development of continental lithospheres by conducting various geophysical experiments: the teleseismic tomographic experiment (*TOR*) aimed to define the complex suture in the mantle, extending from the lithosphere to the asthenosphere beneath the TESZ (PHARAOH 1999). The wide-angle refraction studies *POLONAISE 97* and *CELEBRATION 2000* examined variations in MOHO depths and structural contrasts of the lithosphere. *BASIN 96* performed deep seismic reflection experiments. Moreover, "3D processing of seismic refraction data sets and magnetotelluric experiments, facilitate the correlation of deep and shallow structures within the lithosphere of the TESZ, and imaged Palaeozoic orogenic sutures" (GEE & ARTEMIEVA 2000). Finally, measurement series along drill cores and outcrops aimed to answer questions about the tectono-thermal history of the Palaeozoic terrane accretion, the Permian-Mesozoic subsidence, and Cenozoic inversion history of the sedimentary basin (GEE & ARTEMIEVA 2000).

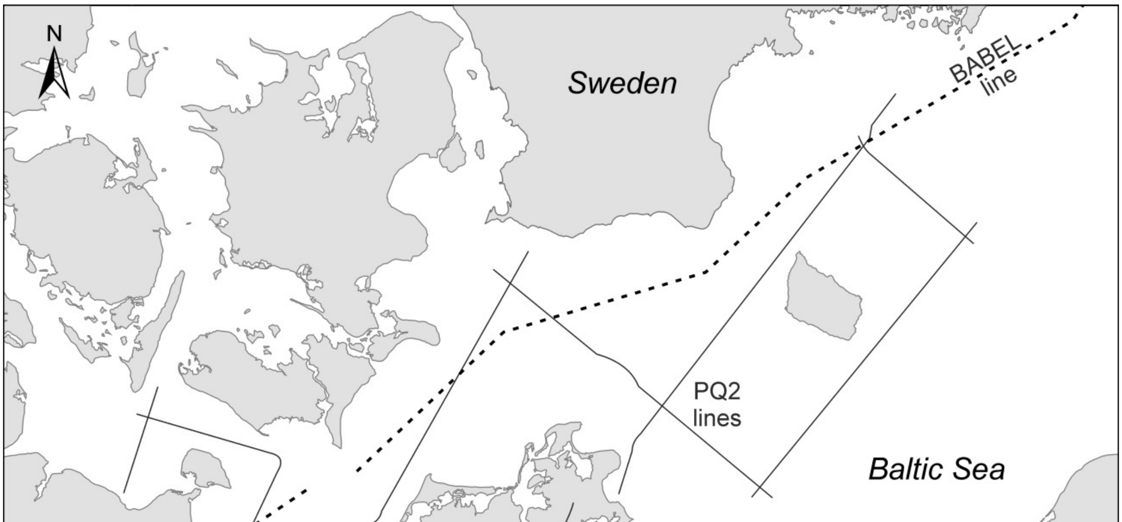


Fig. 2-6: Overview of the SASO, DEKORP-Basin'96 and VPSS research areas (based on BABEL WORKING GROUP 1993, KRAWCZYK et al. 1999, KRAUSS & MAYER 2004)

Another important project was ***DEKORP-BASIN'96*** (BLEIBINHAUS et al. 1999, DEKORP-BASIN RESEARCH GROUP 1999, KRAWCZYK et al. 1999; **Fig. 2-6**), which focused on the evolution of the North German Basin as an intracontinental basin and the Caledonian Collisional Zone between Baltica and Avalonia, using integrated, wide-angle reflection and refraction seismic surveys (BLEIBINHAUS et al. 1999, DEKORP-BASIN RESEARCH GROUP 1999, KRAWCZYK et al. 1999). In 1996, approximately 1250 km of deep marine and land seismic data were gathered in the northeast of Germany and the southern Baltic Sea. The goal was to visualise the entire basin and its margins, especially between the top of the Palaeozoic and the inner mantle reflections (DEKORP-BASIN RESEARCH GROUP 1999). BLEIBINHAUS et al. (1999) presented a 3D velocity model that illustrated the important structures of the transition zone, such as the location of the Caledonian Deformation Front (CDF), the "Rønne Graben", or the pull-apart structures of the Tornquist Zone.

Due to a spatial gap between the seismic offshore and onshore lines of the DEKORP-project, the Western Pomeranian Fault System project (***VPSS I,*** **V**or**P**ommern **S**törungs**S**ystem, **Fig. 2-6**) was initiated in 2000, which reprocessed and re-interpreted earlier CDP seismic data (MAYER et al. 2000, MAYER et al. 2001*a*). The higher resolution of the time sections offered more detailed information of the Trans-European Fault Zone (TEFZ). The main focussed area for the ***VPSS II*** project **(Fig. 2-6)** of the University of Leipzig was in the north-eastern part of the DEKORP-Line BASIN'96 to map the reflection zone of the Caledonian basement with the accretionary wedge (MAYER et al. 2001*b*, KRAUSS & MAYER 2004).

After the publication of the *Millennium Atlas* (2003) of the petroleum geology of central and northern North Sea, the **Southern Permian Basin Atlas** (***SPBA***, **Fig. 2-7**) project, a joint project of the geological surveys of the UK, Belgium, the Netherlands, Denmark, Germany, and Poland, was initiated in March 2005. This project was also supported by exloration & production companies, including GDF Suez (now "Neptune Energy"), RWE Dea, Shell, Total, Wintershall, and E.ON Ruhrgas. The resulting GIS-based atlas was published in 2010 by DOORNENBAL & STEVENSON, which described the regional geology of the South Permian Basin (SPB), its stratigraphic development, and its petroleum generation and migration. While this expansive atlas covers a large portion of middle to northern Europe, its resolution, especially along the German offshore region, is less than optimal.

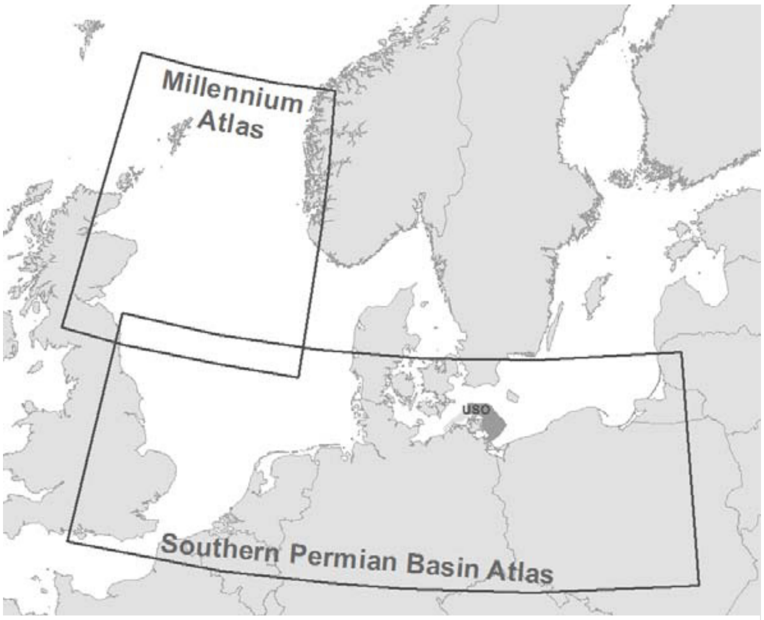


Fig. 2-7: Focused areas of the Millennium Atlas and SPBA (modified according to DOORNENBAL et al. 2010).

Other 3D structural models are available, including SCHECK & BAYER (1999) for the North German Basin (**Fig. 2-8**), LAMARCHE et al. (2003) for the Polish Basin, and HANSEN et al. (2007) for the southwestern Baltic Sea area along the Bay of Kiel and Bay of Mecklenburg.

The 3D model for the eastern part of the North German Basin includes an area between the Trans-European Fault in the north, the Elbe Fault System in the south, and the Polish Basin in the west. This model comprises Permian to Quaternary sediments and describes the subsidence history of the basin as part of the evolution of the basin (SCHECK & BAYER 1999).

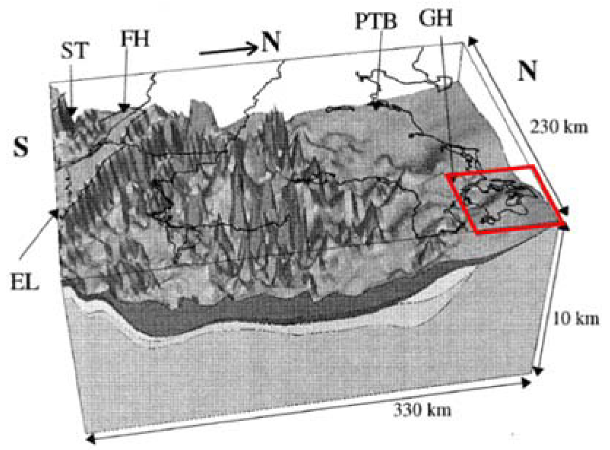


Fig. 2-8: Example of a 3D model with the relief view of the top Zechstein (modified after SCHECK & BAYER 1999). Abbreviations used: AH-Altmark High, EL-Elbe Fault system, FH-Flechtlingen High, GH-Grimmen High, ST-Sub-Hercynian Trough, PTB-Permo-Triassic Basin, PPD-Pre-Permian Depression, RL-Rheinsberg Lineament, the red rectangle marks the location of Rügen, and therefore the working area of USO.

The grids of the 3D model of the Polish Basin cover an area of 667x633 km (most of Poland), and has a horizontal resolution of about 16 km. The model contains five sedimentary layers: Zechstein, Triassic to Lower Cretaceous, Upper Cretaceous, Palaeocene, and Mio- to Pliocene. The depths and thicknesses of this model are the basis for the structural analysis and interpretation of the tectonic inversion of the Polish Basin and the crustal structure underneath it by LAMARCHE et al. (2003).

Since the models of SCHECK & BAYER (1999) and LAMARCHE et al. (2003) focused on the onshore regions, the southern Baltic Sea area in the vicinity of Rügen has only marginally been covered.

The 3D model of HANSEN et al. (2007) incorporates six sedimentary layers from the base of the Cenozoic until the base of Zechstein, covering an area of 190x110 km with a horizontal resolution of about 600 m. It is located west of the USO working area.

Since 1998, shallow seismic data have consistently been collected with one survey per year by the universities of Hamburg and Bremen. The **Baltseis** and **NeoBaltic** projects from the University of Hamburg (HÜBSCHER et al. 2004, 2010, HANSEN et al. 2005, 2007, AL HSEINAT et al. 2016, AL HSEINAT & HÜBSCHER 2017) involve a dense shallow seismic and single-beam echo sounding data set, covering the southern Baltic Sea area. These projects aim to explore the post-Permian structural evolution, and the accompanying salt dynamics and neotectonic processes. The **Baltic Gas** project of the University of Bremen conducted further seismic studies along the Skurup Block and around Bornholm (e.g. JØRGENSEN & FOSSING 2011, TÓTH 2013). Here the focus was the biogenic shallow gas deposits, also along the Arkona High (see **Sections 5.2.1.7** and **6.2.1.2**).

At least for the eastern part of Germany a geological dictionary is available, defining regional units and structures, which has constantly been updated since 2003 by FRANKE (2018).

Tab. 2-1: Summary of the previous exploration projects since the 20th century.

Year	Project	Reference
1906	• First tectonic model of Rügen and its vicinity, based on shallow research wells	DEECKE (1906)
1935-1940	• Geophysical survey of the German Empire	KURRAT (1974)
1937/38	• First magnetic measurements in northern Germany	BUBNOFF (1937/38)
1962-1990	• Numerous deep reconnaissance and exploration drill holes in the former GDR (in Mecklenburg Western Pomerania performed by **VEB Erdöl-Erdgas Gommern and VEB Erdöl-Erdgas Grimmen**)	HOTH et al. (1993)
1951-1987	• Diverse geophysical measurements, performed by **VEB Geophysik Leipzig** in the former GDR	REINHARDT (1993*a,b*), SEIFERT et al. (1993)
1966	• First onshore reflection seismic measurements (VEB Geophysik Leipzig)	LINKE & KRAUSS (1966)
1967	• Results of first Pre-Permian outcrops	ALBRECHT (1967)
1968-1971	• Enhanced geological-geophysical exploration, especially of the Pre-Permian, by the socialist staff collective “Rügen-Hiddensee” of the VEB Erdöl-Erdgas Gommern and VEB Geophysik Leipzig (Expedition Nord)	KURRAT (1974)
1973/74	• New results on the oil and gas prospects by the ZGI Berlin • Doctoral Thesis of W. Kurrat	KURRAT (1974)
1970s to 1980s	• Industrial seismic offshore surveys in Sweden (e.g. OPAB, Oljeprospektering AB) and Denmark (e.g. Jebco Seismic Ltd.)	SOPHER & JUHLIN (2013), GRAVERSEN (2004)
1975-1990	• Petrobaltic (joint venture of the former GDR, Poland, and the former Soviet Union)	REMPEL (2011)
1989-1993?	• BABEL	BABEL WORKING GROUP (1993)
1993-97/98	• SASO & SASO II	SCHLÜTER et al. (1997*a,b*), KRAUSS & MAYER (2004)
1992-2000	• EUROPROBE with TESZ	GEE & ARTEMIEVA (2000)
1996-2000?	• DEKORP-BASIN’96	DEKORP-BASIN RESEARCH GROUP (1999)
1997-1999?	• VPSS I & II	MAYER et al. (2000), MAYER et al. (2001*a,b*), KRAUSS & MAYER (2004)
1997	• POLONAISE	GUTERCH et al. (1999), KRYSIŃSKI et al. (2000)
1998-2015	• Baltseis & NeoBaltic	HÜBSCHER et al. (2004, 2010), AL HSEINAT & HÜBSCHER (2017)
2005-2010	• Southern Permian Basin Atlas (SPBA)	DOORNENBAL & STEVENSON (2010)
2009-2011	• Baltic Gas	JØRGENSEN & FOSSING (2011)
2012	• PolandSPAN	KRZYWIEC et al. (2014), ION (2018)
Since 2012	• USO	OBST et al. (2015) DEUTSCHMANN et al. (2018), SEIDEL et al. (2018)

3 Geological framework

3.1 Regional setting of the working area

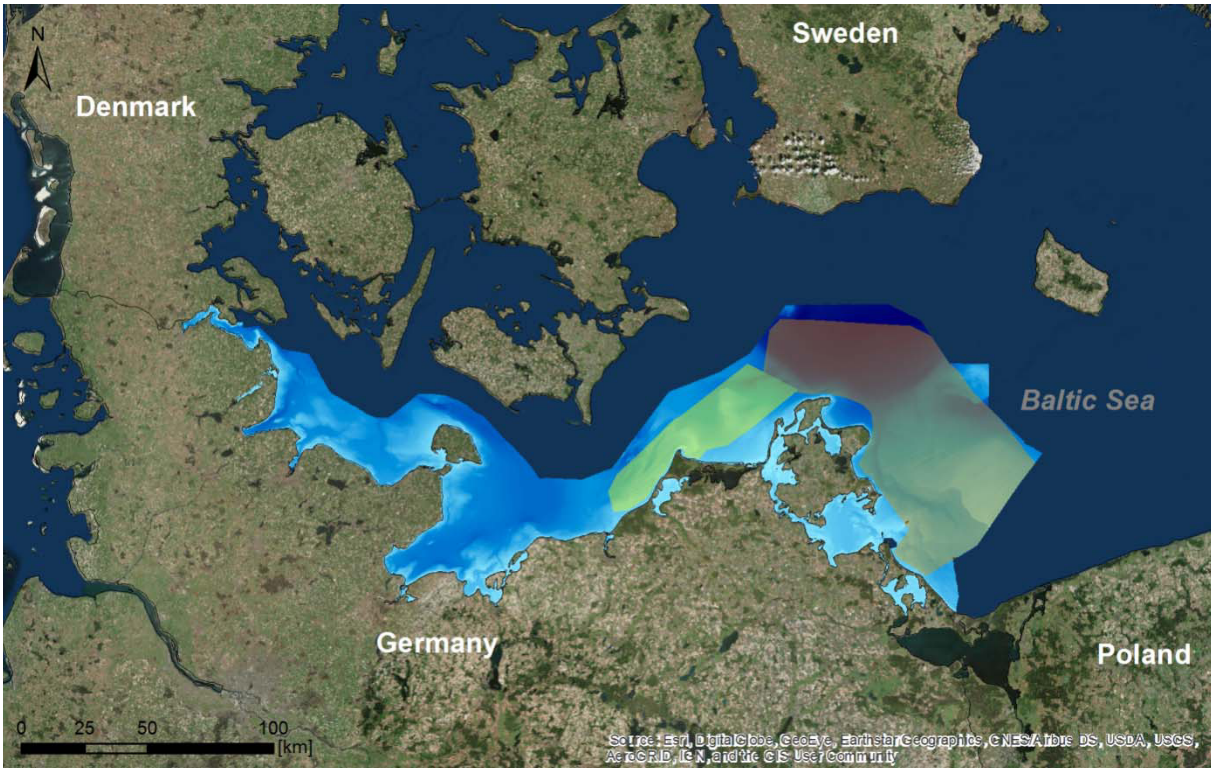


Fig. 3-1: : Research areas of USO West (yellow) and USO East (orange) in the southern Baltic Sea; Bathymetry: TAUBER (2012*a*-*i*).

The USO working area (**Fig. 3-1**) is situated around the island of Rügen in the southeastern part of the Baltic Sea in northern Germany. The reflection seismic profiles of the USO East project and this thesis are located north and east of Rügen (marked in orange in **Fig. 3-1**). The research area is bordered by the German mainland in the south and the national borders of Poland, Denmark and Sweden in the east and north, respectively. The boundary between the areas of USO East (SEIDEL et al. 2018) and USO West (marked in yellow in **Fig. 3-1**; DEUTSCHMANN et al. 2018) runs from Dranske (Rügen) west-northwestward.

Rügen is surrounded by the Pomeranian Bay (or Odra Bay) in the east, the Arkona Bay in the north, the Mecklenburg Bay in the west and the Strelasund, a narrow channel, in the south (**Fig. 3-2**). Smaller embayments are the Greifswalder Bodden in the southeast with water depths of up to 10 m, the Prorer Wiek south of the Jasmund peninsula, and the Tromper Wiek between the Wittow and Jasmund peninsulas. Water depths east and west of Rügen do not exceed 20 m, with local highs such as the Odra Bank and Adlergrund, east of Rügen, or the Plantagenetgrund west of Rügen, having water depths of less than 10 m. The water depth increases rapidly towards the north, to up to 48 m within the German sector.

A dominant channel structure of over 20 m depth is located between the Prorer Wiek and the Odra Bank. The Odra Channel is a former dewatering structure of the river Odra (LUDWIG 2011). This river currently discharges into the Baltic Sea between Germany and Poland. Its former stream bed, which still is conspicuous, runs towards the NNW, turns to the NW along the Odra Bank, and bends back into a NNW direction next to Rügen.

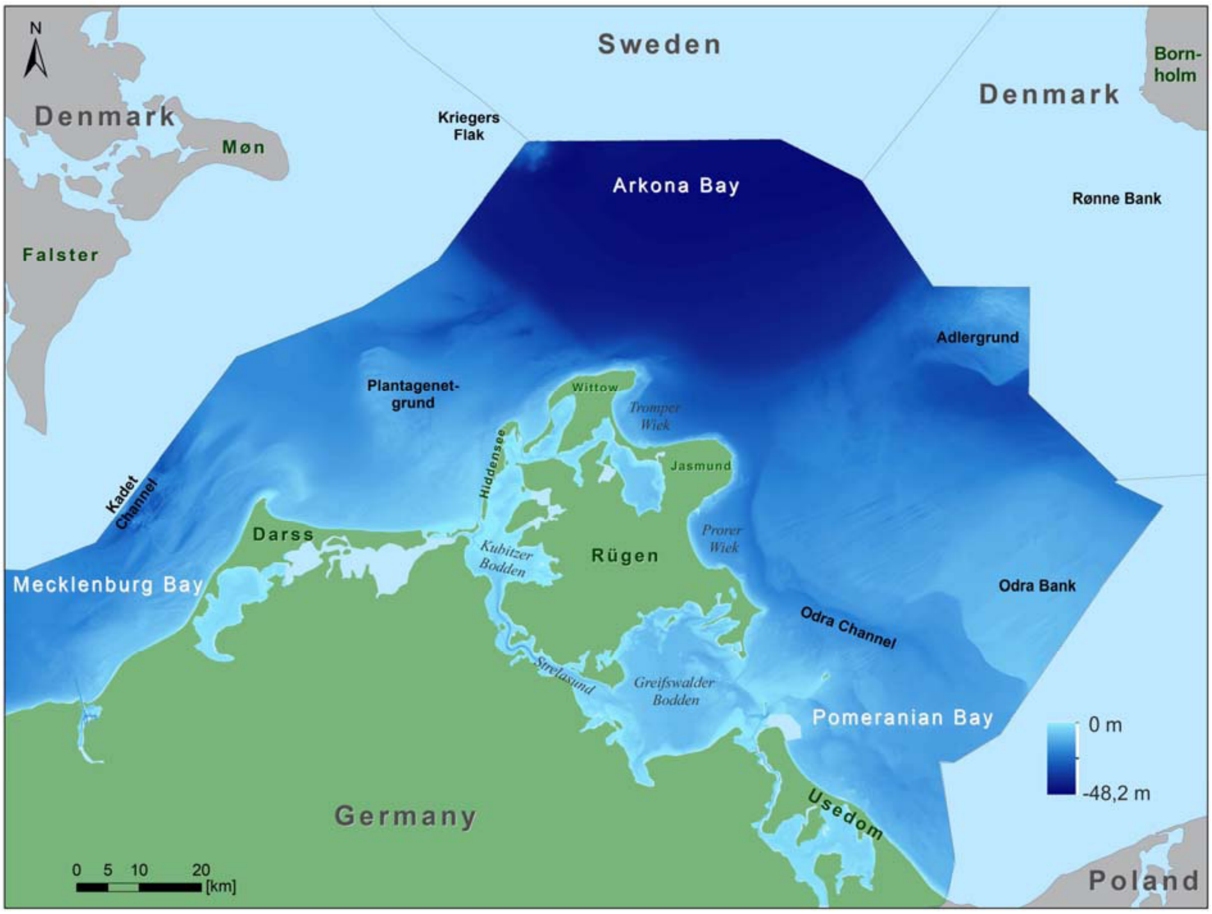


Fig. 3-2: Sea bottom relief and bathymetry of the southern Baltic Sea, around Rügen (Bathymetry: TAUBER 2012*a-i*)

The working area of USO East comprises several tectonic features of different ages and evolutionary backgrounds. Structurally, it is characterised by its position within the **Tornquist Fan** area, a Palaeozoic transition zone between the East European Craton (**EEC**) and the West European Platform, widening northwestward (**Fig. 3-3;** BERTHELSEN 1992*a,b*, DEKORP-BASIN RESEARCH GROUP 1999, THYBO 2000; KRAWCZYK et al. 2002). Its southern branch, the Trans-European Suture Zone (**TESZ,** or Trans-European Fault (the terminology is discussed in **Section 3.3**), but especially the Caledonian Deformation Front (**CDF**), are contemporary witnesses of the Caledonian collision between Baltica and Avalonia.

The northern branch of the Tornquist Fan is embodied by the **Tornquist Zone** (**Section 3.3.2**), an about 2000 km long NW striking lineament, which is further subdivided in a northern (Sorgenfrei-Tornquist Zone, **STZ**) and southern part (Teisseyre-Tornquist Zone, **TTZ**). The whole Tornquist Zone includes several faults and blocks, such as the TTZ, which contains the Gryfice and Kołobrzeg blocks. Within the working area, the TTZ and particularly the Gryfice Block are separated by the Adler-Kamień Fault Zone (**AKFZ**) from the Wolin Block (east of Rügen).

Furthermore, west the deep-rooted, Palaeozoic faults, such as the Wiek, Bergen and Stralsund faults, intersect the Arkona, Middle Rügen and South Rügen blocks (**Section 3.3.3**).

Since the Permian, the intra-continental Central European Basin System (**CEBS**) has evolved. Sub-basins have been formed in the closer vicinity of the working area (**Section 3.3.4**). Thus, the North German Basin (**NGB**) is located in the S-SW and the Mid-Polish Trough (**MPT**, also known as Polish

Basin) in the SE. A further sub-basin is the Danish Basin (**DB,** also known as Norwegian-Danish Basin; e.g. SCHECK-WENDEROTH & LAMARCHE 2005), separated to the south by the Ringkøbing-Fyn High. The Arkona High terminates the NGB towards the north, so especially the Post-Permian sediments thicken towards the basin centre in the south.

Section 3.2 addresses the geological evolution in northern Europe. The above mentioned most important structures and fault systems are discussed in **Section 3.3**.

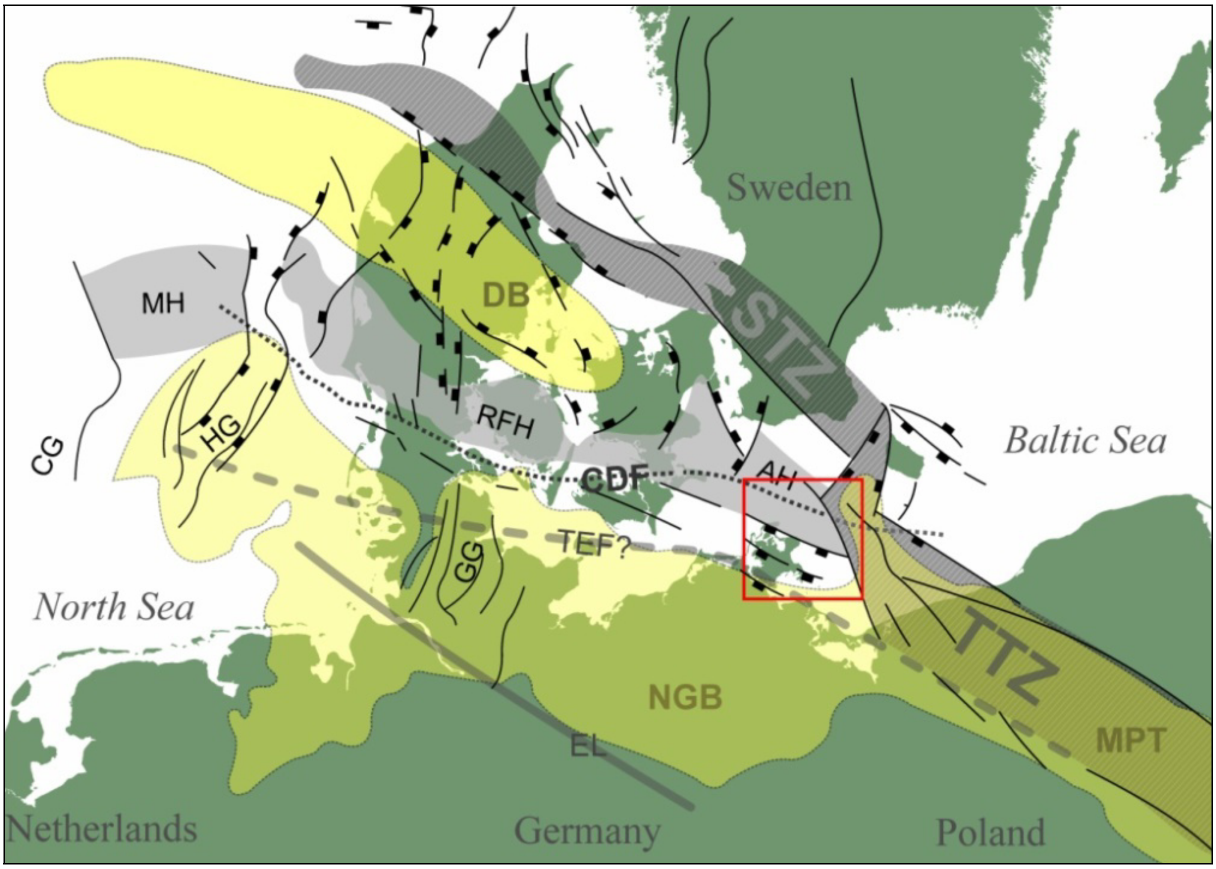


Fig. 3-3: Position of the USO research area (indicated by the red box) within the Tornquist Fan and at the border of the Central European Basin System (CEBS) in yellow. AH–Arkona High, CG–Central Graben, CDF–Caledonian Deformation Front, DB–Danish Basin, EL–Elbe Line, GG–Glückstadt Graben, HG–Horn Graben, MH–Møn High, MPT–Mid Polish Trough, NGB–North German Basin, RFH–Ringkøbing-Fyn High, STZ–Sorgenfrei-Tornquist Zone, TEF–Trans-European Fault, TTZ–Teisseyre-Tornquist Zone (adjusted from SEIDEL et al. 2018 and citations therein).

3.2 Plate tectonic and sedimentary evolution at the southwestern margin of the East-European Craton since the Neoproterozoic

PALAEOZOIC

During the late ***Neoproterozic*** (Ediacaran) the plate tectonic situation was dominated by the supercontinent Gondwana and the smaller continents of Laurentia, Siberia and Baltica. Whereas Gondwana was positioned at the equator between 30°N and 75°S and drifting to the south, the smaller plates were positioned at the southern hemisphere (Laurentia and Siberia between the equator and 40°S and Baltica along the 60°S-latitude) and drifting towards the north (PHARAOH et al. 2010, DE VOS et al. 2010; **see Fig. 3-4 & Fig. 3-5**). Additionally, Baltica was separated from Laurentia by the Iapetus Ocean (**IO**) and from Siberia by the Aegir Ocean (**AO**). The palaeocontinent Baltica mainly comprises the East-European Craton (**EEC**), which is separated into three segments: Fennoscandia, Sarmatia and Volga-Uralia (KATZUNG 2004*a*, SCHOLZ & OBST 2004). According to KATZUNG (2004*a*), the term Fennoscandian Shield mainy comprises the exposed area of Fennoscandia (Scandinavia, Finland, Karelia). The EEC was uplifted by several tens of kilometres and contemporarily eroded. Relicts of epicratonic sediments and volcanics were deposited with increasing thickness towards the craton margin. Today residues reworked as flakes can be found within the Caledonides (KATZUNG 2004*a*).

NIKISHIN et al. (1996) described the different basement provinces of the EEC and the orogenic cycles which affected the craton between the Cambrian and Triassic. During the ***Early Cambrian***, extensional processes were triggered along the southern border of Baltica

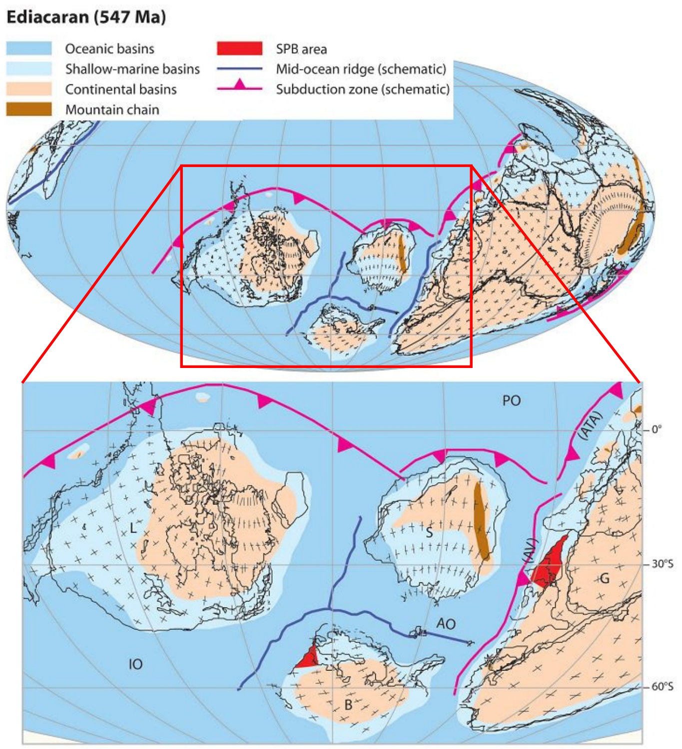


Fig. 3-4: Palaeogeographic maps of the Neoproterozoic (modified after PHARAOH et al. 2010). AO–Aegir Ocean, ATA–Amorican Terrane Assemblage, AV–Avalonia, B–Baltica, G–Gondwana, IO–Iapetus Ocean, L–Laurentia, S–Siberia, PO–Panthalassic Ocean.

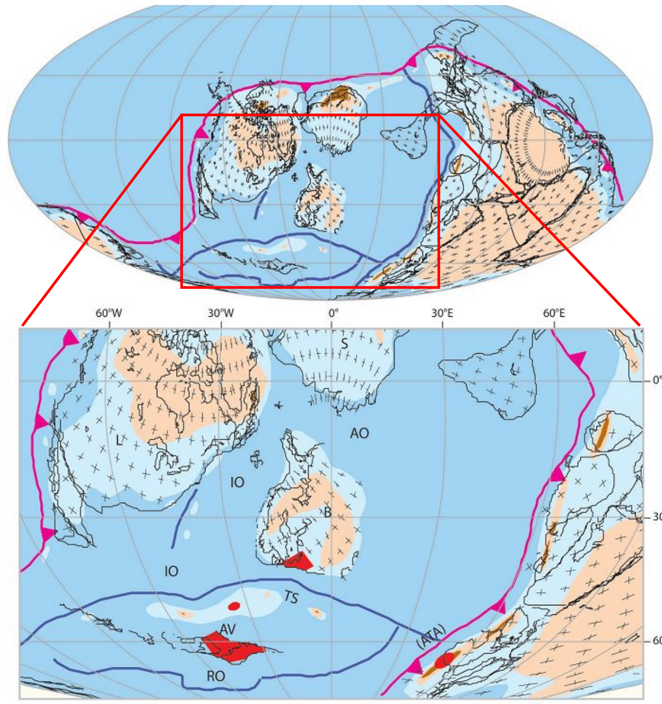


Fig. 3-5: Palaeogeographic maps of the Late Ordovician (PHARAOH et al. 2010). For Legend see **Fig. 3-4**. AO–Aegir Ocean, ATA–Amorican Terrane Assemblage, AV–Avalonia, B–Baltica, IO–Iapetus Ocean, L–Laurentia, S–Siberia, RO–Rheic Ocean, TS–Tornquist Sea.

with the rift along the Tornquist Ocean (KATZUNG 2004*a*, NIKISHIN et al. 1996). The southern part of the Fennoscandian Shield was first covered by coarse grained and later by fine grained clastics (KATZUNG 2004*a*).

During the ***Ordovician,*** Gondwana was located between the South Pole and the equator. Segments, such as the terrane Avalonia, split from its northern margin and drifted in a northerly direction (TORSVIK & REHNSTRÖM 2003**,** KATZUNG 2004*a*, SERVAIS et al. 2008). The drift velocity of Baltica was reduced, while the Palaeo-Ural Ocean opened along the eastern margin of the EEC (NIKISHIN et al. 1996, TORSVIK et al. 1996).

Avalonia and Baltica were separated by the Tornquist Ocean. According to TORSVIK & REHNSTRÖM (2003), both continents drifted northward while undergoing a strong counter-clockwise rotation. South of Avalonia the Rheic Ocean opened (COCKS & FORTEY 1982). During the Early Ordovician the drift of Avalonia was faster than the drift of Baltica, but Avalonia slowed down until the Late Ordovician (TORSVIK & REHNSTRÖM 2003). Therefore, north of Avalonia the oceanic crust of the Tornquist and Iapetus oceans was subducted beneath the terrane, which triggered the formation of an active continental margin. Especially the subduction of the Iapetus Ocean is evidenced by calc-alkaline volcanic rocks in England and Belgium (PHARAOH 1999, KATZUNG 2004*a*).

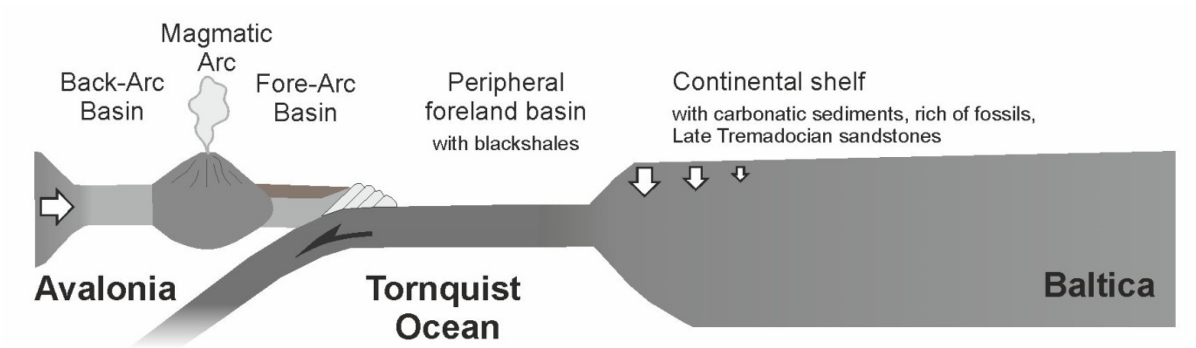


Fig. 3-6: Active continental margin of Avalonia (according to Beier et al. 2000, modified).

In front of the active margin of Avalonia the Arkona black shales were deposited within a hemipelagic basin during the Ordovician (Llanvirn). Along the fore-arc- or trench-slope-basin turbiditic greywacke (Nobbin Greywacke Formation, Llanvirn-Caradoc) was deposited (KATZUNG 2004*a*, DE VOS et al. 2010). At the same time shelf sediments were deposited along the passive SW margin of Baltica, which include Broens Odde Beds (Lower Cambrian) up to the Komstad Limestone (Mid-Arenigian). The latter shows gaps in the lithological successions which indicate eustatic changes in sea-level or rather vertical tectonic movements (BEIER et al. 2000). Due to the ongoing convergence of Avalonia and Baltica, the oceanic crust of the Tornquist Ocean was subducted until the final collision (450-400 ma; ZIEGLER 1990*a*, ERLSTRÖM et al. 1997, BERTHELSEN 1998, DE VOS et al. 2010, GUTERCH et al. 2010, FRISCH & MESCHEDE 2013).

During the Caledonian Orogeny, marine deposits at the Avalonian active continental margin (such as black shales) were deformed, metamorphosed and thrust onto the Cambro-Silurian sediments of the passive continental margin of Baltica (**Fig. 3-6**), thus, forming an accretionary wedge with a peripheral foreland basin in front of it (BEIER et al. 2000, KATZUNG 2004*a*, DE VOS et al. 2010). BEIER et al. (2000) describe four phases of the development of this foreland basin, which are illustrated in **Fig. 3-7**. The **"Initial phase"** (Arenigian/Llanvirnian) is characterised by an increasing surcharge of the growing accretionary wedge and, thus, a strong subsidence of the depression. The following **"Deep water phase"** started in the late Llanvirnian and was featured by increasing convergence of the plates, strong subsidence, a raise of the Caledonian Orogen and thus an increasing amount of sediment supply (BEIER et al. 2000).

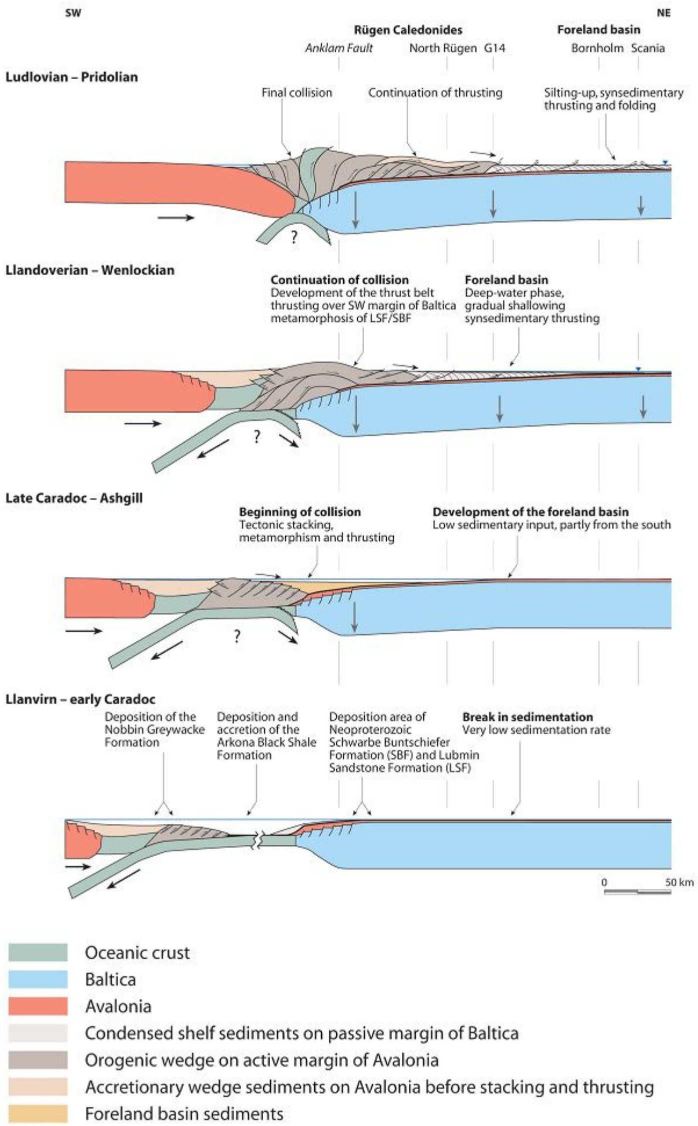


Fig. 3-7: Caledonian Orogeny (DE VOS et al. 2010, according to BEIER 2001).

During the ***Silurian*** Balonia (Baltica and Avalonia) collided with the Laurentia-Greenland craton (**Fig. 3-8**), which led to the formation of Laurussia and a suturing of the Iapetus Ocean along the Arctic-North Atlantic Caledonides and a change in plate motion (NIKISHIN et al. 1996, PHARAOH 1999). The continuing convergence of Avalonia and Baltica (**Fig. 3-7**) triggered the formation of a further, northerly directed subduction along the northeastern border of the Tornquist Ocean. Thus, the according oceanic crust simultaneously submerged in north-northeastern direction below Baltica and in southern direction below Avalonia until the end of Silurian (BEIER et al. 2000, DE VOS et al. 2010). According to FRANKE (1990), the sedimentation during the Silurian was much more equalised than before. Pelite dominating marine sediments are most common and graptolitic shales

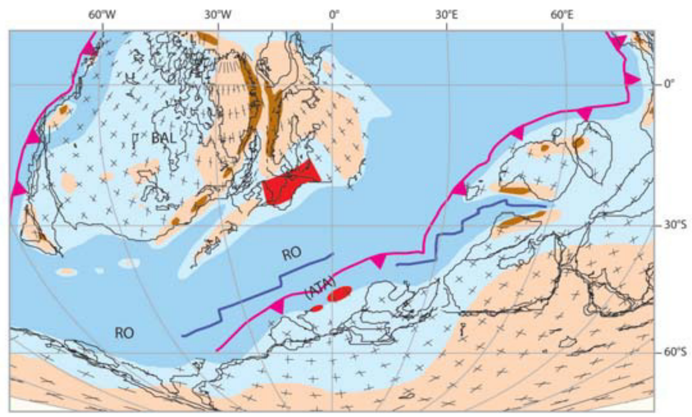


Fig. 3-8: Palaeogeographic map of the Silurian (PHARAOH et al. 2010; for legend see **Fig. 3-4**). ATA–Amorican Terrane Assemblage, Bal–Balonia, RO–Rheic Ocean.

are widely distributed. Thickness differences indicate a migration of the depocentre from SW to NE (BEIER et al. 2000, BEIER & KATZUNG 1999). The subsidence rates continuously increased between the Ordovician and Silurian, due to ongoing folding and uplift of the Caledonides, and the high sediment load associated with it (DE VOS et al. 2010). The Silurian sediments differ between the border and the centre of the basin. The deep water phase remains until the late Llandovery (well G14), Wenlock (Bornholm), or Ludlow in northern Poland, depending on the distance to the Caledonian Orogen (JAWOROWSKI 1971, DADLEZ 1978, MODLIŃSKI et al. 1994 *all in* DE VOS et al. 2010). Due to the collision of the cratons, the orogen was lifted above the sea level, thus significantly increasing the erosion. Finally, the accumulation of material compensated the still ongoing subsidence of the foreland basin (KATZUNG 2004*a*). BEIER et al. (2000) described this third phase as the **"Shallow water phase"**, where sedimentation rates exceeded the subsidence. Thus, the basin depth was reduced.

The final fill of the foreland basin started in the latest Ludlow and was finished in the Early ***Devonian***, as indicated by terrigenous sediments (BEIER et al. 2000). This last stage, named **"Erosion phase"**, is characterised by ceasing convergence between Baltica and Avalonia until the late Silurian (GIESE et al. 1994) or Early Devonian (DE VOS et al. 2010). An epi-orogenic isostatic uplift resulted in erosion of the accumulated wedge and extensional stress (BEIER et al. 2000, and references therein). In Poland the Caledonian Orogeny also terminates during the Early Devonian (BEIER et al. 2000). The remains of the Caledonian thrust belt can be followed from the Danish North Sea over Germany until the Holy Cross Mountains of Poland (PHARAOH 1999). The outcropping boundary between the thrust belt and the basement of Baltica in the north forms a lineament which is called the Caledonian Deformation Front (**CDF**) (BERTHELSEN 1998, PHARAOH 1999, BAYER et al. 2002; see **Section 3.3.1**).

The palaeogeographic situation since the Devonian is characterised by the Palaeotethys Ocean separating the continents Laurussia in the north and Gondwana in the south. The northward subduction of the oceanic crust triggered the northward drift of several Gondwana derived terranes, called the Armorican Terrane Assemblage - ATA (MCCANN 1996). The Rheic Ocean separated the ATA from Laurussia (BEŁKA et al. 2010) and was connected with the Palaeotethys Ocean in western and eastern direction during the Early Devonian (PHARAOH et al. 2010). The starting Variscan Orogeny is governed by an enhanced narrowing between Laurussia and Gondwana. Thereby the southern part of Laurussia and the ATA were dominantly affected. The Rheic Ocean subducted southwards, which is indicated by magmatic rocks of the Mid German Crystalline High, forming a magmatic arc (FRANKE 2000, BEŁKA et al. 2010, ZEH & GERDES 2010). The closure of the Rheic Ocean started at its western pathway towards the Palaeotethys and continued in an easterly direction.

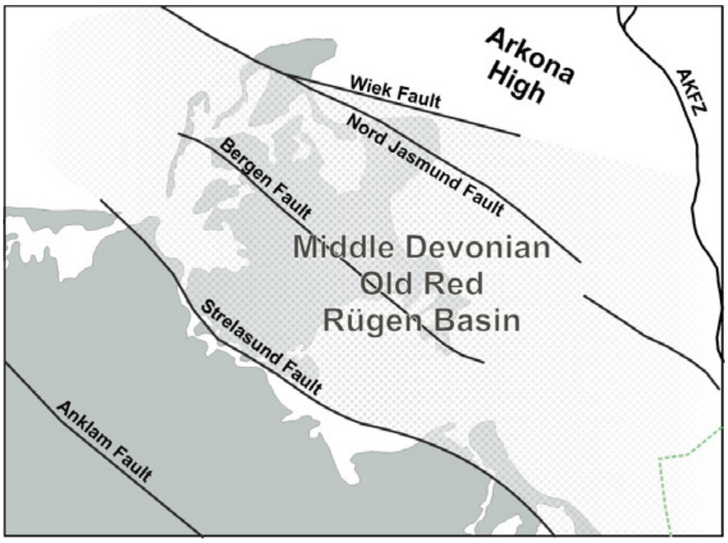


Fig. 3-9: Location of the Middle Rügen Depression (modified after AEHNELT & KATZUNG 2009). AKFZ–Adler-Kamień Fault Zone.

At the same time the hinterland of the stable southern passive margin of Laurussia was affected by extension and thinning of the crust and basins, such as the Rhenohercynian Basin, developed (Ziegler 1990*a*). Especially in the area of Rügen, the Devonian succession was deposited in a NW-trending, fault-bounded depression. The so-called *Middle Devonian Old Red*

Rügen Basin (Aehnelt & Katzung 2009) is positioned between the Arkona and Stralsund uplifts (Zagora & Zagora 2004, Bełka et al. 2010; **Fig. 3-9**). Thus, in northern direction they are limited by the Arkona High, which is the eastern continuation of the Ringkøbing-Fyn-High (Franke 1990).

The sedimentation in northern central Europe was predominantly controlled by the post-orogenic collapse of the Caledonides (McCann 1996, Katzung 2004*a*). The eroded clastics were transported to the south as marine molasse into the Rhenohercynian Trough and towards the north as continental molasse into intermontane depressions (Franke 1990). Those Old Red deposits documented the sedimentation since the Middle Devonian. The silty, clayey to sandy sedimentation in the area of Pomerania was first controlled by a broad alluvial flat, which then changed to fluvial to limnic conditions. Towards the east (area of Poland) a flat shelf area opened. At the end of the Middle Devonian, the shelf sea extended from Poland and the southern Rhenohercynian Basin north–westward (Katzung 2004*a*, Meschede 2018 and references therein). Due to the transgression exposed uplands were also involved in the sedimentation processes. According to Franke (1990), a change of transgressive and regressive sequences within carbonaceous and clastic successions in the area of Western Pomerania indicate an alternating water depth. Lagoonal settings are described for the Late Devonian (Katzung 2004*a*). However, Precambrian highs, maintained their positive position also post-Caledonian.

The sedimentation started after a long time of erosion in the area of the Devonian Rügen Basin. Thus, Middle Devonian deposits lie unconformably on top of the Ordovician (Bełka et al. 2010). The Middle Devonian with still terrestrial conditions is characterised by continental, clastic-terrigenous Old Red strata containing palynomorphs and ostracods, whereas during the Late Devonian (**Fig. 3-10**) clayey-marly sediments of a foreland shelf indicate a transgression (Schmidt & Franke 1977 *in* Franke 1990, Bełka et al. 2010). These younger sediments contain diverse fossil assemblages such as brachiopods, molluscs, corals, stromatoporoids and ostracodes. Furthermore, oolites can be found in the shallow-marine carbonates (Bełka et al. 2010).

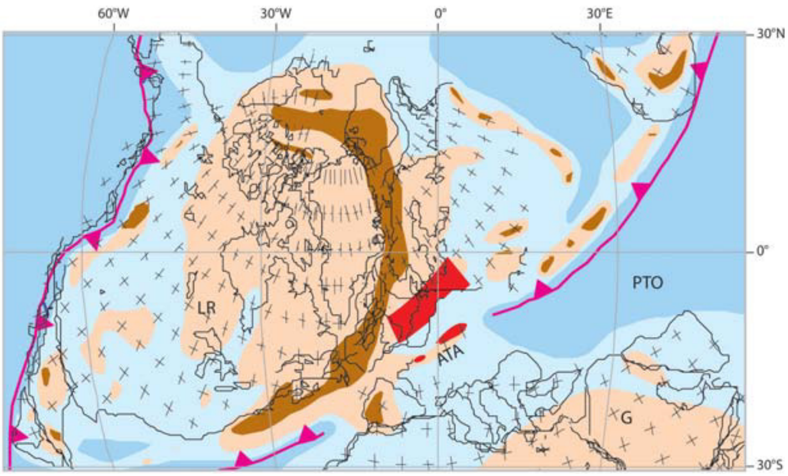


Fig. 3-10: Palaeogeographic map of the Late Devonian (Pharaoh et al. 2010, see **Fig. 3-4** for legend). ATA–American Terrane Assemblage, G–Gondwana, LR–Laurussia, PTO–Palaeotethys Ocean.

Due to deep erosional phases, about 4000 m Devonian-Carboniferous successions are missing today along the Arkona High, north of Rügen (Franke & Hoffmann 1988, Franke 1990). In addition, post Devonian magmatic processes, such as late Palaeozoic intrusions along Rügen might also have deformed the Devonian succession or even metamorphosed the pre-Permian to Devonian sequences (Franke 1990). The depth of the top Devonian increases from 1800 m in the north of Rügen to 6000 m in the south (Franke 1990). The sediments are up to 3000 m thick (Bełka et al. 2010).

The collision of Gondwana and Laurussia started during the Famennian (Late Devonian) which induced the Variscan Orogeny. The clockwise rotation of Gondwana was due to the collision imparted on Laurussia (Nikishin et al. 1996). Today the orogenic belt of the European Variscides reaches a width of 1000 km (FRISCH & MESCHEDE 2013) and was already subdivided by KOSSMAT (1927) into the , Saxo-Thuringian and the Moldanubian zones.

The depositional environment of the ***Carboniferous*** equals the Devonian area of sedimentation (FRANKE 1990). The oceanic crust of the Rheic Ocean was completely subducted by the beginning of the early Carboniferous (MESCHEDE & WARR 2019). Thus, the ongoing collision affected the northern foreland of the Variscan Orogen (Franke 2000). Contemporaneously, a transgression increased the shelf area (**Fig. 3-11**), and islands such as the Strelasund swell were flooded (KATZUNG 2004*a*). North of the Variscides different facies areas developed with increasing distance to the orogen. Turbiditic deposits (flysch) can be found along the northern border of the Variscan Orogen. Further to the north, almost parallel to the Variscan Deformation Front, the clastic-terrigeneous **"Kulm"-facies** characterised an area called the "Hunger basin" (KATZUNG 2004*a*). At the same time the **"Kohlenkalk"-facies** formed along the deeper shelf areas in the flooded pre-Variscan foreland. Carbonatic and clayey sediments dominated with a high content of fossils. The carbonatic platform covered almost all of the northern Middle Europe from the North Sea, via Rügen, until northern Poland.

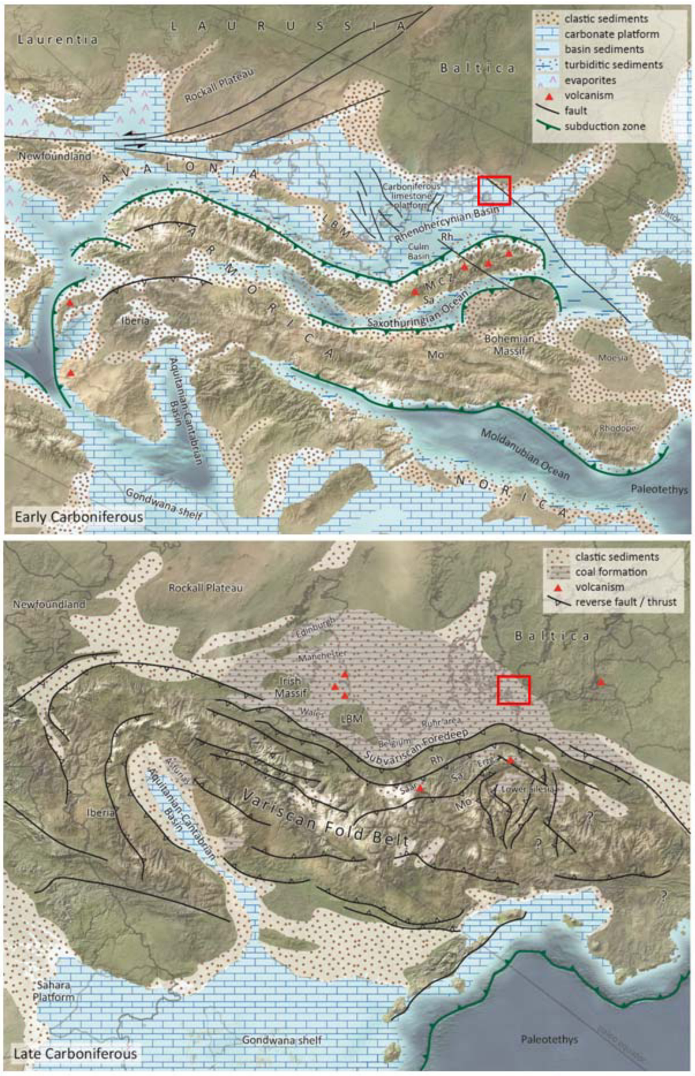


Fig. 3-11: Palaeogeographic map during the Early and Late Carboniferous, working area marked in red (MESCHEDE & WARR 2019, modified). LBM–London-Brabant Massif, MCZ–Mid-German Crystalline Zone, Mo–Moldanubian, Rh–Rhenohercynian, Sa–Saxothuringian.

A primarily regional facial differentiation for the area along the islands of Rügen and Hiddensee was documented since the late Tournaisian and even more since the early Viséan (FRANKE 1990). In Middle Rügen, a 200-600 m thick alternating succession of limestone, marl- and claystone can be found, whereas Hiddensee Island is covered by a layer of about 350 m thick clay- and siltstones. The variation in thickness and lime content increased over time. Thus, a differentiation between a Rügen facies and Hiddensee facies has been made (FRANKE 1990).

However, according to KATZUNG (2004*a*), basic lava and tuff deposits documented the lower Variscan tectogenesis within Western Pomerania. Due to the ongoing Variscan Orogeny, compression led to intense block faulting, especially in the area of Rügen, where the Middle Rügen swell was uplifted (LINDERT & HOFFMANN 2004). In summary, the depositional area is defined by synsedimentary faults and the debris is bound by several sub-basins with a pull-apart character. Thus, the formation of the late Carboniferous is very irregular in N-S and E-W direction (FRANKE 1990). On Rügen and Hiddensee the successions were eroded due to movements along NE–SW oriented faults. Westphalian deposits are known from southern and middle Rügen but may have occurred even further north. Synclines were filled up by marine transgression cycles which covered an area from the British Island until East-Poland. The Variscan Orogeny terminated during the late Westphalian; therefore, the sedimentation during the Stephanian was bound to a SSW-NNE trending Ems-North Sea Basin, which might have been connected with a small remaining depression in Western Pomerania (KATZUNG 2004*a*). According to FRANKE (1990), the molasse formation also terminated with the end of the Carboniferous; instead, the **Central European Basin System** was generated during the Early Rotliegend.

The ***lower Permian,*** known as Altmark Sub-group, is characterised by a short but intense **volcanic phase** (**Fig. 3-12;** MARX et al. 1995, GEBHARDT et al. 2018 & citations therein). It comprises the external area of the Variscan Orogen and its foreland, between the east of Lower Saxony, western Poland, the north of Saxony-Anhalt and the southern Baltic Sea (KATZUNG 2004*a*). The collision of several terranes during the Variscan Orogeny forced the melting of subducted crust segments and led to a high magmatic productivity with syn- to late tectonic magmatism (BENEK et al. 1996, MCCANN 1996). VAN WEES et al. (2000) also described how wrenching resulted in thermal destabilisation of the lithosphere during Stephanian to Autunian. Therefore disruption, crustal fracturing and lithospheric thinning, combined with regional uplift triggered a tectonic subsidence. The crustal fracturing is documented by the intrusive and extrusive magmatic activity and the formation of transtensional pull-apart basins during the late Stephanian (BENEK et al. 1996, MCCANN 1996). According to MCCANN (1996), this volcanic phase marked a new phase of basin development (**Fig. 3-13**).

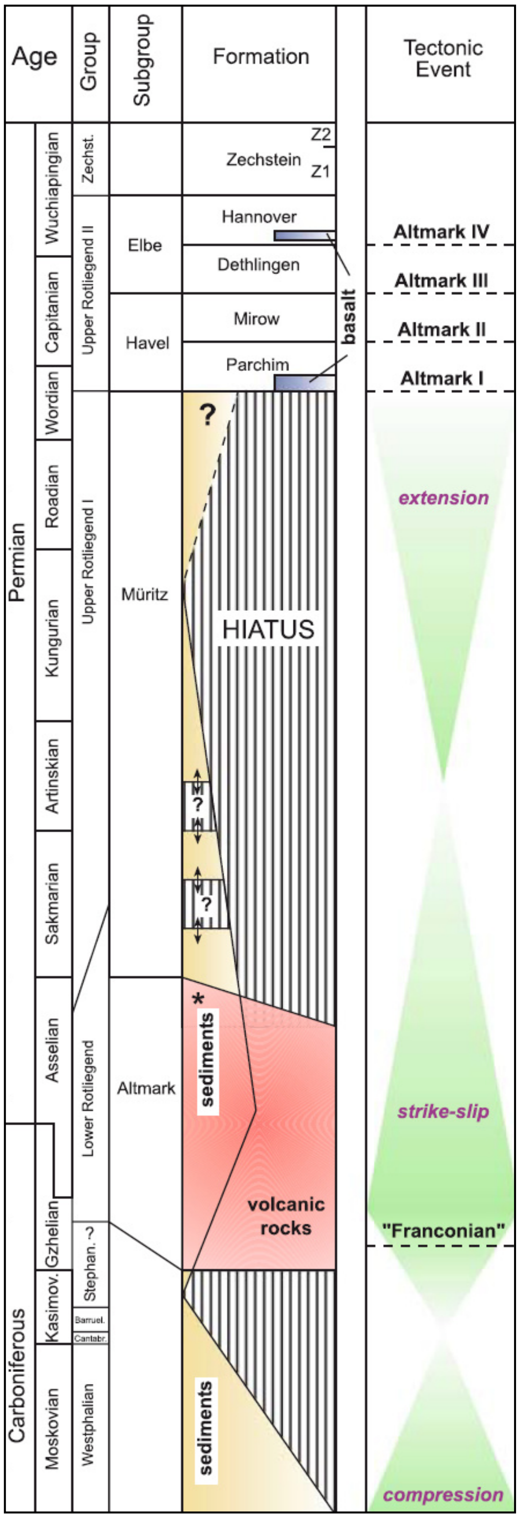


Fig. 3-12: Stratigraphic overview of the Upper Carboniferous and Permian in the North German Basin (GEIßLER et al. 2008, modified).

Three volcanic sub-provinces have been defined for the Southern Permian Basin (BREITKREUZ et al. 2008 & citations therein). One of them is known as the Mecklenburg-Vorpommern sub-province (MVSP; **Fig. 3-13**) in NE Germany. It is characterised by mantle plume-related magmatism and lava domes (NEUMANN et al. 2004, BREITKREUZ et al. 2008, GAST et al. 2010). Further taphrogenic processes during the Early Rotliegend (former Autun) are connected with NNE-SSW and NW-SE striking, active faults. Sill and dykes intruded into Devonian and Carboniferous strata on Rügen and northern Poland (KATZUNG 2004*a,b*, KATZUNG & OBST 2004). Dextral strike-slip motions are also known for the **Tornquist Zone**, a 2000 km long fault zone which coincides with the southwestern margin of the EEC (PHARAOH 1999, GUTERCH et al. 2010, GAST et al. 2010; see **Section 3.3.2**).

The termination of the magmatic activities are indicated by red clastic sediments with interbedded grey limestone and tuff. Subsequently, the subsidence the material was deformed by the late Variscan **Saalian movements**. Younger strata, such as the Saxonian, are lying disconformably on it (KATZUNG 2004*a,b*).

The ongoing thermal subsidence forced the evolution of the intra-continental ***Central European Basin System*** (***CEBS***, MAYSTRENKO et al. 2008). The CEBS (**Fig. 3-13 & Fig. 3-14**) can be subdivided into the Southern Permian Basin (SPB) and the North Permian Basin (NPB). The ***NPB*** is a marginal depression at the Proterozoic basement including the ***DB.*** The SPB is an intra-continental basin between the eastern British coast and the Baltic States, subdivided into the western ***Anglo-Dutch Basin (ADB)***, the ***North German Basin (NGB)***, and the ***Mid-Polish Trough (MPT),*** whose development is closely related to the Teisseyre-Tornquist Zone (see **Section 3.3.4**; KATZUNG 2004*a*, GAST et al. 2010). During the ***Upper Rotliegend*** the sedimentation started in isolation and was controlled by faults within the centre of the NGB and the MPT. Due to epi-orogenetic processes, the depression expanded in westerly direction. Erosional debris of the adjacent Variscan Orogen was deposited within the depressions, although the deposition did not compensate the subsidence, so the sedimentation level remained lower than the sea level. Freshwater evaporated under semi-arid to arid conditions in the drainless basin, which led to alternating deposition of red sediments and evaporites (KATZUNG 2004*a,b*).

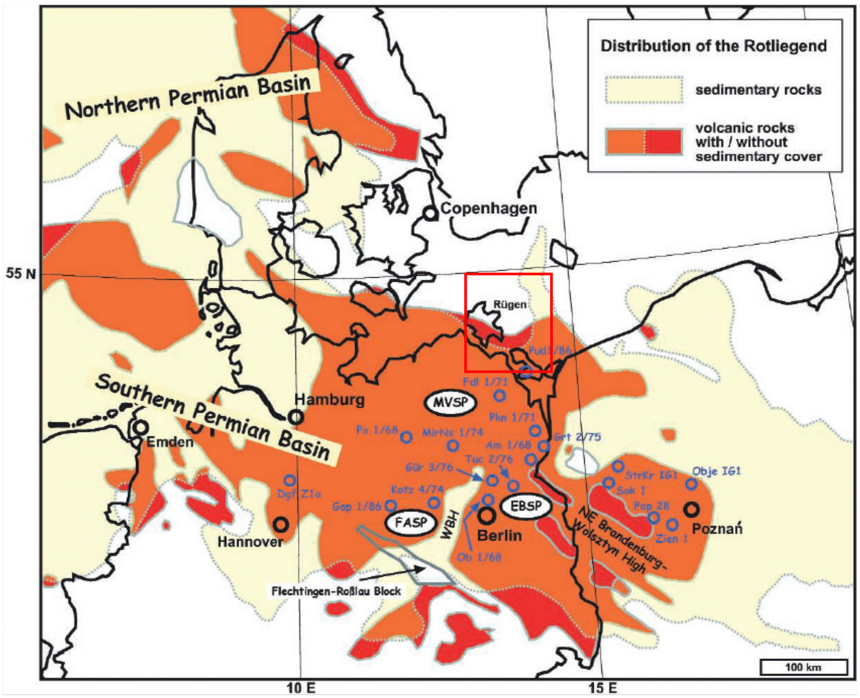


Fig. 3-13: Volcanic and sedimentary rocks of the Rotliegend of the Northern and Southern Permian Basins with the Mecklenburg-Vorpommern (MVSP), East Brandenburg (EBSP)and Flechtlingen-Altmark sub-provinces (FASP) (BREITKREUZ et al. 2008, modified). The working area marked in red.

RIEKE et al. (2001) summarised the tectono-sedimentary evolution of the northern margin of the NGB during the late Carboniferous to late Permian as consisting of three phases: The "Initial Phase" is characterised by extensions with normal faulting and ductile shearing leading to dextral motions, also along the Strelasund Fault and the asymmetric NNE striking Strelasund depression that is marked by a steep-dipping eastern and a shallow-dipping western margin. The subsequent "Post-Extensional Phase" was controlled by a cooling lithosphere which generated the deepening of the sub-basin.

Thermal subsidence characterises the "Final Phase" of regional subsidence in the southerly located NGB (RIEKE et al. 2001).

According to GEIßLER et al. (2008), the volcanic Lower Rotliegend (Altmark sub-group) is covered by the sedimentary Upper Rotliegend, which is further subdivided into the Müritz, Havel and Elbe sub-groups (**Fig. 3-12**). Fanglomerates with volcanic components, fluvial sandstones or playa deposits filled the local fault bounded basins along the NGB and the MPT. Both are partly separated by the Brandenburg-Wolsztyn High (GAST et al. 2010). The Havel Sub-group strata contains a widespread erosional unconformity within central and northern Germany as indicated by the 15 Ma stratigraphic time gap. STOLLHOFEN et al. (2008) described this period for the CEBS as phases with enhanced heat flow and erosion, which led to the development of unconformities. The proceeding uplift of the crust resulted in rifting events such as the opening of the Neotethys or the Arctic-North Atlantic Oceans (STOLLHOFEN et al. 2008). The enhanced tectonic movements are documented by basalts of the Havel Sub-group (GAST et al. 2010). According to GAST et al. (2010), the thermal subsidence was enhanced during the Elbe Sub-group, which is documented by an extension of the deposition area towards the south and west.

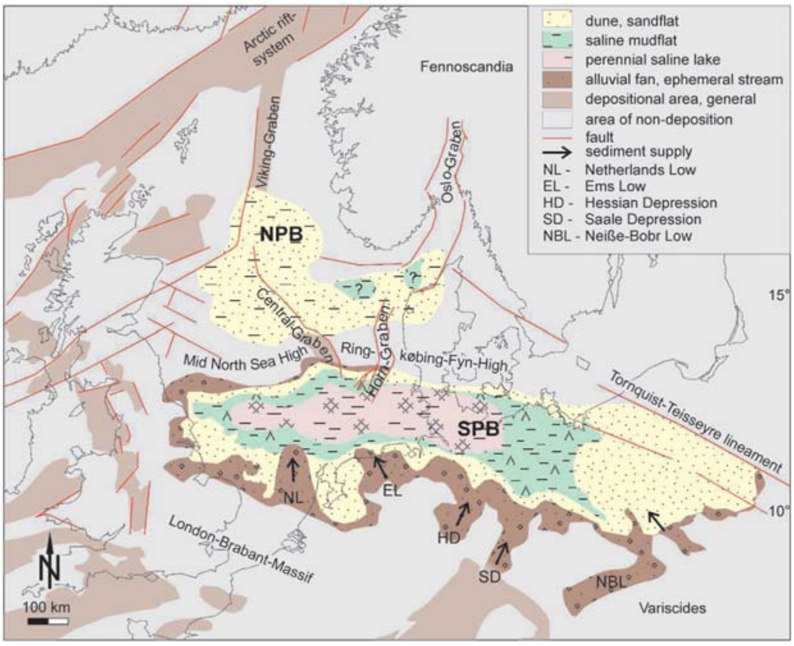


Fig. 3-14: Facies distribution of the Upper Elbe Sub-group (compiled by STOLLHOFEN et al. 2008).

The marine pre-Zechstein ingressions from the northern areas of Greenland and the Fennoscandian Shield used the Viking Graben as a linkage to the Northern and Southern Permian Basin. Due to arctic faunal assemblages, ingressions from southern directions can be excluded (STOLLHOFEN et al. 2008).

The base of the following ***Zechstein*** group is formed by the Kupferschiefer, which indicates the first widespread marine Zechstein transgression 257 Ma ago (STOLLHOFEN et al. 2008). Ongoing rifting processes in the Arctic-North Atlantic region, the subsidence of the basin floor (250-300 m bsl) and a rise of the global sea level induced a further flooding of the CEBS. This was a very rapid and therefore catastrophic event comparable with the Messinian crisis (CLAUZON et al. 1996 *in* STOLLHOFEN et al. 2008). Organic-rich mudstones were deposited as the so called Kupferschiefer under euxinic water conditions, with a stagnant and anoxic laminated bottom layer which reached a thickness of about 30 cm (PAUL 2006 *In* STOLLHOFEN et al. 2008). As shown in **Fig. 3-15,** during the late Permian the CEBS is located between the latitudes 20-30° north, which is comparable with the recent position of deserts such as the Sahara (STOLLHOFEN et al. 2008, PHARAOH et al. 2010). Arid climate conditions with a low amount of precipitation and therefore a reduced clastic input from the surrounding areas induced the evaporation of the seawater. Glacio-eustatic sealevel fluctuations as well as tectonic movements controlled the following seawater influx and the development of further evaporation cycles. The up to 2000 m thick Zechstein strata (in the basin centre) can be subdivided into seven individual cycles: Werra (Z1), Stassfurth (Z2), Leine (Z3), Aller (Z4), Ohre (Z5) and the two rarely developed cycles Friesland (Z6) of Fulda (Z7; PERYT et al. 2010). Whereas the latter two are controlled by clastic depositions of clays and sandstones, the cycles Z1 to Z5 show a typical succession of marine clays, carbonates, Ca-sulfates, rock salt and potash- & magnesium-salts. In comparison with the deposition area of the Upper Rotliegend the Zechstein one increased, especially in northwestern direction due to the incorporation of the Baltic depression (NE) and the Hessian depression (S) within the CEBS. Additionally, the E-W striking hydrological barrier of the Mid North Sea and RF Highs no longer existed (STOLLHOFEN et al. 2008).

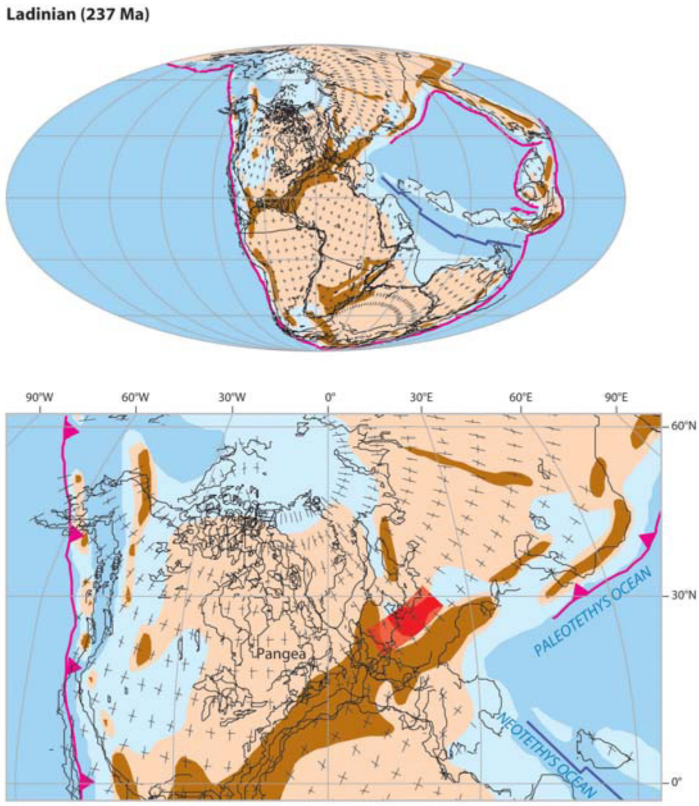


Fig. 3-15: Palaeogeographic map during the Zechstein (PHARAOH et al. 2010)

The crustal extension especially in the area of the SPB led to a reactivation of the Tornquist-Teisseyre Zone and the subsidence of the MPT. Additional sub-basins along the southern border of the CEBS, such as in the north of the Hessian Depression or in SW Poland (WAGNER 1991 *in* STOLLHOFEN et al. 2008), experienced syndepositional tectonics which were connected to the reactivation of Carboniferous-Permian fault systems (ZIEGLER 1990*a*). For the Zechstein transgressions the same seaways as during the Late Rotliegend ingressions had been reactivated but in Poland, faunal admixures of Neotethys-related species indicated an additional East Carpathian Gate (ZIEGLER 1990*a,* STOLLHOFEN et al. 2008). The southern area of the Variscan fold belt was flooded along the Hessian Depression.

MESOZOIC

The ***Germanic Triassic*** (German: "Germanische Trias") is divided into three stages (**Fig. 3-16**): the Buntsandstein characterised by especially terrestrial sandy and clayey deposits, the Muschelkalk with shallow-marine carbonates and hypersaline sediments, and the Keuper with again marine to brackish and even fluviatile strata (MENNING 2018, MESCHEDE 2018). Due to the palaeogeographic situation, the German Triassic in the CEBS differs from the Alpine-Mediterranean Triassic. The plate-tectonic development during the Triassic is characterised by the northwestward opening of the Neotethys and, the subsequent breakup of Pangea (GELUK et al. 2008). The Alpine-Mediterranean area was strongly influenced by the Neotethys rift and therefore also by extensional forces, the setting of the passive continental borders (African, Eurasian and Adriatic-Apulian plates), and the development of big shelf areas. At the same time, further north, the ongoing thermal subsidence (starting in the Permian) still affected the CEBS. This intra-continental basin was delimited to the Neotethys and marked by an independent, mostly terrestrial development. Only short transgressions from the Neotethys via different gates in the south led to marine conditions (MESCHEDE 2018).

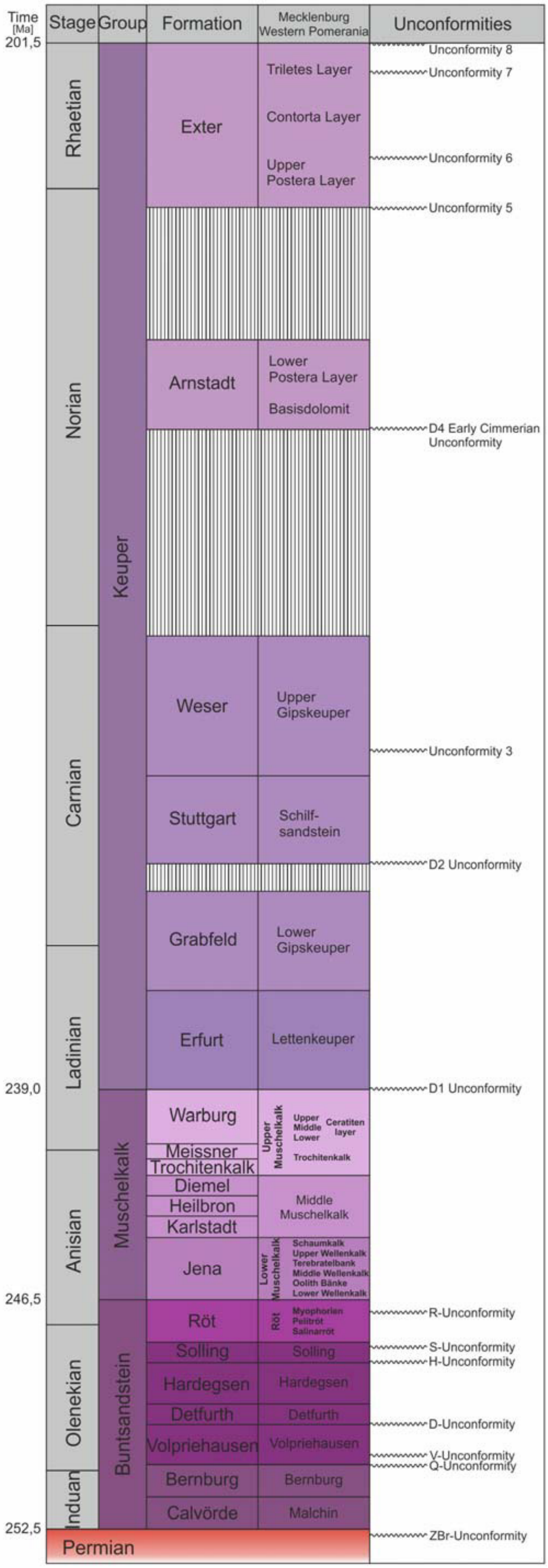


Fig. 3-16: Stratigraphic table of the Triassic with main successions in Mecklenburg-Western Pomerania, as they have been used in the well descriptions, and its prominent discordances within the NGB (compiled after BEUTLER 2004, LUNG 2004, STOLLHOFEN et al. 2008, STG 2016)

The ***Buntsandstein*** within the CEBS is divided into three subgroups (Beutler et al. 2004, LUNG M-V 2004, Bachmann et al. 2010): the **Lower Buntsandstein** with the Malchin Formation (according to LUNG M-V 2004 further subdivided into the Bröckelschiefer – with a transition zone and the Malchin sandstone, the Malchin alternating sequence, and the Nordhausen sequence), and the Bernburg Formation (according to LUNG M-V 2004 divided into the Lower Bernburg alternating sequence, the Haupt-Rogenstein Zone, and the upper Bernburg alternating sequence); the **Middle Buntsandstein** with the Volpriehausen, Detfurth, Hardegsen and Solling Formation; and the **Upper Buntsandstein** with the Röt Formation (Salinarröt and Pelitröt) and the Myophorian Beds (LUNG M-V 2004, **Fig. 3-16**). Those former names and their relation to modern subdivisions are mentioned here because they are found in the original well log descriptions (Diener et al. 1988, 1989, Lück et al. 1987, Pupunyn et al. 1990).

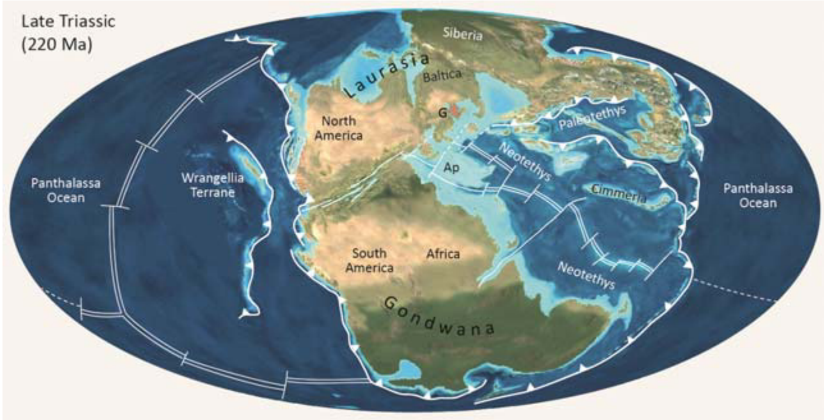


Fig. 3-17: Global plate-tectonic situation during the Late Triassic (Meschede & Warr 2019). Ap–Apulian Plate, G–Germany.

Whereas the CEBS was situated north of the westward opening Neotethys Ocean, its general appearance and extension was similar to the configuration during the Zechstein (Geluk et al. 2008; **Fig. 3-17 & Fig. 3-18**). The depocentre of the Buntsandstein concentrated in a roughly NW-SE striking basin with limnic and alluvial planes. It stretched from Poland to Great Britain in an E-W direction, and from Scandinavia to Switzerland in a N-S direction (Beutler 2004, Katzung 2004*a*, Stollhofen et al. 2008). The massifs in the surrounding of the depressions, such as the Alemannic-Vindelician-Bohemian Massif (S) or the London-Brabant Massif (W), as well as the exposed Fennoscandian region (NE) played an important role as source areas (Geluk et al. 2008). Sediments were transported, e.g. by alluvial fans, into the NGB, ADB, MPT and the DB. Dominant swells intersected those depressions, such as the Eichsfeld-Altmark Swell in the S of the NGB, the East Brandenburg Swell in the E, and the Rügen Swell in the NE (Beutler 2004). Especially the latter caused a thinning of the strata and the generation of internal discordances. Due to the central position of the intra-continental CEBS, at

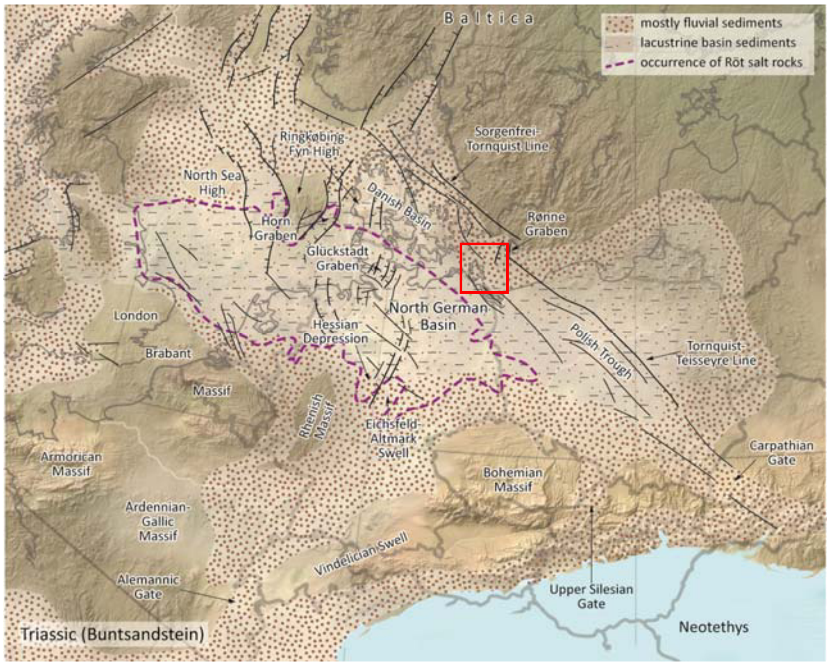


Fig. 3-18: Palaeogeographic map of the Lower Triassic (Meschede & Warr 2019, modified).

Laurussia, this time was characterised by arid climatic conditions (MESCHEDE 2018). Therefore, the Buntsandstein is prominent for its red terrestrial sediments, deposited under fluviatile, limnic or aeolian conditions with only sporadic marine ingressions (STOLLHOFEN et al. 2008). According to GELUK et al. (2008), the thermal subsidence until the Middle Buntsandstein, as well as alternating rifting and basin separations since the Middle Buntsandstein, led to a change of the erosional base level and the formations of typical fining upward sequences of sand, silt and clay stones, which are separated by unconformities (FELDRAPPE et al. 2007, STOLLHOFEN et al. 2008, FRANZ et al. 2018*a*, MESCHEDE 2018; **Fig. 3-16**).

The ***Lower Buntsandstein*** succession deposited in the CEBS is characterised by a general tectonic quiescence. Its distribution and increasing thickness towards the basin centre indicates a gradual basin formation (SPB/CEBS) driven by thermal subsidence (GAST et al. 2010). The Calvörde Formation reflects a transition from the marine Zechstein conditions towards terrestrial Buntsandstein conditions (**Fig. 3-18**). This unit has therefore been subdivided into basal salty clays, covered by cyclic deposits of sand, silt and clay (MESCHEDE 2018). Coarse-grained alluvial and fluvial deposits can be found marginal of the Variscan massifs and local highs, whereas the distal sediments are finer-grained. The latter were usually deposited under lacustrine conditions, because playa lakes and mud flats characterised the basin centre (BACHMANN et al. 2010). The Bernburg Formation is dominated by dolomitic sandstones and carbonatic oolites, so called "Rogensteine" or roestones, and stromatolites. According to BACHMANN et al. (2010), it is still unclear whether those deposits have a marine (transgression through the North Sea rift) or non-marine origin.

With the transition from Early to ***Middle Bundsandstein***, swells and highs started to form, due to multi-directional rift processes and initial Early Cimmerian movements. The westward propagating Neotethys rift and the southward propagating Norwegian-Greenland-See Rift triggered a breakup of Pangaea. This led to basin separation and formation of prominent graben structures, such as the NNE-SSW trending Horn and Glückstadt grabens in NW-Germany, and the Rügen-Vorpommern, Gryfice, and Rønne grabens (ZIEGLER 1990*a,c*, STOLLHOFEN et al. 2008, BACHMANN et al. 2010, PHARAOH et al. 2010). These grabens were formed by WNW-ESE oriented extension. At the same time, transtensional stress affected existing NW trending structures, such as the TTZ (BACHMANN et al. 2010). Although the Volprihausen Formation contains marine fossils indicating a short-term transgression from the Neotethys via the East Carpathian Gate (KATZUNG 2004*a*), the Middle Buntsandstein is generally dominated by terrestric strata (MESCHEDE 2018). The four sub-groups are separated by unconformities, as a result of short-lived tectonic phases. Different thicknesses indicate a syndepositional formation of graben structures and faults (BACHMANN et al. 2010).

During the ***Late Buntsandstein (Röt)*** basal clay- and marlstones were deposited in playa lakes (MESCHEDE 2018) before an additional flooding through the East Carpathian and Silesian-Moravian Gates and a hot and dry climate reduced the clastic sedimentation (STOLLHOFEN et al. 2008). Due to subsequent regression phases, halite and anhydrite accumulated in the west, such as the NGB, whereas carbonates and sulfates were deposited in the east, especially within the MPT. Argillites and widespread carbonates covered the succession, when a new transgression from the SW and SE entered the basin and induced the marine conditions of the Muschelkalk (KATZUNG 2004*a*, STOLLHOFEN et al. 2008). Moreover, salt migration of the Zechstein deposits were triggered by increasing tectonic instability and superimposed load (KATZUNG 2004*a*, FELDRAPPE et al. 2007).

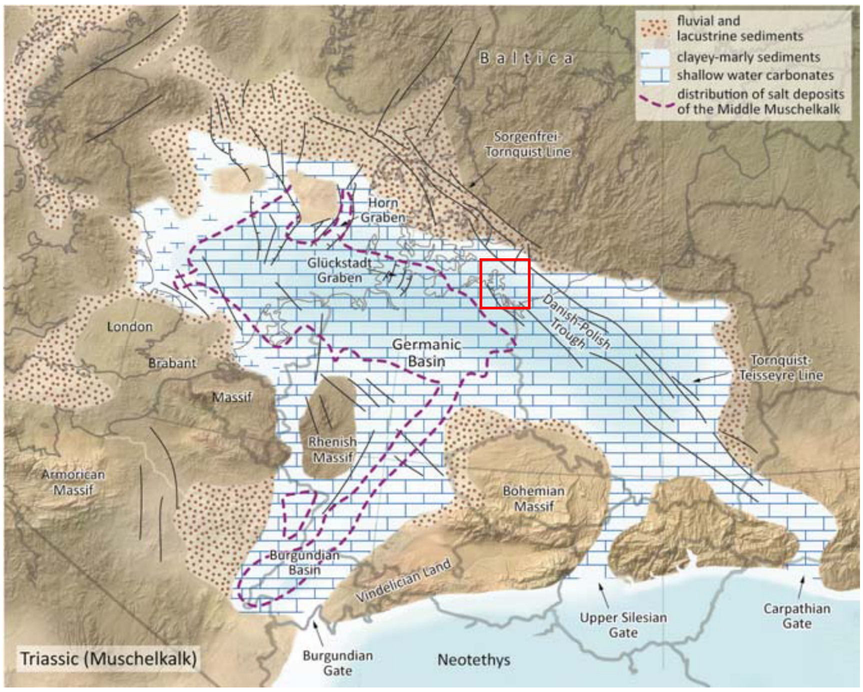


Fig. 3-19: Palaeogeographic map of the Muschelkalk (MESCHEDE & WARR 2019, modified). The red rectangle marks the research area of this thesis.

The marine ***Muschelkalk*** deposits are subdivided in a Lower Muschelkalk (Wellenkalk Formation), a Middle Muschelkalk with an Anhydrite Formation, and an Upper Muschelkalk section with Ceratites and Trochitenkalk beds (LUNG M-V 2004, **Fig. 3-16**). The Muschelkalk sediments, such as marl- and limestones, were deposited within a shallow sea (**Fig. 3-19**). Different gates in the south allowed a transgression of the Neotethys, as evidenced by the marine fauna within the basin. Due to its high content of fossils, the Upper Bundsandstein can easily be distinguished from the Lower Muschelkalk (GÖTZ & FEIST-BURKHARDT 2008). The Muschelkalk Sea, covering the NGB and the MPT, had a high abundance of individuals, but a low density of species compared to the Neotethys. Nevertheless, about 250 species migrated from the Neotethys via the gates (FAUPL 2003).

Due to a greater extent of the basin towards the south, some authors have favoured the term **Germanic Basin** (German: Germanisches Becken) instead of NGB (MESCHEDE 2018). Its extension is triggered by the ongoing thermal subsidence of the lithosphere (PHARAOH et al. 2010, and citations therein). For large parts of Germany, the “Grenzgelbkalk” (yellow basal limestone) signalised the transition from Buntsandstein to Muschelkalk. The basal limestone is covered by nodular limestones of the “Wellenkalk Formation” (***Lower Muschelkalk***). A transgression of the Neotethys via the Silesian-Moravian and East Carpathian gates (starting already during the Late Buntsandstein/Röt) led to the deposition of grey limestones, marlstones and dolomites with a nodular texture. The Lower Muschelkalk deposits are typically thin-layered with brachiopod- and mollusc-rich layers. These tempestites probably formed during storm events (FAUPL 2003, STOLLHOFEN et al. 2008). The generally monotonous limestones of the Wellenkalk Formation are interrupted by intercalated thinner but wide-spread marker horizons of the so-called “Oolithbänke”, “Terebratelbank” and “Schaumkalkbank” (STOLLHOFEN et al. 2008). Those lagoon-like conditions persisted during the transition to the ***Middle Muschelkalk***. The fauna retreated towards the east of the CEBS, whereas in the central and western parts dolomite and anhydrite were deposited (KATZUNG 2004*a*). With the further drop of sea level, the communication through the southeastern gates was restricted, and the East Carpathian Gate even closed. Although in Poland carbonates were still formed due to a fresh water influx, the central and western parts of the Germanic Basin remained in evaporitic conditions. According to STOLLHOFEN et al. (2008), two evaporitic cycles can be detected, which have been named Heilbronn Formation (MESCHEDE 2018). The distribution of the salt containing layers is restricted to the basin centre. In NE Germany, these deposits terminate along a line running from Kühlungsborn through Neubrandenburg to Eberswalde (BEUTLER 2004). The north-eastern basin margin, especially the Rügen area, is characterised by clay-dolomite-sulphate cycles. Further north, the sulphate content is missing (BEUTLER 2004). After a new strong ingression at the beginning of the ***Late Muschelkalk***, along the Burgundy Gate, a carbonate platform developed. According to STOLLHOFEN et al. (2008), the opening of this gate was triggered by the westward shift of the Neotethys rift centre. The fossil-rich carbonates are eponymous for the "Trochitenkalk Formation". Due to a slow regression at the end of the Muschelkalk, clastic facies advanced from the north (KATZUNG 2004*a*). The "Meissner Formation" contains thin-layered, marly carbonates with a high content of fossils (e.g. *Ceratites*). This succession is overlain in the northern part of the basin by dolomitic-clayey deposits of the "Warburg Formation" (MESCHEDE 2018).

The tectonic situation during the Muschelkalk was still controlled by rifting processes in the Tethys, resulting in a reactivation of the Variscan master faults, and by the Arctic-North Atlantic Rift System (STOLLHOFEN et al. 2008, PHARAOH et al. 2010).

The predominantly terrestrial succession of the ***Keuper*** comprises the longest unit of the Triassic (37.5 Ma; STG 2016) but is also marked by several hiatuses and discordances (**Fig. 3-16**). Its strata are subdivided into **Lower** (in Mecklenburg Western-Pomerania: Lettenkeuper), **Middle** (i.e., Lower Gipskeuper, Schilfsandstein, upper Gipskeuper and Steinmergel- or Dolomitmergelkeuper), and **Upper Keuper** (i.e., Rätkeuper) with the Postera-, Contorta- and Triletes strata (LUNG M-V 2004, BEUTLER 2004). At the beginning of the Keuper, the sea level reached a low-stand after a strong regression and the closure of the eastern gates between the CEBS and the Neotethys (KATZUNG 2004*a*). Thus, primordial marine conditions of the Muschelkalk changed into deltaic and terrestrial ones (MESCHEDE 2018, **Fig. 3-19 & Fig. 3-20**).

Fig. 3-20: Palaeogeographic map of the Keuper (MESCHEDE & WARR 2019, modified). The red rectangle marks the research area of this thesis. AM–Armorican Massif, BM–Bohemian Massif, CM–Central Massif, LBM–London-Brabant Massif, VL–Vindelician Land.

The proceeding and accelerating Arctic-North Atlantic Rift extended towards the Central Atlantic. Thus, the resulting transtensional tectonics enhanced the basin differentiation with differential subsidence rates, especially within the graben structures (STOLLHOFEN et al. 2008, PHARAOH et al. 2010). Moreover, the Neotethys opened and the Palaeotethys subducted beneath Laurussia. According to ZIEGLER (1990*a*) and the compilation of PHARAOH et al. (2010), the Early Cimmerian Orogeny in the SE of Laurussia forced an intra-plate compressional stress system and uplift in the crustal part of EEC. However, further west, the thermic subsidence along the CEBS remained active and rifting activity in the North and Central Atlantic, as well as in the Neotethys region, induced an extensional stress system along the West European Platform. Thus, the northern Fennoscandian border zone was uplifted, but the CEBS extended towards the west (FAUPL 2003). The ongoing basin differentiation was intensified by salt tectonic processes (BEUTLER 2004).

The sediment provenance was located north of the CEBS at the Fennoscandian High, which is eponymous for the so-called "Nordic Keuper" (German: "Nordischer Keuper"). The southwestward propagating sedimentation was especially driven by fluvial to deltaic systems, with a southwards drainage flow towards the Neotethys (BACHMANN et al. 2010, FRANZ et al. 2018*a,b*). According to MESCHEDE (2018), the northern part of the basin was characterised by a huge alluvial plain with fluvial and limnic sedimentation processes, while the southern area was located in an intertidal zone with predominately deltaic, lagoonal or estuarine deposits. The typical fluviatile sediment of the ***Lettenkeuper (Early Keuper)*** is the "Hauptlettenkohlen-Sandstein", which is an immature sandstone filling up the channels. Between the meandering rivers, clayey and silty crevasse splay deposits are dominant (BEUTLER 2004). In the south of Germany, a sharp unconformity (D1 base Erfurt Unconformity) marks the border between Muschelkalk and Keuper, whereas in northern Germany this is a soft transition (STOLLHOFEN et al. 2008). With the beginning of the ***Middle Keuper (Early Gipskeuper)***, the climate became more arid, resulting in the development of sabkha and playa environments. Through the Burgundy Gate, the CEBS was flooded several times, depositing various evaporate layers, such as the enormously thick halite in the Ems- and Glückstadt grabens (BEUTLER & NITSCH 2005).

The so-called **Early Cimmerian** stress impulses defined the tectonic processes in the Middle Keuper due to further rifting processes in the Arctic-North Atlantic region. Especially along the northern border of the NGB, this stress impulses resulted in strong extensional and transtensional forces. Thus, the weakness zone of the **TESZ** was reactivated, resulting in the development of the **Western Pomeranian Fault System** (**WPFS**; German: "Vorpommern Störungssystem"). This latter fault system is characterised by several NW-to NNW striking graben and half-graben structures within the Mesozoic strata (KRAUSS & MAYER 1999, MAYER et al. 2000, KRAUSS & MAYER 2004). The development of this fault system and its relation to the TESZ is discussed further in **Section 3.3.2**.

Due to an alternating sea level and a repeating transgression of the Neotethys sea via the Burgundy Gate, the sedimentation varied between fluvio-deltaic (sand- and mudstones) and marine conditions (carbonates and evaporates) (BEUTLER 2004, BEUTLER & NITSCH 2005, STOLLHOFEN et al. 2008). During the ***Schilfsandstein (Stuttgart Formation)*** and ***Lower Postera-Layers (Arnstadt Formation)***, a sea level low-stand facilitated a fluvio-deltaic to limnic-playa environment (**Fig. 3-21**), during the interim late ***Gipskeuper (Weser Formation,* Fig. 3-16*)*** widespread sabkha mudflats and halite deposits accumulated in an arid climate with several marine ingressions. The final deposition of the upper Postera and Contorta layers in NW Mecklenburg-Western Pomerania was driven by fluvial-deltaic progressions,

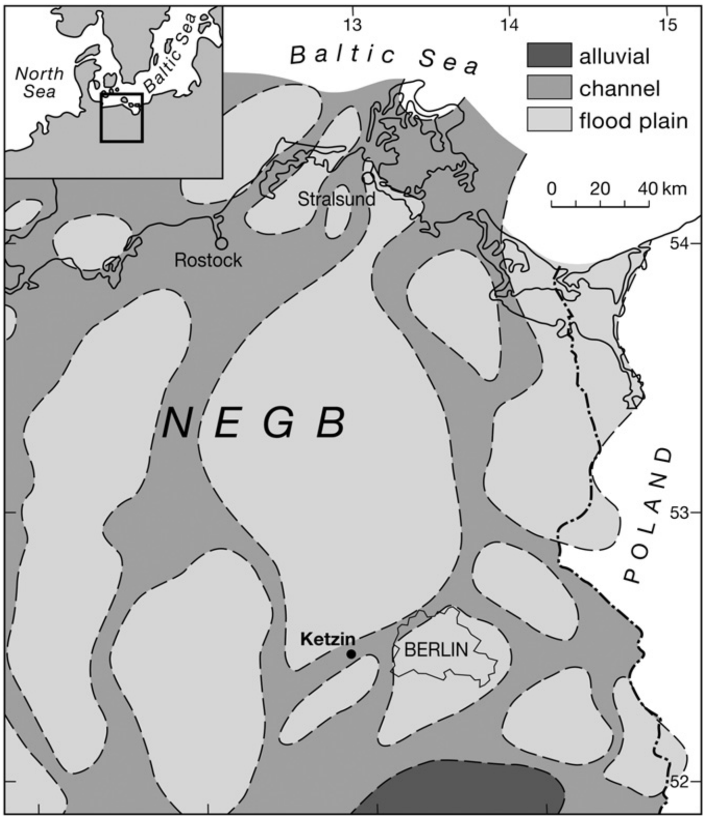


Fig. 3-21: The Schilfsandstein Formation in the eastern part of the NGB (FÖRSTER et al. 2010).

reaching from the north along the Odra and Mecklenburg bay, and around the Rügen swell towards the SW (KATZUNG 2004*a*, BACHMANN et al. 2010).

Widespread unconformities, such as the basal Schilfsandstein (D2) and the basal Lower Postera-Layer (D4- Early Cimmerian Discordance), terminate the successions. The increasing Arctic-North Atlantic rift activity triggered E-W orientated extensional forces along N-S striking tectonic structures and strike-slip movements along NW-SE orientated faults. Furthermore, halokinetic processes within the Zechstein salt deposits deformed the overlying strata, especially between the Late Buntsandstein and Middle Keuper (STOLLHOFEN et al. 2008). The ***Late Keuper (Rhaetian, or Exter Formation)*** is characterised by a transition from the predominantly continental conditions of the Keuper to the marine Jurassic conditions (STOLLHOFEN et al. 2008). The Rhaetian transgression along the Burgundy Gate, and probably also across the English Midlands and the Irish Sea (ZIEGLER 1990*a*), terminated the typical terrestrial sedimentation. Thus, marine sediments dominate in the west and brackish deposits in the east (KATZUNG 2004*a*). The Rügen swell acted during the whole Keuper as a constant regional high where the deposits thinned out. The strata of the Upper Keuper furthermore show differences in thickness, indicating synsedimentary tectonic processes.

The North German ***Jurassic*** strata are divided into Lias (Lower), Dogger (Middle) and Malm (Upper Jurassic). The whole Jurassic is characterised by a shallow shelf sea with an alternating north- and eastward extension and a predominantly sandy-pelitic deposition (KATZUNG 2004*a*). A greenhouse climate prevailed resulting in ice-free poles (FAUPL 2003). Thus, the sea level variations were only controlled by tectonic processes. An important development at this time was the continental rift system intersecting North America and Northwest Africa, which gave rise to the southern North Atlantic (the northern area had not yet opened at this time). Sinistral strike-slip movements along the Neufundland-Azores-Gibraltar transform fault between Gondwana and Europe controlled the strain conditions in the CEBS. Furthermore, with the ongoing breakup of Pangea and Gondwana, the Gulf of Mexico and the Indian Ocean opened (FAUPL 2003). During the ***Lias***, the enduring Rhaetian transgression induced a thalatocratic phase (FAUPL 2003, **Fig. 3-22**). This flooding progressed from the NW Arctic region through the Rockall-Faeroe Trough via the Irish Sea, and from the south through the Burgundy Gate (KATZUNG 2004*a*, STOLLHOFEN et al. 2008). The Fennoscandian High in the north, the Vindelician-Bohemian massif in the east, and the Rhenish, London-Brabant and Armorican massifs in the south remained as regional highs. An arid climate controlled the broad equatorial zone, whereas towards higher latitudes it became more humid with an increasing precipitation rate (FAUPL 2003). While black clays are typical for the Lias successions in Northern Germany, more limy deposits dominate in southern Germany. Fossil rich layers with marine reptiles (e.g. Ichthyosaur) and Crinoides play an important role as marker horizons (FAUPL 2003). A

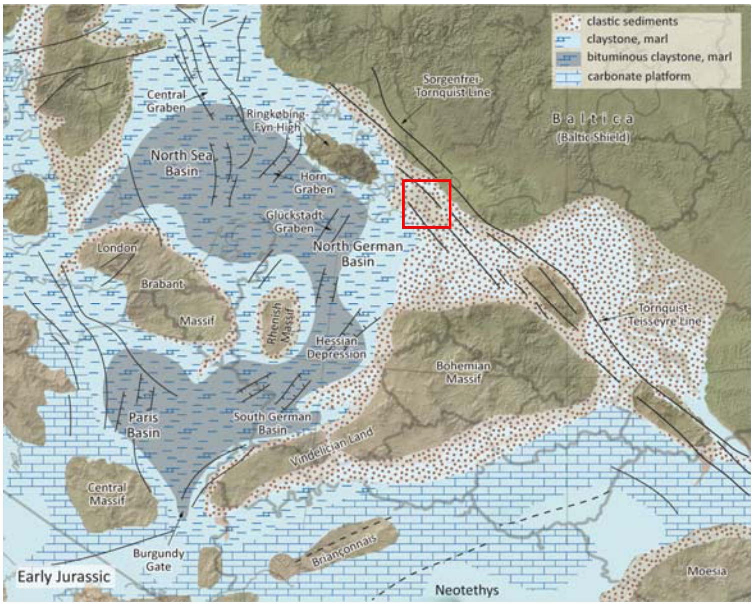


Fig. 3-22: Palaeogeographic map of the Lias (MESCHEDE & WARR 2019, modified). The red rectangle marks the research area of this thesis.

noteworthy example is the marley Posidonia shale, named after the dominating Bivalve Bositra Buchii (before *Posidonia bronni*), which today is the source rock of one third of the German oil production (FAUPL 2003, MENNING & DSK 2012, MESCHEDE 2018). A further transgression through the East Carpathian Gate flooded the CEBS during the ***Dogger*** (KATZUNG 2004*a*). The Jurassic succession is marked by several unconformities, such as the prominent **"Mid-Cimmerian Unconformity"**. Mid-Cimmerian movements resulted from Early to Late Jurassic doming of the asthenosphere in the northwestern part of the NGB. This doming led to a thermal uplift of the crust especially during the Dogger, and rifting during the Malm (FAUPL 2003, STOLLHOFEN et al. 2008). Due to the newly formed local high within the Central North Sea, the basin was separated and the seaway closed. At the same time, the uplift caused widespread erosion (STOLLHOFEN et al. 2008) and the Ringkøbing-Fyn High rose above sea level and formed islands. On the other hand, basins north of the London-Brabant High and along the TTZ, such as the MPT, were still subsiding (KATZUNG 2004*a*). At the late Dogger, the sea level was very high and parts of the EEC were flooded by the boreal Jurassic transgression. At the same time, the new Pre-Uralian Gate between the Arctic, the CEBS and the southern Neotethys developed (FAUPL 2003). Typical Dogger deposits are limonite-rich sand-, marl- and claystones, as well as iron-rich ooliths, especially within shallow tidal border zones (FAUPL 2003).

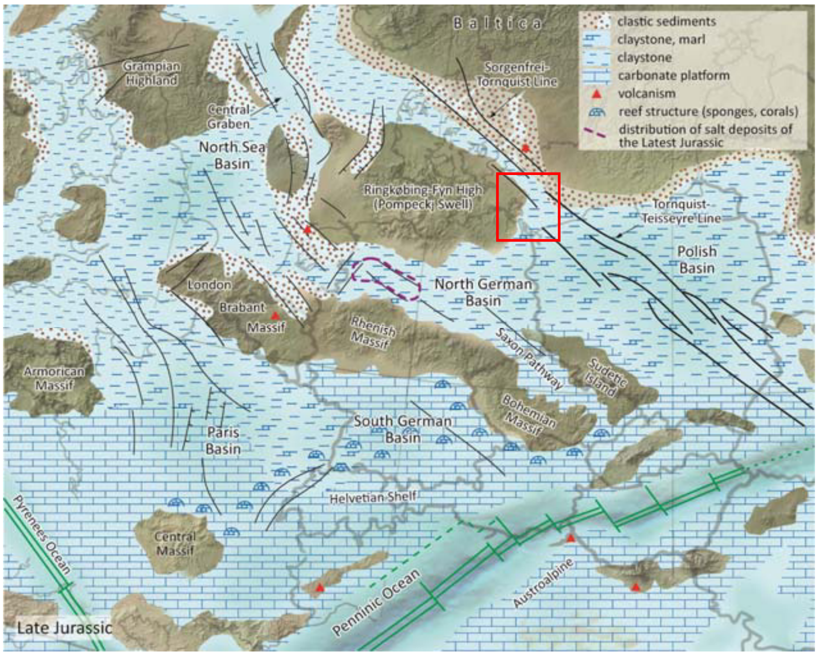


Fig. 3-23: Palaeogeographic map of the Malm (MESCHEDE & WARR 2019, modified). The red rectangle marks the research area of this thesis.

The highest Jurassic sea level stand was reached during the ***Early Malm*** (**Fig. 3-23**). This caused the complete flooding of the Vindelician High, and therefore an open connection of the intra-continental sea towards the Neotethys. Meanwhile, the RFH rose further and connected with the London-Brabant High (KATZUNG 2004*a*, FAUPL 2003). The ongoing uplift, especially of the RFH and parts of the Bohemian Massif, and the regression of the sea during the late Malm, had major palaeogeographic consequences. The **NW Mecklenburg Swell** (KATZUNG 2004*a*) or **Pompeckj Swell** (STOLLHOFEN et al. 2008) intersected the Danish-Polish Trough (connection between the Arctic-North Atlantic area and the Neotethys) and the Lower Saxony Basin. FAUPL (2003) mentioned also the **Mid German Swell**, forming a connection between the London-Brabant, Rhenish and Bohemian massifs further south.

After the rift-doming phase in the Dogger, the major rifting phase with a strong subsidence of grabens, such as the Gryfice Graben, occurred during the Malm (FAUPL 2003). With the reorientation of the stress system, especially due to the Arctic-North Atlantic Rift, transtensional and strike-slip displacements became more intensive. After a counter-clockwise rotation of the stress regime, a NW-SE trending shear zone developed (ZIEGLER 1990*a*, KLEY at al. 2008, STOLLHOFEN et al. 2008). According to STOLLHOFEN et al. (2008), the tectonic situation of evolving horst and graben structures and rotating blocks resulted in a complex depositional pattern. A further unconformity can be found in the southern part of the basin, marking a hiatus between the Jurassic and Cretaceous (Katzung 2004*a*).

The ***Cretaceous*** is divided into an Early (145-100.5 Ma; STG 2016) and Late (100.5-66 Ma; STG 2016) epoch. The ***Early Cretaceous*** comprises the Berriasian, Valanginian, Hauterivian, Barremian, Aptian and Albian stages (Katzung 2004*a*, STG 2016). The global palaeotectonic situation was driven by the ongoing breakup of Pangaea. The Arctic, Australian and Indian continents split off from Gondwana and drifted in different directions (**Fig. 3-24**). The North Atlantic extended in a northerly direction and sea floor spreading continued in the Central Atlantic. Since the South Atlantic (between Africa and South America) opened until Guinea (Africa) or Natal (South America), there was no continuous connection between the South and Central Atlantic during the Early Cretaceous (Faupl 2003). A conjunction between the North and Central Atlantic along NW-SE striking transform faults resulted from the ongoing rifting processes since the Late Jurassic. Moreover, those transform faults connected the rifts within the Central Atlantic, the South Penninic Ocean and the Pyrenees Ocean separating the Iberian microcontinent (**Fig. 3-24**; Kley & Voigt 2008, Meschede 2018). The South Penninic Ocean opened between Iberia in the north and the African and Adrian-Apulian plates in the south (Meschede 2018). In contrast to the rift processes, the **Late Cimmerian** collision proceeded (for location see **Fig. 3-17**, Meschede 2018, Meschede & Warr 2019), introducing a new stress system into the CEBS. The SE drifting African and Iberian plates induced a NNW-SSE to NW-SE oriented extension and the northwestward opening of the Pyrenees Ocean (Rosenbaum et al. 2002 *in* Kley & Voigt 2008, Meschede 2018) during the Late Jurassic to Early Cretaceous. Transtensional forces also played an important role, with sinistral strike-slip displacements occuring along NW-SE orientated faults, causing transtensional or pull-apart basins, such as the Sole-Pit or Lower Saxony basins (Meschede 2018).

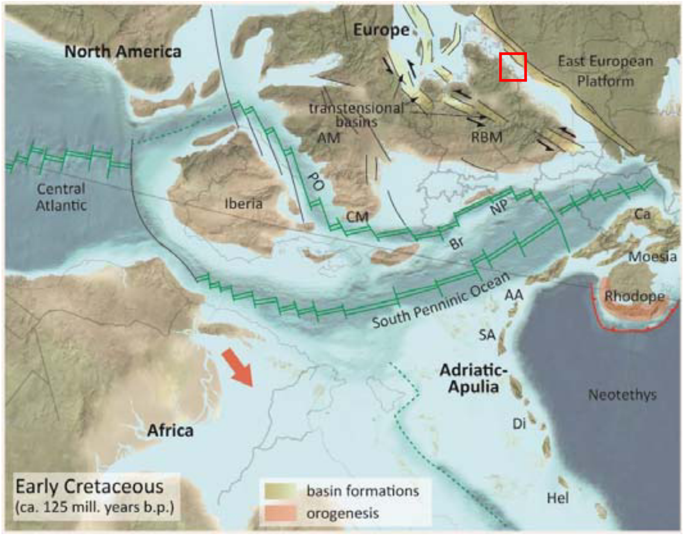


Fig. 3-24: Palaeogeographic map of the Lower Cretaceous (Meschede & Warr 2019, modified). The red rectangle marks the research area of this thesis. AA–Austroalpine, AM–Armorican Massif, Br–Briançonnais, Ca– Carpathians, CM–Central Massif, Di–Dinarides, Hel–Hellenides, NP–North Penninic Ocean, PO–Pyrenees Ocean, RBM–Rhenish-Bohemian Massif, SA–South Alpine.

The **Central European High** was formed by the expansion of the Mid German Swell. Concurrently with an enhanced uplift of the Pompeckj Swell, the Lower Saxony and Prignitz-Altmark-Brandenburg basins narrowed and caused a nearly complete regression of the sea until the North Atlantic and the Neotethys (Katzung 2004*a*). The Prignitz-Altmark-Brandenburg depression remained in the south of Mecklenburg-Western Pomerania, terminated by the North Mecklenburg Swell in the NW and the East-Brandenburg High in the NE. A sub-basin of the Danish-Polish Basin, the Usedom Depression extended between the latter and the Rügen Swell (Diener et al. 2004*a*). The low sea level resulted in a brackish to limnic sedimentation in the local depressions. In the Prignitz-Altmark-Brandenburg and Usedom depressions, the Berriasian succession is divided into the Serpulite (grey-green, fossil rich clay or marlstone) and Wealden (clayey, sandy with coal seams) deposits. The Valanginian is missing in this area, but Hauterivian, Barremian and Aptian deposits – the so-called "Usedom Succession" –

can be found north of the Grimmen Wall. The Lower Cretaceous sediments (glauconitic, silty, fine-grained sandstones with varying fossil content) are predominantly bound to the depressions within the WPFS (Diener et al. 2004*a*). From the Valanginian, the Cretaceous is characterised by a general sea level rise with several transgression phases and minor regressive phases. The increasing sea level is accompanied by ice-free poles, but especially by enormous seafloor spreading activities. As young oceanic lithosphere has a lower density than older oceanic or continental lithosphere, it does not sink as deep into the asthenosphere and reduces the average depth of the oceans. Consequently, seawater is forced out flooding the mainland (Meschede 2018). Three major transgression cycles have been identified: (1) the Early Cretaceous transgression flooded the Danish-Polish Depression and the London Massif from the north, with a connection between the Arctic region and the Neotethys developing in the east (Faupl 2003); (2) the more intensive Albian transgression (Aptian to Turonian) connected the spacious north of Middle Europe with the DB, NGB and MPT, while further sea ways along the Paris Basin, England, and between the Armorican and Central massif evolved (Faupl 2003), (3) during the last transgression from Campanian to Maastrichtian, the sea level reached its maximum highstand, probably up to 300 m higher than present (Faupl 2003). Most of the CEBS was flooded, but it was surrounded by the Fennoscandian High, Rhenish-Bohemian Massif, and the Armorican and the Central massifs (Meschede 2018). During the late Maastrichtian, the sea regressed northward, while the area of Western Pomerania remained under water.

Shallow marine ***Upper Cretaceous*** deposits in Western Pomerania can be divided into calcareous marlstone and limestone of the early Upper Cretaceous (in North Germany called Plänerkalke), and limestone and chalk deposits with flint concretions of the late Upper Cretaceous (Meschede 2018, Diener et al. 2004*b*). The prominent chalk deposits are mainly composed of the algae *Coccolithophorida* and contain large numbers of fossils, such as sea urchins, sponges, belemnites and molluscs (Meschede 2018). Along the border of the sea, terrigenous material influenced the sedimentation, resulting in enormous sand packages, such as those in the Elbsandsteingebirge (Diener et al. 2004*b*, Meschede 2018). The Late Cretaceous is characterised by a major change in the palaeotectonic situation and therefore also in the stress system (**Fig. 3-25**). The drift direction of the African plate changed from SE to NE, which induced the closure of the Pyrenean Ocean and subsequently caused the Pyrenean Orogeny (Kley & Voigt 2008, Meschede 2018). The Pyrenean collision induced a change from extensional stress to compression in Europe. According to Herrig (2004), the Hercynian and Laramian tectonic phases controlled the sedimentation from the Coniacian to the Palaeogene. Former NW-SE striking normal faults changed into reverse and thrust faults. Thus, the Pomeranian-Kuiavian Anticline in the MPT, the Prignitz Lausitz

Fig. 3-25: Palaeogeographic map of the Upper Cretaceous (Meschede & Warr 2019, modified). The red rectangle marks the research area of this thesis. AA–Austroalpine, AM–Armorican Massif, Br–Briançonnais, Ca–Carpathians, CM–Central Massif, Di–Dinarides, Hel–Hellenides, NP–North Penninic Ocean, PO–Pyrenees Ocean, RBM–Rhenish-Bohemian Massif, SA–South Alpine.

swell in the NGB, and the Grimmen High south of Rügen were uplifted (KATZUNG 2004*a*, VEJBÆK et al. 2010, DEUTSCHMANN et al. 2018). Consequently, complete graben structures inverted, such as the Rønne or Gryfice grabens (SCHLÜTER et al. 1997*b*, GRAVERSEN 2004). The synclinal structures between the anticlines were filled by thick Cretaceous deposits, predominantely chalk. Associated depressions include the Mecklenburg depression between the Prignitz-Lausitz Swell and the Grimmen Wall, the Rügen Depression, and the Danish-Polish Depression running subparallel along the TTZ structure, east of the Gryfice Anticline (DIENER et al. 2004*b*, HERRIG 2004).

CENOZOIC

Average global temperatures episodically decreased during the Tertiary, ending in the Quaternary which is dominated by alternating periods of interglacials and interstadials.

Although the NE-SW to N-S oriented compressional stress regime was weaker in the ***Early Tertiary*** (Palaeogene), it remained active until the late Oligocene and influenced the whole CEBS (**Fig. 3-26;** KLEY at al. 2008). Faults were reactivated, but new reverse or thrust faults were also generated. In the Miocene, the stress regime rotated counter-clockwise into a NW-SE orientation when the main phase of the Alpine Orogeny started. During this time, the South and North Penninic oceans were closed and their oceanic crust subducted, transferring the stress of the colliding Adria-Apulian and European plates towards the CEBS (KLEY at al. 2008, MESCHEDE 2018). The northern extension of the Alpine Orogeny is characterised by a NE-SW striking Alpine deformation front. However, the relation with the coexisting NE-SW to NW-SE opening graben structures of the European Cenozoic Rift System is not fully understood (KLEY et al. 2008). This 1100 km long rift system crosses Europe from the Mediterranean area until the North Sea and contains the following graben structures from north to south: Hessian Graben, Lower Rhine Graben, Upper Rhine Graben, Eger Graben, Bresse Graben, Limagne Graben and Rhône Graben (ZIEGLER 1992, DÈZES et al. 2004). The graben development was accompanied by Tertiary and Quaternary volcanism, especially along the Rhine-Leine-Ruhr Valley triple junction (ZIEGLER 1992). The initial rifting was probably due to the extensional forces (which were perpendicular to the compression). Thus, the NE-SW orientated grabens such as the Eger or Upper Rhine grabens opened simultaneously with the Pyrenean Orogeny (NE-SW compression and NW-SE extension). Due to the counter-clockwise rotation of the stress system, from the Eocene to the Miocene, the NW-SE striking grabens such as the Lower Rhine Graben developed (NW-SE compression, NE-SW extension) (FRISCH & MESCHEDE 2013). A mantle doming in the early/ middle Tertiary forced a thermal uplift of the European Crust and enhanced the subsidence within the graben (ZIEGLER 1990*a*, VON BÜLOW & MÜLLER 2004, FRISCH & MESCHEDE 2013, MESCHEDE 2018).

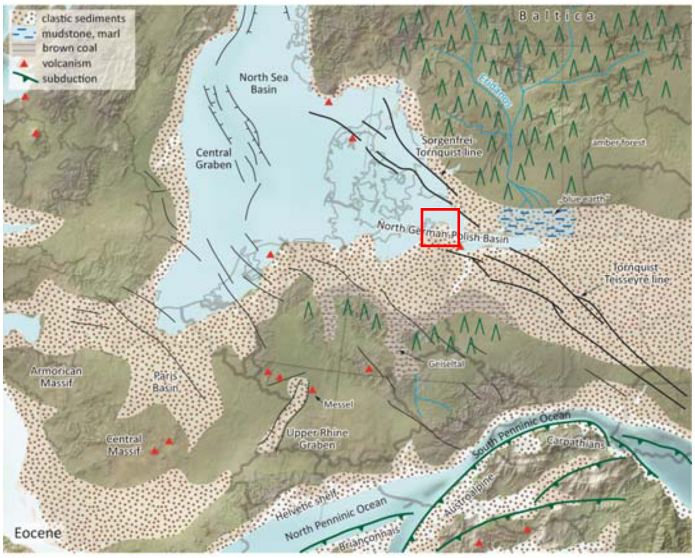


Fig. 3-26: Palaeogeographic map of the Eocene (MESCHEDE & WARR 2019, modified). The red rectangle marks the research area of this thesis.

The regression of the sea starting at the Late Cretaceous forced a sedimentation predominantly in the depressions of the graben structures, but also in the molasse basin north of the Alps (MESCHEDE 2018, **Fig. 3-26 & Fig. 3-27**). Whereas a clastic sedimentation with limnic and fluviatile deposits characterised the mainland, marine conditions can be found at the epicontinental sea in the NW and along the East Mediterranean Basin, south of the forming Alps. Various transgressions from the former area of the North Sea repeatedly flooded the MPT (KATZUNG 2004*a*). During the Oligocene, a transgression flooding the Hessian and Rhône depressions also reached the Upper Rhine Graben, as documented by several evaporates (MESCHEDE 2018). The successive regression of the sea induced palustric conditions along the Central European depression. Enormous swamps and wetlands advanced the evolution of major coal deposits and oil reservoirs.

The area around Rügen also successively changed from marine to terrestrial conditions (**Fig. 3-27**). Thus, the sedimentation of primarily silt, clays and marl with subordinate sandy components changed into silt, sand and especially humid strata with coal beds (VON BÜLOW & MÜLLER 2004). The economic interest in this area during the last decades was based especially on the coal seams but also on the groundwater reserve in the Miocene sand layers (LUNG M-V 2002). Around Rügen almost no Tertiary deposits can be found; the only Palaeocene deposits occur within some depressions of the WPFS. South of the Grimmen Wall, Lower Tertiary sediments have been deposited. Towards the south, the succession thickens and middle and upper Tertiary deposits are increasingly preserved (LUNG M-V 2002). These bedding conditions are a result of the evolution of the Grimmen Wall during the Oligocene. Moreover, the area was repeatedly eroded, faulted and folded by Scandinavian ice shield advances during the three main glacial phases of the ***Quaternary*** (EHLERS 2011, OBST et al. 2017, GEHRMANN et al. 2018). Therefore, under the thick Quaternary deposits of tills and sand-clay alternations, Upper Cretaceous sediments at Rügen, and Lower Jurassic sediments along the anticline structure of the Grimmen Wall, are exposed (LUNG M-V 2002, DEUTSCHMANN et al. 2018).

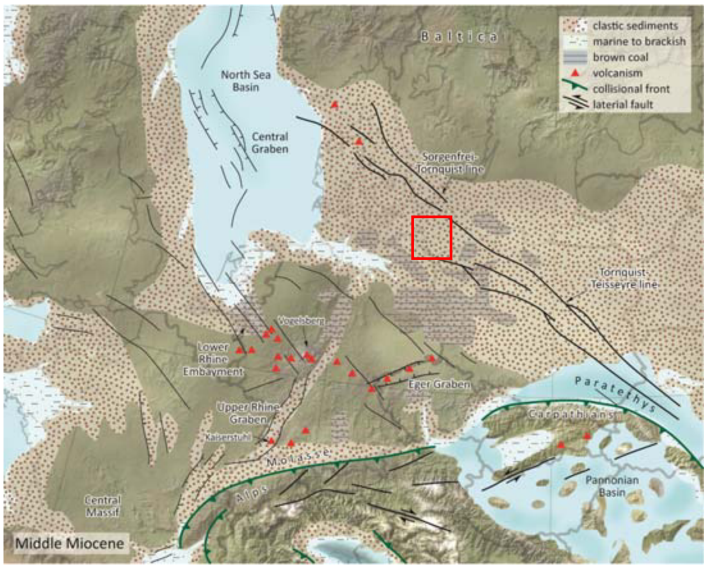


Fig. 3-27: Palaeogeographic map of the Miocene (MESCHEDE & WARR 2019, modified). The red rectangle marks the research area of this thesis.

The ice advances of the Weichselian, Saalian and Elsterian phases, formed the morphology of Northern Germany. All three major advances crossed the area of Rügen. After the final regression of the ice shield, the area is now characterised by isostatic movements (**Fig. 3-28**). Although along Scandinavia isostatic uplift has reached about 300 m since the last glacial maximum, the area of northern Germany was less affected (about 100 m in Rügen). The region south of the river Peene is located within the Central European subsidence zone and is thus lowering by about 1±0.5 mm/a (GRÜNTHAL & KATZUNG 2004). The recent neotectonic components are, therefore, split into isostasic and oscillating compensational movements due to the missing ice load and long-lasting uplift and lowering movements, induced by far field tectonic processes, such as in the Alps, the Mediterranean

Sea, and the Atlantic Ocean (GRÜNTHAL & KATZUNG 2004, KLIEWE 2004). The Baltic Sea has evolved since the last ice regression (KLIEWE 2004, EHLERS 2011).

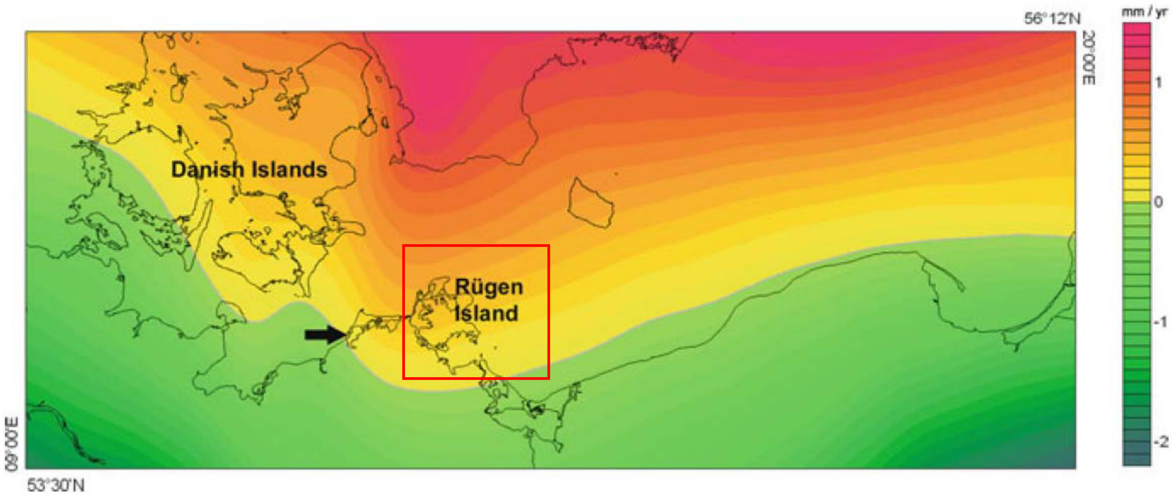


Fig. 3-28: Recent vertical displacements of the crust along the southern Baltic Sea (HARFF & MEYER 2011, modified). The working area is marked by the red rectangle.

3.3 Special tectonic features in the working area

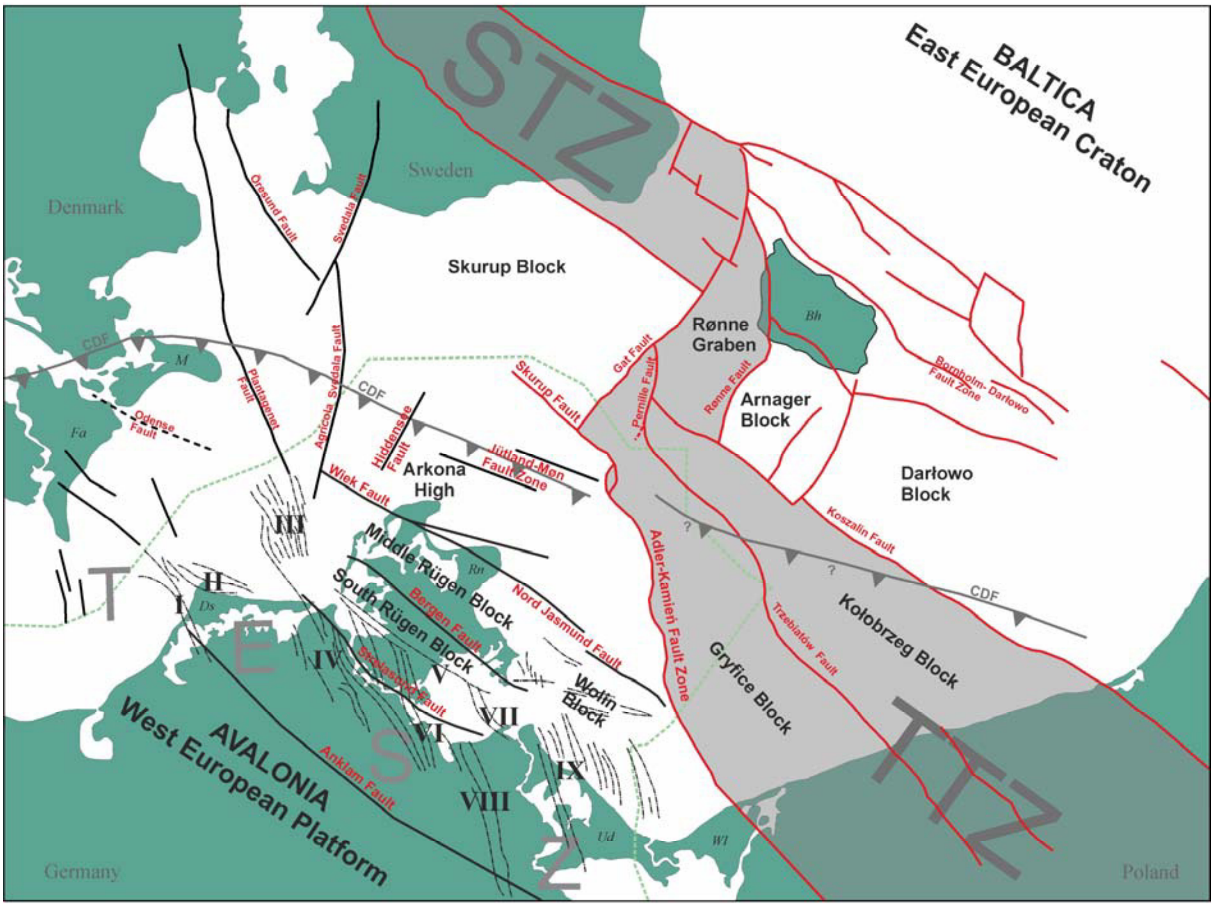


Fig. 3-29: Tectonic situation of the southeastern Baltic Sea (modified after DEUTSCHMANN et al. 2018, SEIDEL et al. 2018 and citations therein): CDF–Caledonian Deformation Front, TESZ–Trans-European Suture Zone, TTZ–Teisseyre-Tornquist Zone, STZ–Sorgenfrei-Tornquist Zone. Fault zones (FZ) of the WPFS: I–Werre FZ, II–Prerow FZ, III–Agricola FZ, IV–Reinberg FZ, V–Samtens FZ, VI–Greifswald-Poseritz FZ, VII–Freest FZ, VIII–Moeckow-Dargibell FZ and IX–Usedom FZ. Bh–Bornholm; Ds–Darss Peninsula; Fa–Falster Island, M–Møn Island, Rn–Rügen Island; Ud–Usedom Island; Wl–Wolin Island.

The map above illustrates the intensively block-faulted area of the southern Baltic Sea, within the Tornquist Fan area (**Fig. 3-29**). Six blocks have been distinguished within the working area: the Skurup, Arkona, Middle Rügen, South Rügen, Wolin and Gryfice blocks. The blocks are separated from each other by Palaeozoic deep faults. The **Arkona Block,** in the north of Rügen, is separated by the Wiek Fault from the Middle Rügen Block and the **Wolin Block** east of Rügen. The Middle Rügen and South Rügen blocks are located west of the Wolin Block are, both separated from each other by the Bergen Fault. The **Gryfice Block** is part of the TTZ and located in the east of the working area. It is separated from the Arkona and Wolin blocks by the AKFZ. Due to the tectonic history, these three main blocks (Arkona, Wolin and Gryfice) show major differences in their structural appearance and lithostratigraphic cover.

The following sections will sum up the complex evolution of the individual tectonic structures within the working area and its immediate surroundings. **Fig. 3-30** provides an overview of the different tectonic phases and the changes of the stress system in the area of Europe since the late Proterozoic. Additionally, some of the contradicting interpretations concerning for example the CDF, Thor Suture, Trans-European Fault or Trans-European Suture Zone, are presented and discussed.

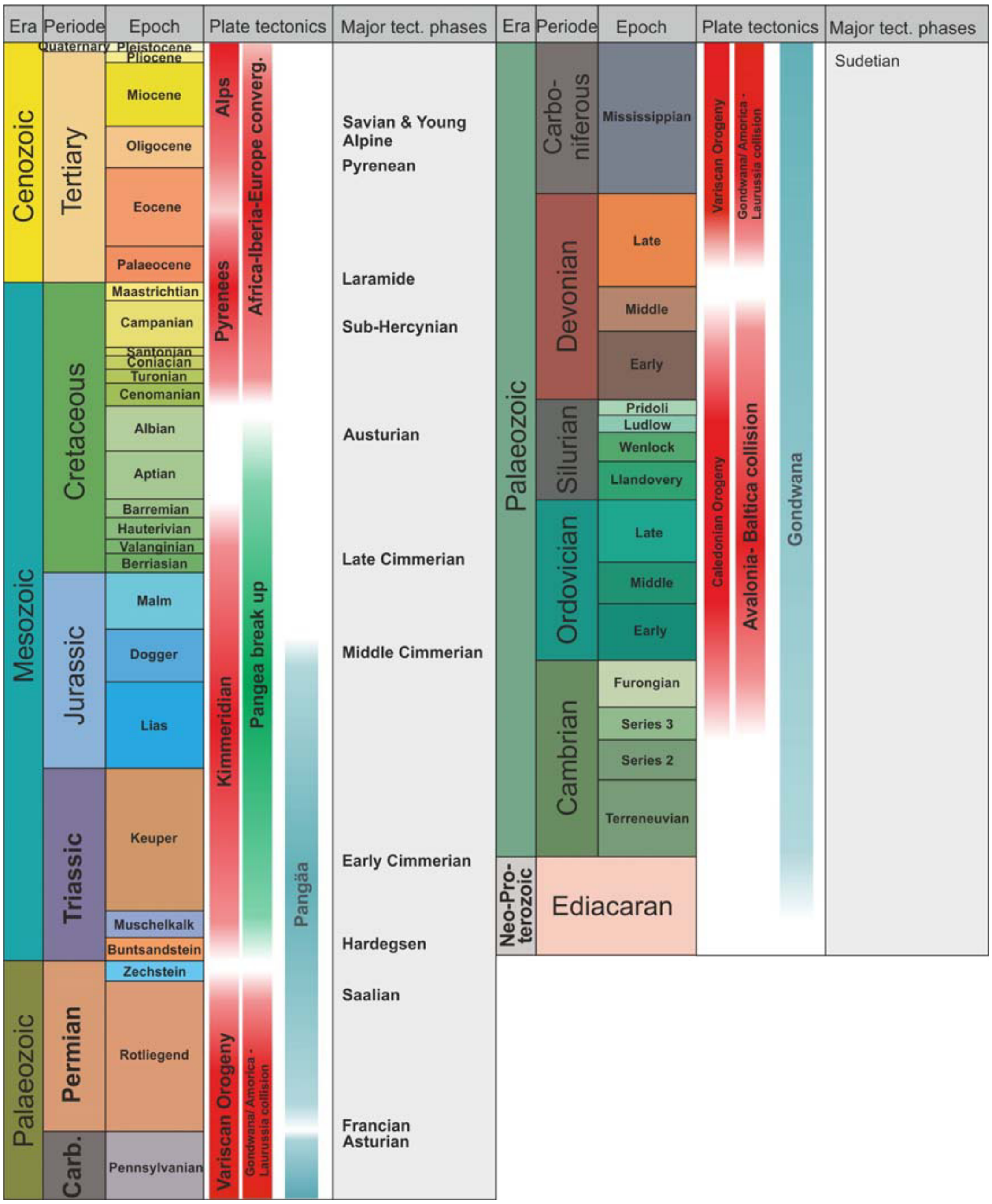


Fig. 3-30: Overview of the tectonic evolution of Europe (modified after FRISCH & MESCHEDE 2013; PHARAOH et al. 2010, MESCHEDE 2018)

3.3.1 The buried Caledonian Suture Zone between Baltica and Avalonia – the problem of terminology, appearance and reactivation phases

Due to the collision of Baltica and Avalonia, the Tornquist Ocean was closed and a 2000 km long marginal thrust belt, the Caledonides, formed (BERTHELSEN 1992*b*, 1998, BEIER 2001, PHARAOH 1999, GUTERCH et al. 2010).

The **Caledonian Deformation Front (CDF)** presents the position of the strike-out lineament of the accreted thrust belt, and thus the northernmost extension of deformed Ordovician strata at the craton of Baltica. Due to substantial erosion, it is unclear how far north the accretionary wedge reached and where the CDF was primarily located (FRANKE & HOFFMANN 1988). The CDF has recently been located south of the Ringkøbing-Fyn-High (SCHECK-WENDEROTH & LAMARCHE 2005) between onshore well Rn 5/66 (northern Rügen, with deformed Ordovician strata) and offshore well G14 1/86 (NE of Rügen, with undeformed Ordovician deposits). As revealed by the discovered deposits, well G14 1/86 is positioned on the Baltic Shield, outside of the accretionary wedge. Shales and older sequences covering the Baltic Crust were also found in this well (FRANKE et al. 1994, BEIER & KATZUNG 1999). Other authors introduced the term **Thor Suture** (COCKS & FORTEY 1982, PHARAOH 1997, 1999, BAYER et al. 2002, GUTERCH et al. 2010) or defined the CDF as an eastern prolongation of the Thor Suture (BERTHELSEN 1998). They also proposed different positions (**Fig. 3-31**). The location of the suture is mostly shown in the north of Rügen (e.g. BAYER et al. 2002), however, some authors assume the CDF at the position of the Strelasund Fault (e.g. BLUNDELL et al. 1992). BERTHELSEN (1992*a,b*) preferred to distinguish between the deformation front and the crustal suture. The Thor Suture marks the former position of the Tornquist Ocean (**Fig. 3-32;** BERTHELSEN 1998) and is also known as the Tornquist Suture (e.g. KATZUNG 2004*a*). According to BERTHELSEN (1992*a,b*), the overall suture zone is steepened in the lower crust and at this position is called **Trans-European Fault**. Additionally, the term Trans-European Fault Zone has been used (BERTHELSEN 1992*a,b*, MARKIS & WANG 1994, ERLSTÖM et al. 1997, KRAUSS & MAYER 2004).

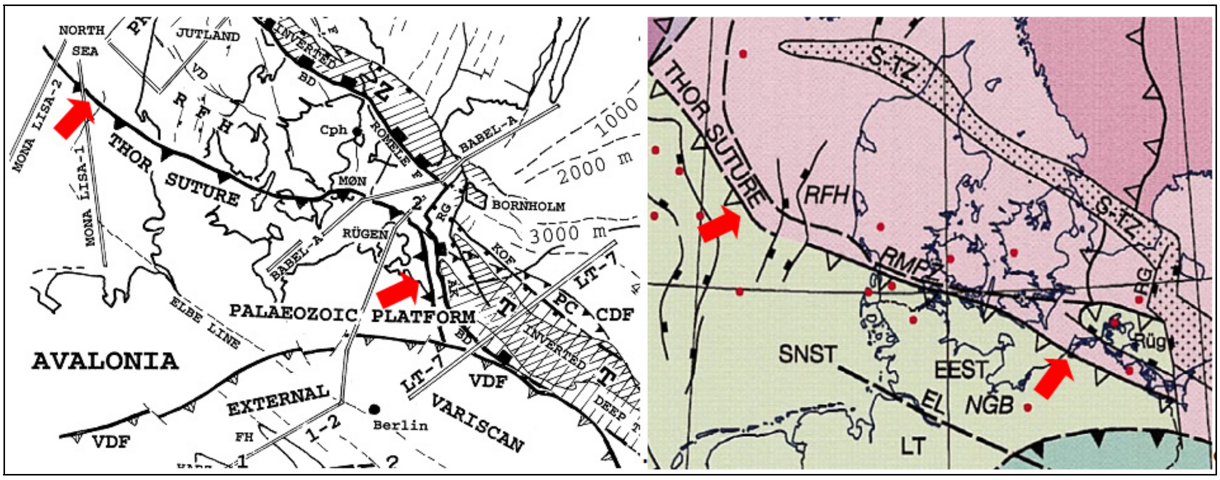


Fig. 3-31: Left– Structural map by BERTHELSEN (1998, modified) with the Thor Suture (marked by red arrows) north of Rügen. **Right**– Structural map by PHARAOH (1999, modified) with the Thor Suture (marked by red arrows) south of Rügen.

According to PHARAOH (1997, and citations therein), the **Trans-European Suture Zone (TESZ)** originated during the assembly of Pangaea and involves a complex zone of terrane accretion during the Caledonian, Variscan and Alpine orogenies. It separates the Precambrian lithosphere of the EEC from the younger Palaeozoic lithosphere of Western and Central Europe (PHARAOH 1997, 1999, BAYER et al. 2002, KRAWCZYK et al. 2002).

However, the transition zone between Baltica and Avalonia has been referred to by various terms and definitions. PHARAOH (1999) defined the CDF as major border between Baltica and Avalonia but favoured like BERTHELSEN (1998) the term Thor suture. PLOMEROVÁ et al. (2002), KRAWCZYK et al. (2002) and THYBO (2000) assume the TESZ as an amalgamation zone, where crust and lithosphere of the younger Palaeozoic West European Platform accreted onto the Proterozoic EEC. Others propose the Elbe Line, or Elbe-Odra line, as a transition (e.g. COCKS et al. 1997).

MCCANN & KRAWCZYK (2001) analysed deep seismic sections of the DEKORP-Basin'96 project and provided evidence against the existence of the Trans-European Fault instead, they proposed not to use this term in future.

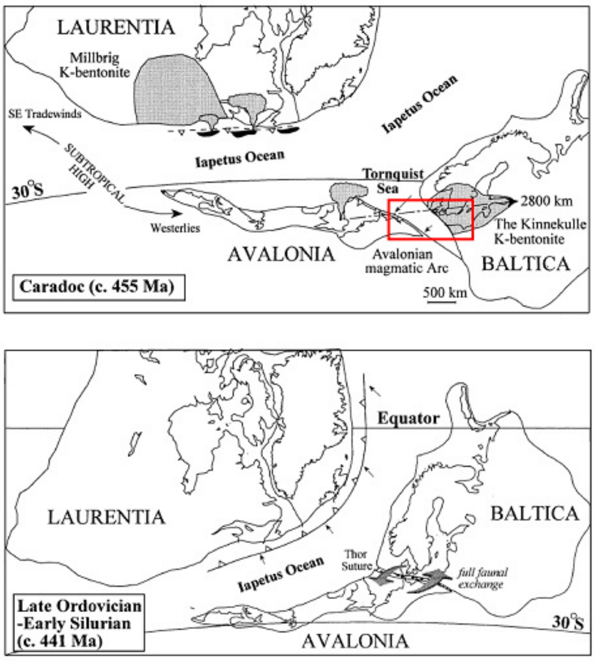


Fig. 3-32: Avalonia - Baltica docking and counter-clockwise rotation (TORSVIK & REHNSTRÖM 2003, modified).

BAYER et al. (2002) recognised the problem of the different terms and concluded that they may be expressions of the same (Thor) suture, but addressing different crustal levels, such as the CDF in the upper crust or the Elbe-Odra line in the lower crust.

Due to the classical definition of suture, which is an "elongated welded seam between two collided continental plates" (MURAWSKI & MAYER 2004, MESCHEDE 2018), the USO working group prefer the term Trans-European Suture Zone (TESZ) and refer to the compilation of GUTERCH et al. (2010). Thus, the TESZ represents the complete amalgamation zone with the accretionary wedge in between the upper crust, terminating along the CDF in the north. According to the definition of PHARAOH (1997, 1999), which is based on the EUROPROBE's TESZ working group, the TESZ comprises all suture zones around the margin of the EEC, such as the Iapetus or Thor sutures in northern Europe. However, the TESZ transects Europe over a distance of 2000 km, from the North Sea, through Poland, the Ukraine and Romania, to the Black Sea. It is concealed by deep basins which are filled with Permian to Cenozoic sediments (PHARAOH 1999, GUTERCH et al. 2010).

The southern extension of the TESZ and thus also of the crust of Baltica is still debated. Scientists of the DEKORP- BASIN '96 working group (DEKORP-BASIN RESEARCH GROUP 1999, MCCANN & KRAWCZYK 2001) posited the southern border about 25-50 km SW of the Grimmen High, at 20-30 km depth (**Fig. 3-33 &**

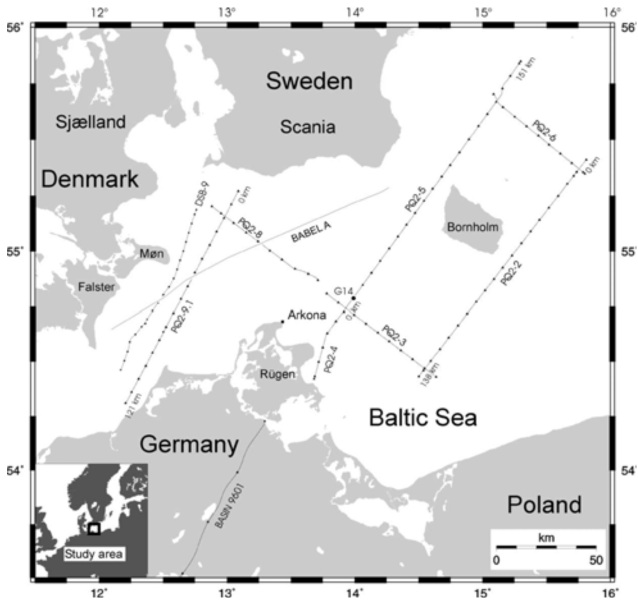


Fig. 3-33: Location of the PQ-, BABEL A-, DSB-9, and BASIN96-seismic lines (KRAWCZYK et al. 2002).

Fig. 3-34),but this position was modified several times (KRAWCZYK et al. 2002, 2008). In more recent work, Baltica is dips continuously under Avalonia (**Fig. 3-35;** GUTERCH et al. 2010), so the crust of Baltica is traceable until the Elbe Line, where the top of the crust terminates along the MOHO. The remains of Baltica are isolated from Avalonia by the suture zone (and the accretionary wedge in the upper part of the lithosphere; BAYER et al. 2002, GUTERCH et al. 2010).

Black shales of Cambro-Ordovician age cover the margin of Baltica. According to SCHLÜTER et al. (1997*b*), they represent the main detachment for the overlying, highly deformed accretionary wedge. Moreover, the top of the shales can be traced as “O-horizon” and represents a marker for the southern extent of the basement of Baltica (e.g. KRAWCZYK et al. 2002). Intra-crustal reflections represent a short-term subduction zone of late Ordovician to Silurian age and a S to SW dip direction. This zone has a chaotic reflectivity pattern (SCHLÜTER et al. 1997*a,b*, KRAWCZYK et al. 2002).

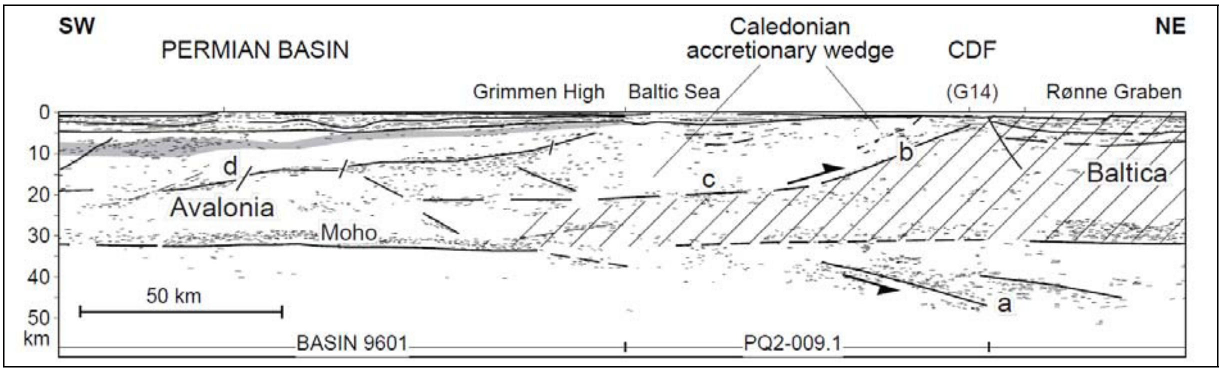


Fig. 3-34: DEKORP-Basin '96 seismic line crossing the Trans-European Suture Zone (MCCANN & KRAWCZYK 2001, modified): **a** - reflections in the mantle which were previously interpreted as Caledonian structure (BABEL WORKING GROUP 1993), **b** - SW dipping reflectors within the accretionary wedge, **c** - surface of the Caledonian suture, often labelled as O-horizon, **d** - SW-dipping reflectors related with later thrusting. For line location see **Fig. 3-33**.

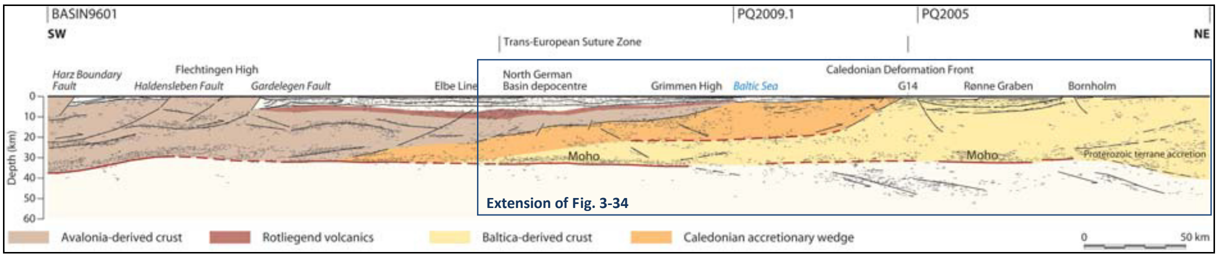


Fig. 3-35: Interpreted reflection seismic line of the BASIN96-transect (GUTERCH et al. 2010, modified). See **Fig. 3-33** for location of the lines BASIN9601, PQ2-9.1 and PQ2-5.

Reactivation phases of the Trans-European Suture Zone

KRAUSS & MAYER (2004), using the term Trans-European Fault for the TESZ, defined it as a complex shear zone. Since the closure of the Tornquist Ocean and the counter-clockwise plate rotation of Avalonia, this suture zone acted repeatedly as a shear zone (**Fig. 3-32**; TORSVIK 1998, TORSVIK & REHNSTRÖM 2003, KRAUSS & MAYER 2004). In northern Germany, the TESZ has a NE-SW extension of about 200 km. During the Palaeozoic and Mesozoic plate tectonic evolution, this intra-crustal weakness zone served as a stress compensation zone, especially during the Variscan and Alpine orogenies (PHARAOH 1997, KRAUSS & MAYER 2004). Additionally, during phases of strong volcanism (late Carboniferous and Early Permian), the rising of tholeiitic melts was linked to channels within this zone. This stress compensation zone was reactivated once more during the Early and Middle Cimmerian (late Triassic-Middle Jurassic), when E-W orientated extensional forces resulted in transtensional strike-slip faults and formed the small NNW trending grabens of the WPFS (KRAUSS & MAYER 2004, KRULL 2004). WEGNER (1966) introduced the term Northeast-Mecklenburg Fault System (German: Nordost-Mecklenburgisches Störungssystem), which was later renamed as Western-Pomeranian Fault System (**WPFS**, German: **V**or**p**ommern **S**törungs**s**ystem **VPSS;** KRAUSS 1994). The research projects SASO, SASO II, VPSS I & II, and DEKORP BASIN'96 (**Chapter 2**) at the end of the 1990s mainly focused on the WPFS, its structure and development (**Fig. 3-29**, KRAUSS & MAYER 1999, MAYER et al. 2000, MAYER et al. 2001*a,b*, KRAUSS & MAYER 2004). This NW-SE orientated fault system is located between the Darss Peninsula and Usedom Island, crossing also Rügen and the adjacent mainland. All faults are concentrated within the late Permian-Mesozoic caprock and form alternating, converging and en echelon pull-apart structures, such as Y-shaped grabens and half-grabens. The set of fault zones is divided into NNW-SSE striking (Werre, Greifswald-Poseritz, Möckow-Dargibell, Freest and the Usedom fault zones) and NW-SE striking faults (Prerow and Samtens fault zones; **Fig. 3-29**). Most of the NNW-SSE striking faults merge into the NW-SE striking Samtens Fault Zone, which is considered as the northern boundary of the WPFS (KRAUSS & MAYER 2004). The changing stress conditions of the Late Cretaceous (**Section 3.2**, **Fig. 3-30**) also triggered a NE-SW oriented horizontal shortening along the TESZ. Besides the reactivation of Palaeozoic deep faults (**Section 3.3.3**), the Rügen Depression, the Grimmen Wall, the Mecklenburg Depression and the Prignitz-Lausitz Wall were formed in northern Germany, as well as the Pomeranian-Kuiavian Anticline in Poland (KRULL 2004). However, the Grimmen Wall is not a typical inverted structure, due to missing faults or related Mesozoic graben or half-graben structures underneath it. KRULL (2004) described its evolution as passive, which means it remained as a local high while depressions in the north and south were formed. At the same time, the area of the TESZ between Rügen and southern Schonen was tilted by the subsidence of the area north of the Grimmen Wall (KRAUSS & MAYER 2004).

3.3.2 Tornquist Fan and Tornquist Zone

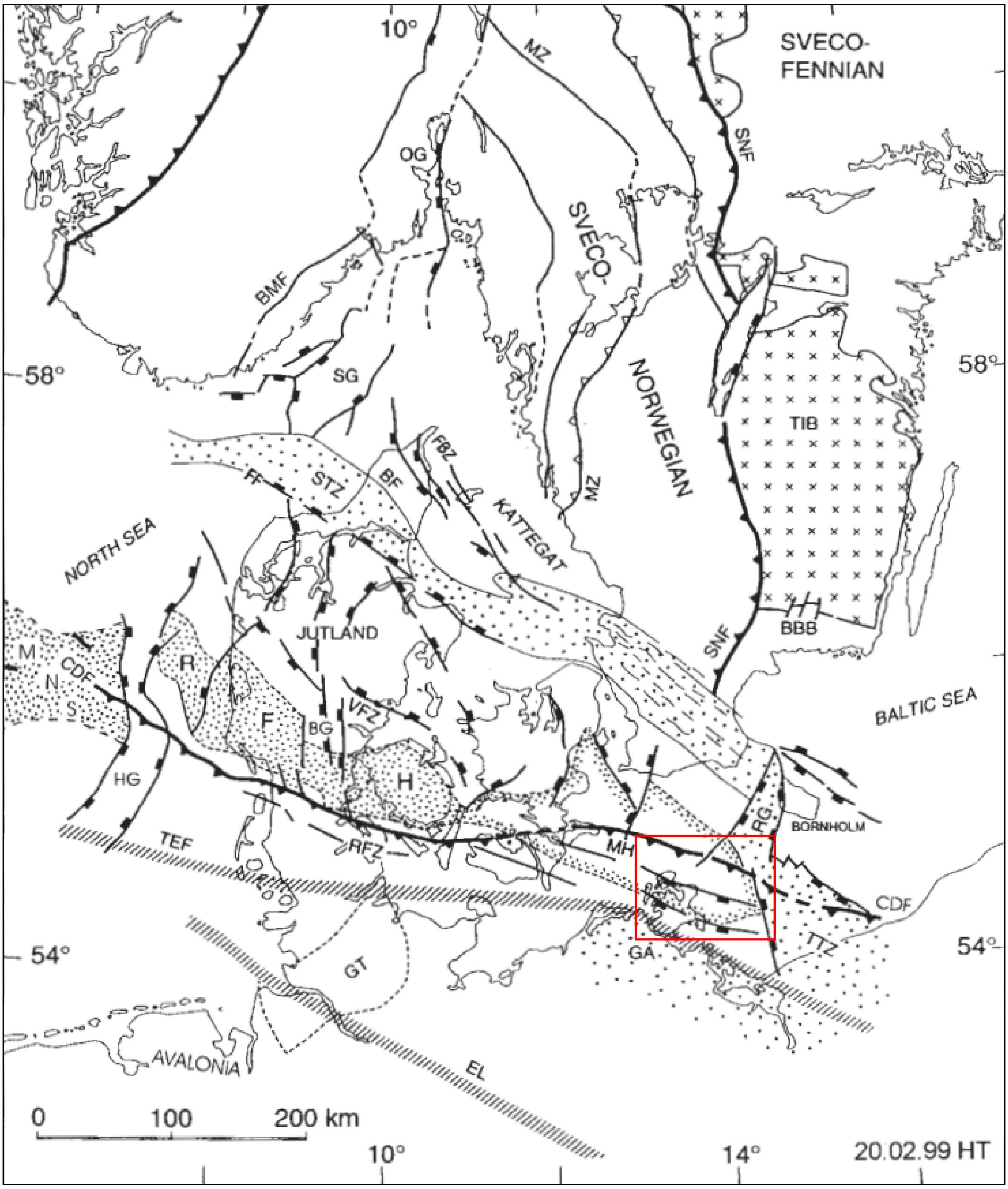


Fig. 3-36: The tectonic units of the Tornquist Fan (compiled by THYBO 2000, modified): BBB–Blekinge Bornholm Block, BF–Børglum Fault, BG–Brande Graben, BMF–Bamble Fault, CDF–Caledonian Deformation Front, EL–Elbe Lineament, FBZ–Fennoscandian Border Zone, FF–Fjerritslev Fault, GA–Grimmen Axis, GT–Glückstadt Trough, HG–Horn Graben, MH–Møn High, MNS–Mid North Sea High, MZ–Mylonite Zone, OG–Oslo Graben, RFH–Ringkøbing-Fyn High, RFZ–Rømø Fault Zone, RG–Rønne Graben, SG–Skagerrak Graben, SNF–Sveconorwegian Front, STZ–Sorgenfrei-Tornquist Zone, TEF–Trans-European Fault, TIB–TransScandinavian Igneous Belt, TTZ–Teisseyre-Tornquist Zone, VFZ–Vinding Fault Zone. The working area is marked in red.

The regional and transregional faults (approximately 20 km to >100 km length) between the Fennoscandian Border Zone and the former Trans-European Fault were analysed by THYBO (1997, 2000, 2001) as a post-collisional feature of the **Tornquist Fan** (**Fig. 3-36**). This structure parallels the transition from the Proterozoic EEC (NE) towards the Palaeozoic West European Platform (SW). Hence the Tornquist Fan represents the northwestern part of the TESZ (**Section 3.3.1**), arising at a later stage than the suture zone during the late Carboniferous to Permian. According to his model this fan region incorporates a northwestward widening splay of mainly W- to NNW tending fault zones, such as the Rømø and Vinding fracture zones terminating the Ringkøbing-Fyn High, the Fjerritslev and Børglum faults, the Fennoscandian Border Zone in the Kattegat, and the Palaeozoic deep faults crosscutting Rügen, as part of the central TESZ. These faults generated during strike-slip movements caused by the Variscan Orogeny and are often the connections between NNW-SSE striking rifts and grabens, such as the Oslo Rift, the Skagerrak, Rønne, Bande or Horn Grabens (THYBO 2000).

As discussed in **Section 3.3.1**, the previously assumed deep fault, referred to as the Trans European Fault separating the EEC and West European Platform, was replaced by a suture zone formed between the crust of Baltica dipping below the crust of Avalonia, and is called TESZ (PHARAOH 1999, GUTERCH et al. 2010). There is no consensus about the southern border of Baltica, although the Elbe Line is favoured by most authors. Thus, there is no clear termination of the Tornquist Fan towards the south. However, the northern border is represented by the Fennoscandian Border Zone in the NW, and the NW-SE striking **Tornquist Zone** in the NE to SE. The Tornquist Zone was previousely known as Tornquist-Teisseyre Line or Lineament (TORNQUIST 1910, ZNOSKO 1979, ZIEGLER 1990*a*). According to BERTHELSEN (1998), it was named after the German geologist Alexander J. H. Tornquist (1868-1944) who in 1910 described a lineament running from Poland across Bornholm until Sweden, and separating the stable Baltic Shield from a block-faulted area in the SW. ZNOSKO (1969) added the second part Teisseyre, honouring the Polish stratigrapher Wawrzyniec K. de Teisseyre (1860-1939), who first recognised the tectonic importance of this structure (ZNOSKO 1979, BERTHELSEN 1998). The Tornquist Zone strikes from Denmark over Poland to the Black Sea over a distance of 2500 km (FRANKE 1993) and represents the longest pre-Alpine tectonic feature in Europe (THOMAS & DEEKS 1994, ERLSTRÖM et al. 1997). It consists of two branches, the Sorgenfrei-Tornquist Zone (**STZ**) in the NW, and the Teisseyre-Tornquist Zone (**TTZ**) in the SE. The junction between the TTZ and the STZ is situated in offset to Bornholm Island within the NW-SE striking Rønne Graben (THOMAS & DEEKS 1994, ERLSTRÖM et al. 1997). This fault system has a general dextral strike-slip character (THOMAS & DEEKS 1994, ERLSTRÖM et al. 1997, SCHECK-WENDEROTH & LAMARCHE 2005). The **TTZ** was for a long-time known as a lithospheric weakness zone, marking the transtension from the Precambrian crust of the EEC towards the younger Palaeozoic West European Platform (**Fig. 3-29**), which has been reactivated several times since the Caledonian Orogeny (e.g. ZNOSKO 1979, ZIEGLER 1990*a*, THYBO 1997, SCHLÜTER et al. 1997*b*, BERTHELSEN 1998, PHARAOH 1999, KRAWCZYK et al. 1999, SCHECK-WENDEROTH & LAMARCHE 2005). ERLSTRÖM et al. (1997) and GUTERCH et al. (1999) described it as an inversion zone and strike-slip zone, especially along the MPT. In the offshore area, the TTZ is terminated by the AKFZ in the SW and the Koszalin Fault in the NE (THYBO 1997, SCHLÜTER et al. 1997*b*, BERTHELSEN 1998, PHARAOH 1999).

Instead, the **STZ** is consistently defined as an intra-continental fault zone within Baltica separating the stable part from the weaker southwestern margin (MICHELSEN & NIELSEN 1993, THYBO 1997, SCHLÜTER et al. 1997*b*, BERTHELSEN 1998, BRANDES et al. 2018). Wells drilled on both sides of the STZ revealed Proterozoic basement rocks of shield types which are over 800 Ma old (BERTHELSEN 1993, 1998). The STZ crosscuts the Tornquist Fan towards the NW. According to THYBO (1997) and BRANDES et al. (2018), the inverted part of the STZ is terminated by the Fjerritslev and Børglum faults, thus, separating the Skakerrak Kattegat Platform and the DB (MICHELSEN & NIELSEN 1993).

However, especially the extension of the southeastern branch of the Tornquist Zone, the TTZ, differs in the various tectonic maps and publications (**Fig. 3-37**). In earlier works, the TTZ incudes all 'Mesozoic graben' and 'Late Cretaceous inversion' structures (Gryfice Block, Kołobrzeg Block and the onshore MPT with the Pomeranian-Kuiavian Anticline), due to its definition as a reactivated strike-slip and inversion zone (MAKRIS & WANG 1994, THYBO 1997, BERTHELSEN 1998, PHARAOH 1999). In later publications, on the other hand, the offshore part of the TTZ comprises only the Kołobrzeg Block, and it thins onshore (KOSSOW et al. 2000, BAYER et al. 2002). Recent geophysical investigations along the onshore part of the TTZ in Poland focused on the detection of lithospheric structures or boundaries (DADLEZ 2000, NARKIEWICZ et al. 2015, MAZUR et al. 2016*a,b*, NARKIEWICZ & PETECKI 2016, MAZUR et al. 2018). Especially the findings of MAZUR et al. (2016*a*) evoked the discussion. MAZUR et al. (2018) showed new results for the PolandSPAN™ profiles (along the southern and central parts of the TTZ in Poland), indicating an undeformed Proterozoic crust of Baltica and lower Palaeozoic sediments, dipping towards the SW. Crustal anomalies southwest of the EEC have been extensively discussed and allocated to the TTZ. According to MAZUR et al. (2018), they represent a crustal keel which is interpreted as a Proterozoic suture, formed during the amalgamation of Rodinia. Compared to the above mentioned previous analyses, the horizontal extension of the TTZ has been reduced to a thin, about 20 km wide band crossing Poland subparallel to the Koszalin Fault.

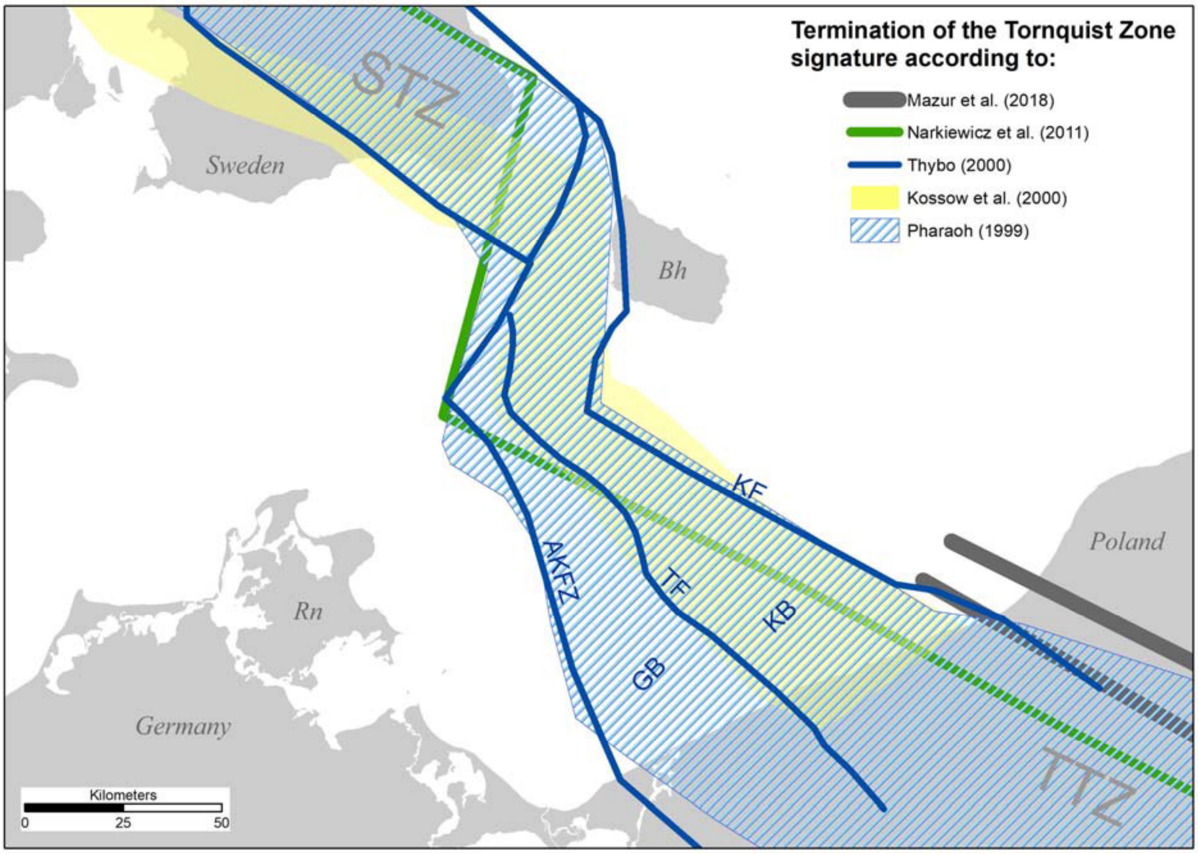


Fig. 3-37: Comparison of the different illustrations of the Tornquist Zone. According to PHARAOH (1999), THYBO (2000) but also SCHLÜTER et al (1997*a,b*) and others, the up to 80 km broad Tornquist Zone is terminated by the Adler-Kamień Fault Zone (AKFZ) and the Koszalin Fault (KF) and included the Gryfice (GB) and Kołobrzeg (KB) blocks. KOSSOW et al. (2000) restricted the southern branch of the up to 40 km broad TTZ to the northern KB, between the Trzebiatow Fault (TF) and the KF. A southeastern prolongation is assumed. According to Narkiewicz et al. (2011), Mazur et al. (2018) and others, the Tornquist Zone comprises an approximately 20 km thick band, which parallels the northern border of the KB. Thus, the TTZ runs close to the KF (Bh–Bornholm, Rn–Rügen, STZ–Sorgenfrei-Tornquist Zone, TTZ–Teisseyre-Tornquist Zone).

The offshore area shows a different tectonic situation than onshore Poland. The crust of the EEC was also drilled within well G14 1/86 (south of the Tornquist Zone). In comparison to the onshore area of Poland, the offshore part of the TTZ was affected by major block-faulting of the Proterozoic basement and the Palaeo- to Cenozoic sediments above it. Therefore, the original extension of this lithospheric polyphase reactivated weakness zone was preferred, including the area between the AKFZ and the Koszalin Fault. Thus, all further mentions of the TTZ in this thesis are based on the early definitions of ZIEGLER (1990a), THYBO (1997), BERTHELSEN (1998) and PHARAOH (1999). The AKFZ borders the TTZ to the west and separates the Gryfice Block from the Arkona High and the Wolin Block. The NW trending Gryfice Block enters into the NNE striking Rønne Graben. Hence, the NNW striking AKFZ is extended by the NW striking Skurup Fault, forming a triple junction together with the northwestern border of the Rønne Graben – the Gat Fault (**Fig. 3-29**). The Trzebiatów Fault separates the Gryfice Block and the Kołobrzeg Block. The eastern border of the Kołobrzeg Block (and the TTZ) is represented by the Koszalin Fault, trending northwestward. Thus, the TTZ narrows towards the NW.

According to BERTHELSEN (1998), the Tornquist Zone has been active since the late Carboniferous. Its evolution was influenced by the polyphase Caledonian, Variscan and Alpine orogenic cycles (PHARAOH 1999) as well as by Late Cretaceous to early Tertiary inversion tectonics which triggered offsets of between 1 and 3 km (THOMAS & DEEKS 1994, ERLSTRÖM et al. 1997).

3.3.3 The Wiek Fault and other deep-rooted Palaeozoic faults, block-faulted Rügen and vicinity

Based on the latest research projects of the 1990s, it is quite difficult to find detailed information on the deep faults intersecting Rügen. This could be due to political constraints such as confidentiality that limited the scientific work in East Germany until 1989. But a comparison of the different maps and publications that have occurred since then revealed a different issue (**Fig. 3-38 A-D**). MAYER et al. (1994) published a detailed map of the tectonic situation of Rügen with several deep-rooted faults, such as the Wiek and Nord Jasmund faults, north of Rügen. Only three years later, SCHLÜTER et al. (1997*b*) published a map showing for example the Wiek Fault as a merger of the former Wiek and Nord Jasmund faults. Later publications ignore the fault north of Jasmund completely (e.g. ERLSTRÖM et al. 1997) or at least the onshore part of this fault, such as KRAUSS & MAYER (2004, **Fig. 3-38 D**), who concentrated on faults within the Mesozoic. Moreover, detailed descriptions of those faults were successively reduced. Hence, it seems that the focus changed to larger-scale tectonic descriptions, leading to a loss of knowledge regarding the detailed structural information especially of deep faults right at our front door. Finally, more recent work since the 1990s has shown simplified applications in bigger research areas. In other words, old publications may still deliver "new information" and should always be included.

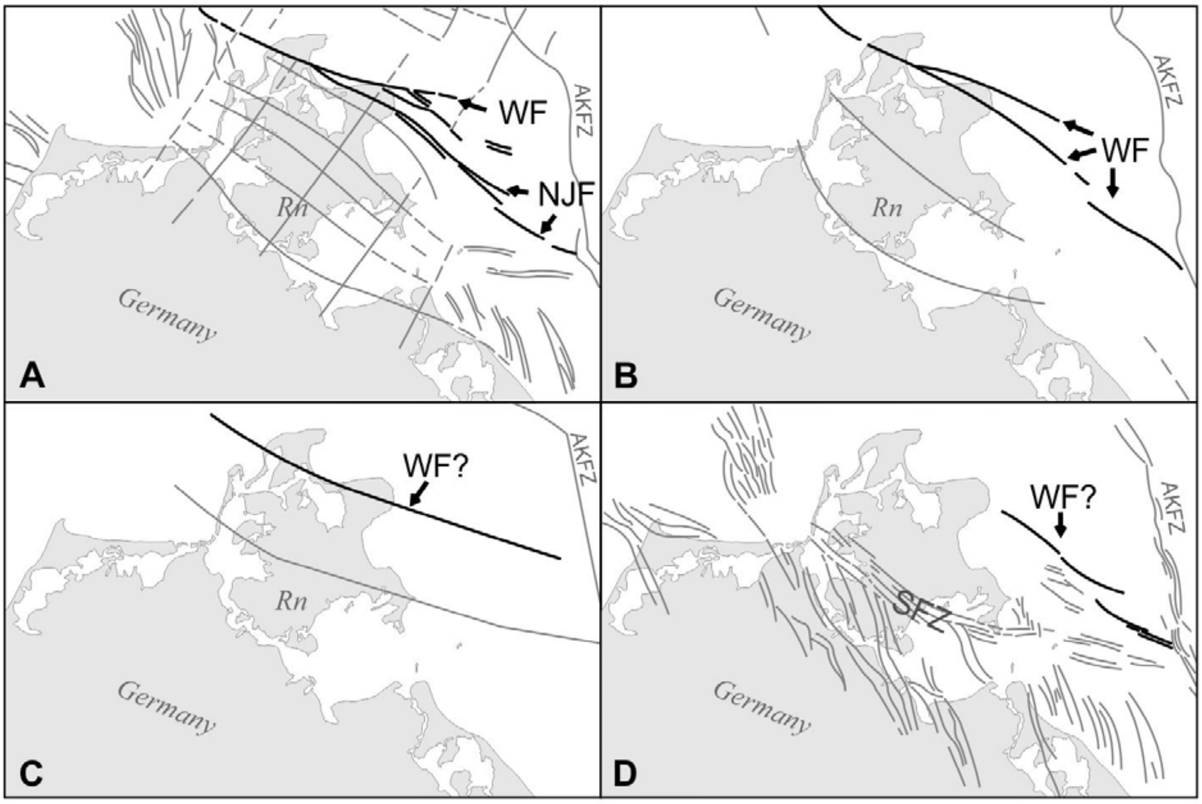


Fig. 3-38: Comparison of different tectonic maps with a varying Wiek Fault, marked as a thick black line, compiled by SEIDEL et al. (2018) and recently modified. The single figures are based on: A–MAYER et al. (1994), B–SCHLÜTER et al. (1997*b*), C–ERLSTRÖM et al. (1997), D–KRAUSS & MAYER (2004). AKFZ–Adler-Kamień Fault Zone, NJF–Nord Jasmund Fault, Rn–Rügen, SFZ–Samtens Fault Zone, WF–Wiek Fault.

The deep-rooted faults, intersecting Rügen and delineating the different blocks, have been the focus of several studies since the early 20th century (DEECKE 1906). KURRAT (1974) summarised the various preliminary studies, based on geophysical methods such as gravimetry, geomagnetic or velocity analyses, and created a structural geological map whose main features are valid until today

(**Fig. 3-39**). The block-faulted area of Rügen is formed by the three major blocks of the Arkona High, Middle Rügen and South Rügen. These three major blocks are bordered by SE striking faults (***Hercynian strike direction***), such as the Wiek Fault - between the Arkona High and the Middle Rügen Block, and the Bergen Fault - between the Middle Rügen and South Rügen blocks. Moreover, the SE trending Nord Jasmund, Parchow and Rappin faults intersect the Middle Rügen Block, forming the sub-blocks of Lohme, Glowe, Neuenkirchen and Trent (KURRAT 1974, FRANKE & HOFFMANN 1988, FRANKE 2018). Especially the Bergen Fault formed a dominant weakness zone, also called "Bergener Tiefenbruch". It was affected by basic magmatites, as indicated by positive magnetic and gravimetric anomalies (FRANKE & HOFFMANN 1988). Those dominant Hercynian faults run parallel to the southwestern border of the EEC. Faults at the Arkona High are known to form a stepwise, southward descending crystalline basement (EEC; SCHLÜTER et al 1997*a,b*). The faults crossing the Middle and South Rügen blocks have only been traced up to the Ordovician, but they might also affect the basement. They are the oldest faults in this area and displaced by younger SW striking (Binz, Litzow and Venzer faults; ***Rhenish strike direction***) and SSE striking (West-Jasmund, Putbus, Bug-Zudar faults; ***Eggish strike direction***) faults. Only the Hiddensee Fault strikes west-southwestward (***"Erzgebirgisch" strike direction***; FRANKE & HOFFMANN 1988, KURRAT 1974). The age of the three younger types of faults (concerning the strike direction) has not been determined so far. KURRAT (1974) plotted the SSE- and SW/SSW-striking faults as broken lines without offsets or displacements along the cross sections, to avoid having to give their relative ages. According to KURRAT (1974, and citations therein; **Fig. 3-39**), the SW striking ***Rhenish structures*** are the deepest and have the highest perseverance, so they play an important role for salt tectonics. Salt diapirs and even salt walls use these weakness zones for migration, which are visible on modern salt structure maps (LUNG M-V 1997).

The influence of the ***SSE striking structures*** is quite high in the E of Rügen and increases, towards the Polish Baltic Sea where they have their highest activity during the Mesozoic (KURRAT 1974).

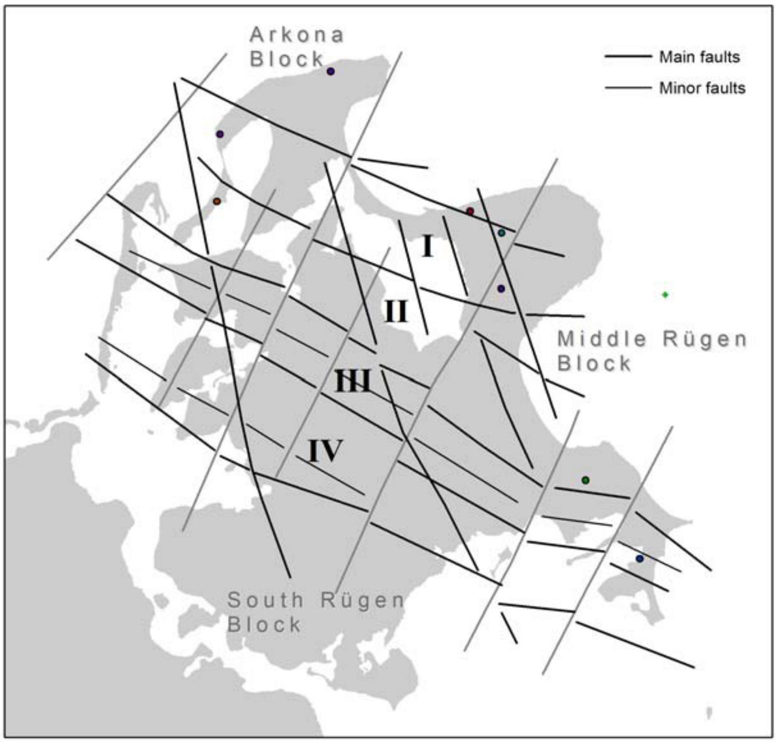


Fig. 3-39: Structural map of Rügen according to KURRAT (1974). **I**–sub-block of Glowe, **II**–sub-block of Neuenkirchen, **III**–sub-block of Trent, **IV**–sub-block of Putbus.

The Wiek and Nord Jasmund faults have previously been investigated by the VVB Erdöl-Erdgas Gommern (SHGENTI et al. 1967). Those structures are thought to be related to the Odense Fault, south Falster, and are therefore known as the Odense-Wiek Fault Zone. The Wiek Fault was identified west of Rügen. Near the village Juliusruh (Rügen) this single fault splits into **(1)** the Wiek Fault north of Jasmund, and **(2)** the Nord Jasmund Fault that crosses Jasmund. Although the fault was not detectable in onshore seismic lines crossing Rügen, a comparison of research wells Arkona 101/62, Rügen 3/63, Rügen 5/66, Wiek 101/62 and Lohme 101/62 (for locations see **Fig. 3-40**) suggested an offset within the Ordovician strata of about 3000 m (SHGENTI et al. 1967). Regarding the eroded Devonian and Carboniferous deposits at the Arkona High, the vertical offset might have reached 6000 m (FRANKE & HOFFMANN 1988). According to SHGENTI et al. (1967), both faults were active from the late Carboniferous until late Permian/ Early Triassic (at the mainland) and at least until late Triassic in the offshore area. Both faults run towards the ESE, until the AKFZ.

MAYER et al. (1994) and PISKE et al. (1994) published the geological and geophysical results based on Petrobaltic seismic data and gravimetry of 1966/67. MAYER et al. (1994) showed a structure map of the shelf area around Rügen with the typical ESE to SE striking faults (such as the Wiek Fault), but also NE-SW striking ones. A modelled cross-section of the transition from the northern EEC towards the southern West European Platform shows an impressive structure and the character of the dominant, Rügen-crossing faults (**Fig. 3-41**): the accreted Ordovician strata dip stepwise and are covered by Devonian deposits. These in turn are discordantly overlain by Carboniferous sediments. According to MAYER et al. (1994), the block-faulting faults are of Variscan age. Other dominant faults are the Nord Jasmund Fault, forming a huge step south of a tilted block, and the Wiek Fault, which separates the Ordovician strata by the Devonian successions. The latter is also known as the Wiek Deep Fault (German: Wieker Tiefenbruch; e.g. KRAUSS 1994).

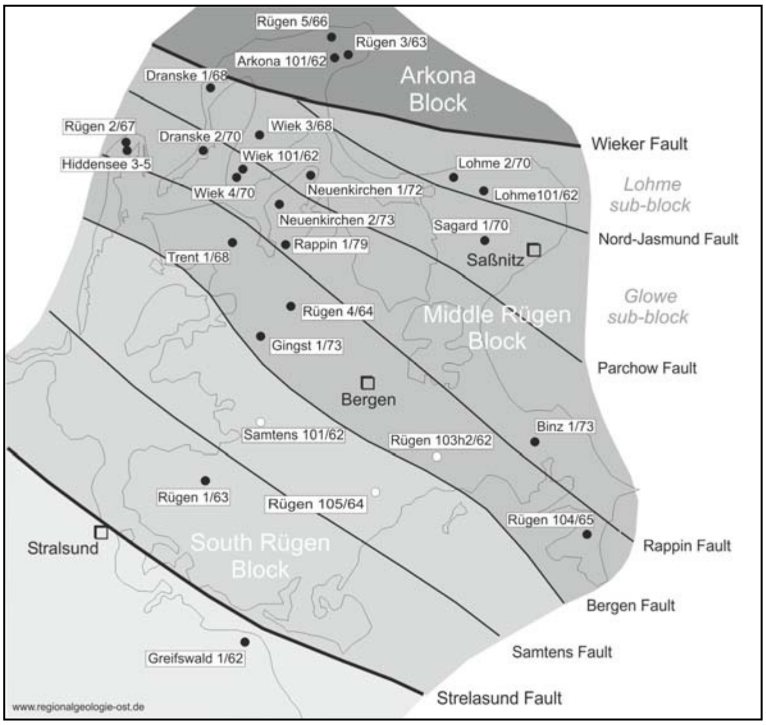


Fig. 3-40: Recent structural map of Rügen and research wells (modified after FRANKE 2018).

According to KURRAT (1974), the several blocks along Rügen have a complex history with multiple phases of uplift and subsidence and an iterating relief inversion. Consequently, the fault planes of different fault zones have been reactivated.

Regarding the various controversial interpretations of the Wiek Fault, various questions arise: What is the real position and character of the Wiek Fault, east of Rügen. Do other faults such as the Nord Jasmund Fault also extend offshore? Which other faults exist and have those Palaeozoic faults been reactivated during the evolution of the Mesozoic WPFS.

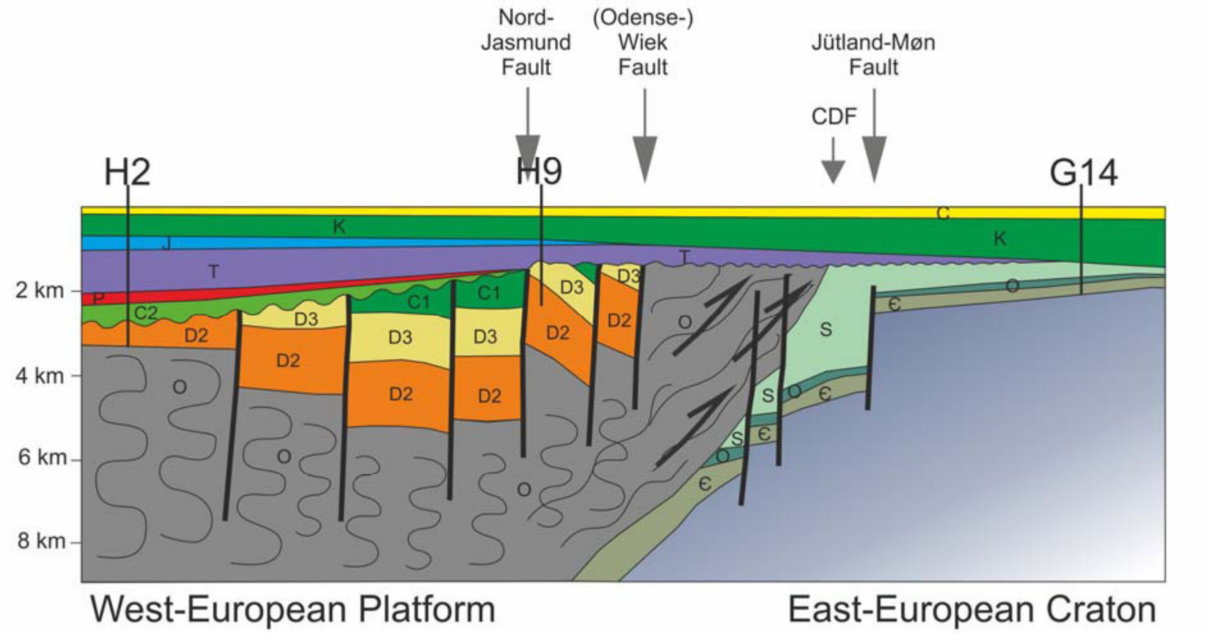


Fig. 3-41: Cross-section through the Caledonian- and Variscan-deformed succession with the location of major faults (modified from MAYER et al. 1994 and PISKE et al. 1994). CDF–Caledonian Deformation Front.

3.3.4 The North German Basin as part of the Central European Basin System

The Central European Basin System (**CEBS, Fig. 3-42**) evolved during the Permian as an intra-continental basin within Pangaea, along the recent area of central and northern Europe. Thus, it extended from the southern North Sea across Denmark, the Netherlands and northern Germany, to Poland; it is separated in a North and South Permian basin. During the Mesozoic, a number of intra-continental sub-basins were initiated: the DB classified as the North Permian Basin, and the Anglo-Dutch Basin (ADB), the NGB, and the MPT classified as the South Permian Basin (ZIEGLER 1990*a*, SCHECK-WENDEROTH & LAMARCHE 2005). Those depressions are compartmented by local highs, such as the mid-North Sea, Ringkøbing-Fyn and Møn highs (GEIßLER et al. 2008).

The intra-continental NGB extends from the southern North Sea (W) to Poland (E) and from Rügen (N) to the Harz Mountains (S). KOSSOW & KRAWCZYK (2002) described the asymmetric shape of the NGB, which is characterised by a gently dipping northern margin and a steep, fault-controlled southern limit. They additionally recognised that the deformation intensity increased from the north to the south at all tectonic levels.

According to SCHECK-WENDEROTH & LAMARCHE (2005), the main controlling factor for the multiphase evolution of the CEBS was the presence of major zones of crustal weakness: the NW-SE striking Tornquist Zone, the Ringkøbing-Fyn High and the Elbe Fault System. The Tornquist Zone also limited the area of subsidence in the north of the basin. The second factor for the initiation and subsidence of the CEBS was a thermal destabilisation of the crust, especially during the Permo-Carboniferous (KOSSOW & KRAWCZYK 2002).

During the Permo-Triassic/Jurassic, the regional stress field changed and caused a declining thermal subsidence and regional E-W extension, followed by regional subsidence. Late Cretaceous-Tertiary convergence resulted in a basin inversion. In the Cenozoic, renewed subsidence movements have been observed (KOSSOW & KRAWCZYK 2002, SCHECK-WENDEROTH & LAMARCHE 2005). The salt mobilisation of the Zechstein played an important role for the structural style and influenced the sedimentary pattern in the basin. According to Kossow & Krawczyk (2002), Zechstein evaporates decoupled the supra-salt from the sub-salt succession and allowed the transmission of deformation over a large distance. A series of horst and graben structures were initiated during the Mesozoic differentiation of several basins: for example, the N-S oriented Central, Horn, and Glückstadt grabens, and the NW-SE oriented Sole Pit, the Lower Saxony and the Subhercynian basins (Scheck-Wenderoth & Lamarche 2005).

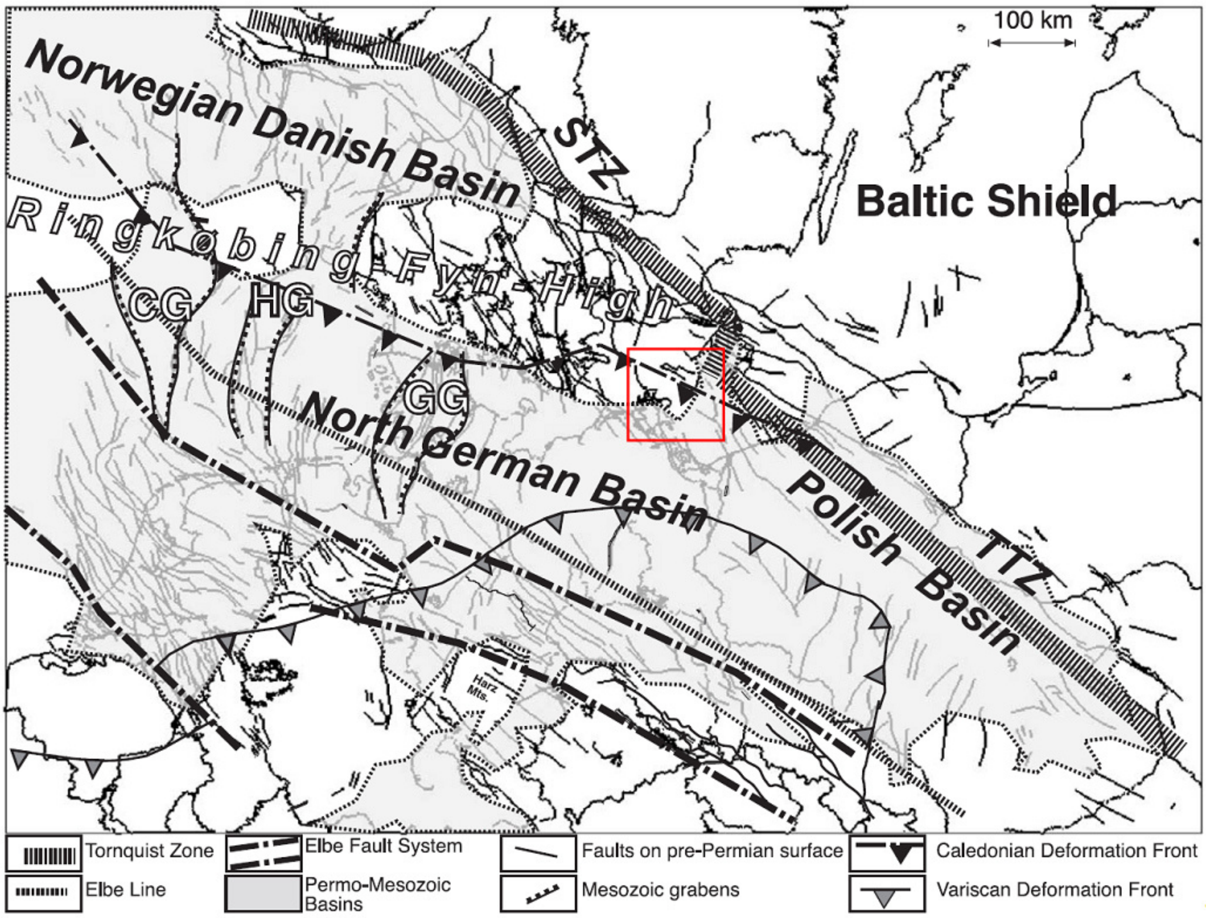


Fig. 3-42: The Central European Basin System (CEBS). CG–Central Graben, GG–Glückstadt Graben, HG–Horn Graben, STZ–Sorgenfrei-Tornquist Zone, TTZ–Teisseyre-Tornquist Zone (Scheck-Wenderoth & Lamarche 2005, slightly modified).

4 Data base and methods

4.1 Seismic and well data

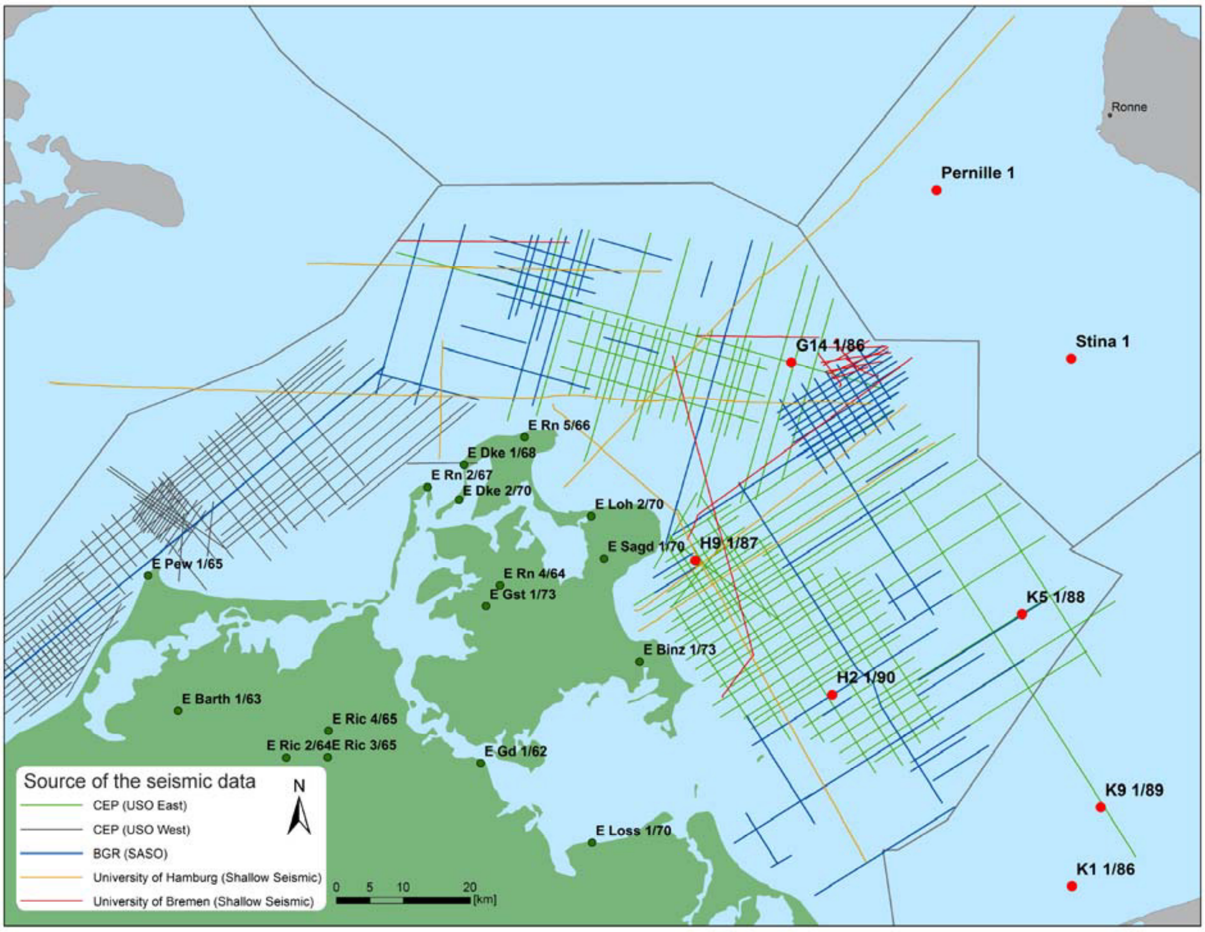


Fig. 4-1: Working area with seismic lines of different sources, and wells (green dots: German research wells; red dots: offshore wells of Petrobaltic and the Danish geological survey – GEUS. For more information see **Tab. 4–2** or **Section 5.1**).

The data base of this project comprises a large number of 2D reflection seismic lines, measured offshore in the 1970s and 1980s by the former consortium Petrobaltic (see **Chapter 2**). These lines were partly reprocessed during the SASO project in the 1990s and more recently by CEP (Central European Petroleum Ltd.) for oil and gas exploration. For the present study, 144 deep seismic sections of 3145 km length (**Tab. 4-1**) were used. The data have a dominant frequency of about 30 Hz (with a sweep of 8-62 Hz) and consequently, a vertical resolution of 17 m to 50 m, assuming $\lambda/4$ as an estimate for the vertical resolution (λ – wavelength) and an interval velocity between 2 and 6 km/s. The upper 150-300 ms are poorly imaged due to the measurement setup. Petrobaltic focussed on detecting oil and gas reservoirs at depths greater than about

Tab. 4-1: Reflection seismic data used for USO East.

Source	Line #	km	Prospected depth (TWT)
CEP (Central European Petroleum Ltd.)	75	2024	Deep seismic 200-5000 ms
BGR (Federal Institute for Geosciences and Natural Resources)	69	1121	Deep seismic 200-5000 ms
University of Hamburg	7	481	Shallow 0-1000 ms
University of Bremen	16	250	Shallow 0-1000 ms
Total	**167**	**3876**	

2000 m bsl, which required a large minimum offset (160-240 m; ARNDT et al. 1996). Due to the shallow water of the Baltic Sea around Rügen (between 10-50 m deep), reflections in the upper few 100 ms were heavily contorted by the normal-move-out correction and were consequently muted. The processing concentrated on an improvement of the vertical resolution within deeper parts (starting at 1500 ms TWT) of the profiles.

The CEP provided 75 reprocessed Petrobaltic seismic lines for this study. The BGR supplied a further 69 Petrobaltic lines, which were reprocessed during the SASO project (**Tab. 4-1, Fig. 4-1**). At a later stage of USO East and this thesis, an additional 16 shallow seismic lines were provided by the University of Bremen (courtesy of V. Spieß) and seven shallow seismic lines were supplied by the University of Hamburg (courtesy of C. Hübscher). Both universities acquire several new profiles every year during scientific/educational cruises. Their shallow seismic sections show a very good resolution in the upper 1000 ms. Some of these lines cross the USO working area, and they are a good support to localise the sea floor within the seismic sections, and to adjust the vertical bulk shift of the deep seismic lines.

The seismic stratigraphy and determination of lithological and geophysical properties were constrained by well data such as lithological records and logs (**Fig. 4-1; Tab. 4-2**). Apart from the borehole information provided by the LUNG M-V, further lithological information was extracted from HOTH et al. (1993), who summarised 63 research wells completed between 1962 and 1990 in the GDR (within the European Basin), and from the appendix of the final report of the SASO project (SCHLÜTER et al. 1997*a*).

Tab. 4-2: Overview of the four German offshore wells (DIENER et al. 1988, 1989, LÜCK et al. 1987, PUPUNYN et al. 1990, REMPEL 1992*a*).

Well	Petrobaltic Block	Tectonic Block	Final depth	Deepest horizon
G14 1/86	G	Arkona High	1987	Crystalline basement
H9 1/87	H	Middle Rügen/ Wolin	2250	Middle Devonian
K5 1/88	K	Gryfice	4149	Ordovician
H2 1/90	H	Wolin	3285	Ordovician

The LUNG M-V provided the lithological well descriptions as a GeoDIN export (pdf-format) for the four offshore wells based on DIENER et al. (1988, 1989), LÜCK et al. (1987) and PUPUNYN et al. (1990). The reworked geophysical logs were provided by CEP and the LUNG M-V as LAS-files. As the German offshore wells are directly crossed by seismic lines, they are very helpful for the identification of major seismic reflectors and the lithostratigraphic correlation with other seismic profiles. The information on the Danish wells were based on the SASO final report, where the data was provided by the Danish geological survey (SCHLÜTER et al. 1997*a*).

Additionally, several reports of former Petrobaltic investigations contain maps of different reflectors and horizons with depth given either in TWT or in metres, provided by the LUNG M-V.

4.2 Reflection seismic data - measurement and processing

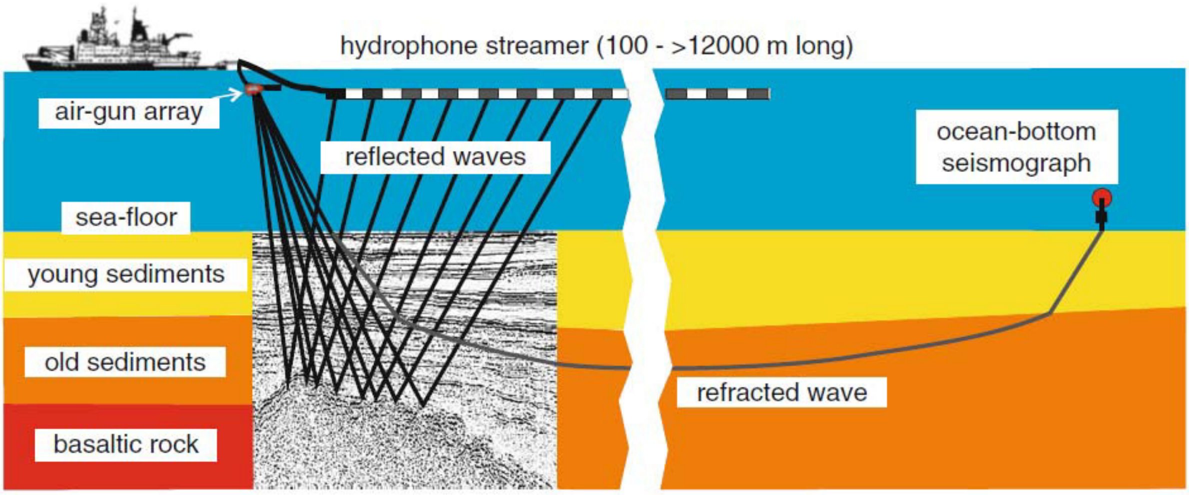


Fig. 4-2: Offshore reflection seismic method (HÜBSCHER & GOHL 2014).

The seismic data used in this thesis were based on offshore reflection seismic measurements. For offshore seismic data acquisition, a research vessel drags a source, such as an airgun or vaporchoc system, and a streamer with a group of receivers, so-called hydrophones or channels, behind it (**Fig. 4-2**). The most common sources for the marine seismic data acquisition are pneumatic sources such as airguns, which release compressed air. In the Petrobaltic study, a vaporchoc source was used as well, which releases superheated steam. The seismic streamer is towed behind the vessel at a constant water depth, which can be realised by buoys and birds (HÜBSCHER & GOHL 2014). The artificially produced signal is a pressure wave, which travels through the water column and the earth's crust. This signal reflects and refracts at layer boundaries, where the acoustic impedance, which is the product of density and interval velocity, changes. Typical layer boundaries are inhomogeneities, the seafloor, lithological boundaries, or faults (FERTIG 2005). The steep angle reflection seismic method is based on the idea that only a small part of the energy is reflected at layer boundaries, whereas the greater part is transmitted into deeper layers (HÜBSCHER & GOHL 2014). After every shot, the reflected signal is recognised by the hydrophones for a distinct registration length and allows conclusions regarding the lithological and structural properties of the subsurface (FERTIG 2005). As discussed in **Section 4.3,** the geological conditions can be physically analysed (HÜBSCHER & GOHL 2014).

During the Petrobaltic investigations in the southern Baltic Sea between 1976 and 1990 (REMPEL 2011), various different cruises were undertaken (see **Chapter 2; Fig. 2–3**). The documented field parameters applied by the deep seismic data (provided by the BGR and CEP) are listed in **Appendix B** and based on the reprocessing reports by the Geophysik GGD and Geophysik Seismic Leipzig GmbH. An example of a protocol of the seismic exploration is also shown in **Appendix B**. A digital multi-channel seismic was used. The profiles had a fold of 24 to 48 and a registration length between 3 and 6 s. Analogue data produced by the streamer were digitised and formatted by a DFS IV, which was used until 1982 by the company Geofizika Torun. Between 1984 and 1986, the field measurements were performed by VEB Geophysik Leipzig using a vaporchoc system source (SN 328) with 60 bar and 350°C superheated steam (AUTORENKOLLEKTIV DES VEB GEOPHYSIK LEIPZIG 1987, ARNDT et al. 1996, SCHLÜTER et al. 1997*a*). Besides the explanations in the Petrobaltic survey reports, more information on the field parameters and the seismic data was given in the header information of the segy-files.

Of about 12000 km of seismic lines from the Petrobaltic dataset, only 6830 km were used in the SASO project (see **Chapter 2**, SCHLÜTER et al. 1997*a*). For this purpose, 1063 km were reprocessed by the

Geophysik Seismic Leipzig GmbH (SCHEIDT et al. 1995) and the Geophysik GGD (ARNDT et al. 1996). The workflow for the data processing was described by SCHEIDT et al. (1995) and ARNDT et al. (1996), which are summarised **Fig. 4-3**. The raw data are characterised by interfering noise, due to e.g. ship traffic during the measurement. However, the strongest interferences were multiples of certain horizons, such as the base of the Upper Cretaceous (ARNDT et al. 1996). The adjusted processing aimed to reduce those unwanted signals and included amplitude attenuations, despiking and several bandpass filters.

The reprocessed seismic sections were plotted and archived as stacked and time migrated versions; the second reprocessing order provided nine additional pre-stack depth migrated profiles. The analyses of USO East were based on the time-migrated lines or, if not available, on the stacked versions (within time domain).

CEP reprocessed the seismic sections for each profile differently and provided pre-stacked time migrated profiles. The workflow is documented in each seismic header.

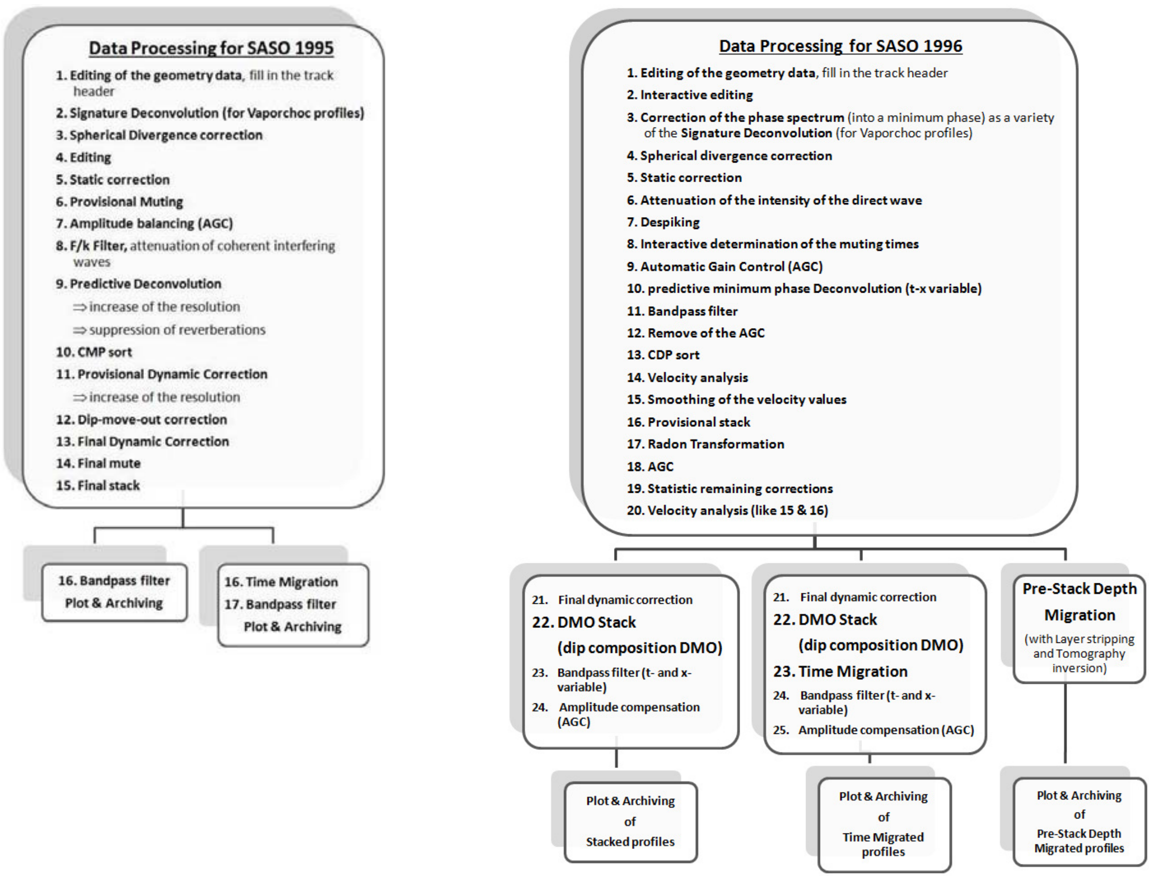


Fig. 4-3: Data reprocessing during the SASO-project. For more information see SCHEID et al. (1995) and ARNDT et al. (1996).

4.3 Data analyses and seismic interpretation

The seismic interpretation aims to analyse the lithological changes in a two- or three-dimensional space. The intensity of a seismic reflection, defined by the reflection coefficient R (**Formula 1**), depends on the contrast of the acoustic impedance (I, **Formula 2**), and thus the contrast of the velocity (v in m/s) and density (ρ in g/cm³) between two layers (VON HARTMANN et al. 2015).

(1) $R= (I_1+I_2)/(I_1-I_2)$

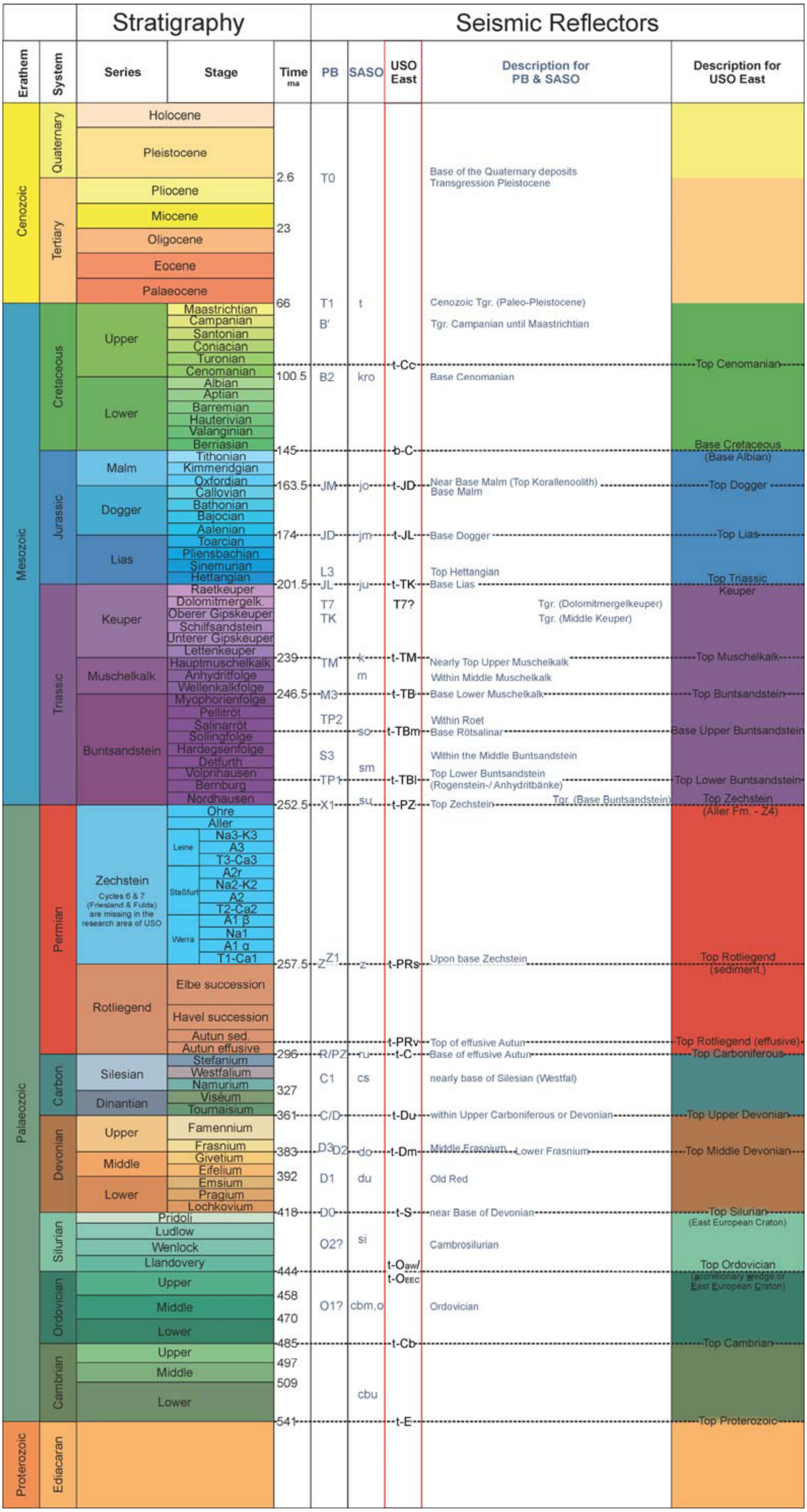
(2) $I=v*\rho$

In the previous projects, specific marker-horizons were chosen according to a conspicuous wavelet, frequency, etc. These horizons predominantly marked the base of lithostratigraphic units (e.g. Petrobaltic reflector B2: Base of Cenomanian) but might also indicate internal reflections (e.g. Petrobaltic reflector TK: within the Middle Keuper; **Fig. 4-4** & **Appendix C**). However, those reflections are restricted to the local lithological situation at the northern borders of the NGB and even the Arkona, Wolin and Gryfice blocks. Thus, it was not possible to trace the previously defined Petrobaltic and SASO horizons in the complete working area. Therefore, predominantly the top of the stratigraphic successions were traced along different seismic reflectors, with regard to the four offshore wells (**Fig. 4-4 & Fig. 4-5**). The selection of seismostratigraphic tops along a wavelet (peak/trough/zero-crossing) was mainly based on the geophysical logs (provided by CEP) and their synthetics calculated with SeisWare^{TM} (**Appendix A.a**). **Fig. 4-4** compares the previously defined Petrobaltic and SASO seismostratigraphic units with the 19 main horizons mapped for USO East. The advantage of selecting the tops by different reflectors is illustrated in **Fig. 4-5**. Lateral facial changes and the thinning of stratigraphic units until striking out is very common along the northern border of the NGB. Choosing only one constant reflector near the top or base of an unit would not represent the total extension of a complete stratigraphic series or stage. However, exactly this extension, as well as the lineament where a stratigraphic unit terminates on another, is important for 3D modelling or the generation of thickness maps. The character and extension of the different seismostratigraphic units are described in **Section 5.1**.

Due to the lack of a velocity model, it was not possible to describe velocity differences and their relations between the seismostratigraphic units (such as an increase or decrease of the internal velocity between two units).

Various **reflection parameters** should be included in the description of seismic stratigraphy or horizons (MITCHUM et al. 1977). As discussed before, the amplitude of a reflector plays an important role and gives information about the physical impedance. This is affected by various rock properties, such as a change in porosity or fluid content. Especially the latter causes attenuation which leads to an amplitude decrease (VON HARTMANN et al. 2015). The lateral extent of the deposits can be derived from the coherence and continuity of a reflector. Moreover, the reflection pattern of one horizon or a complete seismostratigraphic unit might indicate the deposition or bedding pattern, palaeomorphology, erosional discordances or fluid contents (MITCHUM et al. 1977). Typical reflection patterns are illustrated in **Fig. 4-6**. Continuous and discontinuous reflectors might be based on the sedimentary history, compaction effect, or gas content, whereas further special reflection patterns may have a sedimentary background.

Fig. 4-4: Stratigraphic Table according to STG 2016, comparing the selected main horizons with those of the Petrobaltic (PB) and SASO working groups.


Stratigraphy
Seismic Reflectors
Erathem
System
Series
Stage
Time ma
PB
SASO
USO East
Description for PB & SASO
Description for USO East
Cenozoic
Quaternary
Tertiary
Holocene
Pleistocene
Pliocene
Miocene
Oligocene
Eocene
Palaeocene
2.6
T0
Base of the Quaternary deposits
Transgression Pleistocene
23
66
T1
t
Cenozoic Tgr. (Paleo-Pleistocene)
B'
Tgr. Campanian until Maastrichtian
Mesozoic
Cretaceous
Upper
Lower
Maastrichtian
Campanian
Santonian
Coniacian
Turonian
Cenomanian
Albian
Aptian
Barremian
Hauterivian
Valanginian
Berriasian
t-Cc
Top Cenomanian
100.5
B2
kro
Base Cenomanian
145
b-C
Base Cretaceous (Base Albian)
Jurassic
Malm
Dogger
Lias
Tithonian
Kimmeridgian
Oxfordian
Callovian
Bathonian
Bajocian
Aalenian
Toarcian
Pliensbachian
Sinemurian
Hettangian
163.5
JM
jo
t-JD
Near Base Malm (Top Korallenoolith)
Base Malm
Top Dogger
174
JD
jm
t-JL
Base Dogger
Top Lias
L3
Top Hettangian
201.5
JL
ju
t-TK
Base Lias
Top Triassic
Keuper
Triassic
Keuper
Muschelkalk
Buntsandstein
Raetkeuper
Dolomitmergelk.
Oberer Gipskeuper
Schilfsandstein
Unterer Gipskeuper
Lettenkeuper
Hauptmuschelkalk
Anhydritfolge
Wellenkalkfolge
Myophorienfolge
Pellitröt
Salinarröt
Sollingfolge
Hardegsenfolge
Detfurth
Volpriehausen
Bernburg
Nordhausen
T7
T7?
Tgr. (Dolomitmergelkeuper)
TK
Tgr. (Middle Keuper)
239
TM
k
t-TM
Nearly Top Upper Muschelkalk
Top Muschelkalk
m
Within Middle Muschelkalk
246.5
M3
t-TB
Base Lower Muschelkalk
Top Buntsandstein
TP2
Within Roet
so
t-TBm
Base Rötsalinar
Base Upper Buntsandstein
S3
Within the Middle Buntsandstein
sm
TP1
t-TBl
Top Lower Buntsandstein
(Rogenstein-/ Anhydritbänke)
Top Lower Buntsandstein
252.5
X1
su
t-PZ
Top Zechstein
Tgr. (Base Buntsandstein)
Top Zechstein (Aller Fm. - Z4)
Palaeozoic
Permian
Zechstein
Cycles 6 & 7 (Friesland & Fulda) are missing in the research area of USO
Ohre
Aller
Leine
Na3-K3
A3
T3-Ca3
A2r
Staßfurt
Na2-K2
A2
T2-Ca2
A1 β
Werra
Na1
A1 α
T1-Ca1
257.5
Z
Z1
z
t-PRs
Upon base Zechstein
Top Rotliegend (sediment.)
Rotliegend
Elbe succession
Havel succession
Autun sed.
Autun effusive
t-PRv
Top of effusive Autun
Top Rotliegend (effusive)
296
R/PZ
ru
t-C
Base of effusive Autun
Top Carboniferous
Carbon.
Silesian
Dinantian
Stefanium
Westfalium
Namurium
Viséum
Tournaisium
C1
cs
nearly base of Silesian (Westfal)
327
361
C/D
t-Du
within Upper Carboniferous or Devonian
Top Upper Devonian
Devonian
Upper
Middle
Lower
Famennium
Frasnium
Givetium
Eifelium
Emsium
Pragium
Lochkovium
383
D3
D2
do
t-Dm
Middle Frasnium
Lower Frasnium
Top Middle Devonian
392
D1
du
Old Red
418
D0
t-S
near Base of Devonian
Top Silurian (East European Craton)
Silurian
Pridoli
Ludlow
Wenlock
Llandovery
O2?
si
Cambrosilurian
t-Oaw/ t-Oeec
Top Ordovician (accretionary wedge or East European Craton)
444
Ordovician
Upper
Middle
Lower
458
470
O1?
cbm,o
Ordovician
485
t-Cb
Top Cambrian
Cambrian
Upper
Middle
Lower
497
509
cbu
541
t-E
Top Proterozoic
Proterozoic
Ediacaran

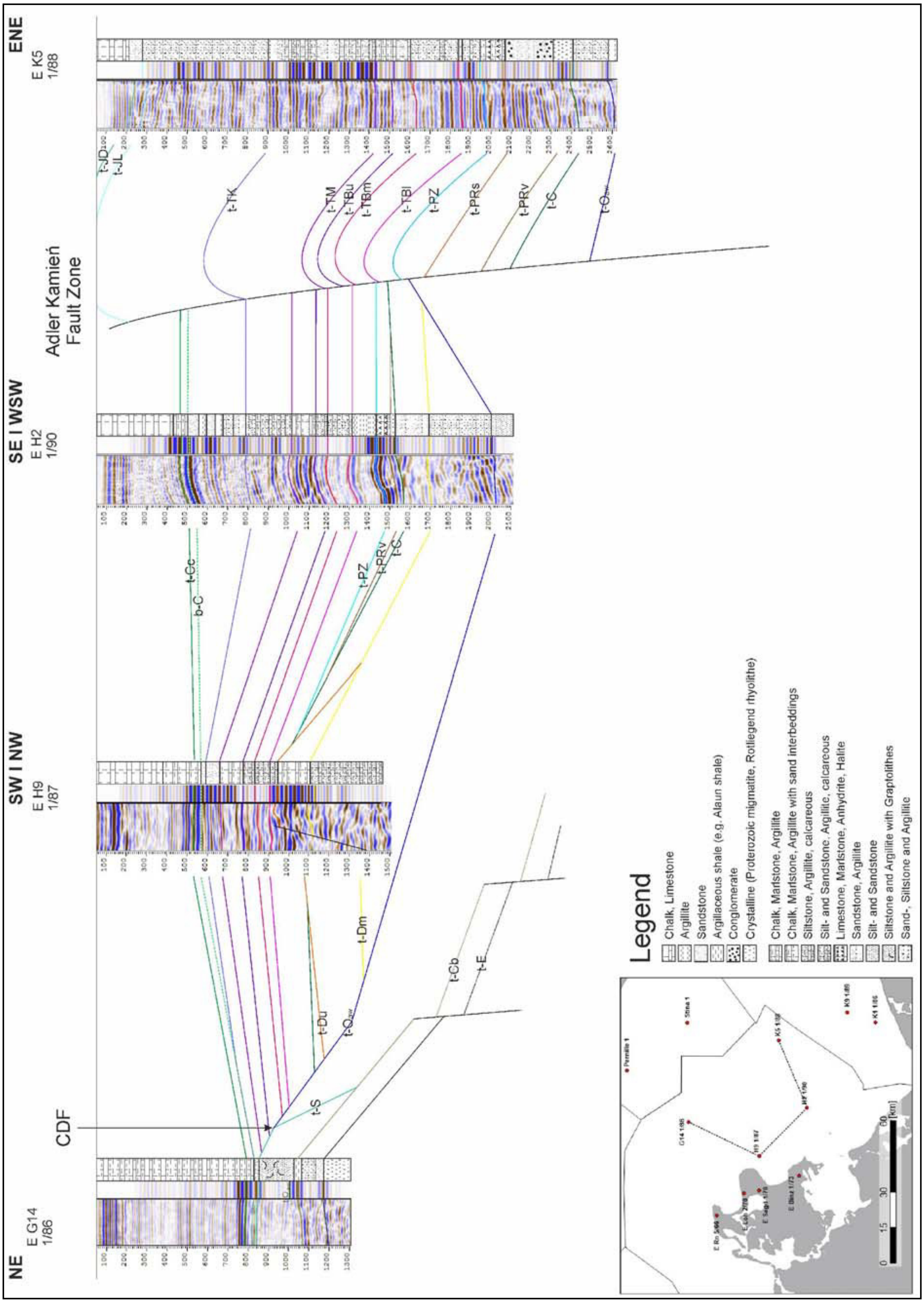


Fig. 4-5: Well ties of the four offshore wells east of Rügen with an extract of the seismic section, the synthetic and physical well logs and the lithology. For legend of the horizons see **Fig. 4-4**.

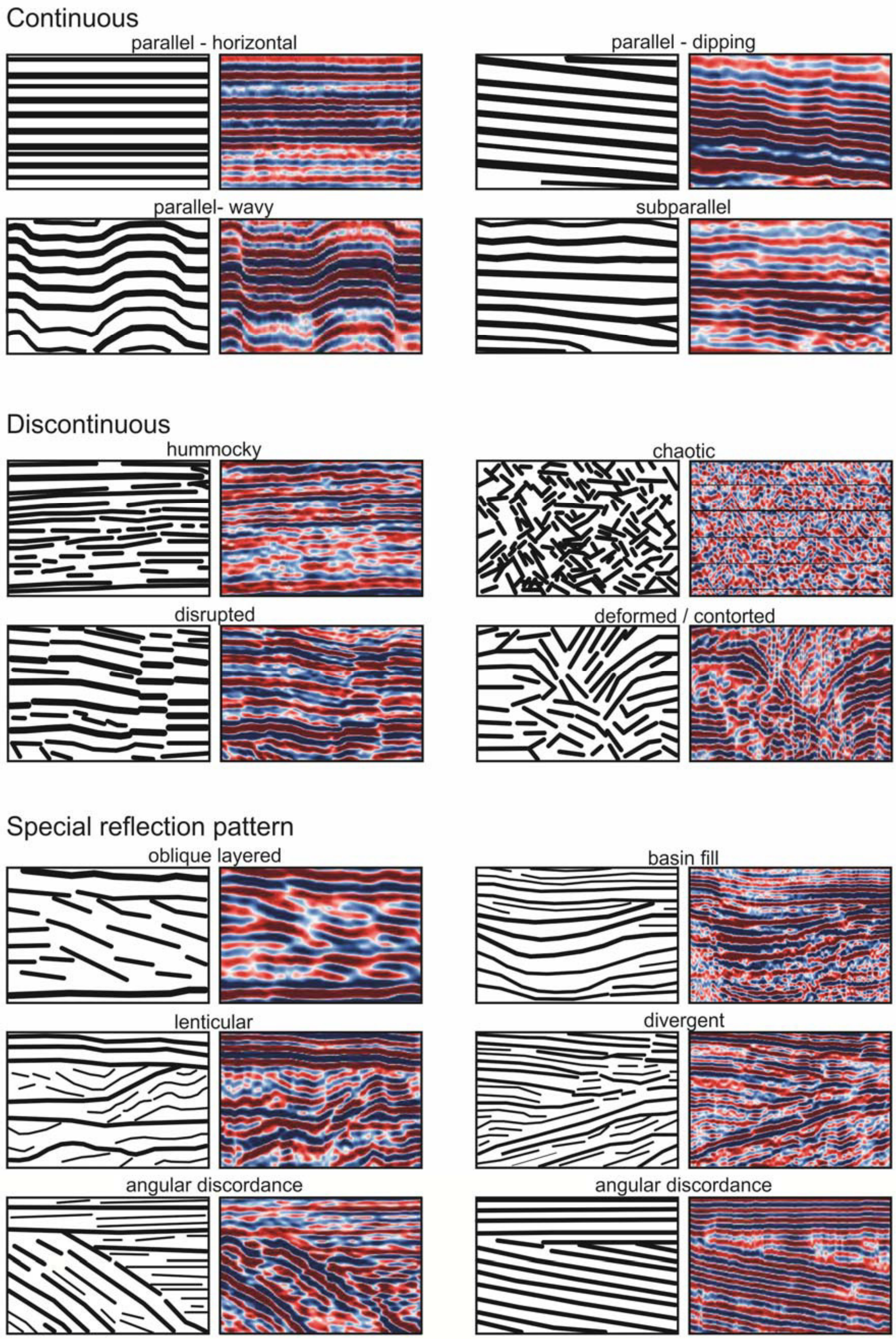


Fig. 4-6: Typical reflection patterns of the seismic lines; left: schematic, right: original seismic sections (subdivision based on MITCHUM et al. 1977 and VON HARTMANN et al. 2015)

4.4 Restoration of seismic lines with MOVE™

An important method for the structural analysis and interpretation of tectonic features and processes is the restoration of interpreted seismic sections. 2D cross-sections or horizons can be restored to their pre-deformational state in a 3D space (FOSSEN 2010). A stepwise restoration might help to understand the mechanism behind subsidence and basin generation, uplift of a region, or fault generation (KLEY et al. 2008). It can also be a tool for the analysis of palaeostress fields. In the literature, a number of different terms are used, including balancing, restoration and backstripping. After FOSSEN (2010), the **restoration** of a line means working back in time, thus, undeform it. A "**balanced section**" shows geologically reasonable structures that are restorable and that must be reasonable in the present state as well as in the restored version. Moreover, the length, area (2D) and volume (3D) are balanced between the restored and the original sections. The **"backstripping"** procedure also incorporates an isostatic restoration to analyse the subsidence history (FOSSEN 2010). This is especially used for the restoration of rift and graben structures.

The best way for the analysis and restoration follows the principle of "less is more" or "Occam's Razor". Hence, simple models and interpretations are favoured (FOSSEN 2010).

Fig. 4-7 shows a typical workflow, using the software MOVE™ by Midland Valley (2D Kinematic Modelling). After the interpretation of horizons and faults (Step 1), polygons have to be assigned for each stratigraphic unit, while faults stay as lines (Step 2). After a possible time-depth conversion (Step 3), an iteration of three steps follows: The uppermost horizon is uncovered, using an included decompaction workflow (Step 4). In case of a block-faulted situation (**Fig. 4-7**, Step 5: right block), the hanging block needs to be moved along the fault until the tops of the upper horizon meet at the same datum at the fault. The simple shear method and a wide shear angle of about 90° to the fault inclination were chosen for the “Move-on-fault” workflow. The upper horizon has to be unfolded and backstripped towards the palaeo-water depth (pwd) or the initial state and condition immediately after its origin.

These three major steps of “Decompaction”, “Move on fault”, and “Unfolding” have to be repeated for all horizons until the entire section is restored. The workflows for the restoration of the seismic sections is presented in **Appendix A.b**.

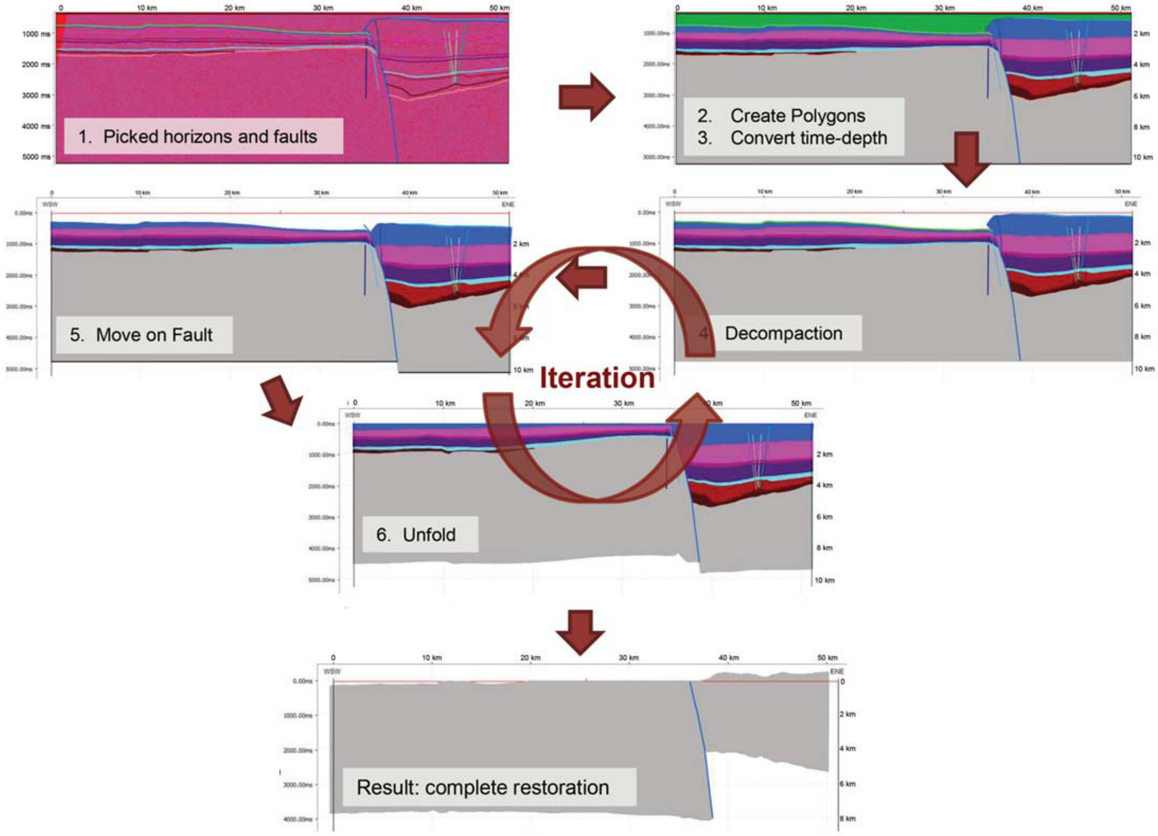


Fig. 4-7: Workflow for the restoration of seismic lines.

5 Results

This chapter is divided into two parts. The first section comprises the results for each stratigraphic unit from the top of the Proterozoic Basement until the base of the Cretaceous (**Section 5.1**). The second section covers the structural inventory (such as the different blocks, which are bordered by faults, see **Chapter 5.2**), all mapped within the working area of USO East, as well as restoration results. **Fig. 5-1** gives an overview of the most dominant faults and blocks, which are currently known from literature, and are mentioned in **Section 5.1.**

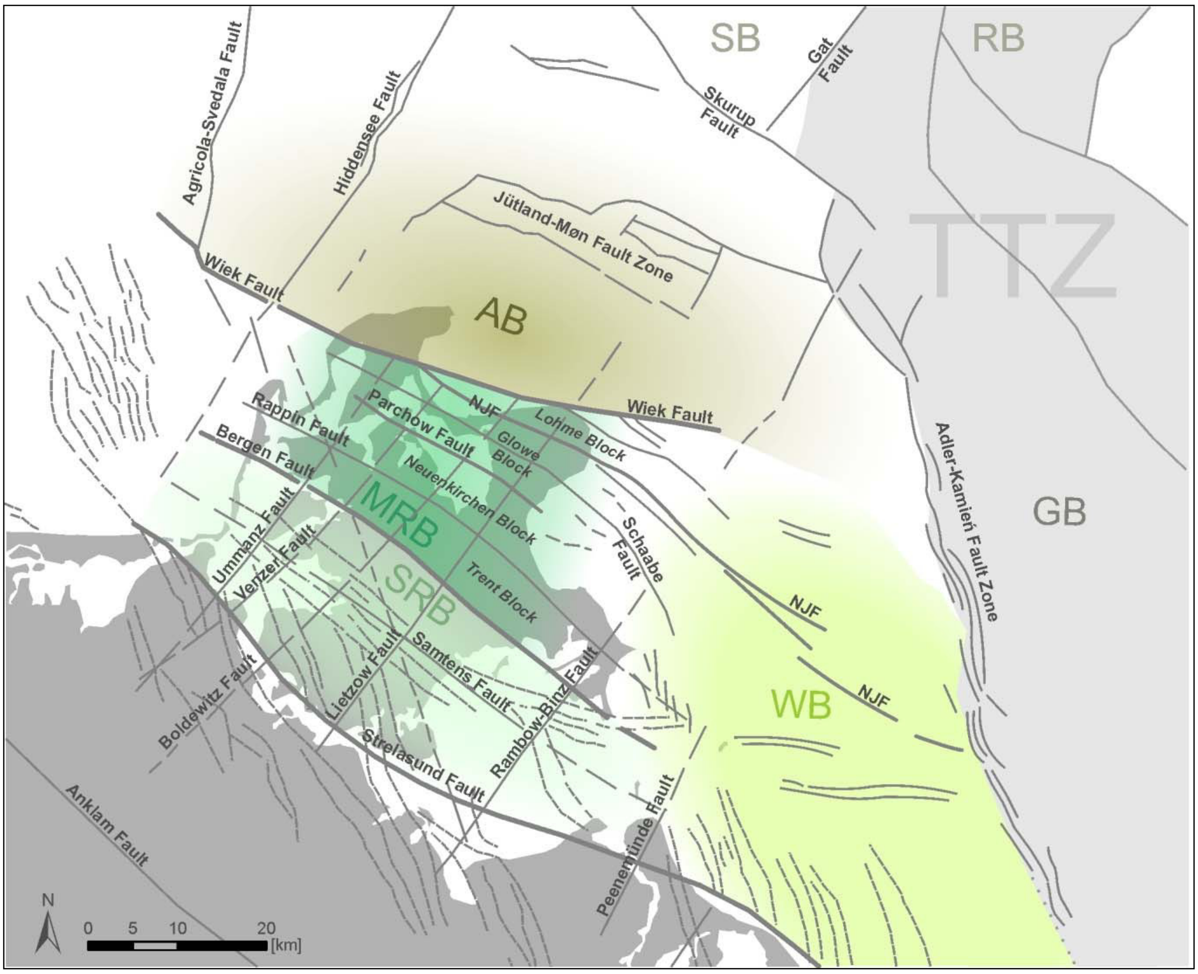


Fig. 5-1: Fault inventory within the area of USO East. The single fault planes have been mapped and illustrated by former projects (**Chapter 5.2**); AB – Arkona Block, GB – Gryfice Block, MRB – Middle Rügen Block, NJF – Nord Jasmund Fault, RB – Rønne Block, SB – Skurup Block, SRB – South Rügen Block, TTZ–Teisseyre-Tornquist Zone, WB – Wolin Block (SEIDEL et al. 2018 and references therein, modified).

5.1 Stratigraphic Units

The mapping of stratigraphic units concentrated on the successions between the base Cretaceous and the top of the Proterozoic Basement in the area of USO East. Due to an insufficient resolution within the uppermost 300 ms the Post-Cretaceous deposits have not be regarded (see **Chapter 4**; SCHLÜTER et al. 1998). The explanation for the main horizons will introduce the informations given by the offshore wells (H2 1/90, H9 1/87, K5 1/88, G14 1/86) and onshore wells (Binz 1/73, Sagd 1/70, Loh 2/70 and Rn 5/66). Subsequently the chosen main horizons (see also **Section 4.3** and **Fig. 4–4**) should be defined and the appearance of the grids for each stratigraphic unit described. The **Figs. 4–4** & **4–5** give an overview of the picked seismostratigraphic horizons, their age and relation to marker-horizons, previously defined by the Petrobaltic and SASO working groups (see **Appendix C**).

Due to the Caledonian history the Lower Palaeozoic units have to be subdivided into those autochthonous ones, covering the Proterozoic basement of Baltica 'insitu' (undeformed, subparallel Cambrian to Silurian deposits) and the highly deformed, allochthonous Ordovician sediments. According to former investigations (e.g. KRAUSS 1994, BEIER 2001, BEIER & KATZUNG 2001) the collision of Baltica and Avalonia forces the overthrusting of marine Ordovician deposits (originally covering the Tornquist Ocean floor) onto the subsiding crust of Baltica. Thus the deformed Ordovician deposits form an accretionary wedge recently (see below).

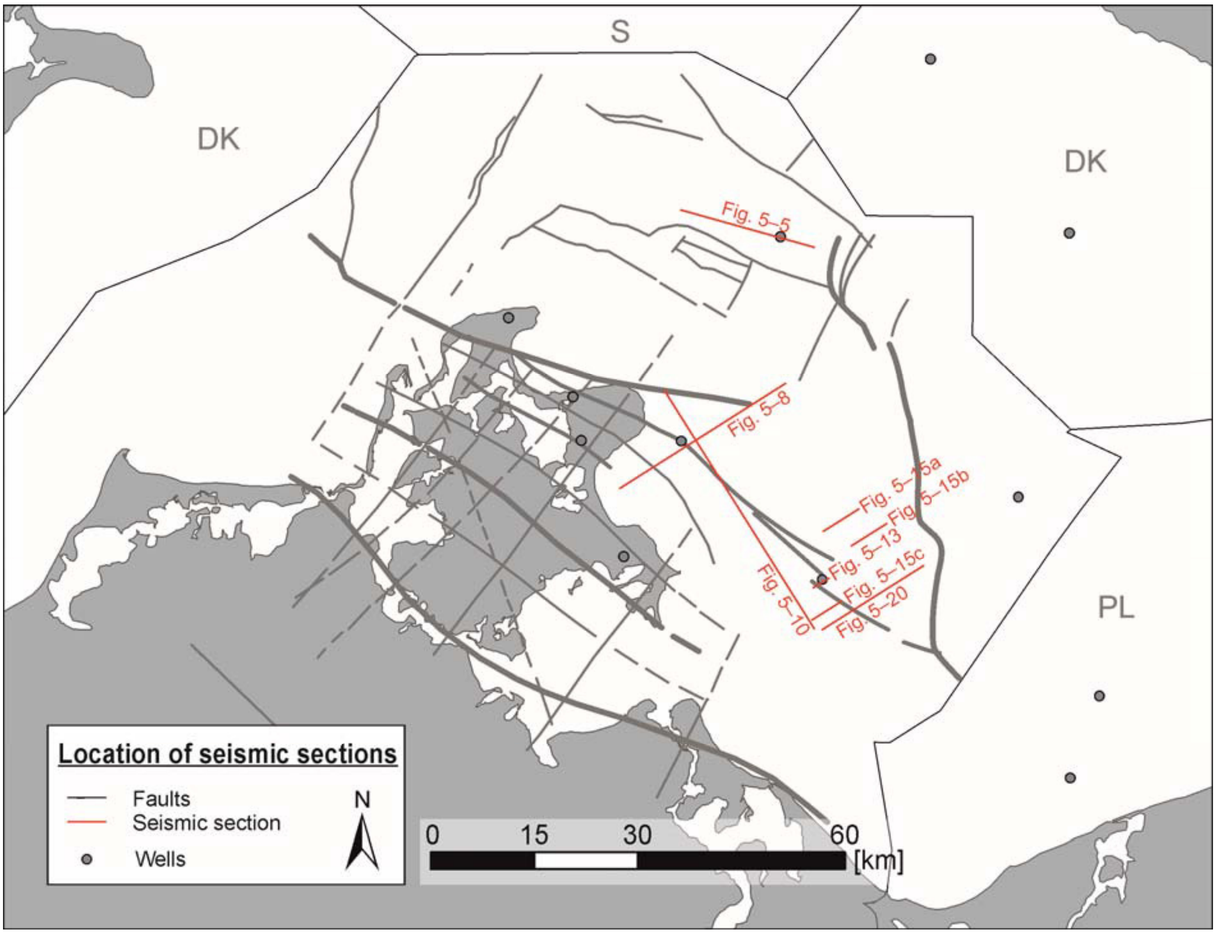


Fig. 5-2: Location of presented seismic sections marked in red. Grey lines indicate previously known faults (e.g. THOMAS et al. 1993, MAYER et al. 1994).

5.1.1 Proterozoic Basement and Neoproterozoic to Cambro-Ordovician cover

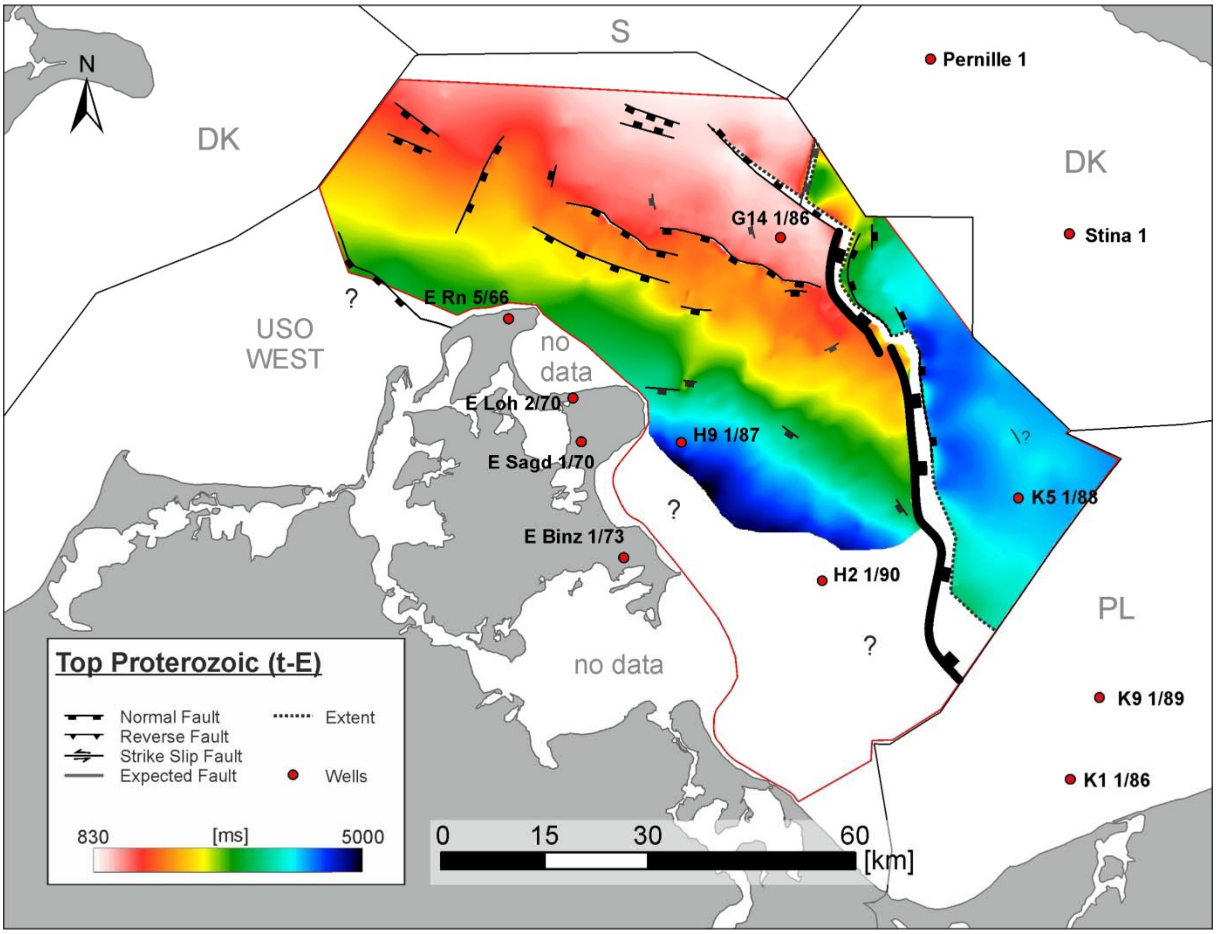


Fig. 5-3: Time-structure map of the Top Proterozoic (EEC/Baltica) within the area of USO East.

Tab. 5-1: Borehole information for the Proterozoic and its Neoproterozoic to Palaeozoic cover, based on HOTH et al. (1993) for the onshore wells and on the original well description tables (DIENER et al. 1988, 1989, LÜCK et al. 1987 and PUPUNYN et al. 1990) for the offshore wells.

Well name	Strata	Top Measured depth in [m] from the surface (onshore) or rotary table (offshore)	Thickness [m]
G14 1/86 Sea level 29.5m Sea floor 68.1m	Ordovician, undeformed with alum shale Cambrian (alum shale, sandstone), Neoproterozoic III (sandstone, conglomerate), Proterozoic – Ediacaran (migmatite/granite, according to OBST et al. 2004)	1538 1599.0 1886.0 1941.75	61.0 287 55.75 55.23 (**397.98**) (well end)
Rn 5/66 [25.2m asl]	**not achieved**	-	-
Loh 2/70 [19.6m asl]	**not achieved**	-	-
Sagd 1/70 [24.9m asl]	**not achieved**	-	-
H9 1/87 Sea level 27.4m Sea floor 46.6m	**not achieved**	-	-
Binz 1/73 [15.2m asl]	**not achieved**	-	-
H2 1/90 Sea level 27m Sea floor 42m	**not achieved**	-	-
K5 1/88 Sea level 29.2m Sea floor 41m	**not achieved**	-	-

The oldest strata of the working area were detected in the north of the Arkona Block. The Proterozoic crystalline basement and its Neoproterozoic and Lower Palaeozoic cover is drilled by the well G14 1/86. The Proterozoic basement is characterised by migmatites of monzogranitic composition (Obst et al. 2004). The Neoproterozoic sediments are dominated by sandstones and partly conglomerates. Whereas the Lower Cambrian strata consist of mud- and sandstone, the prominent Alum shales were sedimented from the Middle Cambrian until the Lower Ordovician (**Tab. 5-1**).

Horizon t-E

The Proterozoic Basement of Baltica with the covering Ediacaran (Neoproterozoic) to Cambrian/Ordovician sediments can be identified by three to four strong parallel reflections within a chaotic reflection pattern. Those reflections are dominantly formed by the transition from the crystalline basement towards the sandy sediments (Є-reflector, according to Petrobaltic) and the strong reflections of the alum shales. The top of the latter was mapped by the Petrobaltic working group as O-horizon (thus, as horizon within the Ordovician). A tracing of those lowermost horizons is hampered by several multiples of the Base Cretaceous crossing it.

The horizon **t-E** of the top of crystalline basement dips from the high positioned platform in the northeast towards the southwest. The reflectors of the covering sediments could not be followed as far as the basement itself. Therefore subparallel depositions of Neoproterozoic to Ordovician strata have been assumed. Due to the reconditioning of the sediments within the accretional wedge during the Caledonian Orogeny, these sediments will not have the same distribution as the basement of Baltica, but follow the same morphology.

The light horizon of the undisturbed Ordovician runs subparallel to the basement and was traced but not gridded here. The Petrobaltic horizons *O1* or the SASO horizons *cbm* or *o* are probably the most comparable ones, as they are defined to be the Cambro-Silurian (most likely Ordovician) and top of the Alum shales (see **Appendix C**).

Surface Grids

The surface gridded here as <u>time</u> structure map (in TWT; **Fig. 5-3**), visualises the top of the Proterozoic basement. The autochthonous lower Palaeozoic sediments, would show the same morphology but could not be traced that far.

The Proterozoic basement of Baltica is dipping from its highest position in the north-northeast (about 830 ms) south-southwestward to about 5000 ms (TWT). Since this depth, which is reached north of the well H2 1/88, the horizon is not traceable anymore. The stepwise descending of this horizon is governed by NW–SE striking faults in the Arkona Block (e.g. Jütland-Møn Fault Zone, Wiek Fault; **Fig. 5-1**; see **Section 5.2**). Further faults cross the Arkona Block NNE-SSW (Hiddensee Fault; **Section 5.2**) forming an elongated, about 500 ms deep, depression. Other faults in the north, like the Skurup and Gat faults, or in the east of the Arkona Block, like the AKFZ, form a normal displacement of the horizon for up to 2000 ms. East of the AKFZ and the Gat Fault, the highest position (about 1900 ms) is also in the north, but the horizon descends towards the centre of the Gryfice Block (about 4500 ms, 50 km east of Jasmund). Further highs are located about 10 km NE of the well K5 1/88 (3900 ms) and south of the researched Gryfice Block (3370 ms).

5.1.2 Silurian cover

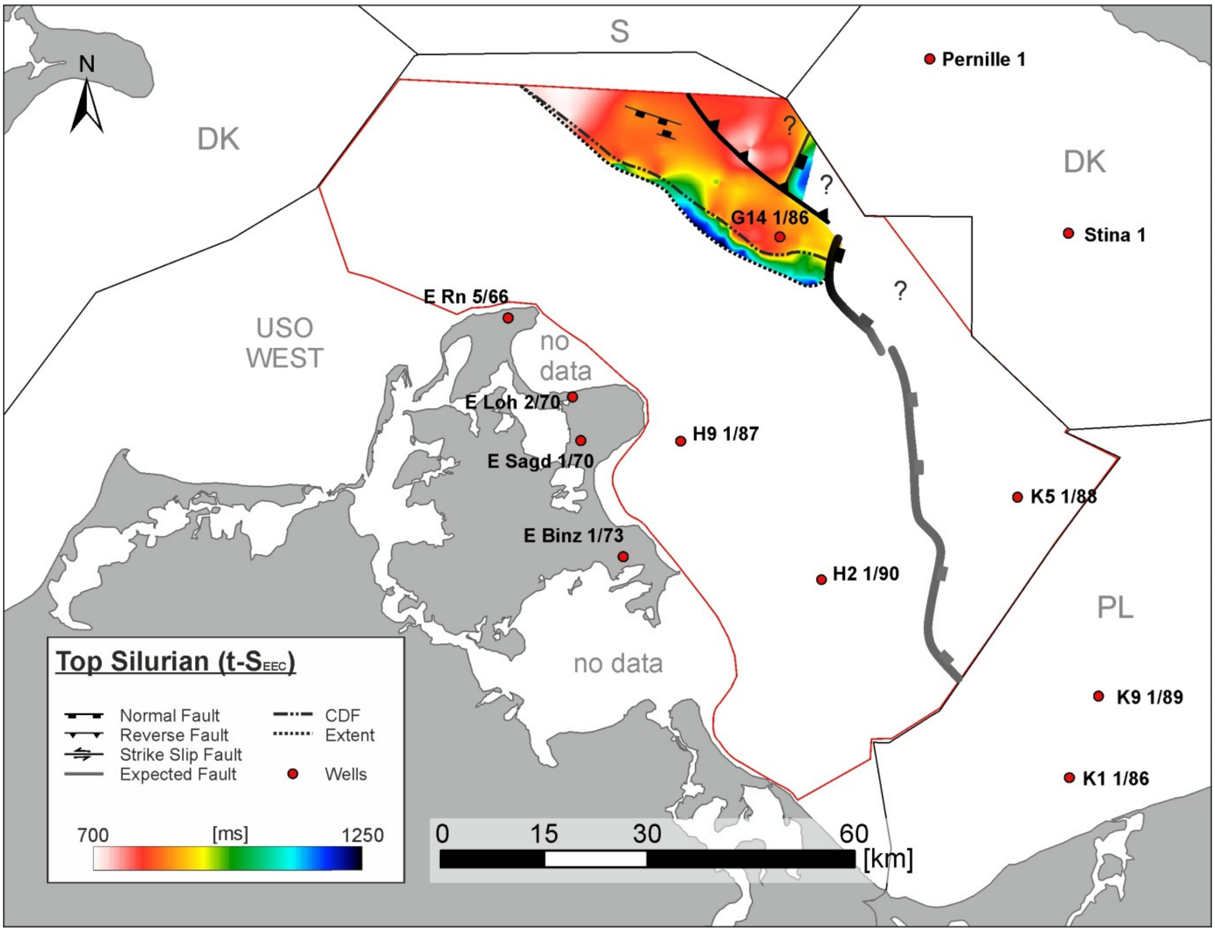


Fig. 5-4: Time-structure map of the Top Silurian (cover of the EEC) within the area of USO East.

Tab. 5-2: Borehole information for the Silurian cover, based on HOTH et al. (1993) for the onshore wells and on the original well description tables (DIENER et al. 1988, 1989, LÜCK et al. 1987 and PUPUNYN et al. 1990) for the offshore wells.

Well name	Strata	Top Measured depth in [m] from the surface (onshore) or rotary table (offshore)	Thickness [m]
G14 1/86 Sea level 29.5m Sea floor 68.1m	Llandovery (clay- and siltstone, sandstone, partly with Graptolithes)	1198.5	339.5
Rn 5/66 [25.2m asl]	missing	-	-
Loh 2/70 [19.6m asl]	missing	-	-
Sagd 1/70 [24.9m asl]	not achieved	-	-
H9 1/87 Sea level 27.4m Sea floor 46.6m	not achieved	-	-
Binz 1/73 [15.2m asl]	missing	-	-
H2 1/90 Sea level 27m Sea floor 42m	missing	-	-
K5 1/88 Sea level 29.2m Sea floor 41m	missing	-	-

Non deformed Silurian sediments have only been retrieved within the well G14. These are predominantly fine grained, interchanging silt- and mudstones, which contain fossils (Graptolites).

Whereas in the wells Rn 5/66, Loh 2/70, Binz 1/73, H2 1/90 and K5 1/88 this strata was missing, the wells Sagd 1/70, H9 1/87 were not deep enough and did not achieve this horizon (**Tab. 5-2, Fig. 5-4**).

Horizon t-S

The Silurian strata is characterised by an internal subparallel to hummocky or even chaotic reflection pattern with low amplitudes. There is a clear distinction between the almost transparent (low amplitude) Silurian internal reflections and the Permo-Triassic sediments above or the Cambro-Ordovician deposits below, which are all characterised by strong acoustic impedance and therefore higher amplitudes (**Fig. 5-5**). All those stratigraphic units are characterised by alternating clay-,silt and sandstones. The difference in the reflection pattern might be triggered by the layer thickness of those alternating sediments. Thus the Silurian sub-layers are quite thin (cm- to m-scale) and not recognisable by the seismic signal. Moreover the successions bear fossils and might be bioturbated. However, there is a low internal acoustic impedance and thus no clear reflections. This horizon can only be revealed in the northern working area at the Arkona and Skurup blocks, as it is proven by the wells (only drilled with the well G14 1/86). The horizon t-S is traced at the zero-crossing moment of the wiggle. This reflector is near the *D0* horizon of the Petrobaltic working group or the horizon *100* of the SASO project (see **Appendix C**).

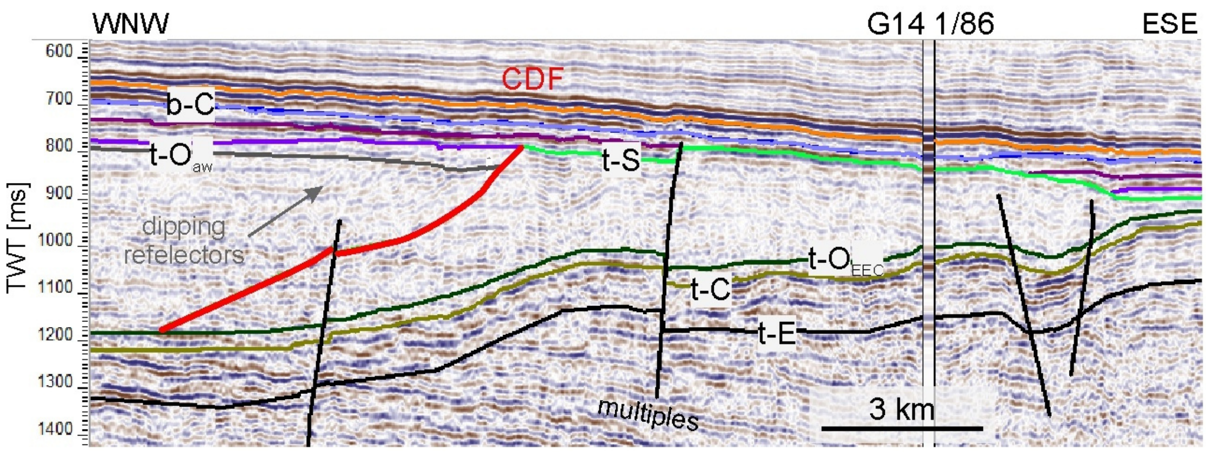


Fig. 5-5: Interpreted section regarding well log G14 1/86, for location see **Fig. 5-2**. (Vertical exaggeration-VE≈5.5, assuming an average velocity of 3000 m/s).

Surface grids

The Silurian sediments have been detected at the northern part of the Arkona Block and the Skurup Block. The used wells give no hints for Silurian sediments south of the Arkona Block. Therefore, the horizon cannot be traced far into the southern direction. The highest points reach a TWT of about 700 ms at the northwestern border of the working area (**Fig. 5-4**). Similar depths are reached north of the reverse Skurup Fault. South of this fault, at the Arkona Block, the horizon is relative flat, and bordered to the east by the AKFZ. Since the CDF, crossing the Arkona Block NW-SE, the horizon steeply dips in a southwestern direction until about 1270 ms. NE of the Skurup Fault, at the Skurup Block, the surface is flat but elevated against the surrounding area. A huge displacement of about 300 ms is formed by the Gat Fault, intersecting the Skurup and Gryfice blocks. Due to a lack of data, the horizon was not traceable at the Gyfice Block.

5.1.3 Deformed Ordovician of the accretionary wedge

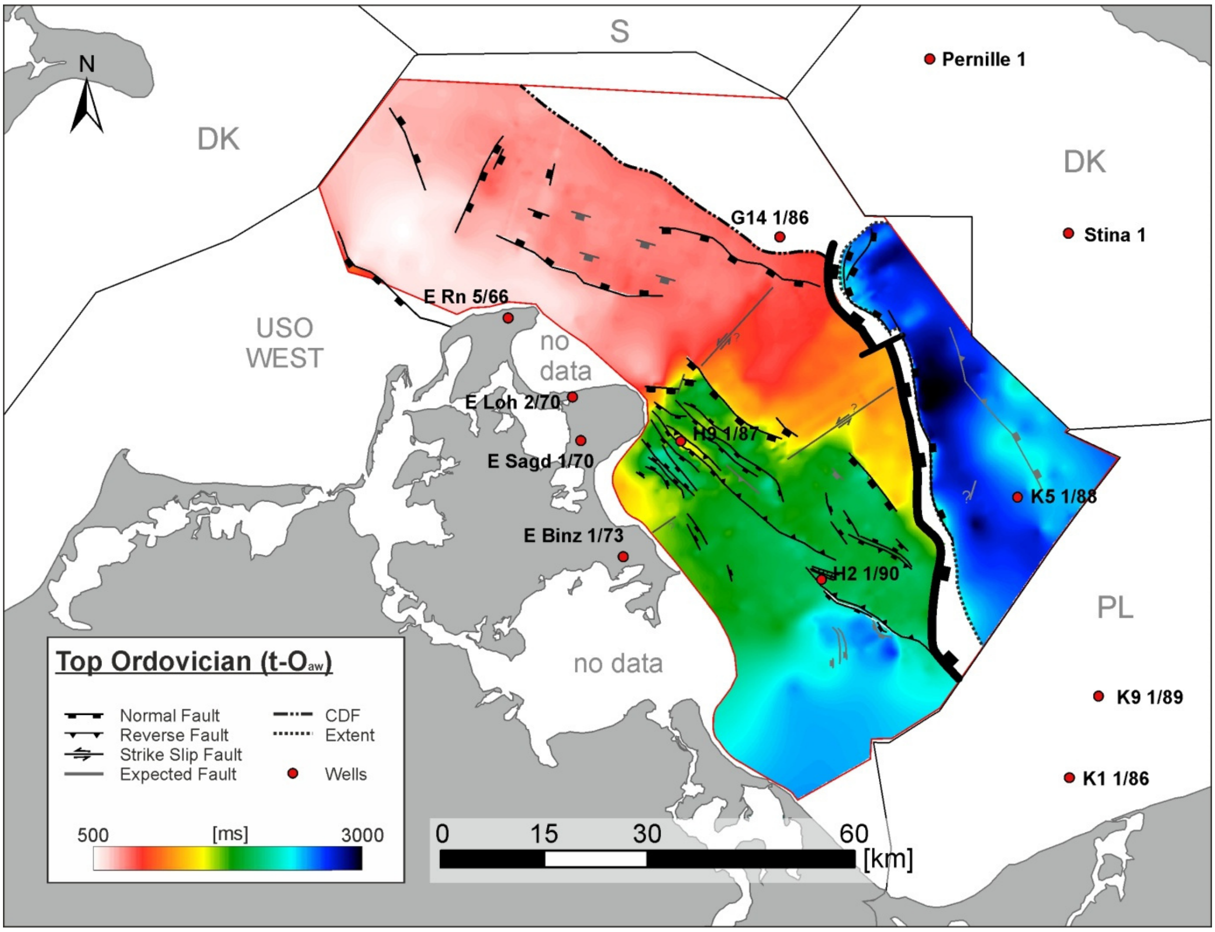


Fig. 5-6: Time-structure map of the Top Ordovician (accretionary wedge) within the area of USO East.

Tab. 5-3: Borehole information for the deformed Ordovician, based on HOTH et al. (1993) for the onshore wells and on the original well description tables (DIENER et al. 1988, 1989, LÜCK et al. 1987 and PUPUNYN et al. 1990) for the offshore wells.

Well name	**Strata**	**Top** Measured depth in [m] from the surface (onshore) or rotary table (offshore)	**Thickness** [m]
G14 1/86 Sea level 29.5m Sea floor 68.1m	Ashgillian-Caradocian, Llandeilo, Arenigian, Tremadocian (Alaunschiefer) undeformed	1538	61.0
Rn 5/66 [25.2m asl]	Dominantly clay and silt, 5-80° dipping; According to HOTH et al. (1993): Upper Ordovician (Llandeilo, Caradocian => Old Red), Lower Ordovician (Llanvirnian with Graptolite zone 7-6, Tremadocian - Arenigian without Graptolites)	720 2923	2203 969.4 (well end) (**3172.4**)
Loh 2/70 [19.6m asl]	Shale with fossils; According to HOTH et al. (1993): Lower Ordovician / Llanvirn Graptolite zone 7	3288	62.4 (well end)
Sagd 1/70 [24.9m asl]	**not achieved**	-	-
H9 1/87 Sea level 27.4m Sea floor 46.6m	**not achieved**	-	-
Binz 1/73 [15.2m asl]	Lower Ordovician (Llanvirnian = varying sediments, partly Diabase no information about deformation)	5015	204.6 (well end)
H2 1/90 Sea level 27m Sea floor 42m	mudstone	3199.5	85.5 (well end)
K5 1/88 Sea level 29.2m Sea floor 41m	mudstone, laminated shales, bedding folded and partly overturned (according to KATZUNG 2001)	3990.5	158.5 (well end)

With exception of the wells Sagd 1/70 and H9 1/87 all wells revealed Ordovician strata. The drilled clayey, Graptolite bearing sediments show indices for a deformation, like the dipping of the strata or metamorphosed rocks (**Tab. 5-3**). Only the well G14 1/86 drilled secondary undeformed Ordovician silt and clay stones as well as alum shales. According to former interpretations (KATZUNG 2001, BEIER & KATZUNG 2001) we differentiated between the undeformed Ordovician, covering the EEC and the deformed Ordovician as part of an accretionary wedge.

Horizon t-O_{aw}

The horizon T11 is dominantly formed by an angular unconformity between a subhorizontal internal reflection pattern above and south-westward dipping internal reflections of the deformed Ordovician itself. Those dipping internal reflections are especially nicely seen in the seismic sections crossing the Arkona Block (**Fig. 5-5**, **Section 5.2.1.6**). Therefore, the horizon is mostly traced in the peak of the wavelets. Towards the south, across the Wolin Block, the horizon was difficult to trace because of overlying multiples of the Muschelkalk in the seismic signal. The working groups of Petrobaltic or SASO did not define reflectors accordingly for the top of the accretionary wedge.

Surface Grids

The horizon t-O_{aw} can be traced across the complete working area and is only limited by the CDF to the north (**Fig. 5-6**). The highest position (about 480 ms) is located in the northwest of the working area. From there on the surface is dipping in southeastern direction across the Wolin Block to about 2500 ms. The horizon is intersected by different faults and fault zones. The Wiek Fault (**Fig. 5-1**) forms a major step of up to 1000 ms. Thereby the blocks of Arkona in the north and Wolin in the south are separated. A further prominent step is formed by the AKFZ of up to 2000 ms. Therefore the depth across the Gryfice Block varies between 2300 ms in the central east or in the north (close to the AKFZ) and 3000 ms in between. The horizon is displaced by one of the Gryfice faults at the Gryfice Block. At the Arkona Block, the NNE striking Hiddensee Fault and other WNE striking faults like of the Jütland-Møn Fault Zone are active. In the Wolin Block further faults of WFS are detected (**Section 5.2.2**). Additional NE to NNE striking faults crosscut the Wiek Fault and displaces the fault segments, as well as the horizon t-O_{aw} of the Wolin and Arkona blocks sinistral. The northern fault runs towards Jasmund and the southern one towards Mönchgut.

5.1.4 Devonian

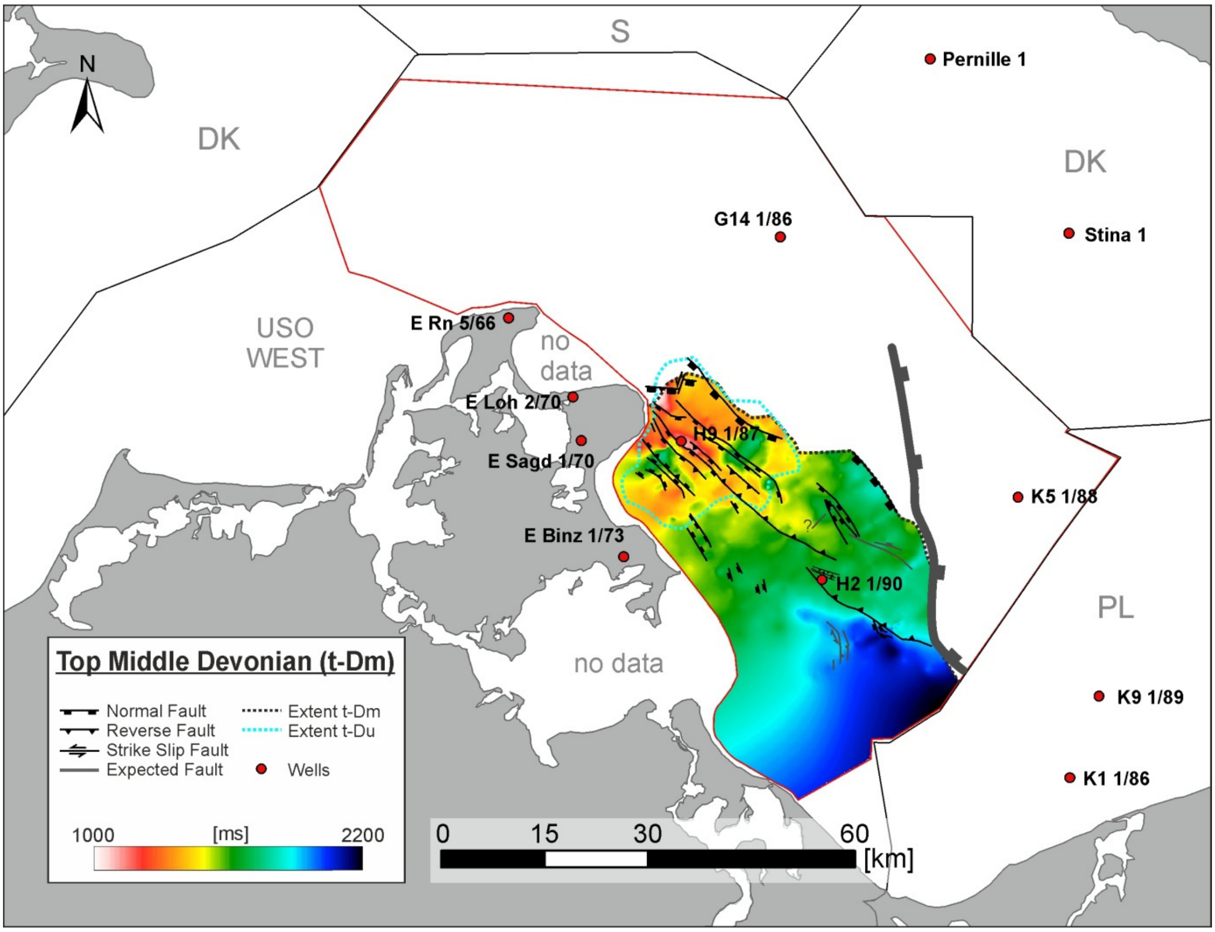


Fig. 5-7: Time-structure map of the Top Devonian within the area of USO East.

Tab. 5-4: Borehole information for the Devonian, based on Hoth et al. (1993) for the onshore wells and on the original well description tables (Diener et al. 1988, 1989, Lück et al. 1987 and Pupunyn et al. 1990) for the offshore wells.

Well name	**Strata**	**Top** **Measured depth in [m] from the surface (onshore) or rotary table (offshore)**	**Thickness** **[m]**
G14 1/86 Sea level 29.5m Sea floor 68.1m	**missing**	-	-
Rn 5/66 [25.2m asl]	**missing**	-	-
Loh 2/70 [19.6m asl]	Middle Devonian (Givetian to Eifelian)	1810	1478
Sagd 1/70 [24.9m asl]	Upper Devonian (Famennian, Frasnian)	2623	1077 (well end)
H9 1/87 Sea level 27.4m Sea floor 46.6m	Upper (Frasnian), Middle (Givetian)	1211 1615	404 635.5 (well end)
Binz 1/73 [15.2m asl]	Upper Devonian (Frasnian), Middle Devonian (Givetian, Eifelian with Old Red-Fazies)	2787 3151	364 1864
H2 1/90 Sea level 27m Sea floor 42m	Middle Devonian	2525.5	674
K5 1/88 Sea level 29.2m Sea floor 41m	**missing**	-	-

Devonian sediments are detected at the offshore Wolin Block and the onshore Middle and South Rügen blocks (**Fig. 5-7**, **Tab. 5-4**). The strata is missing in the wells H5 1/88, within the Gryfice Block and within the northern wells Rn 5/66 and G14 1/86. Thereby a general trend for the Middle and Upper Devonian is dedicated. Whereas the southern wells H2 1/90 and Loh 2/70 showed only the Middle Devonian successions, the wells Binz 1/73 und H9 1/87 contained the Upper and Middle Devonian. Sagd 1/70 incorporates only the Upper Devonian. A slight increase of thickness can be recognised in an east-northeastern direction.

Horizons t-Du and t-Dm

The Middle Devonian contains dominantly sand and mudstone. The reflection pattern changed locally to higher frequencies and lower amplitudes. The Middle and Upper Devonian show dominantly a hummocky to subparallel reflection pattern and are therefore difficult to trace. East of Jasmund the Devonian stratum is block faulted and vertically displaced, which made a trace of the disrupted horizons even more difficult. The Upper and Middle Devonian have been picked in the peak events. The Middle Devonian (**t-Dm**) event is picked below a pattern of three to four reflections. The reflector of the Upper Devonian **t-Du** was only traceable at the northern and middle part of the Wolin Block with regard to the well H9 1/87. It is characterised by the same frequency and amplitude like the internal reflections of the Carboniferous successions. Both units can be subdivided by angular unconformities of the internal reflectors (**Fig. 5-8**). Whereas the Upper Devonian mainly consists of lime- and marlstone, with some mudstone, the Carboniferous sediments are mainly composed of mud- and sandstone.

The Petrobaltic working group defined the reflector *D2* as a border between the Middle and Upper Devonian, the horizon *C/D* should be close to the t-Du. Within the SASO project the reflector *do* or *95* is defined as the top of the Middle Devonian, and the reflector *90* as the top of the Devonian (see **Appendix C**).

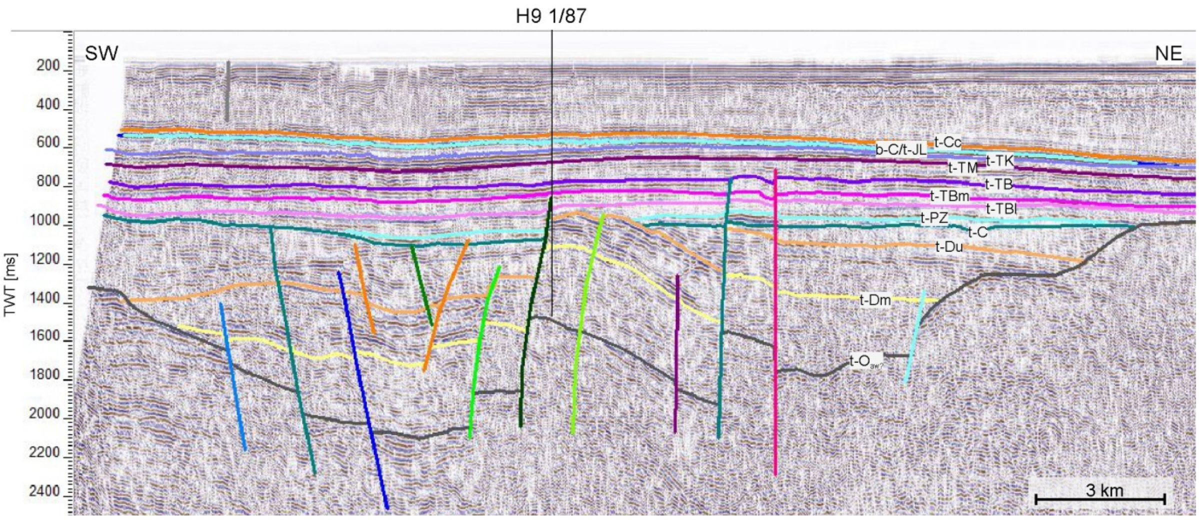


Fig. 5-8: Seismic section showing the block faulted Palaeozoic successions which are subhorizontal covered by Mesozoic deposits. Moreover the projected location of the well H9 1/87 is shown (for location see **Fig. 5-2**). (VE≈3, assuming an average velocity of 3000 m/s)

Surface Grid

Offshore, the Devonian stratum is almost delimited to the Wolin Block (**Fig. 5-7**). The Middle Devonian can be followed until the southern border of the working area. This horizon varies between 1000 ms in the NW and 2200 ms in the SE and is limited by the Wiek Fault towards the NE. The faults and flexures of the Wiek Fault System (**Section 5.2.2.1**) mould the morphology, especially in the northern part of the Wolin Block, and along the NJF. The Upper Devonian concentrated in the area NE of Mönchgut (Rügen), thus, the northern part of the Wolin Block. Its depth varies between 800 and 1500 ms.

5.1.5 Carboniferous

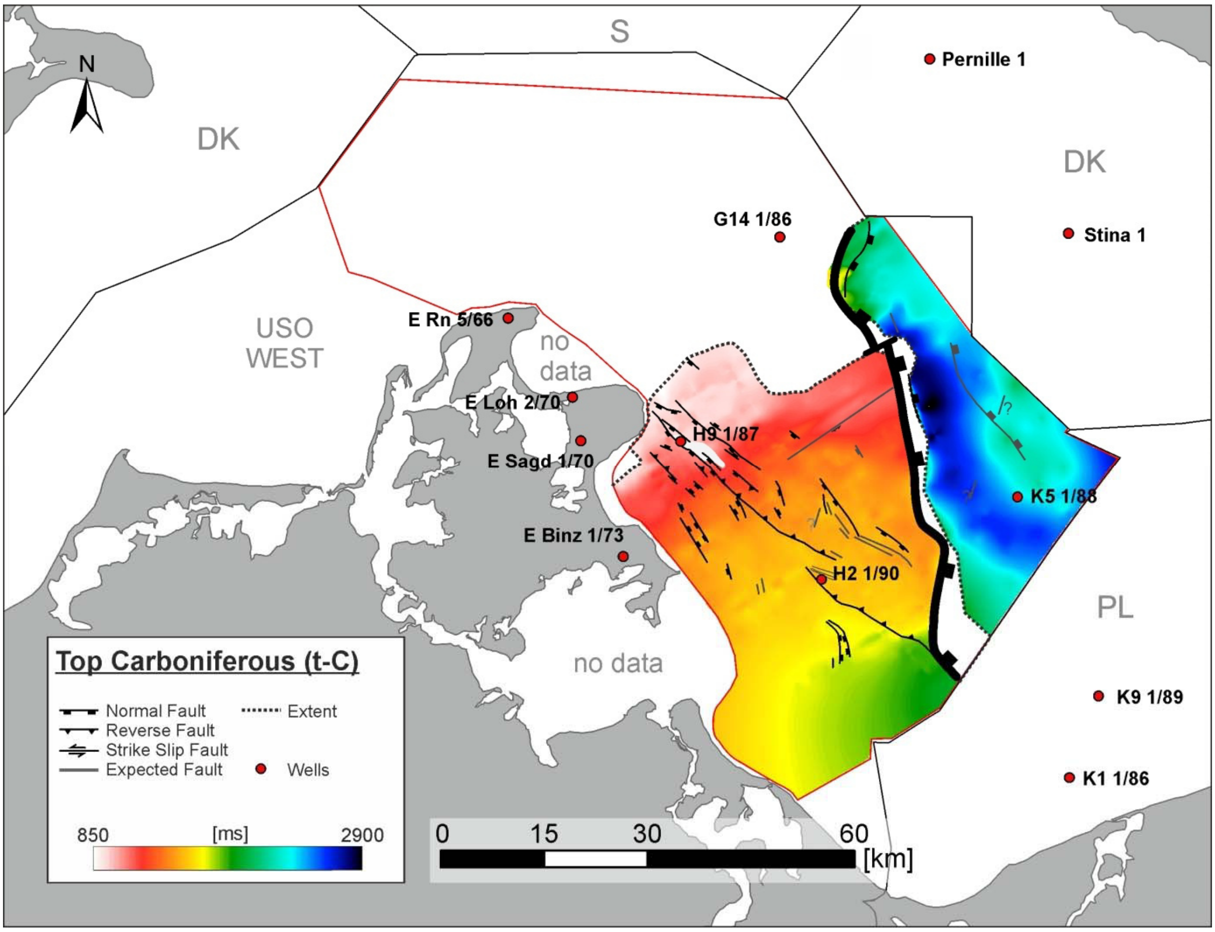


Fig. 5-9: Time-structure map of the Top Carboniferous within the area of USO East.

Tab. 5-5: Borehole information for the Carboniferous, based on HOTH et al. (1993) for the onshore wells and on the original well description tables (DIENER et al. 1988, 1989, LÜCK et al. 1987 and PUPUNYN et al. 1990) for the offshore wells.

Well name	**Strata**	**Top** **Measured depth in [m] from the surface (onshore) or rotary table (offshore)**	**Thickness** **[m]**
G14 1/86 Sea level 29.5m Sea floor 68.1m	missing		
Rn 5/66 [25.2m asl]	missing	-	-
Loh 2/70 [19.6m asl]	Silesian (Westphalian), Dinantian (Viséan)	948 1330	382 480 (**862**)
Sagd 1/70 [24.9m asl]	(according to HOTH et al. 1993): Silesian (Westphalian), Dinantian (Viséan, Tournaisian)	1075 1519	444 1104 (**1548**)
H9 1/87 Sea level 27.4m Sea floor 46.6m	missing	-	-
Binz 1/73 [15.2m asl]	Silesian (Stephanian, Westphalian)	1556.5	1230.5
H2 1/90 Sea level 27m Sea floor 42m	Silesian (Westphalian)	2131.5	394
K5 1/88 Sea level 29.2m Sea floor 41m	Upper Carboniferous/ Silesian (Westphalian)	3601	389.5

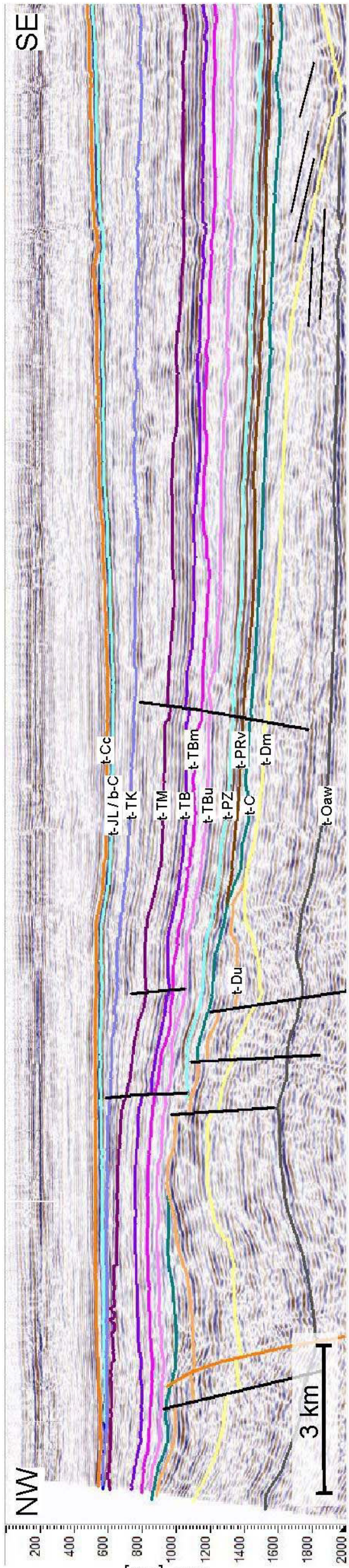


Fig. 5-10: Seismic line crossing the Wolin Block southeastward. Black lines indicating the internal differential dipping reflections and the angular unconformity between the Middle Devonian and the Carboniferous (for location see **Fig. 5-2**). (VE≈2.5, assuming an average velocity of 3000 m/s)

The Carboniferous was found within almost all the wells, with the exception of the northern wells H9 1/87, Rn 5/66 and G14 1/86 (**Tab. 5-5**). The wells Sagd 1/70 and Loh 2/70 detected the calcareous, marls or cleyey Lower Carboniferous (Viséan, Tournaisian) and clayey to sandy Upper Carboniferous (Stephanian, Westphalian). Whereas in the southernmost wells, H2 1/90, Binz 1/73 and K5 1/88 only the Upper Carboniferous, was drilled. The thickest successions with over 1000 m, are drilled in the wells Sagd 1/70 and Binz 1/73 (**Tab. 5-5**).

Horizon t-C

The two offshore wells H2 1/90 and K5 1/88 detected only the Upper Carboniferous, but due to the results of the onshore wells in the vicinity, the Lower Carboniferous would also be expected across the northern and middle part of the Wolin Block. Nevertheless, the general top of Carboniferous was traced by the horizon t-C (**Fig. 5-9**). This horizon is picked along a subparallel peak below the Permian successions with regard to the wells and the internal reflection pattern, which is subparallel to hummocky. The amplitude and frequency does not obviously change from the Permian ones, thus the t-C horizon was difficult to trace, especially in the north. In the northern working area (east of Jasmund) the slightly northeastward dipping internal reflections of the Carboniferous are cut by the internal Zechstein reflections, thus an angular unconformity defines the top (**Fig. 5-8**).

The Carboniferous is limited basal by an angular unconformity towards the pre-Carboniferous strata, like the Devonian or Ordovician, indicated by the black lines in **Fig. 5-10**. This unconformity is also visible in **Fig. 5-8**, above the tilted block in the centre of the section. The internal reflection pattern of the upper Devonian is dipping towards the NW but is horizontally covered by the Carboniferous successions. The horizon of the top of the Carboniferous equals the horizons *R/PZ* (Base of Rotliegend; Petrobaltic working group) and *ru* or *80* of the SASO project (see **Appendix C**).

Surface grid

The Carboniferous deposits dominate in the southeastern part of the working area (**Fig. 5-9**). East of Jasmund the horizon strikes out. A further small outcrop is around the well H9 1/87, close the NJF. At this northern rim the horizon reaches the uppermost position with 850 ms. The horizon is dipping until 1950 ms in a southeastern direction. Along the AKFZ a huge step of up to 1000 ms can be detected. At the Gryfice Block the Carboniferous varies between depths of 1600 to 2900 ms, whereas the deepest position is located in the centre between the AKFZ and the deep fault of the Gryfice Fault Zone. At the Wolin Block the t-C is displaced by the NJF and other NW striking faults of the WFS. A further NE striking flexure was detected due to the morphology and within individual NW striking seismic sections in the southeastern part of the Arkona Block. Similar to the t-O_{aw} horizon, it might have intersected the Wiek Fault and shows therefore a sinistral strike slip character.

5.1.6 Permian

5.1.6.1 Rotliegend

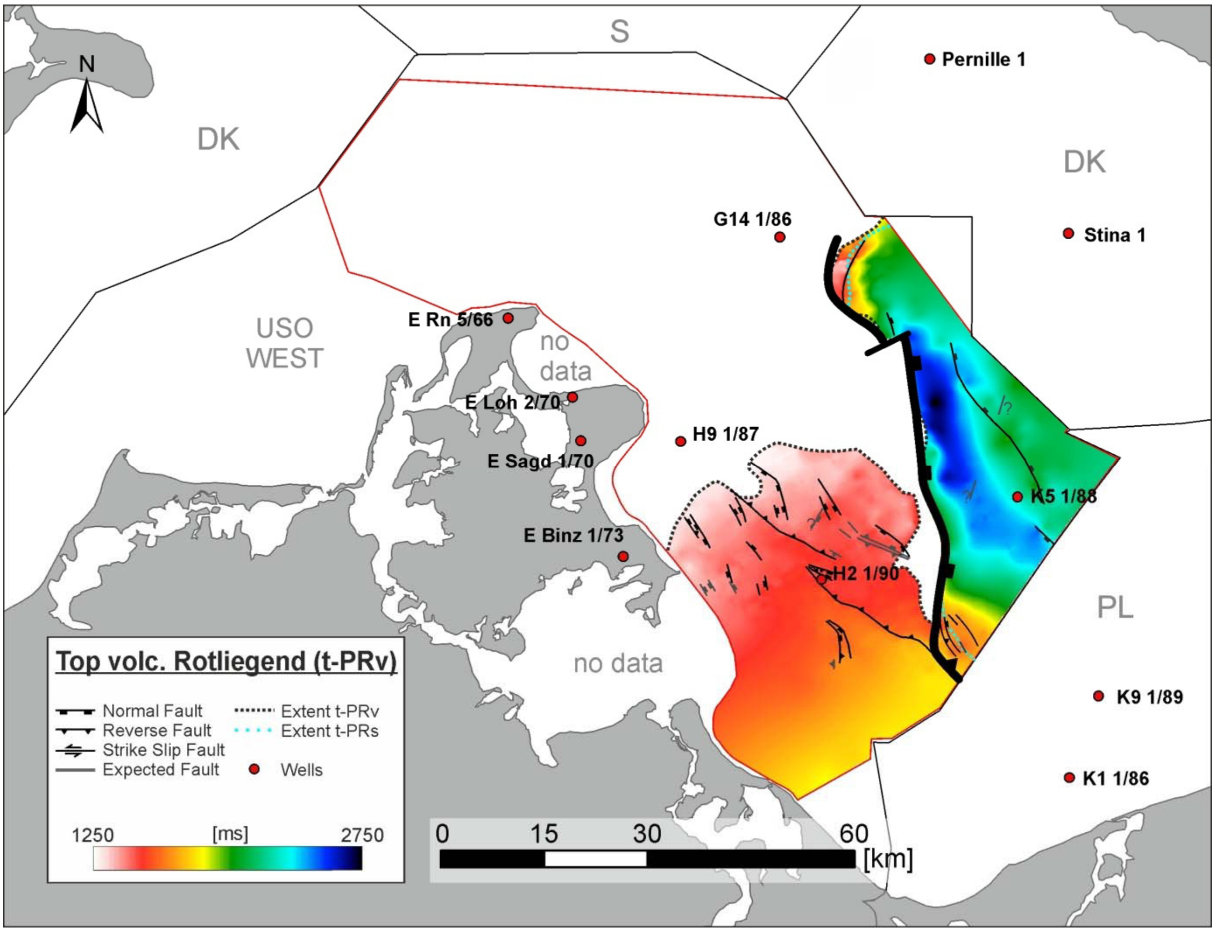


Fig. 5-11: Time-structure map of the Top effusive Rotliegend within the area of USO East.

Tab. 5-6: Borehole information for the Rotliegend, based on Hoth et al. (1993) for the onshore wells and on the original well description tables (Diener et al. 1988, 1989, Lück et al. 1987 and Pupunyn et al. 1990) for the offshore wells.

Well name	Strata	Top MD in [m] – drilled depth from surface (onshore) or rotary table (offshore)	Thickness [m]
G14 1/86 Sea level 29.5m Sea floor 68.1m	**not defined (see Keuper)**		
Rn 5/66 [25.2m asl]	**missing**	-	-
Loh 2/70 [19.6m asl]	**missing**	-	-
Sagd 1/70 [24.9m asl]	**missing**	-	-
H9 1/87 Sea level 27.4m Sea floor 46.6m	**missing**	-	-
Binz 1/73 [15.2m asl]	Lower Rotliegend (sediment), Lower Rotliegend (volcanite)	1409 1437	28 119.5
H2 1/90 Sea level 27m Sea floor 42m	Lower Rotliegend (volcanite)	2070	61.5
K5 1/88 Sea level 29.2m Sea floor 41m	Upper Rotliegend (sediment), Lower Rotliegend (volcanite)	2942 3387	445 214

The Rotliegend strata can be divided into a sedimentary Upper Rotliegend and a volcanic Lower Rotliegend. Whereas both sequences have been drilled in the wells K5 1/88 and Binz 1/73, in H2 1/90 only the Lower, volcanic one was detected (**Tab. 5-6**). Within all other wells of the working area the Rotliegend is missing.

Horizons t-PRv and t-PRs

The volcanic Rotliegend (**t-PRv**) has predominantly one high amplitude and is picked in the peak below the Z2 reflector (the lowermost trough of the Zechstein double reflection at the Wolin Block). At the Gryfice Block the Rotliegend successions are much thicker and both the volcanic Rotliegend successions and the sedimentary Rotliegend are drilled. This **t-PRs** horizon is characterised by a similar amplitude to t-PRv. Both horizons (t-PRs and t-PRv) are difficult to trace due to a subparallel to divergent or even hummocky reflection pattern. Comparing to the horizons of the SASO I report the top Rotliegend horizon equals horizon *z* or *70*. The Petrobaltic working group defined the *X1* reflector as the Base of the Zechstein or top of the Rotliegend, which is dominantly the top of the sedimentary Rotliegend (see **Appendix C**).

Surface Grid

Within the eastern German sea territory the conglomeratic and sandstone deposits of the Upper Rotliegend are restricted to the Gryfice block, with a depth range from 1525 to 2400 ms. From its deepest point in the centre of this block, the sed. Rotliegend is rising towards the NW ad SW. The volcanic strata of the Lower Rotliegend can be mapped at the Gryfice and Wolin blocks, showing a depth range between 1250 and 2750 ms (**Fig. 5-11**). It crops out east of Mönchgut (Rügen), about 15 km SE of the well H9 1/87. At the Gryfice Block it reaches further to the north. Whereas the Rotliegend is almost slightly dipping towards the SE at the Wolin Block, the AKFZ is forming a major displacement, especially in the central part, with up to a 1500 ms vertical offset. East of the AKFZ the t-Rv horizon varies between 2750 ms at its deepest point and 1400 ms in the NW or 1500 ms in the SW. Therefore, the AKFZ forms a normal displacement in its central part, where it strikes NNW-SSE, but a reverse displacement in the north and south of the working area, where the strike direction of the AKFZ changes in a more north-northeastern or respectively south-southeastern direction. The Rotliegend horizons are furthermore displaced by one fault plane of the Gryfice Fault zone, east of the AKFZ. West of the AKFZ, the WFZ dominantly normal faulted the t-Rv. However, the NJF reverse faulted the strata. Here the eastern sub-block is elevated against the western one.

5.1.6.2 Zechstein

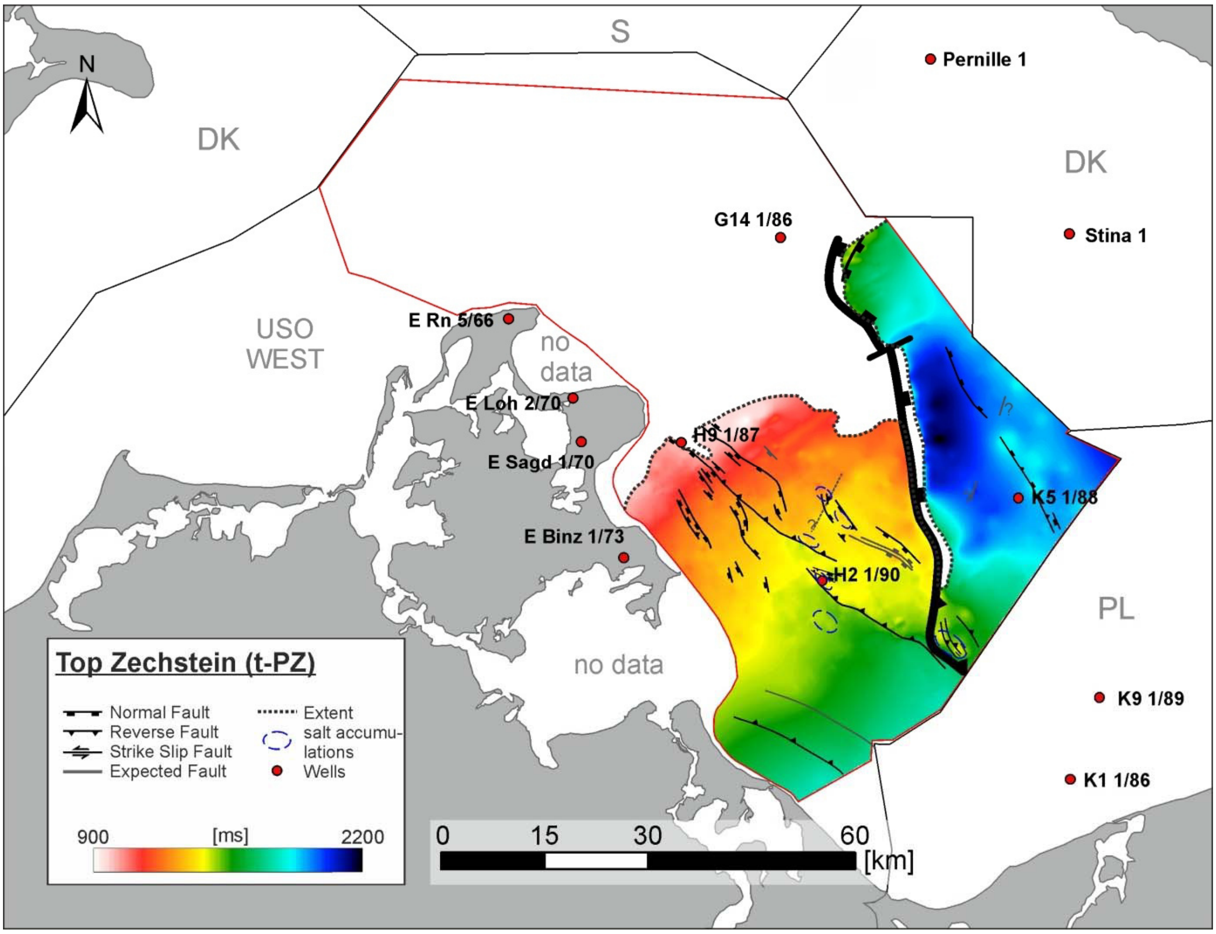


Fig. 5-12: Time-structure map of the Top Zechstein within the area of USO East.

Tab. 5-7: Borehole information for the Zechstein based on HOTH et al. (1993) for the onshore wells and on the original well description tables (DIENER et al. 1988, 1989, LÜCK et al. 1987 and PUPUNYN et al. 1990) for the offshore wells.

Well name	Strata	Top Measured depth in [m] from the surface (onshore) or rotary table (offshore)	Thickness [m]
G14 1/86 Sea level 29.5m Sea floor 68.1m	**not defined (see Keuper)**	-	-
Rn 5/66 [25.2m asl]	**missing**	-	-
Loh 2/70 [19.6m asl]	**missing**	-	-
Sagd 1/70 [24.9m asl]	**missing**	-	-
H9 1/87 Sea level 27.4m Sea floor 46.6m	**missing**	-	-
Binz 1/73 [15.2m asl]	**missing**	-	-
H2 1/90 Sea level 27m Sea floor 42m	Übergangsfolge (corresponding to the Lower Buntsandstein – well description PUPUNYN et al. 1990) Z4-Z1	1893	177
K5 1/88 Sea level 29.2m Sea floor 41m	Übergsangsfolge(corresponding to the Lower Bunts. – well description DIENER et al. 1989) Z4-Z1, Kupferschiefer	2607.5	334.5

Zechstein deposits have only be drilled within the southern offshore wells H2 1/90 and K5 1/88 (**Tab. 5-7**, **Fig. 5-12**). Whereas the basal Kupferschiefer had only been found in the well K5 1/88, both cores incorporated complete sequences of Z1 to Z4 (Werra-, Staßfurt-, Leine-, Aller-sequence) and a so called "Übergangsfolge". The latter was assigned to the Zechstein Ohre Formation by the geophysical log H2 1/90 (**Fig. 5-13**). However, in Germany this succession is defined as part of the "Bröckelschiefer" and thus, referred to as the Lower Buntsandstein. The Zechstein sequences Z5 to Z7 (Ohre, Friesland, Fulda) are missing in all four German offshore wells. Comparing the wells, the thickness of the Zechstein is increasing from the Wolin Block towards the Gryfice Block by approximately 150 m.

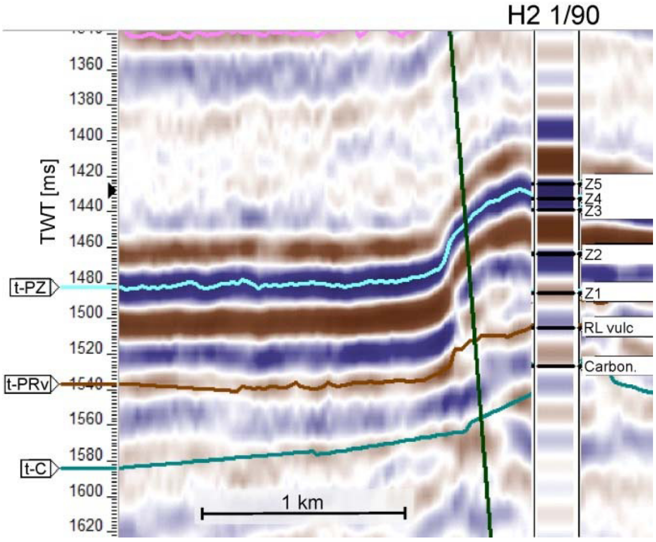


Fig. 5-13: Well tie of the well H2 1/88 and a seismic section (for location see **Fig. 5-2**). VE≈1, assuming an average velocity of 3000 m/s, positive amplitudes are brown (peaks), negative amplitudes are blue (troughs).

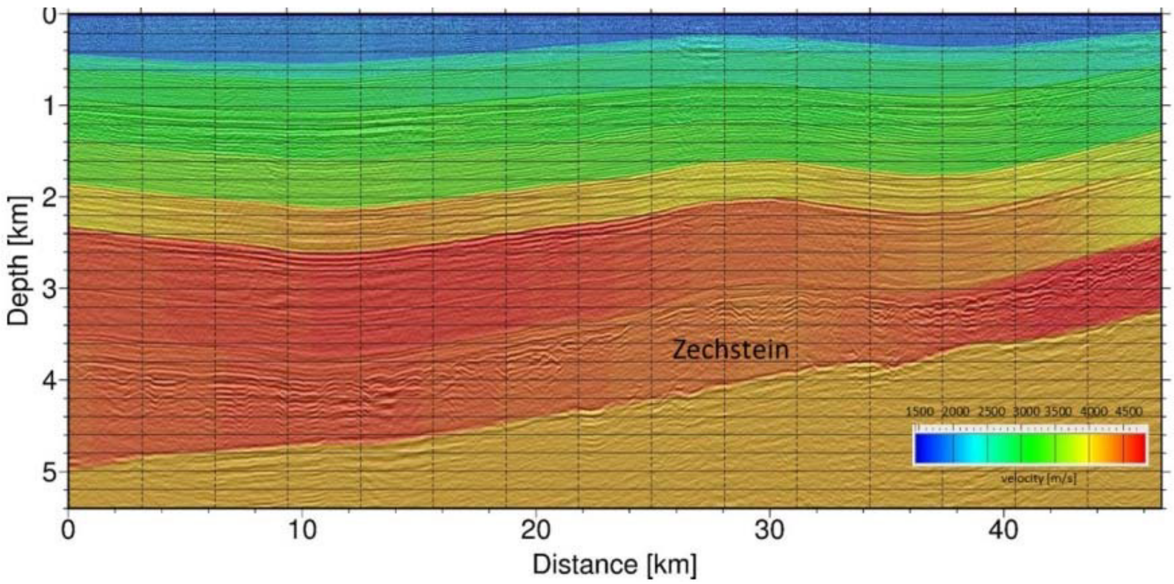


Fig. 5-14: Velocity depth distribution across a profile west of Rügen in the Mecklenburg Bay (NOACK et al. 2018), illustrating a varying velocity of the Zechstein strata with a general velocity decrease towards the Base of Zechstein successions (Pre-Zechstein is not calculated) VE≈4.

Horizon t-PZ

The top of Zechstein (**t-PZ**) is one of the most obvious horizons, due to a strong double reflection. It is characterised by a medium frequency and high amplitudes. The t-PZ horizon indicates the top of the Aller Formation (Z4) and is picked in the trough, between two strong peaks. This phase was chosen with regard to the synthetic logs of the offshore wells (**Fig. 5-13**). The recent studies of NOACK et al. (2018) show a varying interval velocity between 4400 to 4700 m/s and therefore a lateral change of velocity increase or decrease between the Buntsandstein and Zechstein (**Fig. 5-14**). Thus, regarding only the velocity distribution, there is no fixed phase (peak, indicating a velocity increase – or trough, indicating a velocity decrease) definable as t-PZ.

The second trough of the double reflection was traced as the top of the Z2-Staßfurth Formation, showing a strong amplitude as well. This latter formation is known for bearing halite successions, which were drilled by the well H2 1/88 (about 30 m thick; PUPUNYN et al. 1990). At the Wolin Block between the NJF and the AKFZ small pillow-like structures are mapped which might be formed by salt migration (**Fig. 5-12** & **Fig. 5-15**).

The reflector of the top of the Zechstein is close to the *X1* reflector of the Petrobaltic working group, respectively the *su* horizon or *horizon 60* of the SASO project (see **Appendix C**).

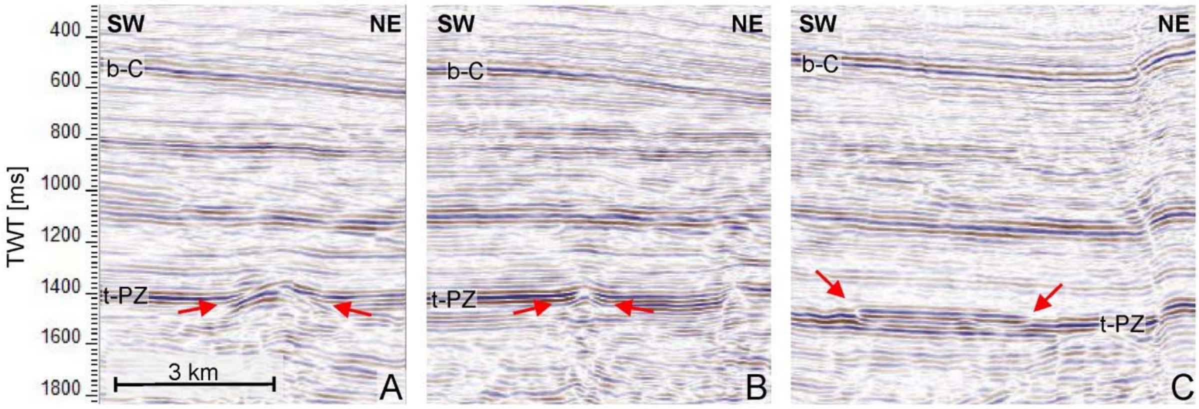


Fig. 5-15: Small salt accumulations (marked with red arrows), about 100 m exaggerated, at the Wolin Block.(For location see **Fig. 5-2**). (VE≈3, assuming an average velocity of 3000 m/s)

Surface Grid

The depth rage of the Zechstein horizons varies between 910 ms and 2210 ms (**Fig. 5-12**). The t-PZ horizon strikes out east of Jasmund and is therefore missing at the Arkona Block. At the Gryfice Block it reaches further to the north. The highest parts of the horizon can be found east of the well H9 1/87 (910 ms). In the vicinity of this well the horizon crops out. Towards the SE of the Wolin Block it dips to about 1600 ms. The horizon is reverse faulted by the NE dipping NJF, therefore the NE sub-block is elevated against the southwestern one for about 100 ms. Besides outer faults and flexures of the WFS folding the top of the Zechstein, the Wiek Fault normal faulted this horizon in the east of the Wolin Block. A major normal fault is given by the NNW striking AKFZ, with a displacement of up to 1000 ms. Only south of the working area, where the AKFZ changes its strike direction into a northwestern one, a reverse motion is indicated by the morphology (with about 1500 ms depth east of the AKFZ and 1700 ms west of the AKFZ). Therefore the deepest point of the Zechstein surface is located in the central part of the Gryfice Block. Here only a deeper fault of the Gryfice Fault Zone was active and normal faulted the t-PZ -Horizon. As described for the t-PZ horizon, small salt tectonic processes are indicated by salt dome formations in the eastern part of the Wolin Block, as they are visible in single seismic sections.

5.1.7 Triassic

The different horizons of the dominant Triassic strata should be described in detail for each epoch of the Buntsandstein, Muschelkalk and Keuper. North of the Wolin Block the interpretation was enhanced by multiples of the Cretaceous successions.

5.1.7.1 Buntsandstein

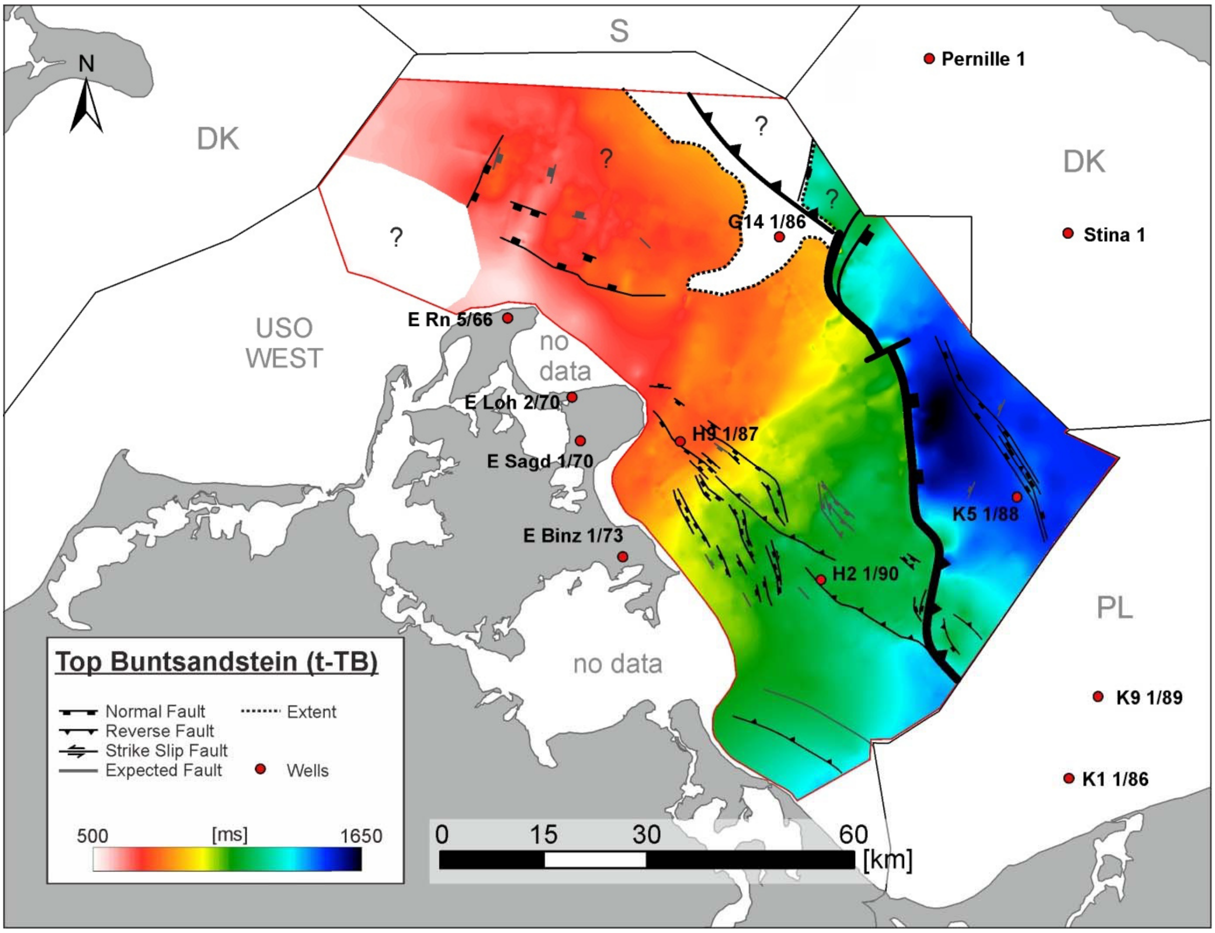


Fig. 5-16: Time-structure map of the Top Buntsandstein within the area of USO East.

Tab. 5-8: Borehole information for the Buntsandstein based on HOTH et al. (1993) for the onshore wells and on the original well description tables (DIENER et al. 1988, 1989, LÜCK et al. 1987 and PUPUNYN et al. 1990) for the offshore wells.

Well name	Strata	Top Measured depth in [m] from the surface (onshore) or rotary table (offshore)	Thickness [m]
G14 1/86 Sea level 29.5m Sea floor 68.1m	not defined (see Keuper)		
Rn 5/66 [25.2m asl]	Upper (Pelitröt-, Salinarröt sequence), Lower (Bernburg-, Nordhausen sequence)	642 700	58 20 (**78**)
Loh 2/70 [19.6m asl]	Upper (Myophorien strata, Pelitröt-, Salinarröt sequence), Middle (Solling, Volpriehausen), Lower (Bernburg, Nordhausen)	793 885 903	92 18 45 (**155**)
Sagd 1/70 [24.9m asl]	Upper (Myophorien strata, Pelitröt-, Salinarröt sequence), Middle (Solling), Lower (Bernburg, Nordhausen)	858 950 960	92 10 115 (**217**)
H9 1/87 Sea level 27.4m Sea floor 46.6m	Upper (Myophorien strata, Pelitröt-, Salinarröt-sequence); Middle (Solling-, Volprihausen-Fmt.) Lower (Bernburg-Fmt., Nordhausen-sequence)	960 1039 1147.5	79 108.5 63.5 (**251**)
Binz 1/73 [15.2m asl]	Upper (Myophorien strata, Pelitröt-, Salinarröt-sequence); Middle (Solling-, Hardegsen-, Detfurth-, Volprihausen-Fmt.) Lower (Bernburg-Formation, Nordhausen-sequence, conglomerate at the base)	1021 1127 1280	106 153 129 (**388**)

H2 1/90 Sea level 27m Sea floor 42m	Upper (Pelitröt-, Salinarröt-sequence) Middle (Solling-, Detfurth-, Volprihausen Formation) Lower (Bröckelschiefer, Nordhausen Sequence, Übergangsfolge)	1361 1480 1700	119 220 193 (**532**)
K5 1/88 Sea level 29.2m Sea floor 41m	Upper (Pelitröt-, Salinarröt-sequence) Middle (Volprihausen-Fmt.) Lower (Bernburg-Fmt., Nordhausen-sequence, Übergangsfolge)	1775 1936 2364	161 428 243.5 (**832.5**)

The succession of the Buntsandstein is subdivided into the Upper Buntsandstein with the Myophorienschichten, the Pelitröt- and Salinarröt sequences, the Middle Buntsandstein with the Solling-, Hardegsen-, Detfurth- and Volpriehausen sequences and the Lower Buntsandstein with the Bernburg- and Nordhausen sequence, Malchin-Wechselfolge, Malchin-Sandstein (Bröckelschiefer) and Übergangsfolge (Bröckelschiefer). The Buntsandstein was found within all wells of the working area, with the exception of G14 1/86 (**Tab. 5-8**). Here only the term "Permo-Triassic" is declared with no detailed information. The average thickness increases in a southeastern direction from the Arkona Block across the Wolin Block (wells H9 1/87 and H2 1/90). An enormous increase of about 300 m is detectable towards the Gryfice Block (wells H2 1/90 and K5 1/88).

Horizons t-TB, t-TBm and t-TBl

For the succession of the Buntsandstein three horizons have been traced across the Wolin and Gryfice blocks, indicating the tops of the Upper, Middle and Lower Buntsandstein. Whereas the Upper and Lower Buntsandstein are dominantly represented by sand-, mud- and limestone, the Lower Buntsandstein comprises argillaceous shales and mudstone. Therefore there is no strong acoustic impedance contrast, especially not between the Upper and Middle Buntsandstein. At the Arkona Block the successions of the Buntsandstein could not be differentiated. Therefore only the general top of the Buntsandstein was traced.

The horizon of the Upper Buntsandstein (**t-TB**) determinates the prominent Muschelkalk reflections downwards. Thus, it runs subparallel to this, mostly in the next trough, below the triple reflection of the Muschelkalk. The top of the Upper Buntsandstein correlates with the horizon *M3* (Petrobaltic working group). The horizon of the Middle Buntsandstein (**t-TBm**) is given by a peak. Due to a hummocky to subparallel internal reflection pattern the t-TBm horizon has a diffuse appearance and is hard to trace. For correlation the comparison with the horizons above and below were necessary. Additionally the correlation in the northeast of the well H9 1/87 was very complicated because of faults of the WFS. This horizon correlates with the horizon *so* or *58* of the SASO Project. The Lower Buntsandstein (**t-TBl**) has a higher amplitude than the t-TBm, shows a parallel reflection pattern and is traced in the peak. This peak is dominantly located between the two strongest troughs above the top of Zechstein (2-3 peaks above the top of Zechstein). The top of the Lower Buntsandstein equals the horizon *TP1* (Petrobaltic working group, top of the Bernburg Formation) and is close to the horizon *sm* (SASO project, see **Appendix C**). The horizons t-TBm and t-TBl are only picked across the Wolin and Gryfice blocks. The Buntsandstein successions are much thicker at the Gryfice Block and, due to a parallel internal reflection pattern, well traceable.

Surface Grid

The presented horizon of the Upper Buntsandstein (**Fig. 5-16**) runs almost subparallel to the Muschelkalk and has nearly the same extension. The depth range reaches from 510 ms to 1700 ms. The shallowest area is located close to Wittow (north of Rügen) where the reflector was traceable along a few seismic sections. Most of the seismic sections in the NE of Rügen have only 1 sec penetration depth and are too shallow. The horizon is dipping from the NW of the Arkona Block to the SE of the Wolin Block. The horizon is normal faulted at the AKFZ. East of this fault zone the horizon is much thicker, but also up to 500 ms deeper. From its deepest point in the central part of the Gryfice Block it is rising towards the NW and SW, where the AKFZ changes its strike direction from a north-northwestern one into a NE or SE one. At the Gryfice Block, the t-TB is deformed by the NE striking Gryfice Fault Zone. The NW to NNW striking faults and flexures of the WFS and especially the NJF are intersecting the horizon across the Wolin Block. Furthermore two NE striking flexures are detected east and west of the NJF. At the Arkona Block, again the NNE striking Hiddensee Fault and other, especially NNW/NW striking faults and flexures, displace the horizon. The t-TB strikes out south of the Skurup Fault, forming a tongue-like outcrop toward the SW. Towards the working area of USO West, the Buntsandstein is also present, but could not be detected, due to the shallow seismic data.

The surface of the Middle and Lower Buntsandstein are not gridded. The depth of the Middle Buntsandstein ranges from 780 ms to 1840 ms the horizon itself runs subparallel to the two reflectors below (top Upper Buntsandstein and top Muschelkalk). The highest parts can also be found at the northern border of the basin, west of the Samtens peninsula, where a few kilometres northward the horizon is cropping out. The deepest parts are bound to the AKFZ where the reflector is dipping very fast. The morphology of the Lower Buntsandstein equals the Middle Buntsandstein. Its depth ranges from 830 ms to 2040 ms. The lateral extension of the Lower Buntsandstein correlates with the horizon of the Middle Buntsandstein. It crops out in the east of the Wiek Fault System also along the border of the basin. Next to the well H9 1/87 a correlation was also very difficult.

5.1.7.2 Muschelkalk

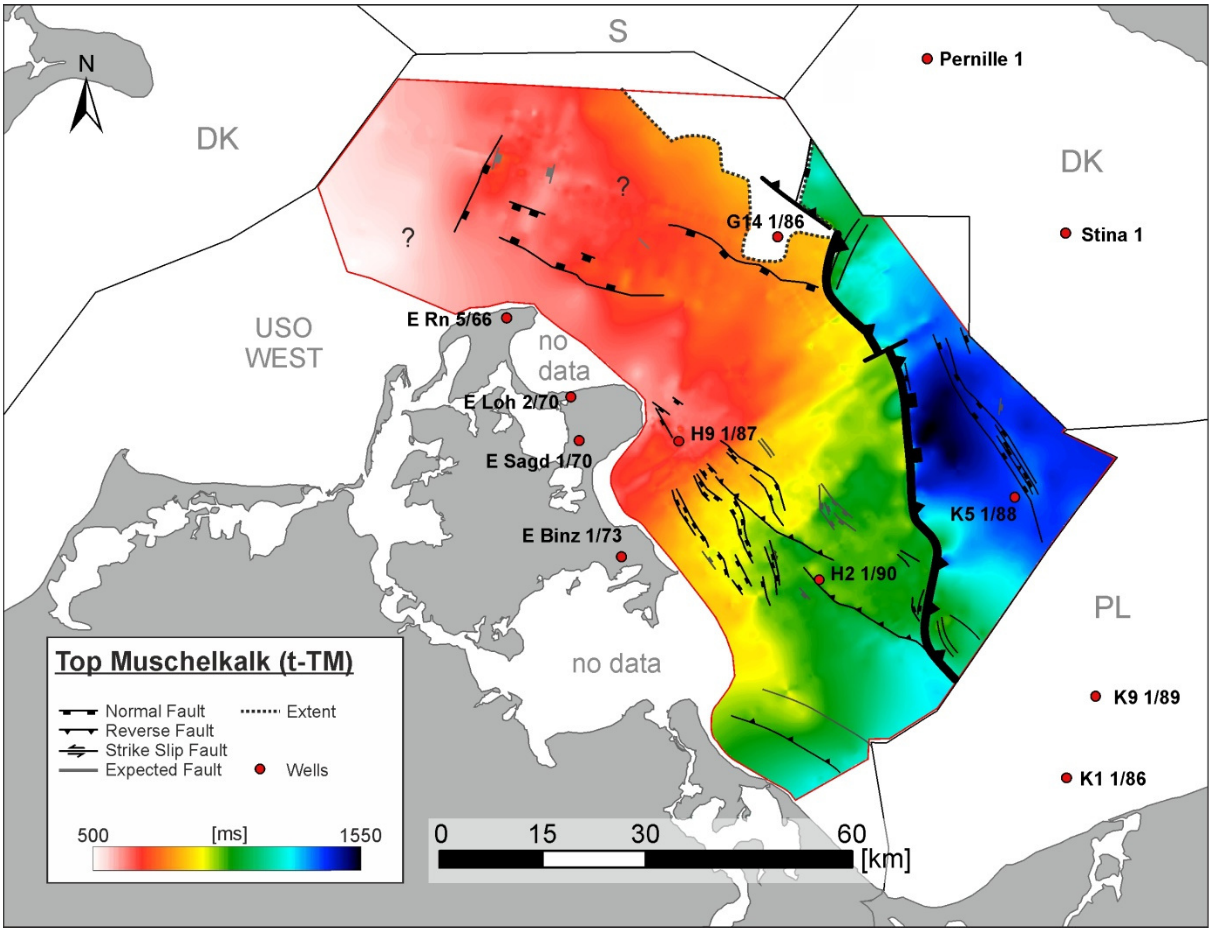


Fig. 5-17: Time-structure map of the Top Muschelkalk within the area of USO East.

Tab. 5-9: Borehole information for the Muschelkalk based on HOTH et al. (1993) for the onshore wells and on the original well description tables (DIENER et al. 1988, 1989, LÜCK et al. 1987 and PUPUNYN et al. 1990) for the offshore wells, in this case without further stratigraphic informations.

Well name	Strata	Top Measured depth in [m] from the surface (onshore) or rotary table (offshore)	Thickness [m]
G14 1/86 Sea level 29.5m Sea floor 68.1m	not defined (see Keuper)		
Rn 5/66 [25.2m asl]	missing	-	-
Loh 2/70 [19.6m asl]	**Middle** (Hauptmuschelkalk sequence, Anhydrit sequence) and **Lower** (Wellenkalk sequence)	650 747	97 46 (**143**)
Sagd 1/70 [24.9m asl]	**Middle** (Hauptmuschelkalk sequence, Anhydrit sequence) and **Lower** (Wellenkalk sequence)	718 798	80 60 (**140**)
H9 1/87 Sea level 27.4m Sea floor 46.6m	**Upper**, **Middle** and **Lower** (not further defined)	798 851.5 901	53,5 49,5 59 (**162**)
Binz 1/73 [15.2m asl]	**Upper** (Ceratiten strata and Trochitenkalk), **Middle** (Rotmergel-Knauernkalk-Zone, Dolomit-Anhydrit-Wechsel seq.) and **Lower** (Wellenkalk seq.)	841 903 960	62 57 61 (**180**)
H2 1/90 Sea level 27m Sea floor 42m	**Upper**, **Middle** and **Lower** (not further defined)	1243 1267.5 1313.5	24.5 46 47.5 (**118**)
K5 1/88 Sea level 29.2m Sea floor 41m	**Upper**, **Middle** and **Lower** (not further defined)	1671.5 1699.5 1739	28 39.5 36 (**103.5**)

The Muschelkalk stratigraphy of Mecklenburg-Western Pomerania is divided into the Upper Muschelkalk with the Ceratiten layer and the Trochitenkalk, the Middle Muschelkalk and the Lower Muschelkalk with Anhydrit- and Wellenkalk sequences. The marine deposits of the Muschelkalk (mostly marl- and limestone) are found in nearly all wells of the working area with a thickness between 103,5-180 m (Loh 2/70, Sag 1/70, H9 1/87, Binz 1/73, H2 1/90, K5 1/88; **Tab. 5-9**). The approximately complete sequence was drilled in the mentioned wells, while Sagd 1/70 revealed only the Middle and Lower Muschelkalk. Within the northern well G14 1/86 the Muschelkalk is not defined, as it is named “Permo-Triassic”, whereas in the well Rn 5/66 the Muschelkalk strata is completely missing. Similar to the Keuper, the succession is thickening towards the south. There are no enormous thickness differences between the western Arkona/Wolin blocks and the eastern Gryfice Block.

Horizon t-TM

The internal reflections of the Muschelkalk are nicely visible, at least at the Wolin Block, due to a triple reflection with a strong amplitude and a low frequency. The **t-TM** can be correlated along the uppermost trough or zero-crossing of this triple-reflection. At the Gryfice Block it varies between triple or double reflection and at the Arkona Block a double reflection is dominating. The t-TM horizon equals the horizon *TM* of the Petrobaltic working group and the *k* horizon (or horizon *55*) of the SASO project (see **Appendix C**).

Surface Grid

The top of the Muschelkalk was traced across almost the complete working area with a depth rage between 460 and 1570 ms (**Fig. 5-17**). Similar to the top of the Keuper, the highest areas can be found at the western part of the Arkona Block (460 ms) and east of Jasmund, where an elongated high descends in a southerly direction (630-910 ms). The horizon dips further to the south of the Wolin Block. The top of the Muschelkalk is normal faulted at the AKFZ, which resulted in a step like displacement of up to 500 ms. Therefore the deepest point can be found at the Gryfice Block, NW of the well K5 1/88 with 1570 ms. West of this point, on the other side of the AKFZ, the Muschelkalk has a depth of 1000 ms. Towards the north and south (east of the AKFZ), the horizon is rising for 300-400 ms. The Muschelkalk crops out close to the well G14 1/86 at the Arkona Block. The t-TM horizon is intersected by the AKFZ, the Gryfice Fault Zone, but also the WFS at the Wolin Block, in particular east of the NJF, the Muschelkalk is lifted. At the Arkona Block, the NNE striking Hiddensee Fault, but also the WNW striking Jütland-Møn Fault and others further south of the block, show normal displacements at this horizon.

5.1.7.3 Keuper

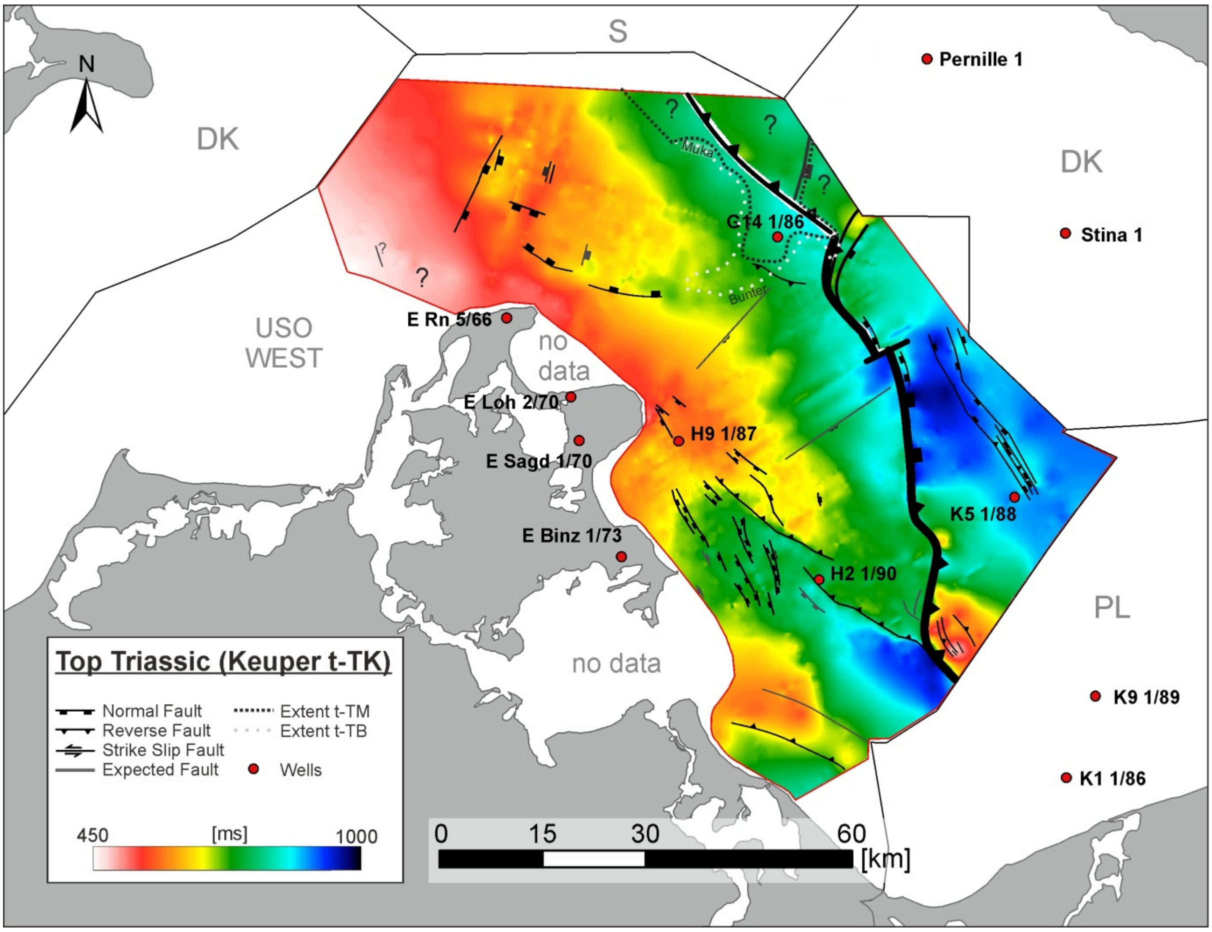


Fig. 5-18: Time-structure map of the Top Triassic/ Top Keuper within the area of USO East. The northern extension of the top Muschelkalk and top Buntsandstein is marked by the dotted lines.

Tab. 5-10: Borehole information for the Keuper based on HOTH et al. (1993) for the onshore wells and on the original well description tables (DIENER et al. 1988, 1989, LÜCK et al. 1987 and PUPUNYN et al. 1990) for the offshore wells.

Well name	Strata	Top Measured depth in [m] from the surface (onshore) or rotary table (offshore)	Thickness [m]
G14 1/86 Sea level 29.5m Sea floor 68.1m	Triassic to Permian (alternating silt – and sandstone, coloured); SCHLÜTER et al. (1997a): Permo-Triassic	1170	28.5
Rn 5/66 [25.2m asl]	missing	-	-
Loh 2/70 [19.6m asl]	Upper Keuper (siltstone)	637	13
Sagd 1/70 [24.9m asl]	**Upper Keuper** – Rätkeuper (Triletes-, Contorta-, Postera strata), **Middle Keuper** (Dolomitmergelkeuper)	651 696	45 22 (**67**)
H9 1/87 Sea level 27.4m Sea floor 46.6m	**Upper Keuper** (Rät) **Middle Keuper** (Steinmergelkeuper, Postera strata, Basisdolomit with old Cimmerian hiatus), **Lower Keuper**	715 758 782	43 27 47 (**117**)
Binz 1/73 [15.2m asl]	**Upper Keuper** (Rät), **Middle Keuper** (Steinmergelkeuper, Karbonatbank) **Lower Keuper** (Grenzdolomit, Upper Lettenkeuper? Lower Lettenkeuper)	736 762 783	26 21 58 (**105**)
H2 1/90 Sea level 27m Sea floor 42m	**Upper Keuper**, **Middle Keuper** (Steinmergelkeuper with old Cimmerian hiatus, Upper Gipskeuper, Schilfsandstein, Lower Gipskeuper) **Lower Keuper** (Grenzdolomit, Upper Lettenkeuper, Lower Lettenkohlensandstein)	906,5 985 1200	78.5 215 43 (**336.5**)

K5 1/88 Sea level 29.2m Sea floor 41m	**Upper Keuper**, **Middle Keuper** (Steinmergelkeuper, Upper Gipskeuper, Schilfsandstein, Lower Gipskeuper) **Lower Keuper** (Grenzdolomit, Upper Lettenkeuper, Lower Lettenkohlensandstein)	1025 1177 1553	152 376 118.5 (**646.5**)

The Keuper successions of Mecklenburg-Western Pomerania can be divided into the Upper Keuper/ Rätkeuper with the Triletis-, Contorta-, Postera-strata; the Middle Keuper with the Steinmergel- and Gipskeuper and the Lower Keuper/ Lettenkeuper. The wells in the middle and southern part of the working area (H9 1/87, Binz 1/73, H2 1/90, K5 1/88) drilled these successions completely (**Tab. 5-10**). In the northern direction the well Sagd 1/70 revealed only the Upper and Middle Keuper, Loh 2/70 just the Upper Keuper and Rn 5/66 no strata. Additionally the well G14 1/86 contained Permo-Triassic sediments which could not be dated in detail. The thickness increases from north to south and doubles within the Gryfice Block (K5 1/88) east of the AKFZ. The Keuper sediments are composed of interchanging mud-, silt-, sand and marlstone, with interbedded gypsium, anhydrite and dolomite layers.

Horizon t-TK

Regarding the four offshore wells, the trough of the wiggle was traced (in areas with thicker successions the amplitudes were also picked at the zero crossing event). The picked reflector is characterised by lower amplitudes and low frequencies, which are similar to the properties of the Lower Jurassic. Therefore the **t-TK** horizon is difficult to interpolate. The horizon picked for the top of the Keuper equals the horizon *JL*, defined by the Petrobaltic working group, and the horizon *ju* or *50* of the SASO I report (all Base Jurassic, see **Appendix C**). Especially in the lower part of the Keuper sequence the internal reflection pattern is dominantly a hummocky to subparallel one. Four stronger parallel reflections are typical within the upper part of the Keuper and are nicely visible close to the wells K5 1/88 and H2 1/90. The t-TK horizon is located above those four reflections. South of the Wolin Block depressions or erosional discordances can be mapped, which will be discussed below. A strong thickening of the strata from the Wolin Block towards the Gryfice Block can also be recognised in the wells and seismic profiles. Therefore, additional strong parallel reflections are visible in the upper and lower parts of the strata east of the AKFZ. At the Arkona Block the t-TK horizon was traced (in the trough) as the top of the Permo-Triassic, according to the well G14 1/86.

Surface Grid

The Keuper covers the whole working area with a depth range from 450 ms to 1000 ms (**Fig. 5-18**). The highest positions within the working area can be found in the NW of the Arkona Block (450 ms), east of Jasmund and close to NJF (590 ms) as well as at the NW striking anticline, SW of the Wolin Block (590 ms). East of the AKFZ anticlines are visible in the north of the AKFZ and Skurup Fault (600 ms), as well as south next to the bounding AKFZ (490 ms). The deepest positions are recognised south of the Wolin Block (970 ms) and west of the central part of the AKFZ (1000 ms). The successions are generally thickening from the Arkona Block in the north across the Wolin Block in the south, but also from north to south across the Gryfice Block, east of the AKFZ. At the latter the successions are even thicker, than west of the AKFZ. Like the Lower Jurassic successions, the Keuper strata is affected by the prominent AKFZ, dominantly by the southern flexures and the NJF of the WFS at the Wolin Block. The Gryfice Faults east of the AKFZ, as well as the NNE and WNW striking faults at the Arkona Block modified the t-TK horizon.

With regard to the four offshore wells internal channel structures have been detected north of Usedom Island, in a small area of about 850 km² (**Fig. 5-19**). **Fig. 5-20** shows a typical seismic section crossing this area. Thus, with regard to the well H2 1/90, the strong double reflection at the top is interpreted as an evaporitic succession of the Exter and Arnstadt Formations. The reflection below represents the Old Cimmerian Unconformity T7 or D4 Unconformity (STG 2016), separating the Arnstadt and Weser Formations. Although, the Middle and Lower Keuper cannot be distinguished, a wavy internal reflector can be attributed to the top of the Grabfeld Formation, indicating the erosional base of the Stuttgart Formation, also known as D2 Unconformity (see **Fig. 3-16**; FRANZ et al. 2018*b*). Its appearance is enhanced by an angular discordance towards the horizontal reflection pattern of the Stuttgart Formation above. Moreover, the frequency differentiates, especially in the NE of the seismic section, between the low frequency, carbonate bearing Grabfeld Formation and the higher frequency, carbonate-free Stuttgart Formation. The morphology of the base of the Stuttgart Formation suggests two depressions west of the NJF and in the NE of the seismic section. Both are separated by an exposed sedimentary body with a steeply dipping southwestern and a shallowly dipping northeastern slope. Its elevation is enhanced by tectonic processes during the Late Cretaceous, when the NW-SE striking NJF was reactivated as a reverse fault (SEIDEL et al. 2018). Thereby the block NE of the fault was lifted about 80 m (assuming a constant interval velocity of 2000 m/s). **Fig. 5-20 (down)** illustrates the structural situation with a flattened base of Keuper, showing a 6 km broad and 100 m incised channel SW of the NJF and an about 200 m incised channel NW of the NJF. **Fig. 5-19** shows the gridded surface of the Grabfeld Formation. Its depth varies between about 1250 m and 600 m. The SE trending channel (SW of the NJF), widened and deepened towards the south. The northwestern about 8 km broad channel is bordered by the AKFZ to the NE. Both channels are assumed as northern prolongation of palaeoriver systems, known from wells on Usedom Island, developing in the fluviatile regime of the Stuttgart Formation. The position and formation was at least partly controlled by pre- and synsedimentary tectonic movements (FRANZ et al. 2018*a,b*)

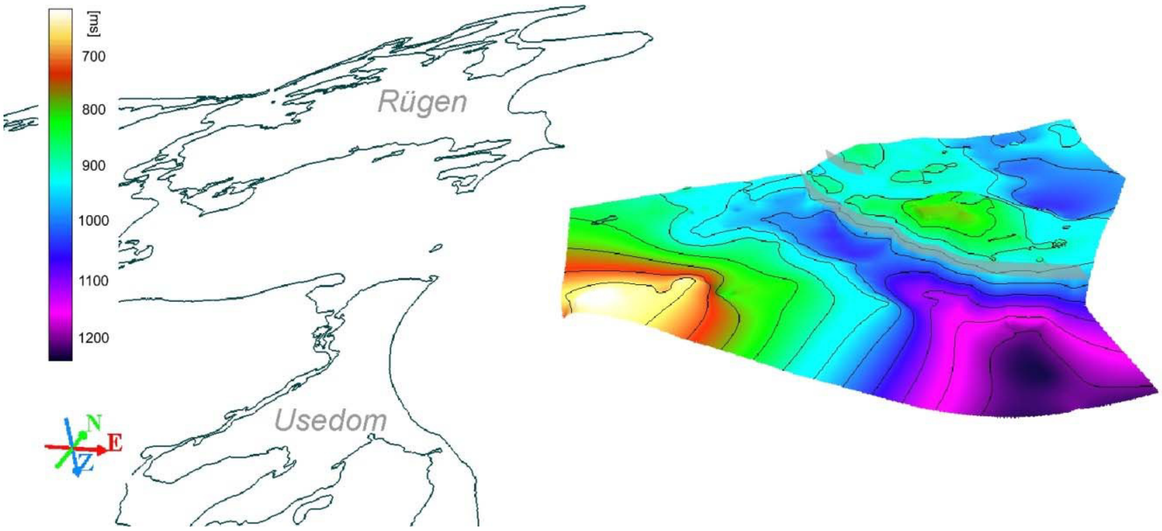


Fig. 5-19: 3D view on the surface of the Grabfeld Formation. Its morphology indicates an elongated depression, SW of the NJF (grey, transparent plane).

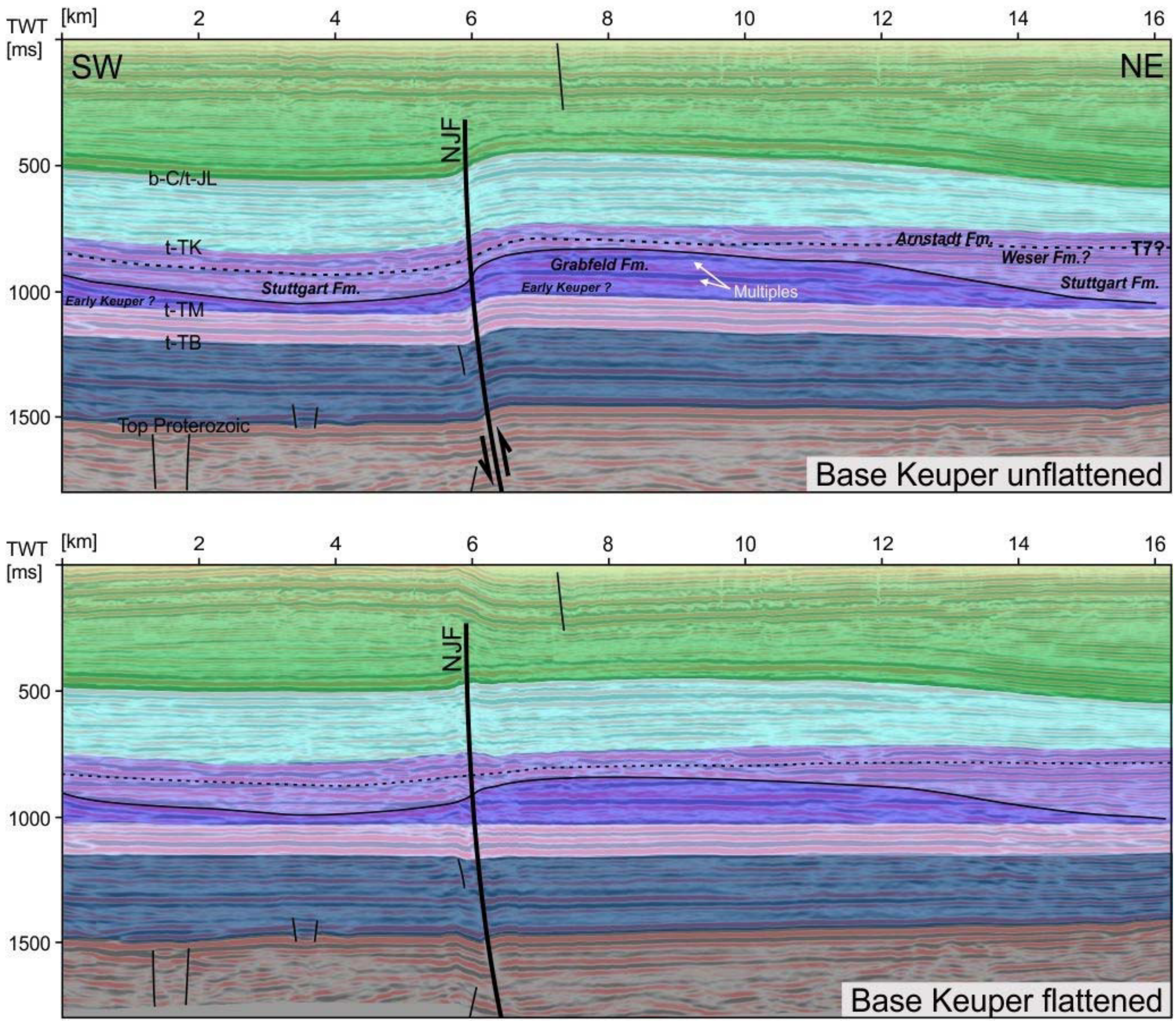


Fig. 5-20: Seismic section crossing the internal Keuper channel (for location see **Fig. 5-2**; according to FRANZ et al. 2018*b*). (VE≈2.5, assuming an average velocity of 3000 m/s)

5.1.8 Jurassic

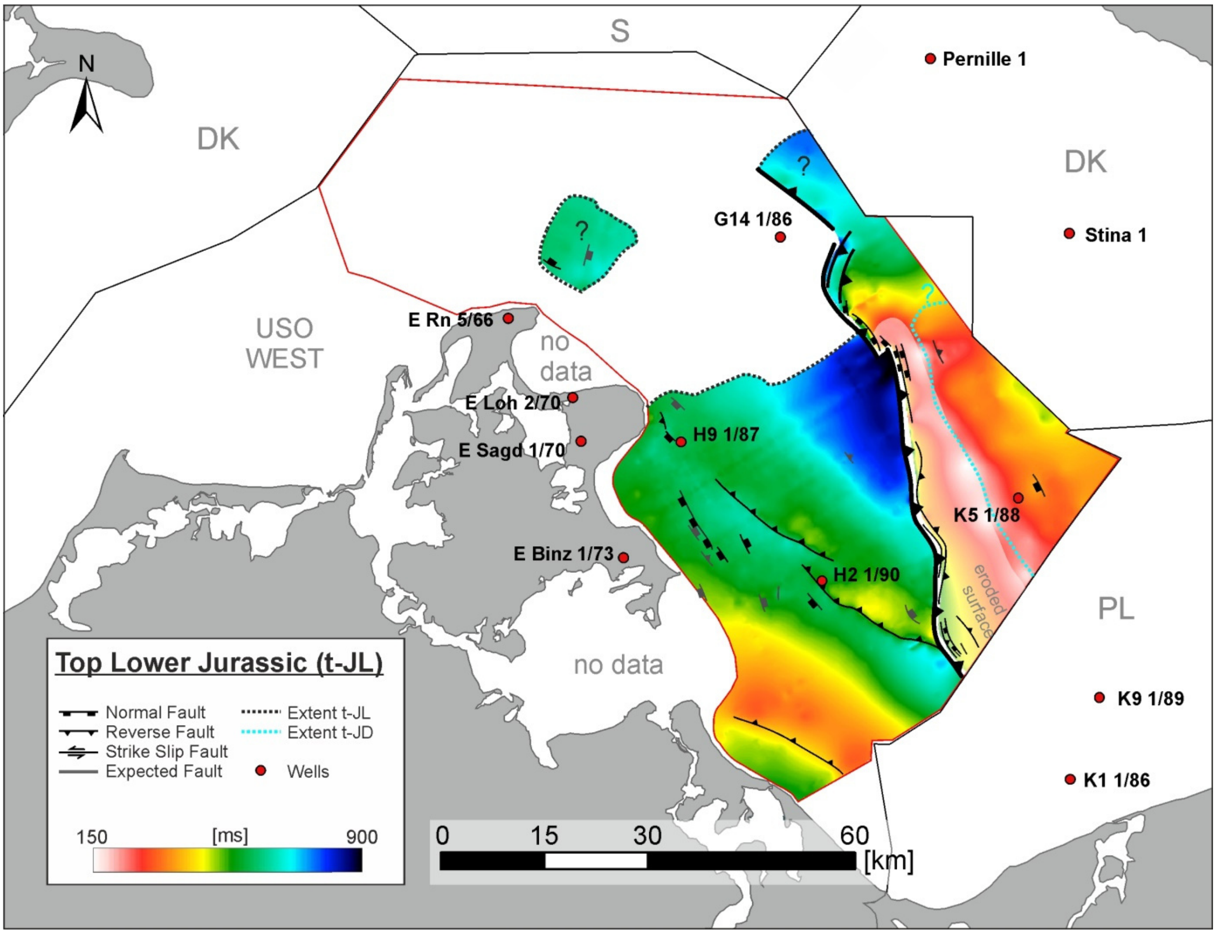


Fig. 5-21: Time-structure map of the Top Lower Jurassic within the area of USO East.

Tab. 5-11: Borehole information for the Jurassic based on HOTH et al. (1993) for the onshore wells and on the original well description tables (DIENER et al. 1988, 1989, LÜCK et al. 1987 and PUPUNYN et al. 1990) for the offshore wells.

Well name	Strata	Top Measured depth in [m] from the surface (onshore) or rotary table (offshore)	Thickness [m]
G14 1/86 Sea level 29.5m Sea floor 68.1m	Lower Cretaceous? /Lower Jurassic? (more likely Lower Cretaceous)	-	-
Rn 5/66 [25.2m asl]	missing	-	-
Loh 2/70 [19.6m asl]	missing	-	-
Sagd 1/70 [24.9m asl]	(after HOTH et al. 1993) Lower Jurassic/ Lias (Sinemur, Hettang)	615 (LJ)	36 (LJ)
H9 1/87 Sea level 27.4m Sea floor 46.6m	Lower Jurassic/ Lias (Sinemurian, Hettangian)	678	37
Binz 1/73 [15.2m asl]	Lower Jurassic (Upper Pliensbachian to Hettangian)	561	175
H2 1/90 Sea level 27m Sea floor 42m	Lower Jurassic/ Lias (Sinemurian, Hettangian)	574	332
K5 1/88 Sea level 29.2m Sea floor 41m	Middle Jurassic/ Dogger (Callovian to Toarcian) Lower Jurassic/ Lias (Toarcian to Hettangium =>complete)	258 (MJ) 487 (LJ)	229 (MJ) 538 (LJ)

Whereas no Jurassic sediments are drilled in the northern part of the working area (well G14 1/86, Rn 5/66, Loh 2/70; **Tab. 5-11**), strata of the Lower Jurassic is abundant in the south. The thickness increases from north (Sagd 1/70: 36 m) to south (H2 1/90: 332,5 m). According to well K5 1/88 Middle Jurassic sediments, with a thickness of 229 m, are present east of the AKFZ, at the Gryfice Block. The Lower Jurassic strata comprises a thickness of 538 m (K5 1/88). Therefore a hiatus can be identified covering a time span from the Early Jurassic until the Early Cretaceous (Albian) at the Wolin Block, but from the Middle Jurassic until the Albian at the Gryfice Block. The Middle Jurassic consists of partly poorly sorted sandstones and mudstones, whereas the Lower Jurassic also contains marlstone, conglomerates and remains of brown coal and plant-based fossils.

Horizons t-JD and t-JL

The upper most horizon of the Jurassic is the top of the Dogger and was picked at the peak event. It was only drilled within the well K5 1/88. Regarding the research area, the extension of the Dogger seems to be reduced to the Gryfice Block. It is characterised by an internal parallel reflection pattern, with a similar frequency and amplitudes as the Liassic strata below. Therefore a subdivision is only possible regarding the well log. The **t-JD** forms an angular unconformity towards the covering Cretaceous sediments, east of the working area. This horizon is close to the *JM* horizon of the Petrobaltic working group or the *jo* horizon (*40*) of the SASO-project.

The horizon **t-JL** represents the top of the Lias (Toarcian) and is characterised by differentiating frequency and amplitudes. A correlation is often difficult, especially in the north and northeast of the well H9 1/87. The t-JL horizon runs subparallel below the T3-4 horizon at the Wolin and Arkona blocks. At the Wolin Block it was traced in the zero-crossing event and across the Gryfice Block in the zero crossing or trough. The top of the Liassic successions are cropped in the north and west of the Gryfice Block, where the Jurassic deposits form a major anticline structure (East of the AKFZ). The t-JL horizon terminates along this outcrop with increasing deposits southward showing a parallel to divergent reflection pattern. This horizon is equal to the horizon *JD* (Petrobaltic working group) or *jm* (SASO; **Fig. 71**, see **Appendix C**).

Surface grid

The depth of the Lower Jurassic (Lias) varies between 160 ms and 970 ms (**Fig. 5-21**), whereas the horizon appears to run subparallel with the top of the Lower Cretaceous. Thus the deepest parts can also be found in the NW-SE striking synclinal structure, east of the well H9 1/87. The highest parts are east of the AKFZ (160 ms), at a NW-SE striking anticline, in the east of the NJF (440 ms) and at the 20 km broad anticline south of the working area (300 ms). The top of Lower Jurassic sediments cropped out at the AKFZ, although within this elongated anticline (47 km x 14 km) Lower Jurassic sediments are still preserved. The Lower Jurassic deposits are displaced by the NE striking Gryfice Fault Zone (Gryfice Block) and some faults and flexures of the WFS at the Wolin Block. The Lower Jurassic sediments strike out east of Jasmund, across the transition from the Wolin towards the Arkona block. A small reservoir of Jurassic deposits might be preserved in a small tectonic depression 10 km-20 km NE of Arkona (Rügen).

Middle Jurassic deposits concentrate on the southeastern part of the working area, within the Gryfice Block, as they have only been found in the well K5 1/88. The top of Dogger (Middle Jurassic) reaches a depth between 135 ms to 420 ms. To the west and probably also in a northern direction, their extension is bordered by an anticline in front of the AKFZ. Due to the decreased profile density, at the Gryfice Block, the Middle Jurassic could not be traced easily towards the north.

5.1.9 Cretaceous

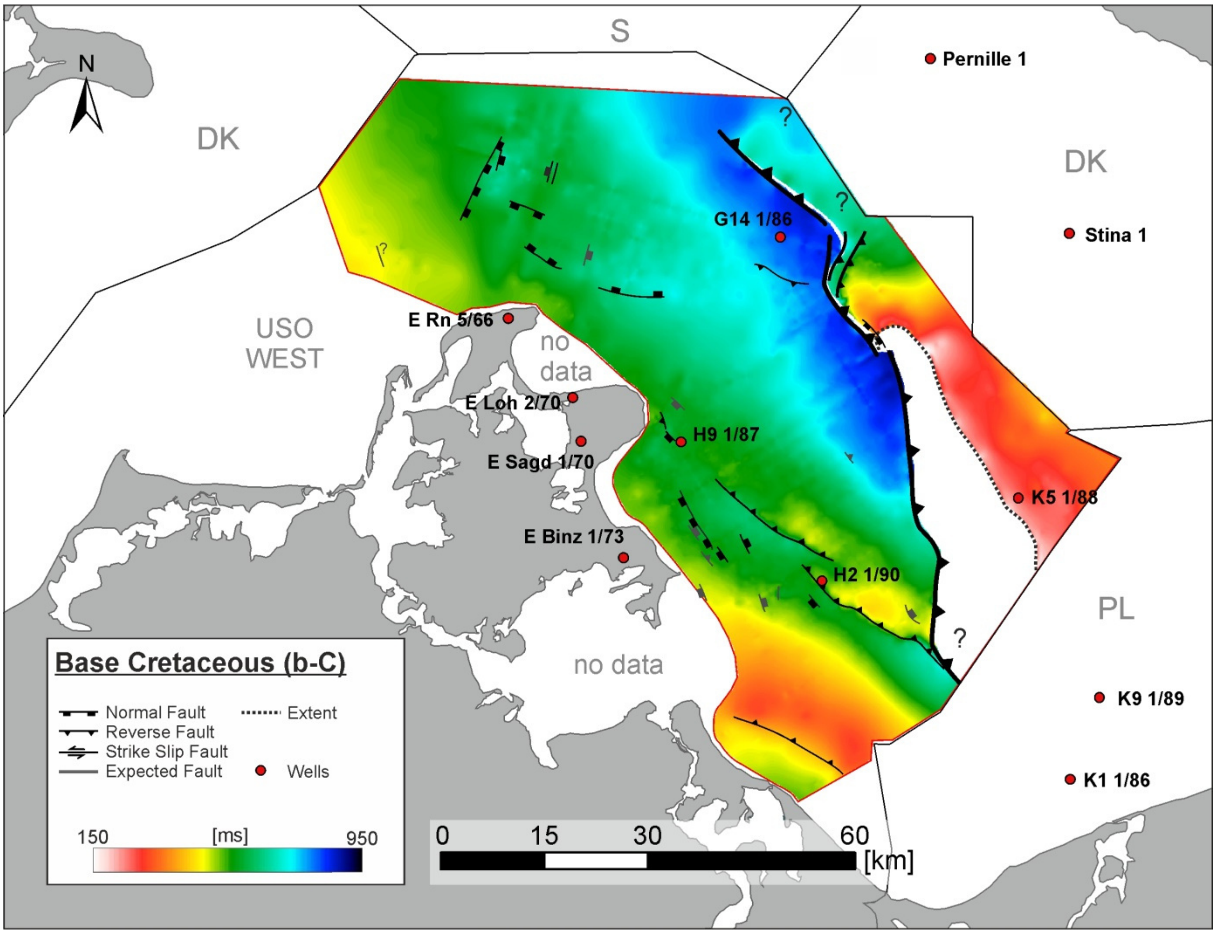


Fig. 5-22: Time-structure map of the Base Cretaceous within the area of USO East.

Tab. 5-12: Borehole information for the Cretaceous based on HOTH et al. (1993) for the onshore wells and on the original well description tables (DIENER et al. 1988, 1989, LÜCK et al. 1987 and PUPUNYN et al. 1990), for the offshore wells

Well name	Strata	Top Measured depth in [m] from the surface (onshore) or rotary table (offshore)	Thickness [m]
G14 1/86 Sea level 29.5m Sea floor 68.1m	Upper Cretaceous complete Lower Cretaceous? to Lower Jurassic?	85.8 (UC) 1143.5 (LC)	1057.7 26.5
Rn 5/66 [25.2m asl]	Upper Cretaceous complete, Lower Cretaceous (Albian)	77 632	555 10
Loh 2/70 [19.6m asl]	Upper (Maastrichtian to Cenomanian), Lower (Albian)	59 627	568 10
Sagd 1/70 [24.9m asl]	Upper Cretaceous complete, Lower Cretaceous (Albian)	72 609	537 6
H9 1/87 Sea level 27.4m Sea floor 46.6m	Upper Cretaceous complete, Lower Cretaceous (Albian)	109 669,5	560,5 8,5
Binz 1/73 [15.2m asl]	Upper Cretaceous complete, Lower Cretaceous (Albian)	41 554	513 7
H2 1/90 Sea level 27m Sea floor 42m	Upper Cretaceous complete, Lower Cretaceous (Albian)	72 570	498 4
K5 1/88 Sea level 29.2m Sea floor 41m	Upper Cretaceous (Lower Coniacian to Turonian, Cenomanian), Lower Cretaceous (Albian)	76 254	178 4

The complete successions of the Upper Cretaceous, thus the Maastrichtian to Cenomanian, are represented in the eastern and northern working area of USO East, west of the AKFZ (H2 1/90, Binz 1/73, H9 1/87, Sagd 1/70, Sagd 3/63, Loh 2/70, Rn 5/66, G14 1/86; **Tab. 5-12**). East of the AKFZ, only the Lower Coniacian until Cenomanian are drilled (Well K5 1/88). The Upper Cretaceous is composed of limestone, also known as the typical chalk formations (cliffs of Rügen), interbedded by sandstones, marlstones and flintstones as well as a huge amount of fossils.

The Lower Cretaceous is represented by thin deposits of Albian sediments, such as marlstone or lime- and sandstone. Its thickness varies between 4-10 m. It was deposited after a hiatus. Thus Cretaceous sediments cover Lower Jurassic deposits west of the AKFZ, Middle Jurassic deposits east of the AKFZ and Permo-Triassic sediments at the Arkona Block.

Horizons b-C and t-Cc

The Cretaceous succession is characterised by a generally parallel reflection pattern. As the uppermost reflector the **"Top Cenomanian" (t-Cc)** has been picked. The lowermost reflectors of the Cretaceous are clearly identifiable due to a very strong double reflection with a low frequency and a strong amplitude. Thereby the upper peak has been picked as t-Cc. This horizon was traced across almost the entire working area and is positioned above the Petrobaltic horizon *B2* (Base Cenomanian, Upper Cretaceous) or the SASO horizon *kro*, see **Fig. 4-4**. The Cretaceous succession strikes out in a NNW-SSE striking area of up to 20 km width, east of the AKFZ.

Due to the thin Lower Cretaceous deposits (4-10m), the "Top Lower Cretaceous" is located within the trough below t-Cc, thus, the **"Base Cretaceous" (b-C)** is given by the following “Zero crossing” point of the wiggle (at least at the Wolin Block). However, due to a wavelength of 20 to 30 ms or 20 to 30 m (assuming an average velocity of 2000 m/s for the Cretaceous), the reflector allows no accurately correlation. The "**b-C**" equals partly the Top of the Lower Jurassic at the Wolin Block; the Top of the Middle Jurassic at the Gryfice Block (traced in the peak of amplitude) and the Top of the Permo-Triassic at the Arkona Block (traced in the trough or zero crossing of the amplitude). The abbreviation "**b-C**" indicates transgression phases which formed discordances between the Hauterivian to the Albian (T3, according to EEG; Goethel 2016) and the Berriasian to the Valanginian (T4, according to EEG; Goethel 2016). A differentiation between those two discordances was not possible. Comparing to the horizons of the SASO I report, the "**b-C**" horizon is located between horizon *38* (base Upper Cretaceous) and horizon *40* (base Upper Jurassic, see **Appendix C**).

Surface grid

The "Base Cretaceous" horizon covers almost the entire working area, apart from a NNW-SSE striking outcrop area of about 45 km x 20 km size, east of the AKFZ, which is widening further in a southeastern direction towards Poland (**Fig. 5-22**). The depth of this horizon varies between 140 ms and 900 ms. Particularly west of the AKFZ, this horizon shows a general deepening trend from SW to NE. The highest areas are located SW of the Arkona High (450 ms), south of the Wolin Block (300 ms) and close to the outcrop area at the Gryfice Block (200 ms). The deepest point (900 ms) can be detected in a NNW-SSE striking, elongated depression, south of the Skurup Fault and west of the AKFZ. This synclinal structure has flat dipping borders towards the SW, but is sharply intersected from the elevated Gryfice Block by the AKFZ and Skurup Fault.

The Cretaceous successions are strongly elevated at the Gryfice Block. The highest differences reach up to 700 ms east of Jasmund, at the AKFZ. From this point towards the SSE, the Cretaceous successions are partly missing and Jurassic strata is covered by Quaternary deposits. Besides the AKFZ and the Skurup Fault, the Base of the Cretaceous (“**b-C**” horizon) is dislocated by further faults and flexures. Most prominent are the NNE striking Hiddensee Fault, the WNW trending Arkona Fault and single faults of the Wiek Fault System like the NW striking NJF. Additionally, further south, east of the Greifswalder Bodden, a NW striking, 20 km broad and 300 ms elevated anticline structure is visible.

5.2 Major tectonic structures at the Arkona, Wolin and Gryfice blocks

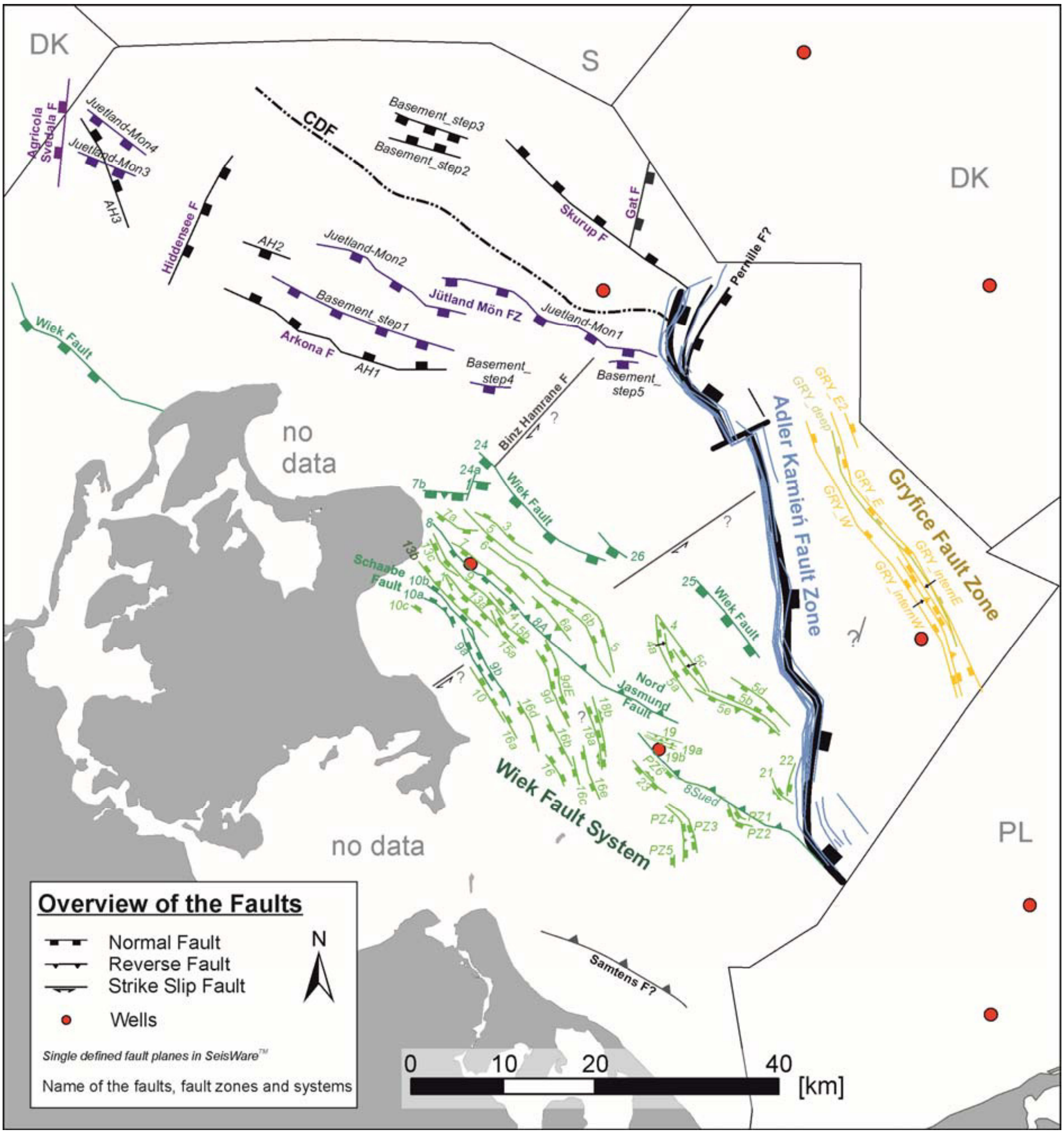


Fig. 5-23: Fault inventory within the area of USO East. The single fault planes have been mapped and summarised as Fault zones and systems. Therefore each fault plane was defined (cursive labels; see **Appendix D** and **E**) and characterised.

The working area is enormously block-faulted (**Fig. 5-1**). Thus, the tectonic structures like fault systems, but also strike out lineaments or "velocity pull down" zones will be separately discussed for the single blocks of the Arkona High north of Rügen, the Wolin Block east of Rügen and the Gryfice Block east of the German offshore area. A comprehensive table can be found in **Appendix E**, defining the character of every fault and flexure (regarding fault zones and systems, the youngest and oldest unit which is evolved, age, reactivation processes, displacement character, as well as strike and dip direction).

The terms "fault (plane)", "fault zone" and "fault system" have to be regarded. A "fault" means a single fault plane, whereas a "fault zone" defines a group of several single fault planes or flexures which strike subparallel to each other and are formed by the same stress system. The according fault planes might have different dip directions. The whole fault zone might be reactivated at later stages, with the TTZ and STZ as typical transregional examples. According to FOSSEN (2010) the width of this zone has to be small, relative to its length. A "fault system" is a complex structure of different fault zones or faults which formed in several phases and where faults have been reactivated or formed at different stages. The fault system outlining the European Cenozoic Rift System is a prime example. It comprises about nine fault zones forming the individual grabens, such as the Upper Rhine Graben.

The designations of the tectonic features (blocks and faults) within the USO research area are based dominantly on different publications. Only a few were identified by the author. Thus, **Tab. 5-13** provides an overview, from which sources the labels are adopted from. Although the earliest publications were attempted to be referred to, it cannot be guaranteed that there are no older quotations. Similar overviews for more structural elements in the vicinity of the working area are given by VEJBÆK & BRITZE (1994), LASSEN & THYBO (2012) and FRANKE (2018). In some cases, like the Wiek Fault, diverse other names existed during the past, therefore those names are also listed here.

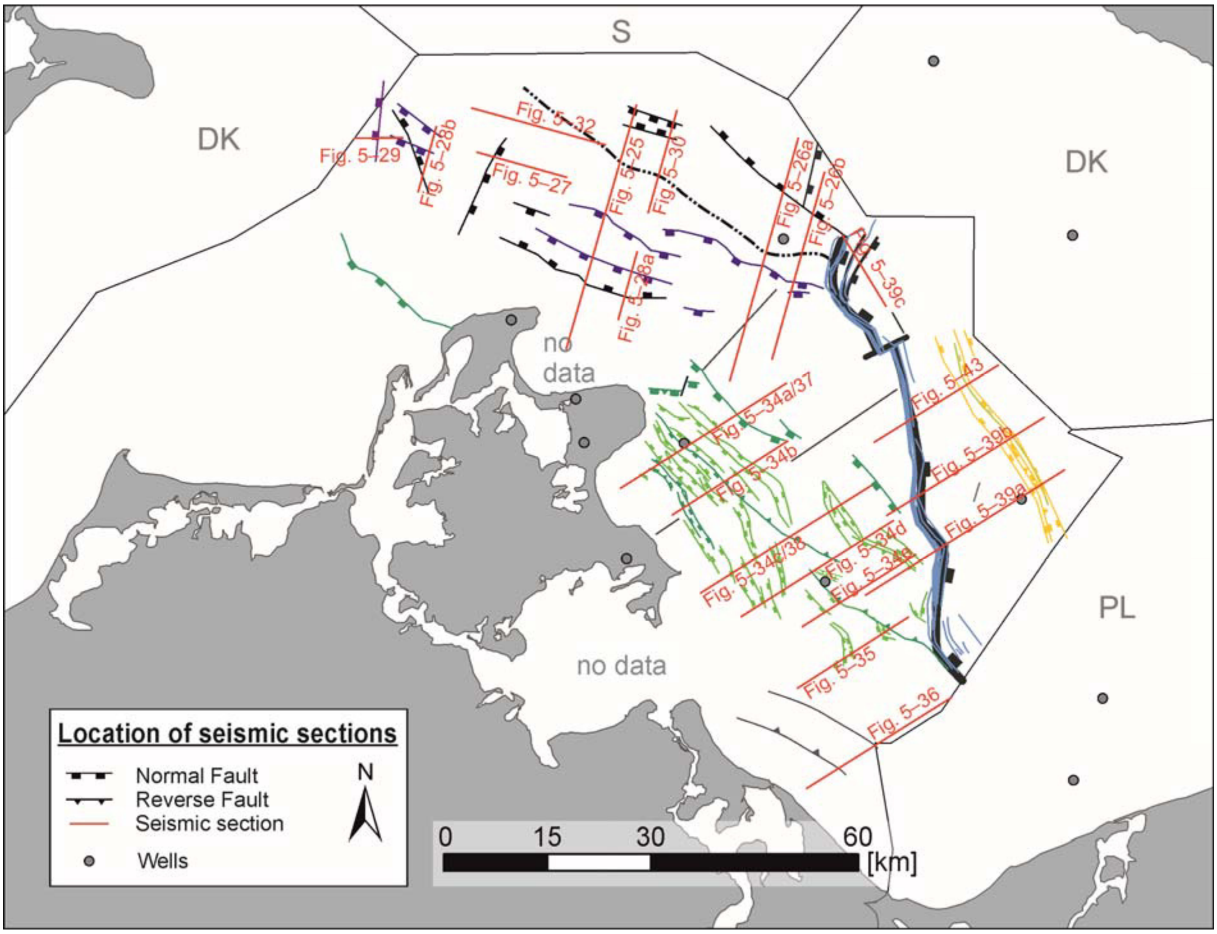


Fig. 5-24: Location of the presented seismic sections (marked red) showing the individual fault planes (see **Fig. 5-23**).

Tab. 5-13: References for single tectonic elements in the working area and its vicinity.

Structural element	Other Denomination	Source
Adler-Kamień Fault Zone	Nord Adler-Kamień Störung	SCHLÜTER et al. (1997*b*) SEIFERT et al. (1993)
Agricola-Svedala Fault	Agricola Fault Øresund-Agricola-Svedala Fault	SEIFERT et al. (1993) THOMAS et al. (1993) HERRIG (2004)
Agricola Fault Zone		MAYER et al. (2000)
Arkona Block		FRANKE (2018), SCHLÜTER et al. (1997*b*)
Arkona High	Nordrügen (North Rügen) Block/ Scholle/ Schwelle/ Swell	ALBRECHT (1967) *In* FRANKE (2018) KURRAT (1974), FRANKE & HOFFMANN (1988)
Arkona Fault		**NEW – SEIDEL et al. (2018)**
Gat Fault		GRAVERSEN (2004)
Gryfice Fault Zone		**NEW – SEIDEL et al. (2018)**
Gryfice Block	Gryfice Graben K5-Graben Oderbank-Trog	DADLEZ (1990) KIERSNOWSKI & BUNIAK (2006) KATZUNG & OBST (2004)
Hiddensee Fault	Schwerin-Vätternsee Fault Nordrügen-Skurup Fault	SCHLÜTER et al. (1998) SEIFERT et al. (1992), MAYER et al. (1994) THOMAS et al. (1993)
Jütland-Møn Fault Zone		FRANKE & HOFFMANN (1988)
Nord Jasmund Fault	Sassnitz Flexure	KURRAT (1974), FRANKE & HOFFMANN (1988) SCHLÜTER et al. (1997*a*)
Middle Rügen Block	Mittelrügen Block / Scholle Wiek-Trent Block	KURRAT (1974), FRANKE & HOFFMANN (1988) SCHLÜTER et al. (1997*b*)
Middle Devonian Old Red Rügen Basin		AEHNELT & KATZUNG (2009)
Rønne Graben		ANDERSEN et al. (1975) *In* VEJBÆK & BRITZE (1994)
Schaabe Fault		MAYER et al. (1994), PISKE et al. (1994)
Skurup Block		VEJBÆK (1985)
Skurup Fault	Nord Adler-Kamień Störung	SCHLÜTER et al. (1997b) SEIFERT et al. (1993)
South Rügen Block	Südrügen Block/ Scholle Gingst-Garz Block	KURRAT (1974), FRANKE & HOFFMANN (1988) SCHLÜTER et al. (1997b)
Tornquist-Teisseyre Zone		ZIEGLER (1990*a*)
Usedom Fault Zone		MAYER et al. (2000)
Western Pomeranian Fault System	Vorpommern Störungssystem Nordostmecklenburgisches Störungssystem	MAYER et al. (2000) WEGNER (1966)
Wiek Fault	Odense-Wiek Fault Wieker Tiefenbruch	MAYER et al. (1994), PISKE et al. (1994) KURRAT (1974), FRANKE & HOFFMANN (1988)
Wiek Fault System		**NEW – SEIDEL et al. (2018)**
Wolin Block		SCHLÜTER et al. (1997*b*)

5.2.1 Structures at the Arkona Block

The tectonic structures at the Arkona High can be separated into four groups: **(1)** basement faults, which are responsible for the stepwise southwestward dipping of Baltica; **(2)** Palaeozoic-Mesozoic faults within the accretionary wedge and the younger overlying successions; **(3)** the lineament of the CDF and **(4)** "velocity pull down" structures.

The first group of basement faults comprises the Jütland-Møn Fault Zone, the Skurup, Gat and Hiddensee faults as well as a small depression bordered by faults between the CDF and the Skurup Fault (**Fig. 5-23**& **Fig. 5-25**). The second group of Palaeo- to Mesozoic faults is formed by the Agricola-Svedala Fault and a so far unknown group of fault planes north of Rügen, named here the Arkona Fault. A few more faults have been detected within the single seismic profiles but a lateral correlation was not possible, hence, they could not be mapped as fault planes. Within the SeisWare™ project those faults are labelled as "Faults on AH".

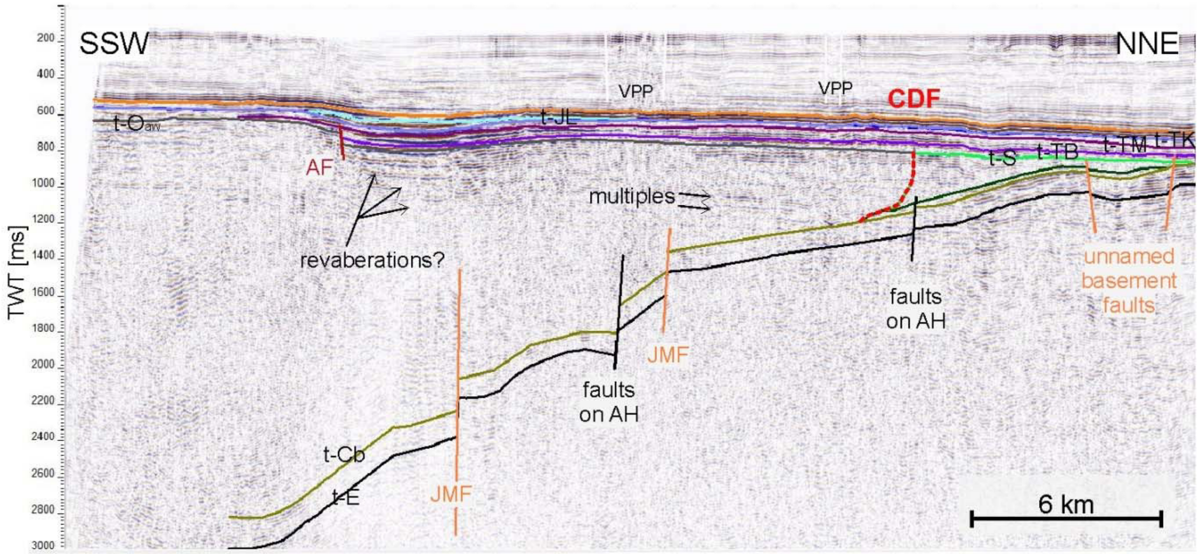


Fig. 5-25: Seismic section crossing the Arkona Block and visualizing the Caledonian Deformation Front (CDF), Velocity Pulldown Patches (VPP), the basement faults, such as the Jütland-Møn Faults (JMF), and the Palaeozoic to Mesozoic faults such as the Arkona Fault (AF). For location see **Fig. 5-24** (VE≈4, assuming an average velocity of 3000 m/s).

5.2.1.1 Jütland-Møn Fault Zone

The Jütland-Møn Fault Zone forms WNW trending steps of the southwestward dipping crust of Baltica (EEC) and its Late Proterozoic to Early-Palaeozoic cover, below the thick (500-2500 ms) thrust and folded Ordovician. The fault zone can be traced over 70 km from the Adler-Kamień Fault Zone at the Arkona Block in a WNW direction, dipping towards SSW. Seven separate single normal fault planes can be traced: Jütland-Møn 1-4, Basement_step 1, 4 & 5 (cp. **Fig. 5-23**). The locations of the overlapping Jütland-Møn 1 & 2 were already known (Franke & Hoffmann 1988, Thomas et al. 1993 and Mayer et al. 1994), although the strike character could be more precisely illustrated. Two further faults, Jütland-Møn 3 & 4, are located between the Hiddensee and Agricola-Svedala faults and form the northwestern extension. The vertical displacement reaches up to 600 ms, but decreases towards the WNW to an offset of about 100 ms.

5.2.1.2 Skurup Fault and Gat Fault

The ***Skurup Fault*** (Schlüter et al. 1997*b*) lies in the northern prolongation of the AKFZ, north of the Arkona Block. It strikes NW and dips towards the NE, contrarily to the other faults at the Arkona Block, displacing the basement. Five profiles of the deep seismic sections crossed this fault. The basement of Baltica and its Early Palaeozoic cover of Cambrian and undeformed Ordovician sediments, is displaced by normal faulting, forming an approximately 6 km broad half-graben (**Fig. 5-26**a). However, younger Silurian to Cretaceous successions, filling the half-graben and covering also its northern and southern slopes, are reversely displaced.

Comparing the five lines, the basement displacement increases from NW to SE from about 300 ms to 1800 ms. Although this vertical displacement increases smoothly in the northern lines, the line in the southeast shows suddenly an enormous offset of the basement (**Fig. 5-26**). Therefore a further fault, the Gat Fault, has to be in between, striking subparallel to the seismic sections.

West of the Skurup Fault a small depression, bordered by faults (basement_step 2 & 3, **Fig. 5-23**), is visible e.g. in **Fig. 5-25**. The faults are restricted to the basement of Baltica and its Early Palaeozoic cover. Due to a lack of data, a direct connection between this depression and the Skurup Fault was not identified.

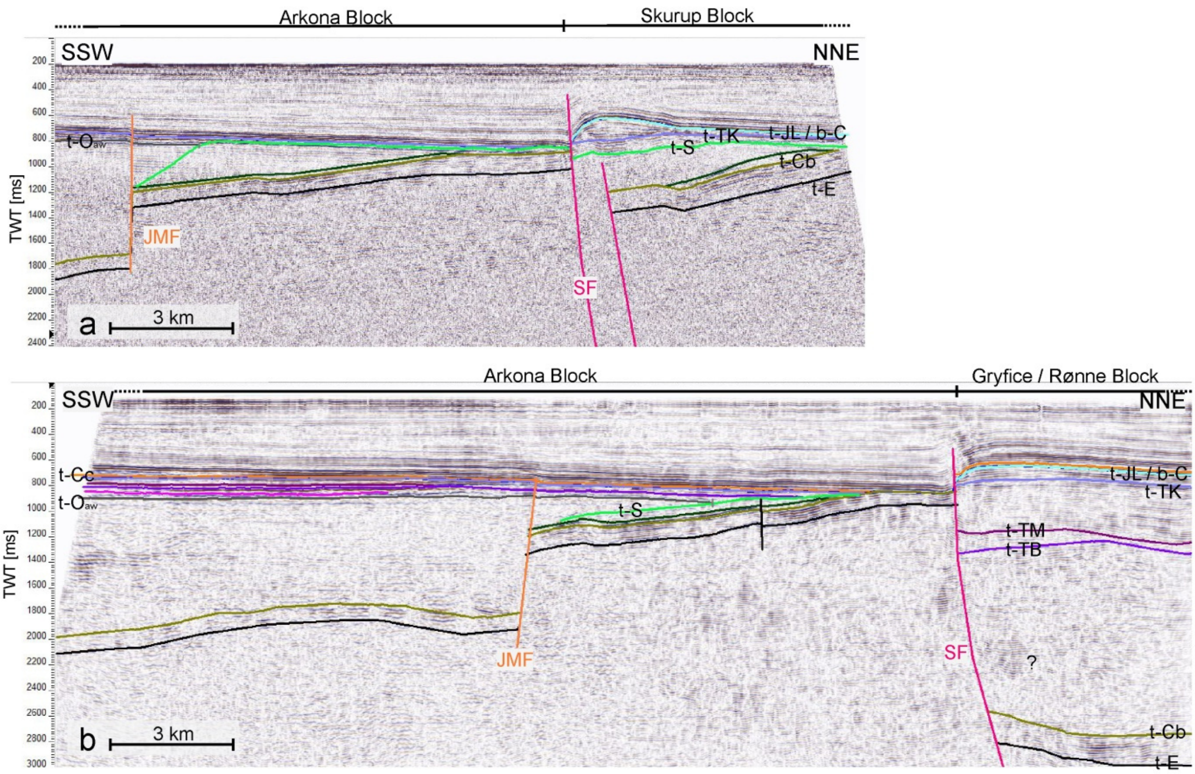


Fig. 5-26: Seismic sections crossing the SF (**a**) west of the Gat Fault and (**b**) east of the Gat Fault (for location see **Fig. 5-24**). (VE≈2, assuming an average velocity of 3000 m/s).

5.2.1.3 Hiddensee Fault

The Hiddensee Fault strikes SSW and dips towards the ESE. It limits an about 10 km broad, SSW striking half-graben to the west (**Fig. 5-23** & **Fig. 5-27**). The half-graben has its deepest point and greatest subsidence close to the Hiddensee Fault. The deep seismic line in **Fig. 5-27** shows the best image of this fault and especially the eastern extension of the half-graben. The Hiddensee Fault could be mapped in a few shallow seismic lines (cut at a depth of 1 sec) further south. It intersects the successions from the basement of Baltica as normal fault with about 500 ms vertical displacement, until the Upper Cretaceous where it acts as flexure. Different vertical offsets of the displaced horizons, indicate reactivation processes.

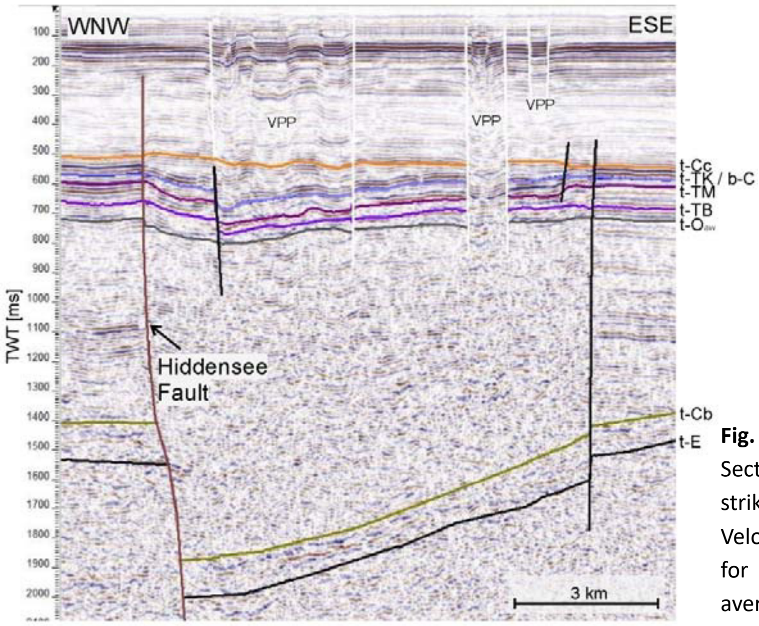


Fig. 5-27:
Section of the Line D014 crossing the NNE striking Hiddensee Fault (abbreviations: VPP – Velocity pull down patches, see Section 5.2.1.7; for location see **Fig. 5-24**). VE≈4, assuming an average velocity of 3000 m/s).

5.2.1.4 Arkona Fault

This normal fault (**Fig. 5-25**) strikes WNW-ESE and dips towards the NNE. It affects especially the Ordovician strata of the accretionary wedge and the covering Permo-Triassic deposits. There are no massive offsets (max. 100 ms), in some lines it formed as flexure. Of note are the change of amplitude and frequency at this fault line. **Fig. 5-25** and **Fig. 5-28*A*** is a good example how the amplitude enhanced and the frequency is reduced towards the north. Further to the west, this effect is not visible anymore. Instead the southwestward dipping internal reflections within the accretionary wedge are visible south of the fault. In the northwestern prolongation a further fault plane, named AH3 (**Fig. 5-23**), strikes northwestward and dips towards the NE, as it is visible in **Fig. 5-28*B***. East of the Arkona Block (**Fig. 5-25** & **Fig. 5-28*A***) the Arkona Fault borders a syncline structure to the south, while further west, in **Fig. 5-28*B***, a half-graben is terminated to the SW. Due to a lack of data between the two fault planes, the transition between both structures remains unsolved.

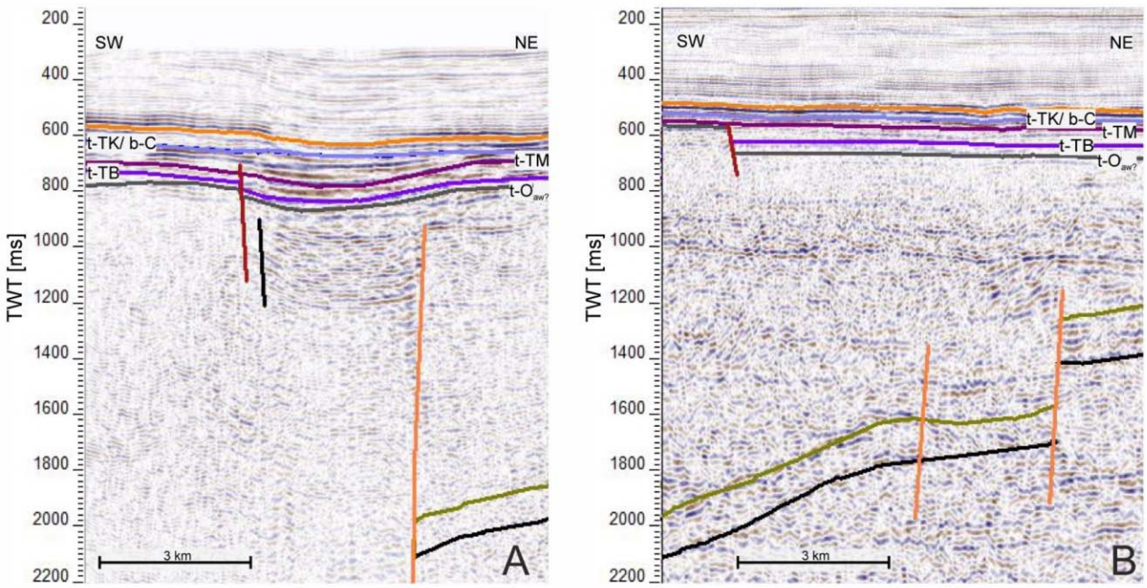


Fig. 5-28: Cross sections across the Arkona Fault (red line), displacing the deformed Ordovician and its Permo-Triassic cover. East of the Arkona Block (**A**) a syncline is terminated to the south, West of the Block (**B**) the top of the Ordovician is normal faulted, leaving an exaggerated southwestern part. Orange lines indicates fault traces of the Jütland-Møn Fault Zone (for location see **Fig. 5-24**, VE≈3.5, assuming an average velocity of 3000 m/s)

5.2.1.5 Agricola-Svedala Fault

The Agricola-Svedala Fault is located in the westernmost part of the working area and is only visible in the shallow seismic data (offered by the University of Hamburg; **Fig. 5-29**). Within those lines the fault shows an almost N-S strike direction and dips steeply towards the west. Within these shallow seismic lines the Cretaceous succession is especially affected by normal flexure causing an offset of about 25 ms.

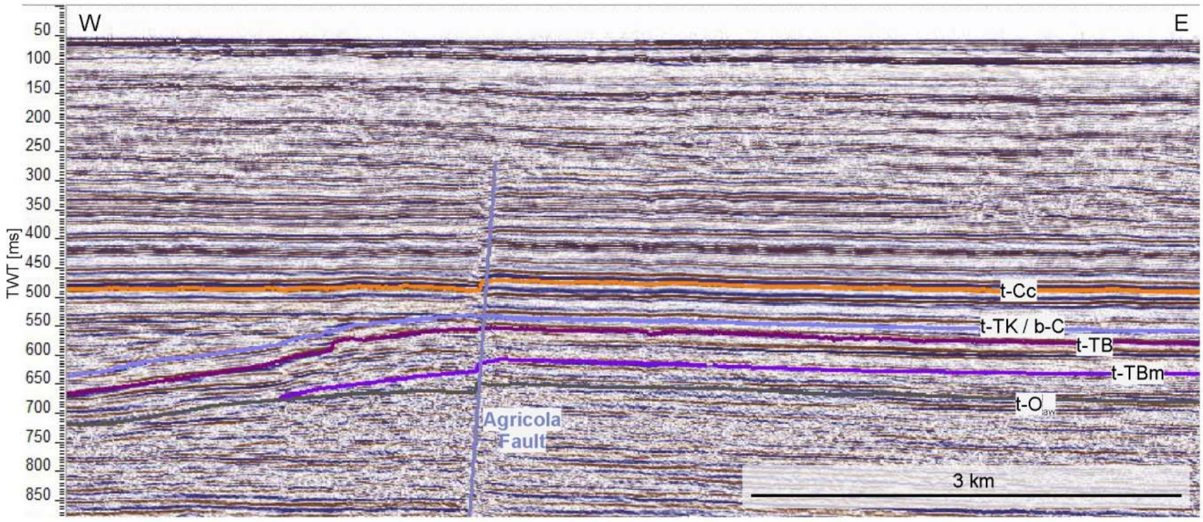


Fig. 5-29: Section of a shallow seismic line, crossing the Agricola-Svedala Fault (for location see **Fig. 5-24**, VE≈2.5, assuming an average velocity of 3000 m/s).

5.2.1.6 The Caledonian Deformation Front (CDF)

The CDF is realised by a plane or discordance marking the northernmost extension of the Caledonian accretionary wedge (**Section 3.3.1**), between the over-thrusting Ordovician sediments onto the southwestern margin of Baltica (EEC). The accretionary wedge shows a typically steep southward dipping internal reflection pattern (**Fig. 5-30**). With increasing depth the reflections range from interrupted to hummocky. However it can be differentiated from the horizontal reflection pattern of the Silurian deposits covering the basement of Baltica in the north. Furthermore the amplitudes of the deformed Ordovician are reduced, in opposite to the stronger Silurian internal reflections. The mapped lineament strikes from the AKFZ towards the NE. This angular discordance was not traceable at the Gryfice Block.

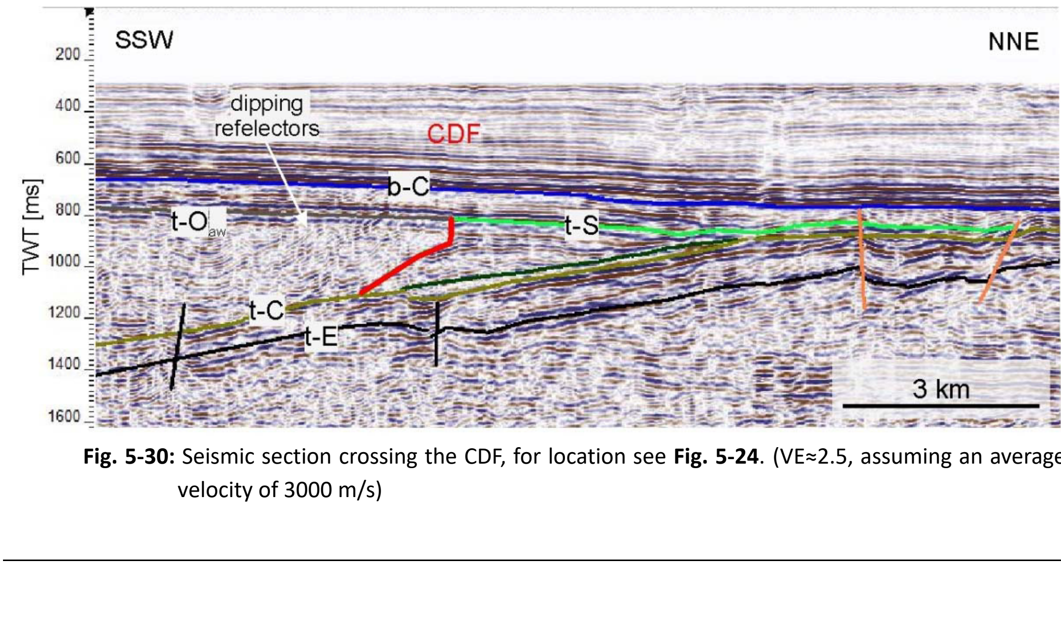


Fig. 5-30: Seismic section crossing the CDF, for location see **Fig. 5-24**. (VE≈2.5, assuming an average velocity of 3000 m/s)

5.2.1.7 Velocity Pull Down patches

Regarding the 2D seismic sections 8 km north of Wittow (Rügen) the single velocity pull down structures could be summarised in round and elongated patches. All these patches occur in a NE striking zone with a NW-SE extension of about 26 km and a SW-NE extension of 42 km. Most of the patches are located close to the half-graben at the Hiddensee Fault (**Fig. 5-31** and **Fig. 5-32**). Further smaller patches, however, exist SW of the fault and further to the east. Those structures form a wavy reflection pattern within the more or less horizontal layered Cretaceous and Triassic strata at the Arkona Block. Due to a **reduction of the seismic velocity** within those zones, the **travel time** of the seismic signal is **extended** and the **reflector** in the seismic section **pulled down**. Following the lateral progression of one reflector in the seismic section, a **polarity reversion** and a change in **amplitude** can be detected (**Fig. 5-32**). The biggest problem with those structures is their **blanking** of all information below by creating **multiples** and **reverberations**. These multiples concentrate in an area like a vertical funnel, narrowing downwards in a symmetrical but also asymmetrical way. The penetration depth is different, but might reach over 1 s (TWT) and therefore reaches until the top of the accretionary wedge at the Arkona Block.

The remarkable velocity pull down structures at the Arkona Block and the Skurup Block (Arkona Basin), have been in focus of many scientific works for the last decades and are thought to be Quaternary channels or degassing structures (Wegerdt et al. 1994, Flodén et al. 1995, Schlüter et al. 1998, Mathys et al. 2005, Thießen et al. 2006, Schmale et al. 2010, Jorgensen & Fo ssing 2011, Gülzow et al. 2014). Their interpretation will be discussed in **Section 6.2.1.2**.

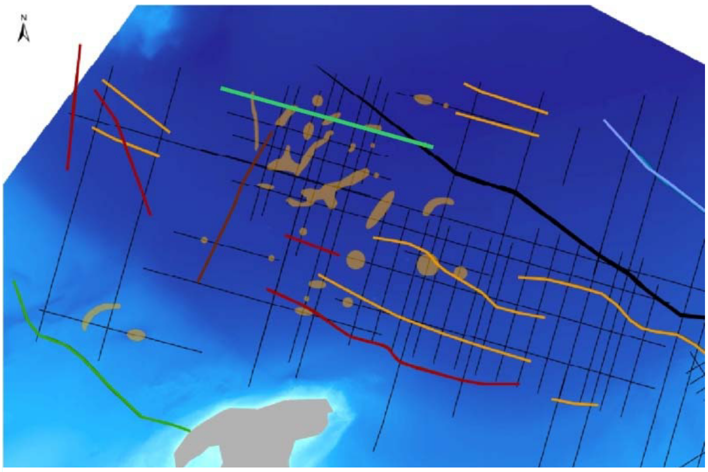


Fig. 5-31: Map of the distribution of velocity pull down patches (orange circles), shown in the seismic. The light green line shows the location of **Fig. 5-32**, faults are differentially coloured (see **Fig. 5-23**). The CDF is marked as black line.

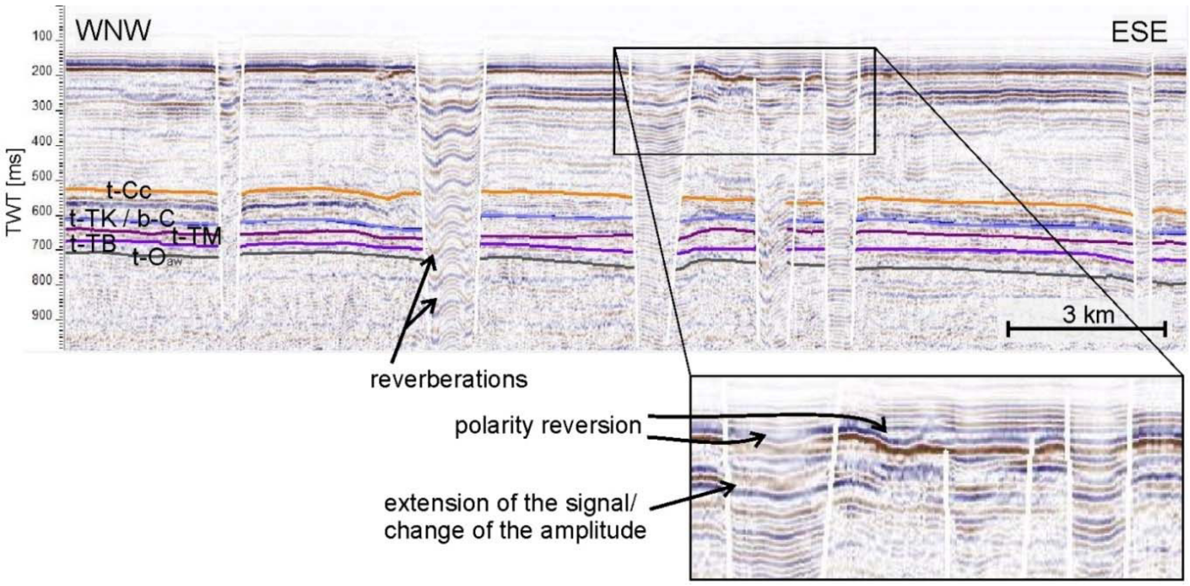


Fig. 5-32: Seismic section (near offset single channel) of crossing velocity pull down patches (for location see **Fig. 5-24** or **Fig. 5-31**, VE≈4.5, assuming an average velocity of 3000 m/s).

5.2.2 Tectonic situation at the Wolin Block

5.2.2.1 Faults of the Wiek Fault System and other faults

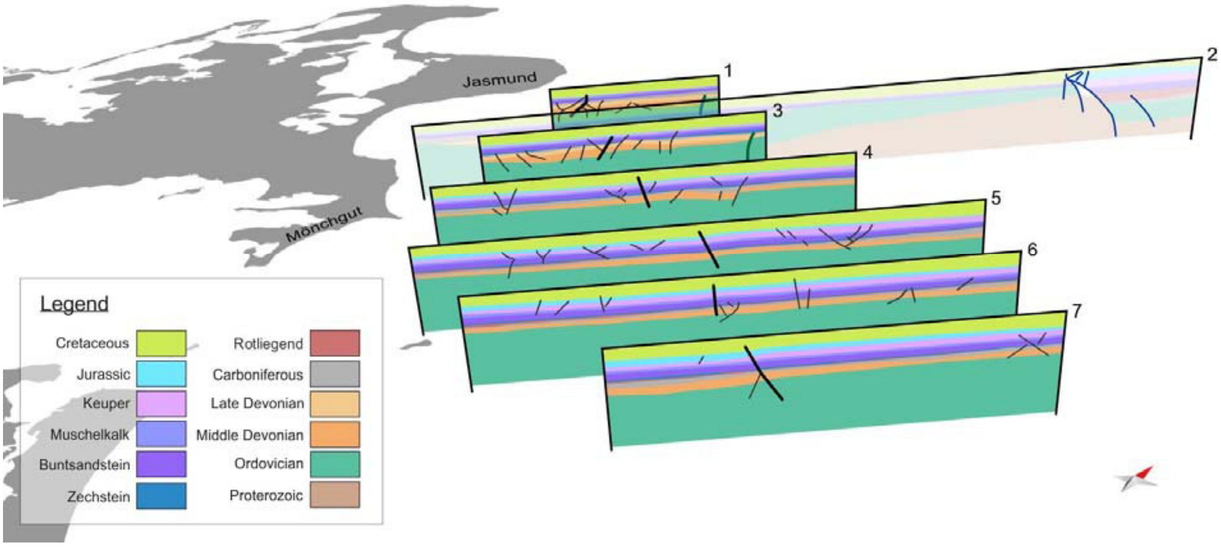


Fig. 5-33: 3D view of seismic sections crossing the Wolin Block and faults and flexures of the WFS. The faults in the NW concentrate on the Palaeozoic successions (as they are coloured in a dark green and orange). Further to the SE, faults and flexures appear in the Mesozoic (purple, blue and light green) successions. The thick black line marks the fault trace of the NJF, and the thick green line, the trace of the WF.

The faults east of Rügen, crossing the Middle Rügen and Wolin blocks are summarised as the Wiek Fault System (WFS, SEIDEL et al. 2018). About 60 faults, flexures and other weakness zones have been mapped during the actual analysis and will be collectively referred to as deformation zones. The complete system strikes from the NW (Jasmund, Rügen) to the SE until the AKFZ. In the southern direction the single deformation planes change their strike direction from the NW into a more north-northwestward direction, east of the Mönchgut Peninsula.

The single faults and flexures of the WFS are shown and labelled in **Fig. 5–23**. Due to multiple reworking of this fault system they are not numbered consecutively.

It is apparent that one major fault plane can be traced across the total length of the fault system between Jasmund and the AKFZ (the thick black line marking the NJF in **Fig. 5-33**). This major fault is accompanied by shorter faults and flexures. In the northern part of the WFS the deformation planes concentrate on the Palaeozoic successions, displacing as normal faults particularly the Ordovician and Devonian successions. Further to the south increasingly Mesozoic strata is deformed. The concave flexures have normal and subordinate reverse characters, causing listric displacements. As master and antithetic planes they typically form Y-shaped small grabens, concentrating in the Lower Jurassic to Keuper successions, terminating in the Buntsandstein or Zechstein.

A special relationship exists for the following deformation planes (for location see **Fig. 5–23** or **Appendix D**):

WFS_8, 8A & 8Sued: These three fault planes are summarised as the **Nord Jasmund Fault** (**NJF**; FRANKE & HOFFMANN 1988, KURRAT 1974; **Tab. 5-13**, **Fig. 5-34**). Due to a varying dip direction and a horizontal offset east of Mönchgut (Rügen) of about 3 km the fault has to be separated into three planes. WFS_8 dips as a normal fault steeply towards the SW. After 13.2 km it changes to a reverse fault dipping steeply towards the NE. The fault plane WFS_8A keep this character over 21 km until the fault is horizontally displaced towards the W. The transition is formed by an approximately 5 km long overlap bordering a relay ramp in between. The WFS_8Sued propagates a further 25.3 km as a reverse northeastward dipping fault. The NJF strikes from Jasmund over 59.5 km until the AKFZ and forms the dominating central major fault of the WFS which is accompanied by other faults and flexures. Thereby it remains in its southeastern strike direction, whereas other deformation planes change their strike direction from SE to SSE. Contemporaneous to the change of dip direction from WFS_8 to 8A, the parallel to the WFS_8 striking **WFS_7** terminates, and **WFS_6a** originates. Although both dip towards the SW the WFS_7 is characterised as a normal fault and the WFS_6a as a reverse flexure (**Fig. 5-23**). The NJF intersects especially the Palaeozoic successions (Ordovician, Devonian, Carboniferous and Permian) as a fault. The Mesozoic deposits are dominantly deformed by a reverse flexure. Fault plane WFS_8 borders a lifted Palaeozoic sub-block of the Middle Rügen Block to the SW, the so called Lohme Sub-block. The Glowe Sub-block is located SW of the NJF. Further to the SE the Middle Rügen Block transforms into the Wolin Block, although there has been no fixed border between the Wolin and Middle Rügen Block defined until now.

WFS_7b, 24, 24a, 25 & 26: Those fault planes are the most northeastern ones at the Wolin Block and are assigned to the **Wiek Fault (WF**; **Fig. 5-23**, **Fig. 5-34a**, **Tab. 5-13)**. As described in **Section 3.3.3** the Wiek Fault is a deep rooted Palaeozoic normal fault, intersecting the Ordovician strata in the north and Devonian and Carboniferous deposits in the south. The vertical displacement of approximately 800 ms next to Jasmund decreases towards the SE to 500 ms (measured for the t-O_{aw}). As identified now, the Wiek Fault can be traced for about 40 km from Jasmund (Rügen) until the AKFZ. It is separated in several ESE to SE striking fault planes with horizontal offsets of 2-8 km between each other. Relay ramps and sinistral NE-SW striking strike slip faults form the transition between the fault planes. Those strike slip faults were not detected in the 2D seismic sections but became obvious in the gridded surface maps as indicated in the time structure map of the Top Ordovician (**Fig. 5-6**). However, the southern Wiek fault planes also displaced the Zechstein formation.

WFS_10c: The location of these fault planes correlate with the **Schaabe Fault** (**SF**; **Tab. 5-13**, **Fig. 5-34a** & **Fig. 5-37**). This fault is known to intersect the Glowe Block. It is also a normal Palaeozoic fault, dipping in a northeasterly direction.

WFS_5-5e & WFS_4/4a: These flexures form a complex structure of syn- and antithetic flexures east of the NJF (**Fig. 5-34c-e)**. The northern group of faults strikes SE and fan out, while the southern group of faults contain subparallel ESE striking faults (**Fig. 5–23**). Between the flexures WFS_4 and WFS_5c as well as WFS_5b and WFS_5c the Zechstein successions are thickening slightly. These elongated structures might be formed by salt accumulations or even small pillows of up to 100 ms high (**Fig. 5-12** & **Fig. 5-15a-b**). A Zechstein reef is also suggested, due to borehole information of well H2 1/90 (**Fig. 5-13**), which confirm a further Zechstein reef, drilled at about 8 km distance from WFS_4, 4a and 5a-e. The Mesozoic strata above this reef show a small depression between WFS_4 and WFS_5a. With exception of the Zechstein, the Palaeozoic deposits are affected and subsided along those planes. Further, the depression, bordered by the flexures WFS_4 and 5c, seems to change to a horst block bordered by WFS_5e and 5b. This interpretation is uncertain due to multiples superimposing the Devonian to Triassic reflection pattern within. The Carboniferous and Devonian showed no strong vertical displacements but instead disrupted internal reflections, indicating horizontal strike slip movements. The flexure of WFS_5d has a normal character and affected the Devonian until Early Triassic successions. An increasing thickness of Buntsandstein between WFS_5d and 5b indicates a depression.

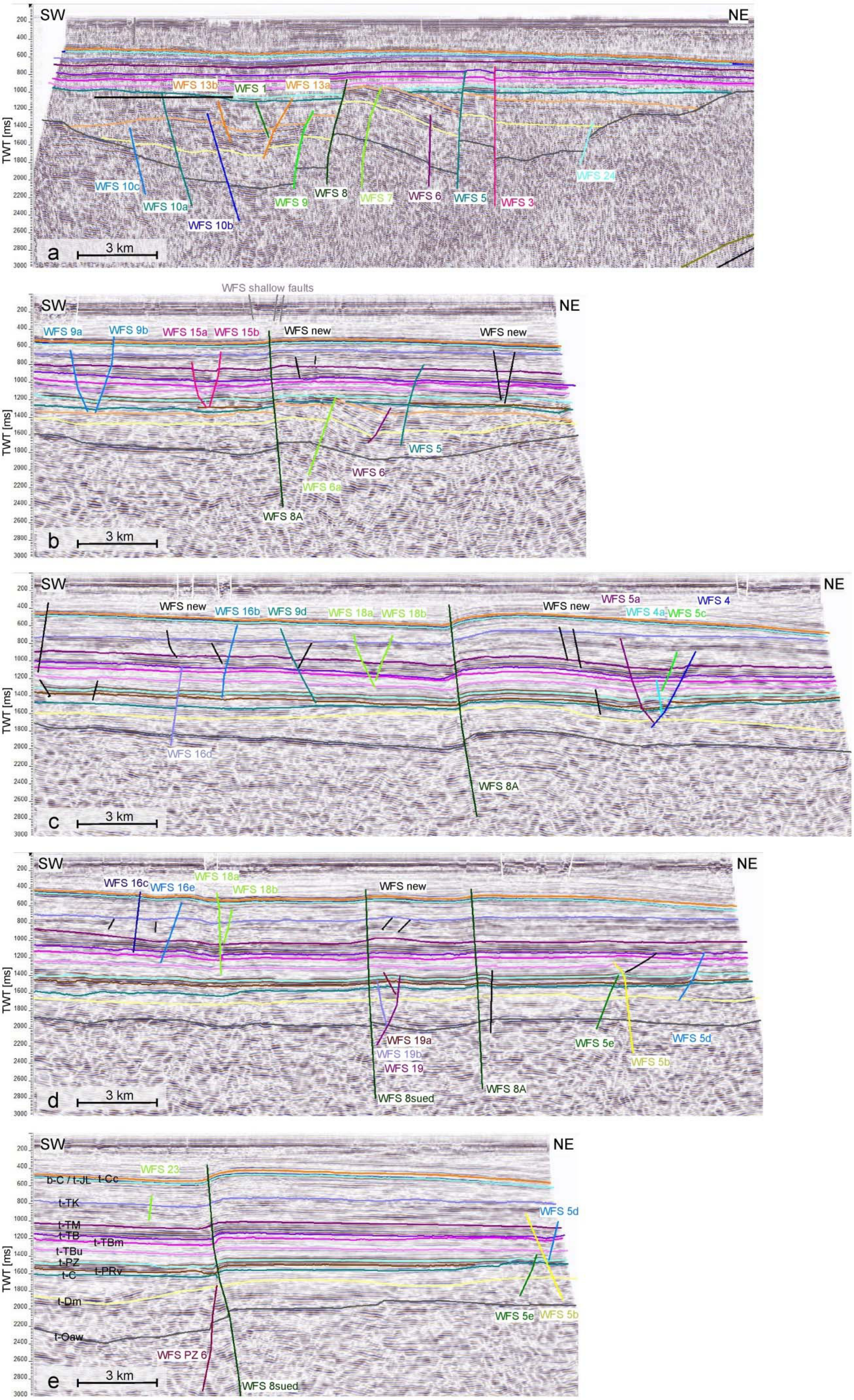

SW
NE
TWT [ms]
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
3000
a
3 km
WFS 13b
WFS 1
WFS 13a
WFS 10c
WFS 10a
WFS 10b
WFS 9
WFS 8
WFS 7
WFS 6
WFS 5
WFS 3
WFS 24
b
WFS shallow faults
WFS 9a
WFS 9b
WFS 15a
WFS 15b
WFS new
WFS 5
WFS 6
WFS 6a
WFS 8A
c
WFS 16b
WFS 9d
WFS 18a
WFS 18b
WFS 5a
WFS 4a
WFS 5c
WFS 4
WFS 16d
d
WFS 16c
WFS 16e
WFS 19a
WFS 19b
WFS 19
WFS 8sued
WFS 5e
WFS 5b
WFS 5d
e
b-C / t-JL
t-Cc
WFS 23
t-TK
t-TM
t-TB
t-TBm
t-TBu
t-PZ
t-C
t-PRv
t-Dm
t-Oaw
WFS PZ 6

Fig. 5-34: Seismic sections crossing the WFS (for location see **Fig. 5-24**). (VE≈2.5, assuming an average velocity of 3000 m/s).

WFS_5 and 6b; WFS_9a & 9b; WFS_9d & 9dE; WFS_16, 16a-e; WFS_18a & 18b: These faults (**Fig. 5-34b-d**) and flexures strike NNW-SSE and belong therefore to the southern part of the WFS (where the strike direction has already changed). Moreover these deformation planes are similar to the previously discussed WFS_4 and 5a. They have a normal character, dominantly border small grabens and dislocate Mesozoic successions. The Y-shaped, conjugating structure equals the fault planes of the WPFS (see **Chapter 3.3.3**). Moreover the faults and flexures south of the NJF (WFS_9a & 9b; WFS_9d & 9dE; WFS_16, 16a-e; WFS_18a & 18b) are located in the northern extension of the **Usedom Fault Zone** (part of the WPFS).

Although the deformation planes concentrate at the southern Wolin Block, dominantly in Mesozoic successions, there are a few exceptions:

WFS_19, 19a & 19b: The flexures are located between the offset of the NJF (**Fig. 5-24** & **Fig. 5-34d**). The conjugating faults dip towards the NE (WFS_19a & b) and SW (WFS_19). The area in between is lifted, thus the master (WFS_19) and antithetic thrusts (WFS_19a & b) form a small positive flower structure in between. The faults terminate upwards within the Zechstein and Lower Buntsandstein successions and displace the successions until the Ordovician.

WFS_21 & 22: These flexures are located close to the AKFZ (**Fig. 5-24**) and dipping like listric planes towards the NE. These weak flexures do not show strong vertical displacements they are dominantly visible due to increasing frequency from the SW to NE. Together with AdlerKamień_W1 flexure they form a small depression. Above this structure, within the upper 300 ms of the seismic section, a velocity pull down structure is visible with a decreasing frequency.

WFS_Prezechstein1-6 (or WFS_PZ1-6)**:** All these faults and flexures concentrate on Ordovician to Permian deposits (**Fig. 5-34e** & **Fig. 5-35**) in the south of the Wolin Block. WFS_Prezechstein1, 2 & 6 are located close to the NJF but dip in the opposite direction (antithetic faults). They have a normal character. WFS_Prezechstein3, 4 & 5 are located further south. The flexures striking in a convex way, turning from a NW strike direction into NNE. Thereby the flexures WFS_Prezechstein3 & 4 conjugating towards each other whereas WFS_Prezechstein4 dips steeper and deeper. The Devonian of the block in between seems to be lifted, whereas the Carboniferous and Permian are more subsided. Furthermore, the reflection pattern of the Carboniferous change in between those flexures from a sub parallel one into a disrupted to hummocky one. Thus this structure might be either reactivated, connected with a lateral displacement,or both. The Y-shaped structure of the conjugating faults confirms the second option. The flexure WFS_Prezechstein6 was only visible in the line shown in **Fig. 5-34e** where it dips towards the SW and has a normal character, although the Rotliegend reflections indicate a reactivation as a reverse flexure.

All faults and flexures which are labeled with "**WFS_new**" (**Fig. 5-34**) could only be mapped in single profiles but a lateral relationship to existing deformation planes are still missing. Those faults and flexures are not regarded in the maps.

Moreover **"Shallow_structures"** and **"WFS_shallow_fault"** have been mapped (**Fig. 5-34b**). All these structures concentrate in the upper 500 ms of the seismic sections. Although this shallow part shows a bad resolution, single faults or flexures with vertical displacements, velocity pull down structures or a change of frequency could be marked. These structures are only mapped in single seismic lines, but not correlated between the profiles, in opposite to the deeper faults and flexures.

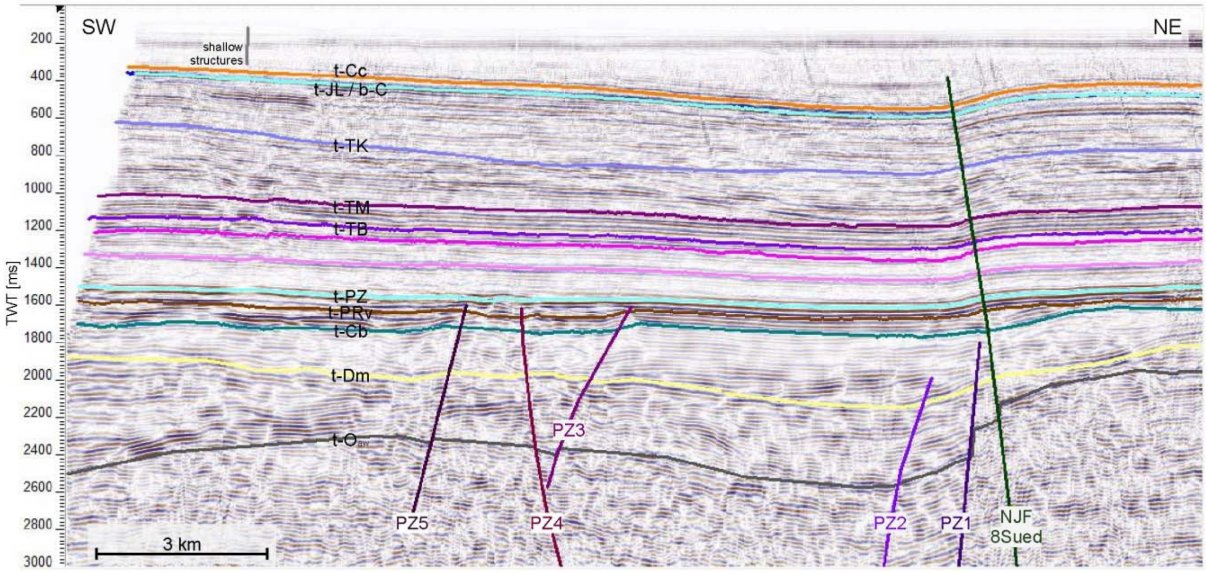


Fig. 5-35: Palaeozoic faults (PZ1-5) indicating strike slip displacements south in the Wolin Block (for location see **Fig. 5-24**). (VE≈2, assuming an average velocity of 3000 m/s).

Further NW-SE striking flexures were mapped south of the Wolin Block, east of the Greifswalder Bodden. Thereby one master, NE dipping, reverse flexure borders an anticline structure to the SE, displacing especially the Mesozoic successions. Due to disrupted reflectors below, it is elongated towards the Palaeozoic. It is accompanied by two synthetic faults, affecting the Muschelkalk and Upper Palaeozoic. 3 km NE of the vertex, a second master flexure parallels the anticline, with a normal character. This flexure is accompanied by two antithetic reverse faults. Thus, the Upper Palaeozoic (Carboniferous/Rotliegend) to Lower Keuper successions seem to be tilted. The anticline structure affects the Upper Palaeozoic deposits until the Upper Cretaceous successions. Thereby the lower deposits until the top of Muschelkalk show no changes in thickness. However the Keuper, Jurassic and Cretaceous successions are thickening towards the centre of the anticline. The tectonic affiliation of this fault is uncertain so far (**Section 6.1**).

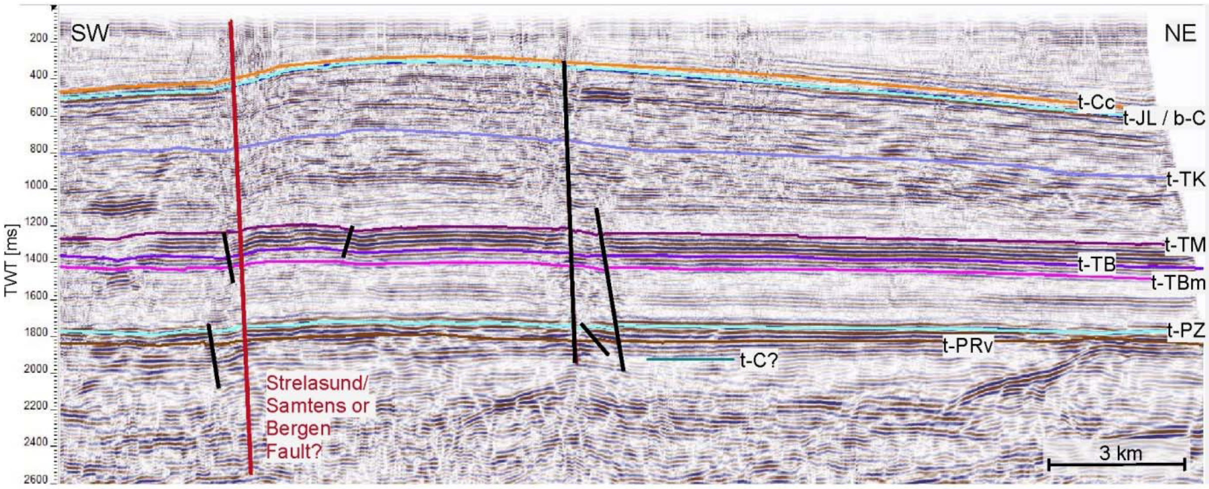


Fig. 5-36: Seismic section crossing an anticline structure south in the Wolin Block and is bordered by a major fault – red line (for location see **Fig. 5-24**, VE≈2.5, assuming an average velocity of 3000 m/s).

5.2.2.1 Kinematic analysis of the Wiek Fault System – results of restoration

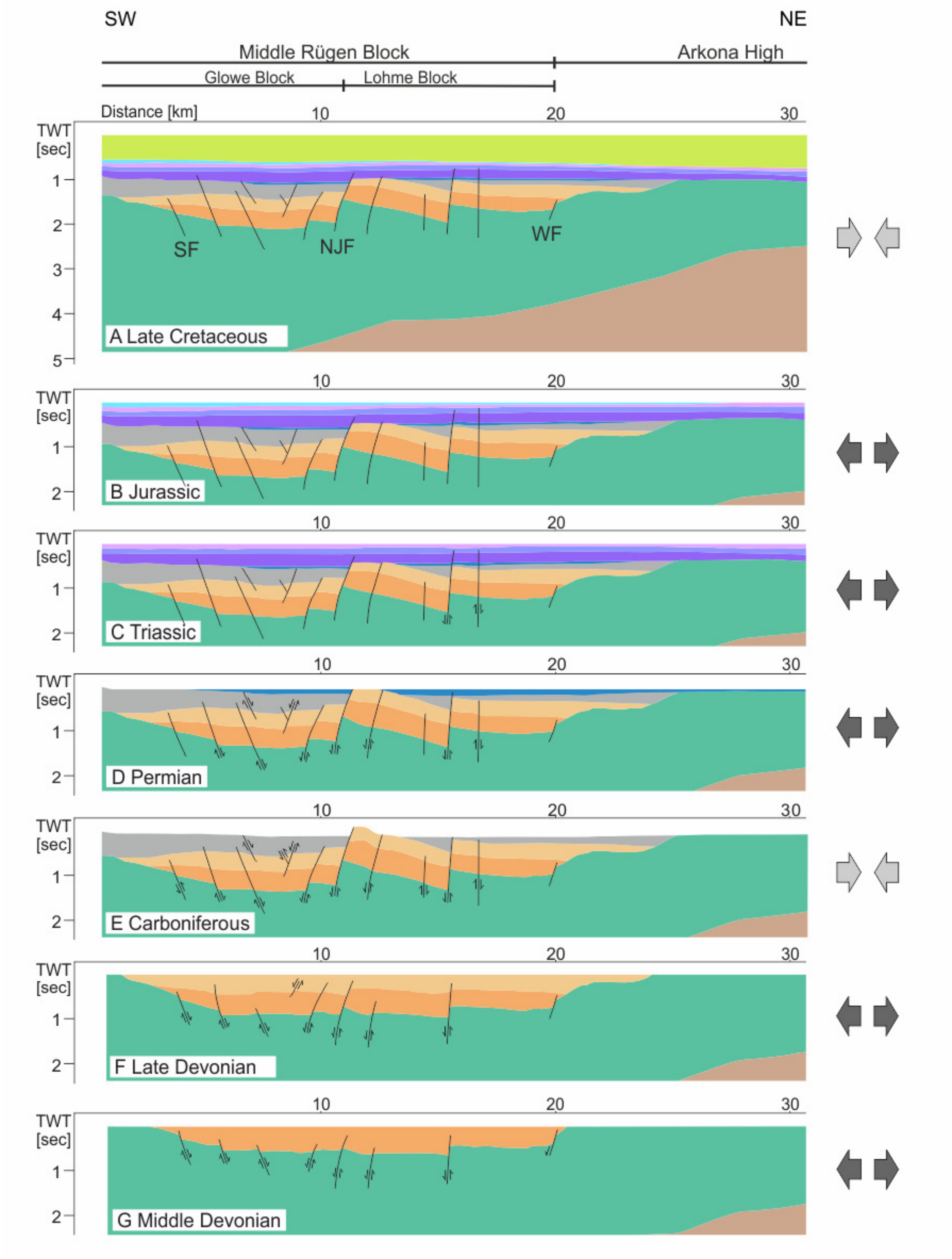


Fig. 5-37: Restoration results of a seismic section, crossing the WFS in the north (Seidel et al. 2018, modified). For location see **Fig. 5-24** or **Fig. 5-33**, line 2, and for legend see **Fig. 5-38**. (VE≈2, assuming an average velocity of 3000 m/s).

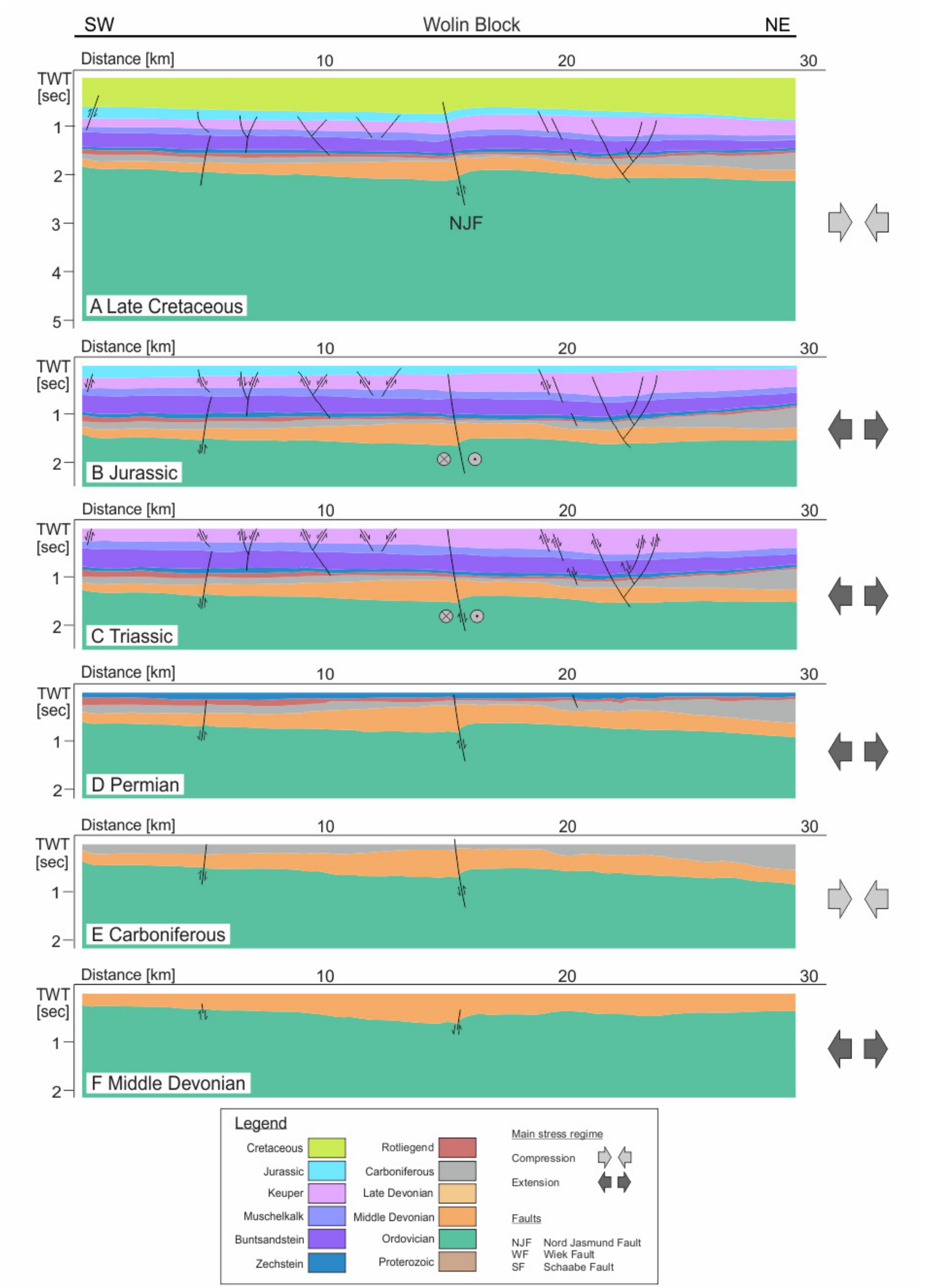


Fig. 5-38: Restoration results of a seismic section, crossing the WFS in the south. For location see **Fig. 5-24** or **Fig. 5-33**, line 5 (Seidel et al. 2018, modified). (VE≈2, assuming an average velocity of 3000 m/s).

Due to the lateral changing fault system, two NE oriented seismic sections have been chosen for restoration purposes. One in the north, crossing the block faulted Devonian, with the NJF dipping towards the SW and one further south crossing the Mesozoic conjugating Y-shaped faults and the northeastward dipping NJF. The results of this restoration have been published by SEIDEL et al. (2018) but should also be introduced here: the formation and evolution of the WFS is subdivided into five stages, starting with the Post-Caledonian in the Middle Devonian SEIDEL et al. (2018).

Both seismic sections have been restored until the Middle Devonian**.** A NW–SE elongated basin was formed by block faulting and the subsidence of the Middle Rügen Block, due to regional extension in the Variscan foreland. It was filled with terrigenous, clastic sediments of Old Red facies (Middle Devonian) and marine, calcareous sediments of the Upper Devonian (**Fig. 5-37*G, F*** **& Fig. 5-38*F***). As indicated by the southern profile (**Fig. 5-38*F***), the basin is widening and flattening towards the SE (at the Wolin Block). The Rügen Basin was bordered and intersected by NW trending en echelon faults. The SW dipping Wiek Fault limited this basin to the NE. The NE dipping Schaabe Fault formed close to the southwestern border of the depression, although the actual Rügen Basin reaches further to the SW. The NJF was formed dipping to the SW and intersecting the sub-blocks of Lohme and Glowe. Also the southern profile shows two flexures with a normal displacement dipping towards the depocentre. Thereby the northern fault embodies the continuation of the NJF. The formation of a relay ramp at the NJF indicates an additional strike slip component and therefore, not only extension but transtension.

Since the **late Carboniferous** a compressive stress field affected the Variscan foreland. Thus, most of the normal faults were reactivated as reverse faults or flexures. Some blocks were lifted asymmetrically and tilted. This rotational component forced a normal displacement at single fault planes. When the southern part of the Lohme Block was lifted and tilted (**Fig. 5-37*E***) the NJF remained with a normal offset of up to 500 ms (750 m assuming an average velocity of 3000 m/s). However, the Schaabe Fault dips towards the NE and was reactivated as a reverse flexure. SE of the Wolin Block, the dip direction of the NJF changed from a SW-dipping normal fault into a NE-dipping reverse fault (**Fig. 5-38*F*** and **Fig. 5-38*E***). This process might be realised by the formation of an antithetic backthrust. However, the northeastern block kept its exaggerated position. Contemporaneous, the Upper Carboniferous deposits indicate a relief inversion of the former Devonian basin, which might have accompanied the local erosion of Upper Devonian and lower Carboniferous successions (not considered during the restoration).

During the **Rotliegend** the stress regime changed again into an extensional one. The increasing thickness of the Permian successions towards the SW indicate the formation of an intracontinental basin, SW of the working area. The Arkona Block remained as a local high and limited the Zechstein sedimentation towards the north. Additional locally exaggerated blocks controlled the sedimentation (**Fig. 5-37*D***). Thus, the Zechstein is missing above the tilted block in the centre, but is 300 m thick nearby. Although most of the faults crossing the Wolin Block were inactive, minimal movement occurred at a few existing ones (**Fig. 5-37*D*** & **Fig. 5-38*D***). As suggested by thickness differences in **Fig. 5-37*D*** the NJF, intersecting the Lohme Block, remained active until the Early Triassic. In the southern part of the Wolin Block, the active faults, such as the NJF, became normal faults, but also new faults were generated, such as east of the NJF in **Fig. 5-38*D***.

The rate of subsidence was enhanced since the **early Triassic** and dominated almost the entire Mesozoic. In the northern profile one normal fault, the NJF and three normal flexures have been active especially in the Buntsandstein and Muschelkalk. Since the Keuper, the existing NW–SE trending Palaeozoic faults were affected by dextral transtensional movements (**Fig. 5-37*C, B*** & **Fig. 5-38*C, B***). Between the Keuper and the Lower Cretaceous, the northern part of the WFS was not remarkably affected by faulting, whereas in the southeastern part of the WFS an increasing shear stress induced the formation of new NNW–SSE striking, normal en echelon and listric faults (**Fig. 5-38*C, B***). The conjugating flexures and faults form Y-shaped graben structures, similar to faults of the WPFS (KRAUSS & MAYER 2004). They occur mostly in the Keuper, and extend down to the Muschelkalk and Buntsandstein strata. The NJF still shows at its southern prolongation a vertical displacement.

Since the **Late Cretaceous** a compressional stress regime affected again the WFS. The northern profile shows a thickness increase of mainly Upper Cretaceous deposits (**Fig. 5-37*A***) slightly towards the NE. Major faults are not observed. The reactivation of the NJF is indicated by a slight uplift of the northeastern part of the Lohme Block, at the northern profile and a dominant uplift of the northern block within the southern profile (**Fig. 5-38*A***). The Mesozoic fault in the SW part of the southern seismic section is indicated by reverse flexures marking the continuation of the deep fault plane.

5.2.3 Tectonic situation at the Gryfice Block

As introduced in **Section 3.3.2** the Gryfice Block is one major block, located in the offshore part of the TTZ. It is bordered by the AKFZ to the southwest and the Trzebiatow Fault to the northeast. This block continues in a southeastern direction, as part of the onshore Mid Polish Trough or Pomeranian Segment (DADLEZ 2003, KIERSNOWSKIE & BUNIAK 2006). Towards the north, the Gryfice Block is terminated by the Rønne Graben (VEJBÆK & BRITZE 1994, GRAVERSEN 2004). Thereby the strike direction changed from the NW trending Gryfice Block to the NNE trending Rønne Graben. The Gryfice Block is also known as the Gryfice Graben, due to its Palaeozoic to Middle Mesozoic appearance. Recent geological maps show an enormous anticline in this area, contradictory to a graben. Thus, the term 'block' is preferred.

The following sections concentrate on the western border of the Gryfice Block, the AKFZ, and a fault zone which is shown in single geological maps(e.g. SCHLÜTER et al. 1998) , but unnamed so far. Here it is called the Gryfice Fault Zone. Furthermore the transition of the Gryfice Block towards the Rønne Graben could be analysed by some single lines.

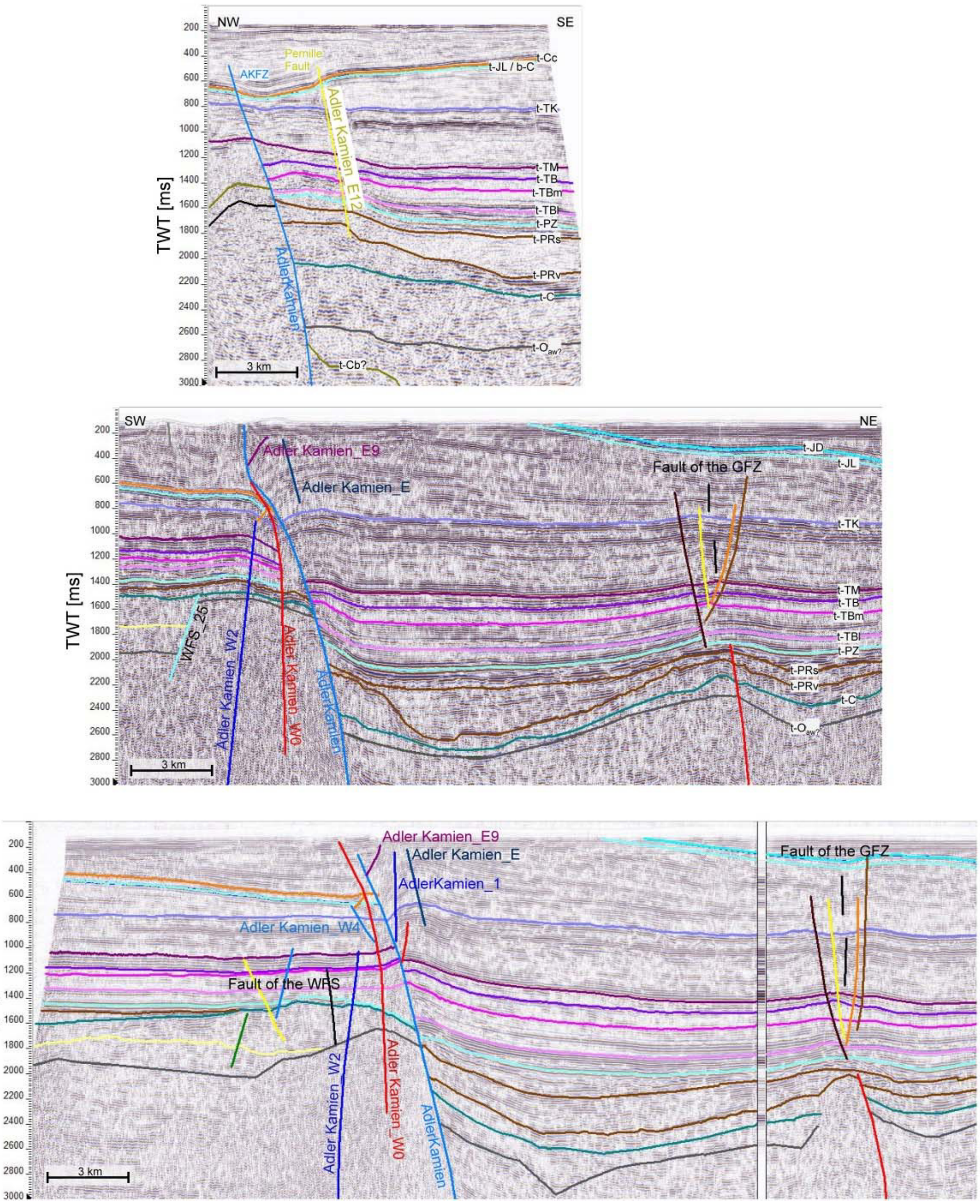


Fig. 5-39: Seismic section crossing the Faults of the WFS, the AKFZ and the Gryfice Fault Zone (for location see **Fig. 5-24**). (VE≈3, assuming an average velocity of 3000 m/s).

5.2.3.1 Adler-Kamień Fault Zone

In contrast to the other structures within the offshore part of the TTZ, the AKFZ strikes NNW and can be traced for about 67 km and a width of about 5 km. At the northwestern edge of the Gryfice Block, the AKFZ enters into a junction of three fault zones, with the NE striking Gat Fault, bordering the Rønne Graben, and the NW trending Skurup Fault.

23 fault planes were mapped for the AKFZ (**Fig. 5**–**23**). Further faults which were only detected in single seismic sections are signed as "Adler Kamień_new". Similar to some faults of the WFS, those faults could not be correlated with other seismic sections, and, hence, not defined as fault planes. A Cross section of the AKFZ (**Fig. 5-39**) shows the complex structure which is a result of a multiphase evolution. The AKFZ is characterised by one major normal fault ("AdlerKamień"; light blue one in the centre of the section, shown in **Fig. 5-39**), which can be traced over the entire extension of the AKFZ. It dips towards the ENE. The Gryfice Block subsided especially along this fault plane. This fault is paralleled to the east and west by other shorter faults with different horizontal and vertical extensions, dip directions and displacement characteristics. Thus, the AKFZ is usually created by up to seven subparallel single syn- or antithetic fault planes. West of the major fault are further dominantly normal faults dipping towards the ENE and WSW. These are affecting the whole succession from the basement until the Cretaceous. The faults east of the major fault concentrate on an anticline close to the major fault and therefore especially in the Keuper, Early and Middle Jurassic as well as Cretaceous sediments. The faults are fold bounded and of normal and reverse characters.

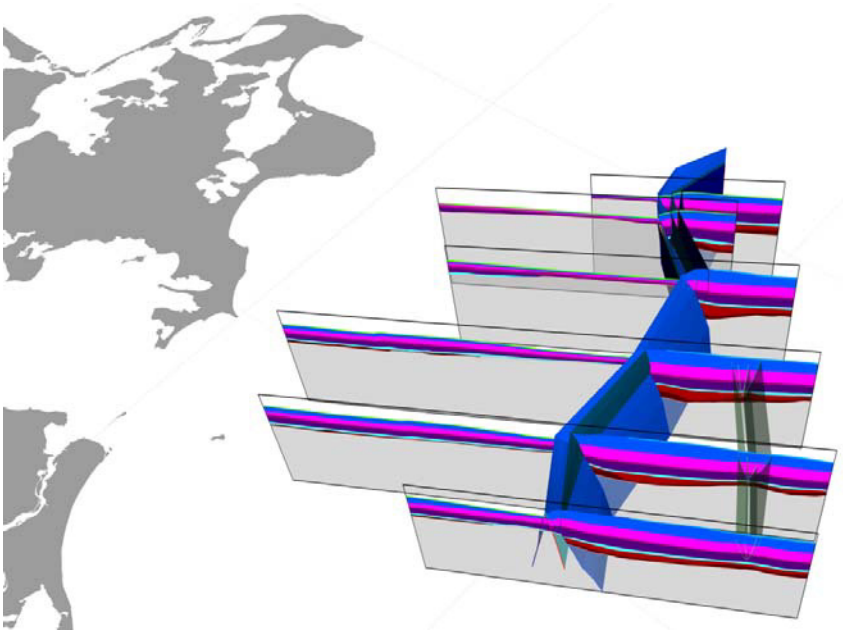


Fig. 5-40: 3D view of several NE striking seismic sections, crossing the Fault planes of the AKFZ (blue) and the Gryfice Fault Zone (green).

The fault plane, called "Adler Kamień_E9" intersects the folded strata east of the "AdlerKamień"-fault plane and the almost horizontal layered, undeformed Cretaceous deposits west of the AKFZ. Thus, it marks an angular discordance and therefore the shallow border between the Gryfice Block and the Wolin Block or the Arkona High.

Moreover the AKFZ is characterised by a few bends and horizontal offsets, where the strike direction undulates between a NNW and NW orientated direction. One example is the offset east of Jasmund (Rügen). Due to insufficient data coverage it is not possible to map the character of these offsets. Most of the seismic profiles cross the AKFZ from SW to NE. Strike-slip faults, which may be the reason for the lateral offsets of the AKFZ would have the same strike direction as those seismic sections.

About 6 km SE of the triple junction, the AKFZ bends about 90° and changes its strike direction into a north-northeastern one. Due to this bend a few more short single fault planes have been generated, fanning out within the northernmost curve.

5.2.3.2 Gryfice Fault Zone

The Gryfice Fault Zone is located above a Palaeozoic high, which could not be explaneed until now. This high is probably formed by Rotliegend volcanics or an unidentified tilted horst block. The fault zone strikes NW towards the Skurup Fault. It is formed by five major subparallel fault planes. One is located within the Palaeozoic strata and connected to the Palaeozoic high. The assumed rotated block might be bordered to the east by the northeastward dipping GRY_deep fault plane. The others are conjugating towards each other and dislocate the Triassic and Jurassic successions. The GRY_W fault plane represents the master fault and is accompanied by the antithetic GRY_E fault plane. In the southern part the fault zone is completed by a second set of fault planes between the GRY_W and GRY_E planes. The fault plane GRY_internW forms a synthetic fault, dipping towards the NE. The GRY_internE joins the GRY_E fault and dips also towards the SW. Those four form a Y-shaped structure above the GRY_deep fault (**Fig. 5-40 & Fig. 5-41**). The character and offsets along each fault change vertically but also laterally from SE to NW. In the south of the fault zone, the four conjugating faults border a depression. The Triassic and Jurassic successions are displaced by flexures. Further to the NW the internal block is lifted and forms an anticline between the remaining master and antithetic faults (GRY_W and GRY_E). The internal faults terminate and a further fault plane is mapped outside of the superior Y-shaped structure. The GRY_E2 plane is a SW dipping flexure, normal folding the Keuper and Jurassic successions.

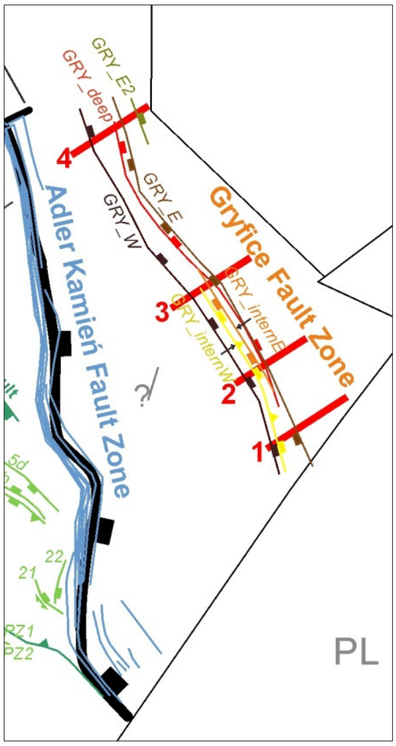


Fig. 5-41: Detailed map of the Gryfice Fault Zone. Thick red lines mark the location of the seismic sections, shown in **Fig. 5-42**.

The evolution of the Gryfice Fault Zone appears to be closely related to the "Palaeozoic high" below. Moreover it is located in the southeastern prolongation of the Skurup Fault. Between the strike direction of the AKFZ and the Gryfice Fault Zone an angular offset of about 30° was measured.

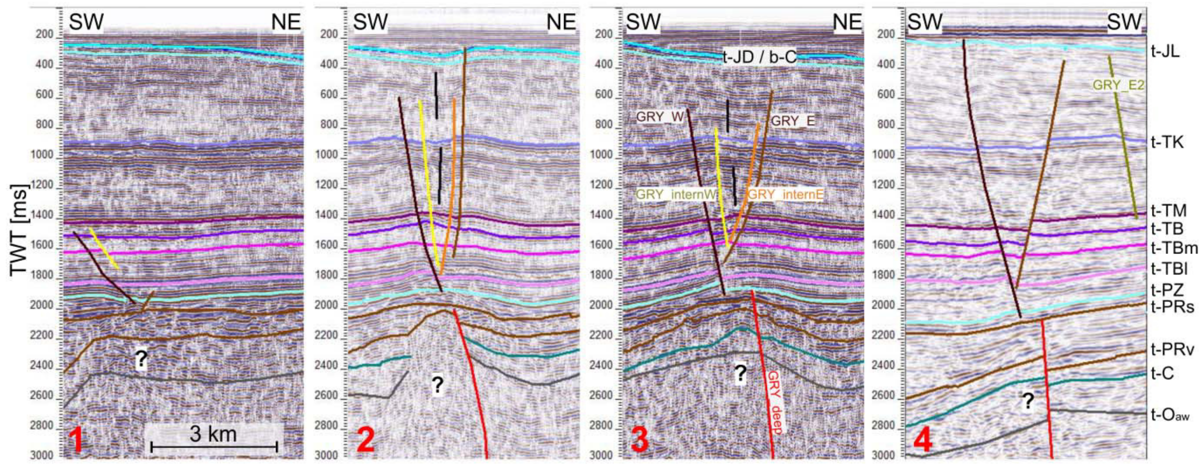


Fig. 5-42: Seismic sections, crossing the Gryfice Fault Zone, for location see **Fig. 5-41.** (VE≈2.5, assuming an average velocity of 3000 m/s).

5.2.3.3 Kinematic analysis of the Adler-Kamień Fault Zone

The tectonic evolution of the Gryfice Block was analysed by the restoration of one seismic section crossing the AKFZ and Gryfice Fault Zone from SW to NE (SEIDEL et al. 2016), see **Fig. 5-43**. The results of the restoration represent the polyphase evolution of the fault zones:

The restoration concentrates on the time span between the Early Permian to Upper Cretaceous. A first tectonic phase of subsidence can be derived for the **Permian.** The Gryfice Block subsided about 1 s (which complies with 1.5 km, assuming an average velocity of 3000 m/s) during the Permian. The resulting graben is asymmetric and its base dipping towards the AKFZ. Thus, the effusive Lower Rotliegend, sedimentary Upper Rotliegend and Zechstein successions filling the graben and are thickening towards the SW. A comparison of the successions at the Wolin and Gryfice blocks provides a lot of information regarding the tectonic activity. The Rotliegend is only preserved or even deposited at the Gryfice Block and is missing at the Arkona High. The Zechstein successions covering both blocks and are generally thickening towards the NE. However there is no major thickness difference at the AKFZ. The syn-sedimentary subsidence of the Gryfice Block seems to be terminated by the end of the Upper Rotliegend. During this phase

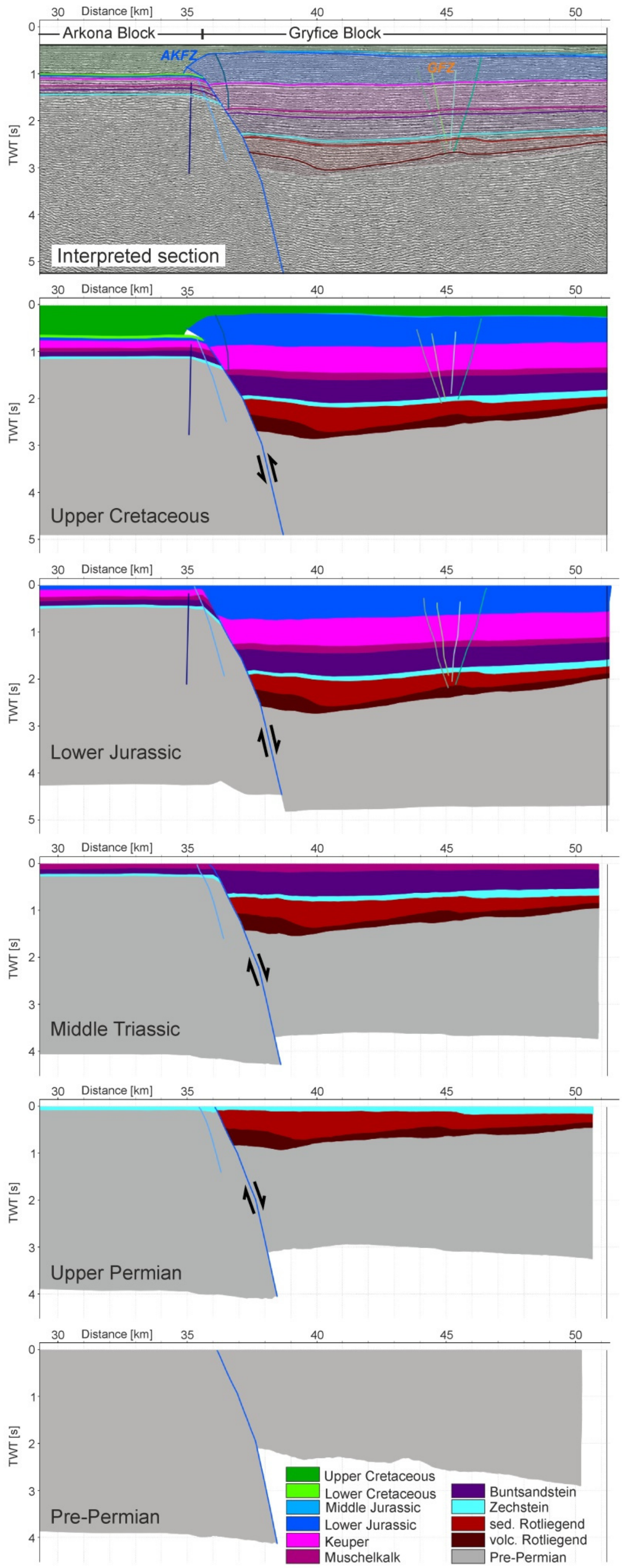


Fig. 5-43: Restoration of a seismic section, crossing the AKFZ in its central part from SW to NE. For location see **Fig. 5-24** (SEIDEL et al. 2016, VE≈2.5, assuming an average velocity of 3000 m/s). GFZ-Gryfice Fault Zone (see **Fig. 41 & 42**).

one NE dipping master fault was active, and a further synthetic fault plane formed SW of it. The minor thickness differences of the Zechstein deposits indicate a phase of **Late Permian tectonic quiescence**.

The Buntsandstein deposits show again major thickness differences between the two blocks and an increase from 100 ms (or 150 m, assuming an average velocity of 3000 m/s) at the Arkona High to 500 ms (or 750 m) within the Graben or Gryfice block. This indicates a second phase of strong subsidence of the Gryfice Graben (**Early Triassic subsidence**). After a further break and tectonic quiescence during the **Muschelkalk (Middle Triassic quiescence)**, indicated by minor thickness differences, the subsidence continued during the Keuper. The phase of **Late Triassic-Early Cretaceous subsidence** is documented by major sedimentation of Keuper and Liassic deposits. Comparing the two blocks, the Keuper is thickening for about 600 ms (or about 900 m, assuming an average velocity of 3000 m/s) and the Liassic for about 650 ms (or about 925 m) within the Gryfice Graben. Even Dogger successions are preserved within the Gryfice Graben**.** Further vertically dipping normal faults (with an almost antithetic character against the eastward dipping faults) are accomplishing the AKFZ now. Moreover a Y-shaped set of synthetic and antithetic normal faults were generated in the centre of the Gryfice Block forming the Gryfice Fault Zone.

Thus, after phases of tectonic quiescence during the Zechstein or Muschelkalk, the Gryfice Graben continued its subsidence. At the same time the AKFZ was reactivated and extended by further synthetic vertical to northwest dipping normal faults. Comparing the extension of the blocks between the Pre-Permian until the Jurassic, the spreading of this line comprises 1100 m.

Since the Late Cretaceous, the transtension changed into a compression, which led to the uplift of the Gryfice Block, the inversion of the graben and therefore a reactivation of the AKFZ as reverse faults. Due to the overthrusting of Jurassic deposits onto the Arkona High, an anticline formed next to the reverse faults of the AKFZ. Moreover fold bounded antithetic faults and flexures evolved above the Adler-Kamień master fault. This phase is named the **Late Cretaceous-Early Cenozoic uplift.** The lateral shortening since the Lower Jurassic, contains about 110 m.

Comparing with the baseline situation in the Pre-Permian, the Gryfice Block shows a total subsidence of 1700 ms (or 2550 m, regarding the base of Permian during the Pre-Permian and Upper Cretaceous) and a horizontal extension of 1000 m.

6 Interpretation and discussion of the structural features along the Arkona, Wolin and Gryfice blocks

The stratigraphic successions and structural units within the intensively block-faulted working area tell the story of the Palaeozoic evolution along the south-western border of the EEC and the Mesozoic development at the northern border of the NGB, all situated in the southeastern corner of the Tornquist Fan. The geological appearances of the three main blocks (Arkona, Wolin, Gryfice) are different but they all constitute single pieces of the complex puzzle, showing the polyphase evolution of this area (see **Chapter 7**).

This chapter is divided into two parts. First, the distinctions of the gridded horizons along the individual blocks will be summarised, and then the tectonic inventory of each individual block will be discussed.

6.1 Time structure maps and morphological implications

The Arkona Block is exposed against the southern Middle Rügen and Wolin blocks, or the eastern Gryfice Block. This can be seen in all time structure maps (**Section 5.1**, **Fig. 6-1*A*-*C***), from the Proterozoic Basement of Baltica (horizon t-E, **Fig. 5**–**3** or **Fig. 6-1*A***) until the Top of Jurassic (t-JL **Fig. 5**–**21**). Whereas some horizons are exposed on the Arkona Block (e.g. **Fig. 6-1*A*-*B***), others strike out along the southern border of this block (e.g. top of Zechstein **Fig. 5**–**12** or top of Lower Jurassic **Fig. 5**–**21**).

The Proterozoic crystalline basement of Baltica and its undeformed Cambro-Silurian cover were only encountered by well G14 1/86; moreover, undifferentiated Permo-Triassic sediments, as well as Upper Cretaceous deposits, have been documented for the Arkona Block. The successions of the Ordovician had to be separated in autochthonous (t-O_{EEC}) unfolded sediments, covering the Baltic Shield (G14 1/86) and allochthonous (t-O_{aw}) faulted and folded Ordovician deposits (Rn 5/66, K5 1/88, such as wells K1 1/86, L2 1/87, K9 1/89 in the Polish area; Rempel 1992*a,b*), which were thrust onto the southern Baltic Shield forming the accretionary wedge of the Caledonian Orogen. The allochthonous Cambro-Silurian sediments, covering the shield of Baltica, and the autochthonous Ordovician deposits are separated by the CDF (**Section 6.2.1.1**). Devonian and Carboniferous sediments are missing on the Arkona Block. However, towards the SW (along the blocks of Middle Rügen and Wolin), the Middle Devonian Old Red Rügen Basin has evolved (Aehnelt & Katzung 2009). The general northern extent of this basin is still visible in the time structure map of t-O_{aw} (**Fig. 6-1*B*, Fig. 3**–**9**), where an approximately 800 ms (approximately 1200 m, assuming an average velocity of 3000 m/s) huge displacement is formed by the Wiek Fault. As revealed by the wells Loh 2/70, H9 1/87, Binz 1/73 or H2 1/90, Middle (t-Dm) and Upper (t-Du) Devonian sediments filling this depression are covered by Carboniferous deposits (t-C). A distinction between Lower and Upper Carboniferous strata was not possible for the seismic sections, due to missing well ties. Well H9 1/87 lies on the tilted part of the Lohme Sub-block (**Fig. 6-2, Fig. 5**–**8)**, where Carboniferous deposits are missing, and well H2 1/90 discovered only the Upper Carboniferous sediments. Only the wells in the central part of Rügen (Loh 2/70 and Sagd 1/70) contained Lower and Upper Carboniferous successions with a hiatus (**Sudetian Discordance**) in between. Comparing the sketch of Franke (2018) in **Fig. 6-2** and the interpreted seismic sections illustrated in **Fig. 5**–**8** and **Fig. 5**–**10**, the Lower Carboniferous appears to be only preserved in the deepest part of the former depression. The Sudetian Movements between the Early and Late Carboniferous led to erosion of the Lower

6 Interpretation and discussion of the structural features

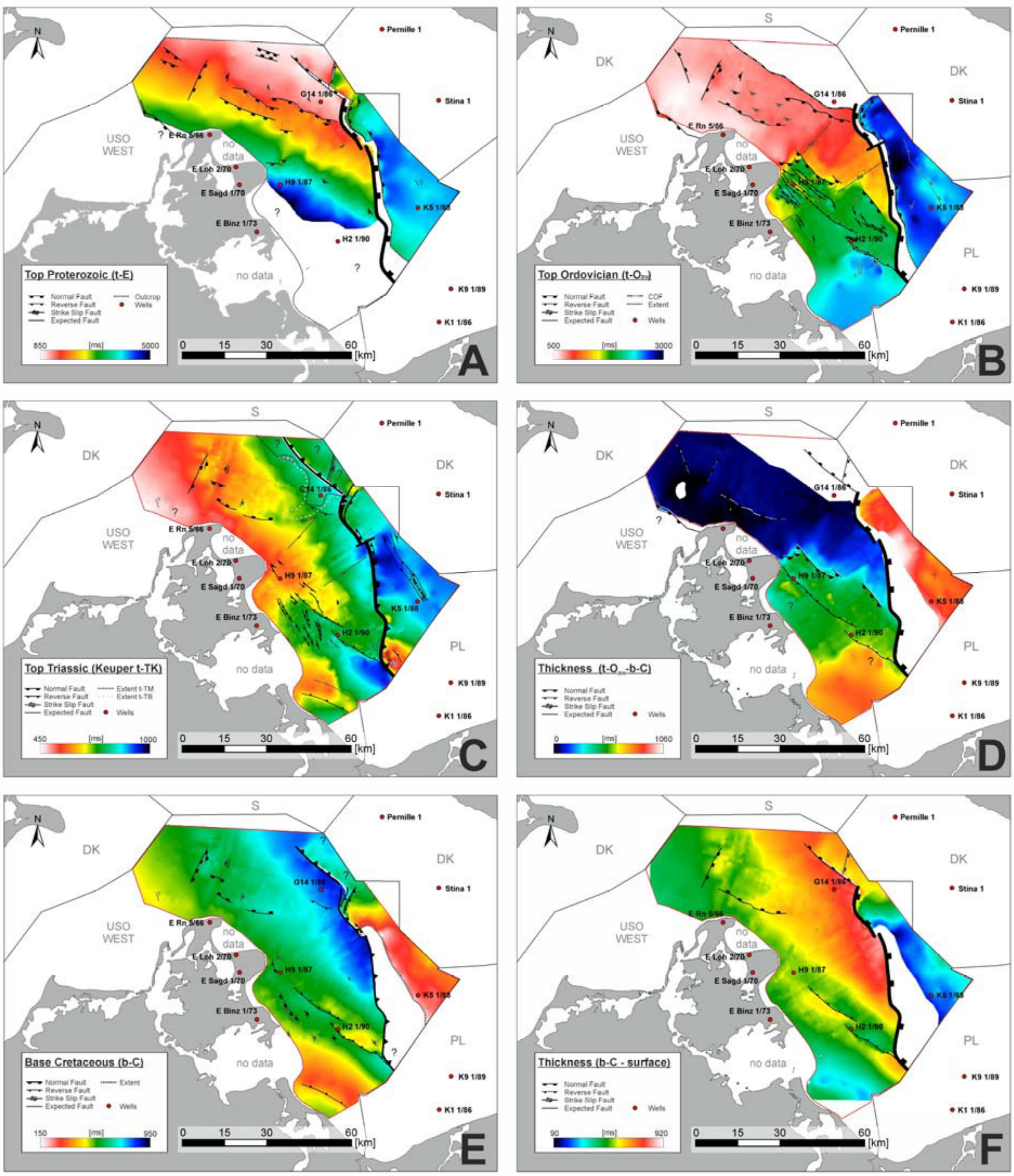


Fig. 6-1: Compilation of time structure and thickness maps (all in TWT [ms]). **Time structure maps:** A–Top of Proterozoic (basement of Baltica); B–Top of the deformed Ordovician as part of the accretionary wedge, which is down-faulted south of the Arkona Block and reflects the base of the Middle Devonian Old Red Rügen Basin; C–Top of Triassic, showing the major inverted areas as anticlines south of the Wolin Block, NE of the NJF and AKFZ; E–Base of Cretaceous, indicating the northward deepening of the Cretaceous depression. **Time thickness maps** (note the flipped colour scale, with thin successions in blue, and thick deposits in red to white): D–thickness of the Palaeozoic to Mesozoic cover above the accretionary wedge, including successions between the Top of the deformed Ordovician and the base of Cretaceous; F–Thickness of the Cretaceous and post Cretaceous successions, indicating a general thickening towards the NE **(see also Appendix D)**.

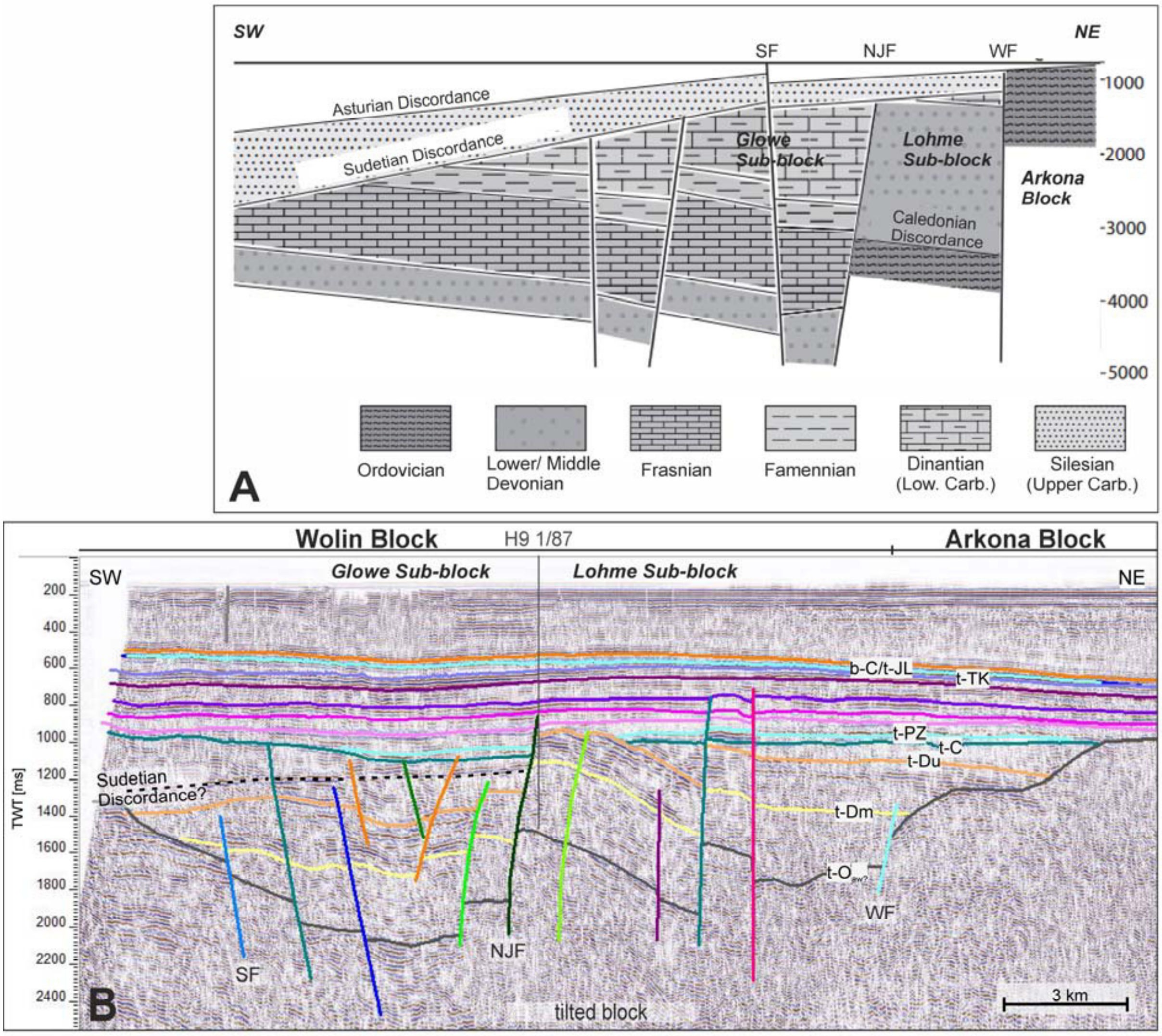


Fig. 6-2: Major faults and unconformities on (**A**), Rügen with depth in m (Franke 2018, modified), compared with (**B**) an interpreted seismic section crossing the Arkona and Wolin blocks east of Rügen, with depth in ms. The location of well H9 1/87 is projected (for location see **Fig. 5–2,**corresponds to **Fig. 5–8**). NJF-Nord-Jasmund Fault, SF-Schaabe Fault, WF-Wiek Fault. VE≈3, assuming an average velocity of 3000 m/s.

Carboniferous and Upper Devonian and the formation of an angular discordance or hiatus. Thus, the remaining Upper Devonian and Lower Carboniferous deposits are bound to local depressions (see extent of Upper Devonian in **Fig. 5–7**), while the Middle Devonian and Upper Carboniferous successions are mapped along the whole Wolin Block. The Middle Devonian strikes out north of well H9 1/87, and is limited by the Wiek Fault. Upper Carboniferous deposits cover the southern part of the Arkona Block and are also mapped along the Gryfice Block, while Devonian and Lower Carboniferous sediments are missing at the latter (see well K5 1/88, **Section 5.1**).

However, the overlaying Permo-Jurassic successions are generally dipping from the exaggerated Arkona Block in the NW towards the AFKZ in the SE (**Fig. 6-1*C*; Tab. 5–8, 9, 10**). The thickness map of the Devonian-Jurassic successions, covering the accretionary wedge, (**Fig. 6-1*D*, Appendix D**) shows a slightly different trend with a southward increase, reflecting the synsedimentary formation of the Middle Devonian Old Red Rügen Basin during the Devonian and the NGB since the Permian further south. For example, the thickness of the Buntsandstein increases about 280 m between wells H9 1/87 and H2 1/90 (**Tab. 5–8**) and also the SE dipping time-structure map of the top of Triassic (**Fig. 6-1*C***) reflects this trend. The anticlines in the south of the Wolin Block and east of the AKFZ are visible within the Triassic to Cretaceous time structure maps and will be discussed below. Furthermore, huge differences in thickness patterns indicate a subsidence of the Gryfice Block and the formation of the Gryfice Graben, as part of the MPT. This joins other graben formations, especially within the Tornquist Zone and its closer vicinity, such as the Rønne and Risebæk grabens (GRAVERSEN 2004).

Special internal reflection patterns were registered for the Keuper and interpreted as channel structures. The Keuper successions were investigated by FRANZ et al. (2018*a,b*), who analysed onshore well data. The detected NW-SE trending channels are up to 100 m incised into the Grabfeld Formation north of Usedom and filled by the Stuttgart Formation (see **Section 5.1.7.3** and **Fig. 5–19** & **Fig. 5–20**). They seem to be related to a channel belt complex, crossing the area east of Rügen from north to south (FRANZ et al. 2018*b*).

As indicated by the restoration results, the Gryfice Block was separated by the AKFZ from the western blocks, at least since the Early Permian (see **Section 5.2.3.3; Fig. 5–43**). The horizons of the top Ordovician (t-O_{aw}) to top Triassic (t-TK) show a morphological depression along the Gryfice Block, whereas the Top Jurassic and Base Cretaceous horizons show a morphological high, as well as an asymmetrical anticline. Comparing the lithostratigraphic successions east and west of the AKFZ, all are thickening towards the east (**Fig. 6-1*D*, Section 5.1)**. Moreover, the Middle Jurassic and sedimentary Rotliegend are only preserved or sedimented at the Gryfice Block, hence within the graben. Most of the units, which strike out along the middle-northern part of the Wolin Block, reach further north at the Gryfice Block (e.g. the top of Zechstein; **Fig. 5–12**). Thus, the Gryfice Block formed a graben during the time span from the Permian until the Upper Cretaceous when subsidence was compensated by syntectonic sedimentation.

The Lower Cretaceous (dominantly Albian) successions discordantly overlie the Permo-Triassic successions on the Arkona Block, the Lower Jurassic sediments on the Wolin/Middle Rügen Block, and the Middle Jurassic deposits on the Gryfice Block; therefore, there is a hiatus with a varying time span in between, indicating the Late Cimmerian Unconformity (ZIEGLER 1990*a*), also known as the Base Cretaceous Unconformity (e.g. AL HSEINAT et al. 2016, AL HSEINAT & HÜBSCHER 2017). According to the four offshore wells, there is no hiatus between the Early and Late Cretaceous.

Time structure maps from the top of the Triassic (t-TK) until the base of the Cretaceous (b-C) show three prominent anticlines in the central and southern parts of the working area. They are all related to faults and are formed by inversion processes. East of the northeastward dipping master fault of the AKFZ, a major NNW striking anticline reflects the inversion of the Palaeo-to Mesozoic Gryfice Graben structure. A second NW-SE striking anticline parallels the Nord Jasmund Fault in the NE, in the central and southern parts of the Wolin Block. South of the working area a further NW-SE striking anticline is visible and also related to a NE dipping fault. However, the southernmost anticline was formed during the inversion phase. Due to an insufficient coverage of seismic sections, neither the fault, nor this anticline, can be attributed to already defined structures. All three anticlines have previously been illustrated in maps by REINHARDT (1993*b*), SCHLÜTER et al. (1997*a*) and KRAUSS & MAYER (1999, 2004). SCHLÜTER et al. (1997*a*) assigned this structure to the Usedom Fault, a SE striking group of faults north of Usedom turning in a SSE striking fault, which also crosses Usedom as part of the WPFS. However, due to its character, strike direction and missing antithetic fault planes, this fault is not belived to be related to the Usedom Fault Zone. Due to its location, this NW trending fault, south of the Wolin Block, might be a prolongation of the Palaeozoic, NE trending Strelasund, Bergen or Samtens faults. In early analyses, KURRAT (1974) already defined the Samtens Fault as a border between the Putbus Block and the South Rügen Block. As summarised by FRANKE (2018), the Samtens Fault lies on the South Rügen Block and was reactivated during the Mesozoic forming conjugating, Y-shaped grabens as part of the WPFS. Later it was identified as the southern border of the Rügen Swell (KRAUSS 1994, KRAUSS & MAYER 2004). The Bergen Fault terminates the South Rügen Block to the north, while the Strelasund Fault terminates it to the south (SCHLÜTER et al. 1997*b*). However, due to a lack of data, none of this three faults can be confidently assigned to this fault north of Usedom.

A syncline south of this flexure intersects the local high from the WNW trending Grimmen Wall. The Grimmen Wall represents a passive structure, which remained as a local high while depressions formed north and south of it (KRULL 2004). Thus, a relation with this wall can be excluded. Comparing these results with the geological map of Poland (DADLEZ et al. 2000, KRZYWIEC 2006), the discussed anticline seems to enter into the Pomeranian Kuiavian Anticline. A cross section along all three antithetic structures along the Wolin and Gryfice blocks visualised similarities regarding the relating faults (**Fig. 6-3**). All faults or fault zones (Samtens, NJF, AKFZ) dip steeply in a northeasterly direction. However, within the upper Mesozoic, the weakness zones are better described as flexures. They border asymmetric anticlines with a steep southern slope, but a gently dipping northern one. All three faults were active as reverse faults during the Upper Cretaceous. This is indicated by the internal reflection pattern of the Upper Cretaceous. Although all three anticlines formed contemporaneously, the inversion of the AKFZ lasted longer and experienced the strongest uplift with about 600 ms (or 900 m, assuming an average velocity of 3000 m/s; **Fig. 5**-**42**). Thus, most of the compressional pressure was released along this weakness zone.

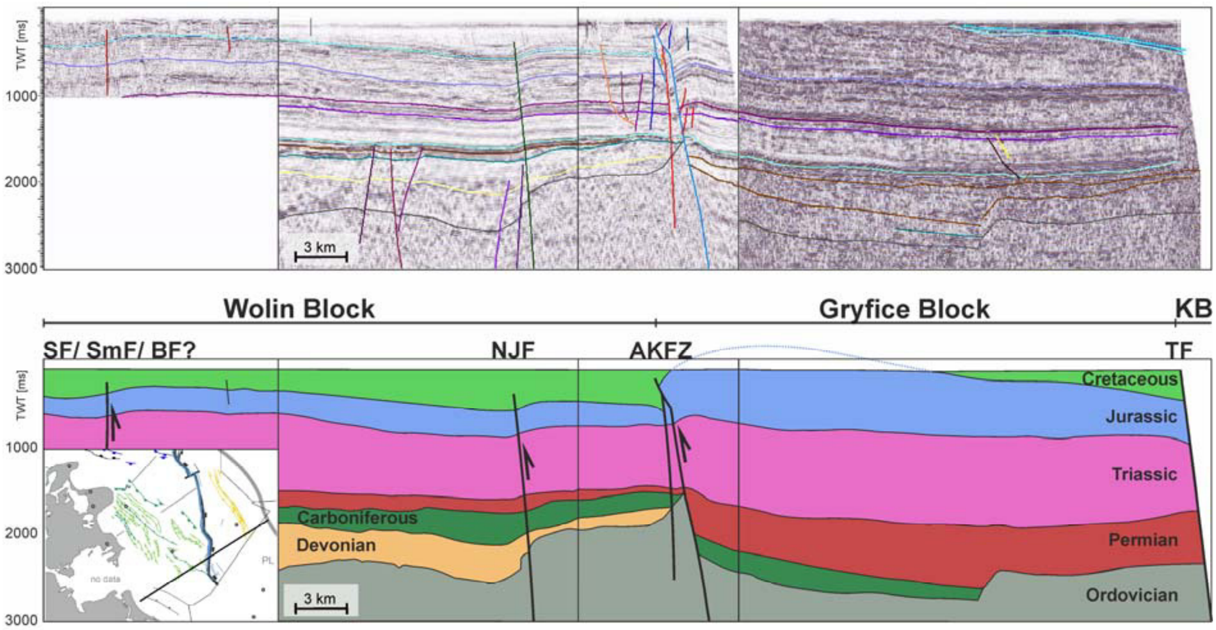


Fig. 6-3: Compilation of seismic sections crossing the anticlines from SW to NE. As can be seen, all anticlines are restricted to inverted faults. AKFZ–Adler-Kamień Fault Zone, BF–Bergen Fault, KB–Kołobrzeg Block, NJF–Nord Jasmund Fault, SF–Strelasund Fault, SmF–Samtens Fault, TF–Trzebiatow Fault. VE≈3, assuming an average velocity of 3000 m/s.

6.2 Structural evidence at the different blocks

6.2.1 Arkona Block

The Arkona Block is limited by the AKFZ towards the east and by the ***Wiek Fault*** towards the south (**Fig. 6-4**; SCHLÜTER et al. 1997*a,b*). According to THOMAS et al. (1993), the ***Agricola-Svedala Fault*** terminates the Skurup and Arkona blocks to the west. It is also known as the Agricola Fault (e.g. MAYER et al. 1994) or Agricola-Arendsee Fault (e.g. SCHLÜTER et al. 1998). ERLSTRÖM et al. (1997) argued that this fault must be separated into the SSW striking Svedala Fault, terminating the Skurup Block to the west, and the southward trending Agricola Fault, limiting the Arkona Block to the west. DEUTSCHMANN et al. (2018) in turn favoured the term Agricola-Svedala Fault. Within this study, only two shallow seismic sections crossed the Agricola(-Svedala) Fault (**Fig. 5–28**) and could not be traced that deep. Thus, a block separation was not discernible. According to SCHLÜTER et al. (1998), this structure was formed by a strike-slip fault, displacing particularly the deformed strata within the accretionary wedge during the Early Palaeozoic.

The ***Skurup Fault*** (SCHLÜTER et al. 1997*b*) is also known as the northern prolongation of the Adler-Kamień Fault Zone and is therefore often referred to as the Nord Adler-Kamień Fault (MAYER et al. 1994, THOMAS et al. 1993; **Tab. 5-13**). As indicated by the seismic sections (**Fig. 5–26**), the northeastward dipping Skurup Fault separates the Arkona Block to the Skurup Block in the north. This is contrary to previous work, which defined the ***Jütland-Møn Fault Zone*** as the northern border (e.g. FRANKE & HOFFMANN 1988, THOMAS et al. 1993 or MAYER et al. 1994). According to FRANKE (2018, and citations therein), the Jütland-Møn Fault was also known to separate the southern part of Baltica, covered by the Caledonian-deformed Ordovician, from the northern part of Baltica with an undeformed Lower Palaeozoic cover. At the same time, the Arkona Block was divided into a northern and southern sub-block (FRANKE 1993). However, the interpretation of the seismic sections show a clear limitation of the Arkona–*horst*–Block by the south-southeastward dipping Wiek Fault and the northeastward dipping Skurup Fault (**Fig. 6-4**). Due to the limitation of the working area, the Skurup Fault could not be traced further in NW direction. As indicated in e.g. VEJBÆK & BRITZE (1994) and SCHLÜTER et al. (1997*a,b*), the Skurup Fault strikes out north of Rügen, so NW of this point the Arkona Block seems to merge with the Skurup Block.

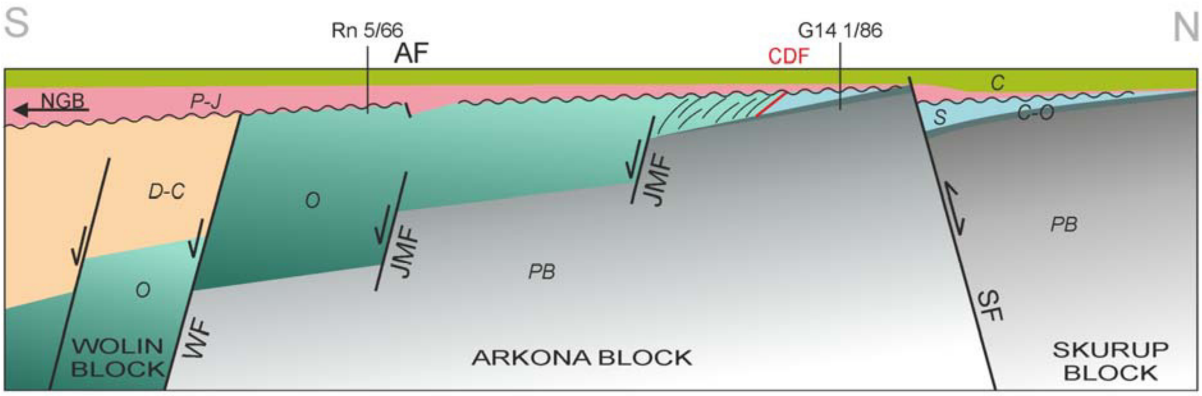


Fig. 6-4: Schematic sketch of the Arkona Block with the bordering Wiek Fault (**WF**) and Skurup Fault (**SK**), such as the block crossing Jütland-Møn Fault Zone (**JMF**) and the Arkona Fault (**AF**). Shown stratigraphic successions are the Proterozoic Basement of Baltica (**PB**) with a Neoproterozoic to Ordovician sedimentary cover (**C-O**), Silurian successions covering Baltica (**S**), the folded Ordovician within the accretionary wedge (**O**), the Devonian to Carboniferous successions along the Wolin Block (**D-C**), the Permo-Jurassic strata thickening towards the centre of the NGB (**P-J**) and the Cretaceous to Quaternary successions (**C**). The undulating line marks the Pre-Permian (Asturian or Sudetian) Discordance.

The uppermost platform of the Arkona Block is dipping slightly towards the E (**Fig. 6-1*B***). The ***Pre-Permian unconformity*** limits the top of the accretionary wedge (south of the CDF) and the Silurian cover of Baltica (north of the CDF), resulting by the exposed position as a local high during Late and Post Variscan tectonic processes and an increased erosion. Even during the formation of the CEBS since the Permian, the area north of Rügen was exaggerated and formed islands in eastern prolongation to the Ringköbing-Fyn and Møn highs. Due to the sedimentary and hydrological effects, this area is also known as the ***Arkona High*** or Arkona Swell (**Tab. 5-13**). The sedimentation was mostly restricted to its flanks or controlled by high water levels. According to well G14 1/86, the reworked Permo-Triassic sediments on top of the Arkona Block could not be stratified in detail. Residual Jurassic sediments maybe preserved in local depressions as indicated in **Fig. 5-21**. Although there are no further well information, one indication was provided by STUMPF et al. (2015), who analysed allochthone, but still well preserved dinosaur bone fossils in Upper Pliensbachian to Lower Toarcian sediments of Grimmen (NE Germany). Those fossils indicate short transportations and are assumed to originate from the Ringkøbing-Fyn High or the Fennoscandian Shield. Hence, they might also originate from the Arkona High and confirm the findings of this work.

Since the Upper Cretaceous, a basin formed north of the Grimmen Wall, between Rügen and Sweden, thus tilting the Arkona Block (KRAUSS & MAYER 2004). The Danish-Polish Trough lies NE of the Arkona Block (VEJBÆK 1985). Concurrent, thick Cretaceous marl was deposited onto the Permo-Triassic strata along the Arkona Block (**Fig. 6-1*F***).

6.2.1.1 Caledonian accretionary wedge, Variscan remains and younger displacements

The Proterozoic crystalline and sedimentary rocks, which belong to the basement of Baltica, have been drilled only 2 km below the surface (see well G14 1/86). The Cambrian shales of the basement of Baltica are covered by autochthonous Ordovician and Silurian sediments. Further to the SW, the

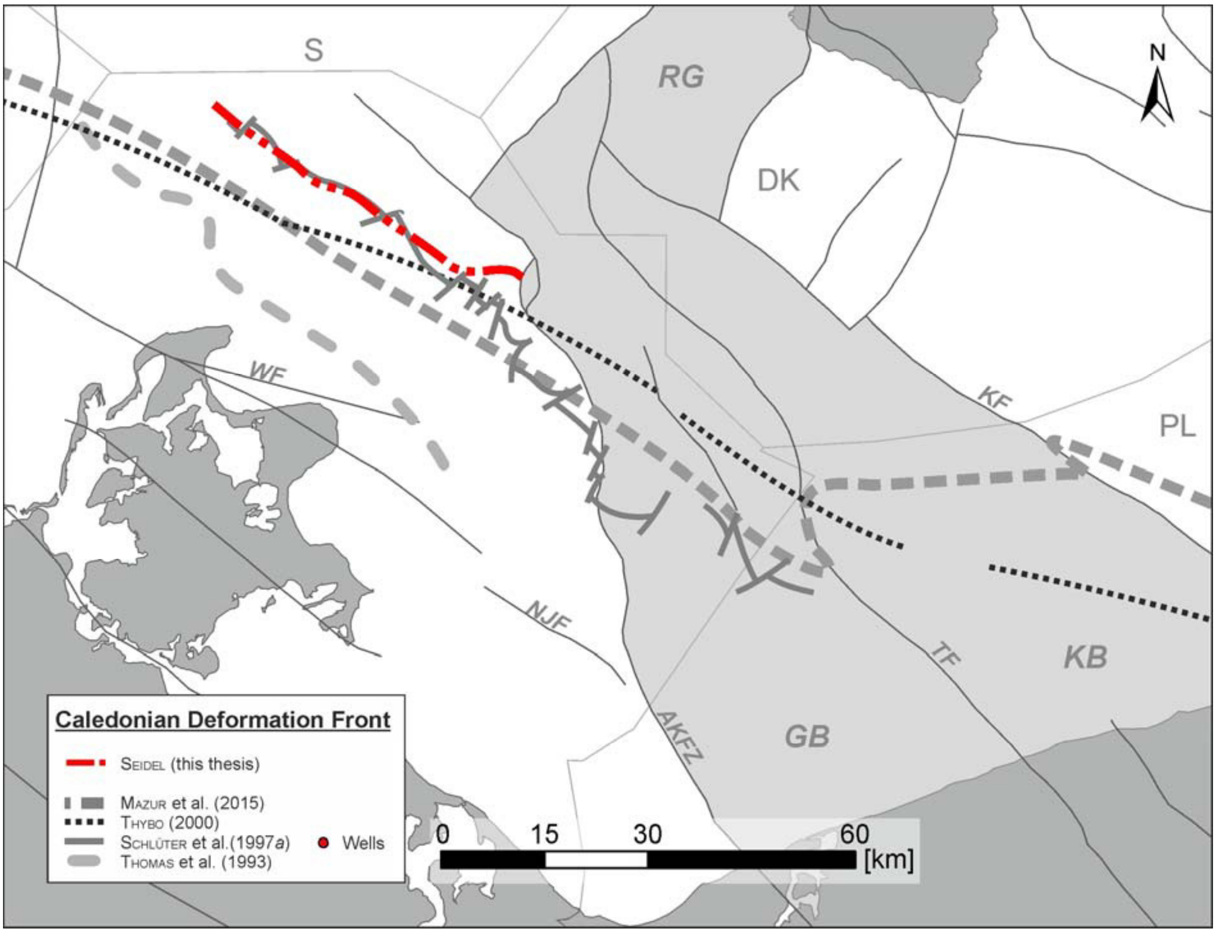


Fig. 6-5: Comparison of various depictions of the CDF with the findings of this thesis.

autochthonous Cambrian to Silurian deposits are overthrust by allochthonous Ordovician sediments, which were originally deposited within the Tornquist Ocean between Baltica and Avalonia. Since the Caledonian Orogeny, these allochthonous sediments form an accretionary wedge between the terranes and are part of the TESZ (**Section 3.3.1**).

The northernmost extension of this accretionary wedge is marked by the **CDF.** Its location was mapped further north than illustrated in previous work (e.g. THOMAS et al. 1993, THYBO 2000, MAZUR et al. 2015). The interpretation of SCHLÜTER et al. (1997*a*) indicated a strong lateral displaced deformation front which runs subparallel west of the AKFZ before it transects the same and crosses well K5 1/88 in an easterly direction. The course of the CDF along the Arkona Block until the vicinity of well G14 1/86 as proposed in this thesis coincides with the results of the SASO project (SCHLÜTER et al. 1997*a,b*), while the southeastward extension was not reproducible. As shown in **Section 5.2.1.6,** an angular discordance is traceable between the southward dipping internal reflections of the overthrust Ordovician strata and the horizontally laying, undeformed but southward thickening Silurian deposits. This structure was not found along the Gryfice Block and could not be traced further east. MAZUR et al. (2015) indicated a sinistral displacement of the CDF along the Trzebiatow and Koszalin faults. This is also conceivable along the AKFZ. Hence, the CDF is assumed further north at the Gryfice Block, due to a sinistral displacement at the AKFZ. The offshore wells at the Gryfice Block K5 1/88, K1 1/86, and L2 1/87 (the latter two are located in the Polish offshore region) also contained folded Ordovician successions (KATZUNG 2001, KOSAKOWSKI et al. 2010). Thus, the CDF has to be located at least north of those wells.

Faults at the Arkona Block introduced in **Section 5.2.1** are divided into basement faults, such as the WNW striking Agricola-Svedala Fault or the Wiek Fault, and the younger faults displacing the top of the accretionary wedge (t-O_{aw}) and the Permo-Triassic successions or even Cretaceous deposits above it (e.g. Agricola-Svedala, Hiddensee or Arkona faults; **Fig. 6-6**).

Thus, all mapped subparallel WNW striking fault planes dipping towards the SW and downfaulting the basement of Baltica and the accretionary wedge are summarised as the ***Jütland-Møn Fault Zone***. This Fault Zone is also known to extend in a west-northwestern direction across Møn, Falster and Jütland until the North Sea bordering the Ringkøbing-Fün High in the south (FRANKE 2018, and citations therein). Further fault planes of the Jütland-Møn Fault Zone (compared to those in MAYER et al. 1994, **Fig. 6-6**), have been mapped between the Agricola-Svedala and Hiddensee faults. According to FRANKE & HOFFMANN (1988), this fault zone reaches from Jütland, separating the Precambrian of the Ringköbing-Fyn High from the Palaeozoic Danish Depression, to Koszalin (Poland).

The affiliation of a small WNW trending graben structure between the CDF and the Skurup Fault remains unclear. Based on its strike direction, it might be part of the Jütland-Møn Fault Zone, but while all other faults concentrate in a zone of about 10 km width (in NNE–SSW extension), the small graben lies at 12 km distance towards the NNE. Its close position near the Skurup Fault might also indicate an affiliation to the northern border of the Arkona Block. MAYER et al. (1994) indicated a relation to the Skurup Fault.

The NNE striking ***Hiddensee Fault*** (SCHLÜTER et al. 1998) is the western border of a previously postulated graben structure named the Nordrügen-Skurup Fault (THOMAS et al. 1993), or the Schwerin-Vätternsee Fault (SEIFERT et al. 1993, MAYER et al. 1994). The eastern synthetic fault plane of a possible graben could only be registered within the seismic section in **Fig. 5–27**. This line shows an asymmetric structure with the highest displacement close to the Hiddensee Fault. Finally, this structure was defined as a half-graben due to a missing antithetic fault plane, which was traced in adjacent seismic sections. As mentioned in **Section 5.2.1.3,** the Hiddensee Fault displaced successions from the base of the Cretaceous to the Proterozoic basement. While the Cretaceous shows indications for a reverse flexure along this fault, the Permo-Triassic successions are almost equally downfaulted. The basement of Baltica reaches a vertical displacement of 500 ms. Assuming an average velocity of 6000 m/s, this corresponds to a depth of 1500 m. Hence, this fault and half-graben probably were Post-Caledonian age and reactivated during the Upper Mesozoic.

The character and origin of the NNE dipping ***Arkona Fault*** might be related to the transtensional stress system during the Mesozoic. The fault seems to border a half-graben or at least a syncline structure to the south (**Fig. 5–25** & **Fig. 5–28**). The decrease of the amplitude within this structure supports this interpretation, and might indicate fluid-bearing deposits within the Permo-Triassic succession, leading to a velocity pull down and amplitude variations, resulting in a final picture that appears like a depression. A neotectonic activity cannot be excluded, due to a disrupted reflection pattern and lateral changing amplitudes above the mapped base of Cretaceous.

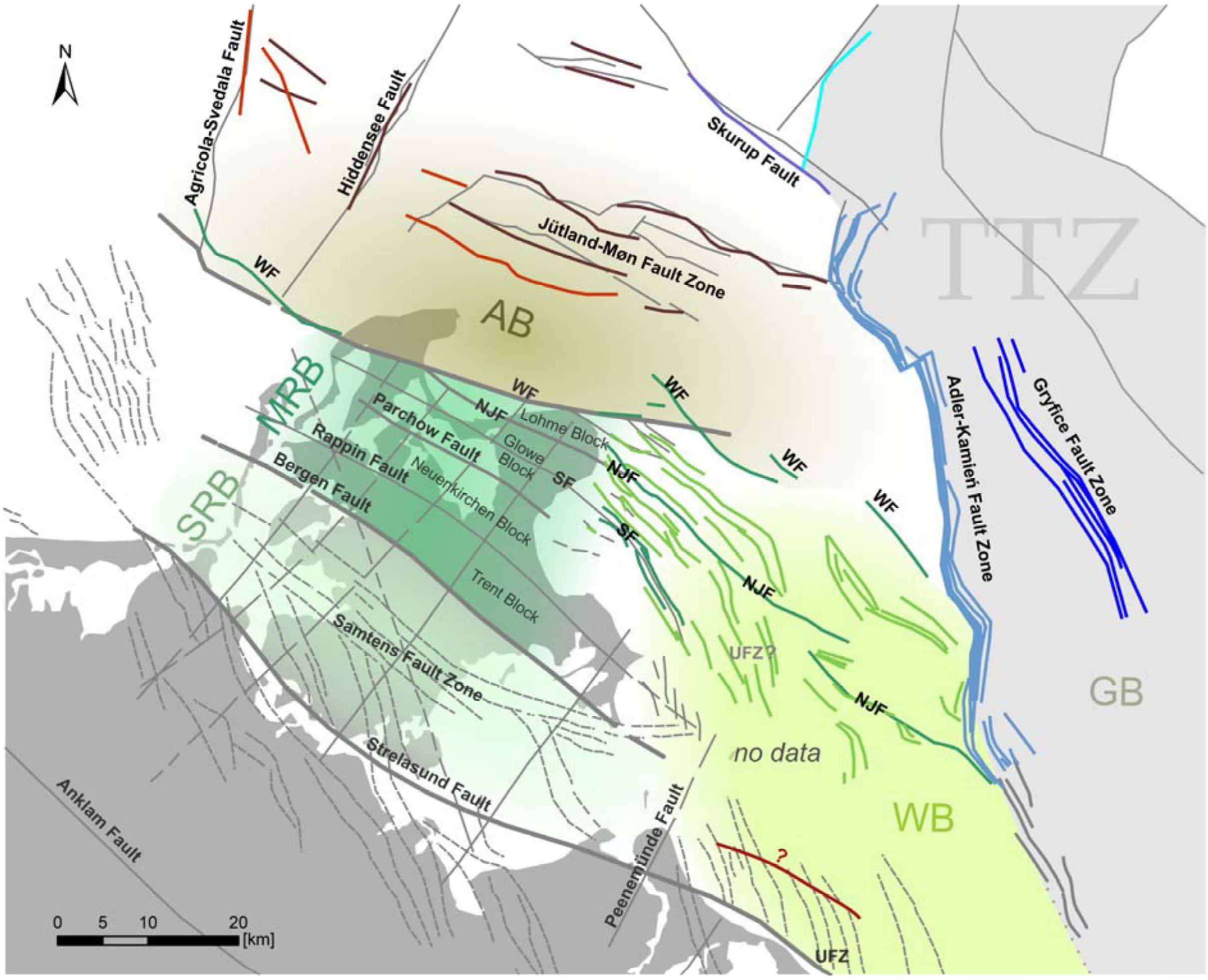


Fig. 6-6: Results of the analysed faults in comparison with previous published fault patterns (grey solid lines – Palaeozoic faults according to THOMAS et al. 1993; MAYER et al. 1994; grey dashed lines – Mesozoic faults according to KRAUSS & MAYER 2004) crossing northern Germany (SEIDEL et al. 2018, modified). Faults at the Arkona Block are separated into deep faults, displacing the basement (brown coloured) and shallow faults, displacing the Ordovician, Permo-Triassic and Cretaceous successions (red coloured). Moreover, the Gat Fault is coloured light blue, WFS–green, AKFZ – light blue, and the Gryfice Fault Zone –dark blue. The dark red fault south of the Wolin Block is not assigned jet, but might be a prolongation of the Strelasund Fault. AB–Arkona Block, MRB–Middle Rügen Block, NJF–Nord Jasmund Fault, SF–Schaabe Fault, SRB–South Rügen Block, TTZ–Teisseyre-Tornquist Zone, UFZ–Usedom Fault Zone, WF–Wiek Fault.

Faults with a WNW to NW or NNE striking direction cross the Arkona Block, and indicate an evolution during different stress systems. Major steep faults strike WNW and intersect especially the basement of Baltica (e.g. the Jütland-Møn Fault Zone). Some of these seem to intersect even the top of the accretionary wedge but due to the transgression at the top and the chaotic to subparallel reflection pattern, a vertical displacement is not clearly visible. Thus, these faults might be formed either during the overthrusting of Avalonia onto Baltica, or, more likely, contemporaneous with the origin of the deep Palaeozoic faults crossing Rügen. They were formed during a phase of extension during the Devonian and Lower Carboniferous, when the Middle Devonian Old Red Rügen Basin formed (AEHNELT & KATZUNG 2009). KRAUSS (1994) described the stepwise dipping of the Ordovician complex. The sediments are about 850 m below the surface along Arkona (north of Rügen) and 7 km below the south of Rügen.

The Skurup Fault and its assumed western extension, such as the about 100 m subsided graben structure (**Fig. 5-25**; assuming an average velocity of 4000 m/s and 50 ms displacement for the base of Silurian), are related to the Palaeozoic evolution of the Tornquist Zone, especially the STZ, which strikes parallel to the Skurup Fault. Moreover, the generation of the Adler-Kamień Fault Zone and the subsidence of the Gryfice Block as part of the TTZ may have occurred contemporaneously.

The SSW striking Hiddensee (**Section 5.2.1.3**) and Agricola-Svedala (**Section 5.2.1.5**) faults trend almost perpendicularly to the steps of the Proterozoic basement, and are therefore subparallel to the ***Gat Fault***, which is the western border of the Rønne Graben and separates the Skurup Block from the western flank of the Rønne Graben. This Gat Fault strikes NNE, parallel to the seismic sections (**Fig. 5-26**) and could therefore not be visualised in the seismic profiles. However, its major displacement of about 400 ms can be seen in the gridded time structure maps (**Fig. 6-1*A&C***). Moreover, since all extend vertically from the Proterozoic basement until the Permo-Triassic sedimentary cover, their evolution seems to be connected with the opening of the Rønne Graben during the pre-Permian and continuing into the Late Mesozoic (DE VOS et al. 2010, PHARAOH et al. 2010).

6.2.1.2 Degassing structures or Quaternary channels?

Early studies, such as WEGERDT et al. (1994), interpreted the ***velocity pull down patches*** as ***Pleistocene channels***. FLODÉN et al. (1995, **Fig. 6-7**) explained the structures more precisely as "valleys [...] in the Upper Cretaceous to Lowermost Tertiary sedimentary bedrock [...] of a periglacial origin, formed during major standstills by meltwater erosion at or closely inside the margin of the ice sheets." Similar glacial valleys are known along the entire southern border of the Fennoscandian Shield, such as the western Swedish coast, SE of Gotland, along the Hanö Bay, NE of Bornholm, and within the Arkona Basin (FLODÉN et al. 1995, SCHLÜTER et al. 1998, JORGENSEN & FOSSING 2011). For the latter, seismic records show a formation within three different stages. The up to 600 m broad channels cut up to 100 m into the underground and were filled by till, silt and clay (FLODÉN et al. 1995). FLODÉN et al. (1995) assumed a correlation of the three different stages with the ice advances of the three last glacial maxima (Elsterian, Saalian and Weichselian). Moreover, FLODÉN et al. (1995) proposed **acoustic pseudo-valley structures** which originated due to gas-driven velocity anomalies. Velocity anomalies within the Baltic Sea, caused by degassing or gas-bearing sediments, have been identified by e.g. TÓTH (2013) and SCHNEIDER VON DEIMLING et al. (2013) in the Hanö Bay, BRODECKA et al. (2013) in the Polish Baltic Sea, and MATHYS et al. (2005) and THIEßEN et al. (2006) in the Arkona Basin. The comprehensive BALTIC GAS final report (2009-2011) illustrates the biogenic gas deposits within the Baltic Sea. The Arkona Basin belongs to an area with high benthic (CH4) flux rates of up to 1220 umol/m²/d (JØRGENSEN & FOSSING 2011).

Hence, the velocity pull down structures, registered in the USO database and shown in this thesis, are bound to single round or elongated predominantly NE striking patches of gas-bearing sediments. Based on their location, they might be related to the Quaternary glacial channels (WEGERDT et al. 1994, FLODÉN et al. 1995, SCHLÜTER et al. 1998), which are filled and covered by clayey to muddy organic-rich sediments, such as postglacial Holocene mud related to the Littorina facies (THIEßEN et al. 2006, SCHMALE et al. 2010). In this case, the shallow gas would be of biogenic origin such as microbial methane production (SCHMALE et al. 2010). **Fig. 6-7** compares the results of this thesis, including the locations of the velocity pull down structures, with the two different channel maps of FLODÉN et al. (1995) and SCHLÜTER et al. (1998). Due to their different data bases, the two older maps show some deviants, but the general WSW-trend of the major channels and their branches correlate each other. Most of the mapped velocity pull down patches are located within the previously observed channels. Some circular structures lie outside the channels. Furthermore, the connection to the faults is not fully understood. Most of the degassing structures and previously mapped channels are positioned between the NNW trending Hiddensee Fault and the related half-graben, or in the vicinity of other WNW striking faults, such as the Arkona or Jütland-Møn faults.

Thus, instead of biogenic gas, another source might be related to degassing processes of the Early Palaeozoic deposits. The German offshore area north of Rügen is characterised by diverse faults and weakness zones partly of Palaeozoic (Variscan) but also of Mesozoic age. Gases might arise from the faulted and folded accretionary wedge (predominantly Ordovician black shales). Although REMPEL (1992) evaluated the Arkona High (Block G, defined by Petrobaltic, see **Chapter 2**) and the northern part of the Gryfice Block (Block K defined by Petrobaltic) as non-prospective for oil and gas bearing sediments, he identified positive source rock properties for the Cambrian to Lower Ordovician sediments with up to 14% C_{org}-content. The main phase for petroleum genesis took place during the Late Silurian and was followed by gas generation. The hydrocarbons probably migrated into the Devonian and Carboniferous reservoir rocks, which have recently been eroded along the southwestern border of the EEC (REMPEL 1992). Organic-rich Cambrian and Lower Ordovician deposits, which have been faulted and folded within the accretionary wedge (similar to those indicated in well Rn 5/66, BEIER 2001), might also be appropriate source rocks for petroleum generation (temperature, pressure, burial depth). Possible gas traps within or between the accretionary nappes could might have been disturbed by subsequent tectonic processes since the Late Palaeozoic. Existing or reactivated faults, fissures, and layer or nappe boundaries could have acted as migration pathways. This theory is based on the huge amount of degassing structures close to the Hiddensee and Arkona faults and the dominating fluid indications south of the CDF. However, the latter might be an effect of the data density (seismic sections), which predominates on an area south of the CDF.

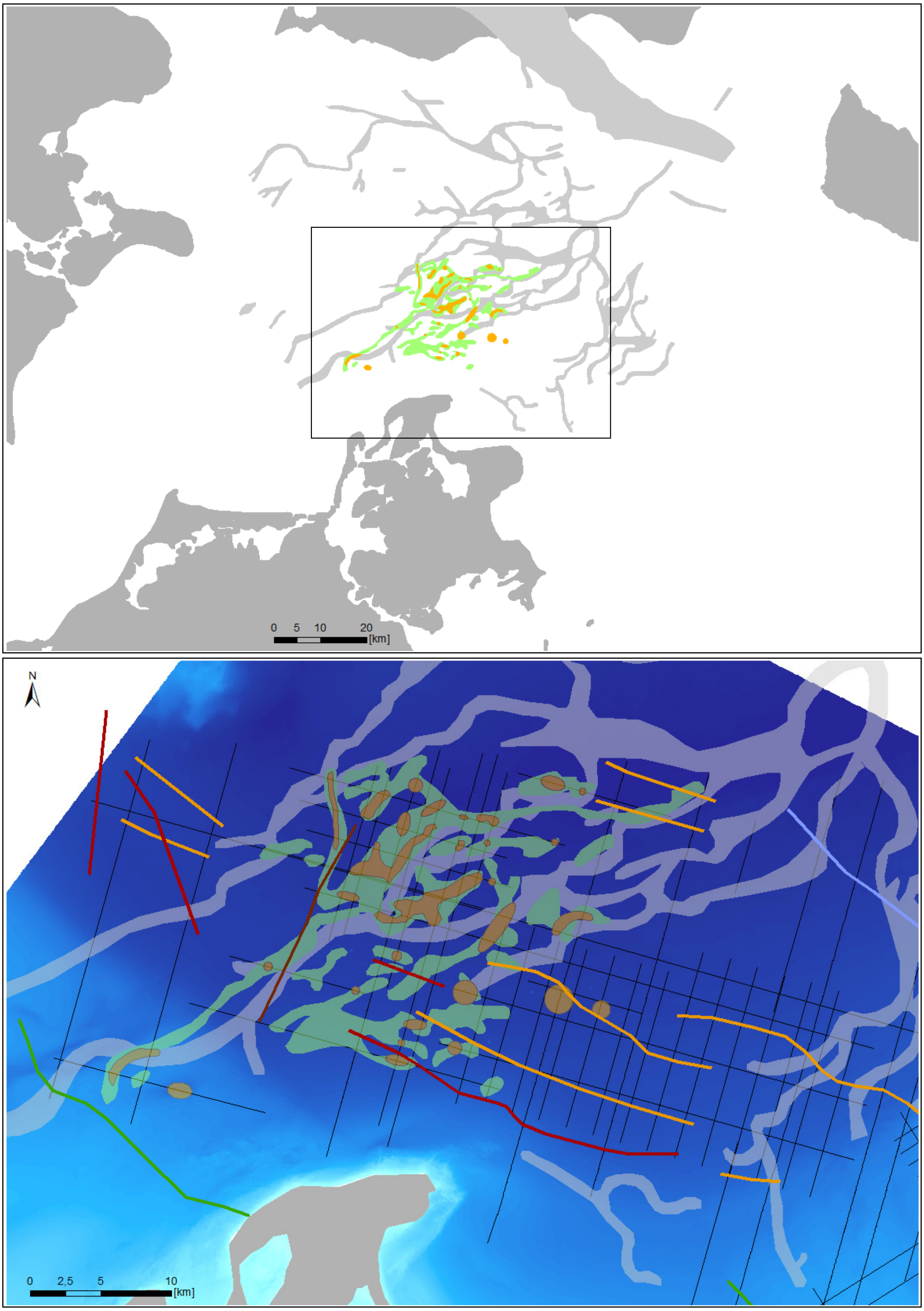


Fig. 6-7: Distribution of Velocity Pull Down Patches (orange) mapped in the USO East area, compared with areas without a significant sea floor relief but filled channel structures as mapped by Schlüter et al. 1998 (green) and the superior valley system as mapped by Flodén et al. 1995 (grey). Bathymetry by Tauber (2012*a*-*i*).

6.2.2 Middle Rügen and Wolin blocks – Wiek Fault System: Characterisation and formation, relationship with other Palaeozoic faults and the WPFS

As introduced in **Section 3.3.3,** the previous work has focussed on one major fault plane that crosses the Wolin Block in a number of different ways. Thus, the location and appearance of the so-called Wiek Fault differs in the works of MAYER et al. 1994, ERLSTRÖM 1997, SCHLÜTER et al. 1997*b* and KRAUSS & MAYER 2004. The results on the faults crossing the Middle Rügen and Wolin blocks and their new compilation within the **Wiek Fault System (WFS)** have already been published by SEIDEL et al. (2018) and are summarised below.

The reinterpretation of NE and NW striking seismic sections shows a very complex fault and flexure inventory for the Wolin Block. About 60 single faults and flexures forming the WFS were mapped. The complete fault system crosses the Middle Rügen and Wolin blocks from NW to SE, similar to the already known Palaeozoic deep faults at the Arkona Block and the Jütland-Møn, Wiek and Bergen faults further south (MAYER et al. 1994 and SCHLÜTER et al. 1997*b*). On closer inspection, the single fault planes of the WFS change their strike direction internally. Thus, on and closely east of Rügen, they have a southeastward strike direction, which changes further south into a south-southeastward direction. Furthermore, towards the south the dislocations increasingly appear in younger strata. Thus, the Mesozoic displacements are predominantly self-standing, especially south of the Wolin Block. Only a minor number of faults indicate a Devonian origin followed by a Mesozoic reactivation.

The major central fault planes of the ***NJF*** changes laterally (towards the SE) from a southwestward to a northeastward dip direction, and a normal displacement to a reverse displacement, with an increasing impact on Mesozoic strata towards the south. Furthermore, the NJF is displaced between the planes WFS_8A and WFS_8Sued. Similar to the schematic sketch in **Fig. 6-8**, both fault planes form an overlap and a relay ramp in between. The general orientation of the overlap and the relay ramp in between form a transition from the exaggerated area in the north of the faults towards the lower area in the south. According to PEACOCK & SANDERSON (1995), antithetic faults are generated along a relay ramp and the overall structure indicates a sinistral displacement. The faults ***WFS 19, 19a*** and ***19b*** (**Fig. 5–34*d***, **Fig. 5–24**), which are located between the two overlapping master fault planes of the NJF, form a small-scale positive flower structure or compensative cleavages within the Ordovician to Buntsandstein successions. Hence, they might represent the antithetic faults formed due to transpression along the relay ramp. The formation of the overlapping fault planes along the NJF and the antithetic faults in between might be related to their primary origin during the Devonian basin formation or the Upper Carboniferous compression, when the Variscan Orogeny resulted in far field transpression. Both phases allow a sinistral displacement along the NJF. The first option is related to a N-S orientated extension, inducing sinistral shearing or transtension along the NW trending faults (**Fig. 6-9A**). The general Variscan-induced compression was NE-SW orientated and caused primordially lateral shortening and compression. The clockwise rotation of the Variscan complex, such as the ATA

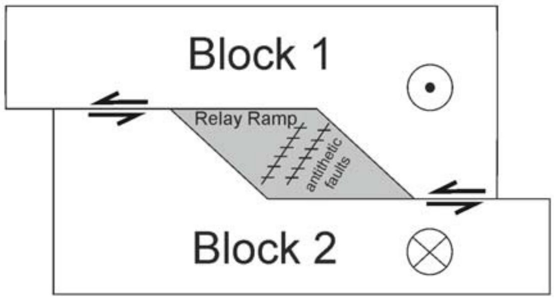


Fig. 6-8: Schematic sketch of a relay ramp between overlapping faults and antithetic faults crossing the ramp, marking the sinistral strike direction along a strike slip fault (modified after PEACOCK & SANDERSON 1995).

and Gondwana, during the collision and orogeny (PHARAOH et al. 2010) might have led to a local variating stress system. Subsequently, the main compressional component trending almost E-W, reactivating the NW trending faults of the WFS by transpression and a sinistral shear sense (**Fig. 6-9B**). Additional indicators for a sinistral displacement are only given by the lateral displacements of the AKFZ. Those offsets can be seen further SE of the WFS_8Sued fault plane, where the NJF merges into the AKFZ, named Oderbank Triple Junction by SCHLÜTER et al. (1997*a*), and at the junction between the AKFZ and the Wiek Fault. At both junctions, the AKFZ seems to be sinistral displaced by the NE trending faults. However, during the following post-Variscan tectonic phases, only dextral transtension or transpression triggered the reactivation of the NJF (for example during the Triassic-Jurassic). Hence, the generation of this ramp cannot be dated confidentially. As shown by the restoration, the Nord Jasmund master faults have been induced during the basin formation (**Fig. 6-9A**) and were reactivated during the Variscan compressional phase. Both scenarios allow a sinistral displacement, whereas the generation of antithetic fault planes between the overlapping master fault planes of the NJF (see **Fig. 6-8**), require transpressional forces, which are only realised during the second phase (**Fig. 6-9B**).

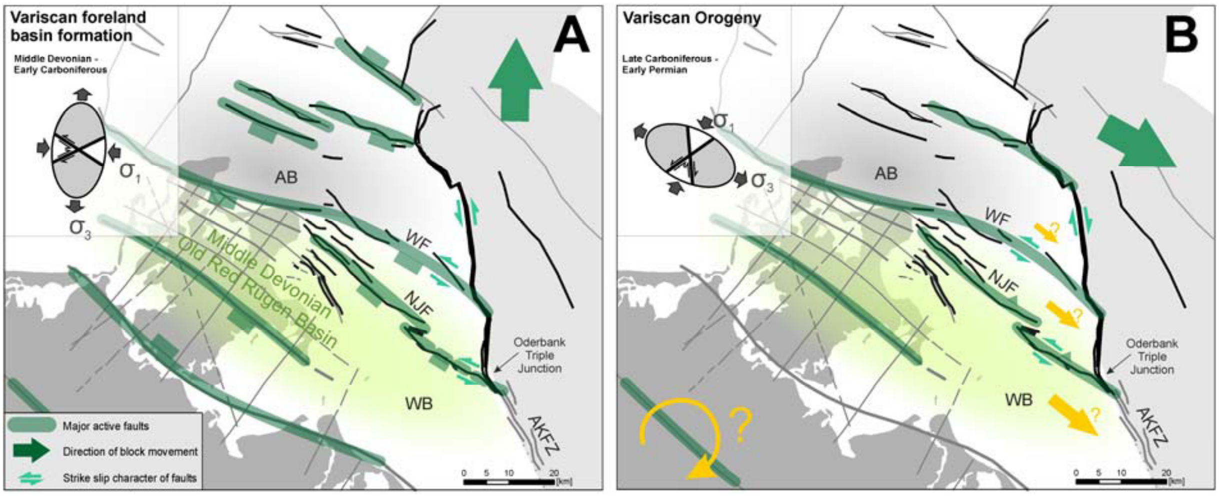


Fig. 6-9: Possible tectonic phases triggering a sinistral strike-slip activity along the Palaeozoic deep faults (NJF-Nord Jasmund Fault, WF-Wiek Fault) which subsequently displaced the NNW striking Adler-Kamień Fault Zone (AKFZ). **Scheme A** shows a possible sinistral displacement during the Variscan foreland basin formation, while a N-S extension was active. Note the deformation ellipse. **Scheme B** illustrates the situation during the Late Carboniferous to Early Permian compression. A pure NE-SW orientated compression (as delineated by the deformation ellipse) would have forced reverse faulting along the NW-SE trending faults. The clockwise rotation of the Variscan orogenic complex (indicated by the yellow arrow) may have been transferred to Laurussia and in particularly on the TESZ. The resulting transpression may have led to a decreasing southeastward motion of the southern and northern Wolin Block (WB) and the Arkona Block (AB), and a relative sinistral displacement along the block-terminating faults (NJF, WF).

As introduced in **Section 3.3.3,** the deep-seated Palaeozoic faults, crossing Jasmund have been illustrated in a number of different ways. The term NJF is based on MAYER et al. (1994) or PISKE et al. (1994), whereas SCHLÜTER et al. (1997*a*) used the term Sassnitz Flexure (**Tab 5**–**13**) and others often referred to it as the Wiek Fault (e.g. ERLSTRÖM et al. 1997). However, as argued by SEIDEL et al. (2018), the original label NJF is preferred.

The true ***Wiek Fault***, on the other hand, is segmented into different fault planes (WFS_7b, 24, 24a, 25 & 26) and borders the WFS to the north. It separates the folded Ordovician at the Arkona Block against the Devonian and Carboniferous within the Old Red Rügen Basin (AEHNELT & KATZUNG 2009) and was already mentioned in previous works such as KURRAT (1974), FRANKE & HOFFMANN

(1988), MAYER et al. (1994) and PISKE et al. (1994). The restoration results of two seismic sections, both crossing the WFS, supports the hypothesis of a first activation of the ESE to SE trending faults during the Devonian, and a relation to the formation of the Middle Devonian Old Red Rügen Basin. The **southern Wiek fault planes** indicate a last activity during the Permian by displacements within the Zechstein successions. According to FRANKE (2018), the Wiek Fault exhibits a total vertical displacement of 3500 m. FRANKE & HOFFMANN (1988) calculated 5000-6000 m for the assumed primary thickness of Devonian and Carboniferous successions along the Arkona and Wolin blocks. However, the vertical displacement varies between 1000 m and 100 m (assuming an average velocity of 3000 m/s), with a general decrease from the NW towards the AKFZ in the SE (e.g. **Fig 5–39*b*)**. The en echelon faults overlap in the north and underlap in the south. The offsets are framed by relay ramps and, in some cases, NE-SW trending sinistral strike slip faults (Wiek_new), which were recognised within the time structure maps by elongated steps in the morphology (see **Fig. 5–6**).

SW of the Nord Jasmund Fault, a set of several faults strike parallel to each other and dip towards the NE. The southwestern one, **WFS_10c** (**Fig. 5–34a** & **Fig. 5–37**), is considered to form the offshore continuation of the Palaeozoic **Schaabe Fault**, known from Rügen, intersecting the Glowe Sub-block (MAYER et al. 1994, PISKE et al. 1994, FRANKE 2018). According to SEIDEL et al. (2018) and the restoration results shown in **Section 5.2.2.1**, the Schaabe Fault was also generated during the evolution of the Middle Devonian Old Red Rügen Basin. As indicated in **Fig. 5–37*G-F***, it lies about 4 km NE of the southwestern margin of the NW striking basin. During the Variscan-induced block faulting (Upper Carboniferous), this fault was reactivated in a reverse sense (**Fig. 5–37*E***).

The single fault planes **WFS_Prezechstein1-6** (also labelled **WFS_PZ1-6**; see **Figs 5–23, 5–34e** and **5–35**) displace the Palaeozoic and have a different orientation and origin. They generally indicate a strike-slip motion and a transpressive stress system. An exact determination of their age has not yet been possible. However, their formation and reactivation is most likely related to the Palaeozoic extension and compressional phases. The fault planes WFS_PZ1 and WFS_PZ2 possibly formed prior to the NJF during the Middle Devonian Basin formation, which is the reason why they dip towards the SW. During the following compressional phase during the Upper Carboniferous, the actual NJF (WFS_8Sued) might have formed as an antithetic thrust fault dipping towards the NE.

The weakness zone formed by **WFS_21&22** possibly continues to the surface. Although these faults are part of the WFS, they lie close to the AKFZ. They are Late Mesozoic to Cenozoic structures formed during the Cretaceous inversion and the associated overthrusting along the AKFZ.

The **WFS_9a, b & d, 16a, c & e** and **18a** displace the base of Cretaceous, but do not propagate through the entire Cretaceous succession. Therefore, they were active at the beginning of the Late Cretaceous.

Some shallow faults were detected close to the surface, indicating neotectonic activity. As indicated by further velocity pull-down structures, these shallow faults could relate to fluid-bearing sediments or degassing structures which concentrate in the area of the Schaabe Fault, close to the eastern coast of Rügen. However, the structures might also be related to the thick mud succession in the Odra-Channel.

There are two general types of faults and flexures, summarised as WFS: **(1)** the WNW to NW trending Palaeozoic deep fault crossing Rügen and the Wolin Block (see **Section 3.3.3**), and **(2)** the NNE striking Mesozoic faults and flexures, which are usually arranged as a set of master and antithetic faults or flexures, forming Y-shaped depressions. As mentioned in **Section 3.3.3,** similar alternating en echelon structures are known from the mainland as WPFS (KRAUSS & MAYER 1999, Mayer et al. 2000, Krauss & Mayer 2004). Seidel et al. (2018) already assumed a lateral correlation of the Usedom Fault Zone (as part of the WPFS, **Fig. 6-6)**, although there is not sufficient data to claim this with any certainty. The faults of the **WPFS** concentrate in an area north of the southern flank of the Grimmen Wall (Krauss & Mayer 2004). The Samtens Fault Zone was previously considered to present the northern boundary of the WPFS (**Fig. 6-6**, **Section 3.3.3**; McCann 1996, Krauss & Mayer 2004), but Seidel et al. (2018) argued for a continuation until the Wiek Fault. Moreover, the NJF and Samtens Fault intersect the WPFS. Towards the east, it is delimited by the AKFZ. The western prolongation of the WPFS is not entirely traceable due to missing data between Germany and Denmark. The Agricola Fault Zone might have a far prolongation towards the NW. Krauss (1994) postulated a transition into the WNW-ESE striking faults south of the Ringkøbing-Fyn High. Deutschmann et al. (2018) presented further results of the reinterpretation of seismic sections, west of Rügen Island, along the Middle Rügen and Falster blocks, and pointed out the association of the Werre Fault Zone and the Agricola Fault System with the WPFS. The Prerow Fault is terminated by the Werre Fault Zone, which is assumed to strike further NW towards Falster Island (Denmark). The Wiek Fault itself enters into the Odense Fault (Franke 2018 & citations therein) separating the Arkona Block from the Middle Rügen and Falster blocks (Deutschmann et al. 2018).

Reactivation of the shear zone

The polyphaser-evolved WFS is the most important key to reflect the reactivation phases along the TESZ. **Fig. 3–35** shows a cross section via the suture zone. The area between the Strelasund Fault (north of the Grimmen Wall) and the CDF frame the strike out zone of the TESZ, which is squeezed between the crust of Avalonia and Baltica, but buried by post-collisional sediments. This intra-crustal weakness zone has served as a stress compensation zone since its Caledonian evolution.

The most important phases after the Caledonian Orogeny are summarised by Seidel et al. (2018). The prominent SE to ESE striking faults formed during the Variscan extension, contemporaneous with the block faulting and evolution of the Middle Devonian Old Red Rügen Basin. Since the Upper Carboniferous, opposing forces have also triggered formation of the hinterland of the Variscan Orogen. Most of the faults have been reactivated and blocks such as the Lohme Block have tilted. A Permian to Lower Cretaceous extensional to varying transtensional stress system forced the formation of small graben structures as part of the WPFS, indicating a dextral strike slip movement along the TESZ. Since the Upper Cretaceous, the Africa-Iberia-Europe convergence has furthermore triggered a compression in the research area. During the Upper Cretaceous, this was NE-SW orientated, and forced the reverse reactivation of orthogonal striking faults (NJF, Samtens Fault) and the formation of anticlines. Herrig (2004) suggests a reactivation of the Wiek Fault, but this was not confirmed by the recent studies.

The debate on the Mesozoic shear sense was also adressed by Seidel et al. (2018). A dextral transtension was finally postulated for the Mesozoic reactivation of the WFS and the subsequent formation of the WPFS, with Y-grabens along releasing bends, in accordance with Krauss & Mayer (2004). Additionally, the northern part of the TESZ was extended from the previously assumed Samtens Fault (Krauss & Mayer 2004) to the Wiek Fault (Seidel et al. 2018).

6.2.3 Gryfice Block - Evolution along the Adler-Kamień Fault Zone and the contemporary formation of the Gryfice Fault Zone

The Gryfice Block is terminated and intersected by some fault zones. As introduced in **Section 5.2.3**, the German offshore area comprises the AKFZ that terminates the Gryfice Block to the west, as well as the Gryfice Faults that intersect this block.

The AKFZ comprises the steep ENE dipping major fault plane (AdlerKamien) and subparallel striking, vertical to steep syn- and antithetic dipping fault planes east and west of it, which are down-faulting the Proterozoic Basement, such as the Palaeo- and Mesozoic cover at the Gryfice Block (**Fig. 5**–**39**). These faults are the oldest ones and document the formation of the Gryfice Graben (**Fig. 5**–**43**). Moreover, there are further syn- and antithetic faults within the thick Mesozoic succession of the Gryfice Graben, bound to the anticline which formed since the Upper Cretaceous graben inversion (**Fig. 5**–**43**). The whole NNW trending fault zone concentrates in a zone of about 10 km width (W-E) and shows four horizontal displacements in its course. From SSE to NNW, those sinistral offsets are formed by the junctions with the NJF (Oderbank Triple Junction, according to Schlüter et al. 1997*a*) and the Wiek Fault further NNE, west of Jasmund (Rügen). These displacements are related to different NE or NW striking faults. In the NNE, the single fault planes of the AKFZ fan out and bend in a north-northeastward strike direction, before they enter into a triple junction with the NW trending Skurup Fault and the NE trending Gat Fault. The transition from the NW striking Gryfice Block to the NNE striking Rønne Graben is represented by a bounding zone where the NE striking faults of the AKFZ turn into NNE striking ones, parallel to the Gat Fault (western border of the Rønne Graben; **Fig. 6-6**) before the AKFZ enters into the Skurup Fault.

This enormous displacement has been previously discussed and attributed to the junction with other NW to NNW trending faults. According to Schlüter et al. (1997*a*), especially the southeastern fault within this bending zone was attributed to the ***Binz-Hamrarne Fault***, which is assumed to be the northern extension of the dominantly onshore, Proterozoic basement- displacing, SW–NE trending Rambow-Binz Fault (Franke 2018). New interpretations of this thesis do not support this hypothesis. The fault which is mapped within the Gryfice Block intersects the thick Late Palaeozoic to Mesozoic successions within the graben. West of the AKFZ, the thick Mesozoic cover is missing. Faults forming a stepwise displacement of the basement can be identified but not laterally correlated. These faults have a different age of development. A connection with the ***Pernille Fault***, described particularly in Danish publications such as Graversen (2004), is more likely. This steep E-SE dipping fault is restricted to the Rønne and Gryfice grabens and the Upper Palaeozoic to Lower Cretaceous successions. The Pernille Fault was also recognised within the seismic sections forming a reverse fault, while the major fault plain of the AKFZ or the Gat Fault

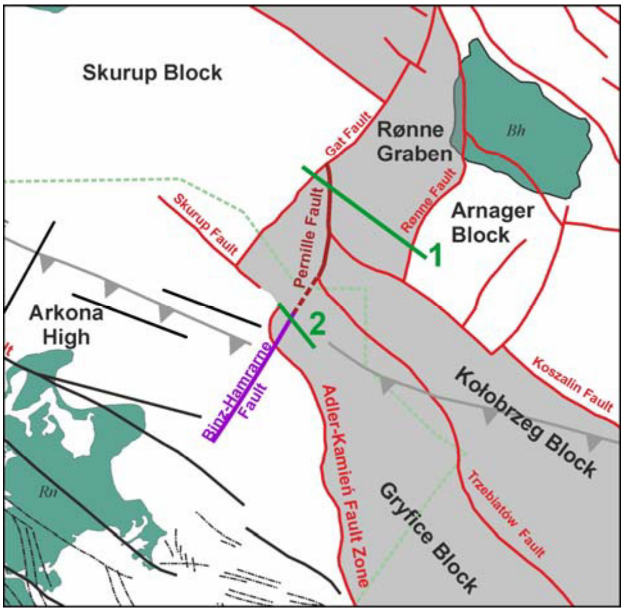


Fig. 6-10: Location of the purple Binz-Hamrane Fault (according to Seifert et al. 1993) and the dark red Pernille Fault (according to Graversen 2004). The green section **1** is based on results of Graversen (2004) and is compared with the actual results of a seismic section crossing the AKFZ (green section **2**).

were not reactivated as reverse or thrust faults (Fig. 6-11 & **Fig. 6-12**). This contradicts the situation further south of the AKFZ, where enormous inversion processes can be seen. Furthermore the structure indicates that along this bending zone, the Cretaceous and Tertiary compression was compensated by the Pernille Fault.

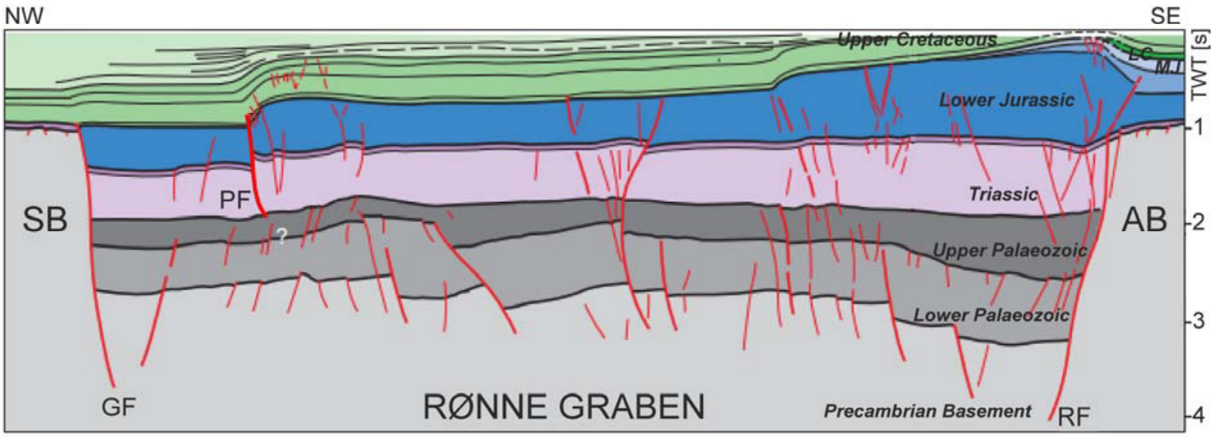


Fig. 6-11: Interpreted seismic section crossing the Rønne Graben, which is terminated by the Gat Fault (GF) to the west and by the Rønne Fault (RF) to the east, such as being cross-cut by the Pernille Fault (PF); AB-Arnager Block, LC-Lower Cretaceous, MJ-Middle Jurassic, SB-Surup Block; for location see **Fig. 6-10**, section 1 (Graversen 2004, modified).

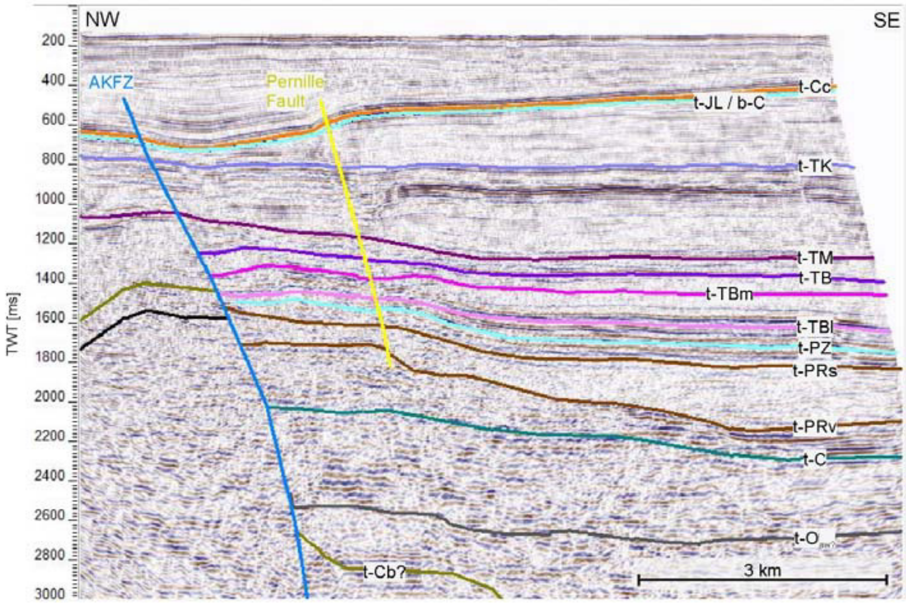


Fig. 6-12: Seismic section crossing the Adler-Kamień master fault (blue) and the Pernille Fault (yellow). For location see **Fig. 6-10**, section 2.

The **Gryfice Fault Zone** comprises conjugating fault planes which indicate a complex Palaeozoic generation and Mesozoic reactivation. It is located above an undefined Palaeozoic anticline, which may be of volcanic origin (**Fig. 5–42**). The GRY_deep fault plane borders this anticline to the ENE. The setting of master and antithetic faults within the Zechstein to Jurassic strata is reminiscent of the WPFS and indicates a lateral displacement along this fault zone. The weakness zone given by the Gry_deep fault belongs to the initial faults, which formed during the origin of the Gryfice Graben. Thickness differences within this Mesozoic structure indicate a Mesozoic transtensional generation of those younger fault planes. During the Upper Cretaceous inversion, those fault planes must have compensated compression and transpression, formed in the SSE prolongation of the Skurup Fault.

Evolution of the Gryfice Graben

According to THYBO (2001), the area of the Tornquist Fan was pre-weakened by the former formation of the Caledonian foreland basin. Due to a bend along the TTZ, the strain was distributed along the faults of the Tornquist Fan. Burial history curves, such as in KOSAKOWSKIE et al. (2010), show the results for well K 1/86 (**Fig. 6-13**) in the south of the Gryfice Block. Similar results exist for the Mid Polish Trough (RESAK et al. 2008). Subsidence started in the Middle Devonian, but was followed by uplift during the late Carboniferous, after the Pre-Westphalian unconformity (according to well K5 1/88; DIENER et al. 1989), when the compressional forces of the distant ***Variscan Orogeny*** increasingly affected the northern foreland (FRANKE 2000, ZEH & GERDES 2010). A complex structural pattern of the Tornquist Fan evolved by induced wrenching and development of strike-slip faults, pull-apart basins and grabens (THOMAS & DEEKS 1994, ERLSTRÖM et al. 1997, THYBO 2001, KIERSNOWSKI & BUNIAK 2006, ZEH & GERDES 2010).

The long-term subsidence of the Gryfice Block restarted during the Early Rotliegend. This is confirmed by the results of the restoration (**Section 5.2.3.3; Fig. 5–43**) and the comparison between well logs H2 1/90 and K5 1/88. Thick Lower and Upper (effusive and sedimentary) Rotliegend successions (about 660 m) cover the Upper Carboniferous at the Gryfice Block, while only thin Lower Rotliegend successions (about 60 m) are drilled and mapped along the southern part of the Wolin Block (**Section 5.1.6.1**; **Tab. 5–6**). ERLSTRÖM et al. (1997) also postulated that Permian strata are only found in the Rønne Graben and south of the CDF. SCHLÜTER et al. (1997*b*) provided another schematic sketch of the evolution along the Gryfice Block, using a NE trending seismic section which crosses well K5 1/88. They also proposed the onset of graben subsidence during the Lower Rotliegend. Thus, the subsidence of the Gryfice Block runs parallel to the evolution of the other basins and grabens, such as the Mid-Polish Trough, Rønne Graben, which are part of the TTZ (PHARAOH et al. 2010).

However, minor thickness differences of the Zechstein strata east and west of the AKFZ indicate a tectonic quiescence phase during the Upper Permian.

According to BERTHELSEN (1998) and THYBO (2000), the **Triassic and Jurassic** were dominated by regional extension which influenced the subsidence of the basins and a normal sense reactivation along the grabens. ERLSTRÖM et al. (1997) described strike-slip movements, which induced block faulting and the generation of pull-apart basins. According to THOMAS & DEEKS (1994), the Rønne Graben opened rapidly as a pull-apart structure between NE-SW striking normal faults. Moreover, the Gryfice Block subsided as a graben along the AKFZ and was filled by thick Mesozoic strata (SCHLÜTER et al. 1997*a,b*). As synsedimentary processes resulted in lateral thickness and lithofacial differences, the most complete Triassic to Jurassic successions can be found within the depressions, such as the Rønne Graben (ERLSTRÖM et al. 1997). SCHLÜTER et al. (1997*b*) proposed a regular deepening of the graben between the Zechstein and Jurassic. Consequently, the burial history curve of KOSAKOWSKIE et al. (2010) shows an increase subsidence since the Early Triassic. However, as shown in **Fig. 5–43** (**Section 5.2.3.3**), comparing the thickness patterns of the Wolin and Gryfice blocks, the subsidence of the Gryfice Graben was subdivided into two phases of strong lowering during the Buntsandstein and Keuper-Jurassic, terminated by a further phase of tectonic quiescence during the Muschelkalk.

Since the **Late Cretaceous until the Early Cenozoic**, the stress field has changed into a compressional one, due to the Africa-Iberia-Europe convergence (KLEY & VOIGT 2008). Thus, reverse movements triggered transpressional deformations and the inversion of former depressions (THYBO 2000, BERTHELSEN 1998), such as the formation of anticlines within the TZ (ERLSTRÖM et al. 1997). As presented in **Section 5.2.3.3** the AKFZ was reactivated along reverse faults and new faults and flexures were generated within the anticline. The results of the restoration the Gryfice Block suggest that it was uplifted about 500-1000 m. SCHLÜTER et al. (1997*b*) assumed an uplift of the Gryfice Block since the lower Late Cretaceous, the Santonian. Similar movements along the Rønne Graben have been analysed by GRAVERSEN (2004), who presented a polyphase Late Cretaceous inversion which is associated with a tilting of the graben. Inversion tectonics between the uplifted Bornholm Block and the Polish coast (Bornholm-Darłowo Fault Zone northeast of the TTZ) were discussed by KRZYWIEC et al. (2003).

Finally, seven phases could be identified for the generation of the AKFZ after a Caledonian- and Variscan-induced weakening along the later TTZ: (1) subsidence during the Rotliegend, (2) Zechstein–quiescience, (3) Buntsandstein subsidence, (4) Muschelkalk–quiescence, (5) Keuper-Jurassic subsidence, (6) Lower Cretaceous quiescence, and (7) Upper Cretaceous inversion. These phases vary slightly from the results of SCHLÜTER et al. (1997*b*), but fit very well with those of KOSAKOWSKIE et al. (2010).

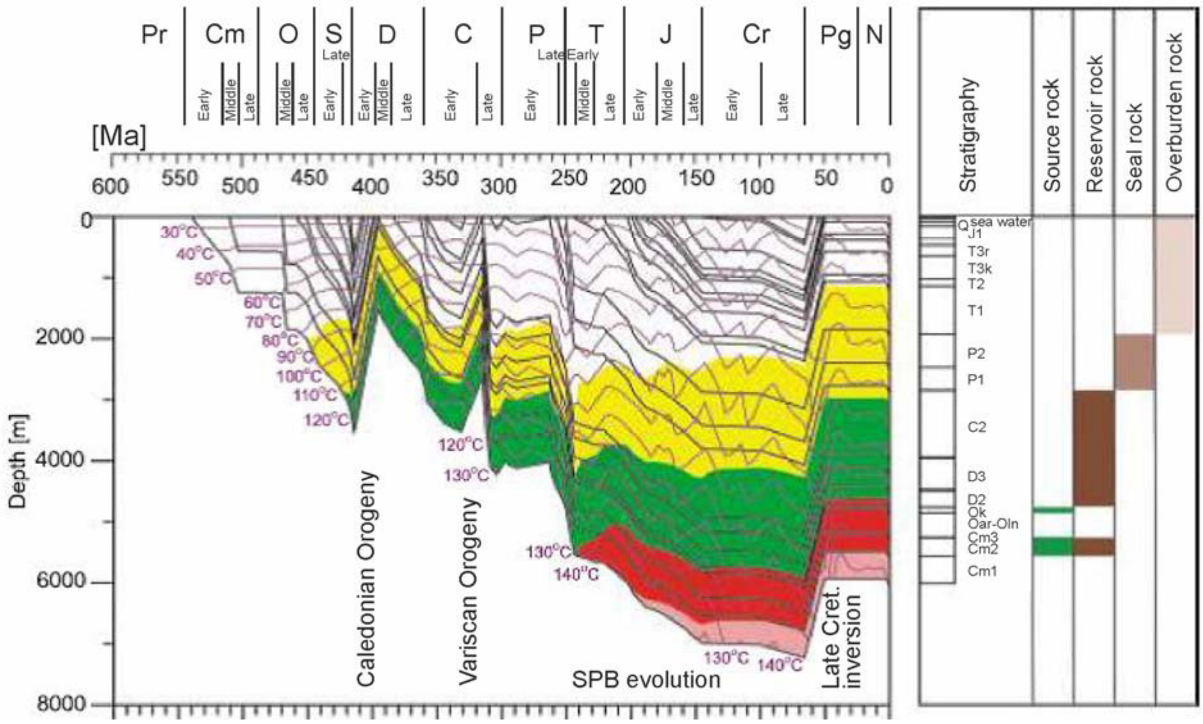


Fig. 6-13: Burial history curve of well K 1/86 at the Gryfice Block with coloured thermal maturity zones (KOSAKOWSKIE et al. 2010, modified), Pr–Precambrian, Cm–Cambrian, O–Ordovician, S–Silurian, D–Devonian, C–Carboniferous, P–Permian, T–Triassic, J–Jurassic, Cr–Cretaceous, N–Neogene, Q–Quaternary.

7 Summary and Conclusions

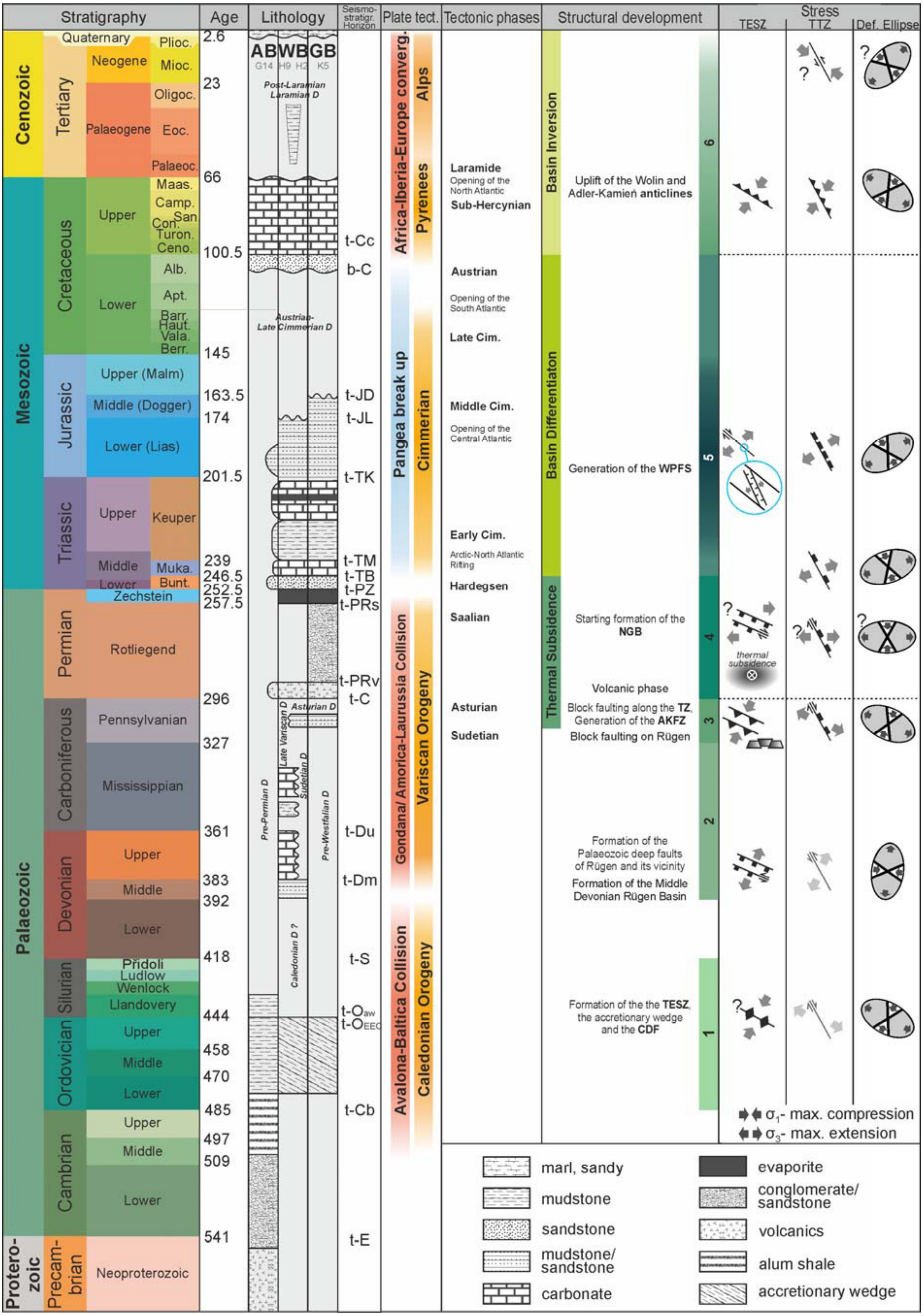
7.1 Overview of the geological development

The area of the TESZ, marking the crustal border of Baltica (East European Craton) and Avalonia (West European Platform) in the southern Baltic Sea, is characterised by a complex fault pattern. The associated fault zones and fault systems were generated during several tectonic phases throughout the Palaeozoic and Mesozoic. Building on SEIDEL et al. (2018), six stages were identified in this thesis:

(1) The first phase (**Fig. 7-1**) lasted from the **Ordovician to Devonian** and includes the **Caledonian Orogeny**. Relicts of this phase can still be found along the Arkona Block. Here the oldest seismostratigraphic units have been drilled by well G14 1/86. Mesoproterozoic granites embody the crystalline basement of Baltica, which is covered by nearly undeformed Cambro-Silurian sediments and dips towards the SW. Due to the closure of the Tornquist Ocean and the concurrent collision of Avalonia with Baltica, an accretionary wedge was thrust onto the basement of Baltica (e.g. TORSVIK & REHNSTRÖM 2003). The faulted Ordovician sediments are represented by southwestward dipping reflectors in the seismic sections. The northernmost extension is marked by the NE striking CDF, which is traceable from the North Sea until Poland (e.g. SCHECK-WENDEROTH & LAMARCHE 2005). Its trend along the Arkona High is in good correlation with SCHLÜTER et al. (1997*a*), whereas the crossing of the Wolin and Gryfice blocks proposed by these authors was not observed in this thesis (**Fig. 6**–**5**). Instead, the AKFZ terminates the CDF ESE of well G14 1/86 but could not be traced further east. However, following the sinistral trend of displacement of the CDF along other NW striking faults of the Gryfice Block (Koszalin or Trzebiatów faults; e.g. MAZUR et al. 2015, and citations therein), a sinistral (northward) displacement is also assumed along the AKFZ. The roughly 3000 m thick and deformed marine Ordovician sediments were present in wells on the Middle Rügen, Wolin and Gryfice blocks. The collision of the Avalonia and the counter-clockwise rotating craton of Baltica (BERTHELSEN 1992*a,b*, TORSVIK et al. 1996, GUTERCH et al. 2010) had a transpressional character and generated a broad dextral transregional suture zone, known as ***TESZ***. During the subduction of Baltica, the NW-SE trending deep faults, e.g. the Jütland-Møn Fault Zone (in the Arkona Block), or the Wiek Fault (bordering the Arkona Block) might have already appeared as a weakness zone in the upper lithosphere.

(2) The time span between the **Middle Devonian and Lower Carboniferous** was characterised by a tectonically stable passive margin of Laurussia. Crustal thinning and extension in the north triggered the formation of basins, such as the Rhenohercynian Basin, after the collapse of the North German - Polish Caledonides (ZIEGLER 1990*a*, ZEH & GERDES 2010). One of the pericratonal sub-basins formed along the TESZ between NE Germany and northern Poland, and is known as the ***Middle Devonian Old Red Rügen Basin*** (**Fig. 7-1** & **Fig. 7-2*A***; AEHNELT 2008, AEHNELT & KATZUNG 2009). The restored seismic sections along the Wolin Block conform to the results of the borehole analysis of AEHNELT (2008), who described an elongated, NW trending depression between the Arkona Block and

Fig. 7-1: Overview of the Proterozoic to Cenozoic lithology, based on the STG 2016, illustrated for the three blocks: AB–Arkona Block, GB–Gryfice Block, WB–Wolin Block; and compared with the mapped horizons (for abbreviations see **Fig. 4–4**). The wells are represented in grey and discordances cursive. The main orogenic cycles and tectonic events are shown and set against the tectonic evolution along the TESZ–Trans-European Suture Zone and the TTZ–Teisseyre-Tornquist Zone (SEIDEL et al. 2018 & citations therein, modified). AKFZ–Adler-Kamień Fault Zone, CDF–Caledonian Deformation Front, NGB–North German Basin, TZ–Tornquist Zone, WPFS–Western Pomeranian Fault System. Numbers labelling the tectonic phases are described in the text.


Stratigraphy
Age
Lithology
Seismo-stratigr. Horizon
Plate tect.
Tectonic phases
Structural development
Stress
TESZ
TTZ
Def. Ellipse
Cenozoic
Mesozoic
Palaeozoic
Protero-zoic
Tertiary
Cretaceous
Jurassic
Triassic
Permian
Carboniferous
Devonian
Silurian
Ordovician
Cambrian
Precam-brian
Quaternary
Neogene
Palaeogene
Plioc.
Mioc.
Oligoc.
Eoc.
Palaeoc.
Upper
Lower
Maas.
Camp.
San
Con.
Turon.
Ceno.
Alb.
Apt.
Barr.
Haut.
Vala.
Berr.
Upper (Malm)
Middle (Dogger)
Lower (Lias)
Upper
Keuper
Middle
Muka.
Lower
Bunt.
Zechstein
Rotliegend
Pennsylvanian
Mississippian
Upper
Middle
Lower
Přidoli
Ludlow
Wenlock
Llandovery
Upper
Middle
Lower
Upper
Middle
Lower
Neoproterozoic
2.6
23
66
100.5
145
163.5
174
201.5
239
246.5
252.5
257.5
296
327
361
383
392
418
444
458
470
485
497
509
541
AB
WB
GB
G14
H9
H2
K5
Post-Laramian
Laramian D
Austrian-
Late Cimmerian D
Asturian D
Late Variscan D
Sudetian D
Pre-Permian D
Pre-Westfalian D
Caledonian D ?
t-Cc
b-C
t-JD
t-JL
t-TK
t-TM
t-TB
t-PZ
t-PRs
t-PRv
t-C
t-Du
t-Dm
t-S
t-Oaw
t-OEEC
t-Cb
t-E
Africa-Iberia-Europe converg.
Alps
Pyrenees
Pangea break up
Cimmerian
Gondana/ Amorica-Laurussia Collision
Variscan Orogeny
Avalona-Baltica Collision
Caledonian Orogeny
Laramide
Opening of the North Atlantic
Sub-Hercynian
Austrian
Opening of the South Atlantic
Late Cim.
Middle Cim.
Opening of the Central Atlantic
Early Cim.
Arctic-North Atlantic Rifting
Hardegsen
Saalian
Asturian
Sudetian
Basin Inversion
Basin Differentiaton
Thermal Subsidence
Uplift of the Wolin and Adler-Kamień anticlines
Generation of the WPFS
Starting formation of the NGB
Volcanic phase
Block faulting along the TZ, Generation of the AKFZ
Block faulting on Rügen
Formation of the Palaeozoic deep faults of Rügen and its vicinity
Formation of the Middle Devonian Rügen Basin
Formation of the the TESZ, the accretionary wedge and the CDF
6
5
4
3
2
1
thermal subsidence
σ1- max. compression
σ3- max. extension
marl, sandy
mudstone
sandstone
mudstone/ sandstone
carbonate
evaporite
conglomerate/ sandstone
volcanics
alum shale
accretionary wedge

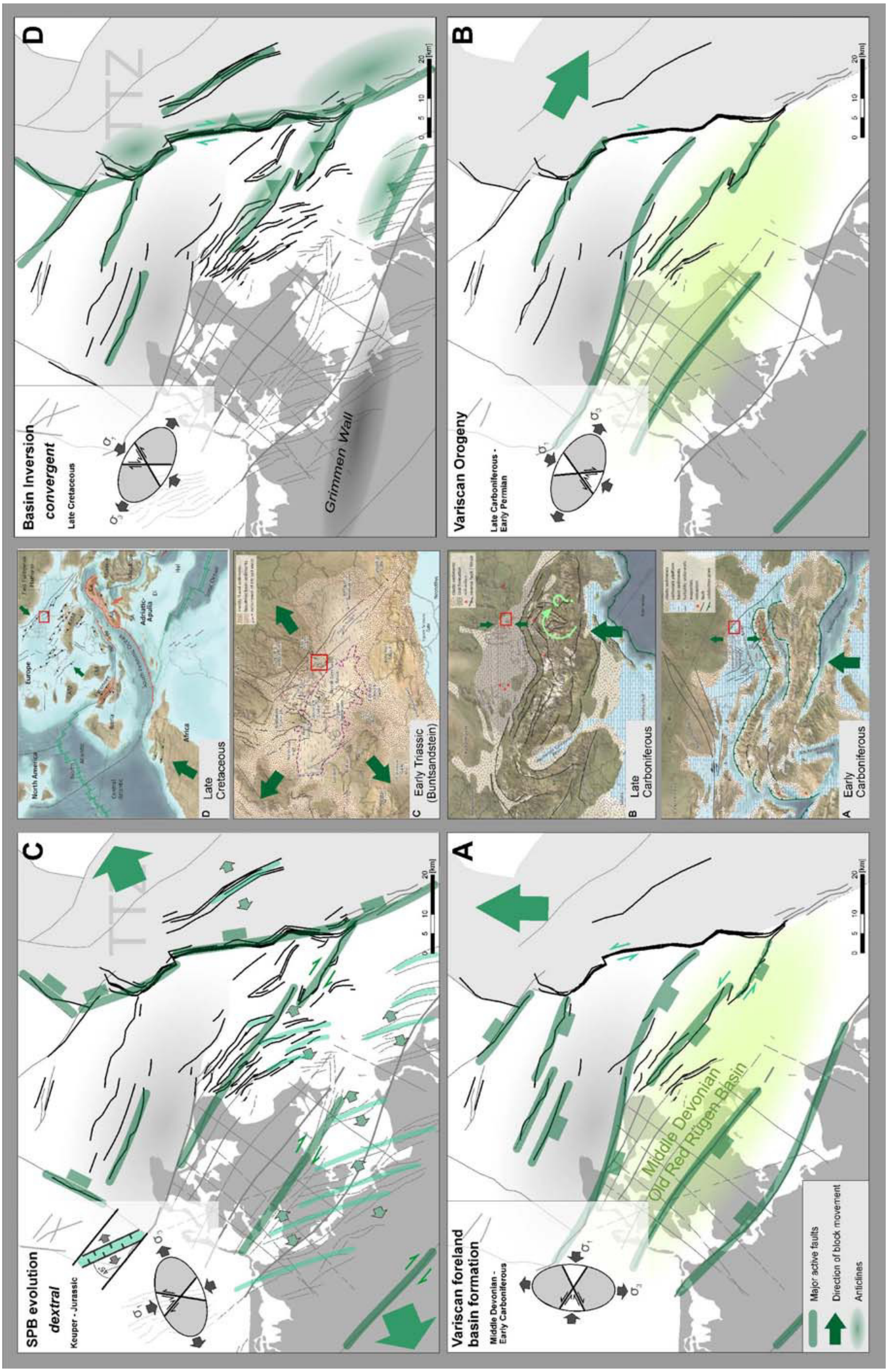


Fig. 7-2: Main phases of the Post-Caledonian tectonic evolution along the TESZ and the Gryfice Graben, as part of the Tornquist Zone with modified palaeogeographic maps from MESCHEDE & WARR (2019). Red rectangle marks the research area.

the Strelasund Fault Zone. The seismic sections show an up to 35 km broad extension from the ***Wiek Fault*** in the north of the Wolin Block towards SW along the Middle Rügen Block. The Strelasund Fault that mark the southern border was not covered by the data set in this work. Thus, the Proterozoic faults crossing the Arkona and Wolin blocks NW-SE, such as the ***NJF*** and ***Schaabe Fault***, must have been active during this phase, since they intersect the accretionary wedge and the synsedimentary Devonian deposits above it. Moreover, WNW trending faults intersecting the deformed Ordovician along the Arkona Block, such as the Wiek Fault, and especially the deep-rooted ***Jütland-Møn Fault Zone*** were active. According to the well description and analysis of AEHNELT & KATZUNG (2009), the clastic 'Old Red' deposits of the Middle Devonian indicate an alluvial to limnic-fluviatile regime which intercalated with marine deposits. Those successions are covered by shallow-marine, calcareous sediments of the Upper Devonian. The Middle and Upper Devonian deposits are restricted to their former depocentre along the Wolin, Middle and South Rügen blocks. Thus, they are missing along the Arkona Block and in the middle and northern parts of the Gryfice Block (these successions have been drilled by wells K1 1/86 and K9 1/89, but not by well K5 1/88). Based on the drilled discordances by wells G14 1/86 (Prepermian Discordance), H2 1/90 (Sudentian Discordance) and H9 1/87 (Variscan Discordance, which includes the Sudetian and Asturian discordances; **Fig. 7-1**), a primary extension further north onto the Arkona Block can be assumed. ZAGORA & ZAGORA (2004) argued that the absence of primary Old-Red deposits at the Arkona Block, and the exaggerated southwestern Fennoscandian Shield, is due to erosion during Sudetian Movements.

(3) Although the ***Variscan Orogeny*** was active during the Devonian, the compressive stress field did not affect the mainland of Laurussia due to the subducting oceanic crust of the Rheic Ocean between the converging palaeocontinent of Laurussia and the ATA, which compensated the stress. Only when the Rheic Ocean was completely closed did the Variscan compression steadily affect the northern foreland, forcing the ***Sudetian and Asturian movements*** (**Fig. 7-1, Fig. 7-2*B***; FRANKE 2000, ZEH & GERDES 2010). Due to NE-SW orientated compression, an intense block-faulting along the Wolin Block occured between the Early and Late Carboniferous, known as a transpressional phase along the TESZ. Erosional and angular discordances between the Devonian and Carboniferous successions document the synsedimentary Sudetian tectonic processes (FRANKE 2018, SEIDEL et al. 2018). The restored seismic section north of the Wolin Block shows the lifted and tilted Lohme Sub-block and a contemporaneous reactivation of the NW-SE striking Palaeozoic faults, such as the ***NJF***. According to SEIDEL et al. (2018), the southeastern branch of the NJF was reactivated, while its dip direction changed from a SW-dipping normal fault to a NE-dipping reverse fault. The change of the dip direction was realised by the formation of a new antithetic fault plane (WFS_8Sued). The primary southeastern extension of the NJF (WFS_8 & 8A; **Fig. 5–23**) was formed by the PZ1 and PZ6 fault planes, which dip towards the SW. During the Variscan compressional stage, the recent WFS_8Sued fault plane was formed, dipping towards the NW. The offset between WFS_8A and WF_8Sued is analysed as a relay ramp, generated by sinistral transpression, so it could have formed during this third tectonic phase (**Fig. 7-1**). There is, however, not much evidence for a sinistral transpressional regime. Instead, the burial history curves of well K1 1/86, from KOSAKOWSKIE et al. (2010) indicate uplift phases along the Gryfice Block between the Lower and Upper Carboniferous, reflecting Late Variscan movements. A strong subsidence of the Gryfice Graben is furthermore visible in the Late Carboniferous. Hence, I conclude that the ***AKFZ*** as northern border of the Gryfice Block and ***TTZ*** evolved due to dextral transtension (as indicate by the deformation ellipse in **Fig. 7-1, Phase 3)**. However, Carboniferous sediments cover most of the Wolin and Gryfice blocks. The wells document marine carbonates and claystones of the Lower Carboniferous Kohlenkalk facies, concordantly overlying the Devonian marine successions in the Middle Rügen depression, and more widespread Upper Carboniferous clastic sediments of the Variscan foreland molasse (limnic and fluviatile facies), covering the successions below with an angular unconformity and a depocentre further south, closer to the VDF. The Upper Carboniferous sediments accumulated posttectonically and are still preserved on the Wolin and Gryfice blocks, as shown by wells H2 1/90 and K5 1/88. Due to this complex tectonic situation, a differentiation between the Lower and Upper Carboniferous deposits within the Middle Devonian Old Red Rügen Basin was not possible throughout the entire seismic interpretation.

(4) The formation of the supercontinent Pangaea was followed by a phase of tectonic stabilisation, with the subsequent cooling of the lithosphere (THYBO 2000) and a general E-W extension (WARSITZKA et al. 2018, and citations within), resulting in dextral transtension along the ***TESZ*** and the ***TTZ***. Subsequently, a high magmatic productivity in the Permian induced **thermal subsidence** and the related formation of the NGB and the MPT, as parts of the Permian Basin System (**Fig. 7-1;** BENEK et al. 1996, KLEY et al. 2008). Internal thickness differences of Lower and Upper Rotliegend and Zechstein successions show an increase towards the SW, where the depocentre of the NGB was located. The Arkona Block was exaggerated to the other blocks and formed a swell together with the Ringkøbing-Fyn High. The Gryfice Block, by contrast, continued to subside and formed a graben structure. In addition, NNE to NNW striking normal faults of the ***AKFZ***, the ***Gat Fault***, and the ***Hiddensee Fault*** originated. The Lower–effusive–Rotliegend was drilled at the Wolin and Gryfice blocks, whereas the Upper–sedimentary–Rotliegend was only identified in the wells of the Gryfice Block. The evaporitic Zechstein succession reveals a further subsidence of the NGB and the Gryfice Block and a polyphase transgression of the Zechstein Sea. In general, the Permian successions are much thicker at the Gryfice Block than at the Wolin Block and they reach further north. Faults of the ***AKFZ*** and the ***Gryfice Fault Zone***, but also single ones of the ***WFS*** such as the NJF, were active and affected by dextral transtension. However, faults of the WFS show only minor displacements and seem to have been more or less inactive, although their horizontal strike slip component cannot be estimated.

(5) The next phase is characterised by the breakup of Pangaea, induced by rifts in the Central Atlantic, Greenland and the North Sea, and the **Early Cimmerian Movements** (**Fig. 7-1**). The resulting ENE-WSW to NE-SW orientated extensional stress regime can be seen in the restored seismic section, crossing the AKFZ (**Section 5.2.3.3**; **Fig. 5**–**43**). Comparing the Wolin Block and the Gryfice Graben, thickness differences of the alternating terrestrial Buntsandstein successions with about 300 m (comparing wells H2 1/90 and K5 1/88, **Tab 5**–**8**) indicate normal faulting along the AKFZ, combined with a strong subsidence of the Gryfice Block. Whereas the thickness of the marine Muschelkalk deposits does not vary significantly east and west of the AKFZ, implying a tectonic quiet phase, the strata of the Keuper and Jurassic differ significantly in their thickness for several hundreds of meters (**Fig. 7-1, Fig. 7-2*C***). The acceleration of subsidence observed in this thesis is also suggested by the burial history curves of KOSAKOWSKIE et al. (2010). The evolving Arctic-North Atlantic rift joined the Central Atlantic Rift and the Middle Cimmerian Movements, and accelerated the formation of N–S orientated graben structures and normal faults along the CEBS. This movements also affected the working area, as evidenced by the active normal faults along the NNE striking AKFZ and Gryfice Fault Zone (as part of the ***TTZ***), and the NW striking reactivated faults of the WFS. Due to the developing rift along the Penninic Ocean as part of the Atlantic Rift System, a strong transtension increased the shearing along the TESZ. The subsequent extension of the WFS by the formation of the conjugating Y-shaped faults as part of the ***WPFS*** indicate a horizontal displacement component. Their NNW orientated strike direction and location suggest a relationship with the onshore trending Usedom

Fault Zone (KRAUSS & MAYER 2004). Although the Permo-Triassic sediments have not been differentiated for well G14 1/86, a thin Permo-Triassic cover was mapped along the Arkona Block. Jurassic deposits could be preserved in some depressions, e.g. north of the Arkona Fault.

(6) Permo-Jurassic and Cretaceous deposits are separated by the **Asturian-Late Cimmerian Discordance**, which was present in all four offshore wells delineating different hiatus time spans (K5 1/88: Middle Jurassic to Albian; H2 1/90, H9 1/87: Lower Jurassic to Albian; G14 1/86: not defined). Albian (Lower Cretaceous) successions, on the other hand, are preserved in all four offshore wells. The Lower Cretaceous continues concordantly into the Upper Cretaceous, which is terminated by the **Laramide to Postlaramide Discordance** (as indicated by offshore wells). The opening of the South Atlantic and the contemporaneous northeastward drift of Gondwana in the Late Cretaceous induced inversion tectonics (**Fig. 7-1, Fig. 7-2*D***). These Sub-Hercynian and Laramide tectonic processes are characterised by the closure of the South and North Penninic Oceans, known as the Africa-Iberia-Europe convergence (**Fig. 3**–**25**, ZIEGLER 1990*a*, KLEY & VOIGT 2008, PHARAOH et al. 2010). The collision of Gondwana and the West European Platform led to different orogenic cycles and had far-reaching effects on middle and northern Europe, such as the opening of the Northern Atlantic. A first SW–NE collision induced the formation of the Pyrenees and the inversion along NW–SE striking faults. Since the Cenozoic, the stress system has rotated anti-clockwise and a northwestward compression has induced the Alpine Orogeny. Therefore, strike slip motions may occurred along the NW to NNW orientated faults, such as the NJF or the AKFZ. A ***relief inversion*** has been documented for the Gryfice Block (also known as Gryfice Graben), the Lohme Sub-block north of the NJF and the ***anticline*** north of Usedom (**Fig. 6**–**3**). Hence, the deep-rooted faults of the ***AKFZ*** and its northern extension the ***Skurup Fault*** were reactivated as reverse faults. Due to the overthrusting of the thick sedimentary fill of the former graben onto the Wolin Block, a parallel-trending anticline was formed, the top of which was subsequently truncated by erosion. Further fissures and normal faults originated in the top of the resulting anticline, dipping antithetically towards the main Adler-Kamień fault. In the Wolin Block, further NW to NNW striking single faults of the ***WFS*** with a NE dip direction, such as the NJF, were reactivated. Some seismic sections indicate a reactivation of the SSW dipping ***Jütland-Møn Fault Zone*** crossing the Arkona Block (**Fig. 5**–**26**).

7.2 Main results of this thesis

The specific questions posed in the Introduction chapter have been answered in this thesis and are summarised below:

- 19 main **seismostratigraphic horizons** (see **Fig. 4**–**4**) marking the tops or bases of stratigraphic successions between the Proterozoic Basement (t-E) and the base of the Cretaceous (b-C) have been mapped. The morphology of the gridded time structure map indicates a southeastward dipping basement of Baltica (horizon t-E), an extension of the Middle Devonian Old Red Rügen Basin (horizon t-O_{aw}, t-Dm, t-Du), a thickening of the Permo-Jurassic sediments towards the North German Basin in the SE, and a contemporaneous formation of the Gryfice Graben in the east (horizons t-PRv, t-PRs, t-PZ, t-TB, t-TM, t-TK, t-JL and t-JD). Furthermore, the Cretaceous basin north of the working area is reflected by thickness maps, and the location of NW-SE trending anticlines document the Late Cretaceous inversion tectonics (t-JL and b-C).
- Approximately 100 **faults and flexures** separating and crossing the three main Arkona, Wolin and Gryfice blocks have been mapped. Their characters were summarised within a fault catalogue (**Appendix E**), including types of displacement, dip and strike direction and the displaced lithostratigraphic units. Moreover their age (first generation) and reactivation phases were studied. Finally subparallel trending faults of the same origin could be grouped by individual major fault zones, such as the AKFZ and the Jütland-Møn Fault Zone; and fault systems, e.g. the Wiek Fault System.
- The WNW trending ***Wiek Fault*** dips towards SSW and separates the Arkona Block in the north from the Middle Rügen and Wolin blocks in the south. Faults of the NNW trending ***AKFZ*** dip dominantely towards ENE and separate the Arkona and Wolin blocks in the west from the Gryfice Block in the east. The Arkona Block is further limited by the ***Skurup Fault*** to the north and presumably by the ***Agricola-Svedala Fault*** to the west. Faults of the ***Jütland-Møn Fault Zone*** cross the Arkona Block from ESE to WNW, displacing especially the basement and Ordovician sediments of the accretionary wedge. The NNE trending ***Hiddensee Fault***, bordering a half-graben, and the WNW trending ***Arkona Fault*** discovered in this thesis displaced mainly the accretionary wedge and its Permo-Cretaceous cover. The NE to NNE trending ***Gat Fault***, forming a triple junction with the AKFZ and the Skurup Fault, and bordering the Rønne Graben to the west, was not crossed by a seismic section (as it is located between two parallel NE orientated seismic sections), but it was visible in the time structure maps. The Wolin Block is the eastern continuation of the Middle and South Rügen blocks without a fault separation. However, the Strelasund Fault (Zone) might terminate the South Rügen and Wolin blocks towards south. The Gryfice Block is bordered by the NW trending Trzebiatów Fault to its east and intersected by the Gryfice Fault Zone located in the southeastern continuation of the Skurup Fault, also trending NE.
- The area between the CDF and Anklam Fault (especially between the Wiek Fault the Grimmen Wall) contains the uppermost part of the ***TESZ*** (see **Fig. 3**–**35**), where the suture is only covered by Palaeo- to Cenozoic sediments. This weakness zone in the upper crust compensated the repeatedly changing stress by the formation and reactivation of single faults, fault zones and systems. Hence, its tectonic history is preserved within the fault pattern in the sedimentary succession (such as the NE trending Jütland-Møn Fault Zone, the WFS with the associated WPFS, and the NNW trending AKFZ).

7 Summary and Conclusions

- Most of the NW-WNW striking faults at the ***Arkona Block*** are of Devonian age and related to the Variscan Orogeny, although a generation of weakness zones during the previous Caledonian Orogeny is assumed. The prominent WFS, along the ***Middle Rügen*** and ***Wolin blocks*** documents the complex polyphase evolution of the TESZ, where NE striking deep faults block-faulted the area in the Middle Devonian and were reactivated and extended during the transtensional Mesozoic. The ***Gryfice*** and ***Rønne blocks*** are of Permo-Carboniferous age, formed during the generation of the TTZ, and subsided as grabens between the Permian and Lower Cretaceous. This is visible along the AKFZ and the Gat Fault, but also along the parallel-striking Hiddensee Fault. The transtension, studied along the grabens of the WPFZ, is also observed for the subparallel-trending Gryfice Fault Zone. The AKFZ and NJF indicate a further reactivation as reverse structures, documenting the Late Cretaceous compression, due to far field orogenic processes in the Pyrenees and later in the Alps.

- ***Six tectonic stages*** were identified in this thesis: **(1)** The compressive phase of the Caledonian Orogeny during the Ordovician to Lower Devonian, **(2)** the Middle Devonian to Lower Carboniferous, post-Caledonian extension **(3)** the Variscan Compression during the Upper Carboniferous, **(4)** Volcanism and thermic subsidence during the Permian **(5)** again plate-tectonically controlled breakup of Pangea leading to extension and transtension between the Permian and Lower Cretaceous **(6)** The Africa-Iberia-Europe convergence forced a monumental change of the stress system and a relief inverting compression.

- The ***AKFZ*** western border of the Gryfice Block was activated as a set of normal faults – bordering the Gryfice Graben, and reactivated as a reverse faults – terminating the Gryfice High. Morphological features, such as local fault bounded anticlines in the NE and SE of the AKFZ, as well as the Mesozoic formation of the Gryfice Fault Zone, are indicators for further strike slip motions.

- The ***Wiek Fault*** was mapped east and west of Rügen forming a steep, SSW dipping fault plane. It separates the blocks of Arkona and Wolin, and moreover the deformed Ordovician deposits of the accretionary wedge and the Old Red successions in the Middle Devonian Old Red Rügen Basin. East of Rügen the Wiek Fault is segmented in separate over- and underlapping fault planes. The Wiek Fault borders the WFS to the north (Seidel et al. 2018). Moreover, the NJF and Schaabe Fault were mapped, crossing the Wolin Block south of the Wiek Fault. Those NE striking Palaeozoic faults are accompanied by Mesozoic faults and flexures of the WPFS, with an increasing intensity towards the south. This set up of about 60 faults and flexures was summarised as WFS crossing the Wolin Block and was argued to represent the Middle Devonian to Upper Cretaceous evolution.

- The overlapping fault planes that together form the ***NJF*** border a **relay ramp** which indicates a sinistral displacement. Due to ongoing dextral transtension since the Permian, this formation has to be older (Pre-Permian) and is possibly related to the primary evolution of this fault. Two scenarios have been discussed, addressing the second or third phase, labelled in **Fig. 7-1**. A sinistral displacement occurred during the Middle Devonian-Early Carboniferous Variscan Foreland Basin Formation (extension), when the faults were originally generated. The following Late Carboniferous-Early Permian Variscan NE- to eastward compression might have resulted in local sinistral transpression and the subsequent formation of antithetic faults in between the overlapping master faults.

- The ***CDF*** could be mapped based on changes within the reflection pattern. The Silurian cover on the basement of Baltica is almost horizontal, subparallel layered, while the internal reflections within the flooded Ordovician accretionary wedge dip towards the SW. This deformational front was mapped across the Arkona Block until the AKFZ. It was not traceable east of the fault zone across the Gryfice Block, but is assumed to continue further north. Deformed Ordovician strata are present in the German and Polish wells along the Gryfice Block.
- The "depressions" along the Arkona Block emerged as ***velocity pull down*** structures, due to shallow gas contents within the uppermost Quaternary loose sediments. The generally by depth increasing velocity is reduced by the gas content, resulting in the visible reflection pattern, which reminds on tectonic synclines or channels. Those velocity pull down structures are bound to circular structures, and more seldom to elongated ones. The occurrence of gas bearing deposits can be related to Quaternary valley systems (which cannot be visualised with this kind of data) or faults, such as the Hiddensee Fault, while the origin of the fluids remains unclear (shallow-biogenic or deep- fossil fluids).

8 Perspectives for future work

The interpretation of the various geological structures and their evolution in this thesis was done within time domain. This allows the analysis of the fault characters (e.g. normal or thrust), strike- and dip-directions and the orientation of the stress field, and investigation of thickness variations of the single horizons. However, since absolute terms, such as dip angles or total sediment thicknesses, could not be measured, a 3D velocity model is required, based on the offshore and onshore (research) wells, as well as on the known distribution and extent of the seismostratigraphic horizons and the tectonic setting. A time-depth conversion of the seismic profiles will enable a more precise depth and thickness analysis. This would significantly improve the restoration results in particular, due to the measurement of fault angles, vertical displacement offsets, and thickness differences in comparing several horizons.

The USO project will address these issues in the next phase. Moreover, the current time structure maps will be recalculated as maps depicting the depth. Finally, a 3D model for the whole USO working area will be created and merged with the recent national model of Mecklenburg-Western Pomerania.

The interpretation of the data in this thesis concentrates on the successions between the Proterozoic basement and the base of the Cretaceous. Because of missing information from the upper 300 ms (TWT) in the seismic section, no younger units could be evaluated for the analysis of changing stress phases. As is known from other studies (e.g. WARSITZKA et al. 2018), the Late Cretaceous-Palaeogene inversion is divided into at least two phases (Pyrenean and Alpine) and was followed by a Late Tertiary extension. This gives rise to the following questions that need to be addressed in future work: How do faults and flexures continue in the upper successions of the Cretaceous and the Post-Cretaceous? Are there hints of neotectonic processes? What can we learn about the Late Cretaceous inversion by the restoration of the deformed Upper Cretaceous and Post-Cretaceous deposits?

In March 2016, the research cruise **MSM 52** with the research vessel Maria S. Merian investigated the area in the southern Baltic Sea with, among others, high-resolution reflection seismic lines and hydroacoustics (HÜBSCHER 2016). A special survey setup allowed a vertical resolution from the sea floor to depths of about 2000 ms, i.e. until the base of Zechstein. This specific data will allow a detailed analysis of the Palaeozoic to Cenozoic deposits and the detection of potential Neotectonic activities. Finally, with these specific data the analysis of fault activities can be completed for the Cretaceous and Post-Cretaceous phases.

Due to missing NW orientated seismic sections along the Gryfice Block, the interpretation of the seismostratigraphy along the Gryfice Block was hampered. The new MSM 52 lines give a better coverage and improve the recent picture. Moreover, more research is necessary to refine the interpretation of the Gryfice Block and the interplay with the surrounding complex structure of the TTZ.

Further questions which could not be addressed in this work but need to be investigated in the future are:

- What is the continuation of the NW trending fault, north of Usedom bordering a further SE tending anticline? So far, I have proposed the Strelasund, Samtens and Bergen faults as possible western extensions.

- What is the western border of the Wolin Block? How is this block separated from the Middle and South Rügen Blocks?
- How do faults of the WFS continue on Rügen? Is there any morphological evidence of (neotectonic) faulting, especially at the peninsulas of Mönchgut, Jasmund and Wittow?
- Are the degassing structures north of Arkona of biogenic or fossil hydrocarbon origin?

Answering these questions will further improve our understanding of the complex tectonic situation in the TESZ.

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Appendix

A Supplementary chapters
- a. Working with the SeisWare™
- b. MOVE™ Workflows
- c. The ArcGIS Project

B Petrobaltic Field Parameters

C Seismostratigraphic horizons of the Petrobaltic and SASO working groups

D Time structure maps and Time thickness maps (all in TWT)

E Comprehensive table characterising faults and flexures north and east of Rügen

F Supplementary material

Appendix A - Supplementary chapters

a. Working with SeisWare™

For the interpretation of the seismostratigraphic horizons and faults, the software SeisWare™ was used (versions 8.0-2013 to 9.2-2018). First, the coordinate system WGS 84 UTM 33N was defined for the project. Then, the seismic profiles, stored as segy-files, were loaded with the help of a very detailed import mask. Among other attributes, header information, such as coordinates, shot points and common depth points (CDP), were assigned. The coordinates, for example of the traces or the several shot points, were mostly stored in the header of the individual segy-files. In contrast, for the "SASO-lines", an additional text file with coordinates for each second shot point along a line was provided by the BGR. Thus, the lines had to be imported first. After attaching the text-file, the coordinates were assigned by the shot points. Due to incomplete coordinate-files some seismic sections could not be loaded, and other loaded seismic sections showed an about 2 km far offset, comparing their position and location maps of the SASO project. Therefore, the location maps of the SASO reprocessing reports (Scheidt et al. 1995, Arndt et al. 1996) were georeferenced and the correct locations digitalised using ESRI-ArcGIS (**Appendix A.c**). Then a similar text file, listing the shot points of the single lines and the appropriate coordinates, was created and used for a successful seismic line import.

In a next step, four offshore wells (G14 1/86, H9 1/87, H2 1/90, K5 1/88) were loaded with the help of an ASCII file containing a table with different information regarding well name, coordinates and depth (meter) of the tops, and the UWI numbers. Subsequently the geophysical logs (LAS files) could be added. Within the seismic viewer (visualising the seismic lines), synthetic seismic traces can be generated. In contrast to the measured seismic section, these synthetic traces are calculated by means of a sonic and a density log. Thus, delta time (DT [us/m]) or DTC (compressional wave travel time) was chosen as a sonic log and RHOB [kg/m] as a density log within the menu. The synthetic logs allow a good correlation between the lithostratigraphic interfaces and the seismostratigraphic horizons.

A few quick processing options, such as frequency analyses, various filters, and a phase rotation, allow a simple editing of the lines. After the adjustment of all the lines (by the accomplishment of bulk shifts or different processing options) dominant horizons and faults were mapped. The offshore well logs were used to dedicate the main reflectors to the base or top of specific lithostratigraphic units. The usage of several visualising options in the basemap (xy-scale), the seismic viewer (xz-scale), and the "3D visualiser" (xyz-scale) enabled tracing of the horizons and faults within a 3D space. It was helpful for the interpretation of horizons and faults to display the parallel seismic sections or arbitary lines (**Fig. A-I**). Moreover, single fault planes required individual names.

The reflectors picked and interpreted along 2D seismic sections, were used for the calculation of individual time structure maps (grids with isolines). The "Kriging" or "Minimum Curvature" methods were chosen for the processing of grids (**Fig. A-II**). Whereas the "Kriging" method lasts up to several hours (using a cell size of 150x150) but gives a very rough surface, the results of the "Minimum Curvature" method showed a smooth surface and the calculation was completed within a few minutes. Therefore, the latter method was chosen for this thesis. The final grids were used for the calculation of pseudo-thickness maps (in TWT), as shown in Section 6.1 (see **Fig. A-III**).

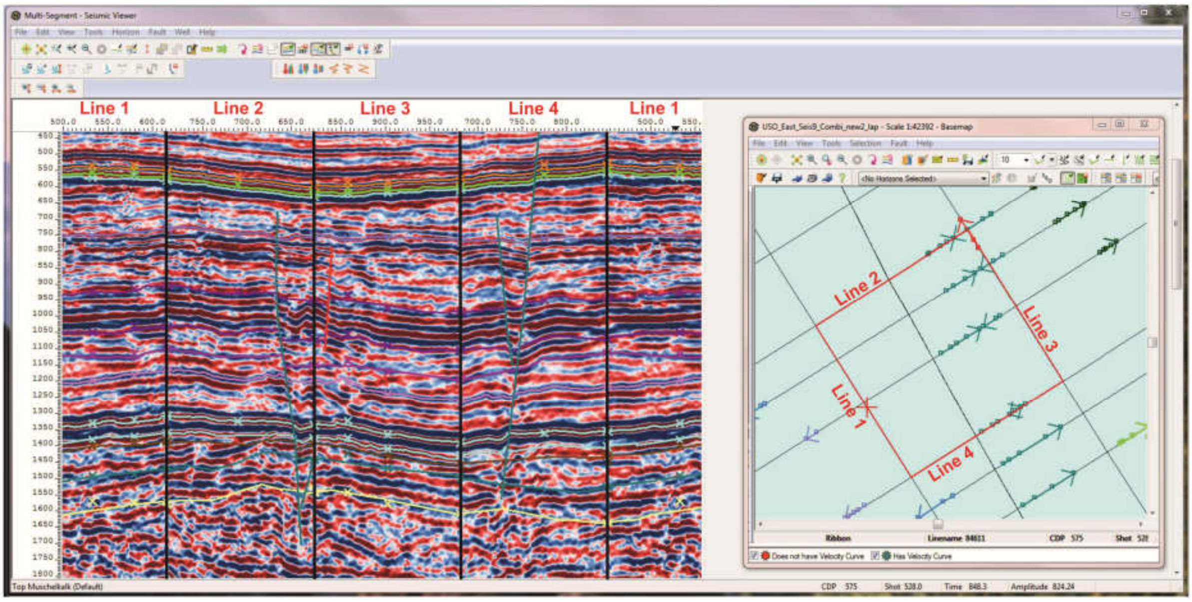


Fig. A-I: Seismic interpretation of horizons and faults by opening the lines as an arbitrary line (positive amplitudes are blue).

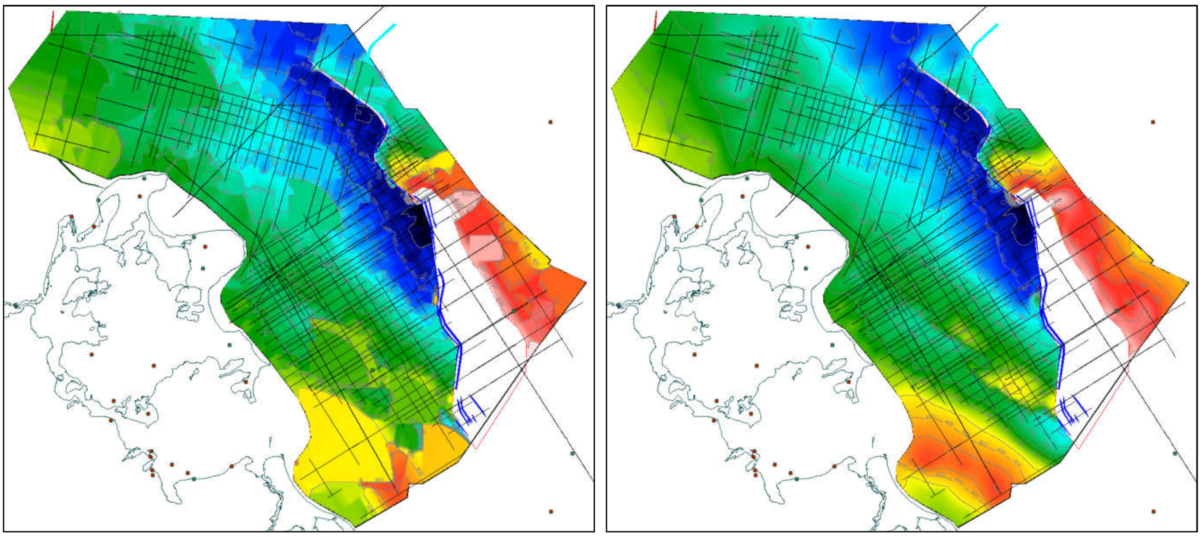


Fig. A-II: Results of different gridding methods: Kriging (left) and Minimum Curvature (right), both with a cell size of 150x150m.

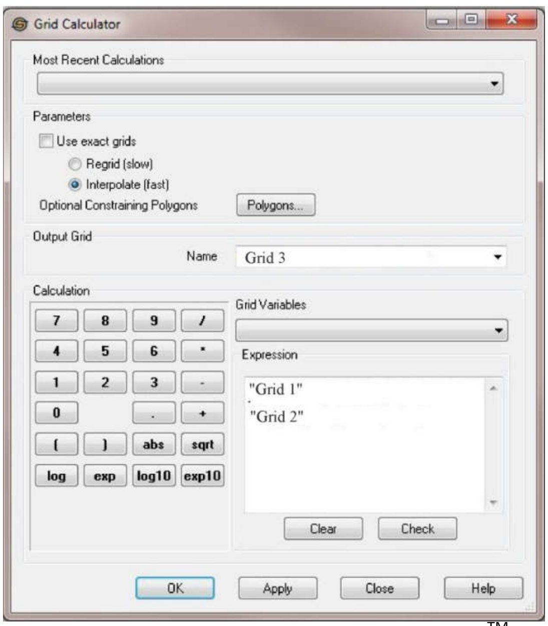


Fig. A-III: Grid Calculator, provided by SeisWare^{TM}.

b. MOVE™ Workflows

Restoration line 82140 (crossing the AKFZ, see **Fig. 5-43**)

1 **Starting Situation:**
Profile loaded, Horizons and Faults redrawn, Polygons created

2 **Decompact** of the uppermost polygon – Upper Cretaceous & Cenozoic (succession deleted)

3 **Move on Fault**
Active Fault: AK
Simple Shear 10°, Pin 90° to the fault
Objects to be moved: the eastern part
Movement: Join beds - Top Lower Jurassic
Foot wall: west of the fault
Hanging wall: east of the fault

4 **Decompact Lower Cretaceous**
Top Bed: Lower Cretaceous (polygon & line)
Active Intermediate: all the rest
Base: Base (line)

5 **Unfold Jurassic**
Simple Shear -80°, Unfold to Datum 0,0m
Template Bed: Top Lower Jurassic, Top Middle Jurassic
Passive Objects: all the rest

6 **Decompact Middle Jurassic**
Top Bed: Middle Devonian (polygon & line)
Active Intermediate: all the rest
Base: Base (line)

7 **Unfold Top Lower Jurassic**
Simple Shear -80°, Unfold to Datum 0,0m
Template Bed: Top Lower Jurassic
Passive Objects: all the rest

8 **Decompact Lower Jurassic**
Top Bed: Lower Jurassic (polygon & line)
Active Intermediate: all the rest
Base: Base (line)

9 **Move on Fault**
Active Fault: AK
Simple Shear 10°, Pin 90° to the fault
Objects to be moved: the eastern part
Movement: Join beds - Top Keuper

Foot wall: west of the fault
Hanging wall: east of the fault

10 Unfold Keuper
Simple Shear 90°, Unfold to Datum 0,0m
Template Bed: Top Keuper
Passive Objects: all the rest

11 Decompact Keuper (succession deleted)

12 Move on Fault
Active Fault: AK
Simple Shear 10°, Pin 90° to the fault
Objects to be moved: the eastern part
Movement: Join beds - Top Muschelkalk
Foot wall: west of the fault
Hanging wall: east of the fault

13 Unfold Muschelkalk
Simple Shear -70°, Unfold to Datum 0,0m
Template Bed: Top Muschelkalk
Passive Objects: all the rest

14 Decompact Muschelkalk
Top Bed: Muschelkalk (polygon & line)
Active Intermediate: all the rest
Base: Base (line)

15 Unfold Buntsandstein
Simple Shear 70°, Unfold to Datum 0,0m
Template Bed: Top Buntsandstein
Passive Objects: all the rest

16 Decompact Buntsandstein (succession deleted)

17 Move on Fault
Active Fault: AK
Simple Shear 10°, Pin 90° to the fault
Objects to be moved: the eastern part
Movement: Join beds - Top Muschelkalk
Foot wall: west of the fault
Hanging wall: east of the fault

18 Unfold Zechstein
Simple Shear -60°, Unfold to Datum 0,0m
Template Bed: Top Zechstein

Passive Objects: all the rest

➔Manual correction of Rotliegend Horizons

19 Decompact Zechstein
Top Bed: Zechstein (polygon & line)
Active Intermediate: all the rest
Base: Base (line)

20 Unfold Rotliegend (split Top Pre Permian before)
Simple Shear -60°, Unfold to Datum 0,0m
Template Bed: Top Rotliegend
Passive Objects: all the rest

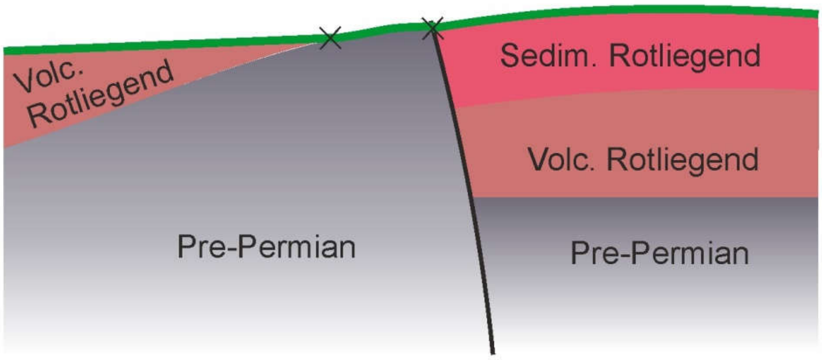


Fig. A-IV: Schematic sketch of the surface (green line) at the end of the Permian.

21 Decompact Sedimentary Rotliegend
Top Bed: sed. Rotliegend (polygon & line)
Active Intermediate: all the rest
Base: Base (line)

22 Move on Fault volc Rotliegend with 10°
Active Fault: AK
Simple Shear 10°, Pin 90° to the fault
Objects to be moved: the eastern part
Movement: Join beds - Top volc. Rotliegend
Foot wall: west of the fault
Hanging wall: east of the fault

23 Unfold volc. Rotliegend
Simple Shear 60°, Unfold to Datum 0,0m
Template Bed: Base Cretaceous, Top Keuper
Passive Objects: all the rest

24 Decompact volc. Rotliegend
Top Bed: volc. Rotliegend (polygon & line)
Active Intermediate: all the rest
Base: Base (line)

Restoration line 82158 (see **Fig. 5-37**)

Starting Situation:
Profile loaded, Horizons and Faults redrawn, Polygons created
Properties as defaults (no rock properties entered)

1. **Decompact Cretaceous**
   Top Bed: Base Cretaceous (polygon), Top (line)
   Active Intermediate: all the rest
   Base: Base (line)

2. **Unfold Base Cretaceous**
   Simple Shear 90°, Unfold to Datum 0,0m
   Template Bed: Base Cretaceous
   Passive Objects: all the rest

3. **Decompact Jurassic**
   Base cretaceous splitted
   Top Bed: Base Cretaceous (line), Top Jurassic (Polygon)
   Active Intermediate: all the rest
   Base: Base (line)

4. **Unfold Keuper**
   Simple Shear 90°, Unfold to Datum 0,0m
   Template Bed: Base Cretaceous, Top Keuper (lines)
   Passive Objects: all the rest

5. **Decompact Keuper**
   Check use Polygons for Decompact
   Top Bed: Top Keuper (line), Base Cretaceous (line), Top Keuper (Polygon)
   Active Intermediate: all the rest
   Base: Base (line)

6. **Unfold Muschelkalk (Muka)**
   Simple Shear 90°, Unfold to Datum 0,0m
   Template Bed: Top Muka
   Passive Objects: all the rest

7. **Decompact Muka**
   Check use Polygons for Decompact
   Top Bed: Top Muka (line), Top Muka (Polygone)
   Active Intermediate: all the rest
   Base: Base (line)

8. **Unfold Buntsandstein (Bunter)**
   Simple Shear 90°, Unfold to Datum 0,0m

Template Bed: Top Bunter (line)
Passive Objects: all the rest

9. **Decompact Bunter**
   Check use Polygons for Decompact
   Top Bed: Top Bunter (line), Top Bunter (Polygone)
   Active Intermediate: all the rest
   Base: Base (line)

10. **Fault planes modified, shortened**

11. **Move on Fault**
    Active Fault: WFS_8
    Check "Automatic select Hanging wall"
    Simple shear -9°, Pin 90° to the fault
    Objects to be moved: the western part, between the top and the top of the accretionary wedge
    Movement: Join beds
    Foot wall: Top Upper Devonian (line), east of the fault
    Hanging wall: Top Zechstein (line), west of the fault

    Gap between Devonian and Ordovician (Accretionary wedge) ➔ Polygon for Ordovician redrawn

12. **A) Unfold Zechstein**
    Complete surface flattened, not only Top Zechstein
    Therefore Top Upper Devonian (at the horst block) was splitted
    Simple Shear 90°, Unfold to Datum 0,0m
    Template Bed: Top Zechstein, Top Carboniferous, Top Zechstein, Top Upper Devonian, Top Ordovician (accret. Wedge) (lines)
    Passive Objects: all the rest

    B) Re-sediment Zechstein
    Upper Devonian modified close to thefault
    Assumed Base Bunter Erosion
    Zechstein lifted

13. **Decompact Zechstein**
    Top Bed: Line set (line), Top Zechstein (Polygone)
    Active Intermediate: all the rest
    Base: Base (line)

14. **Move on Fault (WFS_5&6) – lift Carboniferous**
    Active Fault: WFS_5, Passive Fault:WFS_6; Fault line WFS_6 was extended
    Simple shear -9°, Pin 90° to the fault

Objects to be moved: Objects between the faults WFS_5&6, Middle Devonian (line & polygon), Upper Devonian (line & polygon), Carbonian (polygon)
Movement: Join beds
Foot wall: Top Carboniferous (line), right
Hanging wall: Top C arboniferous (line), left

Move on Fault ➔polygons manually modified

15. **Decompact Carboniferous**
Top Bed: Top Carboniferous (lines & polygons)
Active Intermediate: all the rest
Base: Base (line)

16. **Move on Fault**
➔ With differentiation in the blocks A,B,C &D, from west to east (**Fig. A-V**):

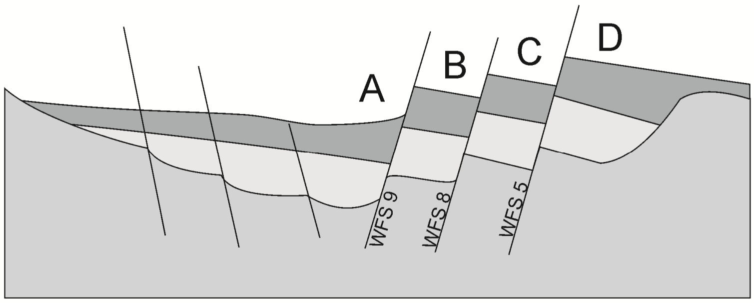


Fig. A-V: Schematic sketch of the block separation (blocks A-D) by the three faults.

➔Delete Polygon of the accr. wedge

A) Move on Fault: WFS_5
Active Fault: WFS_5
Movement: Join beds, Fault Parallel Flow
Objects to be moved: Blocks A, B &C
Foot wall: D
Hanging wall: C

B) Move on Fault: WFS_8
Active Fault: WFS_8
Movement: Join beds, Fault Parallel Flow
Objects to be moved: Blocks C& D
Movement: Join beds
Foot wall: B
Hanging wall: D

C) Move on Fault: WFS_5
Active Fault: WFS_5
Movement: Join beds, Fault Parallel Flow
Objects to be moved: Blocks B, C & D
Movement: Join beds

Foot wall: A
Hanging wall: B

17 Unfold Upper Devonian

Simple Shear 90°, Unfold to Datum 0,0m
Template Bed: Top Ordovician (accr. Wedge), Top Upper Devonian (lines)
Passive Objects: all the rest
Without new created Accr. Wedge

Restoration line 84622 (see **Fig. 5-38**)

1. **Starting Situation:**
   Profile loaded, Horizons and Faults redrawn, Polygons created
   Properties as defaults (no rock propertie entered)

2. **Decompact Cretaceous**
   Check use Polygons for Decompact
   Top Bed: Base Cretaceous (polygon), Top (line)
   Active Intermediate Objects: all the rest
   Base: Base (line)

3. **Unfold Base Cretaceous/Top Jurassic**
   Simple Shear 90°, Unfold to Datum 0,0m
   Template Bed: Base Cretaceous
   Passive Objects: all the rest

   ➔ fault line WFS_new manually modified (shortened)

4. **Decompact Jurassic**
   Check use Polygons for Decompact
   Top Bed: Base Cretaceous (line), Top Jurassic (polygon)
   Active Intermediate Objects: all the rest
   Base: Base (line)

5. **Unfold Keuper**
   Simple Shear 90°, Unfold to Datum 0,0m
   Template Bed: Top Keuper
   Passive Objects: all the rest

6. **Decompact Keuper**
   Check use Polygons for Decompact
   Top Bed: Top Keuper (line & polygon)
   Active Intermediate Objects: all the rest
   Base: Base (line)

7. **Unfold Muka**
   Simple Shear 90°, Unfold to Datum 0,0m
   Template Bed: Top Muka
   Passive Objects: all the rest

   ➔faults manually modified

8. **Decompact Muka**
   Check use Polygons for Decompact
   Top Bed: Top Muka (line & polygon)

Active Intermediate Objects: all the rest
Base: Base (line)

9. **Unfold Bunter**
   Simple Shear 90°, Unfold to Datum 0,0m
   Template Bed: Top Bunter
   Passive Objects: all the rest

   ➔ faults manually modified

10. **Decompact Bunter**
    Check use Polygons for Decompact
    Top Bed: Top Bunter (line & polygon)
    Active Intermediate Objects: all the rest
    Base: Base (line)

11. **Unfold Zechstein**
    Simple Shear 90°, Unfold to Datum 0,0m
    Template Bed: Top Zechstein
    Passive Objects: all the rest

    ➔ faults manually modified

12. **Decompact Zechstein**
    Check use Polygons for Decompact
    Top Bed: Top Zehstein (line & polygon)
    Active Intermediate Objects: all the rest
    Base: Base (line)

13. **Unfold Rotliegend**
    Simple Shear 90°, Unfold to Datum 0,0m
    Template Bed: Top Rotliegend
    Passive Objects: all the rest

    ➔ faults manually modified

14. **Decompact Rotliegend**
    Check use Polygons for Decompact
    Top Bed: Top Rotliegend (line & polygon)
    Active Intermediate Objects: all the rest
    Base: Base (line)

15. **Move on Fault**
    Active Fault: WFS_16d
    Check "Automatic select Hanging wall"
    Simple shear, Pin 90° to the fault

Objects to be moved: the western part, with the accretionary wedge
Movement: Join beds
Foot wall: Top Carboniferous (line), east of the fault
Hanging wall: Top Carboniferous (line), west of the fault

16. **Unfold Carboniferous**
    Simple Shear 90°, Unfold to Datum 0,0m
    Template Bed: Top Carboniferous
    Passive Objects: all the rest

17. **Modify faults**
    Faults WFS_16d and WFS_8 were changed and polygons redrawn

18. **Decompact Carboniferous**
    Check use Polygons for Decompact
    Top Bed: Top Carboniferous (line & polygon)
    Active Intermediate Objects: all the rest
    Base: Base (line)

19. **Unfold Devonian**
    Simple Shear 90°, Unfold to Datum 0,0m
    Template Bed: Top Devonian (4 lines)
    Passive Objects: all the rest

20. **Correction Base Devonian**
    With mass preservation

c. The ArcGIS project

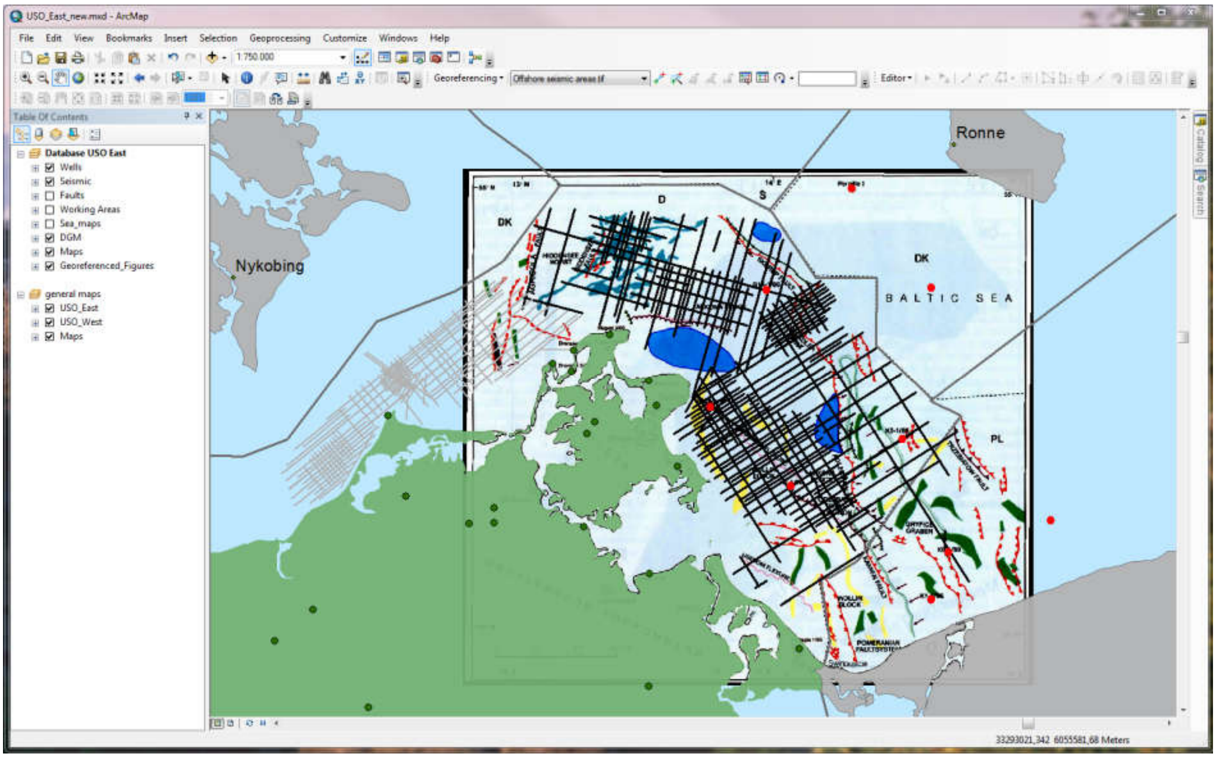


Fig. A-VI: The ArcGIS project for USO East illustrated in ArcMap. Activated are: the shp-files of the country's frontiers, locations of seismic lines and wells, and the georeferenced map of Schlüter et al. (1998).

An ArcGIS project (ArcGIS version 10.3.1, Copyright © 1995-2015 Esri) was created to illustrate the existing data appropriately, such as the different seismic lines, wells, shape files of the country's frontiers, and important figures of former publications. This project allowed for example the comparison of different shape files to check the correct locations. Moreover, maps or other applications were georeferenced (**Fig. A-VI**) and afterwards loaded in SeisWare™ or MOVE™.

New results, generated with SeisWare™, were also added to the GIS project. The locations of important fault planes were loaded as shape file, and the attribute table was extended to characterise each fault plane of the different fault systems.

Appendix B - Petrobaltic Field Parameters

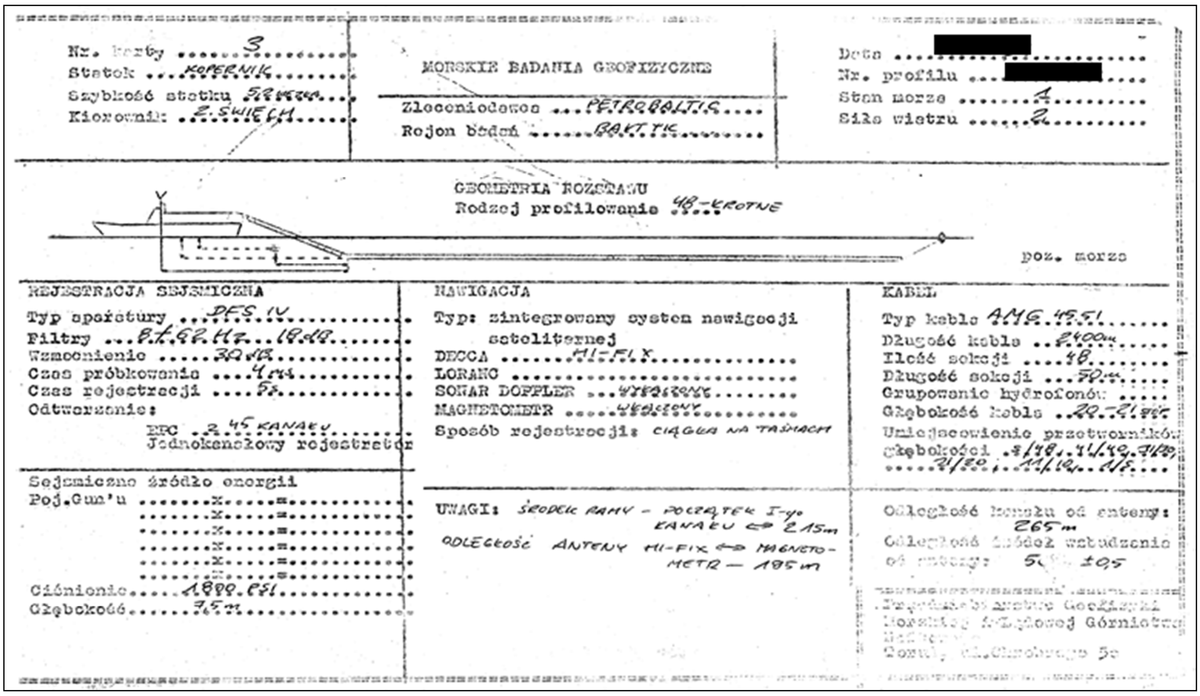


Fig. B-I: Example of a measurement protocol of the Petrobaltic CDP seismic data (source: BGR).

Field parameter	SASO Data reprocessing 1 (Scheidt et al. 1995)	SASO Data reprocessing 2 (Arndt et al. 1996)	CEP Data reprocessing
Shot point distance	25 m	25 m	25 m
Receiver distance	50 m	50 m	50 m
Channel number	24, 28, or 48	48	
CDP fold	48	48	48-?
Offset (source-hydrophone)	160 m (min) to 240 m (max)	Min. 160 m (170 m with Vaporchoc) Max. 240 m (with airgun)	
Active length	160-1310 m (24 channels) 240-1590 m (28 channels) 160-2510 m to 240-2590 m (48 channels)	Vaporchoc: 170 m, 220 m, 2520 m Airgun: 240 m, 290 m, 2590 m	
Geophones per Group		48	50
Instruments	DFS IV (Airgun) SN 328 (Vaporchoc)	DFS IV (Airgun) SN 328 (Vaporchoc)	
Filter	8-62 Hz	8-62 Hz	
Peak frequency	5		
Registration length	5 sec	5 sec (D115: 4 sec.)	
Sample Interval	4 ms	4 ms	
Polarity	Not documented	Not documented	

Tab. B-I: Overview of the field parameters of the reflection seismic data used for USO East (Scheidt et al. 1995, Arndt et al. 1996).

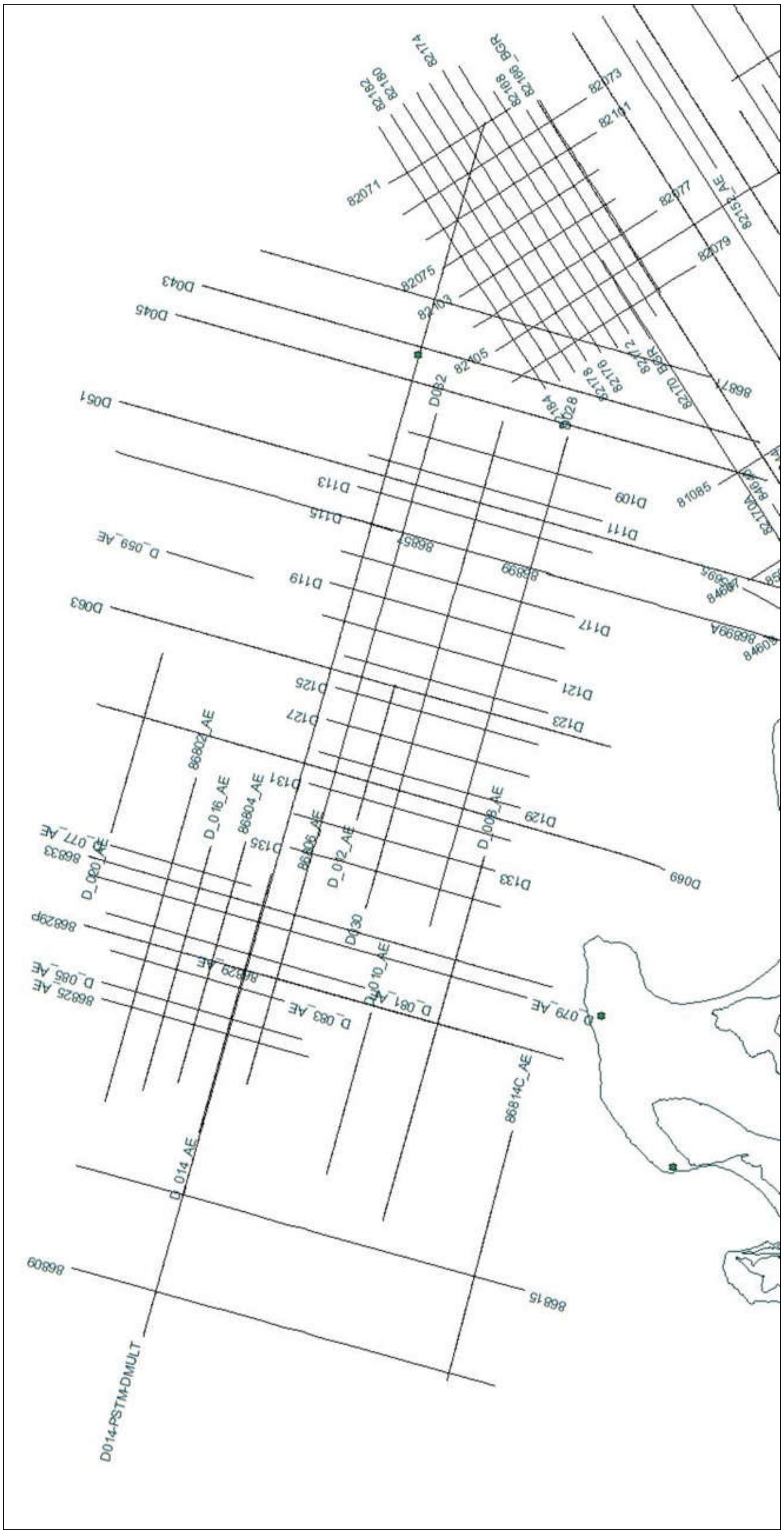


Fig. B-II: Map of Petrobaltic seismic sections north of Rügen.

Fig. B-III: Map of Petrobaltic seismic sections east of Rügen.

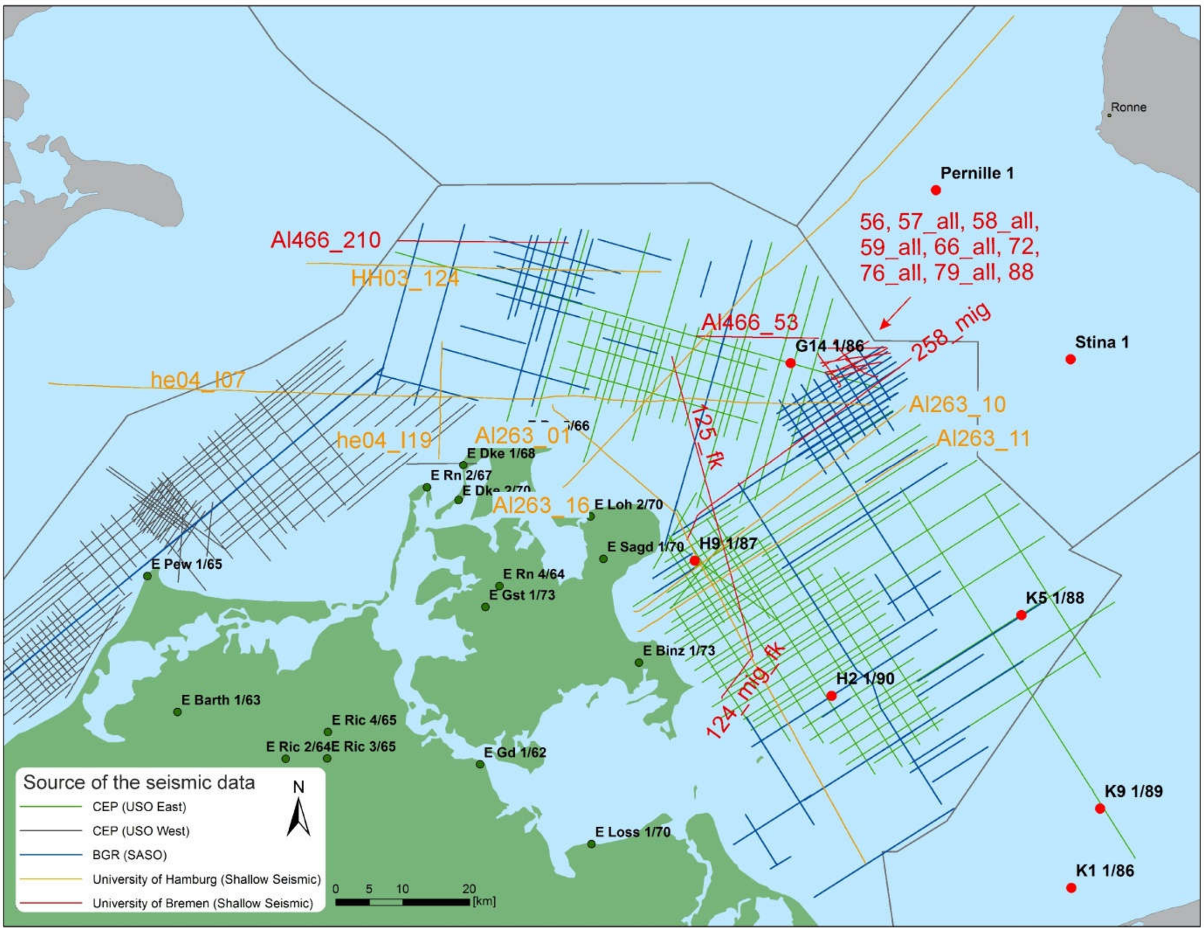


Fig. B-IV: Map of seismic sections provided by the Universities of Hamburg and Bremen.

Appendix C - Seismostratigraphic horizons of the Petrobaltic and SASO working groups

Archive nr.	BGR_1004332	LUNG-MV_EEPB0025
Citation	Glöß & Autorenkollektiv (1989)	Fritzsche & Autorenkollektiv (1987)
Horizon	**Rügen West (See) Sucharbeiten 2. Etappe**	**Oderbucht/ östlich von Usedom**
To	Base of Quaternary deposites (probably 2. phase)	
B'	within Upper Cretaceous (near base Campanian)	within Upper Cretaceous
B2	base Cenomanian (minimum below correlated phase)	base Upper Cretaceous (base Cenomanian)
JM		Lower Cretaceous (near base Wealden) or even Jurassic
JD		within Jurassic (near lower Dogger)
L	within Lias (base of Upper Lias?)	
L3	within Lias (Lower Lias)	
JL	base Lias	within Jurassic (near base Lias)
T7	within Upper Keuper (Transgression)	within Upper Keuper
TK	within Middle Keuper	within Middle Keuper
TM	near base of Upper Muschelkalk	near top Middle Muschelkalk
M3	base of Muschelkalk (minimum below correlated phase)	near base Muschelkalk
TP2	Within Roet	near base Roet
S3	within Middle Buntsandstein	within Middle Buntsandstein
TP1	Top Lower Buntsandstein	within Lower Buntsandstein
X1	Top marine Zechstein	Top Zechstein
Z3	Top Hauptanhydrit	Top Hauptanhydrit (Zechstein, Leine series)
Z2	Top Basalanhydrit	Top Basalanhydrit (Zechstein, Staßfurt series)
Z1	Base Zechstein (minimum below correlated phase)	near base Zechstein
Z	Base of terrestrial Zechstein	
T? P	near base Triassic	
R2		within the effusive Rotliegend
R1		
PZ	top of hardrock older than Permian, probably older than Upper Carboniferous	
R	base Rotliegend	within the effusive Rotliegend
C	within Upper Carboniferous	
C1	near base Upper Carboniferous	near base of Upper Carboniferous
Cu5-Cu0	within Upper Carboniferous (Cu0 near base)	
C/D	within Lower Carboniferous or Devonian	
D3	Middle or Lower Frasnian?	
D2		
D1	old red?	
D0	near base Devonian	
O2?	Cambrosilurian (probably Ordovician)	
O1?		

Tab. C-I: Main seismostratigraphic horizons defined by the VEB Geophysik working group on behalf of Petrobaltic for the area east and west of Rügen.

SASO (according to Schlüter et al. 1996, 1997a)

Horizon	Colour	Stabilo Nr.	Horizon Nr.	Startigraphy
			20	Base Quarternary (Schlüter et al. 1997a)
t	light yellow	8724	30	Base Tertiary
kro	light green	87/575	38	Base Upper Cretaceous (Cenoman)
jo	yellow	8736	40	Base Malm
jm	not mapped		50	Boundary Lower and Middle Jurassic
ju	purpel	8737		Base Lower Jurassic
k	not mapped			Base Keuper
m	light blue	8757	55	Within Middle Muschelkalk
so	not mapped			Base Upper Buntsandstein
sm	not mapped			Top Volprihausen
su	red	8740	58	Boundary between Zechstein and Buntsandstein (Schlüter et al. 1996), Boundary between Lower and Middle Buntsandstein (Schlüter et al. 1997a)
	yellow	8734	60	Base Triassic (Schlüter et al. 1997a)
z	dark blue	8731, 87/410	70	Base Zechstein
			76	Internal reflection within the Rotliegend (Schlüter et al. 1997a)
			78	Early Upper Rotliegend (volcanics-sediments), (Schlüter et al. 1997a)
ru	brown	8738,87/655	80	Base Rotliegend
			82	Top of a deltaic accretion (Schlüter et al. 1997a)
cs	orange	8754	85	Base Upper Carboniferous
	light brown	8739	90	Base Lower Carboniferous (Schlüter et al. 1997a)
do	green	8713	95	Base Upper Devonian
du	dark green	8736	97	Base Middle Devonian
			100	Base Devonian (Schlüter et al. 1997a)
si	red	87/351	105	Within the Siluirian, boundary betwen Upper and Lower Silurian? (Schlüter et al. 1996); top Lower Palaeozoic (Schlüter et al. 1997a)
cbm,o	dark red	8756		Boundary Upper/ Lower Ordovician
cbu	violet	8727, 87/340	110	Base Middle Cambrian?
	dark violet	8755	120	Top Precambrian (Vendian) cristalline

Tab. C-II: Main seismostratigraphic horizons defined by the SASO working group for the area north and east and of Rügen (Schlüter et al. 1996, 1997*a*).

Appendix D - Time Structure Maps and Time Thickness Maps

Fig. D-I: Top Proterozoic (Basement of Baltica).
Fig. D-II: Top Silurian.
Fig. D-III: Top Ordovician (accretionary wedge).
Fig. D-IV: Top Middle Devonian.
Fig. D-V: Top Carboniferous.
Fig. D-VI: Top volc. Rotliegend.
Fig. D-VII: Top Zechstein.
Fig. D-VIII: Top Buntsandstein
Fig. D-IX: Top Muschelkalk.
Fig. D-X: Top Keuper.
Fig. D-XI: Top Lower Jurassic with light blue markers for the Middle Jurassic extent.
Fig. D-XII: Base Cretaceous.

Fig. D-XIII: Pseudo-Thickness of the Cretaceous and Cenozoic successions in TWT.
Fig. D-XIV: Pseudo-Thickness of the Post-Ordovician successions in TWT (successions covering the accretionary wedge until the Base of Cretaceous).

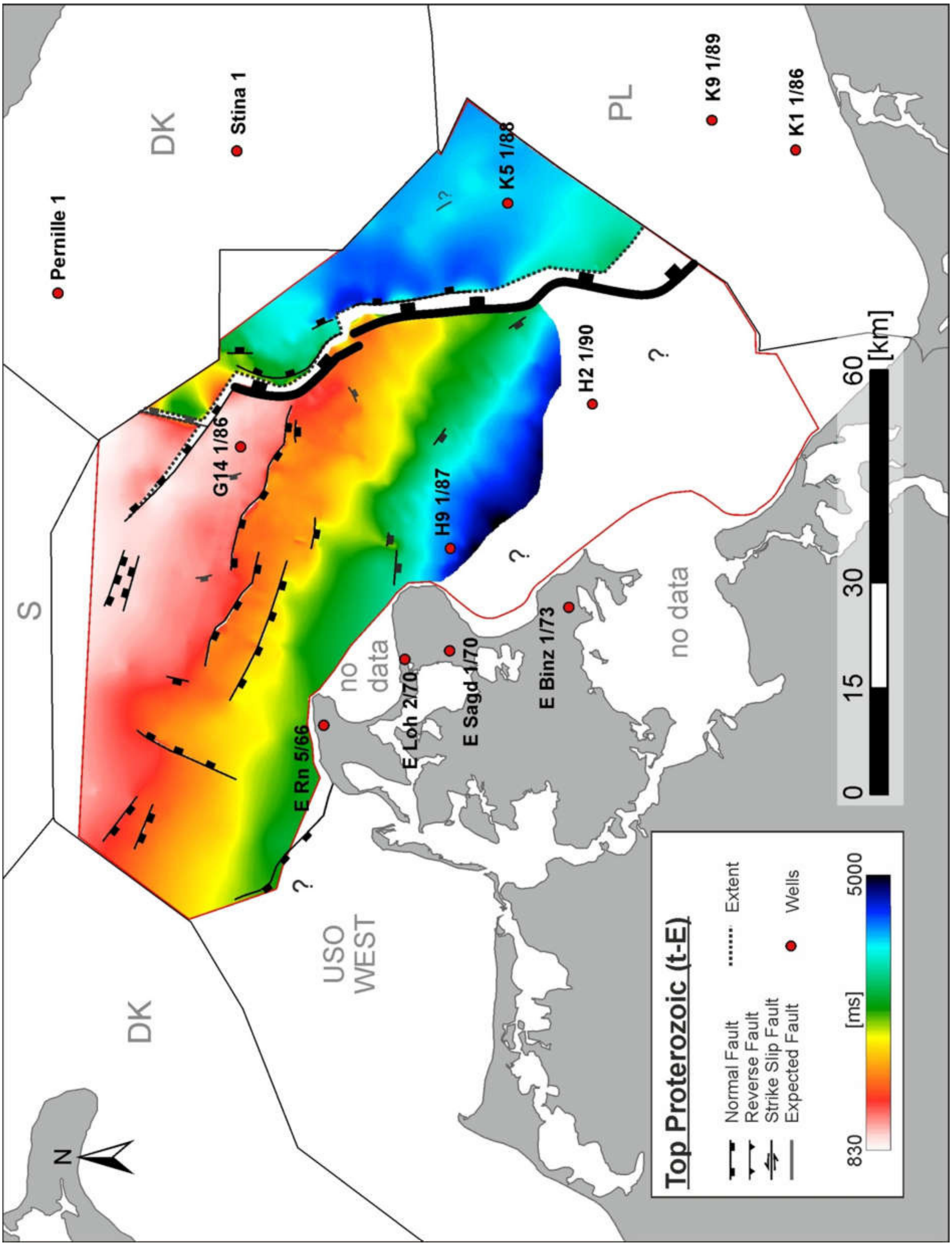


Fig. D-I: Top Proterozoic (Basement of Baltica).

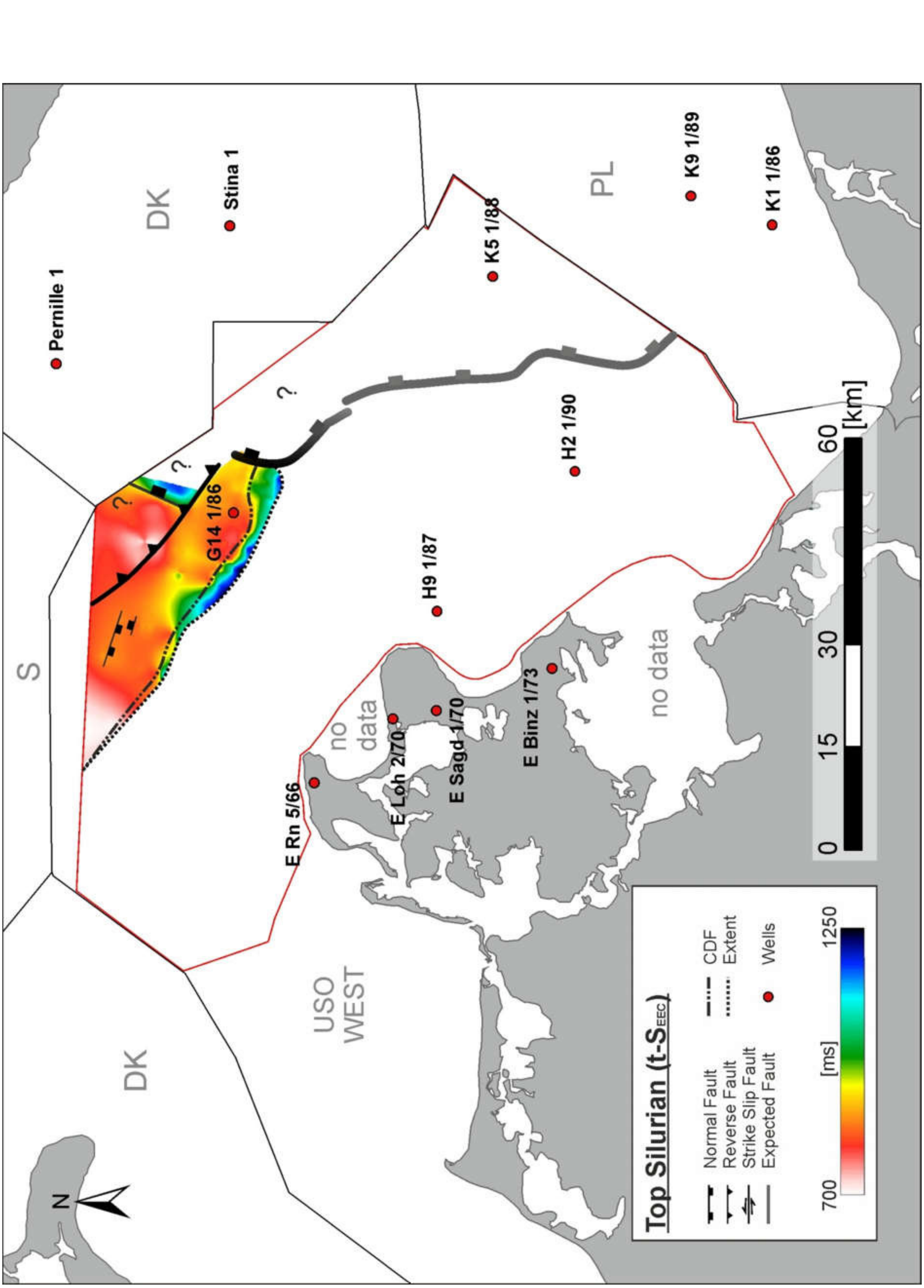


Fig. D-II: Top Silurian.

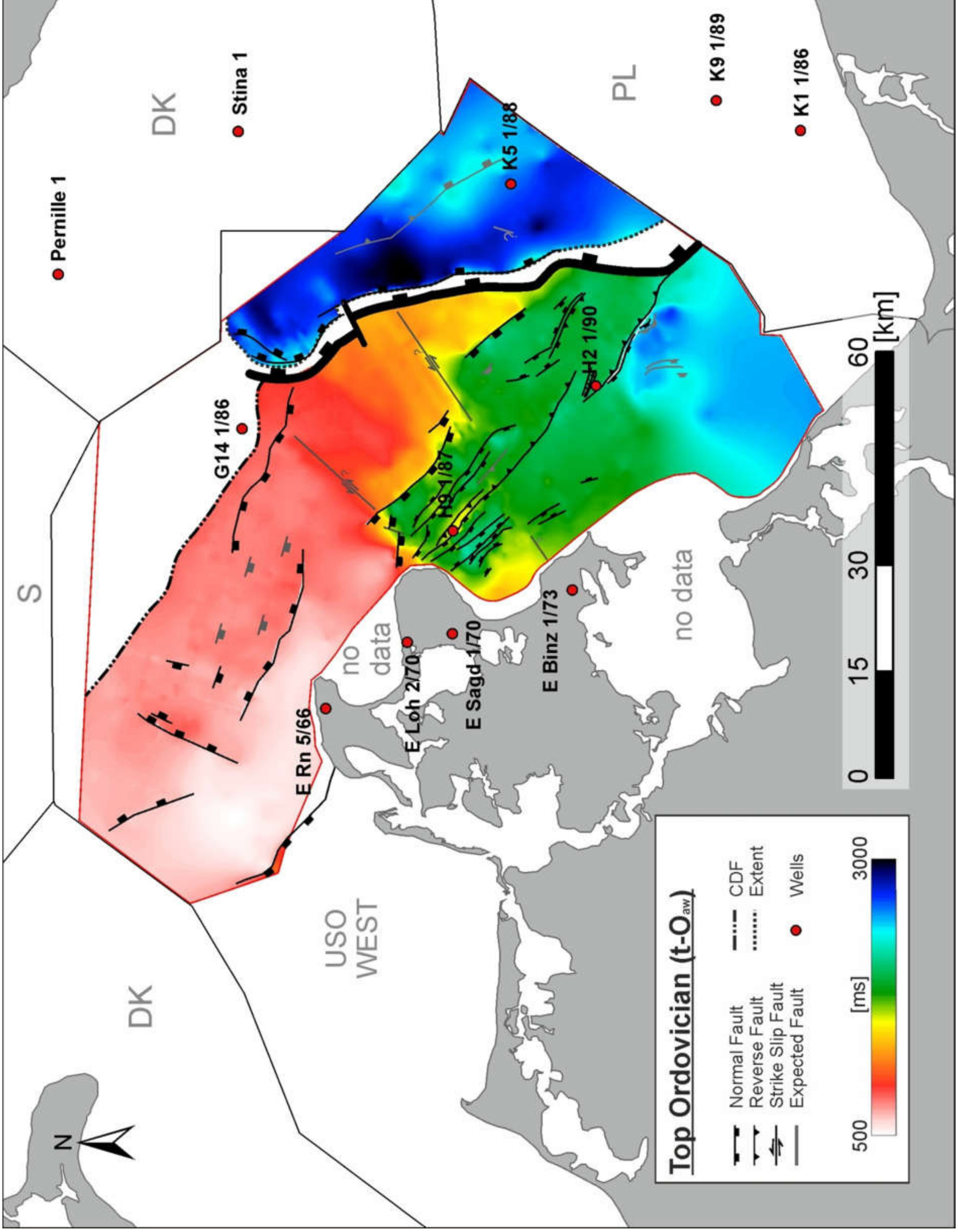


Fig. D-III: Top Ordovician (accretionary wedge).

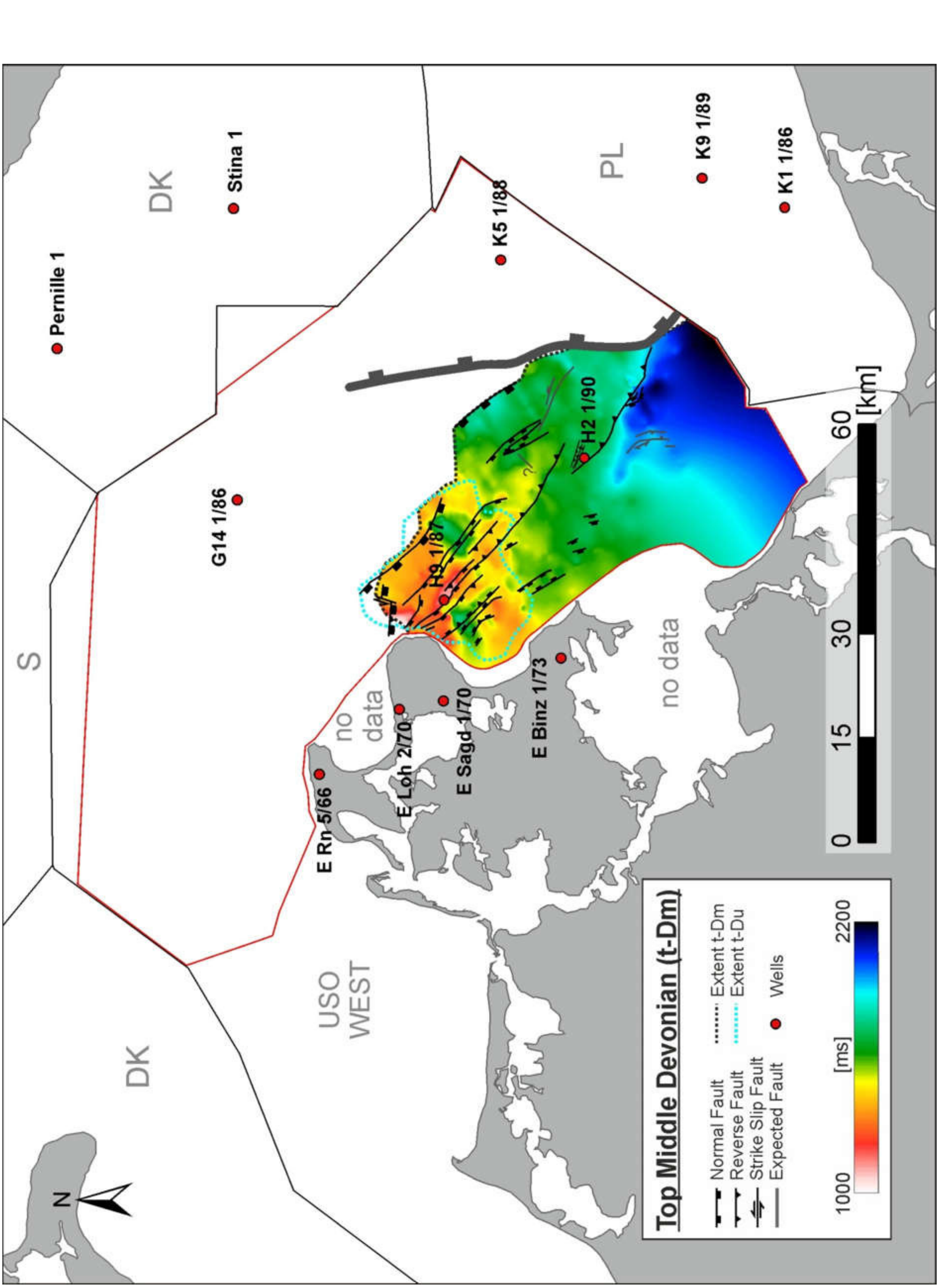


Fig. D-IV: Top Middle Devonian.

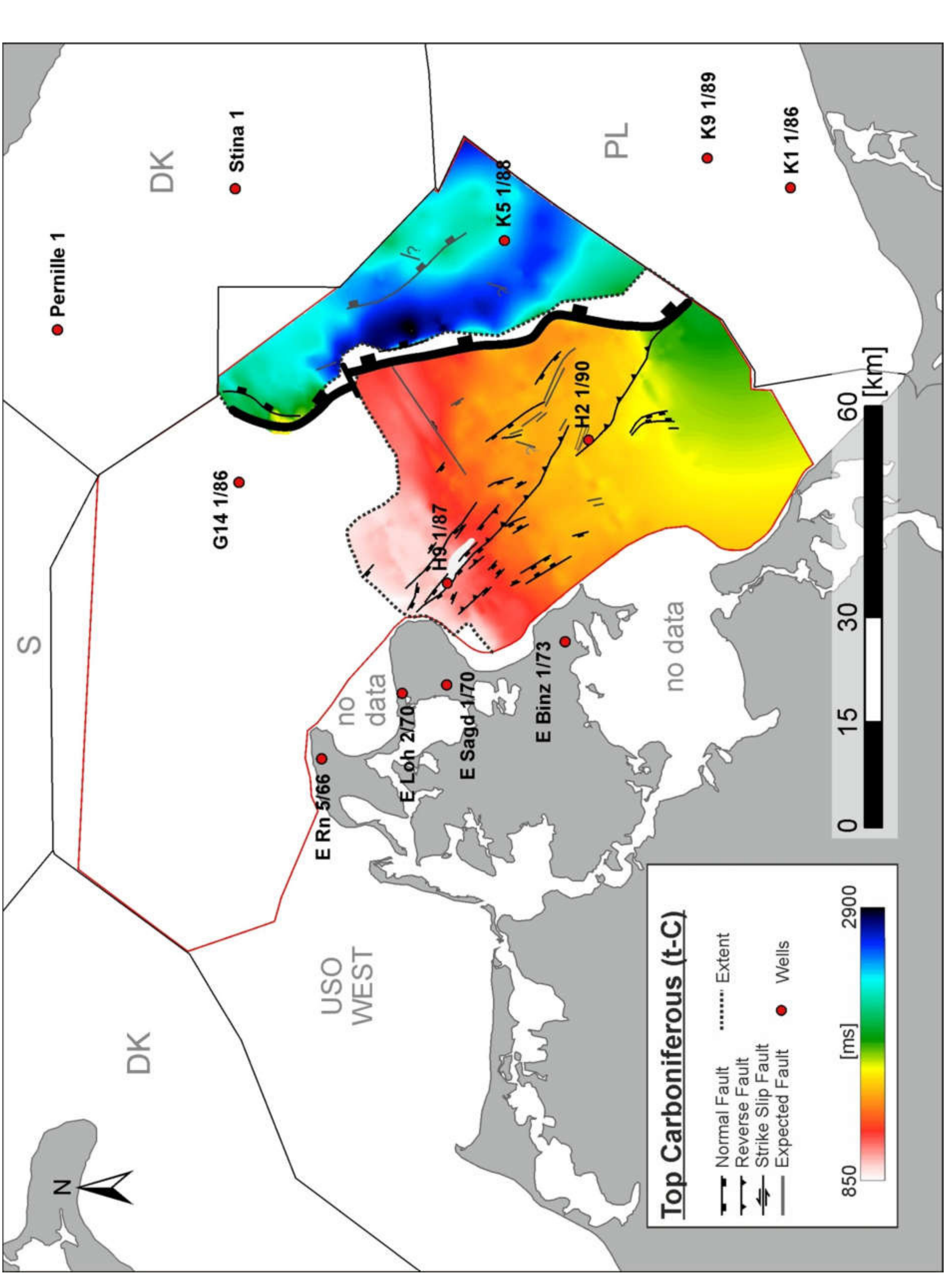


Fig. D-V: Top Carboniferous.

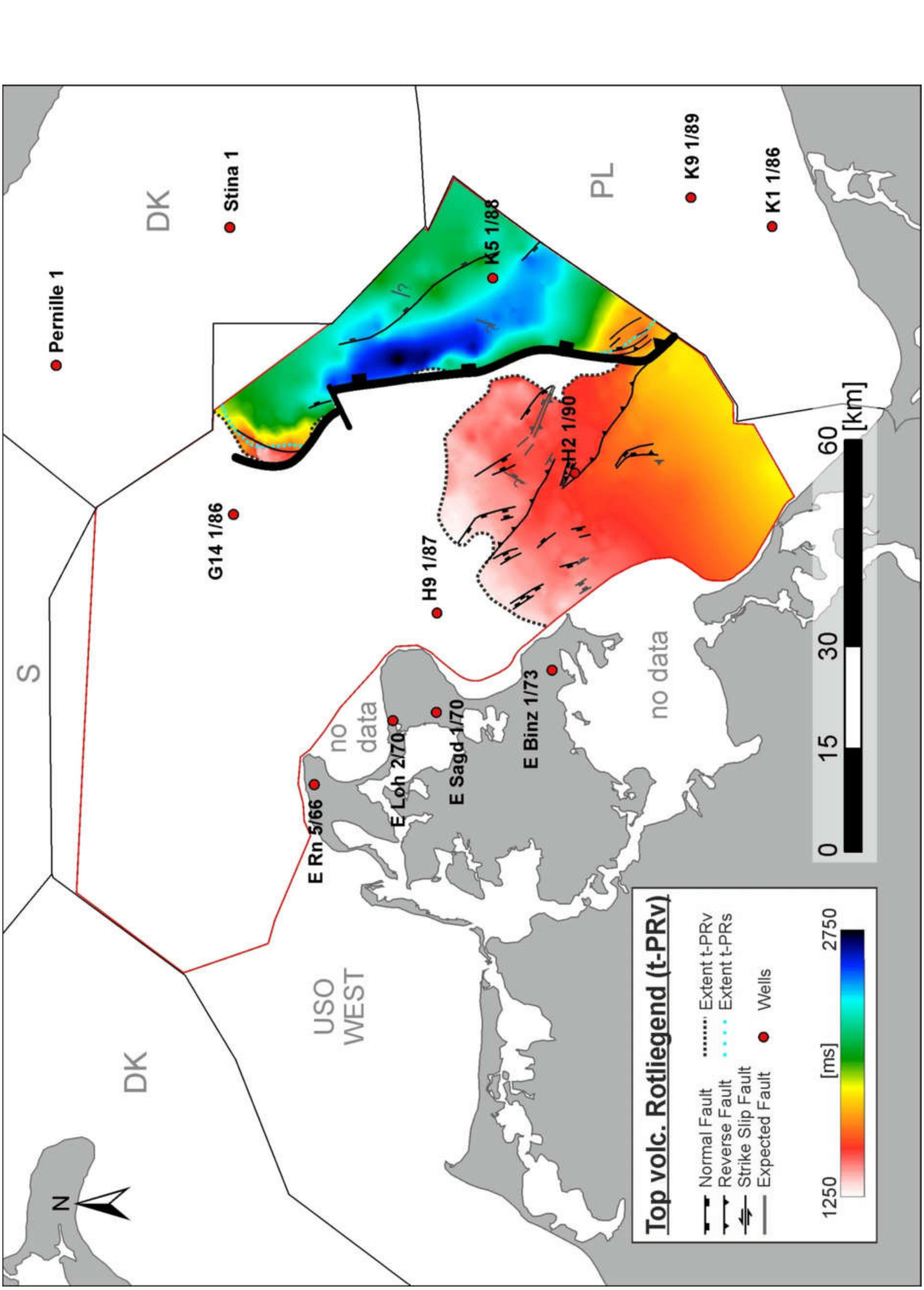


Fig. D-VI: Top volc. Rotliegend.

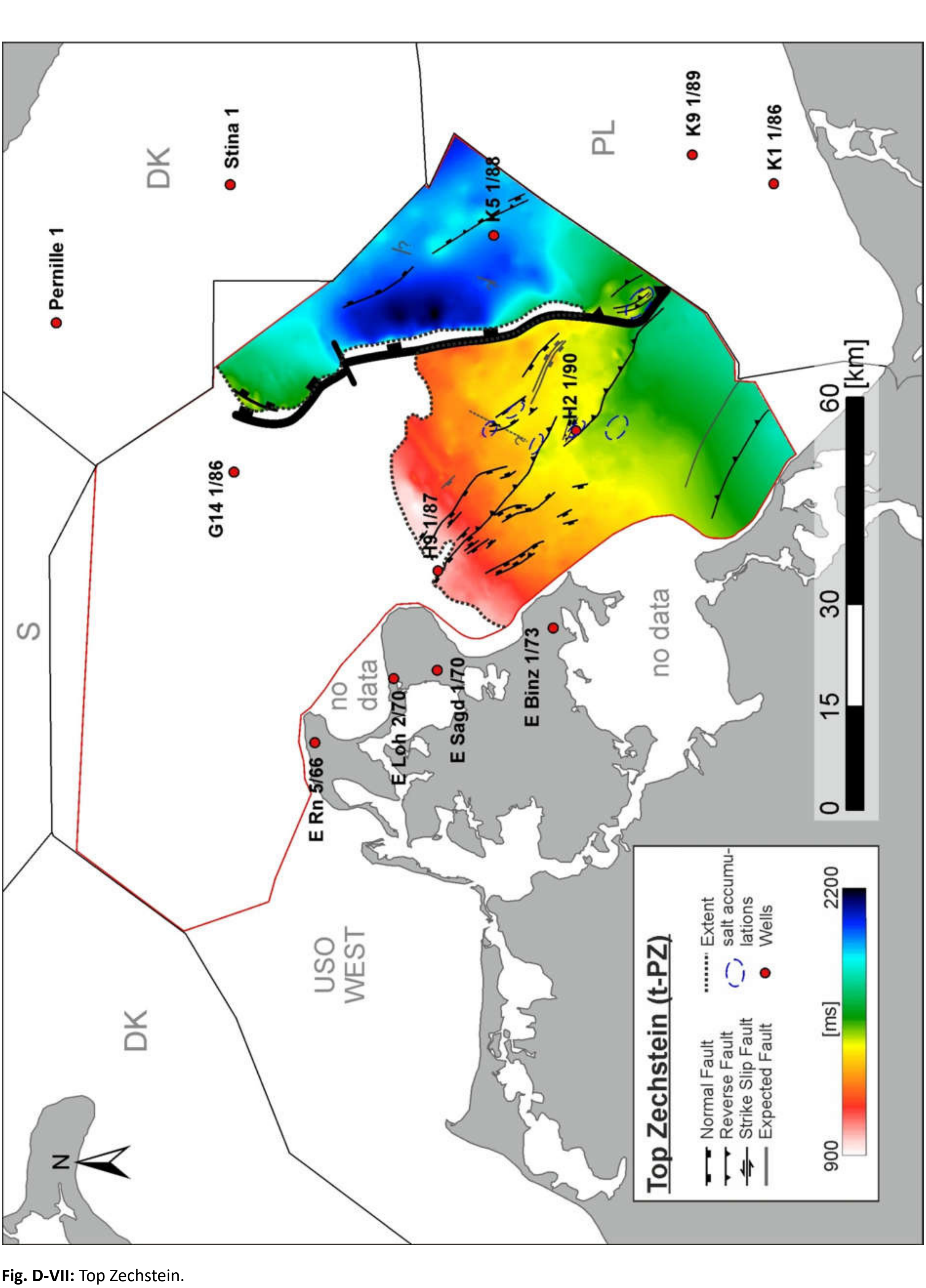


Fig. D-VII: Top Zechstein.

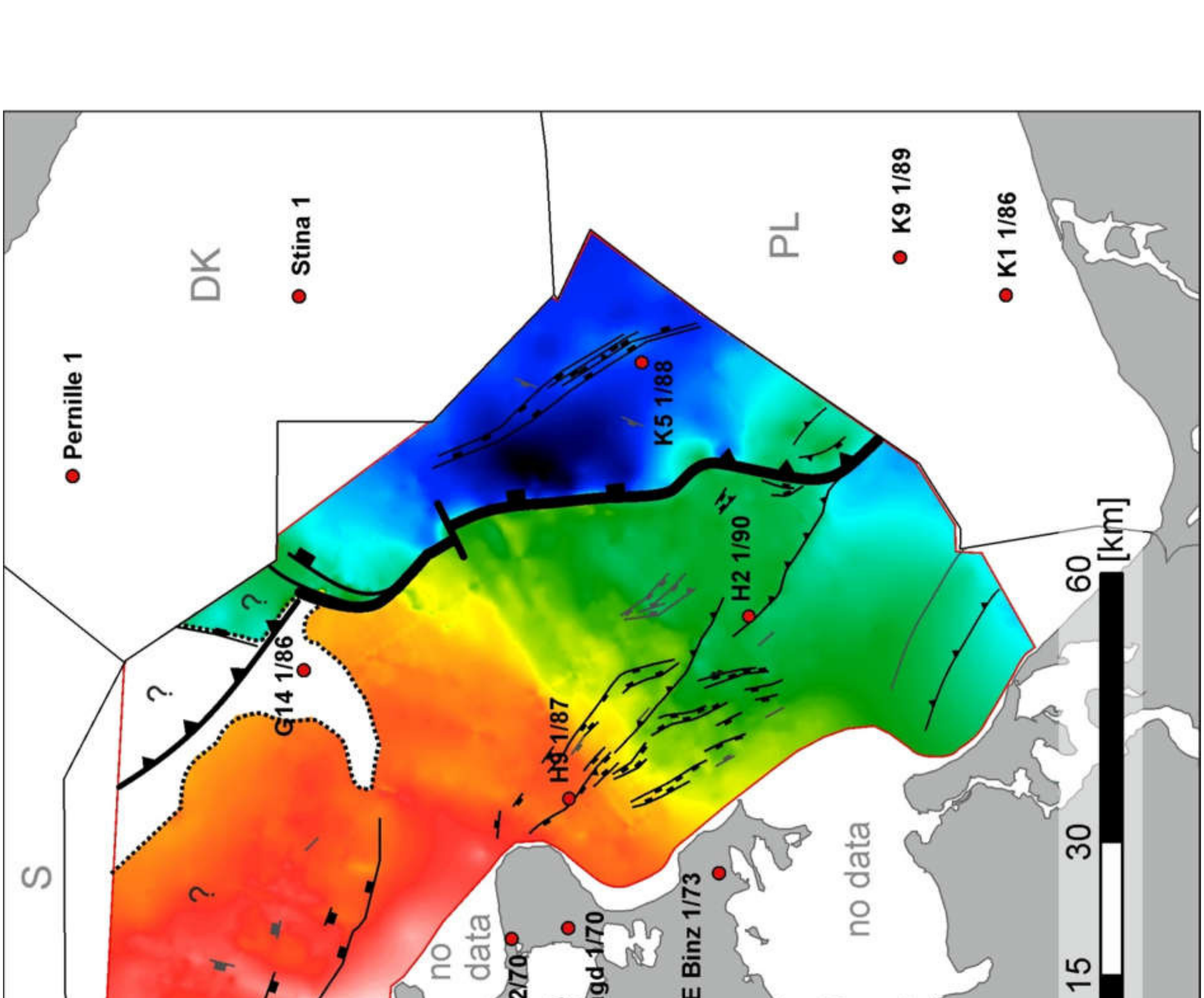


Fig. D-VIII: Top Buntsandstein.

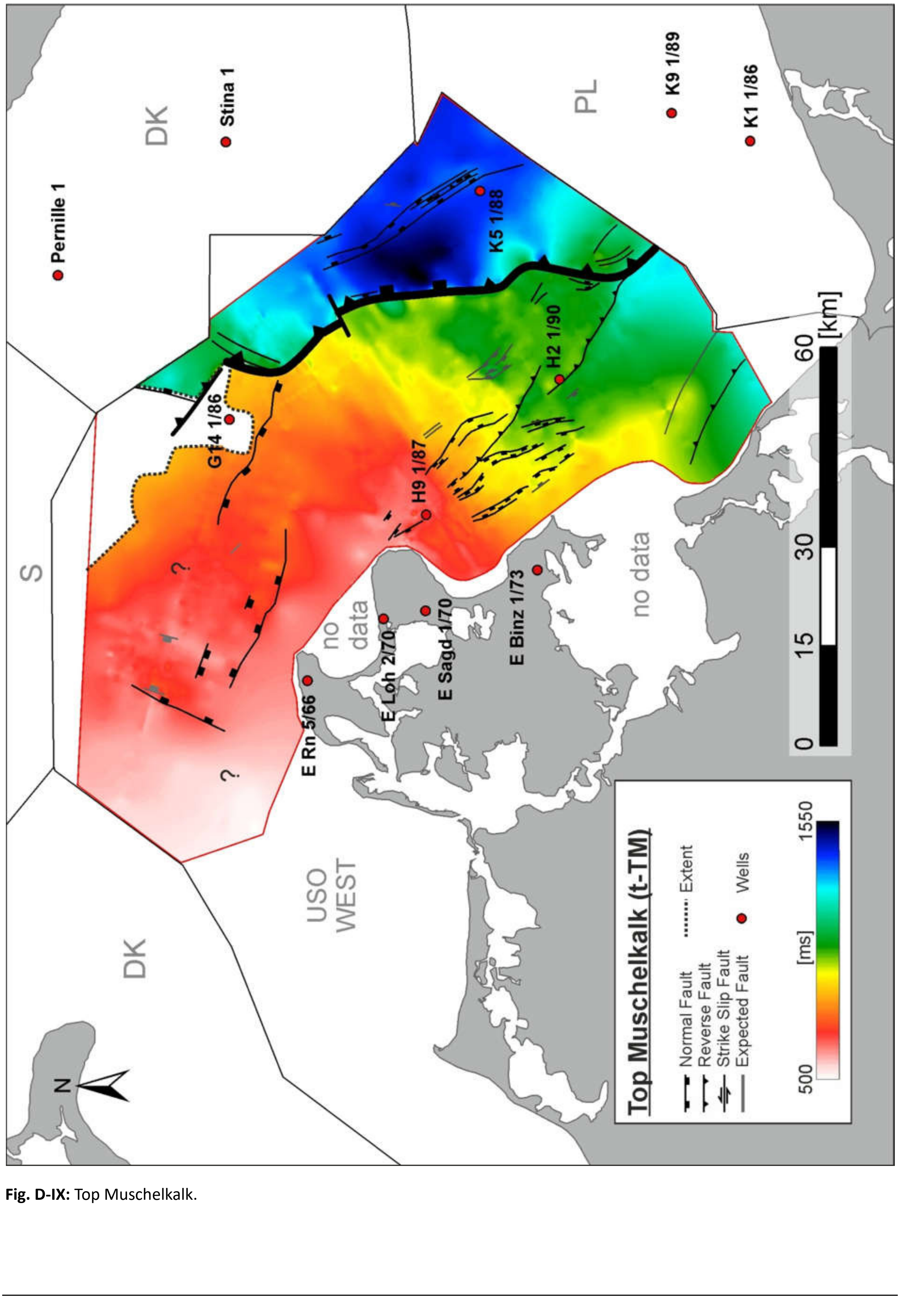


Fig. D-IX: Top Muschelkalk.

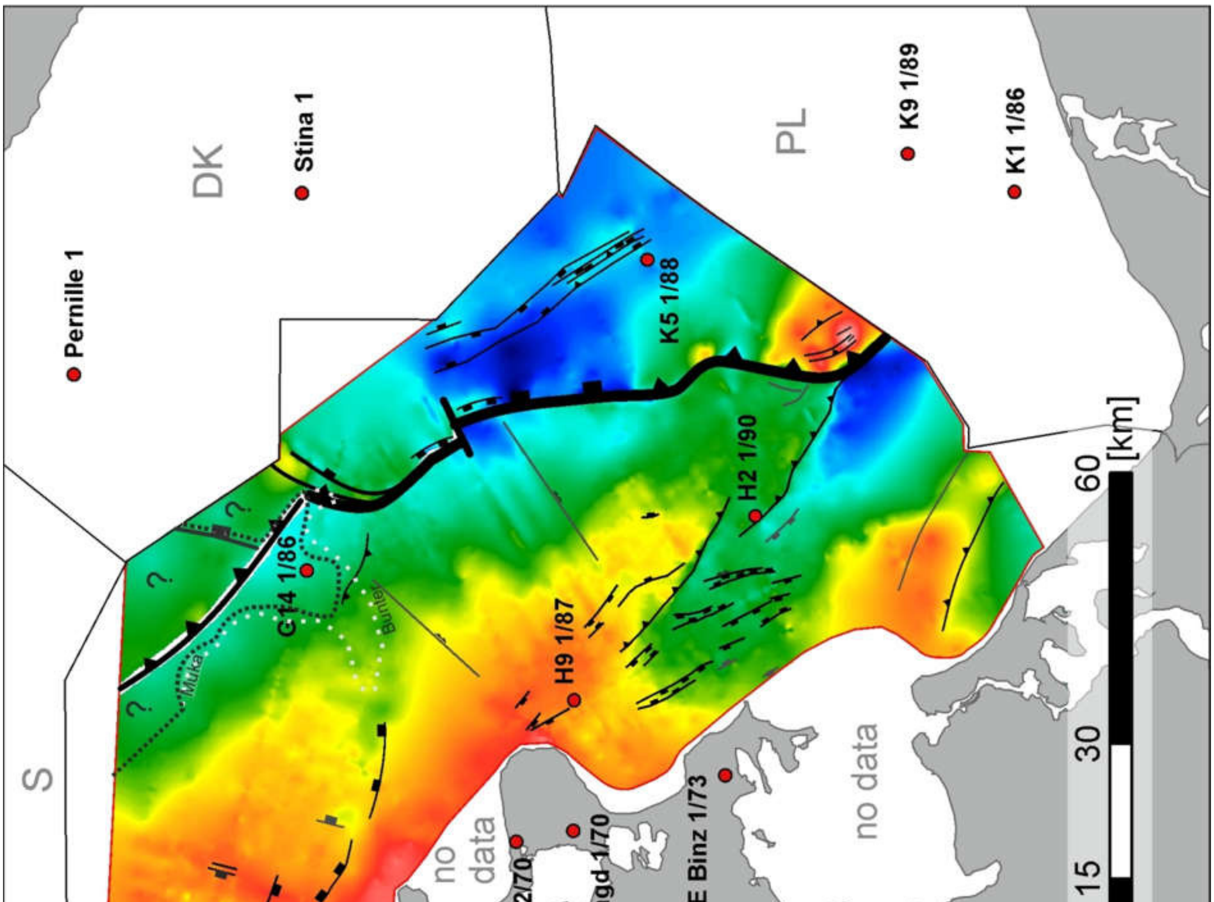


Fig. D-X: Top Keuper.

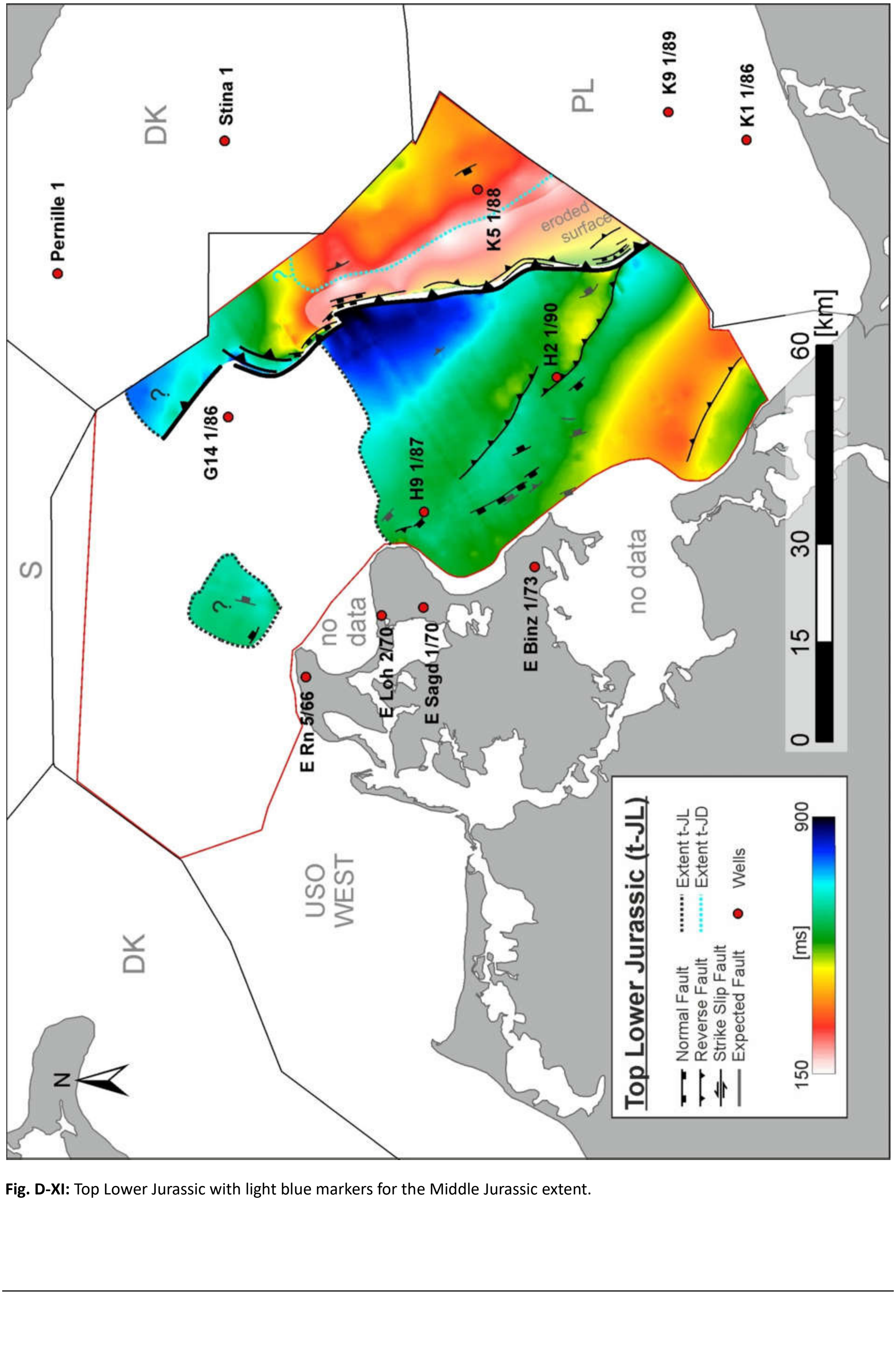


Fig. D-XI: Top Lower Jurassic with light blue markers for the Middle Jurassic extent.

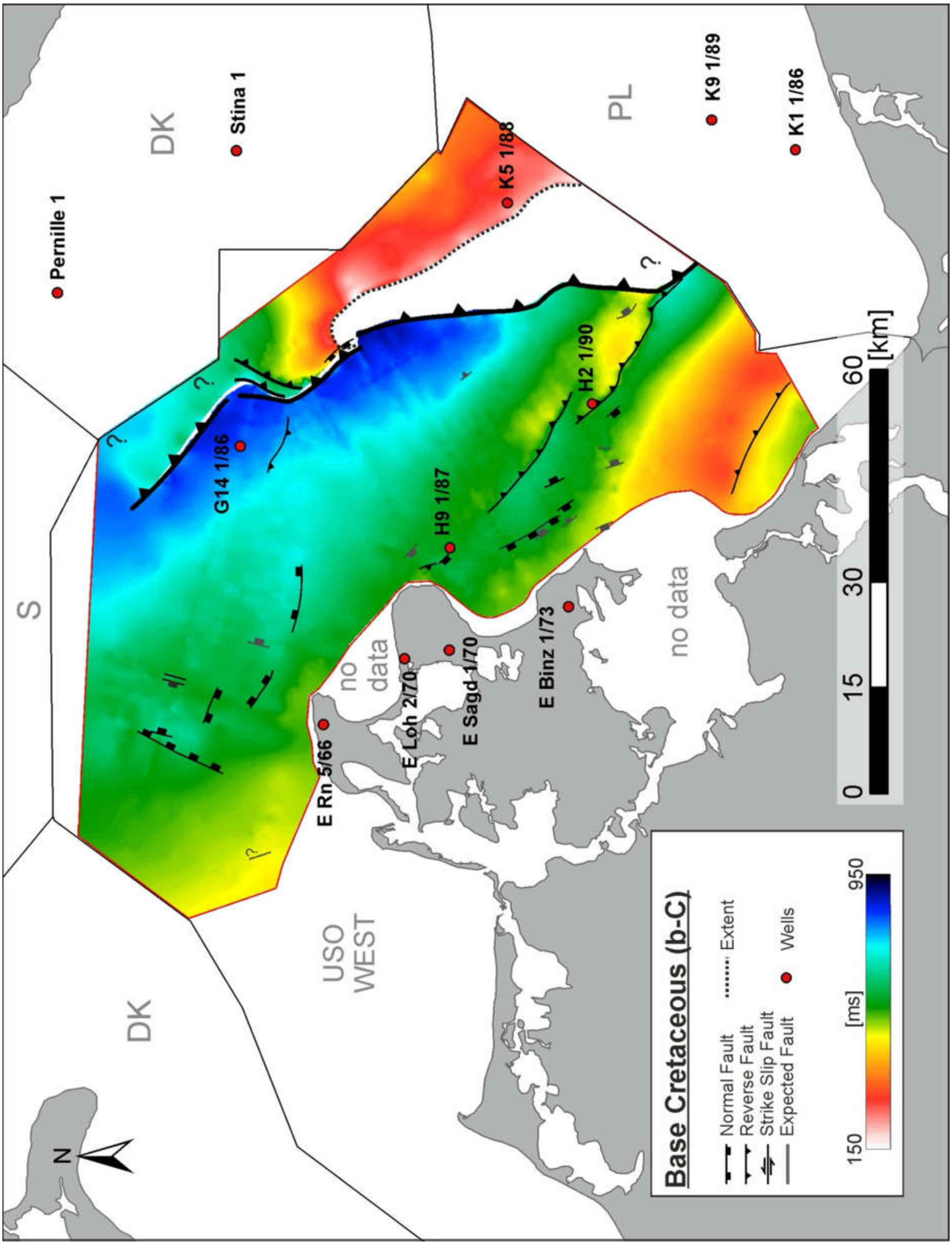


Fig. D-XII: Base Cretaceous.

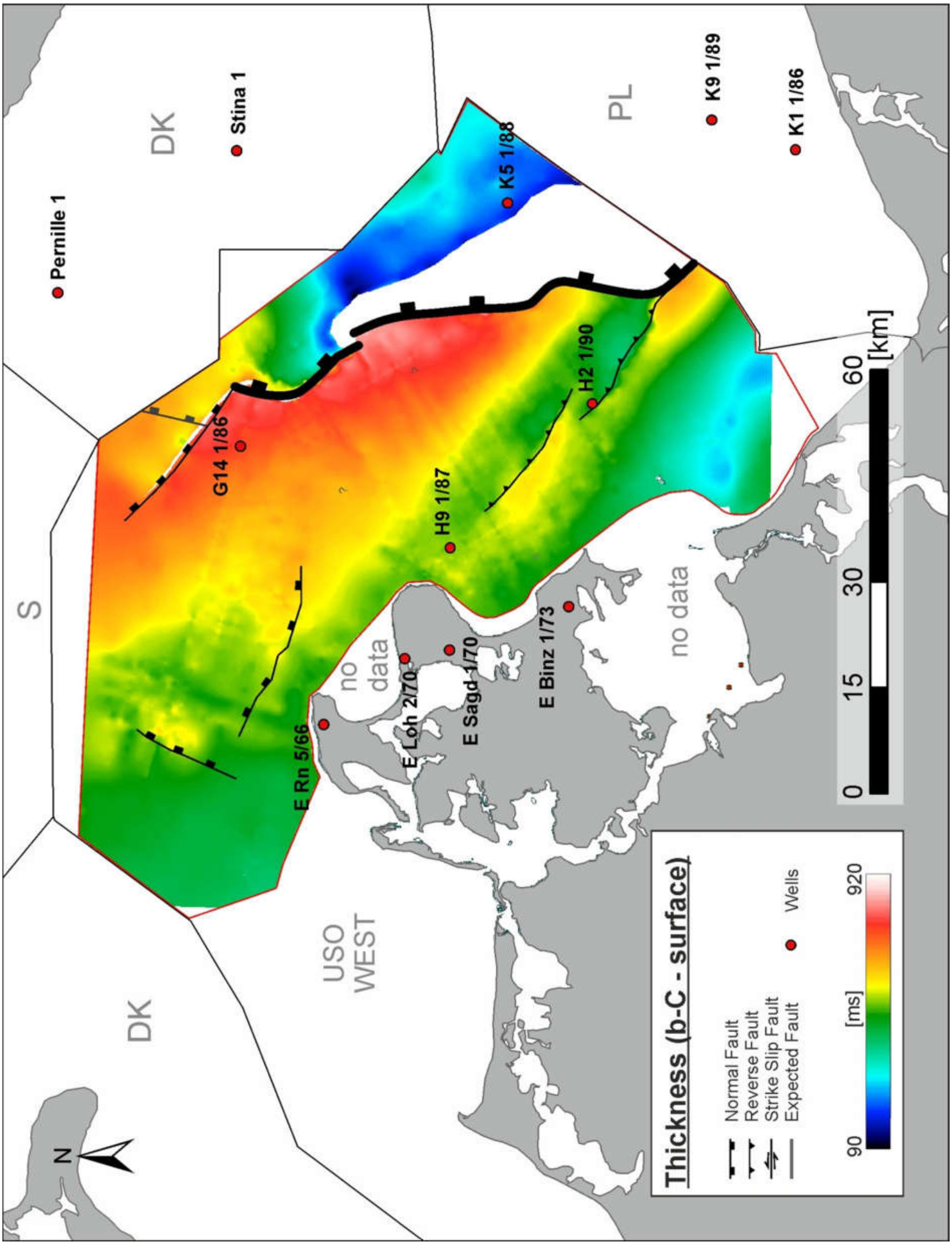


Fig. D-XIII: Pseudo-Thickness of the Cretaceous and Cenozoic successions in TWT.

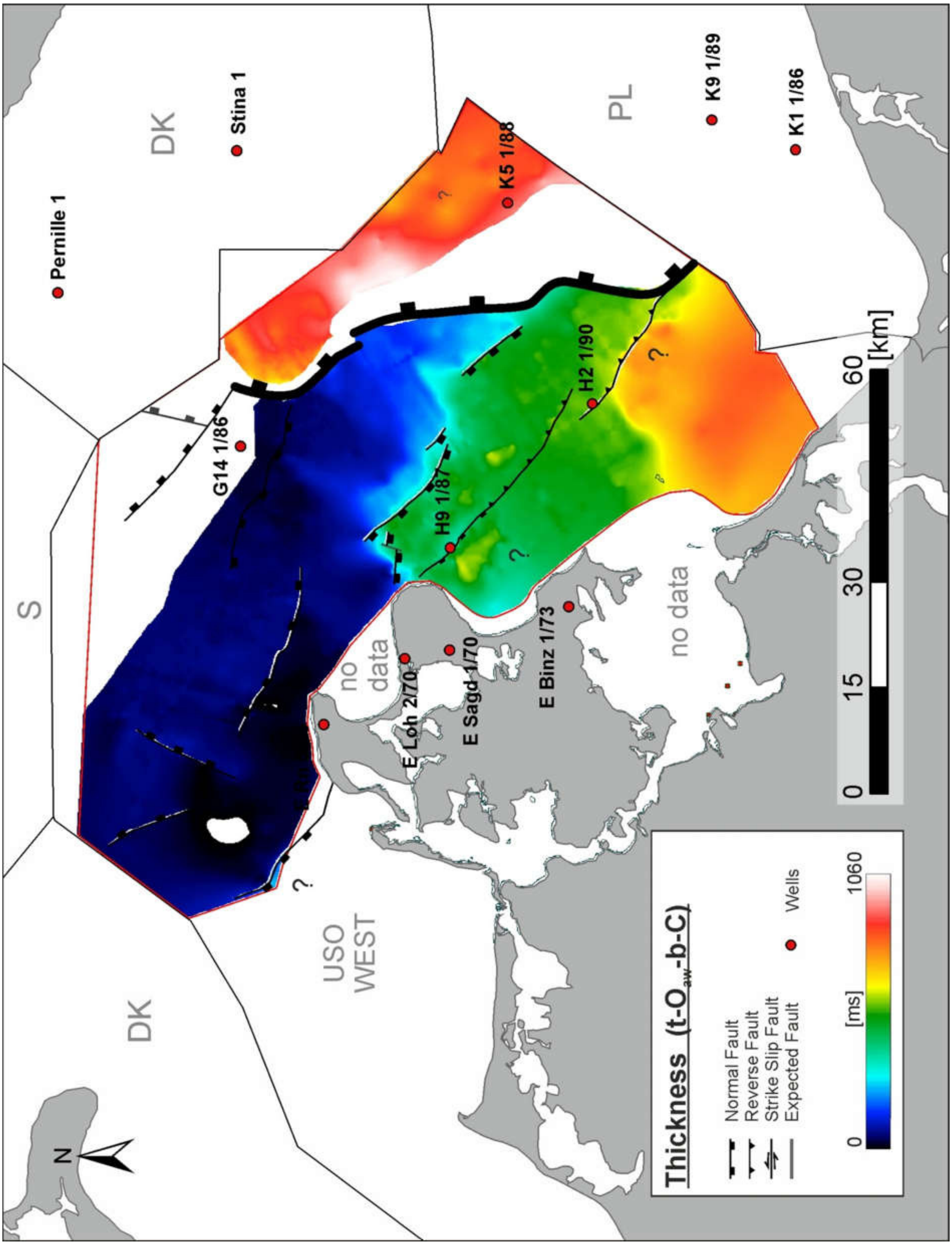
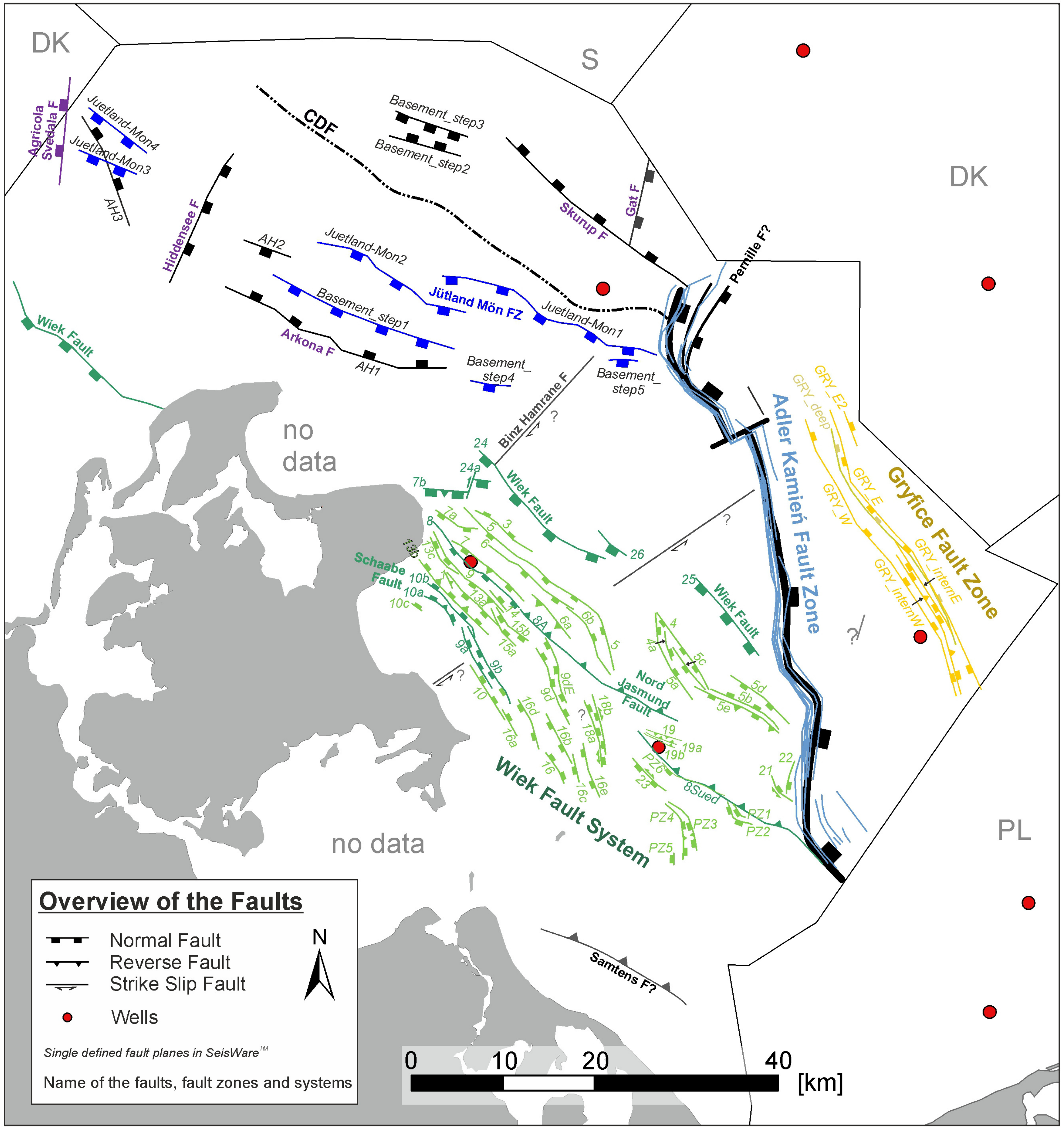
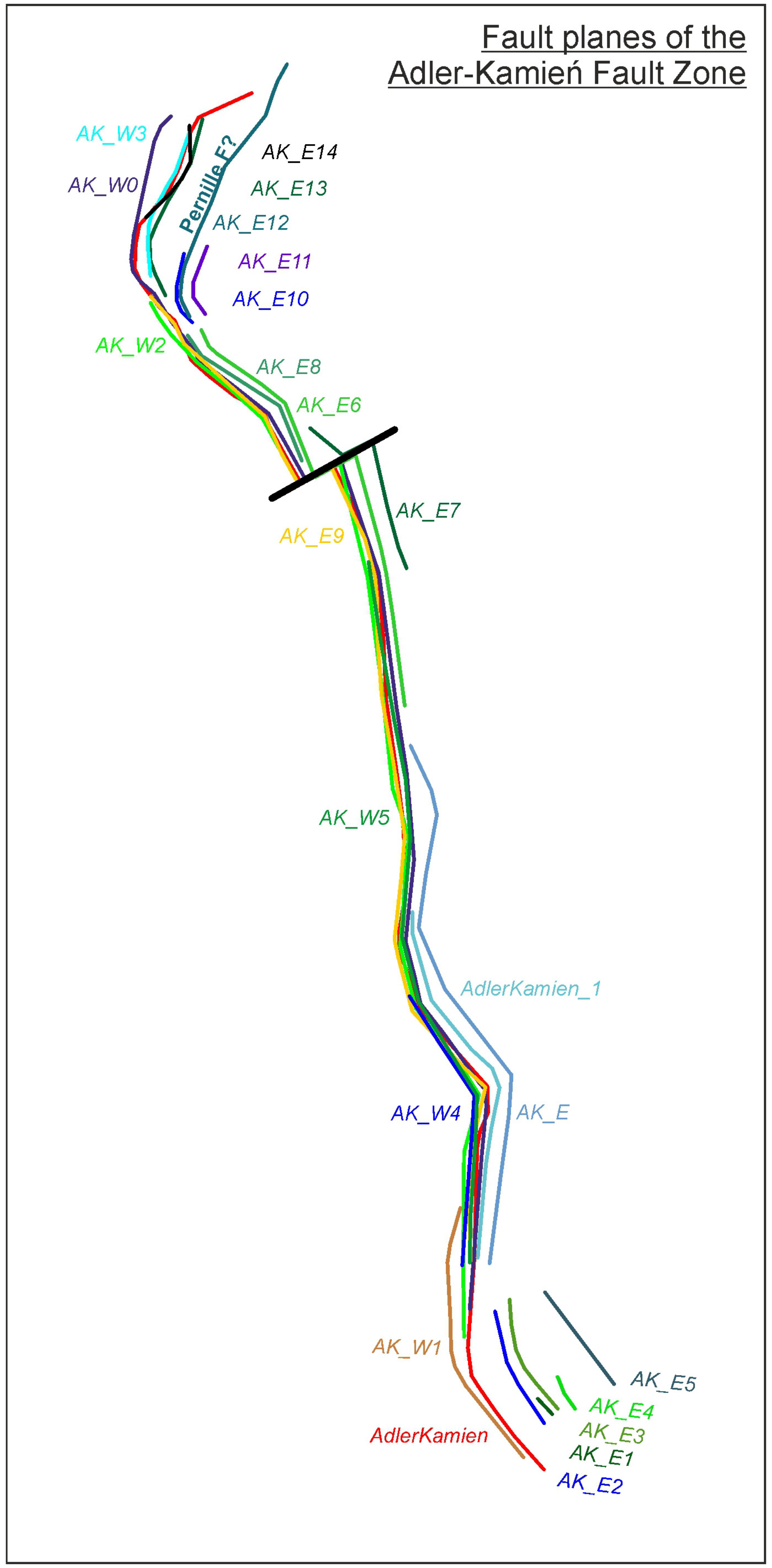


Fig. D-XIV: Pseudo-Thickness of the Post-Ordovician successions in TWT (successions covering the accretionary wedge until the Base of Cretaceous).

Appendix E - Comprehensive table characterising faults and flexures north and east of Rügen


DK
S
DK
PL
Agricola F
Svedala F
Juetland-Mon4
Juetland-Mon3
AH3
CDF
Basement_step3
Basement_step2
Skurup F
Gat F
Hiddensee F
AH2
Juetland-Mon2
Jütland Mön FZ
Juetland-Mon1
Basement_step1
Arkona F
AH1
Basement_step4
Basement_step5
Pernille F?
Wiek Fault
no data
Binz Hamrane F
Adler Kamień Fault Zone
Gryfice Fault Zone
GRY_E2
GRY_deep
GRY_E
GRY_W
GRY_internE
GRY_internW
Schaabe Fault
Nord Jasmund Fault
Wiek Fault System
no data
Samtens F?
Overview of the Faults
Normal Fault
Reverse Fault
Strike Slip Fault
Wells
Single defined fault planes in SeisWare™
Name of the faults, fault zones and systems
N
0 10 20 40 [km]


Fault planes of the Adler-Kamień Fault Zone
AK_W3
AK_W0
Pernille F?
AK_E14
AK_E13
AK_E12
AK_E11
AK_E10
AK_W2
AK_E8
AK_E6
AK_E7
AK_E9
AK_W5
AdlerKamien_1
AK_W4
AK_E
AK_W1
AK_E5
AK_E4
AK_E3
AK_E1
AK_E2
AdlerKamien

Appendix E - Catalouge of faults and flexures north and east of Rügen

FID	F_System	F_plane (SeisWare-Faults)	F_polygone (SeisWare-Culture)	Youngest displaced unit	Oldest displaced unit	Age (assumed)	Reactivate	Displacement Character	Type	Comments	Strike_dir	Dip_dir
1	Agricola(-Svedala) F	Agricola_North	Agricola_North	cr	o	mes	n?	n	fa		NNE-SSW	WNW
2	AKFS	AdlerKamien	AdlerKamien	cr	pal	o_prot	y	n-th	fa		NNW-SSE to NNE-SSW	E
3	AKFS	AdlerKamien1	AdlerKamien1	cr	k	cr_u	n	n	fl		NNW-SSE	ENE
4	AKFS	Adler Kamien_E	AK_E	cr	r	cr_u	n	n	fl		NNW-SSE	ENE
5	AKFS	Adler Kamien_E1	AK_E1	cr	pal		y	th	fa		NNW-SSE	WSW
11	AKFS	Adler Kamien_E2	AK_E2	j	pal		n?	n-r	fl	compression zone	NNW-SSE	ENE
12	AKFS	Adler Kamien_E3	AK_E3	j-cr	pal	cr_u	n	r	fl		NNW-SSE	WSW
13	AKFS	Adler Kamien_E4	AK_E4	j-cr	car	cr_u	n	n	fl		NNW-SSE	WSW
14	AKFS	Adler Kamien_E5	AK_E5	j-cr	b	cr_u	n	r	fl		NNW-SSE	ENE
15	AKFS	Adler Kamien_E6	AK_E6	j-cr	k	cr_u	n	n	fl	tension fault, with lo	NNW-SSE	WSW
16	AKFS	Adler Kamien_E7	AK_E7	j-cr	b	cr_u	n	n	fl	tension fault, with lo	NNW-SSE	WSW
17	AKFS	Adler Kamien_E8	AK_E8	cr	j	cr_u	n	n	fl		NW-SE	SW
18	AKFS	Adler Kamien_E9	AK_E9	cr	cr	cr_u	n	th	fa	border in Cr & Cenozoic between Arkona & Gryfice Block	NNW-SSE	WSW
6	AKFS	Adler Kamien_E10	AK_E10	k	r	cr_u	n	r	fl		N-S	E
7	AKFS	Adler Kamien_E11	AK_E11	k	r-car	cr_u	n	r	fl		N-S	E
8	AKFS	Adler Kamien_E12	AK_E12	cr	o		y	th	fa		NNE-SSW	ESE
9	AKFS	Adler Kamien_E13	AK_E13	cr	k	cr_u	n	n	fl		NNE-SSW	ESE
10	AKFS	Adler Kamien_E14	AK_E14	cr	cr	cr_u	n	n	fl	only in cretaceous	NNE-SSW	ESE
19	AKFS	Adler Kamien_W0	AK_W0	cr	pal		y	n-th	fa	left border of compression zone, with lo	NNW-SSE to NNE-SSW	E
20	AKFS	Adler Kamien_W1	AK_W1	cr	pal	cr_u?	n	n	fl		NNW-SSE	ENE
21	AKFS	Adler Kamien_W2	AK_W2	cr	pal		y?	n-r	fl	with lo	NNW-SSE to NNE-SSW	steep W, E
22	AKFS	Adler Kamien_W3	AK_W3	cr	pal		y	n-th	fl		NNE-SSW	ESE
23	AKFS	Adler Kamien_W4	AK_W4	j-cr	k	cr-u	n	n	fl	left of main fault plane, formed by overthrusting	NNW-SSE	ENE
24	AKFS	Adler Kamien_W5	AK_W5	cr	b	cr-u	n	r	fa	within compression zone	N-S NNW-SSE	WSW
25	Arkona F	AH_1	AH_1	j-cr	o		n	n	fa		WNW-ESE	NNE
26	AH_2?	AH_2	AH_2	j-cr	o		n?	n	fa-fl	parallels the Arkona Fault	WNW-ESE	SSW
27	AH_3?	AH_3	AH_3	mu	o	mes-cr_u?	n	n	fa	extension of the Arkona Fault?	NNW-SSE	ENE
28	JMFZ	AH_Basement_step1	AH_Basement_step1	o	prot	pal	n?	n	fa		WNW-ESE	SSW
29	Skurup Fault?	AH_Basement_step2	AH_Basement_step2	b	prot	pal	y?	n	fl	Faults on AKB	WNW-ESE	NNE
30	Skurup Fault?	AH_Basement_step3	AH_Basement_step3	b	prot	pal	y?	n	fl	Faults on AKB, form Graben with Basement_step2	WNW-ESE	SSW
31	JMFZ	AH_Basement_step4	AH_Basement_step4	o	prot	pal	n	n	fa	Faults on AKB	WNW-ESE	SSW
32	AH_Basement_step	AH_Basement_step5	AH_Basement_step5	o	prot	pal	n	n	fa	Faults on AKB, below G14 & JMF	W-E WNW-ESE	S
33	CDF	CDF	CDF							**no fault**, northern border of the accretionary wedge	NW-SE	
34	Gat F	no fault plane	Gat_Fault							western border of the Rønne Graben		
35	GFZ	GRY_deep	GRY_deep	z	prot?	z	y	n	fa		NNW-SSE	ENE
36	GFZ	GRY_E	GRY_E	j-cr_l	b	me-cr_u	y?	n	fa	as normal and reverse flexure, reac. GRY_deep	NNW-SSE	WSW
37	GFZ	GRY_E2	GRY_E2	j	m	me-cr_u	y?	n	fl	only in one seismic section	NNW-SSE?	ENE?
38	GFZ	GRY_internE	GRY_internE	j	b	me-cr_u	y?	n	fl		NNW-SSE	WSW
39	GFZ	GRY_internW	GRY_internW	j	b	me-cr_u	y?	n	fl		NNW-SSE	ENE
40	GFZ	GRY_W	GRY_W	j	z	me-cr_u	y?	r-n	fa		NNW-SSE	ENE
41	Hiddensee Fault	Hiddensee Fault	Hiddensee Fault	cr	prot	me	n	n	fa	basement fault	NNE-SSW	ESE
42	JMFZ	Juetland-Mon4	Juettland_Mon4	o	prot	pal	n	n	fa	basement fault	NW-SE	SW
43	JMFZ	Juetland-Mon3	Juettland_Mon3	o	prot	pal	n	n	fa	basement fault	WNW-ESE	SSW
44	JMFZ	Juetland-Mon2	Juettland_Mon2	o	prot	pal	n	n	fa	basement fault	WNW-ESE	SSW
45	JMFZ	Juetland_Mon1	Juettland_Mon1	o	prot	pal	n	n	fa	basement fault	WNW-ESE	SSW
46	Skurup Fault	Skurup-AK-Fault	Skurup_AK	cr_u	prot	pal-o	y	n-r	fa-fl	similar to AKFS normal and reverse	NW-SE	SW
47		Strelasund	Strelasund Fault									
48	Wiek Fault System	WFS_PZ_1	WFS_PZ_1	car	o	car	n	n	fa	in cr_u reac as Jasmund F	NNW-SSE	WSW
49	Wiek Fault System	WFS_PZ_2	WFS_PZ_2	car	o	car	n	n	fl	in cr_u reac as Jasmund F	NNW-SSE	WSW
50	Wiek Fault System	WFS_PZ_3	WFS_PZ_3	z	o	pal	n	r	fl	similar to GRY, due to structure below	NW-SE NNW-SSE	SW
51	Wiek Fault System	WFS_PZ_4	WFS_PZ_4	z	o	pal	n	r?	fl	similar to GRY, due to structure below	NW-SE NNW-SSE	NE
52	Wiek Fault System	WFS_PZ_5	WFS_PZ_5	z	o	pal	n	n	fl	similar to GRY, due to structure below	NNW-SSE N-S?	SW?
53	Wiek Fault System	WFS_PZ_6	WFS_PZ_6	car	o	pal	y	n	fl	in cr_u reac as Jasmund F	NE-SE	SW
54	Wiek Fault System	WFS_26	WFS_26	car	prot	pal-o	y	n	fa	**Wiek deep fault**	NW-SE	SW

Type		Displacement		Reactivation	
fault	fa	normal	n	Yes	y
flexure	fl	reverse	r	No	n
		thrust	th		

Startigraphy				
Cretaceous	cr	Mesozoic - me	Upper	u
Jurassic	j		Lower	l
Keuper	k			
Muschelkalk	m			
Buntsandstein	b			
Zechstein	z	Palaeo - pal		
Rotliegend	r			
Carboniferous	car			
Devonian	d			
Silurian	s			
Ordovician	o			
Cambrian	cam			
Proterozoic - prot				

55	Wiek Fault System	WFS_25	WFS_25	z	o	pal-o	y	n	fa	**Wiek deep fault**	NW-SE NNW-SSE	WSW
56	Wiek Fault System	WFS_24a	WFS_24a	d	o	pal-o	n	n	fa	**Wiek deep fault**	WNW-ESE	SSW
57	Wiek Fault System	WFS_24	WFS_24	mes?	o	pal-o	y	n	fa	**Wiek deep fault,** USO East & USO West	NW-SE	SW
58	Wiek Fault System	WFS_23	WTB_23	cr	b	mes	n	l	fl	strike slip?	NW-SE	SW
59	Wiek Fault System	WFS_22	WTB_22	j	b	mes, cr_u?	n	n	fl	listric, degassing structure above	NNE-SSW	ESE
60	Wiek Fault System	WFS_21	WTB_21	cr	b	mes, cr_u?	n	n	fl		NW-SE	NE
61	Wiek Fault System	WFS_19b	WTB_19b	z	o	mes, cr_u?	y	r	fl	Pos. Flower structure, between NJF offset	NW-SE	NE
62	Wiek Fault System	WFS_19a	WTB_19a	b	car	mes, cr_u?	y	r	fl	Pos. Flower structure, between NJF offset	NW-SE	NE
63	Wiek Fault System	WFS_19	WTB_19	b	o	mes, cr_u?	y	r	fl	Pos. Flower structure, between NJF offset	NW-SE	SW
64	Wiek Fault System	WFS_18b	WTB_18b	j	b	mes	n	n	fl	Usedom Fault Zone?, graben with WTB_18a	NNW-SSE	WSW
65	Wiek Fault System	WFS_18a	WTB_18a	cr-u	b	mes	n	n-r?	fl	Usedom Fault Zone?, graben with WTB_18b	NNW-SSE	ENE
66	Wiek Fault System	WFS_16d	WTB_16d	cr-u	o	mes	n	n	fl	Usedom Fault	NNW-SSE	WSW
67	Wiek Fault System	WFS_16e	WTB_16e	j	d	mes	n	n	fl	Usedom Fault	NNW-SSE	WSW
68	Wiek Fault System	WFS_16c	WTB_16c	cr_u	d?	mes	n	n	fl	Usedom Fault	NNW-SSE	WSW
69	Wiek Fault System	WFS_16b	WTB_16b	j	z	mes	n	n	fl	Usedom Fault	NNW-SSE	WSW
70	Wiek Fault System	WFS_16a	WTB_16a	cr_u	b	mes	n	n	fl	Schaabe or Usedom Fault	NNW-SSE	ENE
71	Wiek Fault System	WFS_16	WTB_16	j	b	mes	n	n	fl	Usedom Fault	NNW-SSE	ENE
72	Wiek Fault System	WFS_15b	WTB_15b	j	z	mes	n	n	fl	graben with WTB 15a	NW-SE	SW
73	Wiek Fault System	WFS_15a	WTB_15a	k	z	mes	n	n	fl	graben with WTB 15b	NW-SE	NE
74	Wiek Fault System	WFS_14	WTB_14	k	d	mes	n	n	fl	Graben with WTB 8, listric	NW_SE	NE
75	Wiek Fault System	WFS_13c	WTB_13c	z	d	pal	n	r	fl	positive y-formed structure with WFS_9	NW-SE	NE
76	Wiek Fault System	WFS_13b	WTB_13b	z	o	pal	y	n	fa-fl	Graben with WTB_13a, Var. Inverted	NW-SE	NE
77	Wiek Fault System	WFS_13a	WTB_13a	z	o	pal	n	n	fl	Graben with WTB_13b	NW-SE	SW
78	Wiek Fault System	WFS_10c	WTB_10c	d	o	pal	n	n	fa	Parchow Fault?	NW-SE	NE
79	Wiek Fault System	WFS_10b	WTB_10b	car	o	pal	n	n	fa-fl	Schaabe Fault	NW-SE	NE
80	Wiek Fault System	WFS_10a	WTB_10a	car	o	pal	y	n	fa	Schaabe Fault, Var. Inverted	NW-SE	NE
81	Wiek Fault System	WFS_10	WTB_10	car	o	pal	n	n	fa	Parchow or Schaabe Fault	NNW-SSE	ENE
82	Wiek Fault System	WFS_9dE	WTB_9dE	j	d	mes	n	n	fl	graben with WTB_9d	NNW-SSE	WSW
83	Wiek Fault System	WFS_9d	WTB_9d	cr-u	d	mes	n	n	fa-fl	graben with WTB_9dE	NNW-SSE	ENE
84	Wiek Fault System	WFS_9b	WTB_9b	cr-u	o	pal-mes?	y	n	fa-fl	graben with WTB_9a	NNW-SSE	WSW
85	Wiek Fault System	WFS_9a	WTB_9a	cr-u	car	mes	n	n	fl	graben with WTB_9b, Schaabe Fault	NNW-SSE	ENE
86	Wiek Fault System	WFS_9	WTB_9	mu	o	pal	y	n	fa-fl	reactivated with WFS_8 (NJF)	NW-SE	SW
87	Wiek Fault System	WFS_8Sued	WTB_8Sued	cr-u	o	pal-cr-u	y	n-r	fa-fl	**Nord Jasmund Fault**, old=norm, young= rev, offset to WFS_8A	NW-SE	NE
88	Wiek Fault System	WFS_8A	WTB_8A	cr-u	o	pal-cr-u	y	n-r	fa-fl	**Nord Jasmund Fault**, old=norm, young= rev	NW-SE	NE
89	Wiek Fault System	WFS_8	WTB_8	cr-u	o	pal-mes	y	n	fa-fl	**Nord Jasmund Fault**	NW-SE	SW
90	Wiek Fault System	WFS_7b	WTB_7b	mes?	o	pal-o	y	n-r	fa-fl	**Wiek deep fault**	WNW-ESE	SSW
91	Wiek Fault System	WFS_7a	WTB_7a	b	o	pal-mes	y	n	fa-fl		NE-SW	SW
92	Wiek Fault System	WFS_7	WTB_7	k	o	pal-mes	y	n	fa-fl	change further south in fault 6a (other dip direction!)	NW-SE	SW
93	Wiek Fault System	WFS_6b	WTB_6b	j	b	mes	n	n	fl	strike direction change	NW-SE to NNW-SSE	NE to ENE
94	Wiek Fault System	WFS_6a	WTB_6a	z	o	pal	n	r	fl	border of rotated block, foldlimb?	NW-SE	SW
95	Wiek Fault System	WFS_6	WTB_6	car	o	pal	n	n	fa-fl	Foldlimb/ backthrust?	NW-SE	SW
96	Wiek Fault System	WFS_5e	WTB_5e	b	o	pal-mes	y	n?	fl		NW-SE	SW
97	Wiek Fault System	WFS_5d	WTB_5d	b	d	mes	n?	n	fl		NW-SE	SW
98	Wiek Fault System	WFS_5c	WTB_5c	k	car	mes	n?	n	fl		NNW-SSE	WSW
99	Wiek Fault System	WFS_5b	WTB_5b	k	o	pal-mes	y?	n	fl		NW-SE	NE
100	Wiek Fault System	WFS_5a	WTB_5a	k	o	mes	?	n	fl	Graben with WTB_4, small salt pillow/ reef?	NNW-SSE	ENE
101	Wiek Fault System	WFS_5	WTB_5	k	o	pal-mes	y	n	fa	Odense-Wiek II	NW-SE to NNW-SSE	SW to WSW
102	Wiek Fault System	WFS_4a	WTB_4a	k	r-car	mes	?	n-r?	fl		NNW-SSE	ENE
103	Wiek Fault System	WFS_4	WTB_4	k	d-o	pal-mes	y	r-n?	fl	Graben with WTB_5a, small salt pillow?	NNW-SSE	WSW
104	Wiek Fault System	WFS_3	WTB_3	k	o	pal-mes	y	n-r	fl		NW-SE	NE
105	Wiek Fault System	WFS_1	WFS_1	car	d	pal	n	r	fl	positive y-formed structure with WFS_13a	NE-SW	NE

Appendix F - Supplementary material

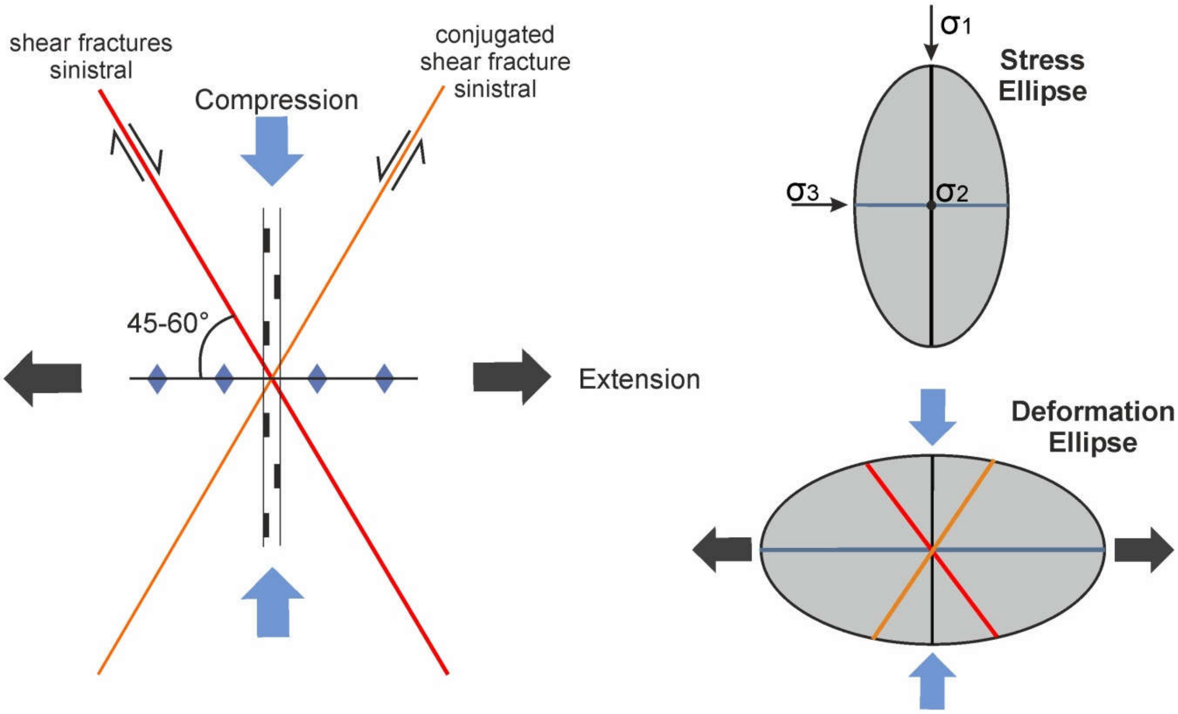


Fig. I: Compilation of compressional, extensional and shearing structures within one stress system and the appropriate stress and deformation ellipses (Reuther 2012, modified).

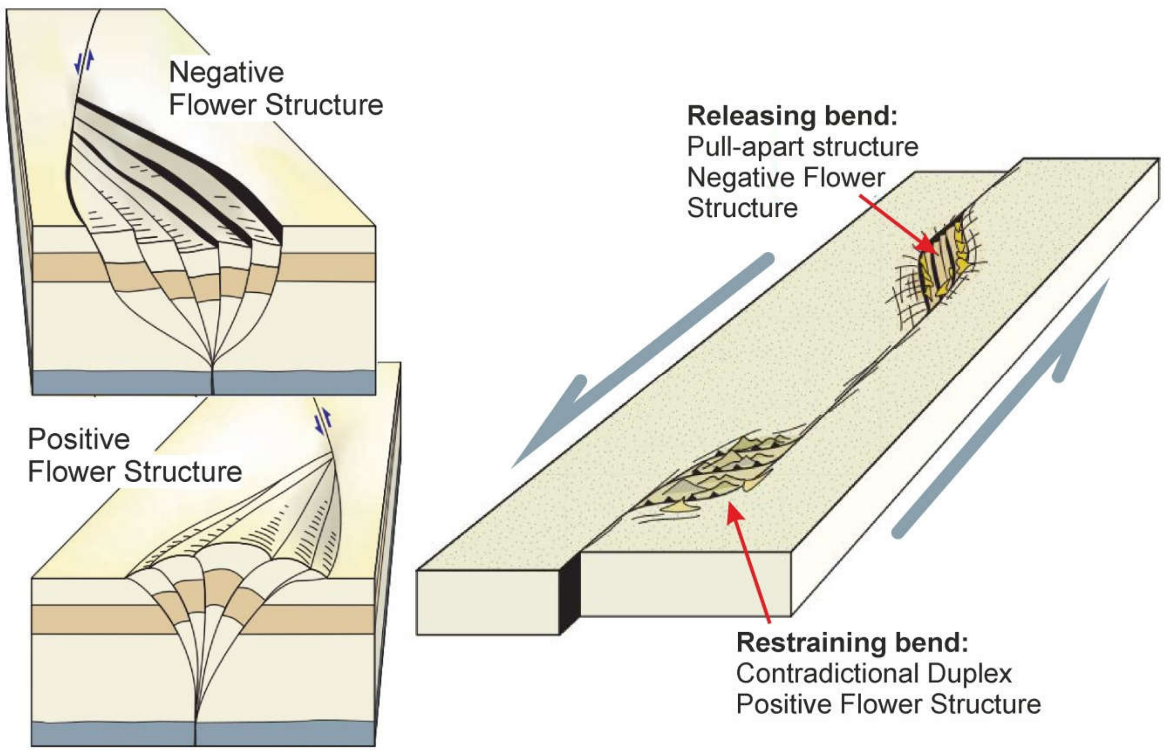


Fig. II: Formation of Positive and Negative Flower Structures along a strike slip Fault with restraining and releasing bends (Fossen 2010, modified).

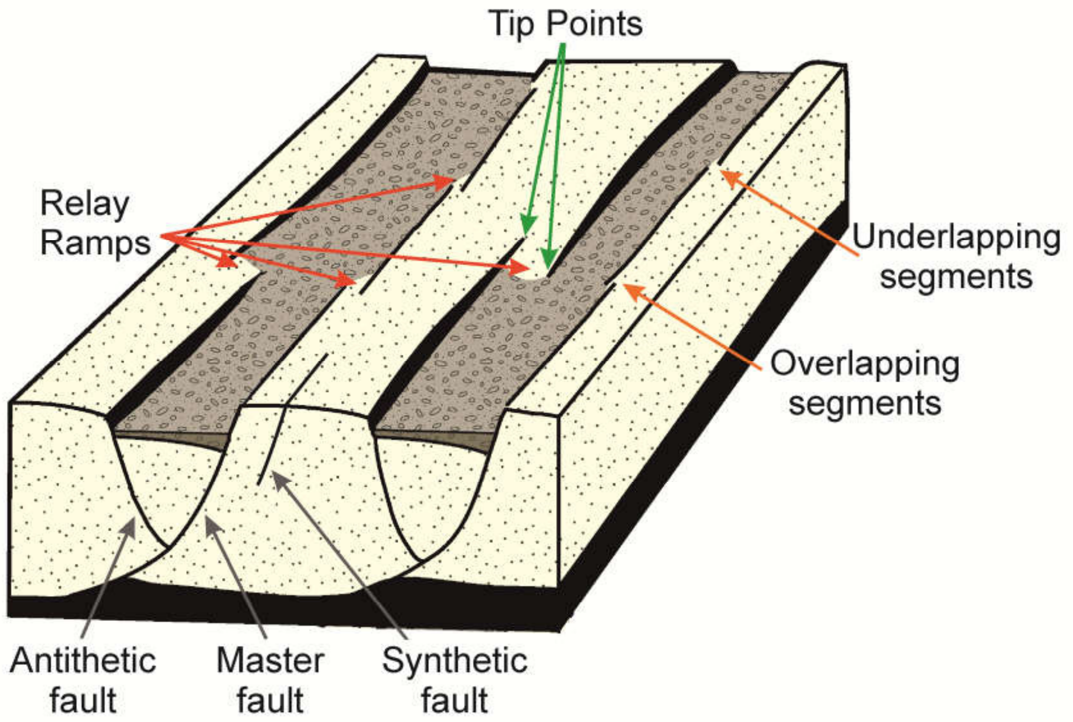


Fig. III: Soft linked faults with overlapping and underlapping segments. Overlapping segments are characterised by fault tips that have passed each other, forming relay ramps in between. Additional the graben structure is limited by a master fault, parallel dipping synthetic faults, and conjugating antithetic faults (FOSSEN 2010, modified).

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Eigenständigkeitserklärung

Hiermit erkläre ich, dass diese Arbeit bisher von mir weder an der Mathematisch-Naturwissenschaftlichen Fakultät der Universität Greifswald noch einer anderen wissenschaftlichen Einrichtung zum Zwecke der Promotion eingereicht wurde.
Ferner erkläre ich, dass ich diese Arbeit selbstständig verfasst und keine anderen als die darin angegebenen Hilfsmittel und Hilfen benutzt und keine Textabschnitte eines Dritten ohne Kennzeichnung übernommen habe.

List of publications, talks and posters

Paper

Flechsig, C., Heinicke, J. & Mrlina, J., Kämpf, H., Nickschick, T., Schmidt, A., Bayer, T., Günther, T., Rücker, C., **Seidel, E.**, Seidl, M. (2015): Integrated geophysical and geological methods to investigate the inner and outer structures of the Quaternary Mýtina maar (W-Bohemia, Czech Republic). International Journal of Earth Sciences. 104.

Franz, M., Nowak, K., Niegel, S., **Seidel, E.**, Wolf, M. & Wolfgramm, M. (2018): Deep geothermal resources of the North German Basin: The hydrothermal reservoirs of the Stuttgart Formation (Schilfsandstein, Upper Triassic), Zeitschrift der Deutschen Gesellschaft für Geowissenschaften, 169 (3), 353-387.

Seidel, E., Meschede, M. & Obst K. (2018): The Wiek Fault System east of Rügen Island: Origin, tectonic phases and its relation to the Trans-European Suture Zone. – In Kilhams, B., Kukla, P.A., Mazur, S., McKie, T., Mijnlieff, H. & van Ojik, K. (eds): Mesozoic Resource Potential in the Southern Permian Basin. Geological Society, London, Special Publications, 469, 59-82.

Poster

Noack V., Schnabel M., Damm V., Hübscher C. & **Seidel E.** (2016): “Challenges for the interpretation of the „BalTec“ expedition Data (March 2016) –a detailed look at the Zechstein layer of the Mecklenburg Bay (southern Baltic Sea).” The Baltic 2016 - 13th Colloquium on Baltic Sea marine Geology, Gdansk.

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Seidel E., Meschede M. & Obst K. (2014): "Structural analyses of Palaeozoic and Mesozoic Fault Systems in the Baltic Sea area east of Rügen Island based on revised Petrobaltic data" GeoFrankfurt 2014.

Seidel E., Meschede M. & Obst K. (2015): "Polyphase evolution of the Tornquist Fan area - Analyses of Petrobaltic seismic sections crossing the Adler-Kamien Fault System, Southern Baltic Sea" DGG conference 2015 (Hannover).

Seidel E., Meschede M. & Obst K. (2015): "USO-Projekt (Teilgebiet Ost): Interpretation und Visualisierung seismischer Profile und Bohrungsdaten östlich von Rügen als Basis für ein 3D-Modell" NGT Güstrow 2015.

Seidel E., Meschede M. & Obst K. (2015): "Interpretation and Visualization of seismic and borehole data for a 3D Model in the Southern Baltic Sea, East of Ruegen Island (Germany) as part of the USO project" EUREGEO conference Barcelona 2015.

Seidel E., Meschede M. & Obst K. (2015): "First steps towards a 3D structural model of the Southern Baltic Sea, Northeast of Ruegen Island " GeoBerlin conference 2015.

Talks

Seidel E., Meschede M. & Obst K. (2014): "USO - Underground Model of the Southern Baltic Sea - USO East" BGR -Colloquium, 15.10.2014, Berlin.

Seidel E., Meschede M. & Obst K. (2015): "USO - Untergrundmodell Südliche Ostsee" 2. Ostsee Workshop, 06.11.2015, Greifswald.

Seidel E., Meschede M. & Obst K. (2016): "Evolution of the Tornquist Fan fault systems along the north-eastern rim of the Southern Permian Basin." Mesozoic Resource Potential in the Southern Permian Basin"; The Geological Society, Burlington House, London 8.9.2016.

Seidel E., Meschede M. & Obst K. (2016): "Structural Analyses and characterisation of the Adler-Kamien fault system as part of the Tornquist Zone." The Baltic 2016 - 13th Colloquium on Baltic Sea marine Geology, Gdansk.