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Middle to Late Devonian basin evolution in the Rügen area, NE Germany

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Abstract

The Middle to lower Upper Devonian succession of the Rügen Depression in NE Germany consists of largely clastic sediments, whereas the Upper Devonian deposits are mixed carbonate and clastic. Petrographic and geochemical data suggest that the sediments were deposited in a cratonic or recycled setting. Deposition was largely confined to a fault-bounded basin, located between two structural highs. During the Devonian, the Rügen area underwent evolution from a continental and marginal marine area during the Eifelian-early Frasnian to a deeper marine environment during the late Frasnian-early Famennian. By the latest Famennian, an open-shelf carbonate-facies environment was established.

Introduction

The North German Basin was situated between the stable Precambrian shield area of the Baltic Sea and Scandinavia to the north and the areas influenced by the Cadomian, Caledonian, and Variscan orogenies to the south. Two major NW–SE striking, deep fault zones occur to the north of Rügen. These include the Caledonian Deformation Front and the Tornquist Zone comprising the Sorgenfrei–Tornquist Zone in the northeast and the Teisseyre–Tornquist Zone in the southeast. Devonian sediments up to 3 km thick have been encountered in the northeast part of the region, in the 40-km-wide Rügen Depression bounded by the Strelasund and Wiek faults (Figure 1). The depression is located between the northern Arkona Uplift and the southern Strelasund Uplift (Katzung & Ehmke 1993, Katzung et al. 1993) and was situated, in Devonian times, at the northern margin of the Rhenish Basin.

The North German Basin is of considerable economic value, and finds of natural gas were made in the late 1980's. Exploration targets and plays for both petroleum and natural gas in the Devonian are currently being investigated. Rempel (1992) noted that there are a number of reservoir units, particularly in the Givetian sediments (with effective porosities of 10–18%), but source potential is poor due to the low organic carbon contents (approx. 0.3%).

The Variscan geosynclinal system of western and central Europe began to evolve during the Early Devonian and was coeval with the continued convergence of the East Avalonia microcontinent and the southern margin of Laurussia (Ziegler 1989). In southern Germany, a back-arc extensional basin, the Rhenohercynian Basin, opened, the development of which was linked to the decrease in the convergence rate between the Rheic Ocean and the southern margin of Fennoscandia (Ziegler 1989). Up to several kilometres of shallow-marine and deltaic sands were deposited along the northern basin margin and subsequently transported by density currents into more southerly basinal areas. By late Gedinnian times there is evidence of sea-floor spreading (Platen et al. 1989) and the first marine incursions (Ziegler 1989). During late Emsian to Eifelian times, complete closure of the Rheic Ocean occurred and this induced initial compressional stresses within the Rhenohercynian Basin. Despite this, alkaline-bimodal, rift-related volcanism continued throughout Middle Devonian times, suggesting continued extension, at least in the central parts of the basin (Ziegler 1989).

The Late Devonian tectonic evolution of the Variscan geosynclinal system reflects a continued in-

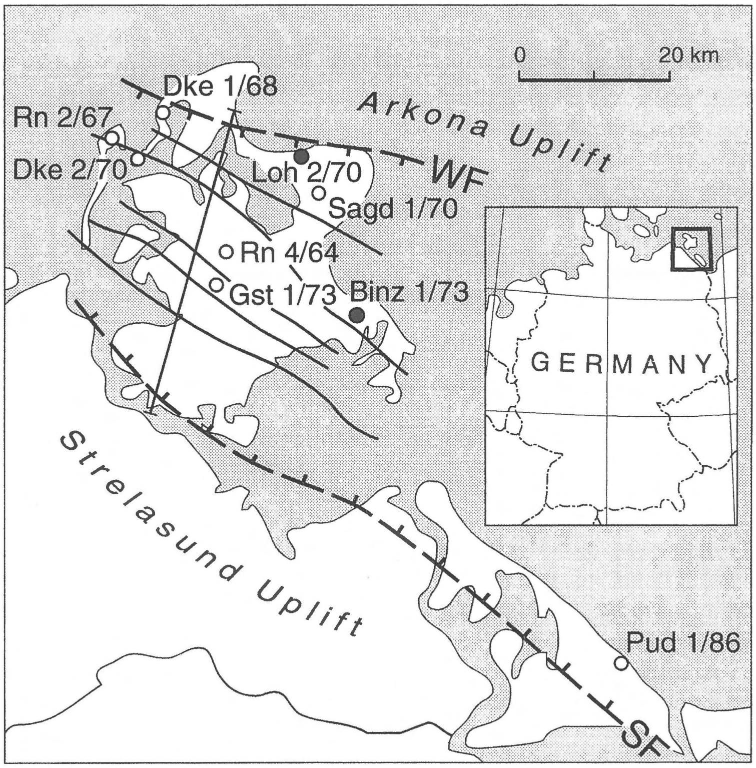


Figure 1. Location map of the study area showing well locations (filled circles = entire section cored; open circles = section partially cored), cross-section location and major structural features. Basin-bounding faults after Katzung & Ehmke 1993 and Katzung et al. 1993; secondary faults interpolated from Piske et al. 1994; well location from Hoth et al. 1993). SF = Strelasund Fault; WF = Wiek Fault.

terplay between back-arc extension and compression. Alkaline-bimodal volcanic activity in the Rhenohercynian Basin accompanied the renewed extension, which ended with the onset of the Bretonian Orogeny, at the Devonian/Carboniferous transition (Ziegler 1984, 1989).

The present contribution examines the basinal setting for the Middle to Upper Devonian from a petrographic perspective, the distribution of the sediments and the relationship between these and the regional structure. The area of study comprises the island of Rügen and its vicinity (Figure 1).

Regional stratigraphy

The database available for the region comprises eleven research boreholes (nine of which were sampled) and 36 km of published seismic data. The succession attains a thickness of almost 3 km. The oldest Devonian sediments, comprising a 10-m succession of coarse to fine-grained clastic-terrigenous Old Red Sandstone facies, are of late Early Devonian (Emsian) age, dated by means of plants and sporomorphs, including *Dicrospora* and *Taeniocrada decheniana* (Zagora 1995). These are overlain by a thick succession of sandstones, siltstones and mudstones with some minor carbonate intercalations. A suite of sporomorphs – including *Acinosporites lindlarensis*, *A. macrospinosus*, *Ancyrospora loganii*, *Dibolisporites eifeliensis*, *D. echinaceus* – and ostracods – including *Costatia* sp., *Polenovula ovata* and *Polyzygia symmetrica* – dates these as Middle Devonian (Zagora 1995). Towards the top of this succession, another ostracod suite including, – ? *Evlanella mitis*, ? *Piastia* sp., and *Subtella* sp. – indicates a late Middle Devonian (Givetian) age (Zagora 1995).

The Upper Devonian is predominantly composed of mudstones and marls with subordinate intercalated sandstones, siltstones and limestones. The finer-grained sediments contain a range of fossil remains, predominantly brachiopods and ostracods, including *Atrypa nalivkini*, *A. symmetrica*, *Favulella lecomptei*, *Lingula bicarinata*, *L. fragilis*, *L. perlata*, *L. rectangularis*, *L. samarica*, *Uchtovia polenovae*, and spe-

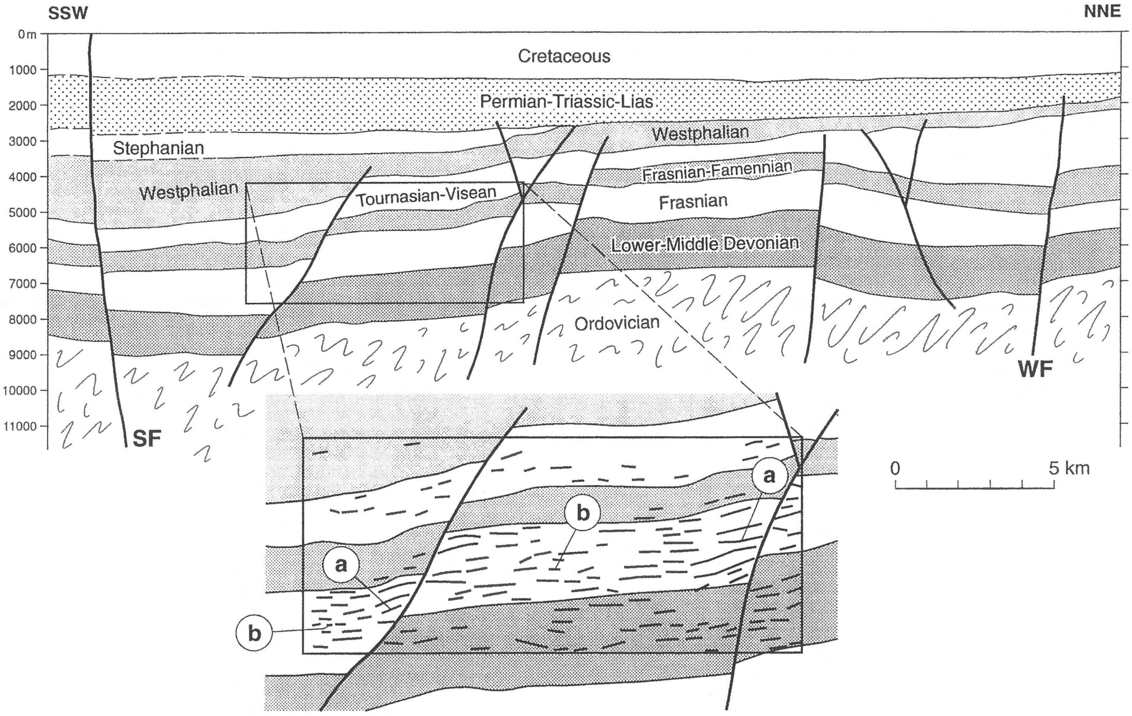


Figure 2. Geological cross-section across the region showing the locations of the two main basin-bounding faults (SF = Strelasund Fault; WF = Wiek Fault). Geological information based on seismic profiles (Piske et al. 1994), magnetotelluric models (Hoffmann et al. 1998) and recent deep-seismic profiling (DEKORP-BASIN Research Group 1999). The inset line drawing is based on Piske et al. (1994). Reflector patterns: a = variable amplitude, laterally discontinuous prograding reflectors; b = moderate amplitude, laterally continuous to discontinuous, flat-lying reflectors. See Figure 1 for location.

cies of *Cyrtospirifer*, *Productella*, *Retichonetes* and *Schuchertella* (Zagora 1995). The limestones contain abundant corals – including *Alveolitella*, *Alveolites*, *Disphyllum*, *Hexagonaria* , *Marisastrum*, *Phillipsastrea*, *Thamnopora* and *Thecostegites* – and stromatoporoids – including *Amphipora* and *Stachyodes*.

Structure and sedimentology

The Devonian of NE Germany is largely known from the area of the Rügen Depression. Devonian sediments have also been recovered from two wells in the Brandenburg region (Huy Neinstedt 1/86, 13.5 km SW of Rügen; Bucholz 6/62 10.5 km south of Rügen) but only the succession in Huy Neinstedt 1/86 has been dated, and the data from both wells are therefore not included in this study.

The distribution of the Middle and Upper Devonian in the Rügen area is strongly influenced by the regional structural pattern. As noted by Katzung et al. (1993), the Devonian sediments were deposited in a small fault-bounded basin (Figure 1). Between the two basin-bounding faults, there are a series of parallel and subparallel faults that further subdivide the area into a series of fault-bounded blocks. Indeed, the structural complexity of the area can be seen on the Upper Frasnian map of Piske et al. (1994, his figure 14) showing the locations of the structural highs and lows.

An indication of the sedimentation pattern within the block-faulted area can be gathered from the rare published seismic profiles (Piske et al. 1994) which show part of the region between the Wiek and Strelasund faults. These, together with more recent deep-seismic (DEKORP-BASIN Research Group 1999) and geological data (Hoffmann et al. 1998), have been used to construct a schematic cross-section across the Rügen Depression (Figure 2). Between the Wiek and Strelasund faults, a series of south-dipping faults extend from the Carboniferous into the Ordovician. Some of these faults indicate synsedimentary movement in Devonian times, subdividing the basin into a series of small horsts and grabens. Although

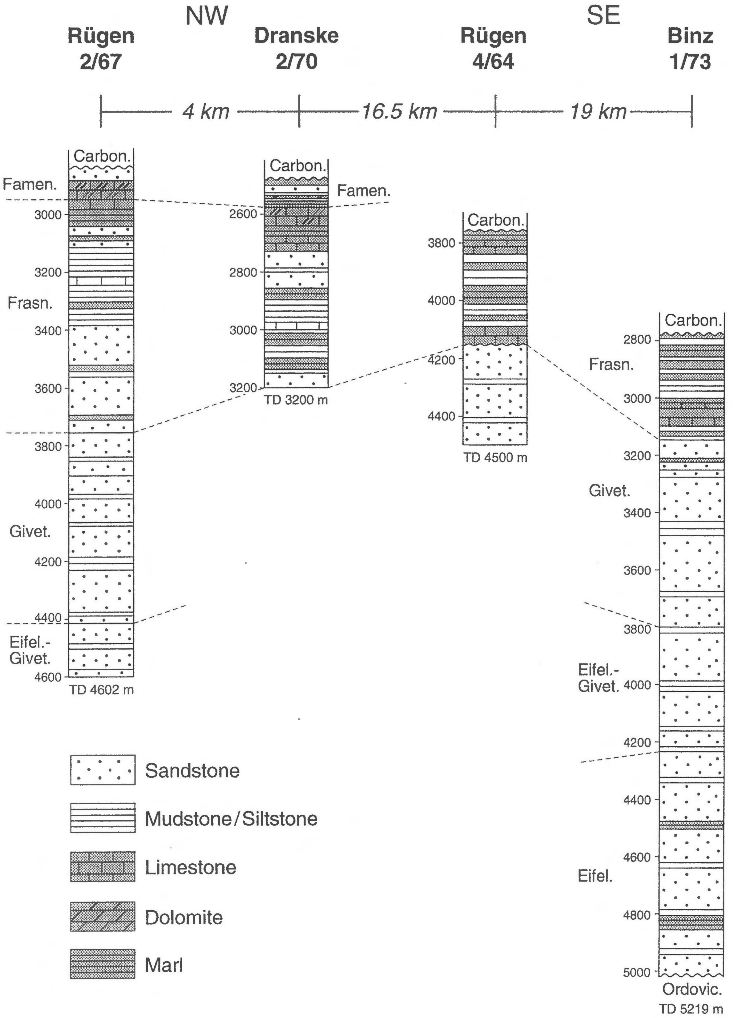


Figure 3. Correlated stratigraphic logs along a NW–SE profile of the Rügen Depression. Stratigraphic information after Hoth et al. (1993). See Figure 1 for location.

the seismic quality is relatively poor, it is possible to determine that sedimentation, particularly in the Frasnian, was contemporaneous with fault activity. In the Frasnian seismic interval a series of variable-amplitude, laterally discontinuous seismic reflectors prograde from the marginal fault into the hanging-wall depression (Figure 2, reflector a). These reflectors are onlapped by more flat-lying, laterally discontinuous, higher amplitude reflectors (Figure 2, reflector b). The variable-amplitude, low-continuity reflectors are located adjacent to the bounding fault; they prograde into the basin, suggesting that they represent a fill of a topographic low. The seismic facies is herein interpreted as representing sediments derived from erosion of the footwall subsequent to fault movement. They probably represent a talus deposit. Away from the fault, the action of water and mass-movement processes served to provide the talus deposit with an interbedded and sorted character, which is reflected in the relative degree of reflector continuity and higher amplitudes. The flat-lying reflectors are interpreted as allodapic carbonates derived from the structural highs.

Movements along the main basin-bounding faults resulted in the development of a complex facies mosaic in the area. This is illustrated using two stratigraphic sections across the region. The NW–SE transect shows a relatively continuous Givetian-Frasnian stratigraphy (Figure 3). In the southeast, the Binz 1/73

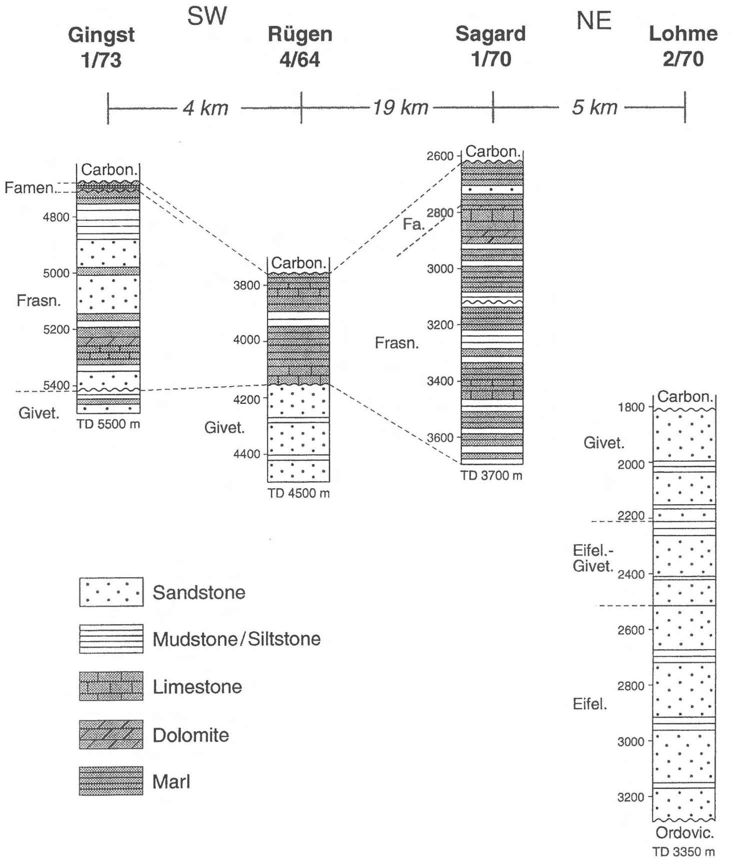


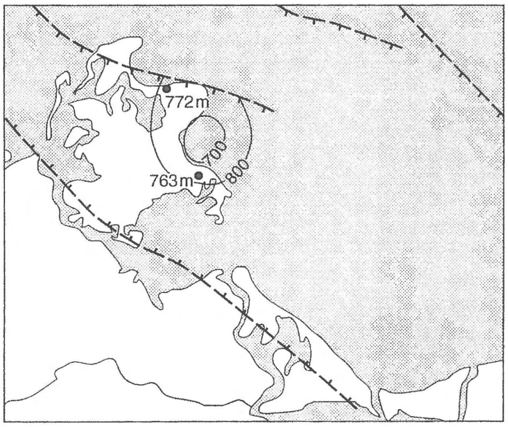
Figure 4. Correlated stratigraphic logs along a NE–SW profile across the Rügen Depression. Stratigraphic information after Hoth et al. (1993). See Figure 1 for location.

well cored the Eifelian to Frasnian succession. The Eifelian unconformably overlies the Ordovician. Givetian sediments are recorded in three of the wells. The Frasnian was partly eroded in the south.

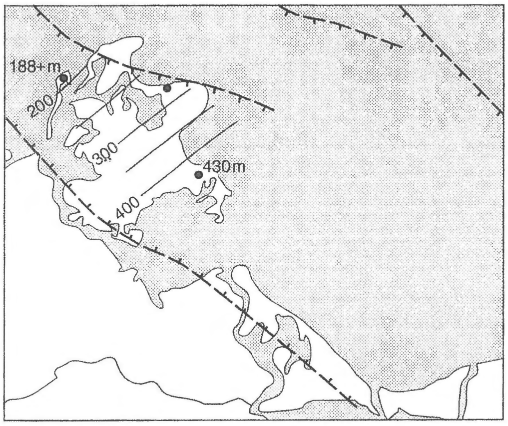
Stratigraphic correlation along the NE–SW section is difficult since it is perpendicular to the dominant fault trend. This is particularly evident in the northernmost part (Figure 4). For example, the Lohme 2/70 well contains an Eifelian-lowermost Givetian succession, while the adjacent Sagard 1/70 well contains no Givetian but only Frasnian and Fammennian sediments below the erosional base of the Carboniferous. The Frasnian can be correlated with the wells to the south, though faults and a change from carbonates to clastics in the Gingst 1/73 well preclude detailed correlation.

Distribution and lithology of the Devonian

A series of isopach maps illustrates the distribution of the Devonian in the Rügen region (Figure 5). The preserved thicknesses shown are based on the published well logs of Hoth et al. (1993), while the lithologies are derived from thin-section and core analyses. Ninety-one siliciclastic and carbonate samples from the Rügen Depression were petrographically analysed. The samples were collected from a series of cores at intervals of about 20–40 m from nine wells, and from all stratigraphic intervals (Eifelian: thirteen siliciclastic; Eifelian–Givetian: five siliciclastic; Givetian: fourteen siliciclastic, one carbonate; Frasnian: twelve siliciclastic, thirty carbonate; Famennian: six siliciclastic, ten carbonate).



Eifelian



Eifelian-Givetian

Givetian

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0 20 km

Figure 5. Thickness and facies maps of the Middle and Late Devonian in the Rügen area. Contours in metres.

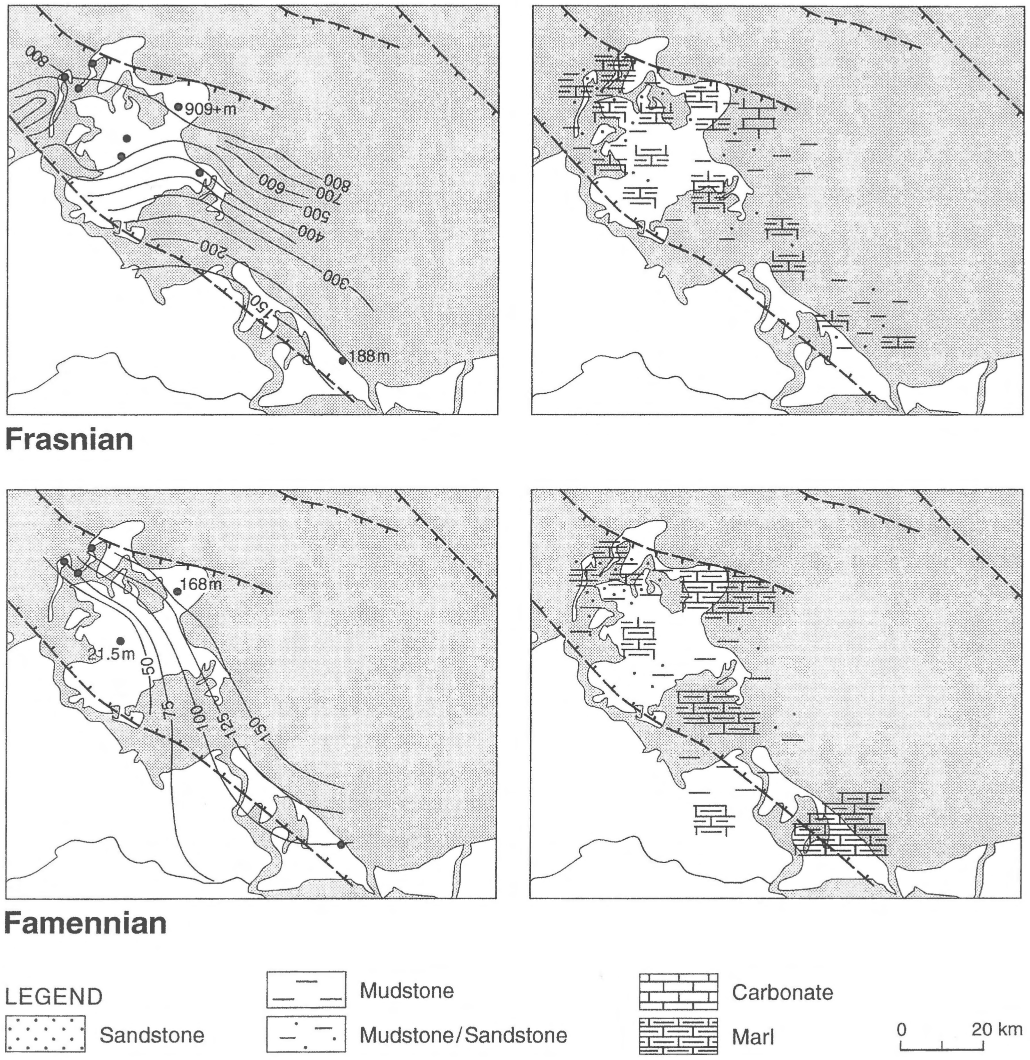

Figure 5. Continued.

Eifelian

The Eifelian succession is only known from the northeast of the Rügen Depression, where it attains a maximum cored thickness of 772 m in Lohme 2/70. It comprises predominantly interbedded quartz-rich sandstones, siltstones and mudstones. Two carbonate-rich marine horizons have been recorded from Binz 1/73 (Hoth et al. 1993); they are indicative of short-lived marine incursions, presumably from the east.

Eifelian–Givetian

This succession is recorded by a larger number of wells than the underlying Eifelian. It thickens from approx. 200 m in the northwest to a maximum of 430 m in the southeast (Figure 5). The sediments are dominantly quartz-rich sandstones in the northwest and also in the region bordering the Wiek Fault. They become finer grained and muddier in a southeasterly direction. The stratigraphic position of this unit is based on localised lithological correlation.

Givetian

The preserved Givetian sediments thicken from a minimum of approx. 300 m to both the northwest (approx. 500 m) and the southeast (maximum 662 m). The sediments are dominantly quartz-rich

Table 1. Selected results of sandstone framework grain analysis from the Middle and Late Devonian of the Rügen Depression.

Age		n	Q	F	L	Qm	Lt
Famennian	mean	2	130.5	5	5.5	121	16
	range		116–145	2.0–8.0	2.0–9.0	104–137	10.0–21.0
Frasnian	mean	2	215	8	6.5	190	31
	range		202–227	5.0–11.0	5.0–8.0	177–202	28–33
Givetian	mean	17	246.5	6.2	5.1	209.6	39.7
	range		182–276	1.0–15.0	0–12.0	163–237	21–67
Eifelian-Givetian		1	194	7	5	182	17
Eifelian	mean	2	215	2	0	208	7
	range		214–216	1.0–3.0	0	203–213	3.0–11.0

Q = total quartzose grains; F = total feldspar grains; L = total lithic fragments; Qm = monocrystalline quartz grains; Lt (= L+Qp) = total lithic fragments including polycrystalline quartzose grains.

sandstones, siltstones and mudstones, although some micritic limestones with bioclasts are recorded from the Gingst 1/73 well.

Frasnian

The known Frasnian succession extends in a broad band paralleling the basin-bounding faults and extending southwards of the Strelasund Fault. The thicknesses range from some 200 m in the south to a maximum of 909 m in the north, adjacent to the Wiek Fault.

The lower Frasnian is predominantly composed of micritic limestones, which are largely biomicrites (sometimes packed biomicrites) to wackestones, though boundstones are also noted. Bioclastic material comprises corals, molluscs, brachiopods, bryozoa, crinoids, echinoid and stromatoporoid fragments. Rare ooliths and peloids are also noted. Terrigenous material, dominantly monocrystalline quartz, is rare in the limestones (< 5% although up to 15% may occur). Patchy sparry and micro-sparry calcite sparry and vuggy dolomite also occur. Siliciclastic sediments, including mudstones, siltstones and fine- to medium-grained sandstones occur across the entire Rügen Depression, though they are most common in the northwest (e.g., Rügen 2/67).

The upper Frasnian is predominantly carbonate-rich, comprising micritic limestones (biomicrite / wackestone) with bioclastic material, including, molluscs, brachiopods, corals, bryozoa and crinoids. Dolomite is also recorded (e.g., Sagard 1/70). Terrigenous material within the carbonates is rare. Sandstones, siltstones and mudstones are also recorded, and dominate the Gingst 1/73 well.

Famennian

The Famennian preserved below the erosional base of the Carboniferous is relatively thin, with a maximum thickness of 168 m in the Sagard 1/70 well, adjacent to the Wiek Fault. The thickness distribution is fairly similar to that of the underlying Frasnian, roughly paralleling the basin-bounding faults. The sediments are dominantly carbonates, with subordinate siltstones, mudstones and evaporites (anhydrite). Sandstones are locally common in the northwest (Dranske 2/70, Rügen 2/67).

The lower Famennian is lithologically similar to the Frasnian with dolomite and micritic limestone predominating. In contrast, the upper part of the preserved Famennian, while dominated by micritic limestones, also contains sandstones, siltstones and mudstones. The limestones are predominantly packed biomicrites/wackestones or packed oobiomicrites/wackestones. Bioclastic material includes corals (both colonial and solitary), crinoids, molluscs, brachiopods and bryozoans. Ooliths and peloids are also common.

Sampling and petrographic methods

The petrography of 39 sandstones from the Rügen Depression was determined by point-counting (300 or 500 points per thin section). The samples were collected from a series of cores at intervals of about 20–40 m from nine wells, and from all stratigraphic intervals (Eifelian: thirteen; Eifelian-Givetian: five; Givetian: fourteen; Frasnian: twelve; Famennian: six). Medium to coarse sandstones were analysed using the

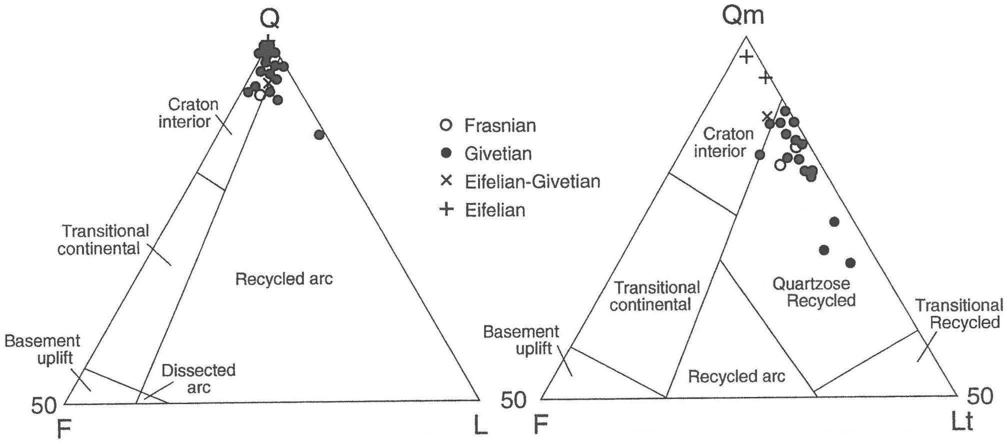

Figure 6. Sandstone modal data for the Middle and Late Devonian of the Rügen Depression. Tectonic discrimination fields as defined by Ingersoll & Suczek (1979). Q = quartz; F = feldspar; L = lithic fragments; Qm = monocrystalline quartz; Lt = total lithic fragments.

Gazzi-Dickinson method to minimize the dependence of calculated rock composition on grain size (Ingersoll et al. 1984, Zuffa 1985). Measured modal grain parameters (Table 1) are those of Ingersoll & Suczek (1979). The majority of the samples were medium to well sorted with subangular to subrounded individual grains.

Forty-six siliciclastic samples were analysed using X-ray diffraction in order to ascertain the presence of matrix materials (using a Siemens DIFFRAC D5000 diffractometer and Cu ka radiation). Quantitative and qualitative mineralogical phase analyses were performed, using the integral sequences of the X-ray diffraction data in the sample spectrum, and calculated using the QUAX 4.0 program (Emmermann & Lauterjung 1990). X-ray fluorescence analysis of the major and trace element geochemistry of the same samples was also performed (using a Siemens automatic wavelength-dispersive XRF, type SRS 303 AS). A lithium-metaborate flux and a sample flux ratio of 1:6 were used. Sulphur, carbon and H_2O determinations were carried out by means of infrared spectroscopy on a LECO Analyser.

Petrographic results

The percentage of matrix in the sandstones ranges from 0 to 53. It occurs as crushed lithic grains, small quartz grains, and phyllosilicates (particularly sericite, pseudomatrix), and as epimatrix and orthomatrix. Poikilotopic, pore-filling and patchy carbonate (sparry calcite, micrite) is abundant in some sandstone samples ($\leq 62\%$). Cementation by quartz is less common ($\leq 4\%$). Anhydrite cement is present in some samples ($\leq 17\%$).

The larger particles within the investigated sandstones are composed of three main detrital constituents: quartz, feldspar and lithic fragments (Table 1).

The sandstones are very rich in quartz (Table 1). A series of ternary diagrams defining a series of tectonic discrimination fields (after Ingersoll & Suczek, 1979) were used to plot the sandstone modal data. The quartz/feldspar/lithic-fragments diagram shows the data falling largely in the Craton Interior and Recycled Orogenic Arc provenance fields (Figure 6). On a monocrystalline-quartz/feldspar/total-lithic-fragmen ts plot, where polycrystalline quartz clasts are counted as lithic fragments, almost all of the samples plot in the Quartzose Recycled field, with the two Eifelian samples plotting in the Craton Interior field (Figure 6).

Quartz (Q)

Monocrystalline quartz (Qm) and polycrystalline quartz occur throughout the succession. Monocrystalline quartz is commonly subrounded to subangular. Undulose (> 5°) and non-undulose monocrystalline quartz is present. They do not show a common orientation, thus suggesting that strain occurred in the source area. Böhm lamellae occur in some samples. Clay rims, with later quartz overgrowths, also occur.

Most polycrystalline quartz grains consist of more than three crystals. The contacts between the subcrystals are straight to sutured; the latter occurs more commonly. The sub-grain size is variable, even within a single composite grain. Chert (microcrystalline polycrystalline quartz) is rarely present.

Inclusions are present within both mono- and polycrystalline quartz grains, but they are more common in the former. They include zircon, tourmaline and rutile.

Feldspar (F)

Plagioclase occurs in all of the sandstone samples and ranges from large, euhedral, compositionally zoned crystals to subangular grains. Twinning is common. K-feldspar is very rare; microcline and orthoclase are the predominant types. Feldspars may be fresh and unaltered but, more commonly, they are replaced by carbonate or altered to sericite and clay minerals.

Lithic fragments (L)

Sedimentary fragments, including fine-grained sandstones, siltstones and mudstones and carbonates, dominate the succession. Internal structures, e.g. lamination, are sometimes noted in the finer-grained clasts. Carbonate clasts include wackestones and shell fragments. Individual mud and silt-rich fragments may be plastically deformed, suggesting erosion and redeposition while still partly unconsolidated, or compaction during burial. The lithic fragments may be replaced by calcite.

In Givetian samples some rare volcanic lithic fragments occur. Some metamorphic lithic fragments, possibly schist and quartzite, were also noted.

The dominant accessory minerals present in the majority of rock samples include, zircon, muscovite, chlorite, epidote, tourmaline and rutile.

Stratigraphic QFL variations

Stratigraphic variations in sedimentation, predominantly related to the overall upwards decrease in clastics and increase in carbonates, occur. The lowermost Eifelian ($Qm_{96}F_1L_3$) comprises reddish-coloured quartz-rich sandstones that are occasionally matrix rich, and may have patchy carbonate, quartz or, more rarely, anhydrite cements. Sedimentary lithic fragments are dominantly siltstones and mudstones. Bioclastic fragments, comprising shell material, also occur. The sandstones of the overlying Eifelian–Givetian unit ($Qm_{88}F_4L_8$) are also quartz rich, commonly with large amounts of matrix, and carbonate and/or anhydrite cements. Siltstones and claystones are the dominant lithic fragments.

Quartz-rich sandstones ($Qm_{82}F_3L_{15}$) also dominate the Givetian. These commonly have carbonate, quartz, or more rarely, anhydrite cements. Clay-rich matrix dominates. Lithic fragments are mainly sedimentary in origin (siltstones, claystones). Rare volcanic and metamorphic lithic fragments also occur. Siltstones, mudstones and micritic limestones are noted.

The overlying Frasnian ($Qm_{83}F_4L_{13}$) shows a significant change in sedimentation pattern, with the presence of a mixed clastic and carbonate sediment package. The sandstones are matrix rich with patchy calcite, and rarely anhydrite, cements. Lithic fragments are dominantly carbonates, though rare possible volcanic lithic fragments have been noted.

The Famennian sediments ($Qm_{85}F_4L_{11}$) are also mixed clastics and carbonates: predominantly sandstones, siltstones and mudstones interbedded with micritic and oolitic limestones. The sandstones are quartz rich with sparry or micritic carbonate cements. Lithic fragments are dominantly carbonate.

Sandstone geochemistry

The majority of the investigated sandstones (Table 2) have a SiO_2 content ranging from 38% to 94% by weight (average 75.46%, i.e., quartz-rich to quartz-intermediate following the criteria of Crook 1974). The Fe_2O_3 (total Fe expressed as Fe_2O_3) + MgO contents (together 0.75–11% by weight (average 4.81%) are low to moderate. Large-ion-lithophile (LIL) elements, such as Rb, Sr and K, show a range of abundances. Similarly, the transition elements (Ni, Cr, V) show variable inter-element ratios. Chemical classification of the sandstones indicates that they are virtually all Fe-rich, lithic sandstones or quartz arkoses with K_2O/Na_2O ratios generally being in the order of 10.

Plots of the major oxides show no clear pattern in the distribution of the data points, with many of the sandstones plotting in a number of the fields (Figure 7). For example, on the TiO_2 vs Fe_2O_3+ MgO plot, the majority of the points plot in or around the Passive Margin and Active Margin fields. Some of the Eifelian samples plot in the region of the Oceanic Island Arc field. On a second diagram, Al_2O_3/SiO_2 vs Fe_2O_3+ MgO, most of the points plot close to the Passive Margin field. On a K_2O/Na_2O vs SiO_2 diagram of sandstones and mudstones, the former plot mostly within the Passive Margin field. The mudstones, how-

Table 2. Selected representative X-ray fluorescence chemical analyses of sandstones from the Devonian of the Rügen Depression

Sample No.	Well	Age	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	H_2O	CO_2	Total	Ba	Cr	Ni	Rb	Sr	V	Y	Zn	Zr
MV 108	Dranske 2/70	Frasnian	77.73	0.136	2.54	1.28	0.043	2.93	4.94	0.11	1.31	0.03	0.64	7.69	99.37	175	83	11	30	63	12	7	10	177
MV 194	Lohme 2/70	Givetian	89.72	0.324	2.19	0.71	0.034	0.91	1.38	0.1	0.88	0.04	0.76	1.96	98.91	153	316	17	19	75	20	5	27	274
MV 195	Lohme 2/70	Givetian	81.57	0.182	2.28	1.12	0.09	2.51	3.86	0.1	1.12	0.032	0.67	6.16	99.59	213	126	12	25	84	20	10	16	163
MV 196	Lohme 2/70	Eifelian Givetian	73.98	0.35	4.33	1.57	0.243	3.47	4.83	0.68	1.46	0.05	0.91	7.52	99.31	397	226	16	35	67	28	23	18	315
MV 198	Lohme 2/70	Eifelian-Givetian	69.04	0.773	10.49	4.44	0.083	1.96	3.73	0.41	2.47	0.071	2.86	2.92	99.25	362	180	57	82	86	76	30	344	448
MV 165	Rügen 2/67	Eifelian	90.06	0.357	3.76	1.48	0.008	0.45	0.21	0.1	1.79	0.034	0.72	0.26	99.13	236	171	15	40	30	21	14	16	422
MV 166	Rügen 2/67	Eifelian	79.53	0.338	4.63	2.63	0.094	2.55	2.86	0.1	1.57	0.057	1.36	3.79	99.59	206	231	28	38	38	45	26	24	247
MV 130	Binz 1/73	Eifelian	92.59	0.215	2.31	0.55	0.016	0.49	0.58	0.1	0.8	0.028	0.73	0.89	99.2	120	201	16	19	<30	16	5	11	349
MV 132	Binz 1/73	Eifelian	79.41	0.433	4.84	1.36	0.072	2.29	2.85	0.1	1.93	0.052	1.2	4.31	98.73	271	213	25	48	56	27	17	17	480

Major oxides in weight percentage, trace elements in ppm. Total Fe as Fe_2O_3.

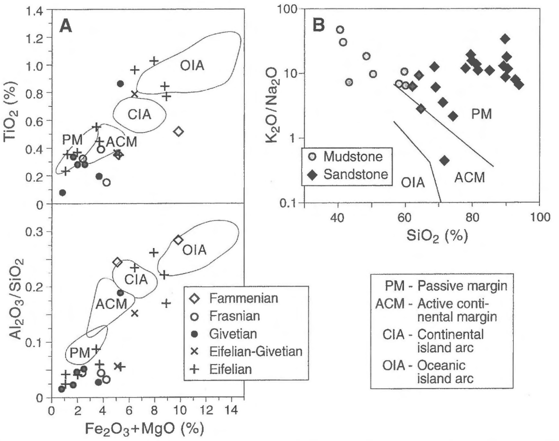

Figure 7. Petrographic characteristics of the Devonian sediments from the Rügen area. (A) bivariate plots for the discrimination of plate tectonic setting of sandstones from the Devonian of the Rügen Depression (after Bhatia 1983). PM = Passive margin; ACM = Active continental margin; CIA = Continental island arc; OIA = Oceanic island arc). (B) tectonic discrimination diagram for mudstones and sandstones from the Devonian of the Rügen area (after Roser & Korsch 1986).

ever, plot across the Passive Margin and Active Continental Margin boundary (Figure 7). Passive-margin sediments are quartz-rich, derived from plate interiors or stable continental margins. In contrast, active-continental-margin sediments are quartz-intermediate (Bhatia 1983, Roser & Korsch 1986).

Discussion

The Devonian of Rügen was deposited in a relatively restricted basin, the Rügen Depression, located to the north of the evolving Rhenish Basin. Petrographic data from the preserved Middle and Upper Devonian sandstones suggest that they were deposited in a cratonic and/or recycled setting. This is confirmed by geochemical analysis, which suggests that the tectonic setting was predominantly a passive margin one (Figure 7). Cratonic sediments are highly mature, being derived from the recycling of other, predominantly sedimentary, rocks. During the Devonian, the Rügen area was continenal and marginal marine during the Eifelian to early Frasnian. Deeper-marine environments predominated in the late Frasnian and early Famennian with the reestablishment of shallow-marine and coastal environments in late Famennian times. By the latest Famennian, much of the Rügen area was an open-shelf environment.

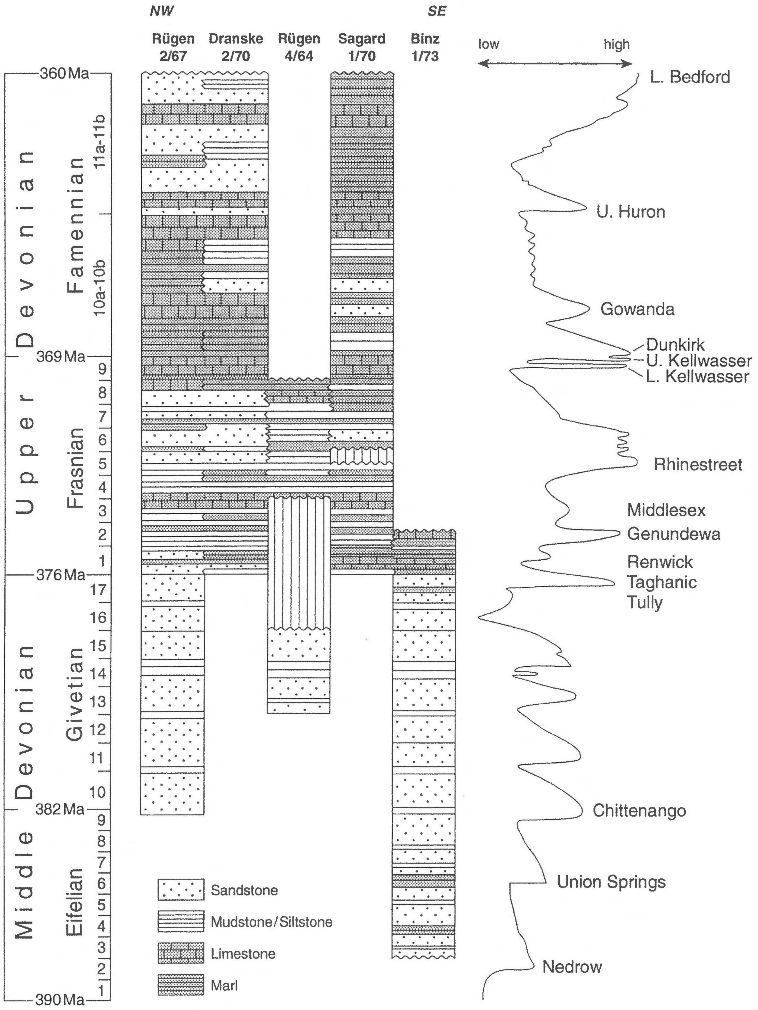

Figure 8. Chronostratigraphic diagram outlining the development of sedimentary facies in the Rügen Depression. Sea-level curve after House (1983) and House & Kirschgasser (1993). Vertical hatching indicates hiatuses. Stratigraphy according to Hoth et al. (1993), i.e., Eifelian (1–9), Givetian (10–17), Frasnian (1–9), Famennian (10–11). The Eifelian-Givetian of Figures 3 and 4 correlates approximately with units 8 to 10 of the Middle Devonian. Timescale after Haq & Van Eysinga (1987).

Relative world-wide sea levels were low at the beginning of the Eifelian, gradually increasing over time, with two distinct peaks prior to the Chittenango highstand at the Eifelian/Givetian boundary (Figure 8). Sedimentation during the Eifelian was predominantly clastic, with the rare carbonates mainly related to the Union Springs regression. In Givetian times, there were a number of major transgressions and regressions, culminating in a major fall (Tully) followed by a steep rise (Taghanic) at the Givetian/Frasnian boundary. Despite these variations, clastic sedimentation continued to predominate, with carbonate sediments only being recorded near the top of the Rügen succession.

The relative sea level began to rise again in Frasnian times, with three marked highs (i.e., Genundewa, Rhinestreet, Lower Kellwasser). Sedimentation throughout the Frasnian was largely mixed clastic and carbonate, with extensive carbonate production correlating with periods of lower sea levels. This is particularly marked at the beginning of the Frasnian, between the Genundewa and Rhinestreet highs, and at the end of the Frasnian (Figure 8). In Famennian times, sea levels once again dropped with a minor transgression (Upper Huron) during the middle Famennian and a more significant one (Lower Bedford) at the Devonian/Carboniferous boundary.

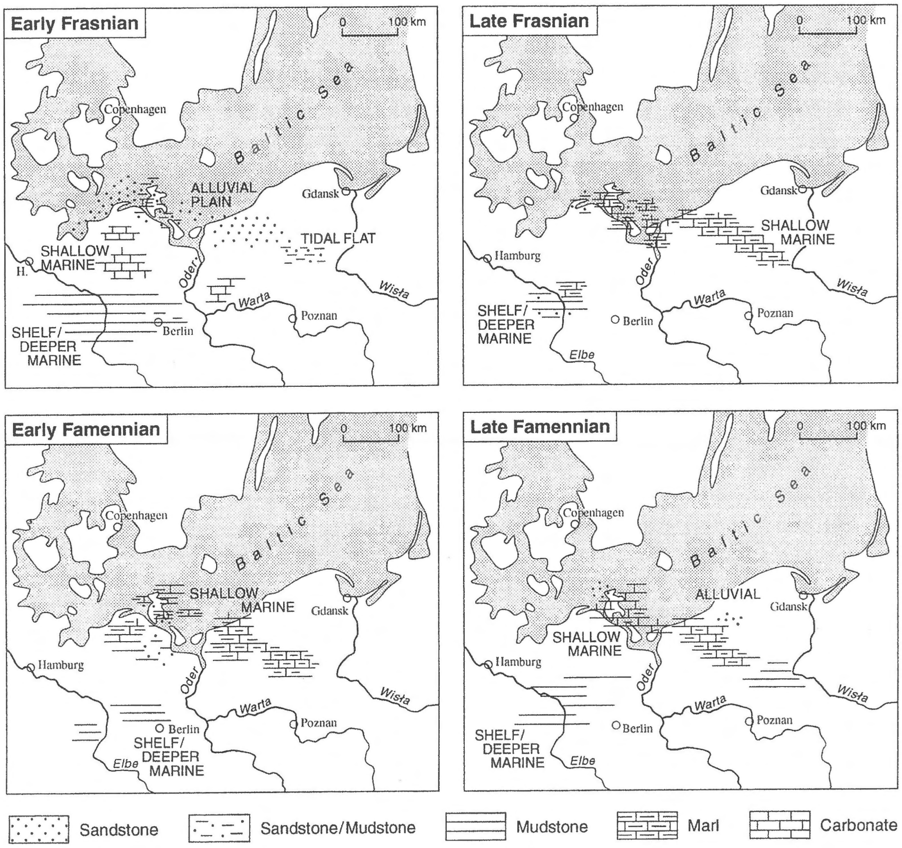

Figure 9. Facies maps for the Late Devonian of northern Germany and western Poland. Information from the Rügen Depression from the current study, south of Rügen from Franke (1990) and Ziegler (1989, 1990) and from western Poland from Matyja (1993) and Ziegler (1989).

As previously noted, the Rügen Depression was located between the Strelasund and Wiek faults, and was crossed by a series of related, smaller faults. The depression lies close to the Tornquist Zone (Cartwright 1990, Ziegler 1990), a series of linked shear zones that extend across the Baltic Sea and where Devonian-age fault movements were possibly related to wrench movements along the Trans-European Suture Zone, or to the continued closure of the Rhenish Basin to the south.

Within the Rügen Depression, both sediment production and deposition were influenced by local tectonic activity. Krebs (1975) suggested a possible model for deposition in the area, with the region being composed of a series of troughs and highs. This view is supported by the limited published seismic data, which allow the Rügen Depression to be characterised as a more complex basin, subdivided into a series of tilted fault blocks and half grabens (Figures 1–2). These formed as extensional or transtensional features during a phase of lithospheric stretching. Within the Rügen Depression, the existence of structural highs and lows, coupled with the variations in relative sea level led consequently to the development of a complex facies mosaic. Localised highs would have been the predominant area of shallow-water carbonate build-ups with peri-platform talus fringing the fault margins. Debris flows and density currents would have transported debris into low-lying areas.

The similarity of the Devonian of the Rügen Depression with coeval sediments to the west and east has been previously noted (e.g. Franke 1990, Schmidt et al. 1977) and has led to a number of regional correlations, notably by Franke (1990), Paproth (1989) and Ziegler (1989, 1990). There are, however, a number of problems involved in these rough correlations, in particular because of the lack of Devonian-age data to the west of the area. Franke (1990) noted how Devonian strata are recorded only from a single borehole in Schleswig-Holstein and some isolated occurrences in the North Sea. To the east, the situation is better, particularly with regard to the Upper Devonian. Recent work on western Pommerania (Matyja 1993) enables a more complete reconstruction than previously possible (Figure 9).

The Devonian succession in northwestern Poland is similar to that of northern Germany. As on Rügen, the Lower Devonian (Emsian) comprises littoral and fluvial deposits with some anhydrite. In the Eifelian, a coastal to shallow-marine succession developed with evidence of occasional marine incursions (Matyja 1993). Full-marine conditions, however, were only established during the Givetian (Matyja 1993). Facies maps for the north German and Polish region have been compiled (Figure 9). In late Givetian and early Frasnian times, the area was continental and marginal marine. Marine incursions may have been occasionally extensive, leading to the development of a wide, shallow shelf extending into the North Sea area (Marshall et al. 1996). By late Frasnian times, a shallow-marine shelf environment, deepening towards the southwest, had been established across the region with the deposition of micritic limestones and rarer clastics. This pattern of sedimentation continued into the early Famennian. In late Famennian times, shallow-marine and continental conditions were re-established in the north.

Detailed evidence on the deeper-water facies to the south is rare. In the Huy–Neinstedt 1/86 borehole, to the southwest of Berlin, the recorded sediments comprise mudstones, sandstones and metagreywackes which, according to Franke (1990), suggest the presence of deeper-water facies. Limestones, however, are recorded from the Givetian and Frasnian of the same well. This evidence of shallow-water sedimentation may be related to either local tectonic uplift or regional low sea-level stand.

In summary, the Middle and Upper Devonian of northeastern Germany comprise a mixed clastic and carbonate succession with siliciclastic sedimentation dominating in the Middle, and mixed carbonates and clastics in the Upper Devonian. Petrographic and geochemical information suggests that the sediments were deposited in a cratonic or recycled tectonic setting. Sedimentation was influenced by both regional and local tectonic activity and variations in sea level.

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References

Bhatia, M.K. 1983 Plate tectonics and geochemical composition of sandstones – J. Geol. 91: 611–627

Cartwright, J. 1990 The structural evolution of the Ringkøbing-Fyn High. In: Blundell, D.J. & A.D. Gibbs (eds) Tectonic Evolution of the North Sea Rifts. Clarendon Press, Oxford: 200–216

Crook, K.A.W. 1974 Lithogenesis and geotectonics: the significance of compositional variation in flysch arenites (greywackes) – Soc. Econ. Paleont. Mineral. Spec. Publ. 19: 304–310

DEKORP-BASIN Research Group 1999 Deep crustal structure of the Northeast German Basin: New DEKORP-BASIN'96 deep-profiling results – Geology 27: 55–58

Dickinson, W.R. & C.A. Suczek 1979 Plate tectonics and sandstone compositions – Amer. Ass. Petrol. Geol. Bull. 63: 2164–2182

Emmermann, R. & J. Lauterjung 1990 Double x-ray analysis of cuttings and rock flour: a powerful tool for rapid and reliable determination of borehole lithostratigraphy – Sci. Drill. 1: 269–282

Franke, D. 1990 Der präpermische Untergrund der Mitteleuropäischen Senke – Fakten und Hypothesen – Niedersachs. Akad. Geowiss. Veröff. 4: 19–75

Haq, B.U. & F.W.B. Van Eysinga 1987 Geological Time Table. Elsevier, Amsterdam

Hoffmann, N., H. Jödicke, B. Fluche, A. Jording & W. Müller 1998 Modellvorstellungen zur Verbreitung potentieller präwestfalischer Erdgas-Muttergesteine in Norddeutschland – Ergebnisse neuer magnetotellurischer Messungen Z. angew. Geol. 44: 140–158

Hoth, K., J. Rüsbult, K. Zagora, H. Beer & O. Hartmann 1993 Die tiefen Bohrungen im Zentralabschnitt der Mitteleuropäischen Senke – Dokumentation für den Zeitabschnitt 1962–1990 – Schrift. Geowiss. 2

House, M.R. 1983 Devonian eustatic events – Proc. Ussher Soc. 5: 396–405

House, M.R. & W.T. Kirchgasser 1993 Devonian goniatite biostratigraphy and timing of facies movements in the Frasnian of eastern North America. In: Hailwood, E.A. & R.B. Kidd (eds) High Resolution Stratigraphy. Geol. Soc. Spec. Publ. 70: 267–292

Ingersoll, R.V. & C.A. Suczek 1979 Petrology and provenance of Neogene sand from Nicobar and Bengal fans, DSDP sites 211 and 218 – J. Sed. Petrol. 49: 1217–1228

Ingersoll, R.V., T.F. Bullard, R.L. Ford, J.P. Grimm, J.D. Pickle & S.W. Sares 1984 The effect of grain size on detrital modes: a test of the Gazzi-Dickinson point counting method – J. Sed. Petrol. 54: 103–116

Katzung, G. & G. Ehmke 1993 Das Prätertiär in Ostdeutschland. Struktursotckwerke und ihre regionale Gliederung – Verlag Sven von Loga, Köln

Katzung, G., U. Giese, R. Walter & C. Von Winterfeld 1993 The Rügen Caledonides, northeast Germany – Geol. Mag. 130: 725–730

Krebs, W. 1975 Geologische Aspekte der Tiefenexploration im Paläozoikum Norddeutschlands und der südlichen Nordsee – Erdöl-Erdgas Zeit. 91: 277–284

Matyja, H. 1993 Upper Devonian of Western Pomerania – Acta Geol. Pol. 43: 27–94

Marshall, J.E.A., D.A. Rogers & M.J. Whiteley 1996 Devonian marine incursions into the Orcadian Basin, Scotland – J. Geol. Soc. Lond. 153: 451–466

Paproth, E. 1989 Devonian palaeogeographic development in Germany and adjacent areas. Der tiefere Untergrund des nordwestdeutschen Beckens: Sedimentologie – Tektonik – Kohlenwasserstoffe. Beiträge der DGG-DGMK-Gemeinschaftstagung Braunschweig 1989 – DGMK Bericht 468: 33–52

Piske, J., H.-J. Rasch, E. Neumann & K. Zagora 1994 Geologischer Bau und Entwicklung des Präperms der Insel Rügen und des angrenzenden Seegebietes – Z. geol. Wiss. 22: 211–226

Platen, K., R. Emmermann & W. Franke 1989 Devonian MORB-type metabasalts from the Rhenohercynian zone in Germany – Terra Abs. 1: 365

Rempel, H. 1992 Erdölgeologische Bewertung der Arbeiten der Gemeinsamen Organisation 'Petrobaltic' im deutschen Schelfbereich – Geol. Jahrb. D99: 3–32

Roser, B.P. & R.J. Korsch 1986 Determination of tectonic setting of sandstone-mudstone suites using SiO_2 content and K_2O/Na_2O ratio – J. Geol. 94: 635–650

Schmidt, K., G. Katzung & D. Franke 1977 Zur Entwicklung des präpermischen Untergrunds und des Magmatismus im südwestlichen Vorfeld der Osteuropäischen Tafel – Zeit. angew. Geol. 23: 426–436

Zagora, K. 1995 Devonian of the Isle of Rügen – Stud. Geophys. Geodaet. 39: 298–301

Ziegler, P.A. 1984 Caledonian and Hercynian crustal consolidation of Western and Central Europe – a working hypothesis – Geol. Mijnbouw 63: 93–108

Ziegler, P.A. 1989. Evolution of Laurussia – A Study in Late Palaeozoic Plate Tectonics. Kluwer Acad. Publ., Dordrecht

Ziegler, P.A. 1990. Geological atlas of Western and Central Europe. Shell Internat. Petrol. Mij B.V., 's-Gravenhage

Zuffa, G.G. 1985 Optical analyses of arenites: influence of methodology on compositional results. In: Zuffa, G.G. (ed.) Provenance of Arenites. Reidel Publishing Co.: 165–189