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Lower Palaeozoic evolution of the northeast German Basin/Baltica borderland

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Abstract – The Vendian–Silurian succession from a series of boreholes in northeast Germany has been petrographically and geochemically investigated. Evidence suggests that the more northerly Vendian and Cambrian succession was deposited on a craton which became increasingly unstable in Ordovician times. Similarly, the Ordovician-age succession deposited in the Rügen area indicates a strongly active continental margin tectonic setting for the same period. By Silurian times the region was once more relatively tectonically quiescent. Although complete closure of the Tornquist Sea was not complete until latest Silurian times, the major changes in tectonic regime in the Eastern Avalonia/Baltica area recorded from the Ordovician suggest that a significant degree of closure occurred during this time.

1. Introduction

The northeast German Basin is situated between the stable Precambrian shield area of the Baltic Sea/Scandinavia to the north and the Cadomian/Caledonian/Variscan-influenced areas to the south. It thus straddles two very different tectonic regimes although it was much more influenced by events to the south. Three major northwest–southeast striking deep fault zones occur in the area, including the suspected Trans-European Fault (TEF) separating Rügen from mainland northern Germany, the Caledonian Deformation Front (CDF) which lies to the north of Rügen and the Tornquist Zone (TZ) comprising the Sorgenfrei-Tornquist Zone (STZ) in the northeast and the Teisseyre-Tornquist Zone (TTZ) in the southeast (Thomas *et al.* 1993) (Fig. 1).

The present study is a broad examination of the Lower Palaeozoic of the region, including the Vendian–Silurian succession of the G14 1/86 well. The location of this well on the southern margin of Baltica (see Section 2) enables the contrasting petrographic and geochemical signatures for southern Baltica and the northern part of Eastern Avalonia to be compared and contrasted.

2. Regional geology and tectonics

The forelands of the North German–Polish Caledonides are formed by the Precambrian Fennoscandian Shield and its extension beneath the Baltic Depression and the stable East European Platform. The bulk of the Fennoscandian–Baltic craton was consolidated in pre-Grenvillian time (Ziegler, 1990). The Caledonian orogenic cycle (late Cambrian to earliest Devonian) was governed by the sinistral oblique convergence and collision of the Laurentia–Greenland and Fennoscandian–Baltic cratons (Ziegler, 1989).

The precise location of the southwestern edge of Baltica (that is, that part of Baltica to the south of the Sorgenfrei-Tornquist Zone) is not known. This is largely as a result of masking by younger sediments (Tanner & Meissner, 1996). Many workers have identified the strike-slip Trans-European Fault, which runs through parts of northern Germany and south of Rügen to join up with the Teisseyre-Tornquist Zone in Poland, as the southern boundary of Baltica (Berthelsen, 1984; EUGENO-S Working Group, 1988; Franke, 1990*a*, 1993; Hoffmann, 1990). However, recent ideas favour a terrane accretional model rather than fault movement to interpret the observed geology of the region (Ziegler, 1990; Berthelsen, 1992; Torsvik *et al.* 1993; Meissner, Sadowiak & Thomas, 1994; Tanner & Meissner, 1996). In such a model, the northward convergence and accretion of Gondwana-derived continental fragments to the southern margin of the newly-forming Laurussian supercontinent is envisaged (Ziegler, 1989). These fragments would have included Eastern Avalonia, which drifted northwards and docked with Baltica by Ordovician/Silurian times (Cocks & Fortey, 1990; Thomas *et al.* 1993; Torsvik *et al.* 1992).

Two possible boundaries have been suggested for the northeast margin of Eastern Avalonia, the Caledonian Deformation Front (CDF) and the Elbe Lineament (Tanner & Meissner, 1996). The CDF forms the northern limit of the Caledonian margin thrust belt which developed following the oblique collision between Avalonia and Baltica, and comprises a series of south–southwest dipping seismic reflectors which are interpreted as having been formed by the thrusting of Caledonian metamorphosed shelf slope sediments over the Precambrian basement of Baltica (Franke, 1990*a*; Thomas *et al.* 1993). North of the CDF the undeformed Lower Palaeozoic succession is found in downfaulted and slightly southwest

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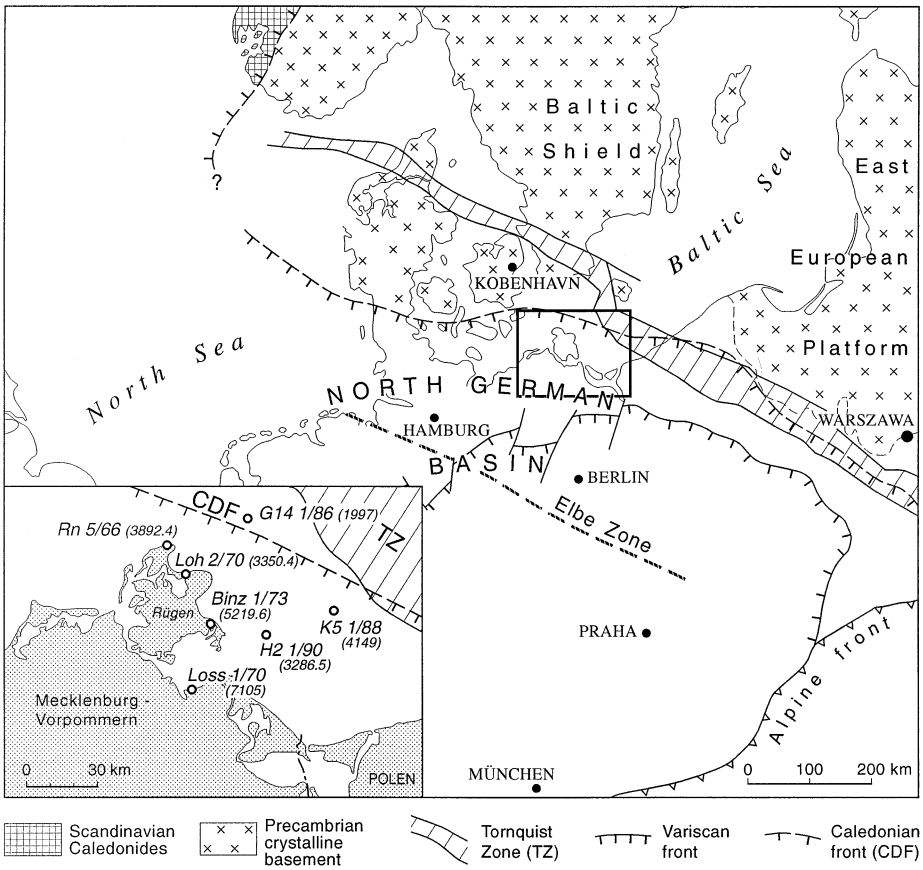


Figure 1. The main tectonic elements in the North German Basin/Baltic Sea region (after Ziegler, 1990; Berthelsen, 1992). The study area and relevant wells in northeast Germany are shown on the inset.

dipping blocks (Thomas *et al.* 1993). The G14 1/86 well is drilled into the North Arkona Block, which is to the north of the Caledonian Deformation Front (CDF) (Fig. 1).

The Lower Palaeozoic succession from G14 1/86 is comparable to similar successions to the north on Bornholm and Scania in terms of, for example, stratigraphic thickness, lithofacies, and faunal contents (Franke, 1993; Maletz, 1997; McCann, 1996*a*). Thus, the region around the G14 1/86 well can be assigned to Baltica, suggesting that no large-scale strike-slip movements can have taken place along the Sorgenfrei-Tornquist Zone in Phanerozoic times (Franke, 1990*b*). In the Rügen area, only an Ordovician succession is recognized, and this is quite different in character from that to the north, comprising a thick succession of deep-marine turbidites.

The exact position of the Rügen area on the Avalonian microcontinent, however, has not been fully determined. Some authors favour a position on the eastern margin of the Avalonia microcontinent (Torsvik *et al.* 1992, 1993) while others (e.g. Channell, McCabe & Woodcock, 1993, fig. 8) appear to suggest that this part of northeastern Germany was part of a separate Western Avalonia microcontinent. Microfossil data, however, would suggest that the Rügen area was unequivocally part of Eastern Avalonia (Servais, 1994).

Arguments favouring the Elbe Lineament as the northeastern boundary of Eastern Avalonia include the evidence of continuity between Baltica and part of northern Germany (Tanner & Meissner, 1996). Such evidence includes the increased crustal velocities in the area extending from the Baltic Shield to the Elbe Lineament (Rabbel *et al.* 1994) and the observed velocity changes across the Elbe Lineament between crust derived from Baltica and that derived from Eastern Avalonia (Abramowitz, Thybo & MONA LISA Working Group, in press). Furthermore, xenoliths have been recorded from Permian basalts in northern Germany which show affinities to Proterozoic anorthosite massifs of the Baltic Shield (Kämpf, Korich & Brause, 1994). In this model the area between the CDF and the Elbe Lineament is interpreted as a thrust onto the passive margin of Baltica (Tanner & Meissner, 1996). The region between the CDF and the Elbe Lineament is, therefore, a complex one with affinities to both Baltica and Eastern Avalonia. Indeed, Abramovitz, Thybo & MONA LISA Working Group (in press) have suggested that the region may be a composite micro-continent made up of a collage of terranes accreted in front of the original micro-continent of Eastern Avalonia. While the palaeontological evidence would suggest that the area is clearly part of Eastern Avalonia, the precise geological setting is unclear, and probably involves a degree of (?low-angle) thrusting. Some of this uncertainty may be clarified following the shooting of some new deep-seismic data in the north German region

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in 1996 (Krawczyk, Lück & Stiller, 1997; DEKORP Research Group, unpub. data.)

3. Lithostratigraphy and distribution of the Vendian–Silurian succession

The lithostratigraphy and biostratigraphy of the northeast German Basin is based on a network of 63 boreholes which were drilled from 1962–86 (Hoth *et al.* 1993). A further four offshore boreholes were drilled between 1986–90 by Petrobaltic – a consortium involving workers from the (then) German Democratic Republic, Polish People's Republic and Soviet Union (Rempel, 1992). These provide a dense data network facilitating cross-borehole correlation in the Rügen area (McCann, 1996*b*).

The work for this study is based largely on Vendian–Silurian core samples from the G14 1/86 well which is located on the passive margin of Baltica (Figs 1, 2). Deposition was in a foreland basin developed to the north of the North German–Polish Caledonides. The preserved Lower Palaeozoic succession is relatively undeformed and is found in downfaulted and slightly southwest dipping blocks (Thomas *et al.* 1993). These samples were analysed in conjunction with a series of Ordovician-age samples from the Binz 1/73, H 2 1/90, K 5 1/88, Lohme 2/70, Loissin 1/70 and Rügen 5/66 wells from the Rügen area (Fig. 1).

Economic basement in the northeast German Basin comprises probable Precambrian crystalline basement and Lower Palaeozoic sediments and metasediments. The oldest recorded rocks in the Rügen area are microcline-rich granites from the G14 1/86 well with a K–Ar age of 530–540 Ma, although it is possible that this date was reset (Piske & Neumann, 1993). Indeed, Franke (1993) suggests that a pre-Cadomian age would be more probable. To the north, K–Ar ages of 1255–1390 Ma have been recorded for granites and gneisses from Bornholm Island (Larsen, 1971; Gravesen & Bjerreskov, 1984), while granites from Scania (Bergström *et al.* 1982) have been dated as 1350–1450 Ma. Lundqvist (1979) reports a variety of ages for granites in the Scania region, ranging from 1215–1655 Ma (Rb/Sr dating) with the youngest granites giving ages of 890 Ma (Bohus granite, Rb/Sr dating) and related pegmatites (910 Ma, U–Pb dating). In Denmark, K/Ar measurements from a hornblende gneiss and a biotite gneiss yielded ages of 815 ± 15 Ma and 870 ± 15 Ma respectively (Larsen, 1971). These dates are in agreement with K/Ar dates obtained in southern Norway and western Sweden (Broch, 1964; Magnusson, 1960). In Poland, Ryka (1982) reported K–Ar ages of 517 Ma for some magmatic intrusions. The variety of dates in the region is largely as a result of the structural complications resulting from Caledonian-age thrusting.

The lowermost G14 1/86 sediments are of possible Vendian age (Franke *et al.* 1989, 1994) and comprise a 55.5 m thick succession of conglomerates and sandstones (Fig. 2). These are overlain by almost 300 m of Cambrian-age sandstones and shales with some limestones occurring close to the top of the succession. The overlying Ordovician unit is dominantly clastic and fine-grained although some limestones also occur close to the top of the unit. Recent work by Maletz (1996, 1997) on the graptolites from the G14 1/86 well reports that the lowermost preserved Ordovician section is Tremadoc in age. This is overlain by mudstones containing *Expansograptus suecicus* and *Pseudophyllograptus*

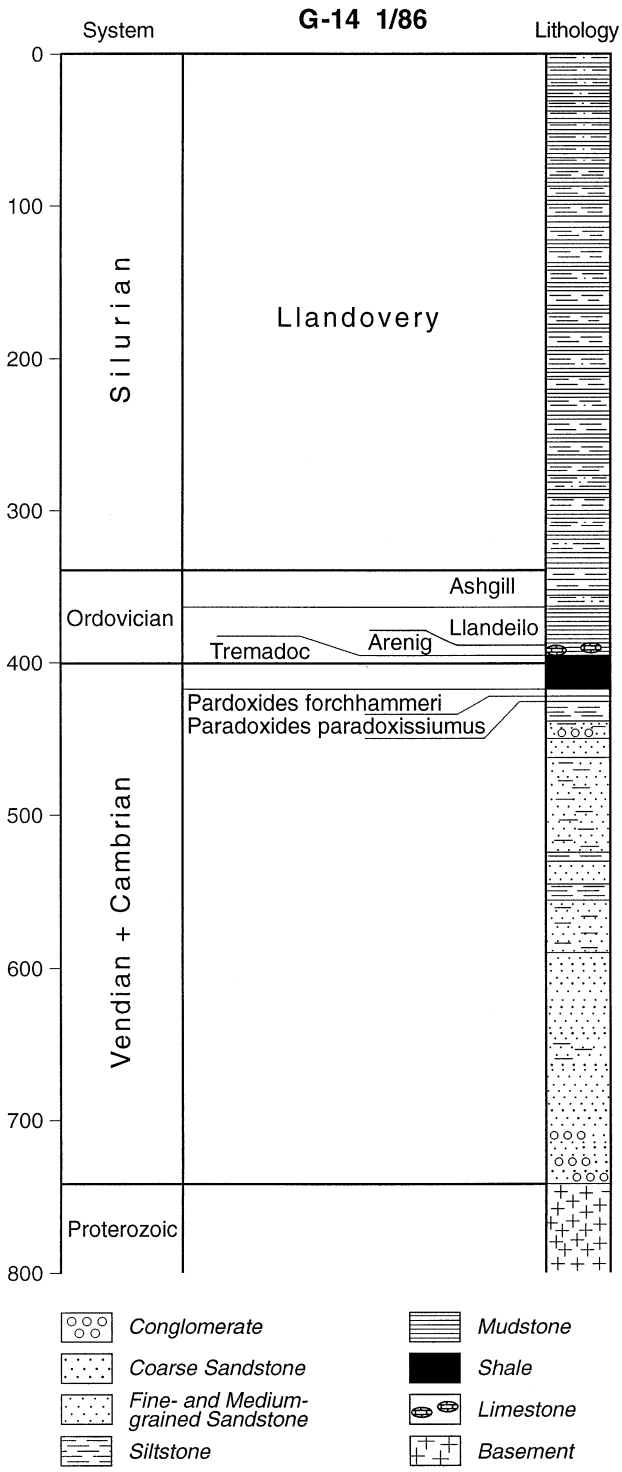


Figure 2. Generalized lithostratigraphic log of the Precambrian to Silurian succession from the G14 1/86 well (after Piske & Neumann, 1993).

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densus suggesting an Arenig age (Maletz, 1996). The overlying thin carbonate unit is followed by tectonized mudstones which contain graptolites suggesting a late Llanvirn (Llandeilian) age. Some of the species, for example, *Hustedograptus teretiusculsus* and *Gymnograptus linnarssoni* are especially indicative of a latest Llanvirn age (Maletz, 1997). The mudstones are overlain by *c*. 30 m of non-fossiliferous shales and subsequent mudstones, siltstones and fine-grained sandstones which have been included in the Upper Ordovician based on lithological interpretations (Franke *et al.* 1994).

In the Rügen area, a thick (in excess of 3000 m) Ordovician succession is recorded. The dominantly marine sediments are Llanvirn–Caradoc in age and thicken to the northwest (McCann, 1996*b*). The Llanvirn succession contains a range of ichnofossils belonging to the *Nereites* ichnofacies (Zagora, 1997). Giese, Katzung & Walter (1994) subdivided the Ordovician section into three parts: a 300 m thick basal unit comprising fine-grained sandstones and shales, the upper part of which has been dated as Upper Tremadoc–Lower Arenig in age; a 1000 m thick central black shale unit with graptolites indicating an age of Lower Caradoc–Lower Llanvirn; and an uppermost 1800 m thick succession of interbedded greywackes and shales with a Llandeilo age suggested by the graptolite assemblages. The section is, however, undoubtedly both incomplete and repeated as a result of localized structural complexity.

The sedimentology of the Silurian succession of the G14 1/86 well was recently described by McCann (1996*a*). Graptolite assemblages have also been recorded from the five cored units (Maletz, 1996, 1997). The oldest of these (1457.4–1465.8 m) includes *Glyptograptus tamariscoides*, *G. fastigatus*, *Monograptus bjerreskovae*, '*Monograptus*' *gemmatus*, *Paradisversograptus runcinatus*, *Pristiograptus variabilis*, *Stimulograptus becki* and *Spirograptus guerichi*. The second cored unit (1376–1384 m) contains *Glyptograptus fastigatus*, '*Monograptus*' *gemmatus*, *Parapetalolithus altissimus*?, *P. conicus*, *P. kurcki*, *Pristiograptus renaudi*, *P. variabilis*, *Rastrites linnei* and *Streptograptus pseudoruncinatus*. The graptolite assemblage of unit three (1306.1–1313.9 m) includes *Glyptograptus elegans*?, *G. fastigatus*, *Parapetalolithus kurcki*, *Rastrites linnei*, *Stimulograptus becki* and *Torquigraptus planus*. Unit 4 (1237–1243.2 m) yielded an assemblage including *Normalograptus* sp.?, *Rastrites linnei* and *Torquigraptus planus*, while the uppermost unit (1224.3–1231.0 m) contained *Monograptus* sp., *Pristiograptus nudus* and a small dendroid fragment. All of the identified graptolites would suggest a middle Llandovery age ("*Monograptus*" *gemmatus* subzone of the *Spirograptus guerichi* Biozone in the early Telychian) for the succession (Maletz, 1996, 1997). Overall, the Ordovician- and Silurian-age graptolite faunas from the G14 1/86 well have a Baltic affinity and are typically Scandinavian in character (Maletz, 1996, 1997).

4. Previous work

Previous work on the provenance region has concentrated on the petrology/heavy mineral spectrum (e.g. Giese, Katzung & Walter, 1994, 1995) and isotopic analysis of specific heavy minerals (e.g. Giese *et al.* 1995). Giese, Katzung & Walter (1994) examined 34 sandstone samples from five boreholes in the Rügen area, concentrating on the petrology and heavy mineral assemblages from the Loissin 1/70 and Rügen 5/66 wells. The heavy mineral spectrum of the Loissin sandstones is dominated by zircons (more than 90 %) with decreasing amounts of pyrite, rutile, apatite and sphene forming the final 10 %. Some samples show large amounts of Fe-rich carbonates (ankerite, siderite), which are probably derived from thin carbonate veins which cut the sandstones (Giese, Katzung & Walter, 1994). The zircons comprise both polycyclic, anhedral forms, derived from reworked sediments and basement rocks and monocyclic, euhedral to subhedral forms, derived from mantle-dominated magmatic, and to a lesser extent, crustal melts and associated magmatic rocks (Giese, Katzung & Walter, 1994, 1995).

The heavy mineral spectrum from Rügen 5/66 is dominated by pyroxene, epidote and chromite, while pyrite and magnetite are also common. Geochemically the pyroxenes are all Ca-rich clinopyroxenes derived from orogenic tholeiitic basalts, the chromites being derived from alpine peridotites and ophiolite sequences. Their high Al/Al+Cr ratio (> 0.46) suggests derivation from harzburgites and cumulates of ophiolite sequences (Pober & Faupl, 1988). The epidotes are Fe-rich. Transparent heavy minerals are rarer (often less than 1.0 %) and dominantly zircon. The zircons are variously derived from mantle-derived melts, older magmatic sources, or simply reworked. Rare apatite, sphene, tourmaline and rutile are also found (Giese, Katzung & Walter, 1994).

5. Petrography

The petrography of 17 sandstones of Vendian–Silurian age from the G14 1/86 well, together with five Ordovician-age samples from Rügen and the adjacent mainland, were examined. Medium to coarse sandstones were analysed using the Gazzi-Dickinson point-counting technique (see Ingersoll *et al.* 1984) to minimize the dependence of rock composition on grain size. Grain parameters and the recalculated parameters (Table 1) are those of Ingersoll & Suczek (1979). The majority of the samples were medium- to well-sorted (rarely poorly sorted) with individual grains being sub-angular to sub-rounded (Fig. 3).

Excluding the cement and matrix the principal constituents of the sandstone samples are as follows:

Quartz (Q). Grains of quartz are dominantly monocrystalline (Qm) and sub-rounded to sub-angular in shape (Fig. 3). Some strained Qm is common in all samples, but there is no common orientation, suggesting that the straining occurred elsewhere and that the grains were subsequently transported into the basin. Qm grains

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Table 1. Framework grain mode parameters of sandstones from the Vendian–Silurian succession of NE Germany

Age	Location	n		Q%	F%	L%	Qm%	F%	Lt%	Qp%	Lvm%	Lsm%	Lm%	Lv%	Ls%
Silurian	G14 1/86	3	Mean	58.3	0.54	41.16	52.9	0.54	46.56	14.31	2.95	82.74	0	3.66	96.07
			Range	43.48–80.53	0.29–1.03	19.17–56.23	39.7–73.7	0.29–1.03	25.96–60.0	6.28–26.13	0–4.55	69.32–93.72	0	0–6.15	90.84–100
			Std Dev.	19.6	0.42	19.47	18.26	0.42	18.12	10.46	2.56	12.38	0	3.24	4.72
Ordovician	G14 1/86	1		75.87	1.74	22.39	65.42	1.74	32.84	31.82	15.15	53.03	0	22.22	75.9
Ordovician	Rügen	4	Mean	80.51	10.53	8.96	66.92	10.53	22.56	68.35	10.84	20.82	4.65	26.88	39.48
			Range	67.51–90.52	6.41–13.23	0–19.49	52.54–76.7	6.41–13.23	14.15–34.46	42.86–100	0–28.69	0–45.71	0–12.5	10.26–50.4	18.01–61.54
			Std Dev.	9.79	3.24	9.41	10.09	3.24	9.14	29.57	12.84	20.22	6.84	20.94	21.77
Cambrian	G14 1/86	5	Mean	86.51	6.28	7.22	76.06	6.28	17.66	67.87	1.48	30.65	0	5.71	89.33
			Range	73.88–92.64	3.65–8.86	0.65–22.47	57.18–85.63	3.65–8.86	6.12–38.79	18.37–91.89	0–7.4	8.1–81.3	0	0–28.57	46.67–100
			Std Dev.	7.47	2.38	9.37	12.62	2.38	14.75	29.85	3.31	30.41	0	12.78	23.85
Vendian	G114 1/86	8	Mean	85.76	11.7	2.55	75.29	11.7	13.01	77.14	2.16	20.7	0	19.44	72.92
			Range	79.18–100	0–19.38	0–5.57	68.21–81.53	0–19.38	5.3–23.91	46.15–100	0–13.73	0–53.84	0	0–100	0–100
			Std Dev.	7.04	7.33	2.28	4.57	7.33	6.45	21	4.84	22.4	0	40.02	43.6

Key: Q – total quartzose grains; F – total feldspar grains; L – total lithic grains; Qm – monocrystalline quartz grains; Lt – total lithic fragments including polycrystalline quartz grains; Qp – total polycrystalline quartzose grains; Lvm – total volcanic and metavolcanic lithic fragments; Lsm – total sedimentary and metasedimentary lithic fragments; Lm – total metamorphic lithic fragments; Lv – total volcanic lithic fragments; Ls – total sedimentary lithic fragments.

showing embayments are common, especially in the Vendian. Bohm lamellae are rarely observed.

Cambrian-age Qm may have quartz overgrowths, frequently with accompanying fluid-inclusion rims. Inclusions of tourmaline may also be present.

Qm of Ordovician age may contain microliths of zircon and tourmaline. Clay rims are also observed.

Polycrystalline quartz grains (Qp) of >3 constituent crystals are more abundant than Qp with 2–3 constituent crystals (Fig. 3). Contacts between the subgrains are straight to sutured. Individual subgrains may be variable in size, even within a single composite grain of Qp.

Feldspar (F). Plagioclase is the most abundant variety of feldspar, and is commonly replaced by calcite or altered to clay mineral (Fig. 3). It commonly exhibits lath- or plate-like morphology. Occasional grains of microcline are present. Rare perthite is observed in the Vendian-, Cambrian- and Ordovician-age samples.

Lithic Fragments (L). Sedimentary lithic fragments (Ls), commonly siltstone and mudstone, dominate the lithic fraction. In the Silurian some microconglomerates have been noted. These are clast supported, with individual clasts being sub-angular to sub-rounded, up to 2 mm long and are dominantly composed of intraclastic mudstones with some bioclastic material (corals, brachiopods) (McCann, 1996*a*). Carbonate fragments, sometimes bioclastic, are also recorded from the Ordovician of the G14 1/86 well.

Volcanic lithic fragments (Lv) (largely trachytic) in the Vendian–Silurian succession are rare with some notable exceptions (Fig. 3). Possible glassy fragments have been recorded from the Cambrian. Ordovician-age samples contain a more varied suite of volcanic lithic fragments, including fragments with spherulitic texture (?rhyolite), ignimbrite-type fragments with shard-like textures, possible trachytoid gabbro, and large numbers with trachytic or andesitic textures. The Ordovician-age volcanic rocks are dominantly of intermediate to acid-intermediate origin.

Metamorphic lithic fragments (Lm) are rare, and are dominantly composed of elongate polycrystalline quartz fragments.

Possible igneous lithic fragments are also found, and are largely quartz/plagioclase composite fragments. They occur in most samples of Vendian to Ordovician age. One particular Cambrian-age sample contains a quartz lithic fragment enclosing a microcline microlith.

Accessory minerals are present in all samples and include pyroxene, zircon and muscovite in the Vendian, epidote, zircon, pyroxene, chlorite and muscovite in the Cambrian, zircon, tourmaline, muscovite, chlorite, pyroxene and epidote in the Ordovician and pyrite framboids and chlorite in the Silurian.

Matrix. Excluding carbonate cement, the matrix comprises fine-grained quartz, feldspar and phyllosilicate fragments with significant amounts of clay mineral, and may form up to 41 % of the rock in some cases (averages: Vendian – 28.28 %; Cambrian – 1.84 %; Ordovician – 21.0 %;

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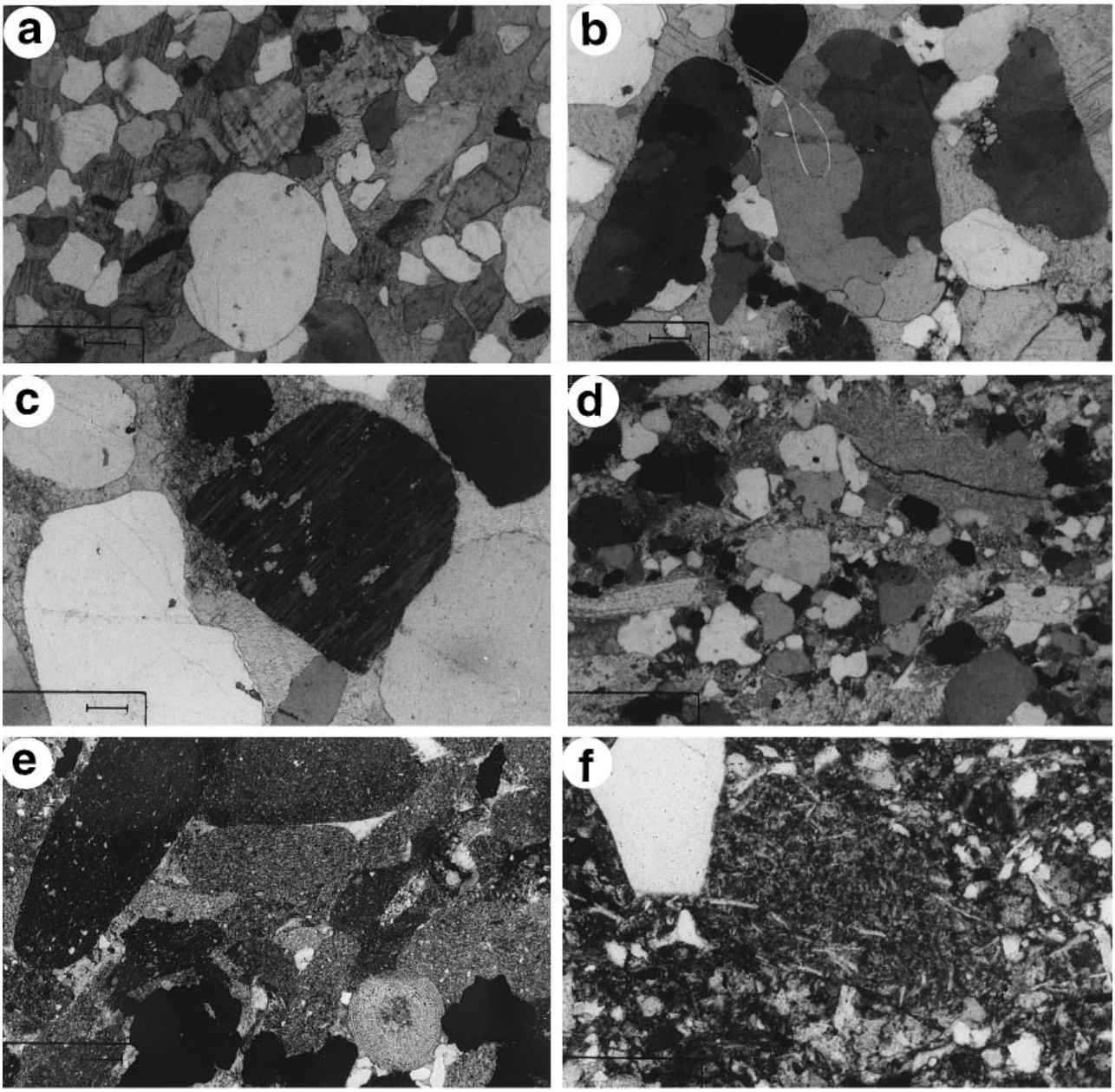


Figure 3. Photomicrographs of selected sandstone samples from the Lower Palaeozoic succession, northeast Germany. (a) Sub-rounded to sub-angular quartz grains in carbonate cement, G14 1/86, Vendian; (b) Polycrystalline quartz grain showing straight to slightly sutured contacts, G14 1/86, Vendian; (c) Plagioclase crystal showing alteration to clay mineral, G14 1/86, Vendian; (d) Subrounded to subangular quartz grains and sedimentary lithic fragments (mudstone), G14 1/86, Ordovician; (e) Clay peloids and bioclastic fragments, G14 1/86, Silurian; (f) Volcanic lithic fragment showing felted texture, Rügen 5/66, Caradoc. All samples are in cross-polarized light. Scale bars are 0.2 mm (except (f) which is 0.1 mm).

Silurian – 23.6 %). Is is composed of highly altered lithic and feldspathic fragments, finely divided quartz, chlorite, sericite, carbonate and material too fine to be identified. Much of the matrix is primary 'pseudomatrix' (see Dickinson, 1970). Some Ordovician-age samples contain significant amounts of illite (e.g. Rügen 5/66).

Cement. Carbonate cement is common (up to *c*. 40 %; averages: Vendian – 6.45 %; Cambrian – 21.08 %; Ordovician – 2.68 %; Silurian – 3.8 %). Calcite cements show a patchy distribution in the Cambrian-, Ordovician- and Silurian-age samples.

5.a. Quantitative petrography

The analysed data, together with those of Giese, Katzung & Walter (1994), have been plotted on a series of ternary diagrams (Fig. 4). An initial plot (QFL) shows the Vendian samples plottting largely in the Craton Interior/Transitional Continental fields and the Cambrian samples plotting in the Craton Interior/Recycled Arc fields (Fig. 4a). The Ordovician samples show a wider range of possibilities, with the samples from the current study plotting in the Transitional Continental/Recycled Arc fields, while the Loissin 1/70 and Rügen 5/66

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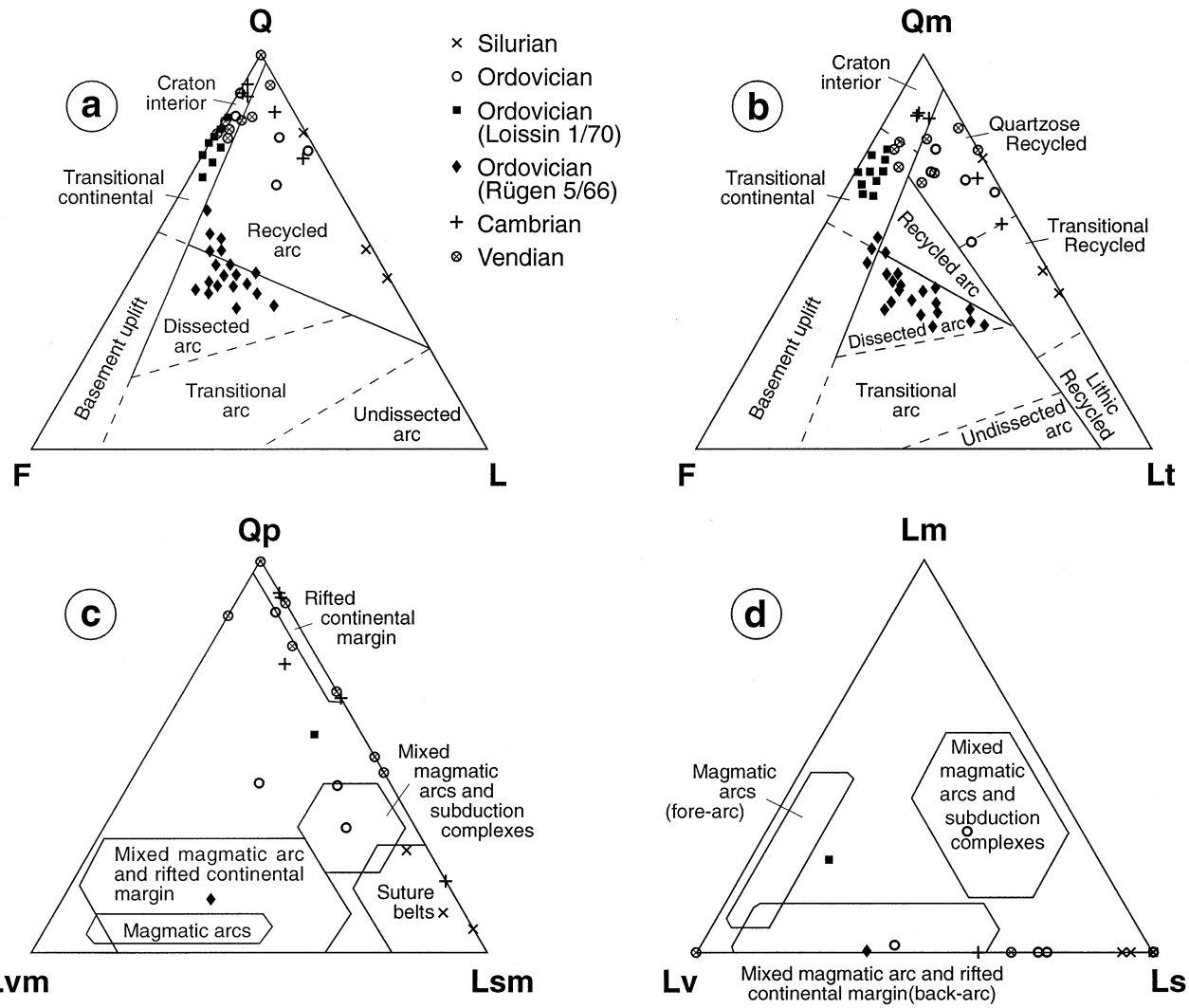


Figure 4. Sandstone modal data for the Lower Palaeozoic succession, northeast Germany. QFL – Quartz–Feldspar–Lithic Fragments; QmFLt – Monocrystalline quartz–Feldspar–Total lithic fragments; QpLvmLsm – Polycrystalline quartz–Volcanic and metavolcanic lithic fragments–Sedimentary and metasedimentary lithic fragments; LmLvLs – Metamorphic lithic fragments–Volcanic lithic fragments–Sedimentary lithic fragments. Tectonic discrimination fields defined by Ingersoll & Suczek (1979).

samples of Giese, Katzung & Walter (1994) plot in the Transitional Continental and Recycled Arc/Dissected Arc fields respectively. The Silurian samples all plot within the Recycled Arc field.

On a second plot (QmFLt), where the polycrystalline quartz clasts are counted as part of the total lithic fragments, the Vendian samples plot in the Quartzose Recycled/Transitional Continental fields with the Cambrian samples falling mainly within the Craton Interior field (Fig. 4b). As previously, the Loissin 1/70 samples fall comfortably within the Transitional Continental field while the Rügen 5/66 samples fall mainly within the Dissected Arc field. The Ordovician samples from the current study plot mostly within the Quartzose Recycled field. The Silurian-age samples fall mostly within the Transitional Recycled field.

Taking just the polycrystalline quartz grains and plotting them against the lithic fragments produces a plot (QpLvmLsm) where the Vendian and Cambrian samples plot largely in and around the Rifted Continental Margin field (Fig. 4c). Some Ordovician samples from the current study plot in the Mixed Magmatic Arcs and Subduction Complexes field, while an average point from the Rügen 5/66 Ordovician samples (Giese, Katzung & Walter, 1994) plots in the Mixed Magmatic Arc and Rifted Continental Margin field. The Silurian-age samples plot within the Suture Belt field.

A final plot (LmLvLs) where just the lithic fragments are used shows the majority of the points falling outside of the indicated fields (Fig. 4d). Some Cambrian and Ordovician samples plot within the Mixed Magmatic Arc and Rifted Continental Margin (Back-arc) field.

6. Geochemistry

Analysis of the major and trace element geochemistry of 44 mudstones was carried out using an automatic wavelength-dispersive XRF (Type: Siemens SRS 303 AS). Major and some trace elements were determined using a lithium metaborate flux and a sample to flux ratio

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of 1:6. Sulphur, carbon and H_2O determinations were carried out by means of infrared spectrascopy on a LECO analyser.

The major and trace element compositions of the Vendian, Cambrian, Ordovician and Silurian mudstones were determined (Table 2). The majority of the mudstones have a SiO_2 range of 40.9–70.64 wt %, low Fe_2O_3 (total Fe as Fe_2O_3) and MgO contents of between 0.02 and 6.61. The Cambrian and Silurian-age samples are the richest in SiO_2 while the Ordovician-age samples from the Rügen area have less SiO_2.

Variations in the major element geochemistry of the mudstones show little evidence of discrimination for a range of elements, including TiO_2, Al_2O_3, Na_2O, V and CaO. On the Fe_2O_3, K_2O and Ni plots, however, there is clear evidence of stratigraphic discrimination (Fig. 5). This is particularly true of the Ordovician-age samples from the Rügen area which form a tight cluster distinct from the other samples. Another cluster, of Cambrian age and with a higher SiO_2 wt %, is also noted, as is a smaller and less defined cluster of some Silurian-age samples which can overlap with the Cambrian-age samples. The Vendian-age samples, together with the Ordovician-age samples from the G-14 1/86 well plot between these clusters.

The distribution patterns for Ni and Cr are similar to those of Fe_2O_3 and MgO (Fig. 5). All of these elements (Cr, Ni, Mg and Fe) occur in basic igneous rocks and the cohesion of the plots, particularly for the Cambrian and Vendian samples and to a lesser extent the Rügen Ordovician-age samples, suggests that they were derived from such a source. Minimal levels of weathering and alteration are also suggested by the cohesion of the plots; the MgO levels have not been altered too much by clay mineral chemistry nor have the Fe_2O_3 levels been affected by oxides.

The most noticeable differences in trace element contents are the relatively high Ba values for the Cambrian (average: 2078 ppm) and G14 1/86 Ordovician (average: 2130 ppm) when compared to the other averages of 611 ppm for the Rügen Ordovician or 472 ppm for the Silurian. Low Cr, Ni, and V values for the Vendian (averages: 50, 35, 79), Cr and Ni for the Cambrian (averages: 67, 37), and Ni for the G14 1/86 Ordovician (average: 43) when compared with the Rügen Ordovician (averages: 90, 107, 132) and the Silurian (averages: 97, 66, 107) were recorded. Low Sr values for the Vendian (76), Cambrian (87) and Silurian (94) were also noted. High levels of Cr (100–1500 ppm) and Ni (50–600 ppm) (see Fig. 6) have been used to indicate an ultramafic provenance for sediments (Haughton, 1988; Wrafter & Graham, 1989), although more moderate levels would also indicate, to some extent, mafic provenance. Cr values of close to 100 are recorded here for the Ordovician (G14 1/86: 133; Rügen: 90) and Silurian (97) successions. In addition, both the Rügen Ordovician and Silurian also show elevated levels of Ni. High Ni contents are also observed, in mainly the Ordovician-age samples, with enhanced Mg contents. This indicates a provenance from a mafic, or possibly, ultramafic source, particularly for the Rügen samples, since the G14 1/86 samples plot on the left-hand side of the general Ordovician trend.

The tectonic settings for the successions may be broadly distiguished by plotting SiO_2 against K_2O/Na_2O (Roser & Korsch, 1986). The Vendian and Cambrian samples plot comfortably within the Passive Margin (PM) field, while the Ordovician samples from both Rügen and the G14 1/86 well plot largely within the Active Continental Margin (ACM) field (Fig. 6). The Silurian-age samples plot mostly on the border of the ACM and PM fields. Plotting TiO2 versus Ni (after Floyd & Leveridge, 1987) reveals that the Vendian, Cambrian and Silurian sediments were predominantly derived from acidic rocks while the Ordovician sediments show a more intermediate derivation, with significant input from mafic/ultramafic sources (see above) (Fig. 6).

7. Discussion

Petrographic evidence suggests that the Vendian and Cambrian sedimentary successions from the G14 1/86 well were derived from a stable cratonic area. The sediments are relatively quartz-rich and show evidence of recycling, suggesting derivation from older granitic or gneissic outcrops and associated platform sediments (Dickinson, 1988). The presence of rare volcanic fragments suggests a subordinate volcanic presence. The geochemical signature reflects the petrography and is that of a strongly passive margin (PM). Further petrographic discrimination indicates that the majority of the Vendian and Cambrian samples plot in the rifted continental margin field. Palaeomagnetic data suggest that Baltica and Gondwana were separated by wide oceanic basins in Cambrian times (Torsvik *et al.* 1990, 1992, 1996) and that the area was a relatively stable cratonic area (Fig. 7). During early to middle Cambrian times, however, the Bornholm region (to the north of G14 1/86) was uplifted resulting in the erosion and redeposition of older sedimentary strata (Vejbaek, Trouge & Poulsen, 1994). This period of tectonic instability has been related to the change from a passive margin setting during spreading to an active margin at the start of subduction along the northern margin of Baltica (Gee, 1987). Significantly, the petrography of the G14 1/86 Ordovician sediments are less cratonic and suggest a more recycled origin. There is also some indication, largely based on lithic fragments, of a magmatic-arc signature probably related to the onset of subduction on the southern margin.

The Ordovician sediments of the Rügen area are quite different from those of the G14 1/86 succession. Here the petrographic signature is predominantly that of an arc, with the geochemistry also indicating a strong active continental margin setting. Lithic fragments suggest the possibility of input from a subduction zone or rifted continental margin. Lithic clasts are predominantly acid and intermediate volcanic rocks although basic rocks are

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Table 2. Representative X-ray fluorescence chemical analyses of mudstones from the Vendian–Silurian succession of northeast Germany

Sample No	Location/Age	SiO2	TiO2	Al2O3	Fe2O3	MnO	MgO	CaO	Na2O	K2O	P2O5	H2O+	CO2	Total	Ba	Cr	Ni	Rb	Sr	V	Y	Zn	Zr
PR202	G14 1/86 – Silurian	64.49	0.81	15.02	7.94	0.46	1.66	0.9	0.8	2.29	0.2	3.57	1.74	99.87	402	91	54	105	84	96	29	173	230
PR212	G14 1/86 – Silurian	70.96	0.63	9.41	6.23	0.5	1.2	2.9	0.48	1.36	0.09	2.78	3.03	99.58	260	95	42	61	74	69	22	71	269
PR219	G14 1/86 – Silurian	53.95	0.66	13.24	13.17	1.32	1.91	1.58	0.44	2.09	0.42	3.97	6.36	99.11	458	126	94	97	89	120	30	156	160
PR236	G14 1/86 – Silurian	57.23	1.01	20.81	6.34	0.16	1.91	0.5	0.84	4	0.07	5.11	2.08	100.06	730	102	66	182	107	147	23	52	182
MV95-41	Rügen 5/66 – Caradoc	57.29	0.63	13.88	8.83	0.35	6.31	1.89	2.16	1.47	0.09	4.93	1.04	98.68	268	345	217	66	99	155	14	82	111
MV95-46	Rügen 5/66 – Llanvirn	45.59	0.99	23.6	10.37	2.47	2.66	0.83	0.91	3.24	0.1	6.63	2.9	100.28	801	82	172	138	139	145	30	129	117
MV95-58	Binz 1/73 – Llanvirn	49.01	1.05	23.33	9.27	1.28	2.11	0.66	0.91	3.54	0.15	5.71	2.76	99.79	714	94	90	162	116	150	28	109	138
MV95-51	Lohme 2/70 – Llanvirn	47.86	1.03	22.02	9.34	0.96	2.1	0.87	0.84	3.2	0.26	7.5	2.98	98.94	595	91	91	145	124	133	35	96	138
MV95-52	Lohme 2/70 – Llanvirn	49.23	0.95	21.66	9.64	0.77	0.02	0.82	0.84	2.91	0.25	7.03	2.55	98.65	538	96	78	136	115	122	32	113	119
MV95-48	Rügen 5/66 – Tremadoc	49.81	1.18	24.56	10.42	0.84	1.3	0.36	1.1	4.75	0.18	4.27	0.66	99.43	1027	82	71	219	234	119	31	90	150
MV95-47	Rügen 5/66 – Tremadoc	62.34	0.74	12.49	6.41	1.52	1.77	3.03	0.88	2.56	0.11	2.33	4.82	99	577	50	85	100	221	69	25	72	481
PB243	G14 1/86 – Ordovician	54.2	1.05	22.15	7.64	0.19	2.11	0.25	0.57	4.85	0.1	0.06	0.77	99.87	1356	109	57	209	72	147	23	106	152
PB258	G14 1/86 – Ordovician	59.12	0.78	15.23	6.51	0.03	2.72	2.12	0.45	4.26	1.23	4.59	2.4	99.45	2905	157	28	159	367	509	35	49	143
MV95-27	G14 1/86 – Cambrian	70.64	0.44	12.2	2.96	0.08	0.53	1.62	0.1	6.64	0.04	1.29	2.89	99.33	2296	30	10	151	101	40	10	27	290
PR258	G14 1/86 – Cambrian	60.65	0.88	15.35	2.97	0.06	1.81	4.89	0.75	4.58	1.25	2.87	3.42	99.48	2905	157	28	159	367	509	35	49	143
PR304	G14 1/86 – Cambrian	65.13	0.94	16.45	4.88	0.02	0.86	0.1	0.1	7.34	0.04	2.65	0.42	98.83	1253	42	18	186	84	65	20	43	623
MV95-18	G14 1/86 – Cambrian	53.7	0.71	12.73	2.36	0.04	1.52	7.7	0.47	3.67	4.04	3.14	8.4	98.49	2762	205	27	144	451	1318	120	293	125
MV95-19	G14 1/86 – Cambrian	51.8	0.75	13.35	7.73	0.03	1.24	1.1	0.49	4.55	0.14	3.55	24.99	109.71	4105	70	280	149	104	962	34	154	137
PR331	G14 1/86 – Vendian	56.93	0.92	18.25	6	0.18	1.4	2.75	0.27	6.44	0.03	3.69	2.33	99.2	839	36	21	181	58	75	29	181	393
MV95-32	G14 1/86 – Vendian	57.37	0.94	21.15	6.43	0.09	1.57	0.43	0.35	7.1	0.04	3.82	0.45	99.74	947	44	49	212	53	83	30	236	361

Major oxides in wt %, trace elements in ppm. Total Fe as Fe_2O_3.

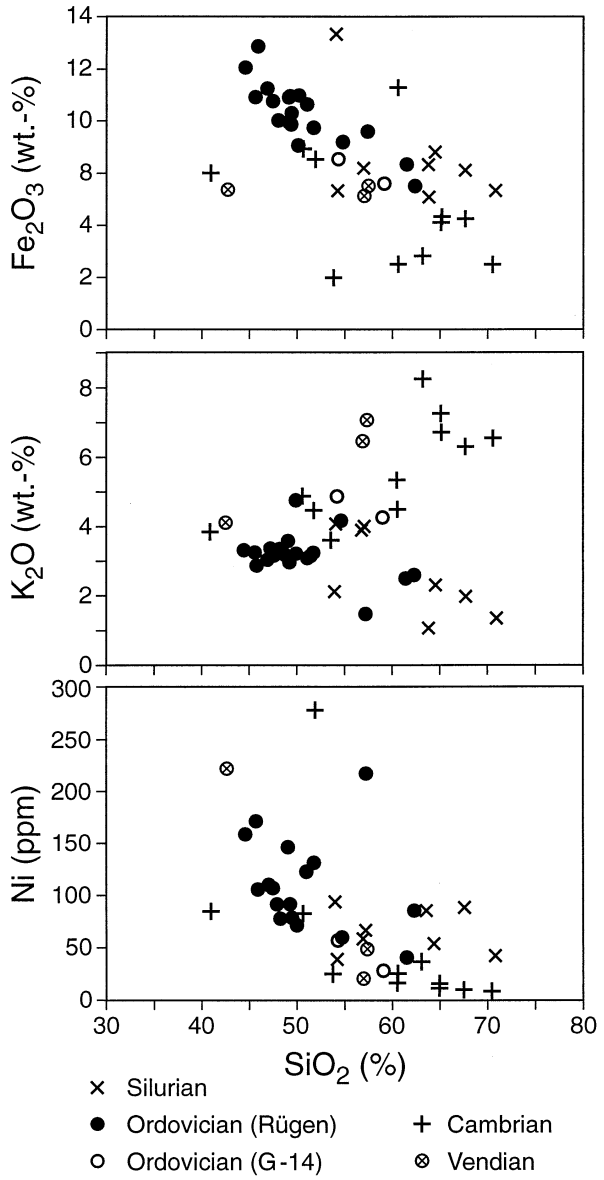


Figure 5. Harker variation diagrams for the Lower Palaeozoic-age mudstones, northeast Germany.

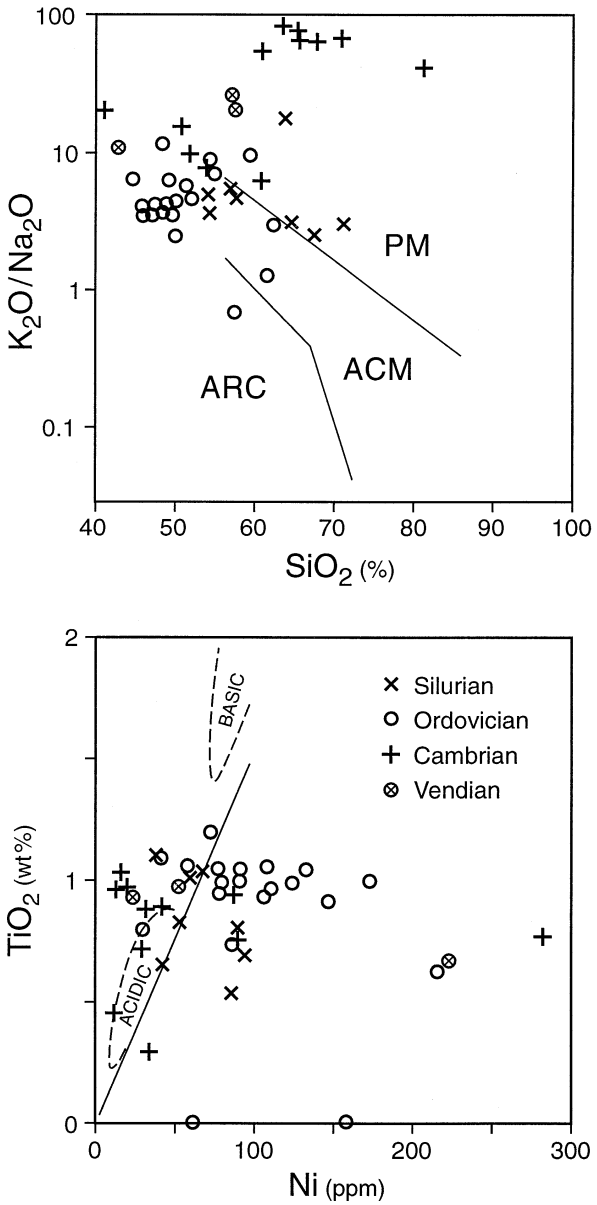


Figure 6. (a) Tectonic discrimination diagram for mudstones from the northeast German Basin (after Roser & Korsch, 1986). PM – Passive Margin; ACM – Active Continental Margin; OIA – Oceanic Island Arc. (b) TiO_2–Ni plot for mudstones from the northeast German Basin (after Floyd, Winchester & Park, 1989). The high Ni contents indicate provenance from a mafic or ultramafic source.

also important. Input from a mafic/ultramafic source is indicated by the high Ni levels. The dominance of pyroxene derived from orogenic tholeiitic basalts and chromite from alpine peridotites and ophiolitic sequences in the the Rügen 5/66 succession confirms that basic igneous activity was also important (Giese, Katzung & Walter, 1994, 1995). Large-scale volcanism in Eastern Avalonia commenced in the early Ordovician, initially in the Welsh Basin and later in the Leinster Basin and Lake District. Indeed, the period of Lake District subduction-related volcanism led to the eruption of significant amounts of tholeiitic basalts and andesites passing southwards into calc-alkaline andesites and rhyolites (Bevins, Stillmann & Furnes, 1985). The extent of this volcanic activity can be gauged from the presence from early Ordovician times of volcanic ash beds, presumably derived from eruptions within the Iapetus region of the Caledonides, on the southern margins of Baltica (Huff, Bergstrom & Kolata, 1992). This major period of tectonic and associated volcanic activity may have been associated with the closure of the Iapetus Ocean between Eastern Avalonia and Laurentia, although this arc system may as easily have formed due to closure of the Tornquist Sea (Pickering, Bassett & Siveter, 1988). Volcanic activity, however, continued intermittently into the early (Bevins, Stillmann & Furnes, 1985) and later Silurian (Teale & Spears, 1986).

Biostratigraphic and palaeomagnetic data suggest closure of the Tornquist Sea between Baltica and Avalonia by late Ordovician times (Cocks & Fortey, 1982, 1990; Tanner & Meissner, 1996; Torsvik *et al.* 1990), but this is poorly constrained (Torsvik *et al.* 1993). Closure of the

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Tornquist Sea by late Ordovician times would suggest that there was a unified sedimentary system spanning the remnant Tornquist Ocean by late Ordovician (Ashgill) times. The actual situation, however, is a little more complex. The thick (hundreds of metres) Ordovician succession on Rügen largely comprises turbiditic sandstones and mudstones, whereas similar age sediments to the north on Bornholm and Scania are dominantly black shales and carbonates (and less than 100 m thick). As already noted, both petrographically and geochemically the Ordovician successions from both the G14 1/86 well and the Rügen area differ. In addition there is a distinct lack of any Silurian sediments in the Rügen area, unlike the Llandovery-age succession, correlatable with sections on Bornholm and Scania, described from the G14 1/86 borehole (McCann, 1996*a*; Maletz, 1997).

Assuming a position along the eastern extension of Avalonia, the Cambro-Ordovician succession of Rügen would represent the link of both domains, implying that the closure of the Tornquist Sea had already begun by middle Ordovician times (Giese, Katzung & Walter, 1994). Accepting the approximate Caradoc–Ashgill palaeogeographic position of Rügen as suggested by Torsvik *et al.* (1992) would imply the existence of strong links, both biological and sedimentological, by this time at the latest. The lack of continuity has been interpreted as the result of later left-lateral displacement of the Rügen area relative to Baltica (Giese, Katzung & Walter, 1994). Recent palaeomagnetic research, however, indicates that the mid-Silurian palaeopoles from Eastern Avalonia and Baltica differ (Torsvik *et al.* 1992, 1996; Trench & Torsvik, 1991), implying that the Tornquist Sea existed until late Ordovician times (Scotese, 1984; Oliver, Corfu & Krogh, 1993; Torsvik *et al.* 1993) and probably beyond. This is supported by the lack of late Ordovician tectonothermal and magmatic events in southwest Poland (Oliver, Corfu & Krogh, 1993). It has even been suggested that closure may not have occurred until as late as the latest Silurian or even early Devonian times (Channell, McCabe & Woodcock, 1993) although faunal and palaeomagnetic data both suggest latitudinal closure prior to Wenlock time (Torsvik *et al.* 1993).

By the late Ordovician, Baltica lay in subtropical latitudes and brachiopods exhibit clear faunal differences from those in Gondwana (Harper, 1992). Palaeolatitudinal estimates for Baltica and Eastern Avalonia are comparable from early middle Ordovician (Llanvirn) times (Torsvik *et al.* 1993, 1996). Harper (1992) suggests that faunal provinciality in brachiopods between Eastern Avalonia and Baltica was still discernable in late Ordovician times, thus implying a degree of separation. By the mid-Silurian times, faunal evidence suggests that Eastern Avalonia and Baltica were separated by < 1000 km (McKerrow & Cocks, 1986), while palaeomagnetic data suggest a distance of *c.* 1000–1500 km (Torsvik *et al.* 1993), largely longitudinal (Torsvik *et al.* 1993; Mac Niocaill & Smethurst, 1994). Thus, differences in the sedimentological successions of Baltica and Avalonia

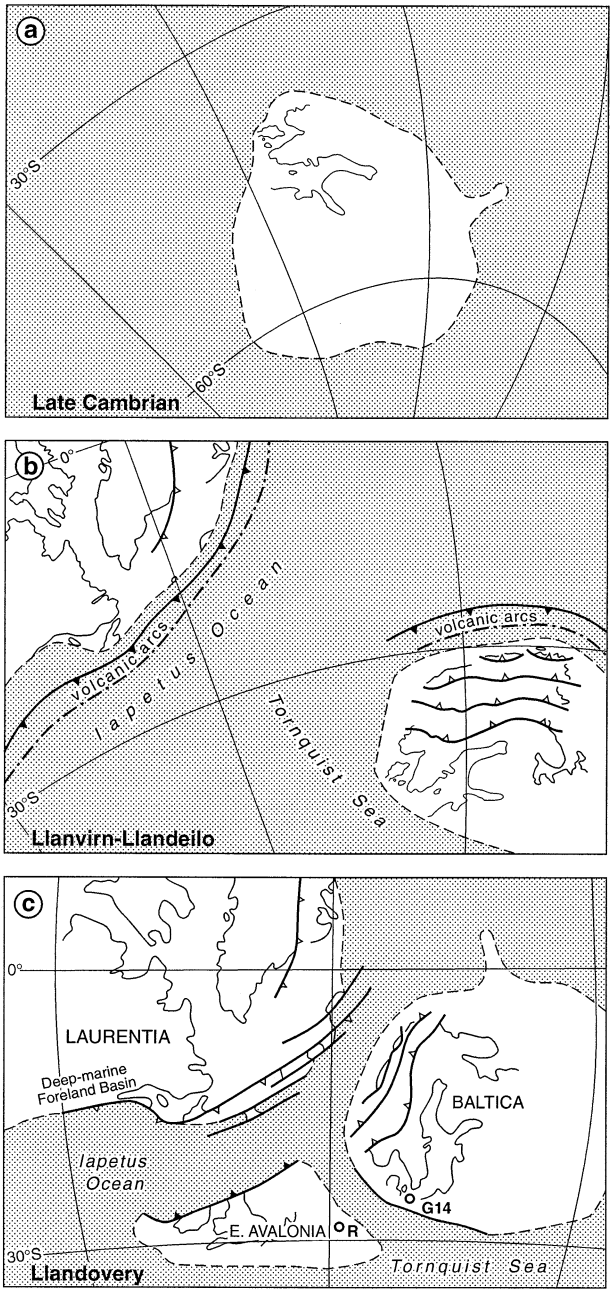


Figure 7. Cambrian to Llandovery palaeogeographic reconstructions for Baltica and Eastern Avalonia (after Pickering, Bassett & Siveter, 1988; Torsvik *et al.* 1993; Mac Niocaill & Smethurst, 1994; present study).

may be interpreted in terms of longitudinal variations together with the variable tectonic environments that prevailed in the individual regions. The relative stability of the Baltic Shield region, for example, is reflected in the provenance of the G14 1/86 Vendian–Silurian succession, where sediment provenance was predominantly from sedimentary sources with magmatic input being significant only during Ordovician times (although Silurian ash layers have also been reported from Bornholm). At this time the framework grains suggest a magmatic arc signature possibly related to the onset of subduction-related processes.

On the opposite side of the Tornquist Sea, the

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Ordovician-age Eastern Avalonia succession (Rügen area) reveals a strong active margin signature although rifting and subduction settings are also indicated. Indeed, active continental margin settings are recorded from elsewhere in Eastern Avalonia (André, 1991; André, Hertogen & Deutsch, 1986; Pharaoh *et al.* 1991; Pharaoh, Brewer & Webb, 1993; Noble, Tucker & Pharoah, 1993; Oliver, Corfu & Krogh, 1993) while in southern Poland there is even evidence of two Ordovician-age metamorphosed ophiolites and one Silurian-age unmetamorphosed ophiolite (Oliver, Corfu & Krogh, 1993). A return to relatively stable tectonic conditions is indicated by the quartz-rich G14 1/86 Lower Silurian succession. Overall, these results would suggest that, although complete closure of the Tornquist Ocean was not complete until the latest Silurian, major changes in tectonic regime in the Eastern Avalonia/Baltica area occurred in the Ordovician suggesting a significant degree of closure during this time.

Final closure, when it occurred, was complex. In one model, the overthrusting of Eastern Avalonia in a northeast/east–northeast direction led to the formation of the seismic reflectors which are interpreted as the Caledonian Deformation Front (Tanner & Meissner, 1996). Deeper seismic reflectors have been interpreted as remnants of a subduction zone, where oceanic material from the Tornquist Sea was subducted beneath an active continental margin, followed by the continent–continent collision which created the thrusts and nappes of the CDF (Tanner & Meissner, 1996). A second model involves initial collision occurring in southwest Poland (Oliver, Corfu & Krogh, 1993) leading to later transpressional closure along the Elbe Lineament combined with an anti-clockwise rotation (Torsvik *et al.* 1993) of Eastern Avalonia and the main subduction of crust at the Iapetus suture (Tanner & Meissner, 1996). Thus the area between the CDF and the Elbe Lineament could have been incorporated as a micro-terrane. Given the complexity of the situation in southwest Poland where six terranes were accreted along the Tornquist suture zone (Oliver, Corfu & Krogh, 1993), it is clearly possible that similar situations are to be recognized along the length of the Tornquist margin resulting from the complex amalgamation of Eastern Avalonia and Baltica.

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