Crustal structure and tectonic evolution of the Tornquist Fan region as revealed by geophysical methods

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Crustal structure derived primarily from geophysical investigations reveals features that may be related to the complex tectonic evolution of the Tornquist Fan region. This northwestwards widening splay of Late Carboniferous – Early Permian fault zones in the Danish region emanates from the Teisseyre-Tornquist Zone in northern Poland. Seismic reflections and velocity anomalies image collisional fault zones that formed during the Proterozoic and Palaeozoic amalgamation of the crust. Re-equilibration of Moho appears to have taken place before late Palaeozoic rifting and magmatism initiated the main phase of basin formation that continued into the Mesozoic. The resulting, strong Moho topography, with variation between depths of 26 and 48 km, has been practically "frozen in" since then, although the late Cretaceous – early Cenozoic inversion tectonics may have formed a crustal keel underneath part of the Sorgenfrei-Tornquist Zone which cuts across the Proterozoic crust of the Tornquist Fan region.

Key words: Crust, Mantle, Geophysics, Seismic velocity, Tornquist Fan

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Crustal structure of the Tornquist Fan region around Denmark has been intensively studied by geophysical investigations since the initiation of the European GeoTraverse project in the early eighties. Primarily seismic projects have contributed substantially to the knowledge of the structure of the deep crust and uppermost mantle in the region. Interpretation of the seismic data has benefited from the extensive and well developed databases of other geophysical data, such as gravity and magnetic data. The detailed knowledge of the sedimentary successions in the region from reflection seismic data acquired for hydrocarbon exploration, provides a wealth of information regarding the main tectonic phases and are invaluable for calibration of the deep seismic data.

The Tornquist Fan region occupies the northwestern part of the Trans European Suture Zone (TESZ), which is the area of Palaeozoic amalgamation of the crust and lithosphere of Central Europe onto the Proterozoic Baltic Shield and East European Platform (Pharaoh & TESZ Colleagues 1996, Thybo, Pharaoh & Guterch 1999). The Tornquist Fan proper comprises the area between the Fennoscandian Border Zone and the Trans European Fault and incorporates other fault zones in between (Fig. 1). The Tornquist Fan is a post-collisional feature, which formed as a northwestwards widening splay of faults during late Palaeozoic rifting of the region which also initiated wide-spread basin formation and general subsidence at the southwestern corner of the former Baltica plate (Thybo & Berthelsen 1991, Berthelsen 1992, Thybo 1997, Fig. 1). The area is characterised by pronounced positive Bouguer gravity anomalies in spite of the occurrence of very deep sedimentary successions of more than 10 km thickness (Thybo 1990, Berthelsen 1992, Zhou & Thybo, 1997).

The main geophysical projects in the region of the Tornquist Fan include the deep seismic projects (Fig. 2): FENNOLORA (e.g. Guggisberg, Kaminski, & Prodehl 1991), EUGENO-S (EUGENO-S Working Group 1988), EUGEMI (Aichroth, Prodehl & Thybo 1992), MOBIL Search (Lie & Husebye 1994), BABEL (BABEL Working Group 1993), MONA LISA (MONA LISA Working Group 1997a,b), and Baltic'96 (DEKORP – BASIN Research Group 1998). These projects have provided models of the distribution of seismic velocities and reflective structures in the crust and upper mantle of the region.

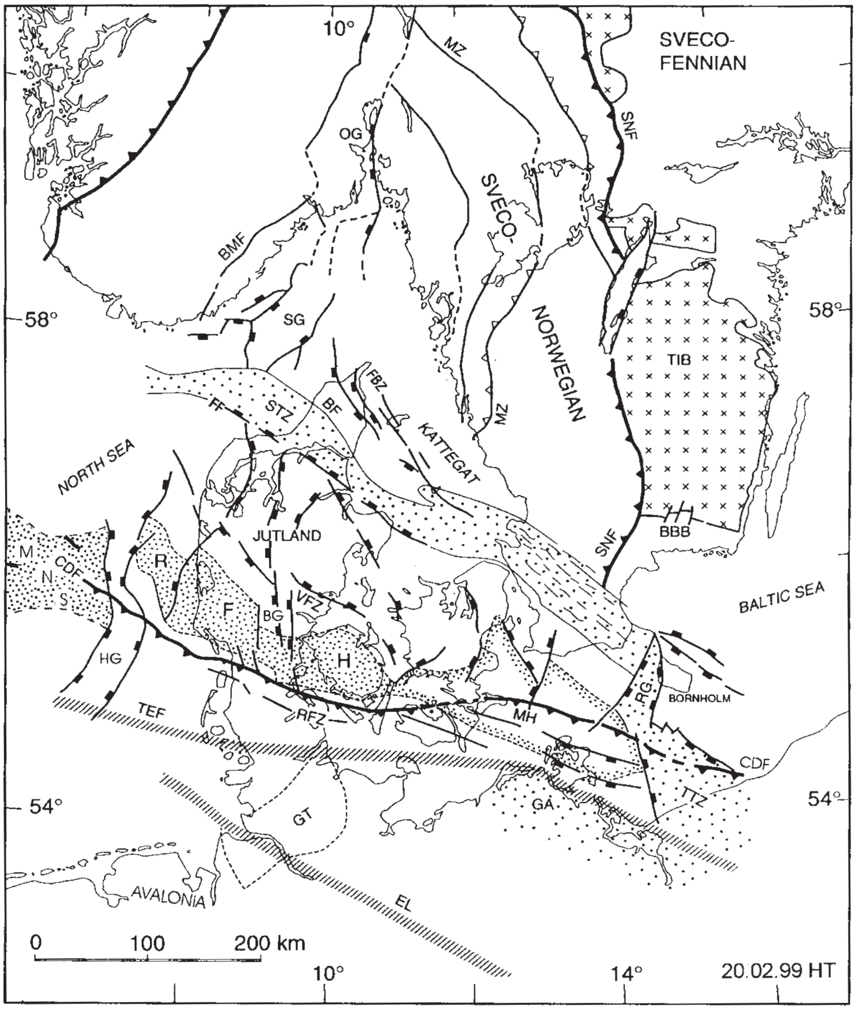


Fig. 1. Map of main tectonic and geological features of the Tornquist Fan region (based on Ziegler 1990 and Berthelsen et al. 1992, after Thybo 1997). The same Lambert projection has been used for all maps in this article; for conformity the same projection as used by the EGT project (Blundell et al. 1992) has been selected. The Tornquist Fan proper comprises the area between the FBZ and the TEF, incorporating other fault zones such as BF, FF, VFZ and RFZ. Abbreviations: 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 – Trans-Scandinavian Igneous Belt, TTZ – Teisseyre-Tornquist Zone, VFZ – Vinding Fault Zone.

This papers reviews some of the main findings from the projects with the primary aim of illustrating the general tectonic evolution of the region. Such analysis of deep structure holds the potential of unravelling primary geodynamic problems.

Main tectonic phases

The Tornquist Fan developed in an area of the southwestern part of the former Baltica plate that was amalgamated mainly during the Proterozoic (Table 1). Radiometric age determinations and stratigraphic relations indicate that the crust belongs to the Sveconorwegian orogen (1050–950 Ma). This orogen consists of largely reworked parts of former units of the Baltic Shield: (1) the Svecofennian orogen (2100–1750 Ma) in the eastern part, (2) the Trans-Scandinavian Igneous Belt (1840–1650 Ma), and (3) the Gothian orogen (1700–1600 Ma) which today is only present in the Bleking-Bornholm Block (Fig. 1; EUGENO-S Working Group 1988, Gorbatchev & Bogdanova 1993). The NS-striking Sveconorwegian Deformation Front is exposed in southern Sweden,

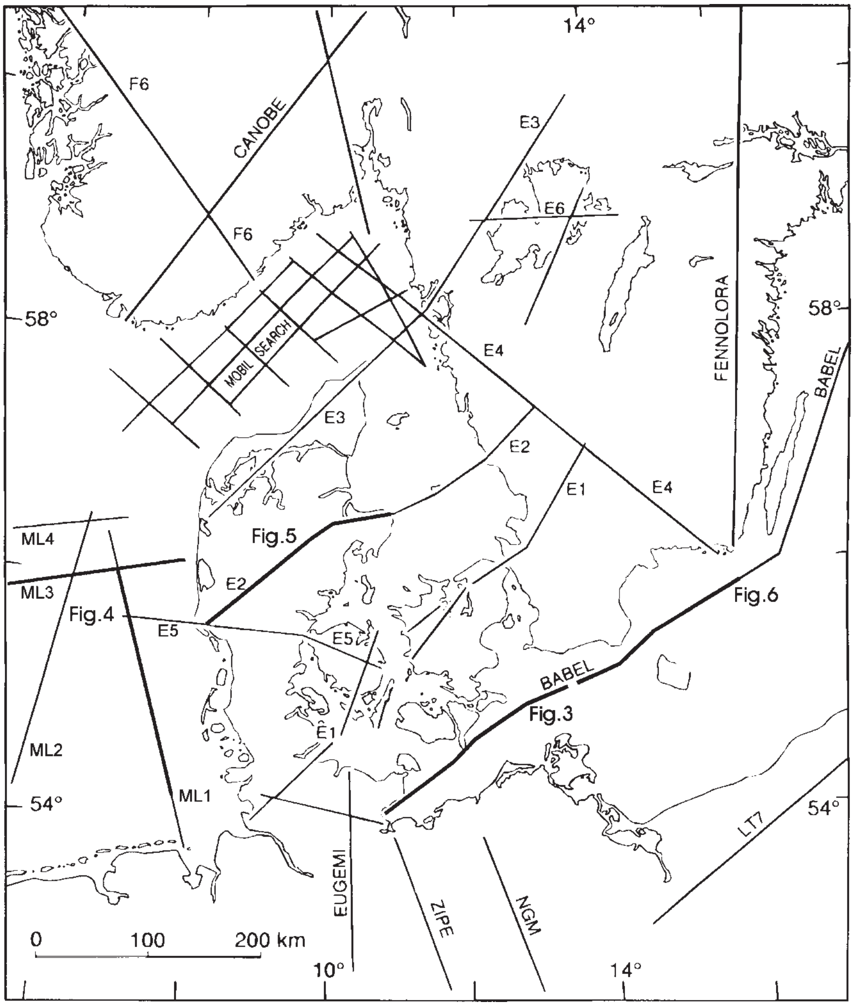


Fig. 2. Coverage of the Tornquist Fan region by deep seismic profiles, including refraction/wide-angle reflection and normal-incidence reflection profiles. A much denser network of commercial seismic profiles (not shown) images the sedimentary succession in parts of the area. For a list of deep surveys, see Thybo (1997). Additional lines are the MONA LISA lines ML1-4 (MONA LISA Working Group, 1997a,b). The highlighted parts of the profiles are illustrated in Figs. 3-6.

but its southward continuation is hidden below the sedimentary basins. The southern Baltic Shield probably was covered by sediments during the Precambrian to Early Palaeozoic (e.g. Berthelsen et al. 1992).

The Phanerozoic geological evolution of the region around the Tornquist Fan has been governed by four major tectonic events: (1) Caledonian collision tectonics, (2) the distant Variscan orogeny, (3) Mesozoic rifting and graben formation, and (4) Late Cretaceous to Early Cenozoic inversion (Ziegler 1990).

1. Caledonian collision tectonics resulted in amalgamation of a micro continent or a series of terranes of Avalonian origin onto the Baltica plate. The suture between Baltica and Avalonia as well as the Caledonian Deformation Front in the study area have been identified from borehole information between the North Sea (Frost, Fitch & Miller 1981) and the Baltic Sea (Katzung et al. 1993). Seismic interpretations (e.g. Thybo 1990, BABEL Working Group 1993, Guterch et al. 1994, MONA LISA Working Group 1997a,b) identify the Caledonian Deformation Front between northwest Poland and the North Sea (Fig. 1). Undeformed lower Palaeozoic sedimentary rocks in parts of the deep basins indicate that a deep foreland basin existed in front of the Polish-Danish-North German Caledonides, but there is only sparse evidence for Silurian volcanism (Berthelsen 1992).

2. Stresses induced by the distant Variscan orogeny probably caused dextral strike-slip movement during the Late Carboniferous and Early Permian. This acti-

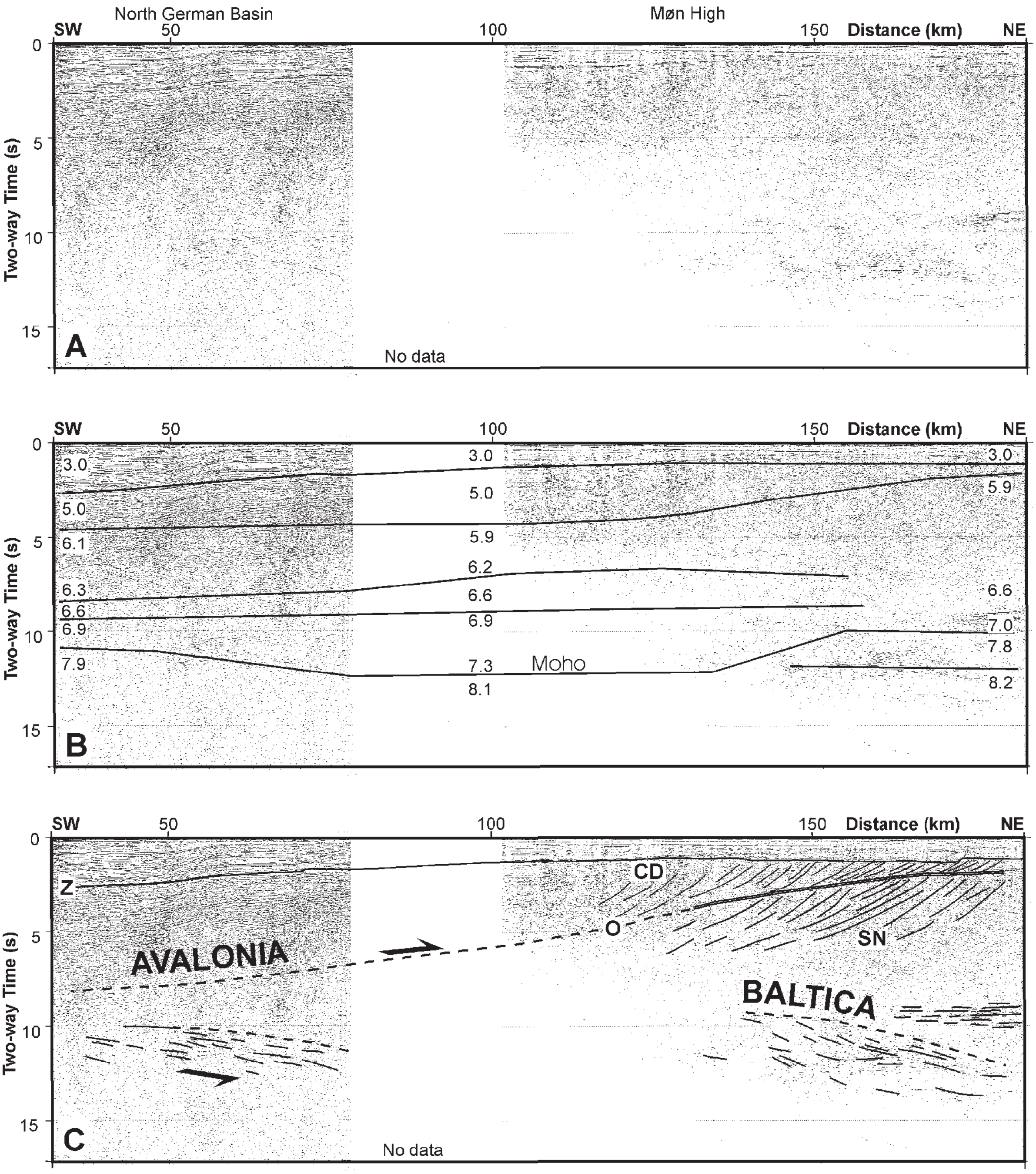


Fig. 3. Part of BABEL profile A in the southern Baltic Sea (location is shown in Fig. 2; data after BABEL Working Group, 1993). This profile crosses the Caledonian Deformation Front and the suture between Avalonia and Baltica. Notice the structural division between the upper sequence of Caledonian deformed Palaeozoic sediments (CD) and the lower sequence of Sveconorwegian deformed crystalline crust (SN). These two entities are separated by the characteristic double reflection from the O-horizon (O). Structures around the Moho indicate northward deformation, which is consistent with "a crocodile type" Caledonian collision. A) Seismic normal-incidence reflection section, B) with seismic velocity model superimposed, C) main reflections and a sketch tectonic interpretation of the collision structures.

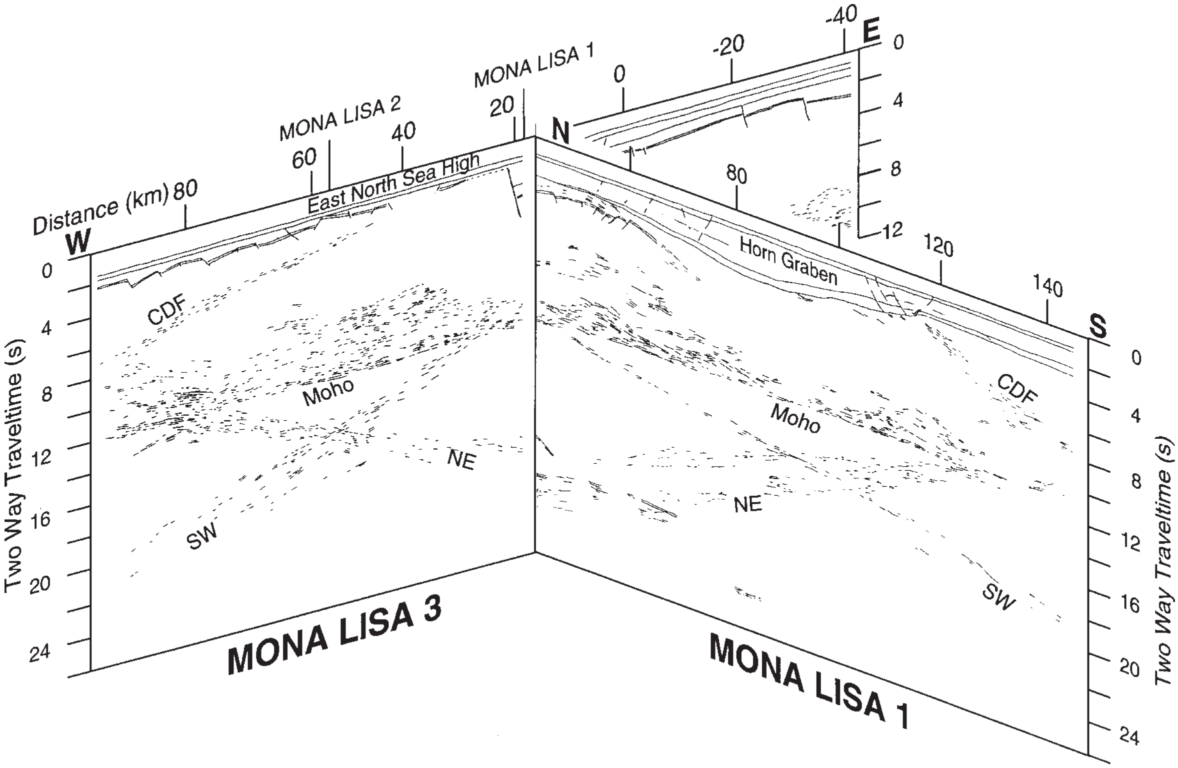


Fig. 4. Line drawings of reflection sections along MONA LISA profiles 1 and 3 in a fence diagram. The two profiles, as well as the other two MONA LISA profiles, show both NE and SW dipping reflections from the upper mantle. The reflections cross in this non-migrated version, but the NE-dipping reflection stays above the SW-dipping reflection after migration, which indicate that the former is oldest. This is consistent with a model of Caledonian, NE-dipping collision structures in the upper mantle associated with the SW-dipping crustal suture. Abbreviation: CDF – Caledonian deformation Front (the crustal suture). After Abramovitz and Thybo (1998).

vated the faults of the Tornquist Fan as links between NNE–SSW trending rift and graben structures, such as the Oslo Rift, the Skagerrak, Rønne, Brande and Horn Grabens, and other possible deeply buried grabens. As such, the Tornquist Fan comprises the following W- to NNW-trending fault zones (Fig. 1): the Trans-European Fault Zone (Berthelsen 1984), which alternatively here will be defined as the southernmost extent of the Precambrian crust of the former Baltica plate (BABEL Working Group 1993); the Rømø and Vinding Fracture zones (Cartwright 1990); the Fjerritslev and Børglum faults which were strongly reactivated during Mesozoic basin development (Surlyk 1980, Michelsen & Nielsen 1993); and the Fennoscandian Border Zone in Kattegat which is the transition from shield proper to basin areas (Liboriussen, Ashton & Thygesen 1987). The Ringkøbing-Fyn High (RFH) formed as a residual structural high between the Rømø and Vinding Fracture zones while a large area around the Tornquist Fan was subject to extensive volcanism and magmatism in a probable transtensional environment (Dixon, Fitton & Frost 1981, Ziegler 1990, Thybo & Schönharting 1991, Neu-mann et al. 1992). A dense swarm of magmatic dykes developed simultaneously in Scania (Bylund 1984). Subsequent cooling may have initiated the Permian and Triassic regional subsidence in the Danish and North German Basins (Sørensen 1986). Lately, it has been suggested that an east-dipping detachment into the upper mantle has governed this late Palaeozoic evolution (Berthelsen 1998).

3. Triassic to Jurassic rifting of the Central, Viking and Horn grabens and normal faulting in the Danish Basin caused by regional extension undoubtedly accelerated the subsidence (Nielsen & Balling 1990, Brink, Dürschner & Trappe 1992).

4. Inversion and transpressional deformation characterise the area during the Late Cretaceous and Early Cenozoic, probably caused by Alpine compressional stresses. The Sorgenfrei-Tornquist Zone (STZ) developed as an inverted zone that cuts across other structures of the Tornquist Fan region. In North Jutland the zone is bounded by the Fjerritslev and Børglum Faults of the Tornquist Fan, suggestive of reactivation of earlier fault zones during inversion. In Poland, the inversion zone developed in a Late Palaeozoic rift zone

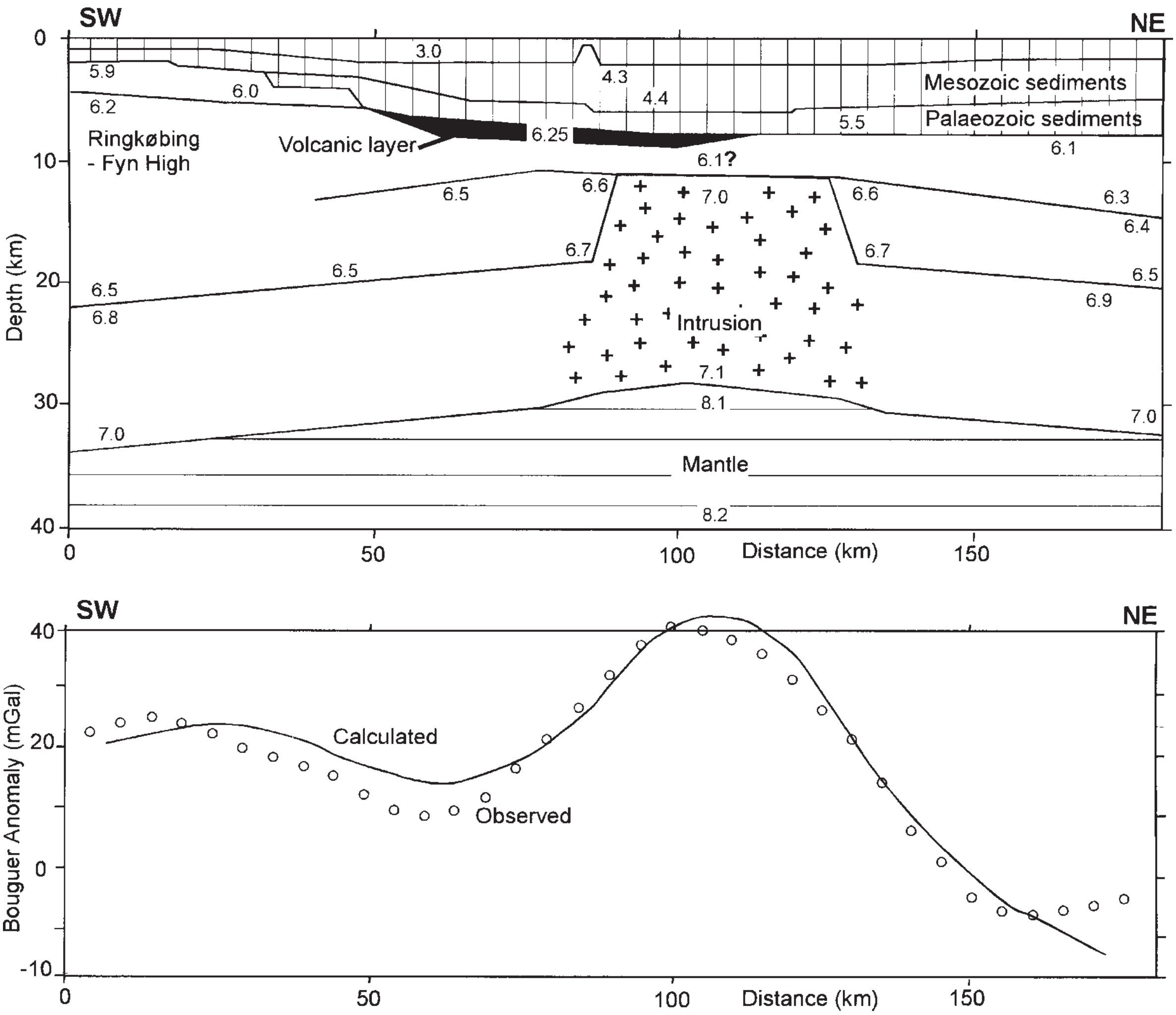


Fig. 5. Crustal model across the Silkeborg Gravity High along EUGENO-S profile 2 (location is shown in Fig. 2) based on integrated interpretation of seismic reflection and deep refraction, gravity and magnetic data (after Thybo & Schönharting, 1991).
A) Model of seismic velocity with main tectonic and magmatic features indicated: interpreted Carboniferous-Permian volcanic body (black) and deep intrusive body (crosses), Mesozoic and Palaeozoic sedimentary successions (vertical ruling), upper mantle (horisontal ruling). Numbers indicate seismic velocity values in km/s. B) Gravity fit of the model; the full curve shows calculated gravity anomalies and the circles show measured values.

(Ziegler 1990) and possibly coincides in parts with the palaeo-margin of the platform (Guterch et al. 1986). The Grimmen Axis forms another short inverted zone (Fig. 1). The geological evolution since the Early Cenozoic is characterised by regional subsidence in the North Sea area and uplift of the Baltic Shield (Ziegler 1990).

Seismic images and models

Sveconorwegian and Caledonian collision, BABEL and MONA LISA profiles

The BABEL seismic reflection profiles image at least three Proterozoic and one Phanerozoic sutures in the Baltic and Bothnian Seas (BABEL Working Group 1990 and 1993). Abramovitz, Berthelsen & Thybo (1997) interpreted a hidden terrane between the Svecofennian and the Gothnian orogens in the southern Baltic Sea, now concealed beneath a cover of sediments. In the southern Baltic Sea, BABEL Working Group (1993) interpreted south dipping reflections from the crust and north dipping reflections at the crust-mantle boundary as images of the Caledonian suture between Baltica and Avalonia (Fig. 3). The image indicates a "crocodile type" of suture where the uppermost crust of Avalonia obducted onto the Baltica craton while the lower crust and mantle subducted below Baltica. Thereby, BABEL Working Group relocated the Caledonian Deformation Front at least 50 km further to the north in the southern Baltic Sea than previously believed.

The collisional structures are conveniently located beneath the Møn Block, which is the eastward extension of the Ringkøbing Fyn High into the Baltic Sea area. Because of only a thin Mesozoic cover, crustal reflectors are well resolved in reflection seismic profiles, even with relatively small airgun arrays. This allows interpretation of crustal structures from commercial seismic profiles, originally acquired for oil and gas exploration. Lassen (1998) and Lassen, Thybo, & Berthelsen (submitted) present interpretations of such data that clearly identify two sets of dipping reflections, one south dipping set from the Palaeozoic sedimentary sequence and another, primarily west dipping from the crystalline crust. The two sets of dipping reflections are divided by a strong regional marker, the O-reflection, from the reflector between Ordovician shales and Cambrian quartzites. The direction of the BABEL profile is at an angle of ~45° to the two sets of dipping reflections, such that they both appear to be southwest dipping in the direction of the seismic profile. Therefore, only identification of the O-reflection and the apparent change in dip across this reflector may reveal the structural division of the two sets of reflections in the BABEL profile.

The original interpretation by BABEL Working Group (1993) must therefore be refined, such that only the upper set of dipping reflections is of Caledonian origin, and the lower set is from the crystalline crust, most likely from thrusts and shear zones of the Sveconorwegian orogen, which thereby has been traced further south than the Sorgenfrei-Tornquist Zone (Fig. 3). This observation indicates that the Caledonian crustal suture at depth extends further south than earlier interpreted by BABEL Working Group (1993), at lower crustal depths perhaps as far as to the Elbe Lineament. The northeast dipping reflections from depths around the Moho were interpreted by BABEL Working Group (1993) as images of subduction structures of the Caledonian orogeny.

This interpretation is also consistent with later data from the North Sea (MONA LISA Working Group 1997 a,b, Abramovitz, Thybo & MONA LISA Working Group 1998), where similar structural relations have been imaged, although both northward and southward dipping reflections from the uppermost mantle are observed (Fig. 4). The two events may be correlated with westward resp. eastward dipping events in the EW striking profiles, indicative of NE- and SW-dipping mantle reflectors. The crustal suture of Caledonian age has been interpreted from a crust cutting,

Table 1. Main tectonic events in the region of the Tornquist Fan.

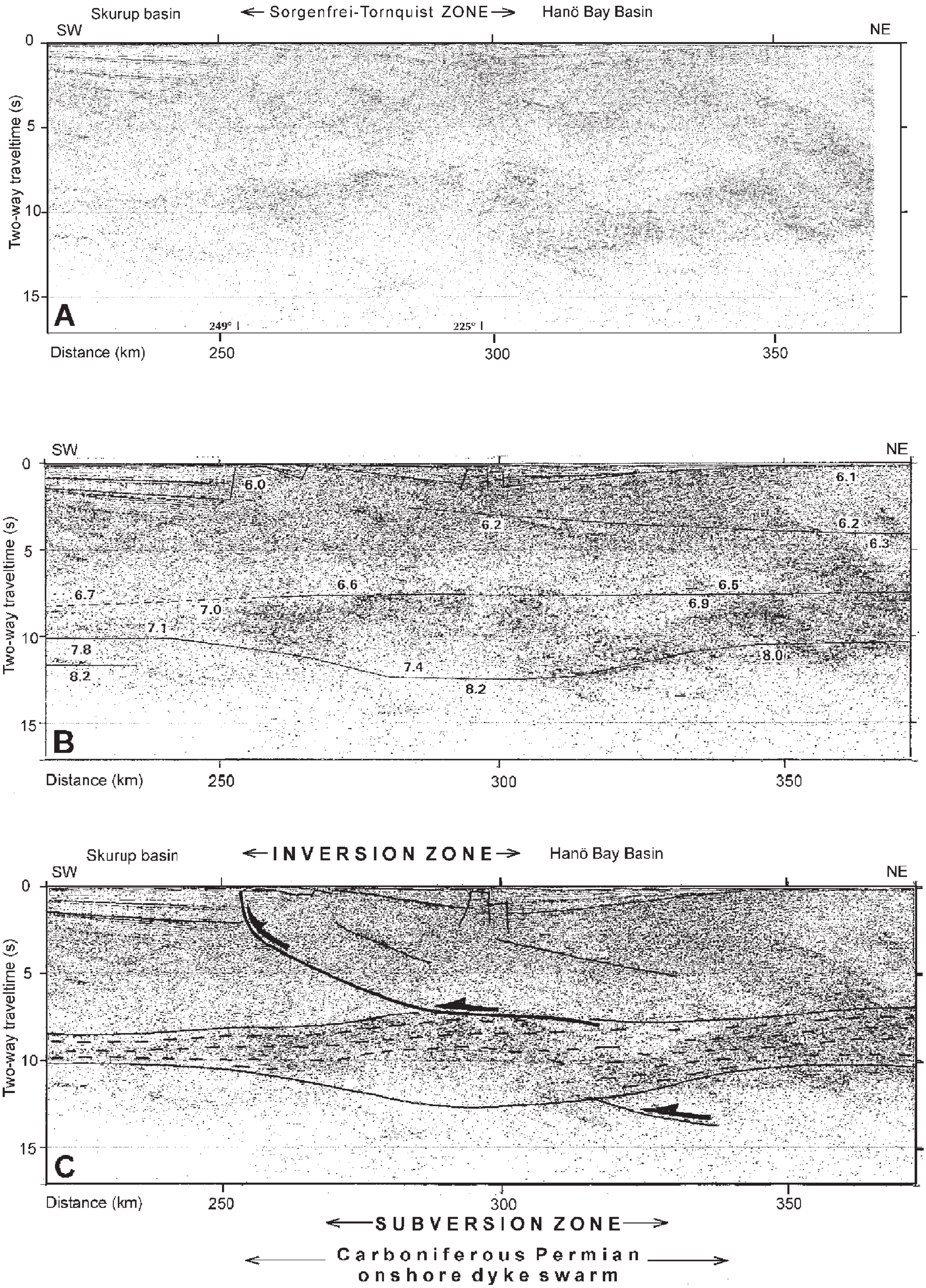
Event	Age	Effect
Svecofennian orogeny	~1.9 Ga	Bulk part of Baltica crust forms
Gothian orogeny	~1.6 Ga	Plate accretion (only marginal parts remain undisturbed)
Jothnian	~1.3 Ga	Basin formation
Sveconorwegian orogeny	~900 Ga	Formation and deformation of the basement of most of the Tornquist Fan area
Vendian Rifting	~750 Ma	Rifting and basin formation
Caledonian orogeny	~450 Ma	Formation of southern basement and foreland basin
Late Variscan orogeny	~250 Ma	Rifting and volcanism, formation of the faults of the Tornquist Fan
Mesozoic subsidence	<~220 Ma	Basin formation
Africa-Europe collision	~65 Ma	Inversion (Late Cretaceous-Early Cenozoic)

SW-dipping reflection (Abramovitz and Thybo 1999). Migration of the mantle events shows that the NE-dipping reflector is confined to the zone above the SW-dipping mantle reflector. The former reflector must therefore be oldest, which indicate that it represent a Caledonian structure such that the SW-dipping event should be related to a later tectonic event, such as late Palaeozoic extension.

A series of profiles of the Baltic' 96 experiment only shows north dipping reflections from Moho level in the Baltic Sea area. Hence, northward subduction or shearing in the uppermost mantle is indicated by the available information between the North Sea and the Baltic Sea. It may appear enigmatic that magmatic rocks, which may be related to Caledonian subduction, generally are not identified in the Baltic Shield. However, this may be explained by either a polarity flip in subduction direction during the late phases of collision, cf. results of numerical modelling of collision tectonics (Beaumont, Fullsack & Hamilton 1994), or it might be because the subduction zone had a very shallow dip, such that no or only small amounts of melts were produced from the subducting slab.

Late Carboniferous – Early Permian transtension, EUGENO-S profile 2

One of the major features of the gravity field in the Danish area is the Silkeborg Gravity High, a positive


Skurup basin
Sorgenfrei-Tornquist ZONE
Hanö Bay Basin
SW
NE
Two-way traveltime (s)
A
249°
225°
Distance (km)
B
6.0
6.1
6.2
6.2
6.3
6.6
6.5
6.7
7.0
6.9
7.1
7.8
8.2
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8.2
8.0
C
INVERSION ZONE
SUBVERSION ZONE
Carboniferous Permian
onshore dyke swarm

Bouguer anomaly of 40-50 mGal compared to the surrounding gravity level (cf. Fig. 8). Thybo & Schönharting (1991) present an integrated interpretation of gravity and magnetic data with seismic data from EUGENO-S profile 2, which crosses the gravity high at an oblique angle (Fig. 5). The integrated model explains the gravity high by a batholith in the crust below ca. 11 km depth. The body is characterised by high seismic velocity and density. It probably extends to the crust-mantle boundary. Moho is slightly elevated beneath the body, which further contributes to the gravity anomaly. A thin layer of volcanic or subvolcanic origin may explain the main magnetic anomalies and residual gravity anomalies in the area. It also explains some weak, but clear, first seismic arrivals from a shot point at the northern end of the profile. These arrivals are up-to .5 s earlier than the main seismic phases from the crystalline crust.

The structural trend of the feature has been estimated by stripping off the gravity effects of the Mesozoic sediments from the Bouguer anomalies in the Danish area. The processed gravity anomalies indicate that the body extends along the northern edge of the eastern Ringkøbing-Fyn High with a northward bend toward the Skagerrak from mid-western Jutland (Thybo & Schönharting 1991, Zhou & Thybo 1997). This trend is also supported by a contoured map of depth to Moho (Fig. 7a). The southern side of the body coincides with the Vinding Fault zone, as inferred from magnetic anomalies and seismic interpretation (Dikkers 1977, Cartwright 1990). Magnetic modelling shows that the interpreted shallow volcanic sequence has reverse polarity, which may be correlated with a long polarity reversal in the Early Permian. The SSE-NNW elongated feature is, therefore, interpreted as a batholith that intruded into the crust during the late Carboniferous – early Permian because of transtensional, strike-slip movement on the Vinding Fault zone of the Tornquist Fan.

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Figure 6. Part of BABEL profile A across the Sorgenfrei-Tornquist Zone due north and west of Bornholm in the Baltic Sea Seismic normal-incidence reflection section (A), with seismic velocity model superimposed (B), and with a sketch tectonic interpretation of the inversion and subversion structures (C). The inversion feature near the surface is interpreted as caused by transpressional displacement on a listric fault which terminates downward in the top of the reflective lower crust. Simultaneously, the lower crust was subdued by "subversion" such that a deep crustal keel developed. This keel may balance the weight of the surficial inversion structure, such that isostatic balance is maintained. However, the possibility cannot be completely ruled out that the lower crustal keel was caused by "underplating", i.e. by magmatic crystallization at the Moho during Carboniferous-Permian volcanic activity.

The Sorgenfrei-Tornquist Zone, BABEL profile A

The Sorgenfrei-Tornquist Zone is defined as the geological inversion zone that extends in the Tornquist Fan region between Bornholm in the southeast and the North Sea in the northwest (EUGENO-S Working Group 1988). The Tornquist Zone was originally identified from a magnetic lineament which appears as the northwestern continuation into Scania of an anomaly in the area of Poland, although it cannot be continued further into Kattegat. Modelling indicates that the magnetic anomaly is caused by the edge of the Proterozoic platform in Poland (Krolikowski & Petecki 1998), whereas it is most likely caused by the Permian volcanic dykes in Scania. Hence, the magnetic anomalies in Scania probably are not generically connected to neither the anomalies in Poland nor the inversion zone.

BABEL profile A crosses the Sorgenfrei-Tornquist Zone northwest of Bornholm (Fig. 2, BABEL Working Group 1991 and 1993, Thybo et al. 1994), where the inversion is strongly developed (Fig. 6). The two main features of the reflection seismic profile are the inverted block of crystalline rocks near the surface and the crustal keel, imaged as a subdued Moho. The interpretation is based on integrated interpretation of reflection and refraction data, such that both reflection structures and seismic velocities are known along the profile. Therefore, the 7–10 km deep crustal keel has been reliably constrained by the data.

The reflection seismic profile images the Sorgenfrei-Tornquist Zone as a "pop-up" structure of crystalline basement around Bornholm between two sedimentary basins, the Hanö and Skurup basins of possible Carboniferous-Permian or older age (Fig. 6). Both basins thickens towards the inversion zone, giving the impression that they once formed a single wide basin that was split into two by the inversion tectonic event. A pronounced intra-crustal reflection dips to the northeast from the southwestern boundary fault of the "pop-up" structure and sole as a listric fault in the top of the reflective lower crust. This has been interpreted as a main transpressional fault that accommodated the main compressional displacement that caused the inversion (Thybo et al. 1994). During basin formation it may have been a normal fault, which subsequently was reversely reactivated by the inversion tectonics. The reflective lower crust may have been a ductile layer during inversion such that it could act as a decollement for the displacement.

The crustal keel beneath the inversion zone extends slightly to the northeast of the zone, perpendicular to the strike direction. The reflective lower crust extends across the inversion zone with relatively constant thickness, whereas the keel appears non-reflective. BABEL Working Group (1993) interpreted the keel as a *subversion zone*, i.e. as the lower counterpart of the *inversion zone*, such that the compression at lower

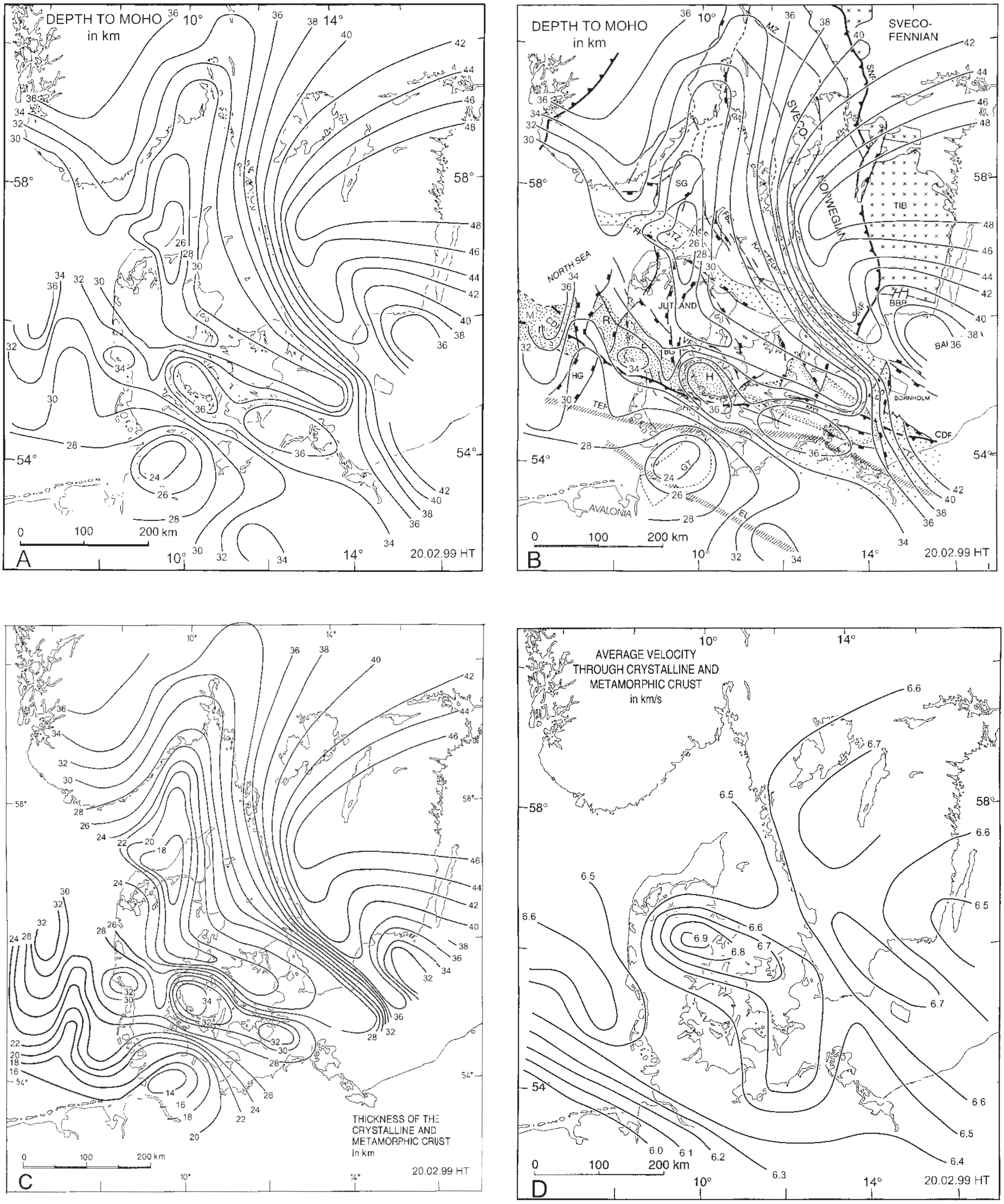

Fig. 7. Maps of seismic features of the crust in the Tornquist Fan region. (A) Depth to the Moho discontinuity in km; (B) Contours of Moho depth superimposed onto the map of main tectonic features; (C) Map of thickness in km of the crystalline and metamorphic crust, i.e. the consolidated crust without sediments; (D) Average velocity through the crystalline and metamorphic crust in km/s.

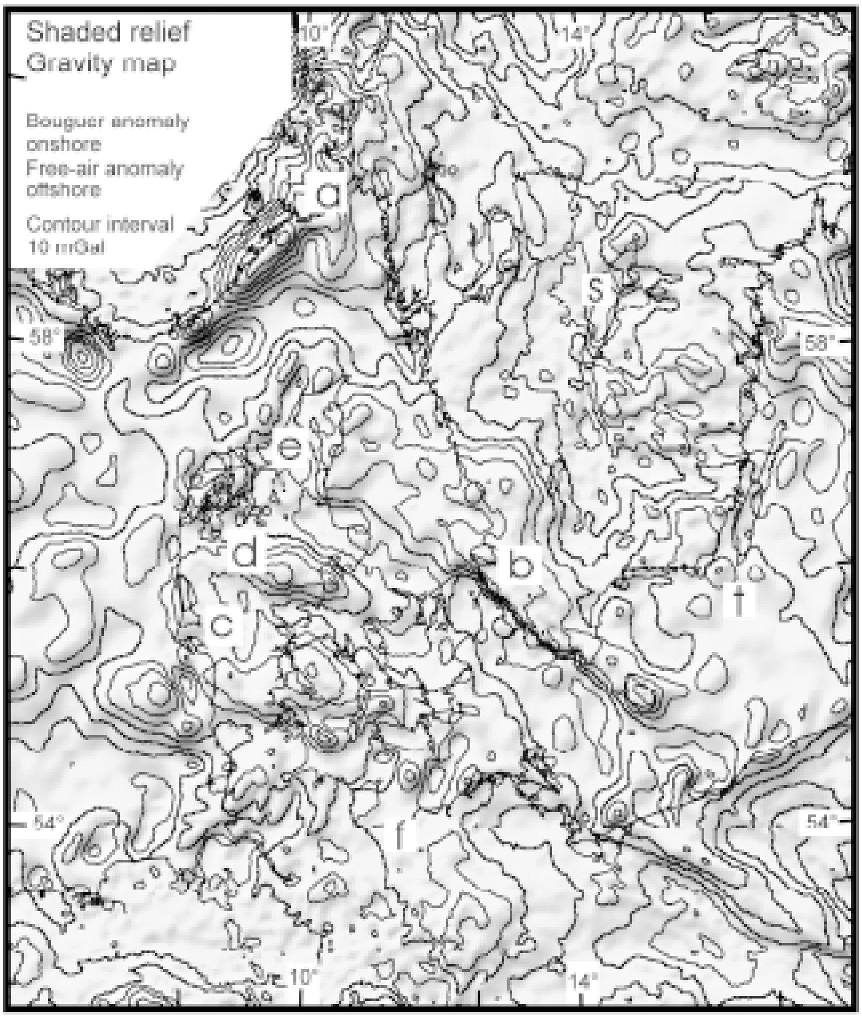

Fig. 8. Shaded relief, Bouguer gravity anomaly map. The gravity topography has been illuminated from the north to enhance lineaments in the data; this also identifies gravity highs and lows. Contour interval is 10 mGal (data from Wybranic et al., 1998). Letters refer to anomalies discussed further in the text: a-d: positive gravity at the Oslo Graben, the Scanian dyke swarm, the Ringkøbing-Fyn High, and the Silkeborg gravity High; e-f: negative gravity along the axis of the Danish Basin and in the North German Basin; s – lineament along the Sveconorwegian Front; t – positive gravity at a hidden Svecofennian terrane and the Bleking-Bornholm Block.

crustal level was accommodated by formation of this deep crustal depression. The keel of low velocity and density may balance the weight of the crustal column beneath the elevated basement, such that isostatic balance is retained. This interpretation is in agreement with Thybo et al. (1994) who, however, also point out that the keel may instead originate from "underplating", i.e. from magma that solidified at the base of the crust during the Late Carboniferous to Early Permian magmatic event. The keel coincides laterally equally well as the inversion zone with the suite of volcanic dykes in the area and a magmatic origin cannot be ruled out (Fig. 6). However, the lower part of the keel appears reflection free, which cannot easily be explained by magmatic sills or a magma chamber that has solidified at the base of the crust. A similar keel also has been interpreted further to the northwest (Thybo 1990) and in Poland (Guterch et al. 1986, Guterch et al. 1999), where the Carboniferous-Permian volcanism was wide-spread and no localized dyke swarm has been identified above the crustal keel. Unless such a swarm be identified, the crustal keel must most likely be regarded as associated with inversion-subversion tectonics.

Other geophysical data and evidence

Moho depth and average seismic velocity of the crystalline crust

Moho depth in the Tornquist Fan region shows strong undulation which correlates with main tectonic features of the area (Fig. 7a-b). The Moho is defined as the depth at which the seismic velocity exceeds 7.8 km/s, although originally defined from strong reflections in earthquake seismograms. This level is often assumed to correspond to the crust-mantle boundary, but recent research has shown that this is not always the case (Griffin & O'Reilly 1987, Mengel & Kern 1992). The sub-Moho velocity is generally 8.0 km/s in the basin areas and significantly higher (>8.2 km/s) beneath the Baltic Shield and the Ringkøbing-Fyn High. Abramovitz et al. (1998) interpreted occurrences of crustal type rocks in eclogite facies from relatively small sub-Moho velocities due north of the north-dipping mantle feature at the Caledonian suture in the North Sea, similar to velocities to the north of the Caledonian suture in the BABEL profile (Fig. 3).

Moho depth is as large as 48 km in parts of the Baltic Shield and up-to 36 km beneath the Ringkøbing-Fyn High, whereas it is as small as 24–26 km beneath the basin areas where the Mesozoic sedimentary successions are thickest (Fig. 7b). The thickest crust appears to be related to the Svecofennian part of the shield, although the crust is also thick along the trend of the Sorgenfrei-Tornquist Zone and the Permian dykes in Scania.

There is a pronounced southward trend of thin crust from the Oslo Rift – Skagerrak Graben to central Jutland, from where a southeastward trend parallels the Vinding Fracture Zone at the northern edge of the Ringkøbing – Fyn High. Very thin crust is also associated with the Glückstadt Graben in North Germany of Mesozoic age but only slight crustal thinning is associated with the graben structures that dissect the Ringkøbing-Fyn High. However, removing also the thickness of the sedimentary successions from the crustal thicknesses, the map of thickness of the crystalline and metamorphic basement also shows pronounced thinning beneath the grabens (Fig. 7c). The crystalline and metamorphic crust is in places as thin as 16 km, such that its thickness varies by a factor of three in the south Scandinavian area.

Thybo, Perchuc & Gregersen (1998) analyse the seismic reflectivity from Moho in the Tornquist Fan region. They find a pronounced difference between areas with thick basins and areas of the shield and the basement high. Beneath the Norwegian-Danish basin, the reflections from Moho are distinctly “ringing”, i.e. showing long reverberative reflectivity immediately after the onset of the interpreted reflection from Moho. This is modelled by a series of strongly reflective layers which is interpreted as mafic layering at the base of the crust. The authors argue that underplating associated with the formation of the basins is indicated. Contrary, the waveform of Moho reflections from the Baltic Shield and the Ringkøbing-Fyn High has very short duration, indicative of a sharp Moho transition of less than 2 km thickness.

The map of average seismic velocity through the crystalline crust (Fig. 7d) shows two trends which are similar to the Moho map: One trend coincides with the shallow Moho at the Silkeborg gravity anomaly and another trend coincides with the thick crust along the volcanic dyke swarm and the Sorgenfrei-Tornquist Zone in Scania. Both trends are also associated with positive gravity anomalies (Fig. 8), which shows that rocks of high density must be present in both places. These anomalies are most likely caused by crustal, mafic plutonic bodies of Carboniferous-Permian age, as also supported by gravity and magnetic modelling.

These features and their structural trends have been integrated into a model of the Carboniferous-Permian tectono-magmatic evolution of the Tornquist Fan region, which originally formed a marginal part of the palaeo Baltica plate (Thybo 1997). Because the area was situated at the northwestern end of the long Central European Tornquist Zone between present-day Black Sea and North Sea, Variscan tectonics induced right lateral displacement that caused distributed lateral displacement across the faults of the Tornquist Fan. The NS-trending grabens across the Ringkøbing-Fyn High, the Skagerrak Graben and the Oslo Rift may be understood as extensional grabens and rift structures that formed because of the displacement. Only a fraction of the total displacement on the Central European Tornquist Zone was released across each of the several individual fault zones. Strong influence of a mantle plume in the area cannot be ruled out, but may not be necessary to explain the geophysical observations in the area. Based on the available geophysical-geological data and interpretations between southern Poland and the North Sea, Berthelsen (1998) proposes a new tectonic model of the Carboniferous-Permian volcanism and rifting of the area. The model involves lithospheric buckling because of compression from the Variscan orogens, and east-dipping listric faults at the main basin boundaries which extends into the mantle. Future research will focus on the nature of the faults of the Tornquist Fan.

Gravity anomalies

The map of gravity anomalies (Fig. 8) is based on a new database, which recently was constructed by a European working group as part of the EUROPROBE project on studies of the Trans European Suture Zone (Wybraniec et al. 1998). It shows the Bouguer anomaly onshore, and the free-air anomaly offshore. The map demonstrates that gravity anomalies are large in the Tornquist Fan region and smaller in the shield area. Mantle densities are expected to be comparable to other areas because of “normal” sub-Moho seismic velocities. Therefore, an explanation of the high gravity level requires high densities within the crust, at least locally, which further support the interpretation of extensive mafic intrusions. The structural trends of the high gravity anomalies coincide with the trends derived from seismic information along the interpreted mafic bodies and the Ringkøbing-Fyn High. The three largest anomalies in the area are at the Oslo Rift – Skagerrak Graben, the volcanic dyke swarm in Scania, and the Silkeborg Gravity High, even though some of these anomalies are in areas of thick Mesozoic sedimentary cover.

Palaeozoic sediments in the North Sea

The extensive acquisition of geophysical data in the North Sea area has also facilitated studies of deep sediment occurrences in more detail than is usually possible for geophysical studies. Such studies have been concentrated around the Ringkøbing-Fyn High which was previously understood as a structural basement high where crystalline rocks were assumed to be closely underlying a thin Mesozoic sequence (EUGENO-S Working Group 1988). Also basin areas show occurrences of pre-Zechstein sedimentary rocks of up-to 5 km thickness, although details cannot be resolved because of decreasing resolution with depth (Thybo 1990). Most commercial reflection seismic sections show coherent seismic energy below the "acoustic basement" which is often considered as the top pre-Zechstein stratigraphical level. Below this level, it is difficult to distinguish the useful reflections from the ambient noise, because they are weak compared to waves that were multiply reflected in the shallow sequences and to the general background noise level.

Geophysical information about these intervals are mainly from refraction seismic, magnetic and gravity data. In an interpretation of the gravity and magnetic fields integrated with commercial reflection seismic profiles, Zhou & Thybo (1997) concluded that there are substantial occurrences of 2-6 km thickness of pre-Zechstein sedimentary rocks throughout the Danish North Sea area. The study involved stripping off the gravity effect of the Mesozoic sedimentary sequences from the Bouguer anomaly in order to focus on the deep sequences. Depth determination based on spectral analyses of the magnetic field was also applied. Abramovitz & Thybo (1998) and Nielsen, Klinkby & Balling (1998) interpret similar occurrences of 2-4 km of Palaeozoic sediments below some of the MONA LISA seismic lines in the North Sea, even beneath the Central and Horn Grabens. Some of these occurrences may have been deposited in the Caledonian foredeep basin. However, they occur on both sides of the Caledonian Deformation Front (CDF) (e.g. Vejbæk 1989 and 1997), which indicates later subsidence during the Palaeozoic. If these pre-Zechstein sediments were deposited exclusively in the foredeep basin, Caledonian thrusting should have developed far into the foredeep of the orogen itself without affecting the deeper crystalline basement. The MONA LISA deep seismic reflection profiles (Fig. 5) all show crust cutting dipping reflections which are interpreted as images of the Avalonia-Baltica suture (MONA LISA Working Group 1997a,b).

Concluding remarks

The deep structure of the crust and uppermost mantle in the Tornquist Fan region has been the subject of intensive geophysical-tectonic interpretation over the last 15 years. New data acquisition has mainly applied seismic methods, both refraction and deep seismic reflection methods. The two methods have been integrated wherever practically and economically possible. This new data has added substantially to our knowledge of the deep tectonic structure of the region and of the types of rocks that are present. Interpretation of the data has proven particularly successful where the seismic data has been integrated with other types of geophysical data, such as gravity and magnetic data.

Interpretation of the new data has made it possible to identify structures that were caused by the main tectonic events in the area. Nevertheless, several problems remain for future research on the tectonic evolution of the crust and mantle in the area. At the present stage of interpretation we may make the following conclusions which also lead to several new questions to be addressed by future research projects:

1. A crustal keel has been identified around the Tornquist Zone between southern Poland and Kattegat? Is it a feature related to subversion, underplating or localized metamorphism?
2. Widespread tectono-magmatic events took place in the Carboniferous-Permian. The rifting processes and subsequent cooling may have initiated the Mesozoic subsidence of the basin areas. What is the relative importance of Variscan induced deformation versus a possible mantle plume in the region? Are the bounding faults of the basins listric and do they merge in a major mantle reaching east-dipping fault? To which degree may thermal subsidence after the magmatic heating explain the subsequent subsidence?
3. Geophysical research has identified significant occurrences of Palaeozoic sedimentary sequences of up-to 5–6 km thickness over much of the Tornquist Fan region. Is it possible to distinguish sedimentary rocks deposited in the Caledonian foredeep from those deposited during later subsidence? How far north and east may Caledonian deformation be traced in the sedimentary sequences? May the Palaeozoic strata be hydrocarbon bearing?
4. The Caledonian collision structures indicate crust-penetrating, relatively steep sutures near to the deformation front; but may there be other similar faults further south, or does the main boundary fault extend far southward to e.g. the Elbe lineament such that Baltica crust today forms the lower crust underneath northern Germany? Did Avalonia dock onto Baltica as a single micro continent or as separate terranes? Were the collisional faults reactivated during subsequent basin formation?
5. The crust still shows structure that may be related to the Proterozoic orogens of more than 900 Ma age. Have such structures been reactivated in later collisional and extensional events? How may such structure have survived later tectonic events, that apparently have affected most of the area?

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Dansk sammendrag

I de seneste 15 år har der været intensiv aktivitet omkring geofysisk-tektonisk tolkning af strukturer i skorpen og den øverste kappe i det danske område. En række tektoniske begivenheder har præget områdets geologiske udvikling: (1) Den svekonorvegiske orogenese, hvorunder store dele af det krystalline grundfjeld blev foldet, (2) Den kaledoniske orogenese, hvorunder de sydlige skorpeområder (omfatter bl.a. det sydlige Danmark og det nordlige Tyskland) blev samlet med de øvrige områder, (3) Dannelse af riftstrukturer og intensiv magmatisk aktivitet i et stort område omkring Danmark i sen Karbon til tidlig Perm, (4) Generel indsynkning gennem det meste af Mesozoikum, med enkelte strækningsbegivenheder, som accelererede den generelle indsynkning, og (5) Den sen kretassiske til cenozoiske inversion i Sorgenfrei-Tornquist Zonen.

Med navnet "Tornquist Fan" menes en vifteformet del af det danske område, som er gennemsat af et sæt af sen karbone til tidlig permiske forkastningszoner i en vifteform med udspring i det polske område. Der argumenteres for, at horisontale bevægelser hen over disse forkastningszoner har haft afgørende betydning for dannelsen af sen-palæozoiske grabenstrukturer i området og for den samtidige, kraftige magmatisk-vulkanske aktivitet.

Det analyserede datamateriale omfatter primært seismiske data, der er blevet indsamlet i forbindelse med en række af dybseismiske projekter i området. Der har været intensiv dansk deltagelse i de fleste af projekterne: FENNOLORA projektet langs en profillinie fra Nordkap til Polen i 1979, EUGENO-S projektet hen over det danske område i 1984, det centrale EGT profil fra Nordtyskland til Italien i 1986, MOBIL Search projektet i Skagerrak i 1997, BABEL projektet i Østersøen i 1989, LT-7 profilet i Polen i 1990, MONA LISA projektet i den sydøstlige Nordsø i 1993 og 1995, og Basin'96 i Østersøen 1996. Projekterne har så vidt teknisk og økonomisk muligt været gennemført som integrerede refleksions- og refraktions-/ vid-vinkel refleksions-seismiske projekter, således at vi i dag har betydelig viden om dybe strukturer og fordelingen af seismiske hastigheder til 80 km dybde i det behandlede område.

De seismiske profiler viser strukturer, der kan relateres til alle de ovennævnte tektoniske begivenheder. Der præsenteres eksempler, som omfatter dykkende seismiske refleksioner, der kan relateres til svekonorvegisk og kaledonisk deformation i grundfjeld og sedimenter samt antyder nordhældende deformationsstrukturer ned i øvre kappe af kaledonisk alder; magmatisk intrusion i skorpen af sandsynlig Karbon-Perm alder som kan relateres til dybe forkastninger i Tornquist Fan systemet; og dybe strukturer omkring Sorgenfrei-Tornquist inversionszonen, som antyder at deformationen skete over listriske forkastninger med et decollement i nedre skorpe.

Tolkede dybder til Moho viser en kraftigt ondulerende topografi i dybder mellem 26 og 48 km. Moho er defineret som en seismisk laggrænse, som ofte antages at befinde sig nær overgangen mellem skorpe og kappe. Topografien kan ikke umiddelbart relateres til de orogene strukturer, hvilket antyder at der er sket en udjævning af skorpe-kappe overgangen inden de sen-palæozoiske tektoniske begivenheder, hvorunder strækning og "underplating processer" synes at have forårsaget hovedparten af den observerede topografi. Den kretasisk-cenozoiske inversionstektonik kan dog muligvis have forårsaget skorpefortykkelse omkring inversionszonen. I et bælte omkring inversionszonen mellem Kattegat og det sydlige Polen finder man en dyb "Moho-køl" til 44–55 km dybde. Denne kraftige fortykkelse af skorpen kan derfor tilskrives "subversionprocesser", hvorunder den nedre skorpe er blevet presset ned i kappen i forbindelse med, at den øvre skorpe er blevet skubbet opad langs de listriske forkastninger. En anden mulighed er dog, at skorpe-kølen skyldes magmatisk "underplating", hvorved magmatiske smelter er størknet ved bunden af skorpen. Den sidste mulighed synes sandsynlig i området omkring Bornholm og Skåne, hvor der findes en sværm af vulkanske gange, hvorimod noget tilsvarende hidtil ikke er observeret under det tykke sedimentære dække i Polen.

Tolkningen af de seismiske data viser strukturer i det danske område, der kan relateres til de kendte tektono-magmatiske begivenheder, der er foregået siden den Svekonorvegiske Orogenese for næsten 1000 millioner år siden. Det er stadig en gåde hvordan sådanne strukturer har kunnet overleve de kraftige omdannelser, der er sket siden de oprindeligt blev dannede.

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