Upper Triassic – Cretaceous stratigraphy and structural inversion offshore SW Bornholm, Tornquist Zone, Denmark

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Geological interpretations by various authors of exploration reflection seismic data offshore SW Bornholm show good agreement for the Rønne Graben. However, major differences exist regarding the Mesozoic stratigraphy and structural development of the Arnager-Darlowo Block and the Risebæk Graben. Major problems relate to the distribution and structural position of the Jurassic, and interpretation of inversion structures in the Rønne and Kolobrzeg grabens along the Arnager Block. In addition to the Pernille-1 and Stina-1 wells that document the stratigraphy of the Rønne and Kolobrzeg graben sections, the bedrock geology along the south coast of Bornholm is discussed. The Jurassic is established as a major constituent of the Arnager Block above the Risebæk Graben, in contrast to previous interpretations. The revised stratigraphy and reinterpretation of the inversion zones help to establish a new interval of basin inversion during the Jurassic – Early Cretaceous prior to the Late Cretaceous inversion. Analysis of the Late Cretaceous inversion across the Rønne Graben supports the proposed revision of the stratigraphy and leads to a new model. Previous interpretations invoked a major uplift of the graben along a reverse fault at the eastern border of the Rønne Graben. In the new model, Late Cretaceous inversion across the Rønne Graben is associated with tilting of the graben during differential subsidence/uplift of the Skurup Platform and the Arnager Block, whereas reverse faulting was limited.

Keywords: Inversion, Tornquist Zone, Rønne Graben, Arnager Block, Bornholm.

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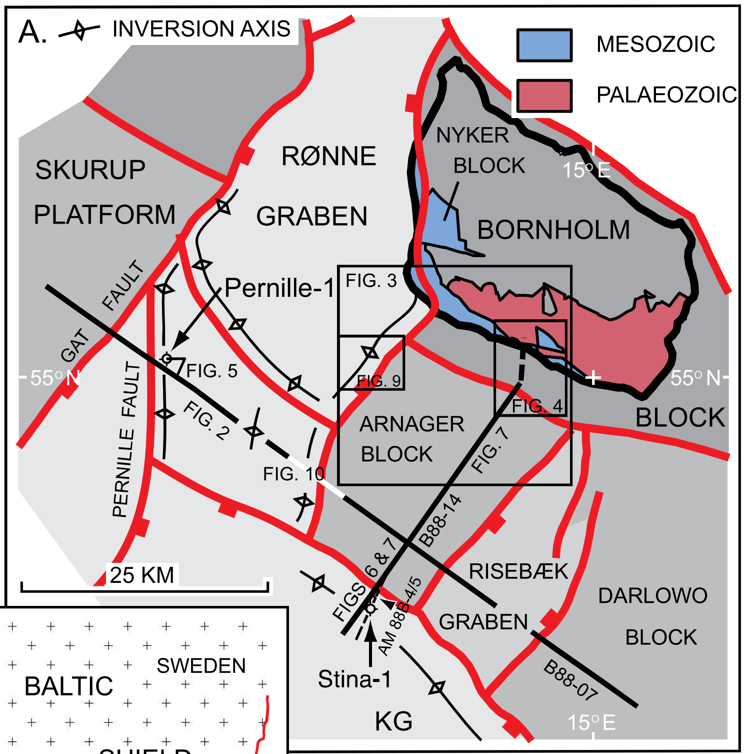
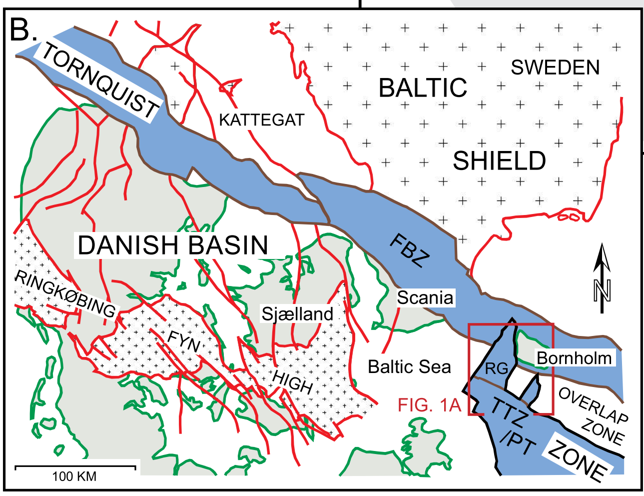
The Bornholm horst block together with surrounding fault blocks and grabens form a complex mosaic in the southern Baltic Sea (Fig. 1A; Vejbæk *et al*. 1994). This area forms an integral part of the NW–SE trending Tornquist Zone at the transition between the Fennoscandian Border Zone (Sorgenfrei & Buch 1964) to the northwest and the Teisseyre-Tornquist Zone (EUGENO-S 1988) to the southeast (Fig. 1B). The two segments of the Tornquist Zone are joined by the SW–NE oriented Rønne Graben. Gry (1969), Gravesen *et al*. (1982), and Koppelhus & Nielsen (1994) have described the Mesozoic geology of Bornholm. Information from the offshore geology was sampled during exploration for energy and raw material resources. Beginning in the mid-1970s and through the 1980s exploration for oil and gas was active in the Danish acreage in the southern Baltic Sea. Between 1975 and 1988 a number of industrial seismic surveys around Bornholm focused on the Rønne Graben, the Risebæk Graben and the Kolobrzeg Graben to the west and south of Bornholm (Fig. 1A). The Mesozoic and upper part of the Palaeozoic sequences were drilled in 1989. These hydrocarbon exploration activities were not successful and both the Pernille-1 well drilled in the Rønne Graben and the Stina-1 well drilled at the northern margin of the Kolobrzeg Graben were dry holes (Fig. 1A; Amoco 1989; Norsk Hydro 1989). In addition to the search for energy resources, marine geological mapping and prospecting for raw materials on the sea floor around Bornholm were carried out with side scan sonar and shallow seismic reflection methods (Jensen 1988; Jensen & Hamann 1989).

The raw-material investigations resulted in the preparation of a pre-Quaternary geological map that shows the Mesozoic deposits to the south-west of

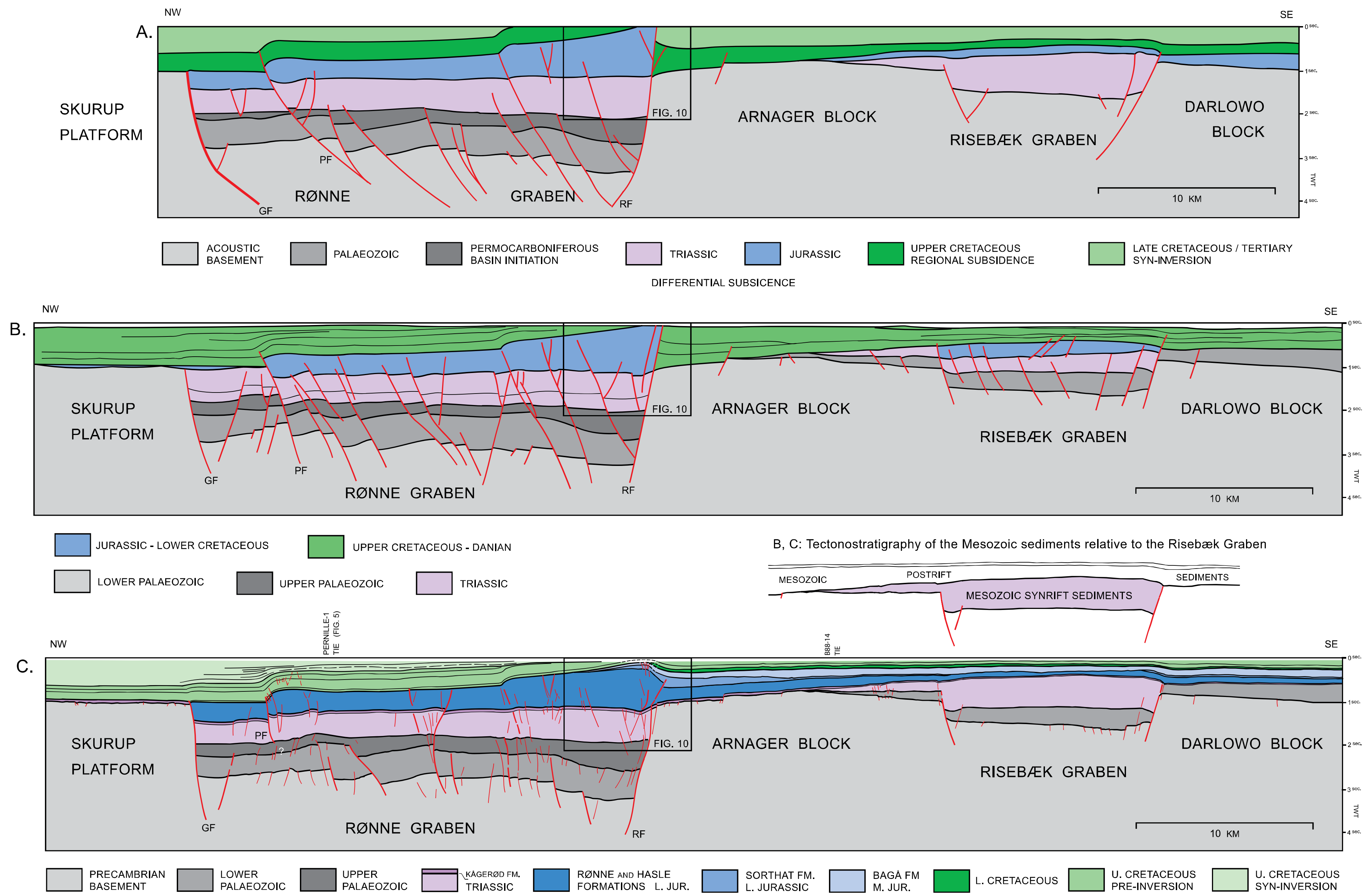
Fig. 1. A: Major tectonic elements west and south of Bornholm (Vejbæk et al. 1994). Positions of wells, and analysed seismic lines and cross sections, and detailed geological map indicated. B: Position of the Bornholm area (Fig. 1A) in the Tornquist Zone between the Baltic Shield/East European Platform and the Danish Basin/NW European craton. Tectonic elements based on Vejbæk & Britze (1994), Vejbæk (1997). FBZ: Fennoscandian Border Zone; TTZ: Teisseyre-Tornquist Zone; PT: Polish Trough; RG: Rønne Graben.





Bornholm as a continuation of the onshore outcrops (Hamann 1987; Jensen & Hamann 1989). Interpretation of the seismic surveys resulted in the delineation of the fault structure of the Rønne Graben and the Risebæk Graben separated by the Arnager Block (Vejbæk 1985; Vejbæk *et al*. 1994; Fig. 1A). The Rønne and Risebæk grabens terminate to the southwest against the Kolobrzeg Graben. In addition to block faulting, structural inversion is identified in the Rønne Graben and along the northeast margin of the Kolobrzeg Graben (Fig. 1A). Published geological cross sections reveal that major differences exist in the interpretation of the Jurassic–Cretaceous interval in the Arnager Block and the Risebæk Graben offshore south Bornholm (Fig. 2). An up to *c*. 1 km thick post-rift package above the Risebæk Graben has been assigned to either the Upper Cretaceous (Vejbæk 1985, 1997; Liboriussen *et al*. 1987; Rasmussen 1989; Thomas & Deeks 1994; Vejbæk *et al*. 1994; Erlström *et al*. 1997; Kramarska *et al*. 1999) or to the Jurassic–Cretaceous interval (Graversen 2004). The stratigraphic identification of the sediments has a considerable influence on the interpretation of both rifting and structural inversion; and the tectonic modeling of the Tornquist Zone is dependent on the strati-

Facing page:
Fig. 2. Contrasting geological interpretations of the Rønne Graben, the Risebæk Graben, and associated fault blocks, i.e. the Skurup Platform and the Arnager-Darlowo Block. All interpretations are based on seismic line Jebco B88-07. A: Thomas & Deeks (1994). B: Vejbæk (1997). C: Graversen (2004) and this paper. GF: Gat Fault; PF: Pernille Fault; RF: Rønne Fault. Frame indicates position of seismic section and interpretation in Fig. 10.


A.
NW
SE
SKURUP
PLATFORM
RØNNE
GRABEN
PF
GF
RF
FIG. 10
ARNAGER BLOCK
RISEBÆK GRABEN
DARLOWO
BLOCK
TWT
10 KM
ACOUSTIC BASEMENT
PALAEOZOIC
PERMOCARBONIFEROUS BASIN INITIATION
TRIASSIC
JURASSIC
UPPER CRETACEOUS REGIONAL SUBSIDENCE
LATE CRETACEOUS / TERTIARY SYN-INVERSION
DIFFERENTIAL SUBSICENCE
B.
NW
SE
SKURUP
PLATFORM
RØNNE GRABEN
GF
PF
RF
FIG. 10
ARNAGER BLOCK
RISEBÆK GRABEN
DARLOWO BLOCK
TWT
10 KM
JURASSIC - LOWER CRETACEOUS
UPPER CRETACEOUS - DANIAN
LOWER PALAEOZOIC
UPPER PALAEOZOIC
TRIASSIC
B, C: Tectonostratigraphy of the Mesozoic sediments relative to the Risebæk Graben
MESOZOIC
POSTRIFT
SEDIMENTS
MESOZOIC SYNRIFT SEDIMENTS
C.
NW
SE
PERNILLE-1 TIE (FIG. 5)
B88-14 TIE
SKURUP
PLATFORM
RØNNE GRABEN
PF
GF
RF
FIG. 10
ARNAGER BLOCK
RISEBÆK GRABEN
DARLOWO BLOCK
TWT
10 KM
PRECAMBRIAN BASEMENT
LOWER PALAEOZOIC
UPPER PALAEOZOIC
KÅGERØD FM.
TRIASSIC
RØNNE AND HASLE FORMATIONS L. JUR.
SORTHAT FM. L. JURASSIC
BAGÅ FM M. JUR.
L. CRETACEOUS
U. CRETACEOUS PRE-INVERSION
U. CRETACEOUS SYN-INVERSION

graphic interpretation. This paper discusses the stratigraphy and structure of the Late Triassic through Cretaceous basins offshore south-west Bornholm.

Contrasting geological interpretations

The geological cross sections illustrated in Figure 2 are all based on the interpretation of seismic line B88-JS-07 acquired by Jebco Seismic Ltd. in 1988. The cross-sections show a fair agreement of the interpretations of both structure and stratigraphy of the Rønne Graben and the adjoining Skurup Platform to the north-west. Likewise, the interpretation of the structural outline of the Risebæk Graben, and the Arnager and Darlowo blocks follow uniform trends, whereas contrasting views are displayed regarding interpretation of the stratigraphy.

In the Rønne Graben, both the Triassic and Jurassic intervals are interpreted to extend to the western border fault in sections A and C (Fig. 2). In section B, however, the Pernille Fault restricts the thick Jurassic interval to the centre of the graben, while thin Jurassic sediments are indicated on the Skurup Platform and the western graben block between the Pernille and Gat faults.

The Mesozoic sediments to the east of the Rønne Graben can be separated into a Risebæk Graben syn-rift package and a post-rift interval deposited above the graben and across the Triassic and pre-Mesozoic basement of the flanking Arnager and Darlowo blocks (Fig. 2B, C). The major difference between these interpretations concerns the position of the Jurassic interval. In section B, the Jurassic is restricted to the Risebæk Graben as a syn-rift deposit whereas the Jurassic in section C outline a post-rift package laid down above the Arnager and Darlowo blocks across the Risebæk Graben. The Jurassic in section A is encountered across the Risebæk Graben and above Palaeozoic basement of the Darlowo Block; this interpretation does not fit the syn-rift/post-rift depositional system in relation to the Risebæk Graben. The Upper Triassic Kågerød Formation is established as the earliest post-rift deposit in section C; otherwise, the Triassic interval in all sections is interpreted as a syn-rift deposit restricted to the Risebæk Graben. The Cretaceous deposits above the Risebæk Graben, the Arnager Block and the Darlowo Block occupy a post-rift position in all three sections (Fig. 2).

The stratigraphy of the Arnager Block has a major impact on the interpretation of the structural inversion along the Rønne Graben and the Kolobrzeg Graben to the west and south of the Arnager Block (Figs 1A, 2). In the case where the Mesozoic of the Arnager Block is dominated by Upper Cretaceous deposits (sections A, B, Fig. 2), the Jurassic (– Lower Cretaceous) of the Rønne Graben and the Upper Cretaceous of the Arnager Block are juxtaposed along the Rønne Fault, i.e. the eastern Rønne Graben border fault. In this case, the Late Cretaceous – Danian structural inversion implies a *c.* 1 sec TWT uplift of the Rønne Graben along the Arnager Block (Fig. 2 sections A, B). By contrast, in the interpretation put forward in section C (Fig. 2), the Jurassic of the Rønne Graben is restricted to the Lower Jurassic Rønne and Hasle formations; the western Arnager Block is, however, dominated by Jurassic – Lower Cretaceous deposits below the relatively thin Upper Cretaceous at the top of the section. The Rønne-Hasle formations continue from the Rønne Graben across the border fault to the Arnager Block. The border zone is characterized by relative uplift/inversion of the thick Jurassic graben section and conspicuous thinning of this interval at the transition to the Arnager Block. The overlying Lower Jurassic – Lower Cretaceous package of the Arnager Block most likely extends into the eastern Rønne Graben where it pinches out in the inversion zone (Fig. 2 section C). The interpretation put forward in section C (Fig. 2) involves two periods of structural inversion in the eastern Rønne Graben: Early inversion within the Jurassic – Early Cretaceous, and renewed inversion during the Late Cretaceous. In this case, the Late Cretaceous structural inversion along the Rønne Fault in the southern Rønne Graben is in the order of 150 msecs TWT while the early inversion of the Rønne-Hasle formations amounts to *c.* 400 msecs.

Stratigraphic database and seismic ties

The structural inversion along the border faults in the Rønne Graben and the Kolobrzeg Graben may be an obstacle to stratigraphic correlation between the grabens and the Arnager Block. To establish the stratigraphy of the reflection seismic lines traversing the Arnager Block, seismic ties have been constructed to the marine and onshore bedrock geology along the south-coast of Bornholm and in the Rønne Graben (Figs 3, 4). In the grabens, the seismics are tied to the offshore Pernille-1 (Norsk Hydro 1989) and Stina-1 (Amoco 1989) hydrocarbon exploration wells (Figs 1A, 5–6, Tables 1–2).

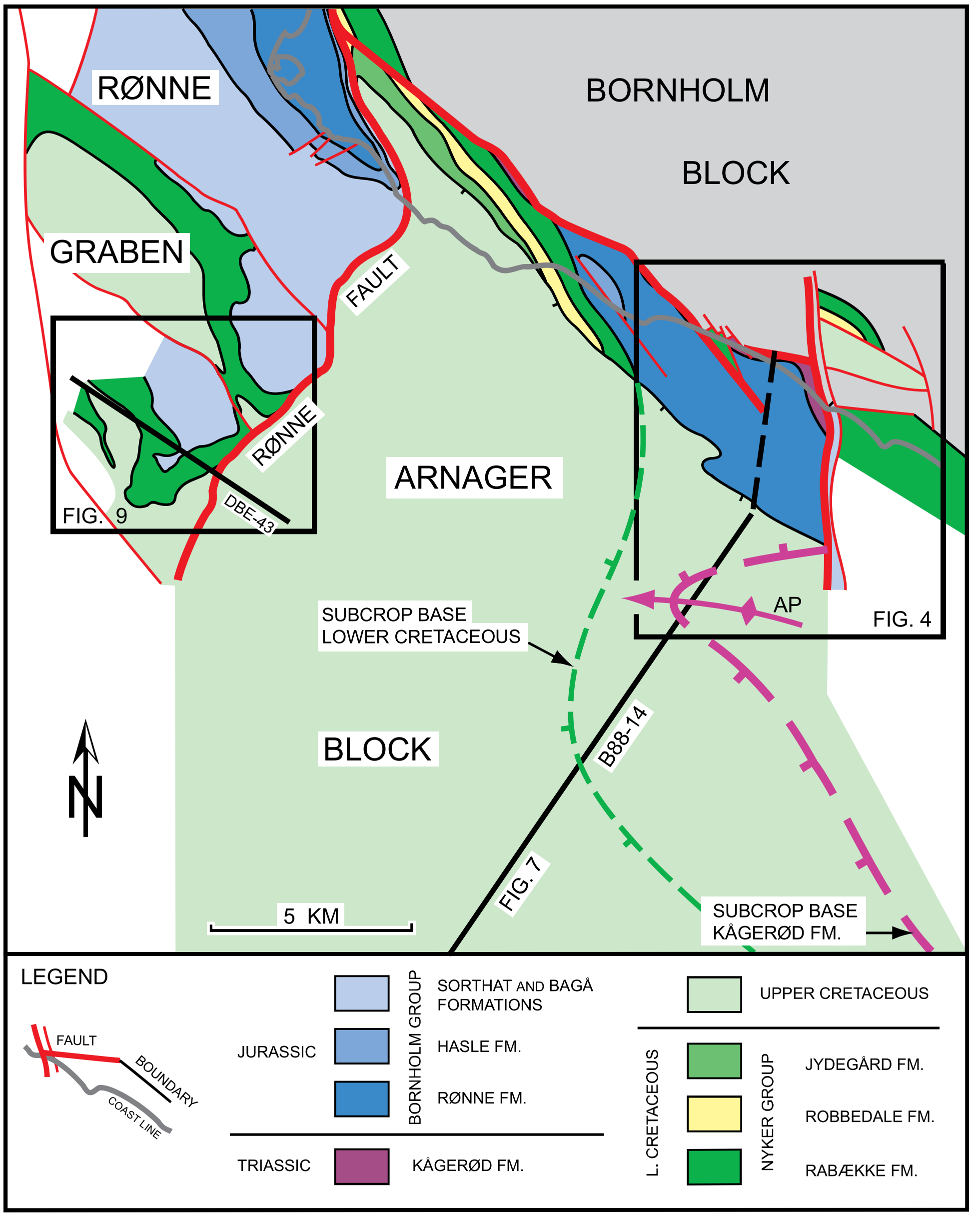


Fig. 3. Geological map of the Mesozoic formations on- and offshore southwest Bornholm (adopted from Jensen & Hamann 1989). The position of the base Lower Cretaceous and base Kågerød Formation subcrops below the Upper Cretaceous cover are mapped on reflection seismics (Graversen 2004). Frames and heavy lines indicates positions of detailed maps and geological cross-sections based on seismic images. AP: Trace of axial plane of anticline plunging in a westerly direction.

Marine and onshore bedrock geology

The Mesozoic deposits outcrop in a downfaulted zone on the Nyker Block, on the Arnager Block and in the Rønne Graben along the south and west coasts of Bornholm (Figs 1A, 3) (Gry 1969; Gravesen *et al.* 1982; Hamann 1987; Jensen & Hamann 1989; Michelsen *et al.* 2003). A review of the geological evolution is given in Graversen (2004). The detailed onshore and marine investigations illustrate a folded and faulted Mesozoic sediment package with an overall dip and younging upwards direction towards the south-west (Figs 3–4) (Gry 1969; Jensen & Hamann 1989). The Upper Triassic Kågerød Formation was presumably laid down with an angular unconformity on faulted and eroded Lower Palaeozoic sediments now outcropping on the footwall block, the Bornholm Block, to the north (Fig. 4). Hamann (1987) mapped an angular unconformity at the base of the Upper Cretaceous trending NW–SE across the Arnager Block (Fig. 3). The unconformity cuts through the Lower Cretaceous and down into the Lower Jurassic Rønne Formation to the east (Fig. 4). The Lower Cretaceous overlies directly the Rønne Formation, and there is a gap, corresponding to the Hasle Formation and the Sorthat and Bagå formations, encountered in the Rønne Graben (Fig. 3; Michelsen *et al.* 2003).

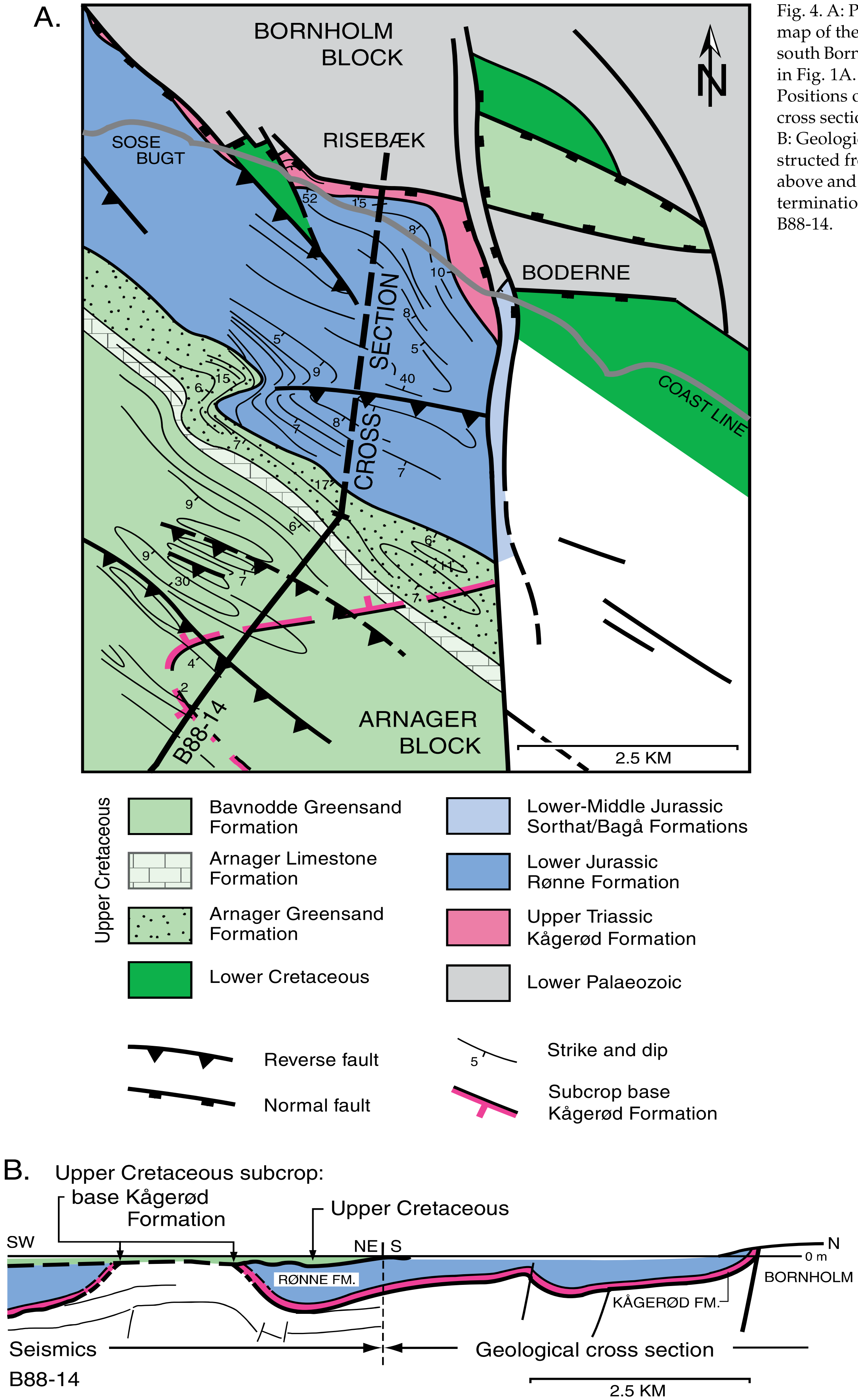


Fig. 4. A: Pre-Quaternary geological map of the Risebæk-Boderne area, south Bornholm. Position indicated in Fig. 1A. From Hamann (1987). Positions of seismic line B88-14 and cross section below are indicated. B: Geological cross section constructed from the geological map above and tied to the northeast termination of seismic line Jebco B88-14.

The Rabække Formation in the east central Rønne Graben represents the Lower Cretaceous; the overlying Robbedale and Jydegård formations mapped on the Arnager Block to the east have not been identified in the Rønne Graben (Fig. 3; Jensen & Hamann 1989). The stratigraphic gap below the Upper Cretaceous package increases towards the south in the Rønne Graben, where the Upper Cretaceous Chalk Group equivalent is identified directly above the Lower Jurassic Rønne and Hasle formations (Fig. 5, Table 1) (Norsk Hydro 1989; Nielsen & Japsen 1991). The base Upper Cretaceous stratigraphic gap in the southern Rønne Graben and on the north-east Arnager Block thus corresponds to the Lower – Middle Jurassic Sorthat and Bagå formations and the Lower Cretaceous Nyker Group in the east-central Rønne Graben and on the northern Arnager Block. The total thickness of the missing interval is in the order of 500–600 metres (Jensen & Hamann 1989; Koppelhus & Nielsen 1994).

Seismic tie with bedrock geology

A geological cross section has been constructed from the geological map in order to tie the onshore Bornholm bedrock geology with the seismic section B88-14 (Fig. 4B). The Upper Triassic Kågerød Formation and overlying Lower Jurassic Rønne Formation can thus be linked with the seismic section above an angular unconformity. At the top of the section, the basal Upper Cretaceous cuts across the Kågerød-Rønne formation succession. The position of the basal Kågerød Formation cut-off below the Upper Cretaceous has been mapped as the trend of the base of the Kågerød Formation subcrop (Figs 3, 4). The Upper Cretaceous internal structures are discordant with respect to the trend of the Triassic subcrop (Fig. 4). This discordant relationship is in agreement with the track of the Upper Cretaceous angular unconformity established from the geological map (Fig. 3).

The trend of the basal Lower Cretaceous bound-

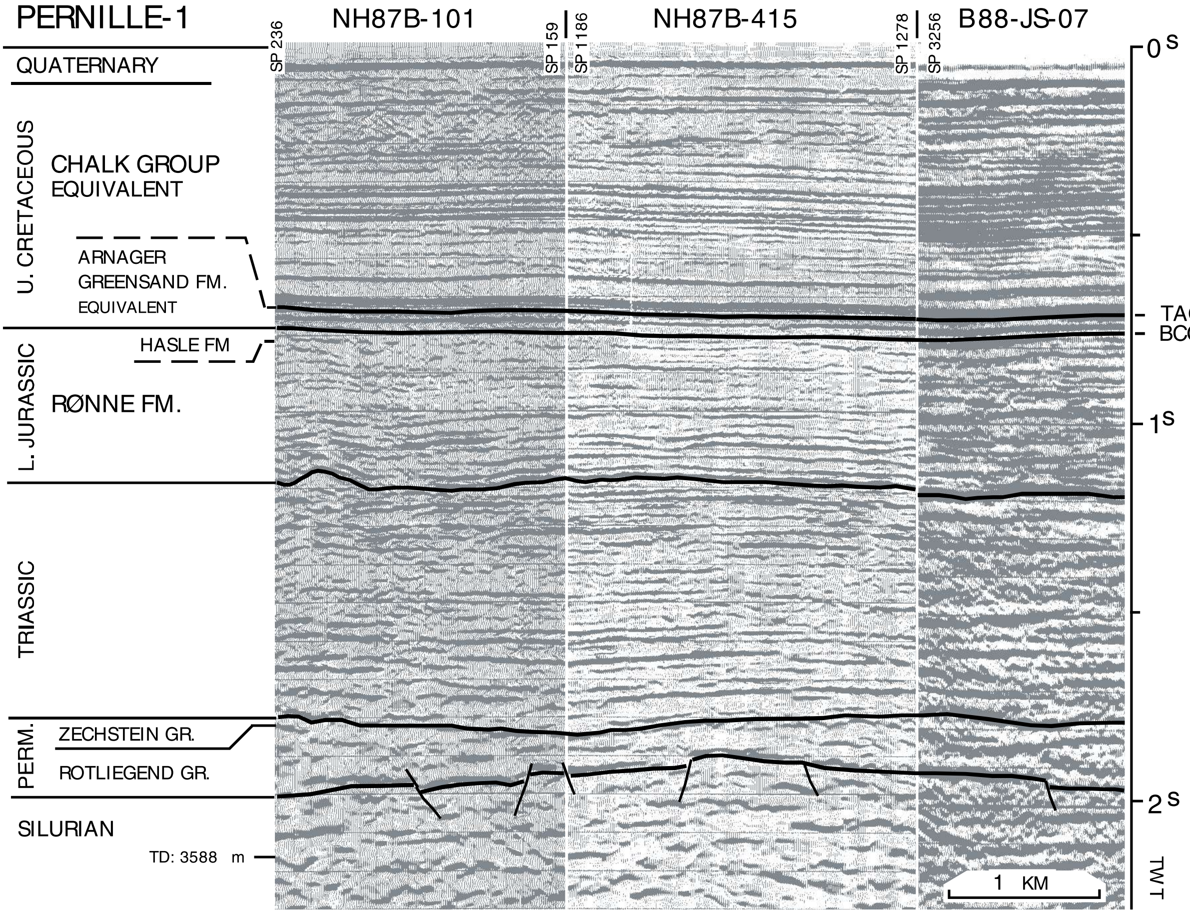


Fig. 5. Stratigraphy of the Pernille-1 well tied to the seismic line NH87B-101. The stratigraphy is based on Table 1 (Nielsen & Japsen 1991), Norsk Hydro (1989), and Michelsen *et al.* (2003) and Graversen (2004). The drilled interval is linked up with seismic line B88-07 via NH87B-415 (see Figs 1A, 2C).

Pernille-1 — Well completed by Norsk Hydro, June 1989

Location	Reference level	Total depth (drill)
Lat. 55° 00' 53.5" North Long. 14° 18' 43.9" East	Rotary table 36.0 metres above msl	3624.5 metres below reference level 3588.5 metres bleow msl

Lithostratigraphic Unit	Depth b. ref. l. metres top	base	Depth b. msl metres top	base	Thickn metres	Two-way time msecs top	base	Thickn. msecs	Average vel. m/sec top	base	Int. vel. m/sec
Post Chalk Group	80	95	44	59	15	59	-	-	1491	-	-
Quaternary undiff.	80	95	44	59	15	59	-	-	1491	-	-
U. Cretaceous undiff.	95	943	59	907	848	-	743	-	-	2441	-
Jurassic Units	943	1552	907	1516	609	743	1157	414	2441	2620	2942
Rønne Formation eq.	943	1552	907	1516	609	743	1157	414	2441	2620	2942
Triassic units	1552	2749	1516	2713	1197	1157	1777	620	2620	3053	3861
Kågerød Formation eq.	1552	2749	1516	2713	1197	1157	1777	620	2620	3053	3861
Zechstein Group	2749	2788	2713	2752	39	1777	1796	18	3053	3065	4193
Rotliegend Group	2788	3248	2752	3212	460	1796	1988	192	3065	3231	4781
Pre-Permian units	3248	3624	3212	3588	376	1988	2149	161	3231	3339	4670
Silurian undiff.	3248	3624	3212	3588	376	1988	2149	161	3231	3339	4670

Table 1. Lithostratigraphy, depths, and geophysical parameters of the Pernille-1 well (Nielsen & Japsen1991).

ary can be mapped on the seismic section below the Upper Cretaceous blanketing deposits (Fig. 3). The basal Lower Cretaceous subcrop trend identifies the position of the Lower Cretaceous between the Rønne-Hasle formation and the Upper Cretaceous on B88-14 (Fig. 7).

Seismic line DBE-43 cuts across the boundary between the Arnager Block and the Rønne Graben (Figs 3, 9). Integration of the seismic interpretation with the bedrock geology shows that the Sorthat and Bagå formations identified in the Rønne Graben (along with the Rønne and Hasle formations) continue onto the Arnager Block below the Cretaceous deposits. The Sorthat and Bagå formations have been mapped across the Arnager Block and tied to B88-14 (Fig. 7; Graversen 2004).

The Upper Cretaceous is divided into the Arnager Greensand Formation (base), the Arnager Limestone Formation, and the Bavnodde Greensand Formation (top). The Arnager Limestone Formation is 10–20 metres thick, and below resolution on the exploration seismics used in the present investigations. The Arnager Greensand Formation at the base of the Upper Cretaceous is *c.* 100 metres thick and the upper boundary can be identified as a strong reflection on the high resolution seismics (Jebco B88 survey). It is possible, however, that the strong signal may be related to the siliceous Arnager limestone above; if this is the case, the Arnager Greensand Formation mapped in the present investigation may also include the Arnager Limestone Formation below the Bavnodde Greensand Formation at the top of the Upper Cretaceous package.

Seismic-to-well tie

The regional seismic lines traversing the Arnager Block (Jebco B88-JS-07, B88-JS-14) have been tied to the Pernille-1 and Stina-1 wells (Figs 5, 6A). Below the Quaternary, the Pernille-1 well penetrated the Upper Cretaceous Chalk Group equivalent (Norsk Hydro 1989). The Jurassic interval is identified as the Lower Jurassic Hasle and Rønne formations, while the base of the Mesozoic column is of Triassic age (Table 1; Michelsen *et al*. 2003). The identification of an Arnager Greensand Formation equivalent is noted in the well report (Norsk Hydro 1989). The Palaeozoic is composed of the Permian Zechstein and Rotliegend groups above Silurian shales (Table 1; Vejbæk *et al.* 1994).

The Stina-1 well was drilled on an inversion anticline, where a Lower Jurassic package is identified directly below the Quaternary (Fig. 6, Table 2). The Jurassic is interpreted as the Rønne Formation, superceded by the Hasle Formation, the Sorthat Formation, and possibly the basal Bagå Formation (Nielsen 1995; Michelsen *et al*. 2003; Graversen 2004).

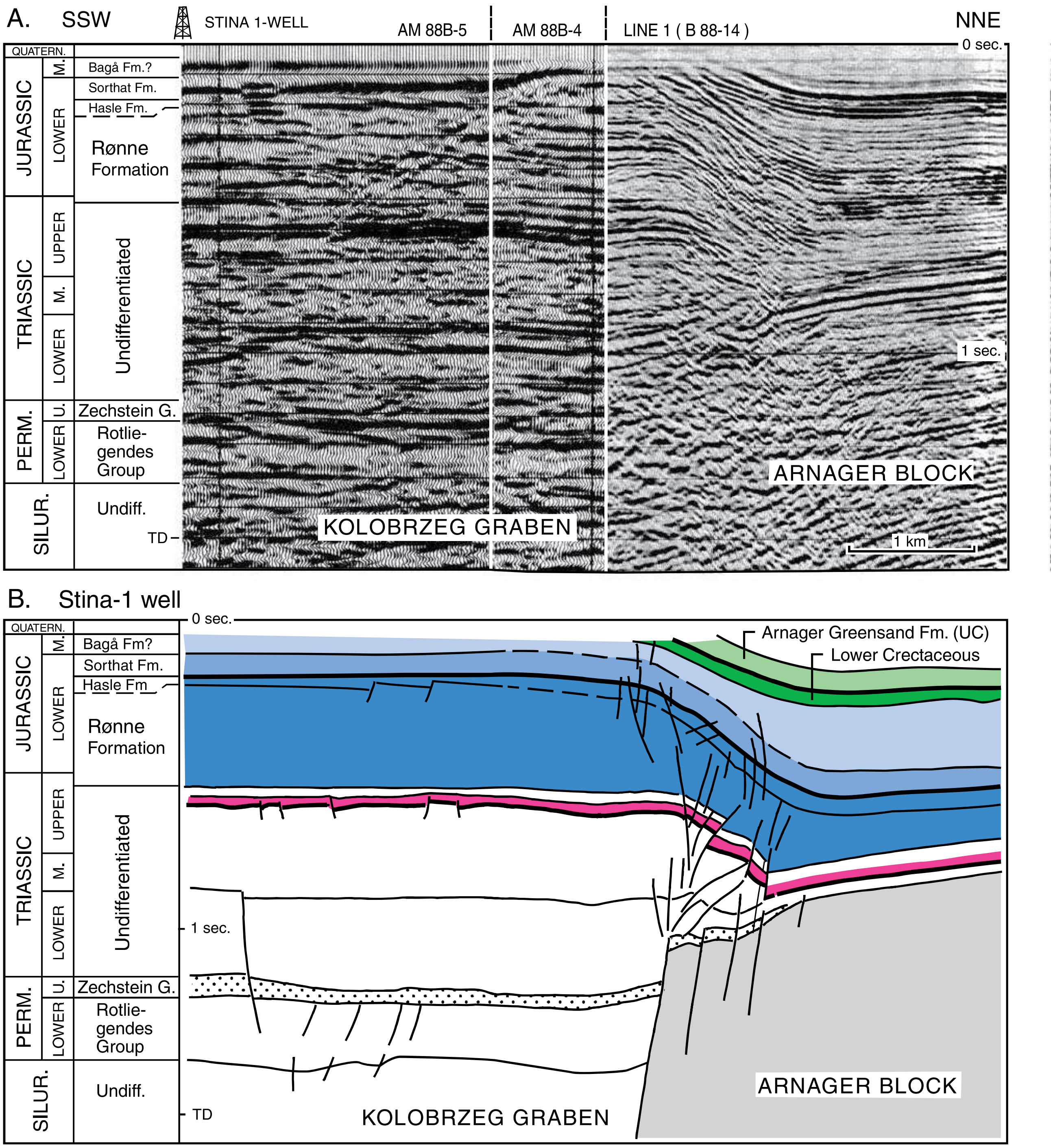


Fig. 6. A: Stratigraphy of the Stina-1 well tied to the seismic line AM88B-5. The stratigraphy is based on Table 2 (Nielsen & Japsen 1991), Amoco (1989), and Michelsen *et al*. (2003). Position of well and composite seismic section is indicated in Fig. 1A. B: Geological interpretation of composite seismic section above.

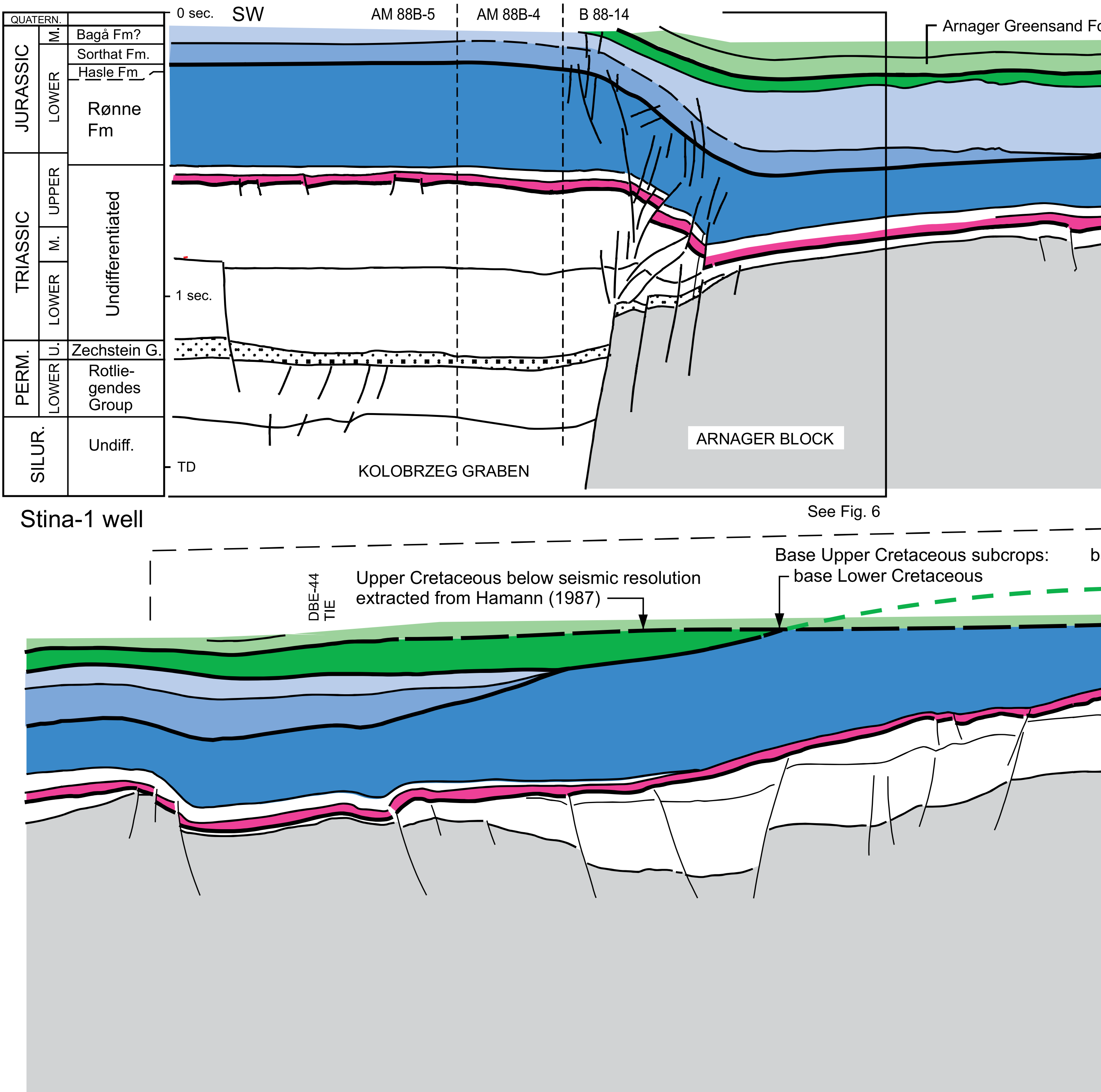
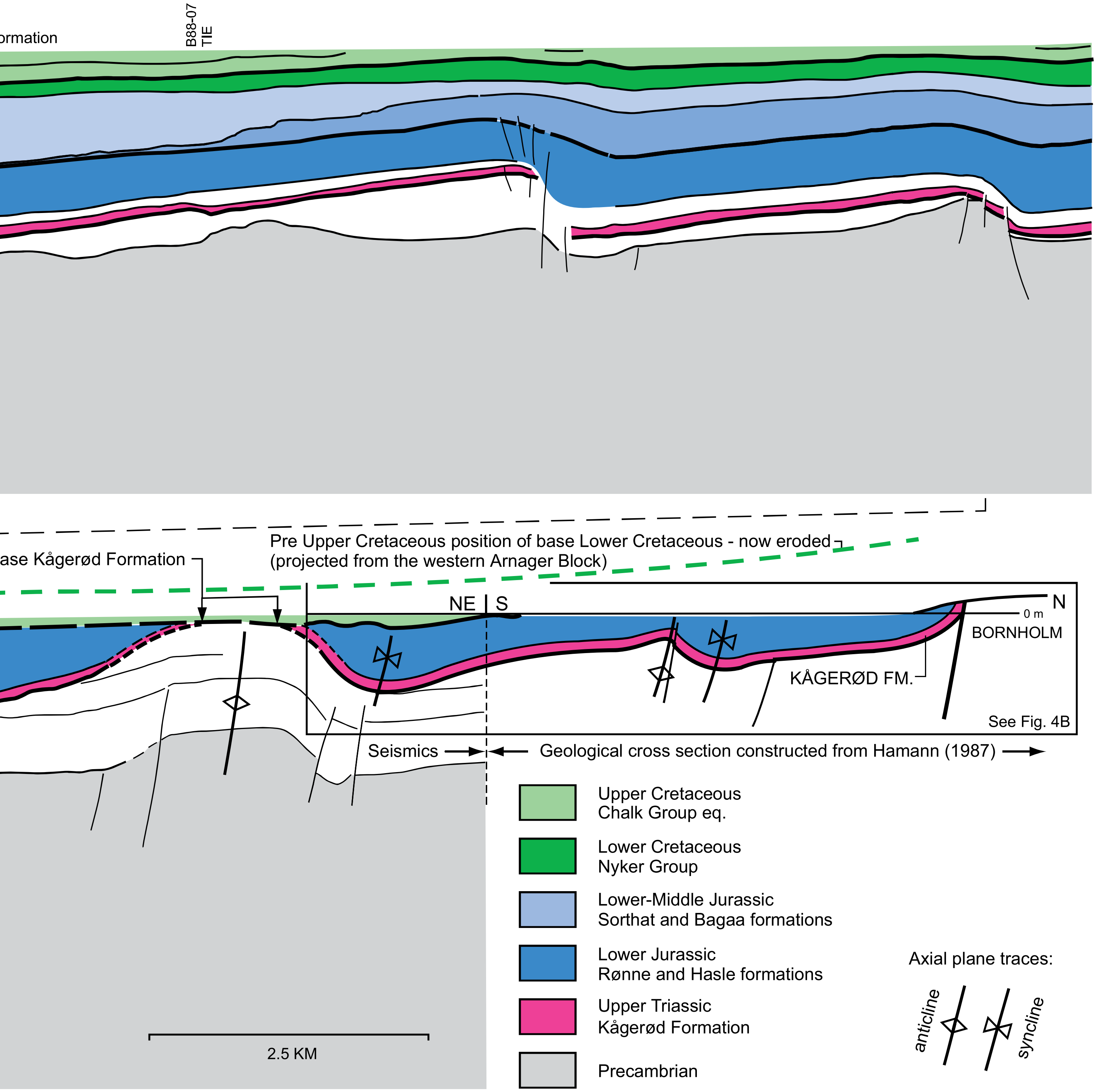


Fig. 7. Geological interpretation of composite seismic line (AM88B-5/AM88B-4/B88-JS-14) and geological cross-section (adapted from Fig. 4B) between the Stina-1 well and onshore bedrock geology. Position indicated in Fig. 1A. The interpretation links the onshore outcrops of the Rønne and Kågerød formations with the Rønne Formation and uppermost Triassic drilled in the Stina-1 well.



ormation
B88-07
TIE
ase Kågerød Formation
Pre Upper Cretaceous position of base Lower Cretaceous - now eroded
(projected from the western Arnager Block)
NE
S
N
0 m
BORNHOLM
KÅGERØD FM.
See Fig. 4B
Seismics
Geological cross section constructed from Hamann (1987)
2.5 KM
Upper Cretaceous
Chalk Group eq.
Lower Cretaceous
Nyker Group
Lower-Middle Jurassic
Sorthat and Bagaa formations
Lower Jurassic
Rønne and Hasle formations
Upper Triassic
Kågerød Formation
Precambrian
Axial plane traces:
anticline
syncline

Stina-1

Well completed by Amoco, July 1989

Location	Reference level	Total depth (drill)
Lat. 54° 47 19.9" North Long. 14° 37 43.5" East	Rotary table 36.2 metres above msl	2518.0 metres below reference level 2481.8 metres bleow msl

Lithostratigraphic Unit	Depth b. ref. l. metres top	Depth b. ref. l. metres base	Depth b. msl metres top	Depth b. msl metres base	Thickn metres	Two-way time msecs top	Two-way time msecs base	Thickn. msecs	Average vel. m/sec top	Average vel. m/sec base	Int. vel. m/sec
Post Chalk Group	67	70	31	34	3	42	-	-	1466	-	-
Quaternary undiff.	67	70	31	34	3	42	-	-	1466	-	-
Jurassic Units	70	559	34	523	489	44	512	468	1536	2042	2089
Lower Jurassic undiff.	70	213	34	177	143	-	186	-	-	1901	-
Rønne Formation	213	559	177	523	346	186	512	326	1901	2042	2122
Triassic units	559	1547	523	1511	988	512	1143	631	2042	2643	3131
Upper Triassic undiff.	559	910	523	874	351	512	759	247	2042	2302	2842
Middle Triassic undiff.	910	1084	874	1048	174	759	879	120	2302	2384	2900
Lower Triassic undiff.	1084	1547	1048	1511	463	879	1143	264	2384	2643	3507
Zechstein Group	1547	1710	1511	1674	163	1143	1224	81	2643	2734	4024
Rotliegend Group	1710	2112	1674	2076	402	1224	1420	196	2734	2923	4102
Pre-Permian units	2112	2511	2076	2475	399	1420	-	-	2923	-	-
Silurian undiff.	2112	2511	2076	2475	399	1420	-	-	2923	-	-
Silurian undiff. endl.	2112	2488	2076	2452	376	1420	1600	180	2923	3064	4177

Table 2. Lithostratigraphy, depths, and geophysical parameters of the Stina-1 well (Nielsen & Japsen 1991).

Below the Jurassic, the Stina-1 well penetrated a Triassic–Palaeozoic succession similar to the interval drilled by the Pernille-1 well.

Deformation of the Arnager Block

In the northern part of the Arnager Block, the Lower Cretaceous is cut out by the basal Upper Cretaceous that farther to the north cuts down through the Rønne Formation and across the anticline defined by the Upper Triassic Kågerød Formation with a marked angular unconformity (Fig. 7). In map view (Fig. 3), the basal Lower Cretaceous combined outcrop-subcrop trend indicates a gentle monoclinal fold concealed below the Upper Cretaceous cover. The monocline has been projected eastwards to intersect with the geological cross-section, where the projection illustrates the basal Lower Cretaceous structure prior to erosion. The Lower/Upper Cretaceous interrelationship is a result of deformation of the Lower Cretaceous (and older deposits) followed by uplift and erosion prior to deposition of the Upper Cretaceous package (Fig. 7). Timing of the deformation can be estimated from the onshore Bornholm stratigraphy, where the Lower Cretaceous Nyker Group is of Berriasian–Valanginian (–Hauterivian?) age (Christensen 1972; Gravesen *et al.* 1982), and the Arnager Greensand Formation at the base of the Upper Cretaceous is of Mid Cenomanian age (Kennedy *et al.* 1980). In addition, the lower Arnager Greensand Formation contains a complex conglomerate composed of marine glauconitic sandstone and phosphatised pebbles. Primary nodules are of Early Albian age and are included in secondary pebbles and cobbles composed of Early Cenomanian glauconitic sandstone (Ravn 1925; Kennedy *et al.* 1980; Tröger & Christensen 1991). Deformation and erosion of the Nyker Group followed by marine transgression may thus be confined to the Barremian–Aptian interval. The Lower Albian in the primary nodules contains clasts of Nexø Sandstone, quartzite (Balka Sandstone?), Lower Palaeozoic shales, Jurassic – Lower Cretaceous (?) lithified wood and occasional large grains of quartz and mica (that may have been washed out of kaolinised Precambrian crystalline basement) (Ravn 1925). The polymict clast content in the primary nodules suggests that the Precambrian, Palaeozoic and Mesozoic of the Bornholm Block was exposed to erosion during deposition of the marine Lower Albian. Kennedy *et al.* (1980) pointed out that Albian/Cenomanian transgression has also been recorded in the Danish Basin, and they suggested that the transgressive event was associated with the global eustatic sea-level rise. The higher frequency relative sea-level fluctuations illustrated by the hiatuses in the Middle – Upper Albian and at the Lower – Middle Cenomanian transition (Kennedy *et al*. 1980) may be associated with tectonic pulses during the Early – Late Cretaceous transition (Ravn 1925).

The base Kågerød Formation subcrop trend indicates the structure of a westerly plunging anticline (Fig. 3). The northern limb dips towards the north – north-west, and the trace of the axial plane strike across the flank of the Lower Cretaceous monocline. The discordant relationship between the structures outlined by the Lower Cretaceous and the Upper Triassic – Lower Jurassic respectively, suggests that the two structures were formed during separate deformation episodes. The discordant relationship between the lower and upper levels may also be illustrated in cross-section by the steep axial plane traces established for the folds at the Kågerød-Rønne formation level that are discordant with the (now eroded) base Lower Cretaceous boundary (projected from the map and eastwards to intersection with the geological cross-section) (Fig. 7). In a seaward position, the Lower Cretaceous overlies the Hasle Formation with no indication of erosion recognized on the reflection seismics (B88-14) (Graversen 2004). In a landward position, however, the Lower Cretaceous was deposited on an erosion surface that cuts through the Hasle Formation and down into the Rønne Formation (Fig. 3; Gry 1969). The Upper Jurassic hiatus identified onshore Bornholm (Gry 1969; Gravesen *et al*. 1982) may suggest that landward erosion was active during the Late Jurassic. Pre-Cretaceous erosion may even have taken place in the Early – Middle Jurassic during basinward deposition of the Sorthat and Bagå formations (Fig. 7) that are interpreted to represent lowstand systems tracts on the Arnager Block (Graversen 2004). Jurassic uplift of the Rønne Formation in the Sose Bugt section (Fig. 4) has been modeled from organic maturity data to *c*. 335 m (Petersen *et al*. 2003).

Interpretation of inversion structures

Kolobrzeg Graben

The Cretaceous is absent in the Stina-1 well; however, the basal Chalk Group equivalents and the top Arnager Greensand equivalents reflections have been traced from the Pernille-1 well (Fig. 5) in the Rønne Graben to the south-west limb of the inversion anticline (Fig. 8D). The Cretaceous reflections have been correlated across the inversion anticline with similar strong reflections in the upper part of the section above the Arnager Block (Figs 6, 8). On the Arnager Block, the strong reflections correlate with the Arnager Greensand Formation identified on the geological bedrock map (Figs 4, 7; Graversen 2004).

The illustrated seismic sections across the Kolobrzeg Graben inversion zone trend NNE–SSW at nearly right angles to the axis of the inversion anticline (Figs 1A, 8). On the seismic sections, both the southern and northern flanks of the anticline are characterized by faulting and monoclinal deformation zones, where the inverted package steps down to the south into the Kolobrzeg Graben and to the north onto the Arnager Block (Fig. 8A, C). The reflections of the transition zone between the Kolobrzeg Graben and the Arnager Block show a somewhat chaotic character at deeper levels with discontinuous reflections and multiple diffractions probably related to a more intense fault deformation of the northern flank. Previous interpretations illustrate a discontinuous Jurassic interval restricted to the Kolobrzeg Graben and excised from the Arnager Block by a fault (Fig. 8B). However, in the upper *c*. 200–450 msecs TWT, primary reflections above the Arnager Block can be connected to reflections in the upper part of the adjoining graben section and linked with the Jurassic drilled by the Stina-1 well (Fig. 6). The discontinuous reflections at lower levels (*c*. 450–700 msecs TWT) on the northern flank are equal to a similar reflection discontinuity shown at the same depth interval on the southern flank. This indicates that the interpreted continuity of the folded and faulted Jurassic interval below the Cretaceous established on the southern flank (Fig. 8A–B, D) should be repeated on the northern flank of the inversion anticline. Based on these observations, the Jurassic Rønne and Hasle formations, along with the overlying Sorthat and Bagå (?) formations, as well as the upper Upper Triassic (Kågerød Formation) penetrated by the Stina-1 well are interpreted to continue onto the Arnager Block (Figs 6B, 8A, D; Graversen 2004).

In the transition zone between the Kolobrzeg Graben and the Arnager Block, the Bagå reflections, and to a lesser degree the Lower Cretaceous reflections, have a steeper dip and mutually diverge towards the Arnager Block (Figs 6, 8D). This is interpreted to mean that the pre-Bagå Formation graben section underwent structural inversion prior to deposition and inversion of the Upper Cretaceous package. A previous structural analysis of the inversion zone concluded that structural inversion was active during deposition of the Bagå Formation and the Lower Cretaceous sediments (Graversen 2004).

Rønne Graben

Seismic line DBE-43

Interpretation of the folded continuous reflections from the Rønne Graben onto the Arnager Block indicates that the Sorthat and Bagå formations, in addition to the Rønne and Hasle formations below, continue from the Rønne Graben onto the Arnager Block (Fig. 9C). Integration of the geological cross-section (Fig. 9B) with seismic line DBE-43 (Fig. 9C) illustrates that the reverse fault dipping to the north-west into the Rønne Graben (Fig. 9A, B) has a position halfway down the south-east flank of the inversion anticline marked by the boundary between the Hasle and Sorthat formations (Fig. 9C). The structural position of the reverse fault is not compatible with the structures interpreted from the deeper seismic reflections. A possible reverse fault along the south-east border of the Rønne Graben would be expected to have a position at the hinge of the open syncline developed at the border between the Rønne Graben and the Arnager Block. However, the reflection between the Hasle and Sorthat formations continues with no offset (within seismic resolution) from the graben and onto the Arnager Block. An alternative interpretation that combines the deep and shallow seismic interpretations is illustrated by the normal fault with a down-to-the-south-east displacement (Fig. 9C). Structural inversion of the graben section may thus be linked to normal faulting at higher stratigraphic levels on the (south-east) flank of the inversion anticline.

Seismic line B88-JS-07

Along B88-07, the reflections in the transition zone between the Rønne Graben and the Arnager Block have a rather chaotic appearance that is thought to be related to the difficulty to migrate correctly the reflections of the steep layers in the inversion zone (Fig. 10). However, the stratigraphy and structure in the upper part of the section may be reasonably reconstructed since the Arnager Greensand Formation at the base of the Upper Cretaceous package has been identified in both the Rønne Graben (Fig. 5) and on the Arnager Block (Figs 4, 7). Below the Upper Cretaceous, the stratigraphic section of the Jurassic – Lower Cretaceous interval established on the Arnager Block strongly constrasts with the stratigraphy in the Rønne Graben tied to the Pernille-1 well (Fig. 10). While the Lower Jurassic Rønne and Hasle formations identified in the Pernille-1 well are recognized both in the Rønne Graben and on the Arnager Block, the upper Lower Jurassic through Lower Cretaceous interval established on the Arnager Block has not been identified in the Pernille-1 well (Fig. 5, Table 1). It is suggested that the discontinuous interval of the Arnager Block is contained within a wedge-shaped package thinning towards the north-west across the inversion anticline. The wedge-shaped body is separated from the underlying top Rønne-Hasle formations by an unconformity identified by the baselapping reflections (Fig. 10). The proposed interpretation implies that the Rønne-Hasle formations in the Rønne Graben underwent structural inversion during deposition of the overlying Jurassic – Lower Cretaceous package.

The Late Cretaceous structural inversion along the Arnager Block is analysed in a separate paragraph below.

Risebæk Graben

The Lower Jurassic Rønne and Hasle formations thin from the north-west and the south-east towards the apex of the Risebæk Graben indicating that the Risebæk Graben suffered mild inversion associated with north–westward tilting during deposition of the Rønne and Hasle formations in the early Jurassic (Fig. 2C). A structural analysis of the Risebæk Graben is outside the scope of the present paper and a comprehensive analysis has already been presented in Graversen (2004).

Seismic link between the Stina-1 well and onshore bedrock geology

Seismic line B88-14 traverses the Arnager Block from SSW to NNE where it terminates close to the Jurassic – Cretaceous boundary identified on the bedrock map (Figs 1, 3, 4). Integration of the seismic section with the geological profile constructed from the pre-Quaternary map links the northern part of the seismic line with the onshore Upper Triassic Kågerød Formation and overlying Lower Jurassic Rønne Formation; the Upper Cretaceous is identified at the top of the section (Figs 4, 7). The Lower Cretaceous Nyker Group and the Lower – Middle Jurassic Sorthat and Bagå formations were mapped on the seismics and

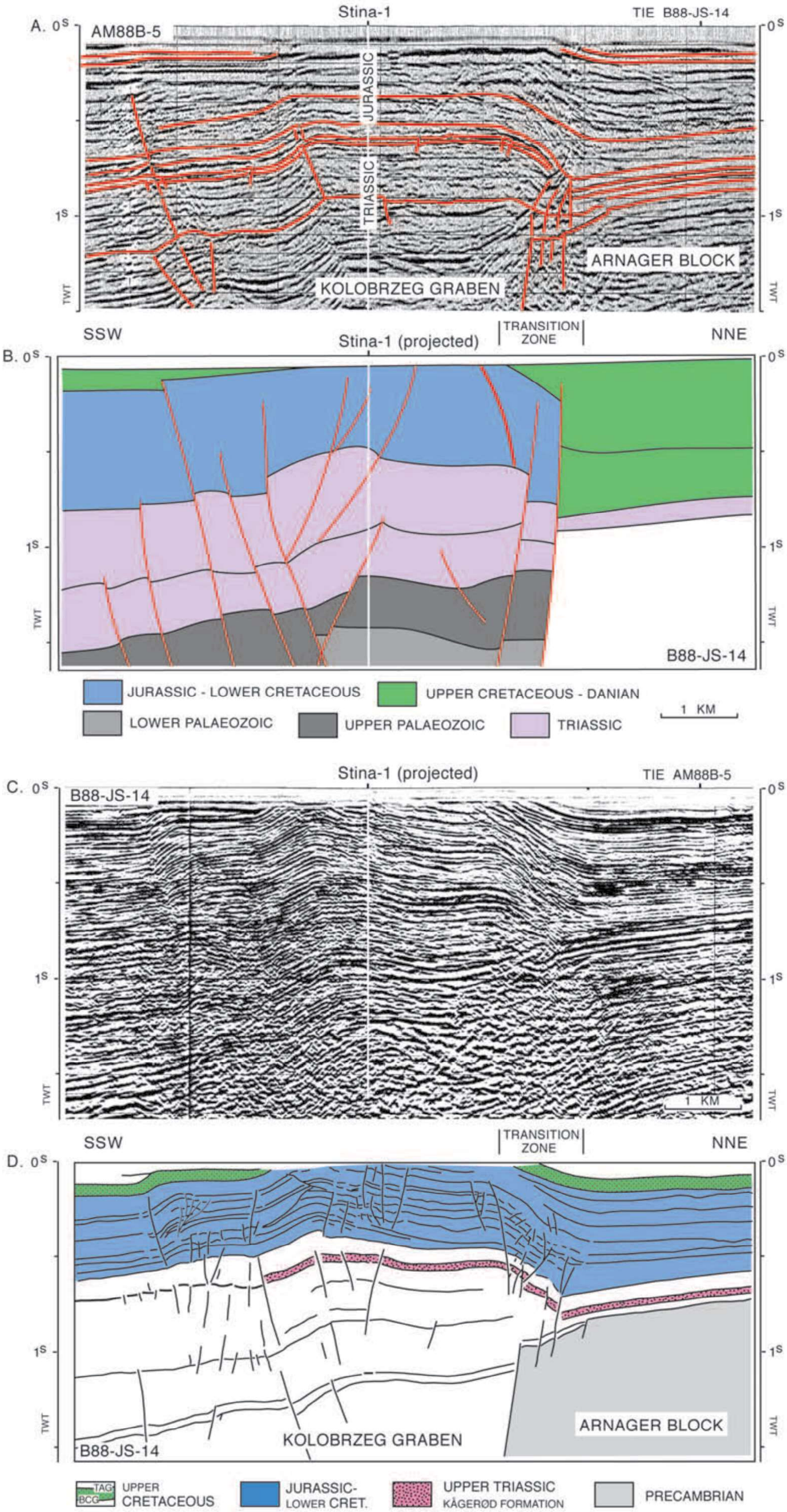


Fig. 8. Geological interpretations of the inversion structure drilled by the Stina-1 well. Positions of the interpreted sections shown in Fig. 1A. A: Reflection interpretation of seismic line AM88B-5. The interpretation illustrates continuity of the inverted upper Triassic-Jurassic interval from the Kolobrzeg Graben onto the Arnager Block. B: Geological interpretation of seismic line B88-14 (from Vejbæk 1997; see also Rasmussen 1989). The interpretation illustrates discontinuity of the Jurassic interval onto the Arnager Block. C: Seismic image of the Kolobrzeg Graben inversion structure, B88-14. D: Geological interpretation of the seismic section above. The interpretation favours continuity of the Upper Triassic Kågerød Formation and overlying Jurassic interval from the Kolobrzeg Graben onto the Arnager Block.

tied with the bedrock geology on the Arnager Block (Fig. 3) and in the Rønne Graben (Fig. 9; Graversen 2004). To the south, the seismic section is tied to the Stina-1 well (Figs 6–7). The proposed interpretation of the inversion zone indicates that the upper Upper Triassic – Middle Jurassic of the Stina-1 well can be traced onto the Arnager Block (Fig. 6). The Rønne Formation and uppermost Upper Triassic can be mapped across the Arnager Block to the northern part of B88-14, where the Rønne Formation traced from the Stina-1 well can be linked with the Rønne Formation identified on- and offshore south Bornholm. The Kågerød Formation onshore Bornholm can be tied to the upper Triassic marker that was traced across the Arnager Block from the Stina-1 well (Figs 4, 7). Likewise the Sorthat and Bagå formations proposed in the Stina-1 well join up with the Sorthat and Bagå formations mapped in the Rønne Graben (Fig. 7; Graversen 2004).

Late Cretaceous structural inversion of the Rønne Graben

Superimposed folds

The evolution of the inversion structures in the Rønne Graben can be evaluated from the geometry outlined on the pre-Quaternary geological map (Fig. 9A; Jensen & Hamann 1989). The map illustrates the boundary between the Rønne Graben and the Arnager Block separated by the SW–NE trending Rønne Fault. Within the Rønne Graben two fault blocks are separated by a reverse fault trending NW–SE perpendicular to the Rønne Fault. The Mesozoic package is folded and the fold trends parallel the reverse faults. The axes of the major F2 folds along the Rønne Fault plunge towards the SW, while the transverse minor F1 folds are governed by undulating fold axes plunging to the southeast and northwest. In agreement with the two sets of intersecting fold axes, F1 and F2, the outcrop pattern is interpreted to have resulted from erosion of an interference pattern produced by superimposed folds. The outcrop pattern to the southwest indicated by the Rabække Formation is thus interpreted to illustrate an arrowhead interference pattern established by superposition of the F2 folds on the older F1 folds i.e. the F1 folds plunging to the north-west and south-east were refolded by the younger F2 folds plunging to the south-west (see Pedersen 2000). The interpretation of the arrowhead structure to the south-west is in agreement with the relationship between the F1 and F2 folds in the north-east fault block. The interference patterns illustrate the occurrence of two inversion episodes after deposition of the Bavnodde Greensand Formation in the late Coniacian – early Santonian. This interpretation is in agreement with Jensen & Hamann (1989) and Vejbæk & Andersen (2002). However, Jensen & Hamann (1989) interpreted the structural evolution of the Rønne Graben according to a wrench fault model. They regarded the structural inversion along the Rønne Fault as an early 1st-order anticline while the transverse folds were considered to be later 2nd-order folds. The relative age of the two foldsets is thus reversed in the alternative model put forward in the present paper.

Reconstruction of the structural evolution

Based on internal reflection geometry, the Upper Cretaceous of the southern Rønne Graben and the Skurup Platform can be divided into a lower pre-inversion interval superseded by an upper syn-inversion series (Figs 2C, 11A). The lower Upper Cretaceous pre-inversion interval is characterized by parallel reflections, whereas the syn-inversion of the upper Upper Cretaceous rocks is characterized by convergent reflections and thinning towards the south-east. Structural analysis of the Upper Cretaceous has enabled a restoration of Late Cretaceous basin evolution (Fig. 11).

Reconstruction of the pre-inversion interval illustrates a stepwise thickening across normal faults from the Skurup Platform in the west and eastwards into the Rønne Graben. The interval is eroded over the eastern Rønne Graben and above the Arnager-Darlowo blocks to the southeast (Figs 2C, 11D). The syn-inversion series are characterized by internal

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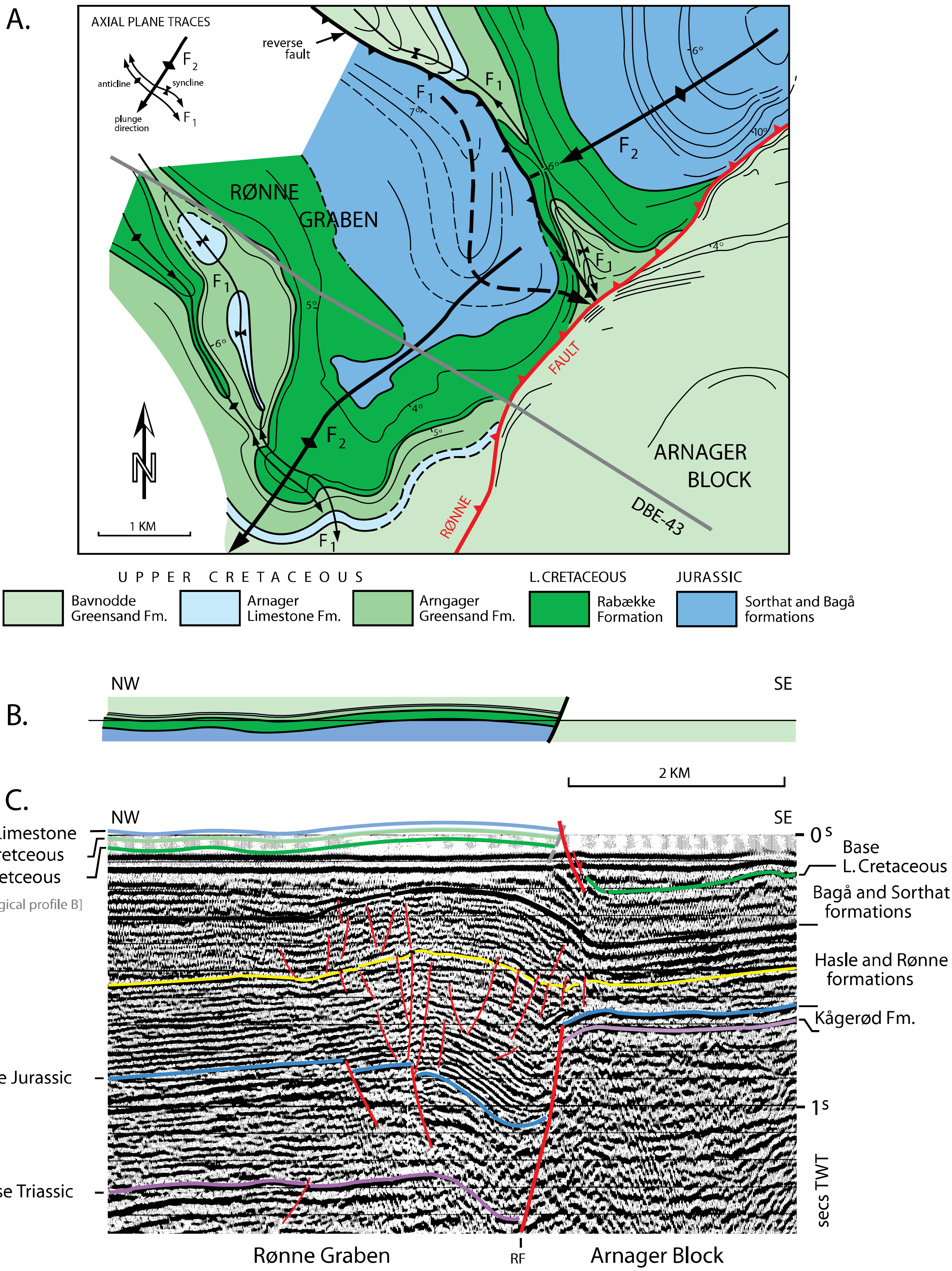
Fig. 9. A: Geological map of the Mesozoic formations in the east central Rønne Graben and adjoining Arnager block (detail of geological map in Jensen & Hamann 1989). Position of the map indicated in Fig. 3; heavy line indicates position of geological cross-section (B) and seismic line (C) below. Interpretation of axial plane traces by the present author. The geometry of the oucrop pattern around the southern F2 anticline is interpreted as an arrowhead interference pattern developed by refolding of early NW-SE striking F1 folds by the later F2 anticline plunging towards the southwest. B: Geological cross-section constructed from the geological map (A) by the present author. C: Extract of seismic line DBE-43 with geological interpretation.


A.
AXIAL PLANE TRACES
F2
anticline
syncline
plunge direction
F1
reverse fault
RØNNE GRABEN
F1
F2
ARNAGER BLOCK
DBE-43
RØNNE FAULT
1 KM
N
UPPER CRETACEOUS
L. CRETACEOUS
JURASSIC
Bavnodde Greensand Fm.
Arnager Limestone Fm.
Arngager Greensand Fm.
Rabække Formation
Sorthat and Bagå formations
B.
NW
SE
2 KM
C.
NW
SE
Arnager Limestone
Base U. Cretceous
Base L. Cretceous
[From geological profile B]
Base Jurassic
Base Triassic
0 s
1 s
secs TWT
Base L. Cretaceous
Bagå and Sorthat formations
Hasle and Rønne formations
Kågerød Fm.
Rønne Graben
RF
Arnager Block

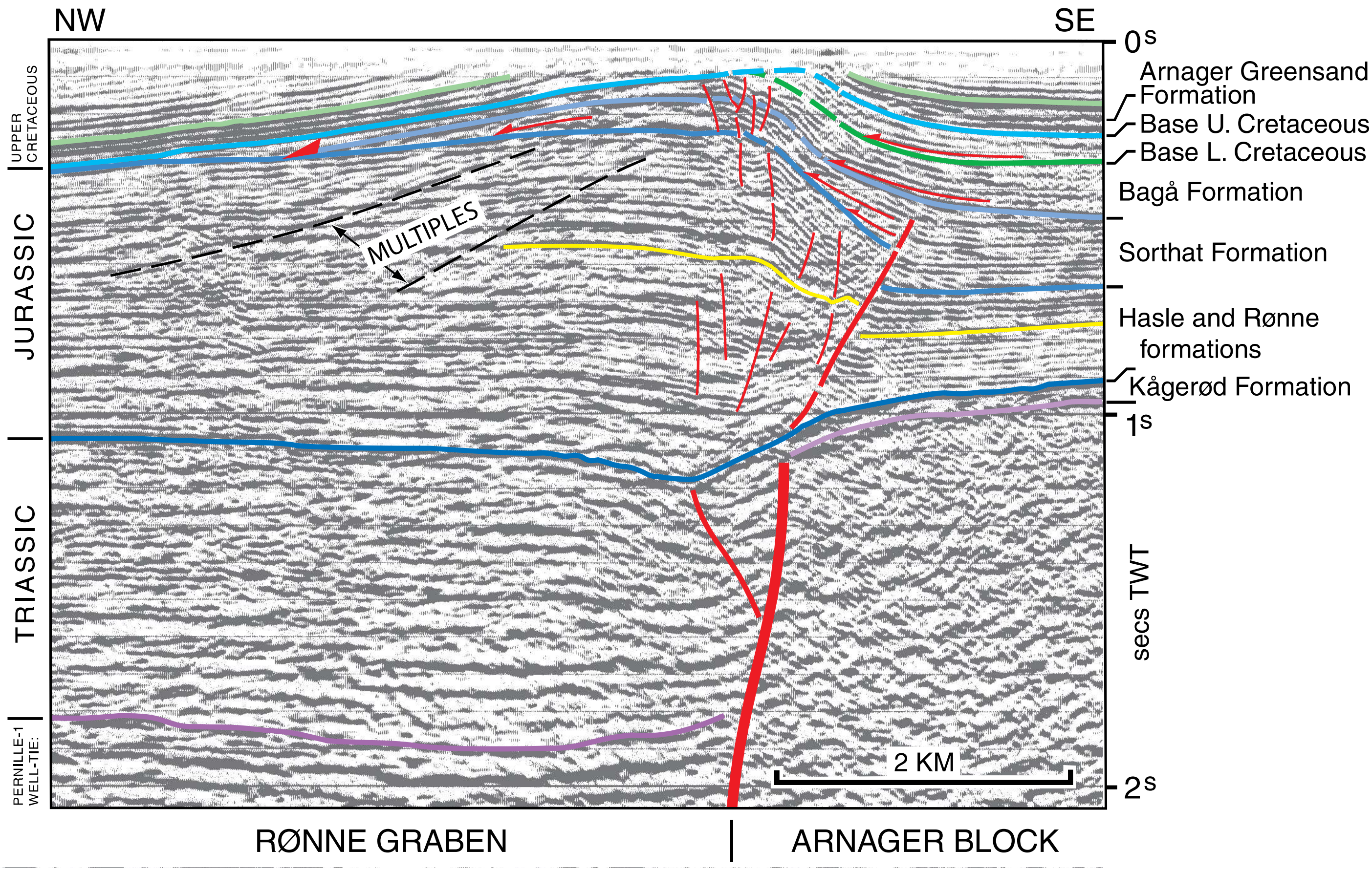


Fig. 10. Detail of seismic line Jebco B88-07. The seismic image strikes across the structural inversion in the eastern Rønne Graben along the Arnager Block; position indicated in Fig. 2. The geological interpretation illustrates that reverse faulting was limited. The pinch out of the Sorthat and Bagå formations across the inversion anticline is interpreted to illustrate that early inversion of the southern Rønne Graben was active during deposition of these formations in the late Early-Middle Jurassic. Baselapping reflections at the base Lower Cretaceous indicate that limited inversion was active in the Early Cretaceous. The Lower Cretaceous and the upper part of the Bagå Formation are truncated by the base Upper Cretaceous unconformity.

reflections that converge towards the south-east against structural inversion zones. This relationship is interpreted to result from folding and uplift of the syn-inversion series around the inversion monoclines outlined by the pre-inversion interval. This interpretation is in accordance with Thomas & Deeks (1994) and Vejbæk & Andersen (2002). The inverted (folded) pre-inversion interval is truncated and overlain by the early syn-inversion series within the eastern Rønne Graben (Fig. 11C).

The restored syn-inversion stages (Fig. 11B, C) are interpreted to illustrate that during deposition of the upper Upper Cretaceous the Skurup Platform subsided, while the eastern Rønne Graben (together with the Arnager Block) was uplifted and eroded. During differential subsidence/uplift, the Rønne Graben section was tilted towards the north-west and at the same time underwent structural inversion. The thickest syn-inversion section was deposited on the Skurup Platform indicative of continuous subsidence to the north-west (Fig. 11A). Folded Cretaceous pre-inversion reflections in the eastern Rønne Graben and truncated by early syn-inversion series extending from the north-west, suggest that inversion and uplift followed by erosion started in the eastern Rønne Graben (along with uplift and erosion of the Arnager Block). The development illustrates that the Upper Cretaceous pre-inversion package was eroded away above the inversion anticline outlined by the underlying Jurassic – Lower Cretaceous in the eastern Rønne Graben. This indicates a net uplift corresponding to the maximum missing section of the Upper Cretaceous pre-inversion interval i.e. in the order of 500 msecs TWT during deposition of the Cretaceous syn-rift series (Fig. 11D). The uplift (»erosion) above the Arnager Block is estimated to be in the order of 300 msecs TWT. The subsidence of the Skurup Platform to the north-west is in the order of

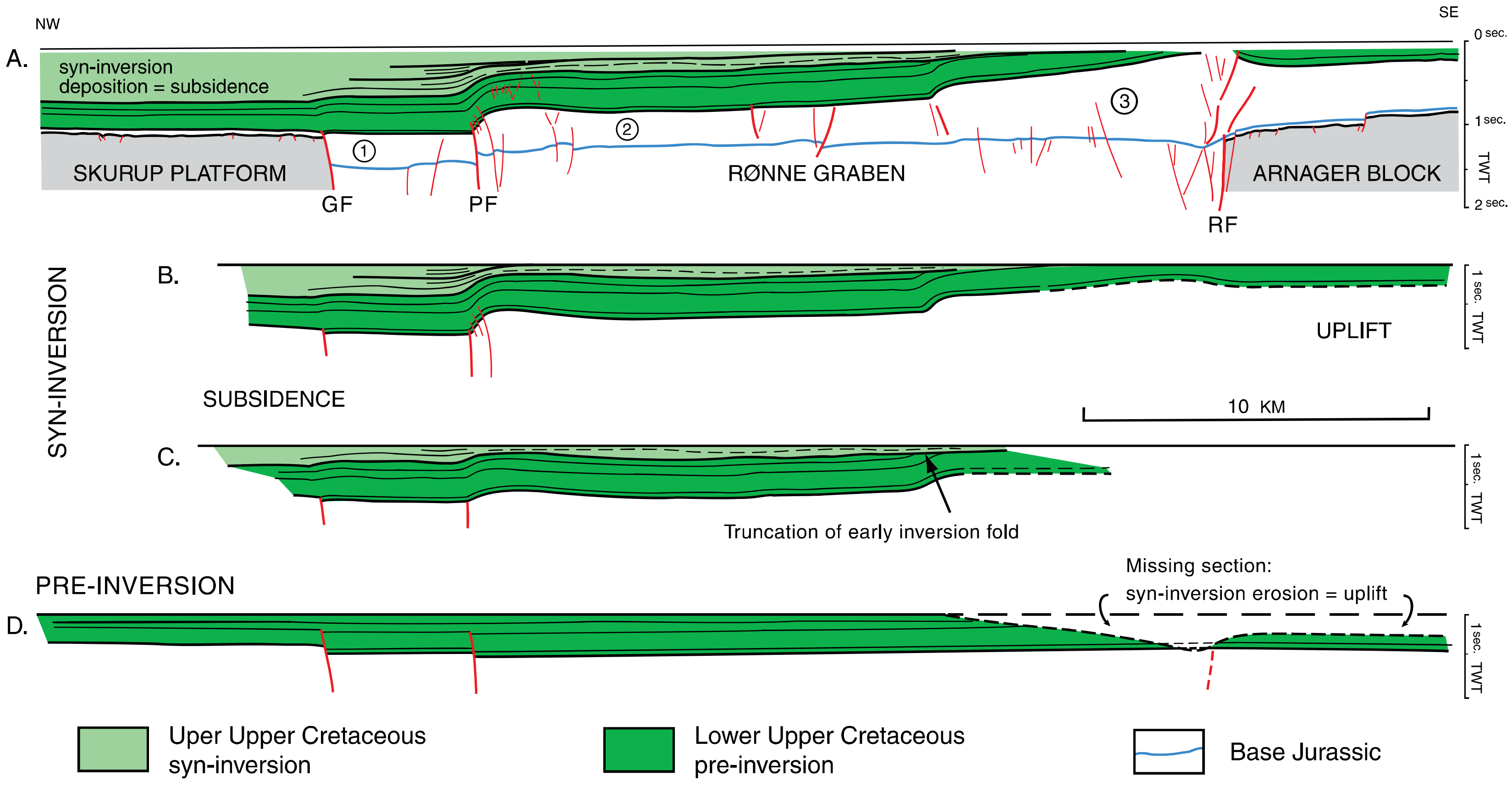


Fig. 11. Geological interpretation of the Late Cretaceous structural evolution across the Rønne Graben between the Skurup Platform and the Arnager Block. GF: Gat Fault; PF: Pernille Fault; RF: Rønne Fault. A: Cross section of the Jurassic-Cretaceous interval (recent stage extracted from Fig. 2C). 1-3 indicates positions of seismic interval velocities of the Jurassic package given in the text. B, C: Interpretation of early inversion stages: Subsidence and deposition prevailed to the northwest, whereas uplift and erosion were active to the southeast. D: Reconstruction of the pre-inversion stage. Stepwise thickening of the lower Upper Cretaceous interval towards the SE across normal graben faults indicates minor extension associated with differential subsidence during the early Late Cretaceous deposition.

600 msecs TWT equivalent to the thickness of the syn-inversion series. Differential subsidence/uplift across the Rønne Graben between the Skurup Platform and the Arnager Block is thus in the order of 1 sec TWT during deposition of the upper Upper Cretaceous package.

Seismic velocities

Seismic stacking velocities of the Jurassic interval in the Rønne Graben extracted from seismic section B88-07 change in a systematic way from west to east (Fig. 11A):

1. Rønne Graben, west	(SP 3527):	3576-4390 m/sec.
2. Rønne Graben, central	(SP 3207):	3478-4590 m/sec.
3. Rønne Graben, east	(SP 2647):	2675-4098 m/sec.

The stacking velocities from the top of the Jurassic section are *c.* 1 km/sec higher in the western and central Rønne Graben as compared with the eastern graben section. The velocities at the base of the Jurassic section increase to *c.* 4.5 km/sec to the west, while the velocity in the eastern Rønne Graben only reaches *c.* 4.1 km/sec despite the much larger thickness of the Jurassic interval to the east. If the Jurassic of the Rønne Graben was not inverted until the post-Cretaceous (Fig. 2A, B), one should expect about equal seismic velocities in the upper part of the Jurassic interval. However, the increase of *c.* 1 km/sec from east to west indicates that the Jurassic in the eastern Rønne Graben was never buried to the same depth as the Jurassic in the western part of the graben. The low velocities at the base of the thick Jurassic section to the east indicate that the higher velocities at the base of the thinner Jurassic in the western graben section could not have been obtained prior to the Late Cretaceous syn-inversion subsidence and associated burial. The observed variations of the seismic velocities are in agreement with the structural analysis above i.e. Late Cretaceous syn-inversion subsidence of the western Rønne Graben (along with the Skurup Platform) and contemporaneous uplift of the eastern graben section (along with the Arnager Block).

Discussion

Stratigraphy

Clarification of the stratigraphy in the Arnager Block is not only of interest for the local geology offshore south Bornholm. The area has a key position in the understanding of the structural evolution of the Tornquist Zone, as the Rønne Graben and surrounding structural elements are positioned in the transition zone between the Teisseyre-Tornquist Zone to the south-east and the Fennoscandian Border Zone to the north-west (Fig. 1B). The proposed revision of the Mesozoic stratigraphy to the east of the Rønne Graben i.e. on the Arnager Block, in the Risebæk Graben, and on the Darlowo Block (Fig. 2C) is established by integration of reflection seismic with bedrock geology. The seismic ties are based on published on- and offshore pre-Quaternary geological maps and cross-sections constructed from these maps (Figs 3–4, 9) (Gry 1969; Hamann 1987; Jensen & Hamann 1989; Graversen 2004). The basal post-rift deposit above the Risebæk Graben has been tied to the onshore Upper Triassic Kågerød Formation (Fig. 4) and this relationship precludes the occurrence of Jurassic within the Risebæk Graben (Fig. 2C). The seismic ties have demonstrated that the Upper Triassic – Lower Cretaceous package identified along the south coast of Bornholm continues southwards on the Arnager Block below a thin Upper Cretaceous cover (Fig. 7). In addition, the Lower – Middle Jurassic Sorthat and Bagå formations encountered in the Rønne Graben have been traced onto the Arnager Block (Fig. 9) where they pinch out in a landward direction (Fig. 7; Graversen 2004).

The basal Upper Cretaceous angular unconformity identified on the bedrock map (Fig. 3) is repeated on the cross-section of the Arnager Block (Fig. 7) where the Lower Jurassic and Lower Cretaceous in turn are cut out towards the north-west (map) and south-west (cross-section) respectively. The pre-Upper Cretaceous younging directions are in agreement with the general dip towards the south-west. Instead of the thick Upper Cretaceous cover interpreted above the Risebæk Graben and the flanking Arnager and Darlowo blocks (Fig. 2A, B), the seismic-to-bedrock ties established in the present paper illustrates a geological section equivalent to the established onshore Bornholm Mesozoic stratigraphy (Fig. 2C; Gry 1969; Hamann 1987; Koppelhus & Nielsen 1994; Surlyk *et al*. 1995; Graversen 2004).

The syn-rift/post-rift age relationship established for the Risebæk Graben is similar to the dynamic stratigraphy of the Triassic rift basins situated in Scania to the northwest along the south-west border of the Tornquist Zone. In Scania, the NNE–SSW trending Svedala Fault bound the Höllviken Graben. The syn-rift package is of Early to Late Triassic age while the early post-rift sediments are established as the Kågerød Formation of late Late Triassic age (Troedsson 1942; Norling & Bergström 1987; Norling *et al*. 1993; Erlström *et al*. 1997). Based on this relationship, the Kågerød Formation is interpreted to continue onto the Skurup Platform below the Cretaceous (Fig. 2C). The Kågerød Formation extended as a blanketing deposit across the Triassic grabens and bounding fault blocks, and the formation identifies a major change in the tectonic regime.

Seismic-to-well ties (Fig. 6) and reinterpretation of the inversion structure in the Kolobrzeg Graben along the southern margin of the Arnager Block (Fig. 8) enabled the construction of a seismic and stratigrapic link between the Stina-1 well and onshore bedrock geology (Fig. 7).

Jurassic – Early Cretaceous basin inversion

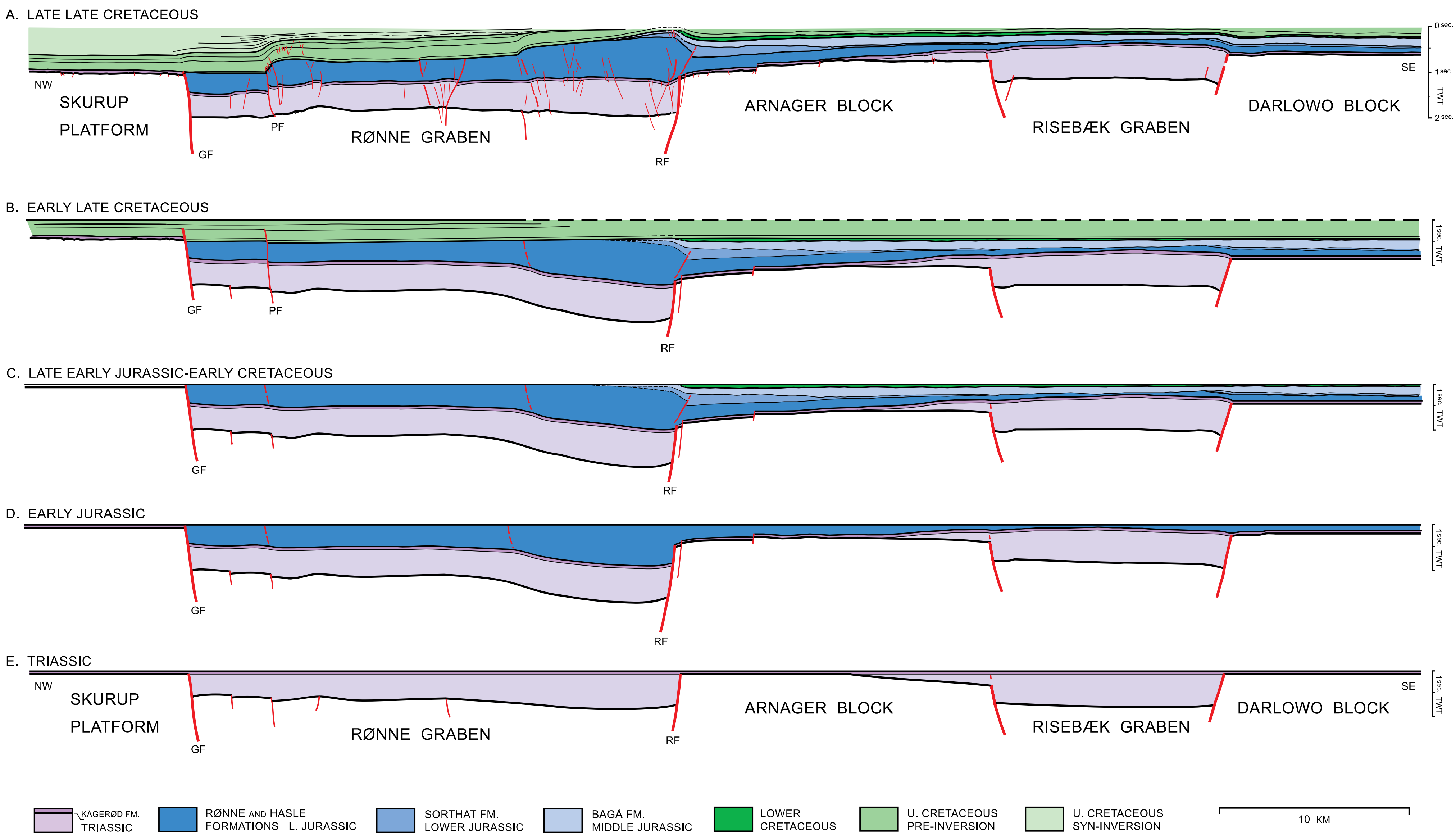
Inversion of the southern Rønne Graben and the Kolobrzeg Graben resulted in folded and discontinuous primary seismic reflections in the deformation zones along the Arnager Block. However, the line interpretations of the seismic profiles indicate that the Jurassic interval of the graben sections can by traced across the transition zone above the border faults and onto the Arnager Block (Figs 8A, 9C9). The continuous reflections do not give room for an interpretation where the graben border fault extends up through the flank of the inversion anticline and totally separates the Jurassic graben sediments from the sediment package of the Arnager Block. In accordance with this, the interpretation in the present paper illustrates a continuation of the upper Upper Triassic sediments and the Rønne and Hasle formations from the Stina-1 well in the Kolobrzeg Graben and onto the Arnager Block (Fig. 6B). As uplift during inversion increases, the interpretation of the deformation zones becomes increasingly difficult. It is still possible - with some difficulty - to trace the Upper Triassic – Jurassic of the Kolobrzeg Graben onto the Arnager Block along B88-14 (Fig. 8C–D). However, it may not be possible to interpret the stratigraphy across the border fault between the Rønne Graben and the Arnager Block along B88-07 without a detailed knowledge of the stratigraphy on either side (Fig. 10).

In addition to the Late Cretaceous inversion (Vejbæk & Andersen 2002) the revised stratigraphy has enabled the recognition of early structural inversion of the Risebæk Graben and in the Rønne and Kolobrzeg grabens along the Arnager Block during the Early – Mid Jurassic and the Early Cretaceous (Figs 2C, 6, 8, 10) (Graversen 2004). Timing of the inversion along the Arnager Block is in agreement with episodes of differential subsidence/uplift within the Arnager Block associated with seaward deposition of the Sorthat and Bagå formations along with possible landward erosion in the Early – Mid Jurassic. For the Early Cretaceous, Noe-Nygaard & Surlyk (1988) and Jensen & Hamann (1989) suggested that structural inversion (of the Rønne Graben) during deposition of the Nyker Group was responsible for the restricted development of the Lower Cretaceous in the Rønne Graben (i.e. non-deposition/erosion), where only the Rabække Formation represents the Lower Cretaceous. An alternative explanation to the restricted occurrence of the Nyker Group in the Rønne Graben is that the Lower Cretaceous was partly eroded during the structural uplift/inversion in the Barremian–Aptian and prior to the deposition of the Arnager Greensand Formation at the base of the Upper Cretaceous angular unconformity.

The lower Upper Cretaceous pre-inversion package shows a uniform thickness across the inversion zone in the eastern Rønne Graben (Figs 10–11). The pre-inversion interval separates the Jurassic – Early Cretaceous inversion from the Late Cretaceous inversion episodes and the lower Upper Cretaceous package identifies a major change in the tectonic regime.

Late Cretaceous structural inversion across the southern Rønne Graben

Erlström *et al*. (1997) modeled the evolution of the Tornquist Zone according to the interpretation in Figure 2A. The stratigraphy illustrated in sections A and B (Fig. 2A, B) invokes an interpretation where the inversion of the Rønne Graben is concentrated in a reverse fault movement along the eastern border fault of the Rønne Graben after deposition of the involved Upper Cretaceous sediments. In this case reverse fault movements associated with uplift of the eastern Rønne Graben were in the order of 1 sec. TWT and differential movements between the Arnager Block and the Skurup Platform negligible. However, both the structural analysis of the Upper Cretaceous across the Rønne Graben and the seismic stacking velocities of the Jurassic sediments indicate that the Late Cretaceous structural inversion of the Jurassic – lower Upper Cretaceous package was linked to differential subsidence/uplift between the Skurup



A. LATE LATE CRETACEOUS
NW
SKURUP PLATFORM
PF
GF
RØNNE GRABEN
RF
ARNAGER BLOCK
RISEBÆK GRABEN
DARLOWO BLOCK
SE
0 sec.
1 sec.
TWT
2 sec.
B. EARLY LATE CRETACEOUS
GF
PF
RF
1 sec. TWT
C. LATE EARLY JURASSIC-EARLY CRETACEOUS
GF
RF
1 sec. TWT
D. EARLY JURASSIC
GF
RF
1 sec. TWT
E. TRIASSIC
NW
SKURUP PLATFORM
GF
RØNNE GRABEN
RF
ARNAGER BLOCK
RISEBÆK GRABEN
DARLOWO BLOCK
SE
1 sec. TWT
KÅGERØD FM.
TRIASSIC
RØNNE AND HASLE FORMATIONS L. JURASSIC
SORTHAT FM. LOWER JURASSIC
BAGÅ FM. MIDDLE JURASSIC
LOWER CRETACEOUS
U. CRETACEOUS PRE-INVERSION
U. CRETACEOUS SYN-INVERSION
10 KM

Platform and the Arnager-Darlowo Block. In addition, it was associated with northwestward tilting of the Rønne Graben during deposition of the upper Upper Cretaceous syn-inversion series (Figs 11, 12A, B). The revised inversion model developed in this paper is supported by organic maturity data from the Rønne Formation in the Pernille-1 well in the western Rønne Graben. The reflectance values fall on the regional coalification curve and this indicates that the present depth of the Jurassic deposits corresponds to the maximum burial depth (Petersen *et al*. 2003). Organic maturity measured on the Sose Bugt Member of the Rønne Formation in the Sose Bugt section on the northern Arnager Block indicates a post-Early Cretaceous uplift of *c*. 290 m (Petersen *et al*. 1996; Petersen *et al*. 2003). This number is of the same magnitude as the uplift modeled on the southern Arnager Block along line B88-07. The Late Cretaceous syn-inversion uplift and erosion of the lower Upper Cretaceous package is estimated to *c*. 300 msecs (Fig. 11). This is equivalent to *c*. 300 m when using the seismic interval velocities around 2 km/sec read from the uppermost levels of the seismic section. The correspondence between the uplift numbers suggests that the post-Early Cretaceous uplift established from organic maturity data was coupled with the Late Cretaceous uplift of the Arnager Block during inversion of the Rønne Graben.

Facing page:
Fig. 12. Reconstruction of the Triassic through Cretaceous structural evolution of the Rønne Graben, the Risebæk Graben, and the associated Skurup Platform and Arnager-Darlowo Block. A: Late Cretaceous structural inversion of the Rønne Graben associated with subsidence of the Skurup Platform and uplift of the Arnager-Darlowo Block. B: Early Late Cretaceous regional subsidence associated with limited normal faulting across the Gat and Pernille faults. C: In the late Early-Middle Jurassic structural inversion was active in the eastern Rønne Graben during deposition of the Sorthat and Bagå formations on the Arnager Block. It is uncertain to what extent the Lower Cretaceous was deposited in the Rønne Graben prior to erosion at the base Upper Cretaceous. D: In the early Early Jurassic, subsidence of the southern Rønne Graben was associated with subsidence of the Arnager-Darlowo Block. Major faulting was concentrated along the Gat Fault at the NW border of the Rønne Graben; maximum subsidence was attained along the Rønne Fault at the transition between the Rønne Graben and the Arnager Block. The subsidence was associated with tilting and minor faulting of the Arnager Block along with structural inversion of the Risebæk Graben. E: Triassic subsidence was focused in the Rønne Graben and the Risebæk Graben. Differential graben subsidence stopped during the Late Triassic where regional subsidence prevailed during deposition of the Kågerød Formation. GF: Gat Fault; PF: Pernille Fault; RF: Rønne Fault.

Basin inversion and intraplate deformation of the Alpine foreland

Structural inversion of the Tornquist Zone is dominated by Late Cretaceous through Early Paleogene compressional deformation and uplift of the Polish Trough (incl. Kolobrzeg Graben), the Fennocandian Border Zone (incl. Bornholm), and the Danish Basin (Fig. 1B) (Ziegler 1990). The deformation episodes coincide with major phases of the Alpine Orogeny of the Carpathians and Eastern Alps, and a causal relationship between (Alpine) continental collisional compression and intraplate deformation of the foreland basins is now generally accepted (e.g. Ziegler *et al*. 1995; Vejbæk & Andersen 2002). In the overlap zone between the Polish Trough (Teisseyre-Tornquist Zone) and the Fennoscandian Border Zone, the Late Cretaceous structural inversion along the Arnager Block was superposed on an early structural inversion established during the Jurassic – Early Cretaceous (Figs 8, 10). In the Alpine domain, the Jurassic and earliest Cretaceous is characterized by rifting and seafloor spreading (Ziegler 1990; Coward *et al*. 2003) during deposition of the Jurassic – Lower Cretaceous in the Bornholm area. The driving mechanism for the early inversion (Jurassic – Early Cretaceous) around the Arnager Block therefore can not be attributed to Alpine foreland compression. An alternative cause for the early inversion may be sought in the intraplate stresses established in connection with the initiation and uplift of the Central North Sea Dome in the Jurassic (Ziegler 1990; Underhill & Partington 1993; Graversen 2002. See also Andsbjerg *et al*. 2003; Michelsen *et al*. 2003; Nielsen 2003).

Conclusions

The conclusions based on the revised stratigraphy and structural evolution offshore south-west Bornholm are illustrated in a number of geological cross-section time slices (Fig. 12). Major changes in interpretations of the Mesozoic geological evolution, analysed from the Skurup Platform (NW) and across the Rønne Graben, the Arnager Block and the Risebæk Graben to the Darlowo Block (SE) are based on the revised geological cross-section discussed in the present paper (Fig. 2C). Rifting and subsidence were active in the Risebæk Graben and in the Rønne Graben during the Triassic and renewed faulting continued the subsidence that was established by Palaeozoic rifting. The Upper Triassic Kågerød Formation is seen (interpreted) as a blanketing deposit across the entire section (Fig. 12E). During deposition of the Rønne and Hasle formations in the Early Jurassic, subsidence and deposition was at a maximum in the eastern Rønne Graben, where the Jurassic attained its greatest thickness. Along with the graben subsidence, the Arnager Block was tilted towards the Rønne Graben and the Risebæk Graben suffered mild inversion (Fig. 12D; Graversen 2004). Structural inversion was attained to the south in the Rønne Graben along the southern Arnager Block during deposition of the Lower – Middle Jurassic Sorthat and Bagå formations and the Lower Cretaceous Nyker Group (Fig. 12C). In the early Late Cretaceous, the structural inversion had ceased. During deposition of the lower Upper Cretaceous, minor extension was active across the western graben faults (Fig. 12B). It is not possible to evaluate the movements along the eastern Rønne Graben due to later erosion. However, extensional faulting was probably restricted. The Late Cretaceous structural inversion of the Rønne Graben was associated with differential subsidence/uplift between the Skurup Platform and the Arnager-Darlowo Block and contemporaneous tilting of the Rønne Graben towards the north-west (Fig. 12A). These movements gave rise to structural inversion along with minor reverse faulting.

The tectonic activity can be subdivided into three major regimes separated by periods of relative quiescence. Breaks in fault block activity are identified by the blanketing deposits, with only minor faulting during the Late Triassic (the Kågerød Formation) and in the early Late Cretaceous (the pre-inversion Upper Cretaceous deposits) (Figs 11, 12E, B). The early graben activity in the Triassic was characterized by subsidence along opposing graben border faults in the Rønne Graben and the Risebæk Graben prior to deposition of the Kågerød Formation (Fig. 12E). In the second tectonic phase, i.e. the Early Jurassic through Early Cretaceous, subsidence of the Risebæk Graben was discontinued and the Kågerød Formation is established as a post-rift deposit relative to the Risebæk Graben. Major changes in the structural evolution are related to the interaction between the Rønne Graben and the adjoining Arnager Block. In the Early Jurassic, the Arnager and Darlowo blocks subsided along with the Rønne Graben. The Arnager Block was tilted towards the north-west during differential subsidence along the Rønne Fault in the eastern Rønne Graben while the Risebæk Graben suffered mild inversion (Fig. 12 D). Subsidence of the southern Rønne Graben ceased in the late Early Jurassic – Early Cretaceous. The Arnager and Darlowo blocks continued to subside while structural inversion was active in the eastern Rønne Graben (Fig. 12C). During the third tectonic phase, the Late Cretaceous structural inversion of the Rønne Graben was associated with westward tilting of the graben section linked with subsidence of the Skurup Platform and contemporaneous uplift of the Arnager-Darlowo Block. Reverse faulting was limited (Figs 11, 12A).

The structural development during inversion of the Rønne Graben is focused on the evolution of the Tornquist Zone. It should be realized, however, that the movements identified between the Arnager Block and the Skurup Platform are a consequence of movements between the East European Platform and the Northwest European Craton, which may have influenced the regional setting over a much wider area (Graversen 2004).

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