Structural analysis of superposed fault systems of the Bornholm horst block, Tornquist Zone, Denmark

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The Bornholm horst block is composed of Precambrian crystalline basement overlain by Palaeozoic and Mesozoic cover rocks. The cover intervals are separated by an angular unconformity and a hiatus spanning the Devonian through Middle Triassic interval. Late Palaeozoic faulting of the Early Pal-aeozoic Baltica platform is correlated with early-middle Carboniferous deformation in the Variscan foreland and with faulting associated with dolerite dyke injection in Skåne in the Late Carboniferous – Early Permian. The Palaeozoic fault systems are striking NW-SE and WNW-ESE and the platform series are dipping towards the SE and ESE respectively.

The Mesozoic faulting was associated with the development of a horst-graben framework in the Bornholm-Skåne segment of the Sorgenfrei-Tornquist Zone. Mesozoic fault subsidence started in the Rønne Graben in the Triassic. In the Jurassic the Arnager-Sose block became active, cut off from the Bornholm block; in addition the Læså Graben (new) and the Øle Å fault block complex (new) were cut into the central Bornholm block from the south. In the Late Cretaceous the central Bornholm block was perforated by isolated fault blocks, i.e. the Nyker block, the Bøsthøj block and the Lobbæk block (new) along with subsidence of the Holsterhus block and renewed subsidence of the Arnager-Sose block. The Mesozoic series are dipping towards the southwest.

The Palaeozoic fault systems were associated with two-dimensional plane strain during ENE-WSW and NNE-SSW extension. By contrast the Jurassic and Cretaceous fault systems were associated with three-dimensional strain with maximum extension striking NE-SW and secondary extension strik-ing NW-SE. The Mesozoic palaeostress fields were associated with the break down of the Pangea supercontinent.

Keywords: Tornquist Zone, Bornholm horst block, superposed fault systems, two-dimensional plane strain, three-dimensional strain.

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The pre-Quaternary geology of Bornholm is composed of a Precambrian crystalline basement overlaid by Lower Palaeozoic and Mesozoic sediments that are broken down into a mosaic of lower order fault blocks (Fig. 1). The island of Bornholm constitutes the emergent part of a composite horst block, the Bornholm Block, and the N-S trending eastern part of the Rønne Graben along the west coast of the island (Fig. 2). Structural elements of Bornholm include faults and fractures of the Precambrian terrain (Milthers 1930; Micheelsen 1961; Münther 1973), Precambrian dolerite dykes (Milthers 1930; Callisen 1934; Münther 1945, 1973), a Palaeozoic (?) dyke (Jensen 1989), Lower Cambrian sandstone-filled fissures (Ussing 1899; Milthers 1930; Callisen 1934; Bruun-Petersen 1975; Katzung 1996), and faults of the Palaeozoic and Mesozoic series (Gry 1960, 1969a, b; Hamann 1987).

The present paper deals with a structural analysis of the superposed fault and fracture systems based on the map-scale outcrop pattern of the bedrock onshore Bornholm. Field investigations were not undertaken as part of the present study. The main emphasis is on the Phanerozoic fault systems associated with the evolution of the Tornquist Zone. In order to be able to analyze the repeated Mesozoic faulting of the Rønne Graben and the Arnager-Sose block there is included an overview of the Mesozoic tectonostratigraphy. The analysis has enabled the establishment of a number of fault and fracture systems associated with the Precambrian, and the Palaeozoic and Mesozoic eras. Special interest has been focused on basement-cover relationships, Mesozoic faulting of the Palaeozoic bedrock, and evaluation of the palaeostress fields.

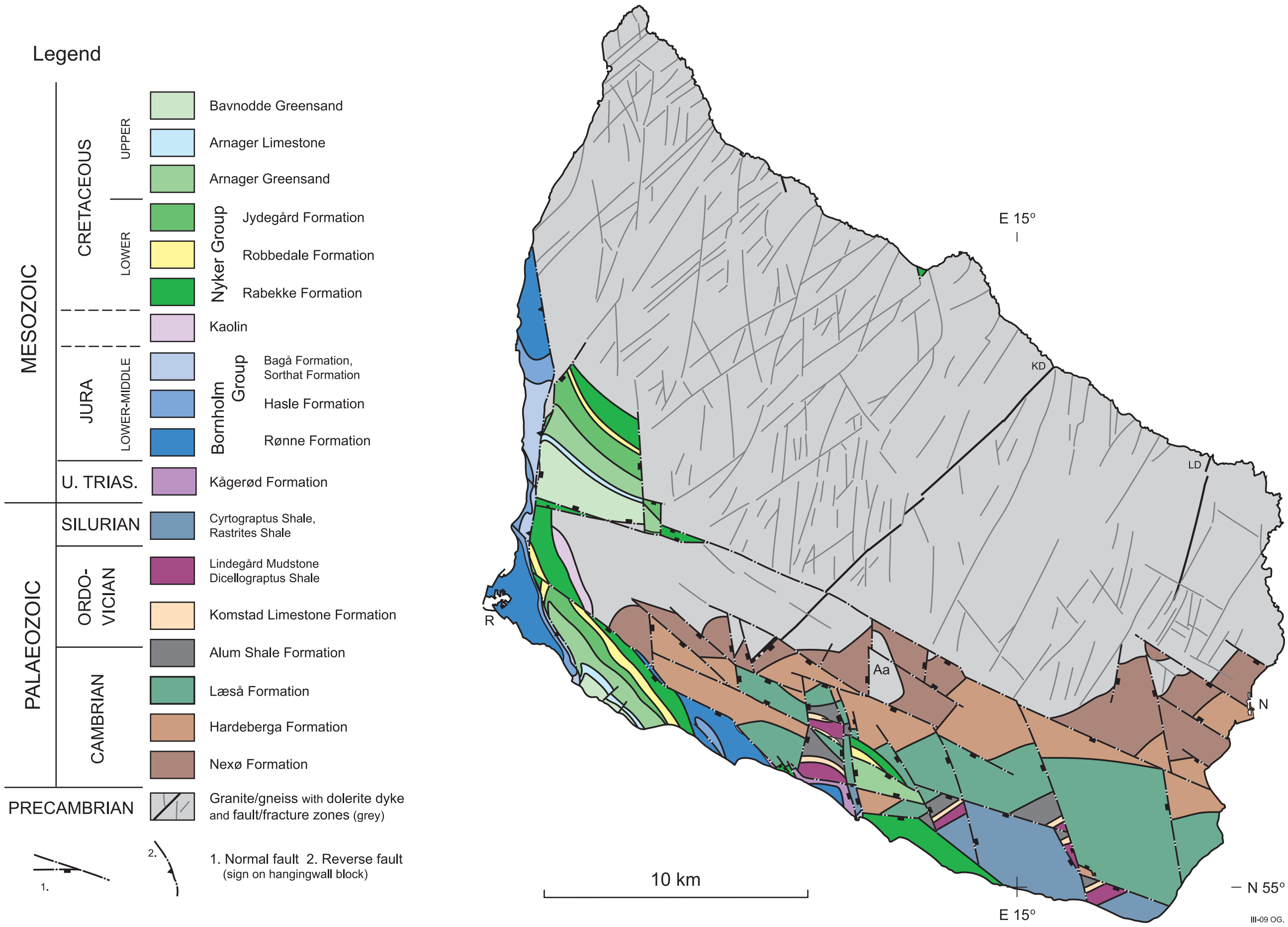


Fig. 1. Bedrock geology of Bornholm. The map is compiled from Gry (1969a, b), Münther (1973), Hamann (1987) and Nielsen (1988) and fault/fracture zones from Fig. 5. KD: Keldseå dyke; LD: Listed dyke; R: Rønne; Aa: Aakirkeby; N: Nexø.

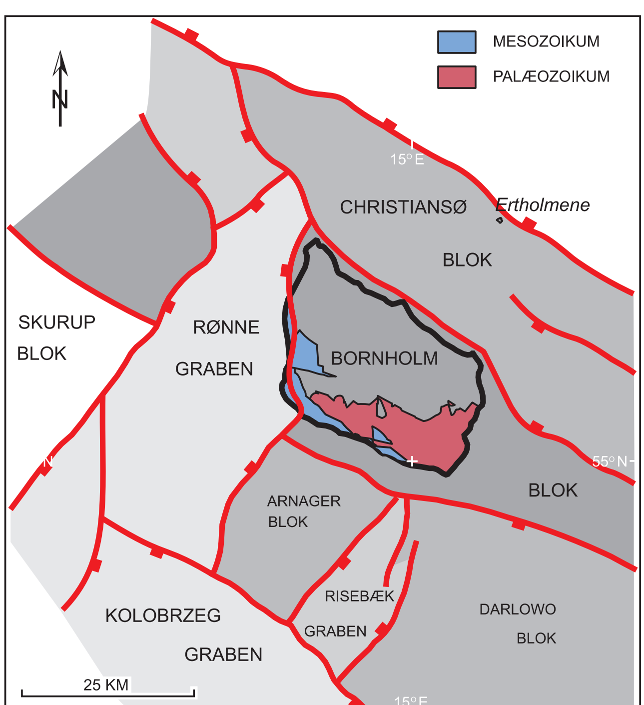


Fig. 2. Major fault blocks of the Bornholm region. The fault pattern is based on Vejbæk & Britze (1994) and Vejbæk (1997).

Geological setting

The Bornholm horst block together with the surrounding fault blocks (Fig. 2) make up an integral part of the composite Tornquist Zone in the southern Baltic Sea (Fig. 3A). The Tornquist Zone is a 50- to more than 100 km wide intracontinental fault zone extending from Skagerrak in the eastern North Sea Basin towards the southeast to the Black Sea. The fault zone separates the Baltic Shield and the East European Platform to the northeast from the Northwest European Craton to the southwest (Fig. 3B). The Tornquist Zone is divided into the Sorgenfrei-Tornquist Zone to the northwest and the Teisseyre-Tornquist Zone to the southeast (EUGENO-S Working Group 1987; Berthelsen 1998). The two NW-SE trending fault zones overlap at the Bornholm fault block complex, where the NE-SW trending Rønne Graben and Risebæk Graben cut across the regional trend (Figs 2, 3) (Graversen 2004a, b). Based on the structural and tectonic differences the Sorgenfrei-Tornquist Zone is further subdivided into the Kattegat-Skagerrak segment to the northwest and the Bornholm-Skåne segment to the southeast (Fig. 3A). The Bornholm-Skåne segment is characterized by uplift illustrated by the development of a horst-graben morphology with numerous elevated horst blocks, where the Precambrian basement is exposed at the surface (Fig. 4). The basement horst blocks are 5-25 km wide and up to 50 km long. The Bornholm block to the southeast and the Hallands Åsen block to the northwest outline the extent of the Bornholm-Skåne segment. The onshore sedimentary cover of the graben blocks and the deeper seated part of the horst blocks is made up of Lower Palaeozoic and Mesozoic series (Bergström et al. 1988) (Fig. 1).

The high level of the Precambrian basement in the Bornholm-Skåne segment contrasts with the deep-seated position of the basement in the Kattegat-

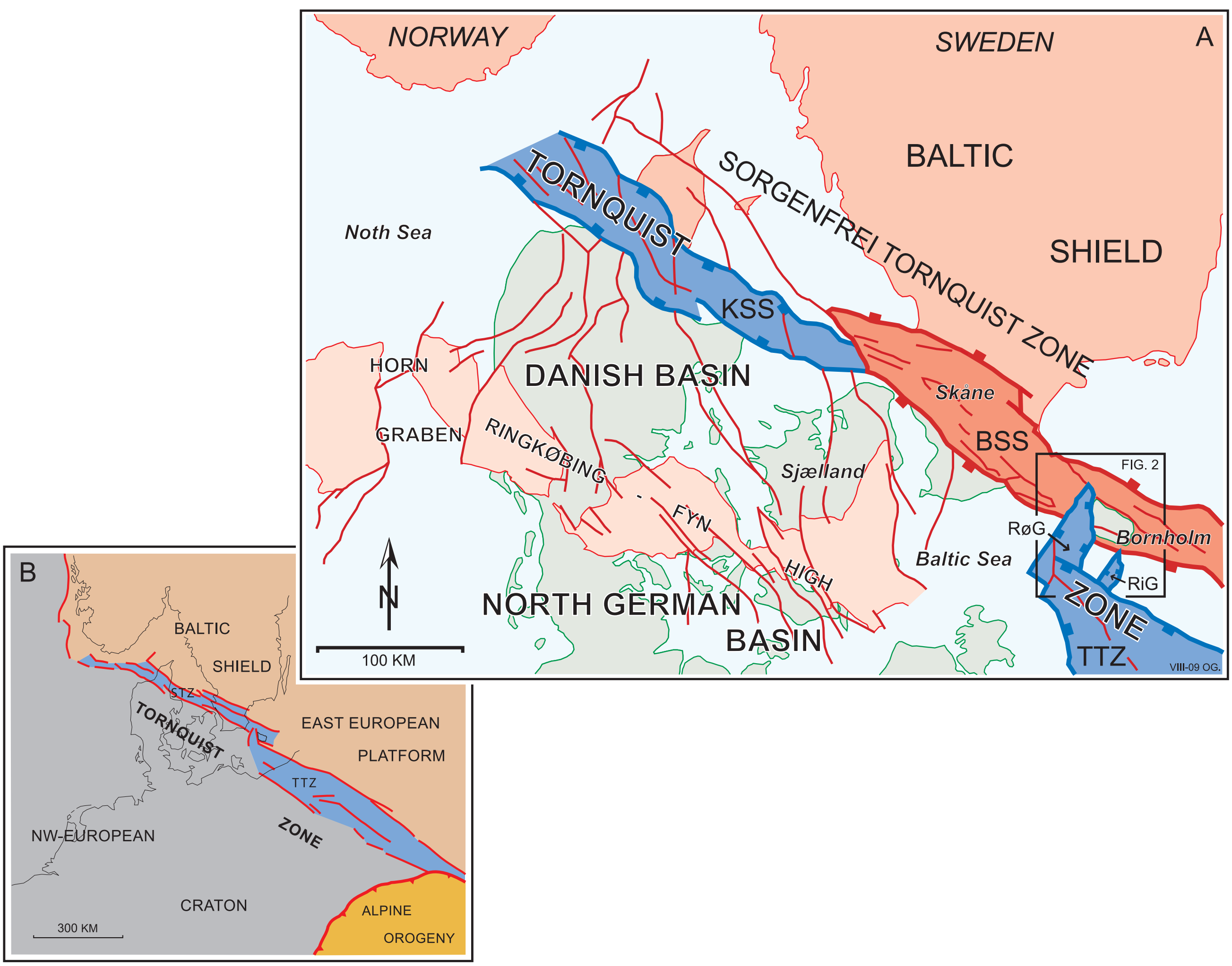


Fig. 3. A: Structural map of the Sorgenfrei-Tornquist Zone. KSS: Kattegat-Skagerrak segment; BSS: Bornholm-Skåne segment; TTZ: Teisseyre-Tornquist Zone. B: Major structural elements of central, eastern and northern Europe.

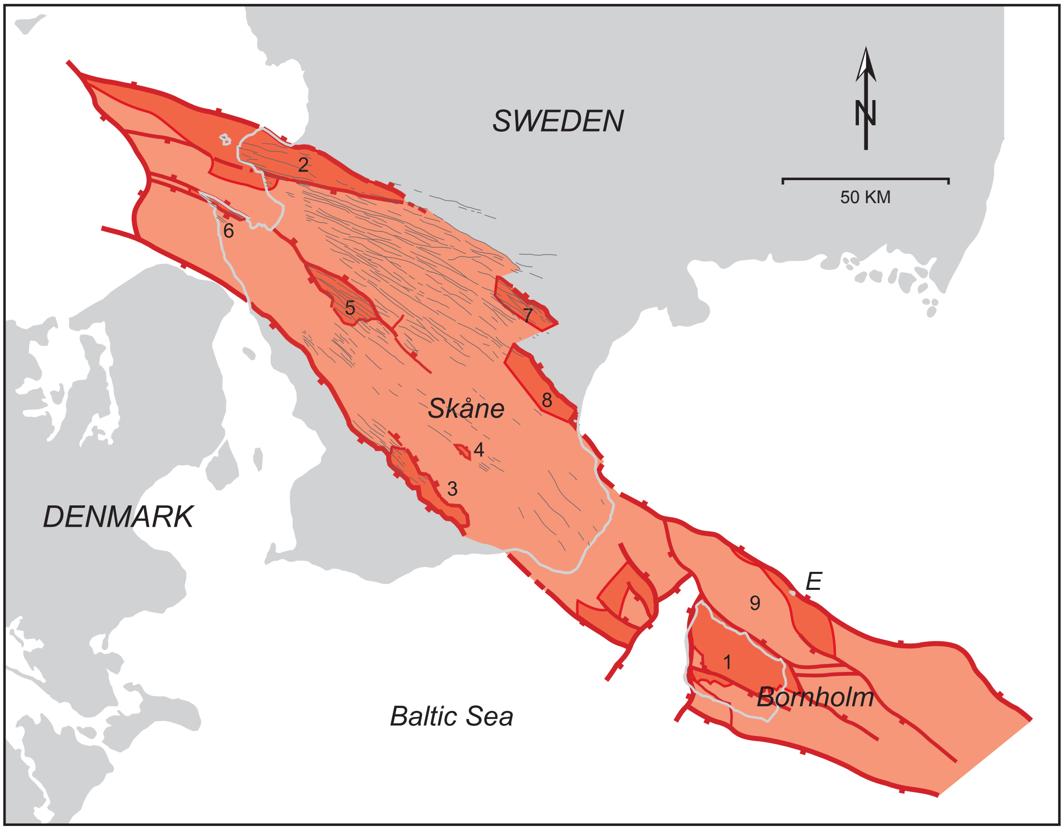


Fig. 4. The Bornholm-Skåne segment of the Sorgenfrei-Tornquist Zone and associated Permo-Carboniferous dykes (black) and major basement horst blocks. Dark red colours indicate Precambrian basement below the Quaternary in horst blocks and footwall fault crests. Compilation based on Bergström et al. (1988), Vejbæk & Britze (1994), Vejbæk (1997), Holm (2004). 1: Bornholm Block; 2: Hallands Åsen; 3: Romele Åsen; 4: Torpa Klint; 5: Søder Åsen; 6: Kullen; 7: Nävlinge Åsen; 8: Linderöd Åsen; 9: Christiansø Block; E: Ertholmene.

Skagerrak segment to the northwest and in the Polish Trough of the Teisseyre-Tornquist Zone to the southeast (Fig. 3) (Ziegler 1990). The tectonic contrast is expressed by the offset to the northeast of the elevated Bornholm-Skåne segment separated from the deeply buried sedimentary basins of the Kattegat-Skagerrak segment and the Polish Trough.

Overview of the pre-Quaternary geology of Bornholm

The pre-Quaternary geology of Bornholm can be divided into the Precambrian crystalline basement that is overlain by the Lower Palaeozoic and Mesozoic series separated by angular unconformities (Figs 1, 5B). The Precambrian crop out in the central and northern part of the island, the Lower Palaeozoic is situated to the south and southeast, while the Mesozoic interval is concentrated to the southwest. The Palaeozoic bedrock has a northeast-southwesterly strike and dips 4°-6° towards the southeast. The Mesozoic strikes perpendicular to the Palaeozoic interval and is dominated by a NW-SE strike with an overall dip between 6°-10° towards the southwest. The different orientations of the Paleaozoic and Mesozoic series illustrates the angular unconformity between the two intervals.

The Lower Palaeozoic once covered the entire region as part of the Early Palaeozoic Baltica platform. The Palaeozoic stratigraphy does not vary between the fault blocks, and no major depositional thickness variations of the mapped units have been identified. This indicates that the deposition of the Lower Palaeozoic cover took place in a stable tectonic environment, and that the faulting postdated the platform subsidence and sedimentation. During the early break-up of the Baltica platform along the Tornquist Zone in the Late Palaeozoic, the Bornholm area was faulted, tilted and eroded. The hiatus at the base Mesozoic unconformity on the Bornholm block covers the Middle Silurian through Middle Triassic interval.

In contrast to the Early Palaeozoic platform development, the sedimentation up through the Mesozoic was associated with fault block activity characterized by repeated phases of deposition followed by uplift and erosion. The active Mesozoic tectonic environment was a characteristic element not only of the Bornholm area, but of the entire Sorgenfrei-Tornquist Zone during the main development of the intracratonic fault zone (Bergström et al. 1982; Ziegler 1990; Erlström et al. 1997; Graversen 2002; Mogensen & Korstgård 2003; Nielsen 2003; Petersen et al. 2003).

Mesozoic tectonostratigraphy

The Mesozoic tectonic evolution of the Bornholm area was dominated by repeated vertical fault block movements. Major structural episodes are documented by rifting, and folding associated with structural inversion. The episodes of structural deformation was followed by erosional unconformities indicating that the Bornholm block remained close to sea level. In order better to understand the Mesozoic fault block movements, a tectonostratigraphy of the Mesozoic of southwest Bornholm has been establishsed from the onshore and offshore bedrock geology across the fault boundary between the Arnager-Sose block and the central Bornholm block (Figs 6, 7).

The Triassic was characterized by rifting and subsidence of the Rønne Graben and the Risebæk Graben (Fig. 2). The Triassic graben fill does not crop out at the surface but has been established from seismic mapping and well ties (Thomas & Deeks 1994; Vejbæk 1997; Graversen 2004b). In the Late Triassic the graben activity stopped, the base level was raised, and the Kågerød Formation was laid down as a thin cover across the entire region (Fig. 7.1) (Troedsson 1942; Graversen 2004a). The base of the Kågerød Formation thus marks the transition from Triassic rifting associated with blockfaulting to a stand-still of the large-scale differential subsidence. The Kågerød Formation crops out on the Arnager-Sose block at the base of the Mesozoic series (Figs 1, 6).

The cut-off of the Late Triassic and the overlying Jurassic series along the Arnager-Sose fault illustrates that these intervals once extended onto the central Bornholm block (Gry 1969a; Gry 1969b). Deposition of the Rønne and Hasle formations on the Arnager-Sose block was accompanied by faulting (Graversen 2004b), and the Early Jurassic deposition is interpreted to have been accompanied by subsidence along the Arnager-Sose fault (Fig. 7.2).

The Cretaceous is the only Mesozoic interval that is preserved on the central Bornholm block. Here the Lower Cretaceous rests with and angular unconformity above the Precambrian basement to the west and above the Lower Palaeozoic series to the south (Figs 1, 6). On the Arnager-Sose block the Lower Creta-

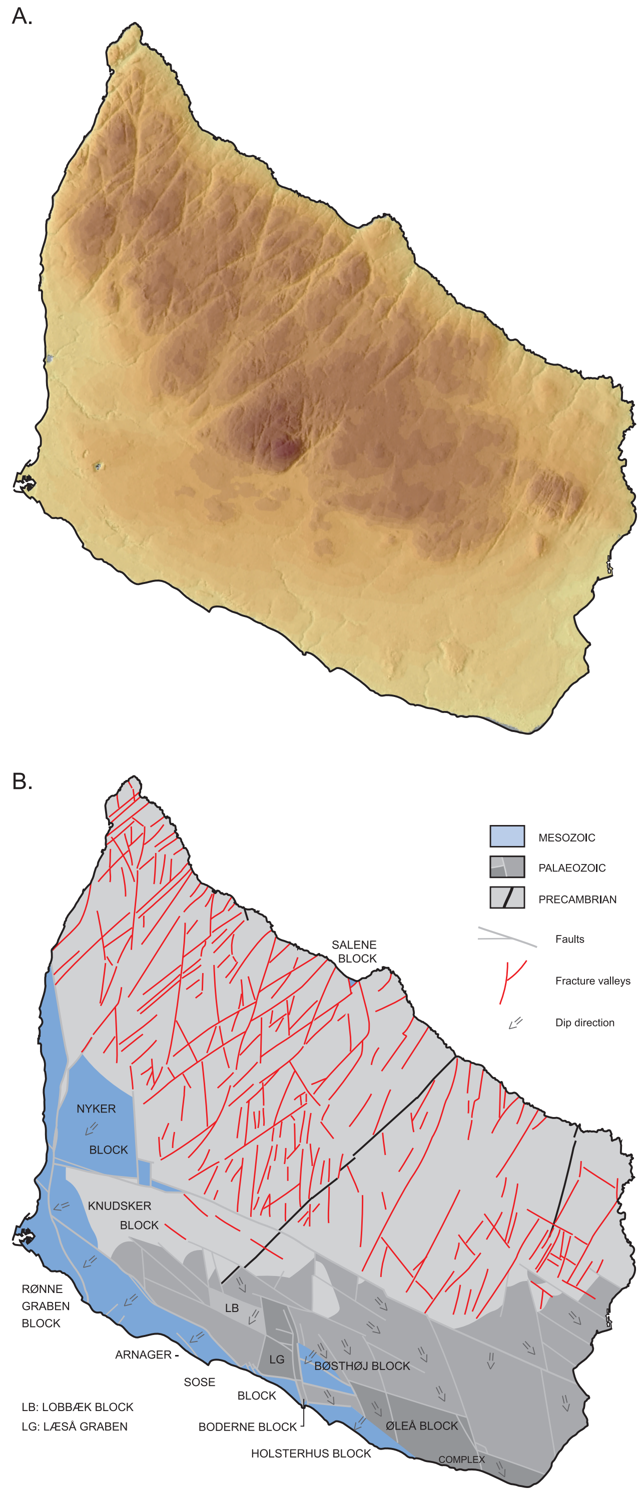
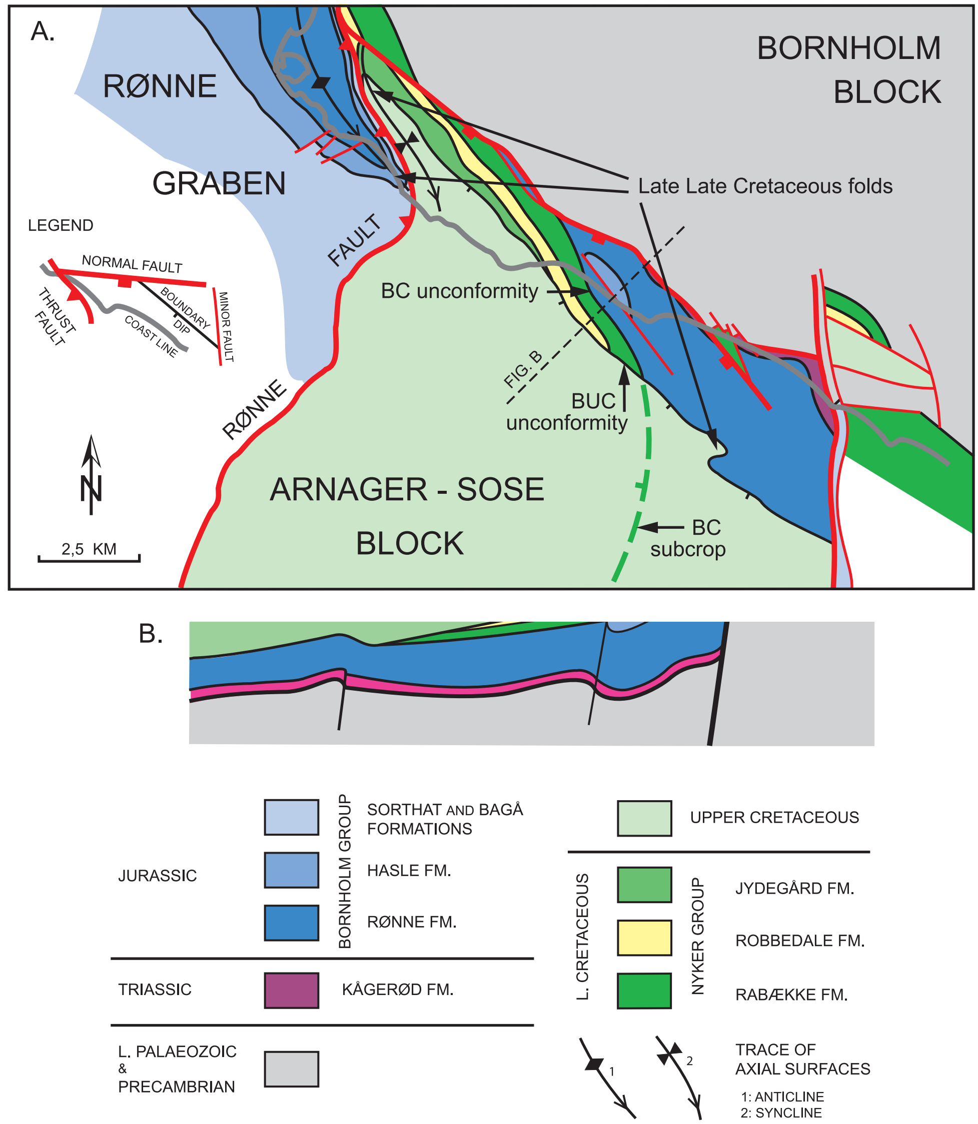


Fig. 5. A: Terrain model of Bornholm. Elevation 0-162 m (yellow-dark brown). Copyright Kort- og Matrikelstyrelsen; reproduced with permission (G. 15-03). B: Fault block map of Bornholm. Fault/fracture valleys of the Precambrian basement are based on the terrain model above.

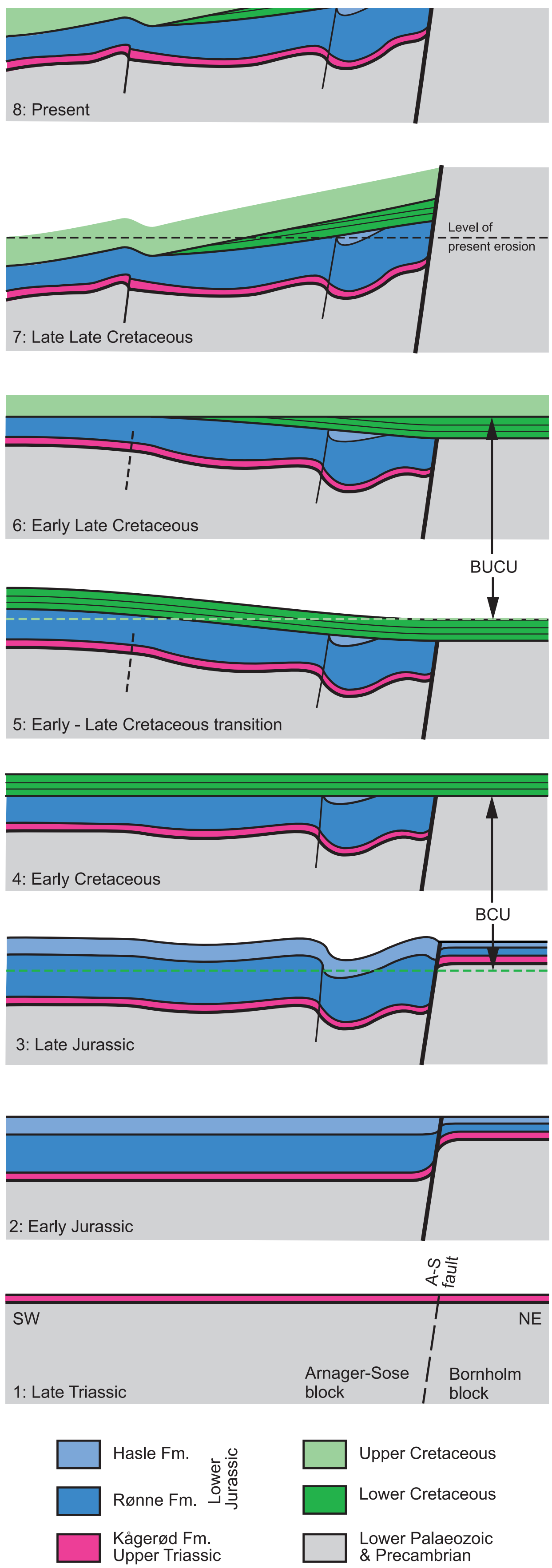
Fig. 6. Geological map of the Mesozoic formaitions on- and offshore southwest Bornholm. Compiled from Hamann (1987), Jensen & Hamann (1989) and Graversen (2004b). BC: Base Cretaceous; BUC: Base Upper Cretaceous.



ceous was deposited onto the eroded Lower Jurassic interval. A reconstruction of the Lower Jurassic on the Arnager-Sose block illustrates that the Rønne and Hasle formations were folded and faulted during structural inversion prior to the erosion that formed the base Cretaceous unconformity (Graversen 2004b) (Fig. 7.3-4).

A base Upper Cretaceous unconformity is established on the Arnager-Sose block. The unconformity cut across the Lower Cretaceous Nyker Group and down into the Lower Jurassic Rønne Formation (Fig. 6). The trace of the base Lower Cretaceous subcrop at the base of the Upper Cretaceous (Fig. 6) was folded in a large, open, northwesterly plunging inversion structure prior to erosion of the Lower Cretaceous interval (Graversen 2004b) (Fig. 7.5). The sedimentation was resumed across the Bornholm region during the early Late Cretaceous (Fig. 7.6).

During deposition of the Cretaceous, the Bornholm block acted as one continuous block. After deposition of the Bavnodde Greensand in the Santonian, i.e. the youngest pre-Quaternary interval preserved on Bornholm, the Cretaceous cover was subsequently broken down into lower order fault blocks, where the sediments are still preserved on the downfaulted hangingwall blocks (Figs 1, 6, 7.7). The westward dipping Lower Cretaceous interval to the west on the Knudsker block is interpreted to result from drag on the footwall block towards the hangingwall Rønne Graben block during the Late Cretaceous. Subsequently folding of the Cretaceous and underlying Jurassic deposits was associated with structural inversion and reverse fault movements of the Rønne Graben and the Arnager-Sose block during the late Late Cretaceous (Figs 6, 7.7).



Structural analysis of fault and fracture patterns

The bedrock of Bornholm is highly disintegrated by steep (> 60°) faults and fractures (Fig. 1). In the present paper the focus is on the Phanerozoic intervals, where the strike and displacement along the faults can be established from the stratigraphy of the macroscale geology compiled in the bedrock map. Due to the limited exposure and the lack of suitable marker horizons in the basement, no attempt has been made to distinguish between faults and fractures in the Precambrian areas.

The faults and fractures of the geological map (Fig. 1) have been registered by their strike direction and length; the faults are grouped into 10° strike intervals according to the age of the downfaulted hangingwall block or the age of the fractured rock. The cumulative lengths of the established fault groups have been plotted in rose diagrams using the net radius for scale (Fig. 8A-F). The Precambrian dykes and the fault/fractures of the basement are located in the NE-SW quadrants while the fault directions of both the Palaeozoic and the Mesozoic rock groups are dominated by WNW-ESE and NNW-SSE strikes.

Remark that the cumulative length plot deviates from most rose diagrams that plot the percentage represented in each sector of the illustrated element. The cumulative length plot gives you the opportunity to identify and compare the magnitude of the basic values illustrated in the rose diagrams.

Fault/fracture patterns of the Precambrian basement

The Precambrian basement occupy about two thirds of the bedrock on Bornholm. The disintegration of the crystalline basement has been established from the Precambrian dolerite dykes and from the widespread fault/fracture zones (Fig. 1). The basement is sculptured by erosion of the dykes and the fault/fracture zones, that are displayed as linear valleys in the topography (Callisen 1934; Micheelsen 1961). The distribution of the fault/fracture zones is based on a terrain model (Fig. 5A), where the strike and length of the linear valleys have been used as a proxy for the extent of the fault/fracture zones (Fig. 5B).

Fig. 7. Reconstruction of the structural evolution on- and offshore southwest Bornholm during the Mesozoic. The interpretation is based on the map and the cross section in Fig. 6. BCU: Base Cretaceous unconformity; BUCU: Base Upper Cretaceous unconformity; A-S: Arnager-Sose.

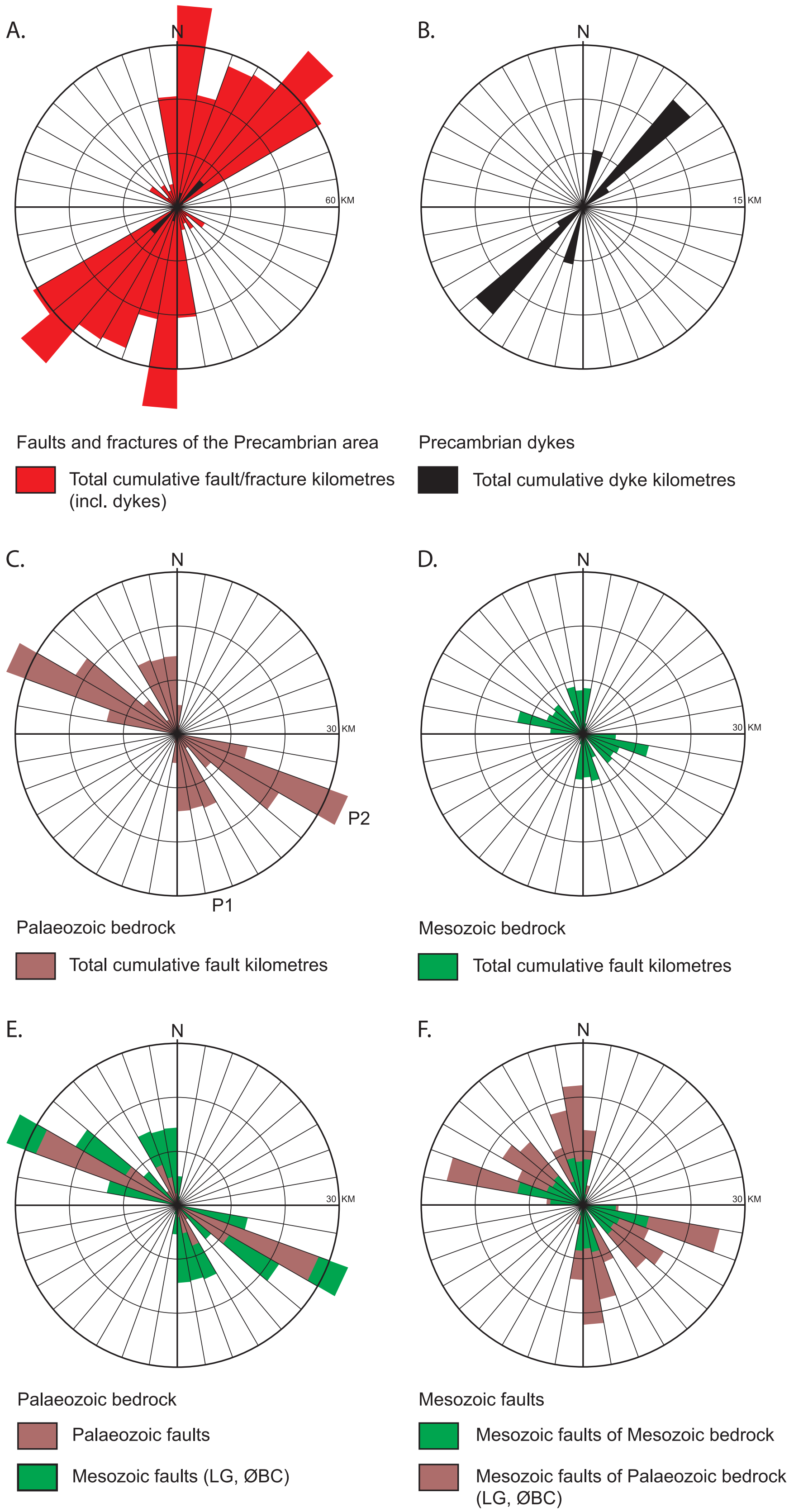


Fig. 8. Rose diagrams of the faults/fractures of the Precambrian basement and faults of the Palaeozoic and Mesozoic cover rocks. The faults/fractures are separated into 10° strike intervals, and the cumulative lengths are plotted using the radius of the diagrams for scale. LG: Læså Graben; ØBC: Øle Å block complex.

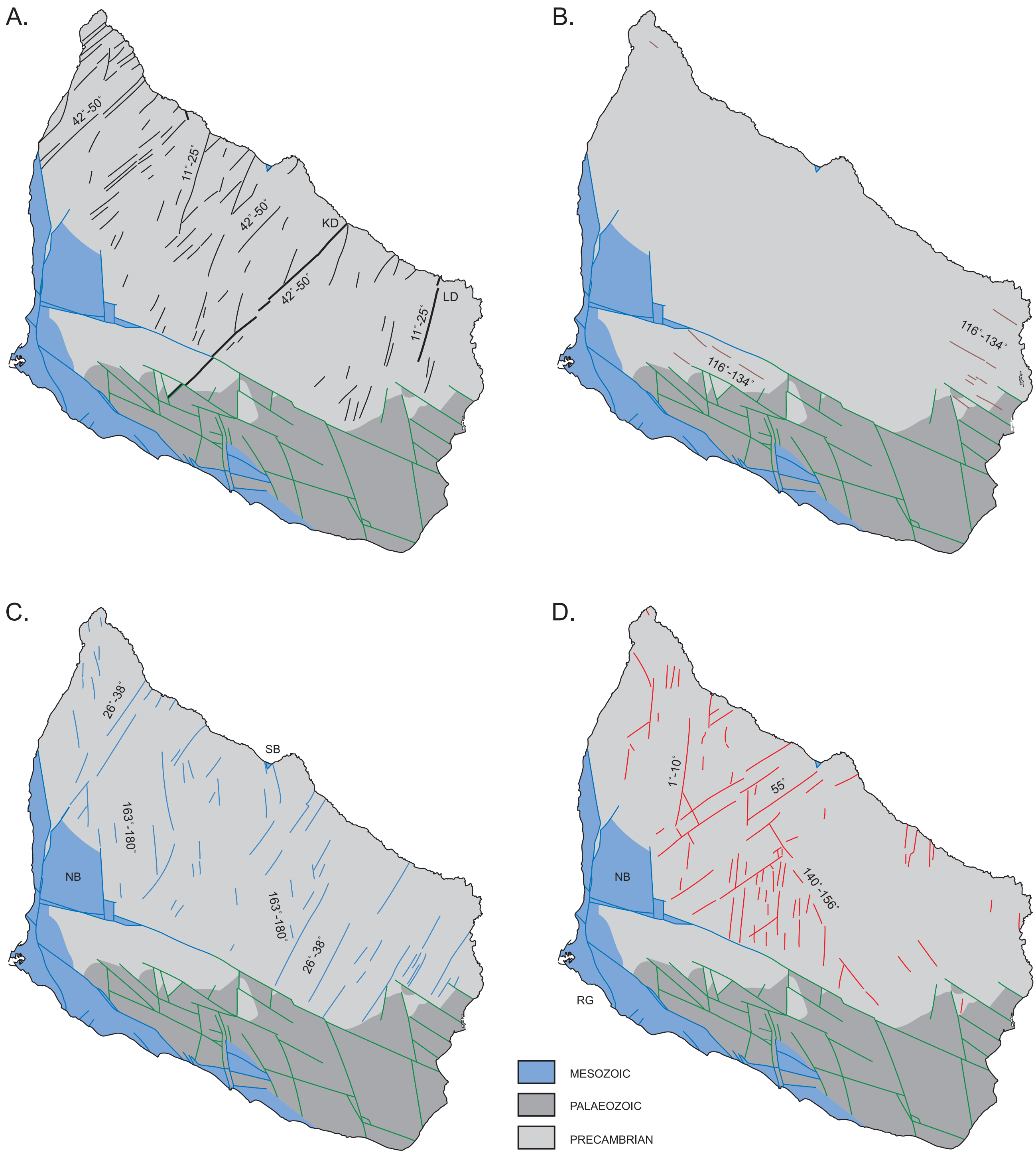


Fig. 9. Faults/fractures of the Precambrian basement separated into strike groups. A: Faults/fractures parallel with the Listed dyke (LD):11°-25°; faults/fractures parallel with the Keldseå dyke (KD): 42°-50°. B: Faults/fractures parallel with the Late Paleaozoic P2 faults: 116°-134°. C: Faults/fractures parallel with Mesozoic faults: 26°-38° and 163°-180°. D: Faults/fractures with no corresponding fault directions in the Phanerozoic cover rocks: 1°-10°, 55° and 140°-156°. NB: Nyker block; RG: Rønne Graben block; SB: Salene block.

The Precambrian dolerite dykes were intruded along fractures or faults. Only the larger Keldseå and Listed dykes are included in the map and the rose diagram (Figs 1, 8A, B). The Keldseå dyke strikes NE-SW and the Listed dyke is striking NNE-SSW. The dykes are not continuous but exhibit minor offsets; it is not possible to evaluate whether the offsets are the result of an en echelon intrusion fashion, or wether the offsets are the result of later faulting.

The majority of the faults/fractures in the Precambrian area are distributed in the NE-SW quadrants and adjoining sectors to the west and southeast (Fig. 8A). There are two maxima: One trending NE-SW (including the Keldseå dyke), and the second trending N-S in the 1˚-10˚ sector. In addition a restricted number of faults/fractures are distributed in the NW-SE quadrants.

In order to establish an overview of the fault/fracture zones of the Precambrian basement, a number of fault/fracture groups that parallel the Precambrian dykes and elements of the Palaeozoic and Mesozoic fault patterns have been separated (Fig. 9). Two fault/fracture groups that parallel the Keldseå (42˚-50˚) and Listed (11˚-25˚) dykes are illustrated in Fig. 9A. A minor segment of faults/fractures (116˚-134˚) parallel the WNW-ESE trending faults of the Palaeozoic bedrock (Fig. 9B). Two fault/fracture groups of the Precambrian area striking 26˚-38˚ and 163˚-180˚ are in continuation of or parallel with the bounding faults of the Cretaceous in the Nyker and Salene blocks (Fig. 9C). In addition to these directions, the 1˚-10˚ sector is represented in the eastern margin of the Rønne Graben block and the western border of the Nyker block. In the Precambrian area we are now left over with the 55˚ and 140˚-156˚ fault/fracture segments that are not aligned to any of the Palaeozoic or Mesozoic fault directions (Fig. 9D); the two fault sets are about perpendicular to each other, and the 1˚-10˚ sector bisect the intersection angle between the 55˚ and 140˚-156˚ fault groups.

Late Palaeozoic fault patterns of the Early Palaeozoic platform

The outline of the Palaeozoic fault blocks follow two fault directions: The dominant fault assemblage trends WNW-ESE with a maximum in the 110°-120° sector; the second fault group trends NNW-SSE within a 30° sector with no preferred maximum (Figs 1, 8C). In the eastern part of the Palaeozoic area, the outcrop patterns associated with the two fault groups show different characteristics. The layers cut by the WNW-ESE trending fault system dip to the ESE, and the layers are displaced to the WNW as you cross the faults from north to south. The layers cut by the NNW-SSE trending faults dip to the SSE, and the layers are displaced to the NNW as you cross the faults from east to west (Figs 1, 5).

P1 and P2 fault systems

A model that focus on the interrelationship between the two fault systems is illustrated in a simplified map and a block diagram (Fig. 10). The age relationship between the two fault systems has been estblished from (1) the WNW-ESE trending fault system that cut off the NNW-SSE trending faults, and (2) from the Pedersker block, where the SSE dipping boundary between the Hardeberga and Læså formations associated with the NNW-SSE trending fault system was cut off by a WNW-ESE striking fault (Fig. 10A). The structural relationships are interpreted to illustrate that the WNW-ESE striking faults represent the younger fault system, P2, and the NNW-SSE fault system is established as an older fault system, P1.

The P2 fault system cut across the NE-SW trending Precambrian Kjeldseå dyke with no or only little displacement of the dyke (Figs 1, 10). This illustrates that lateral fault movements along the P2 fault system have been negligible, and the observed displacements across the faults are the result of near vertical movements with relative subsidence down to the south. The displacement associated with the older P1 fault system is interpreted to result from a down-to-the-west relative block movement; there is no information of a possible lateral fault component. The areas affected by the two fault systems are indicated in Fig. 11 along with 3D diagrams of the two fault block systems.

The regularity of the superposed P1 and P2 fault systems established in the Palaeozoic core area to the east is discontinued as you move to the south and west. Additional fault systems of the Palaeozoic area are assigned to the Mesozoic described later.

Age of the P1 and P2 fault systems

The P1 and P2 fault systems were superposed onto the the Early Palaeozoic Baltica Platform. During the Mesozoic, the subsidence of the Rønne Graben was established across the WNW-ESE strike of the P2 fault system. The P2 and the older P1 fault systems are therefore assigned with a Late Palaeozoic age. The break down of the Early Palaeozoic platform and the early development of the Tornquist Zone was associated with deformation of the Variscan foreland during the Carboniferous and the Early Permian (Ziegler 1990).

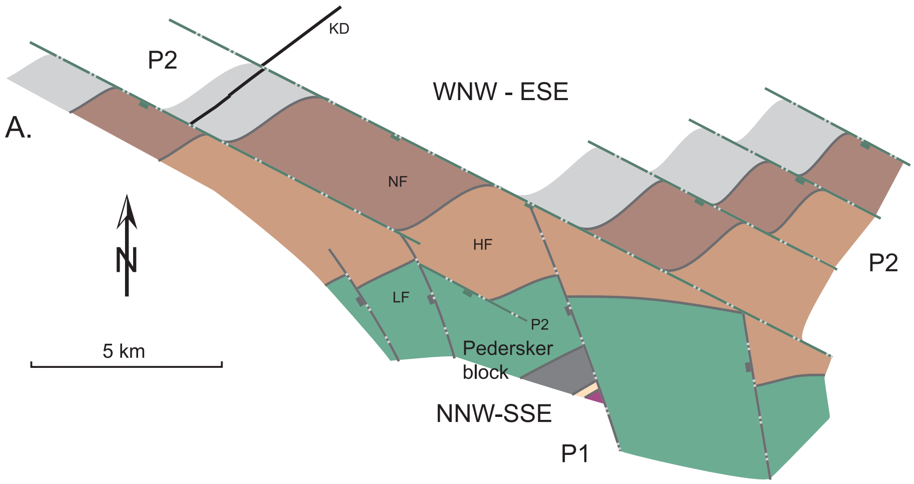
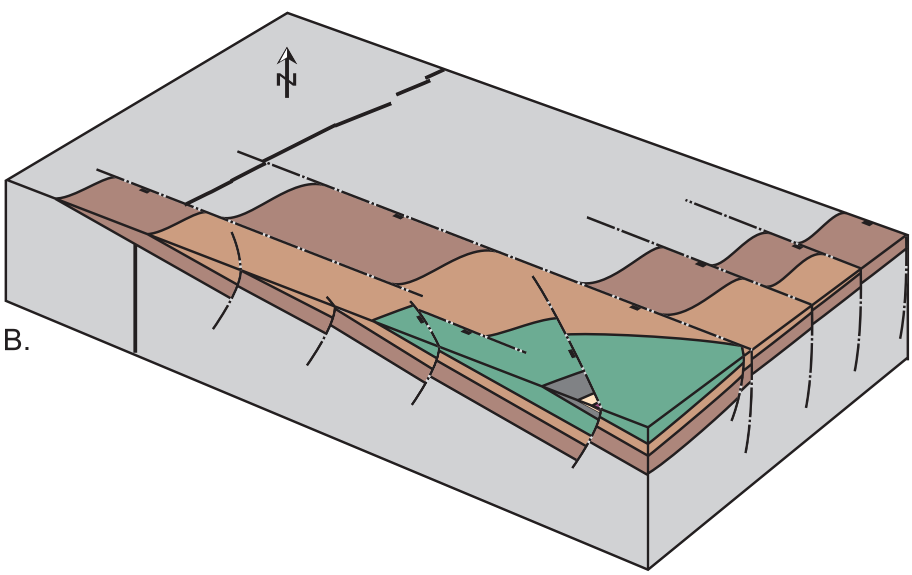


Fig. 10. A: Model of the Late Palaeozoic fault systems. B: Block diagram of the Late Palaeozoic fault systems. KD: Keldseå dyke; NF: Nexø Formation; HF: Hardeberga Formation; LF: Læså Formation.



The P2 fault system parallels the main direction of the Tornquist Zone and the Late Carboniferous-Early Permian dolerite dykes intruded into the Bornholm-Skåne segment (Fig. 4). The age of the P2 fault system is therefore suggested to be contemporaneous with the dyke injection and be of Late Carboniferous-Early Permian age. The older P1 fault system is proposed to be associated with Variscan foreland deformation during the early-middle Carboniferous.

Fault patterns of the Mesozoic bedrock areas

The evolution of the Bornholm area during the Mesozoic was charachterized by repeated subsidence and deposition of the Arnager-Sose and Rønne Graben blocks, while the central Bornholm block suffered repeated uplift and erosion (Fig. 7). Major structural changes were followed by flooding episodes in the Late Triassic (Fig. 7.1), in the Early Cretaceous (Fig. 7.4), and in the early Late Cretaceous (Fig. 7.6). The deposition of the Kågerød Formation in the Late Triassic marked the end of the widespread rifting up through the Triassic. In the Cretaceous, the flooding episodes followed upon structural inversion and erosion in the Late Jurassic (Fig. 7.3) and at the Early-Late Cretaceous transition (Fig. 7.5). In the Late Cretaceous, the central Bornholm block was disintegrated into a number of lower order fault blocks, i.e. the Nyker, Knudsker, Holsterhus and Bøsthøj blocks to the west and south, and the Salene block to the north (Gravesen et al. 1982) (Fig. 5A).

The cumulative lengths of the fault sectors that

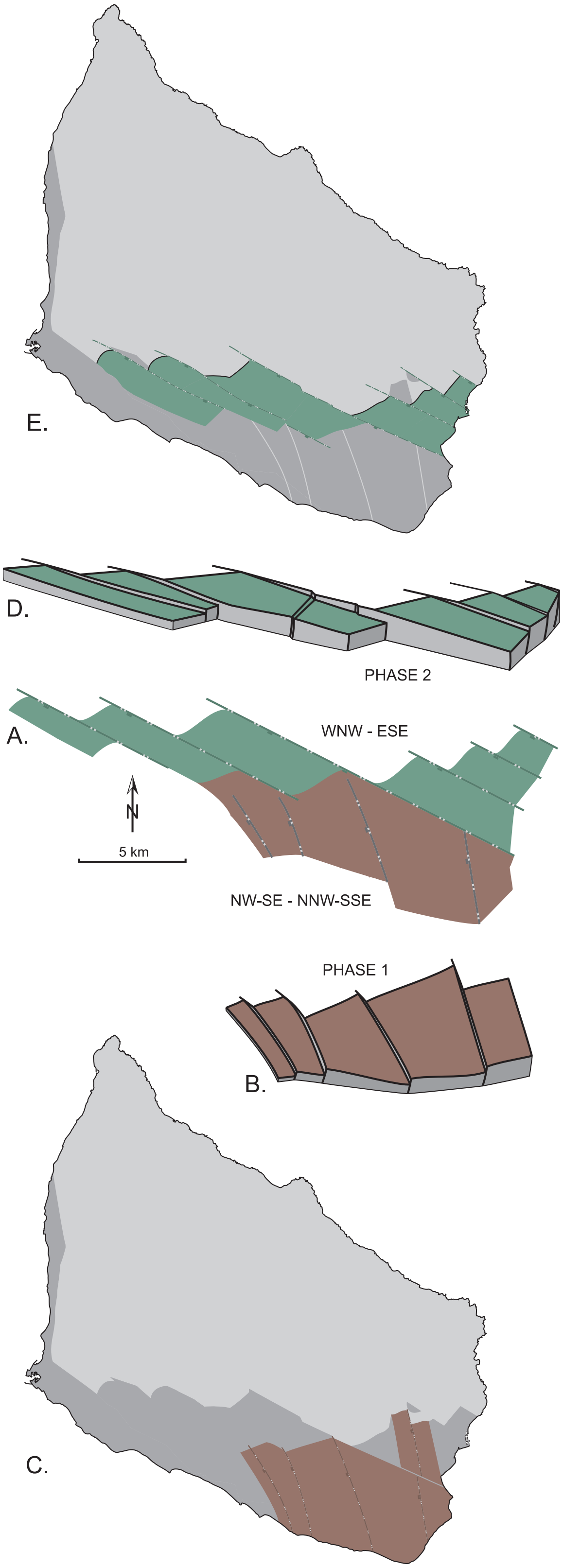


Fig. 11. Maps and blocks diagrams of the Late Palaeozoic fault systems. A: Interference of the P1 and P2 fault systems. B: Block diagram of the P1 fault system. C: Map of the distribution of the P1 fault sytem. D: Block diagram of the P2 fault system. E: Map of the distribution of the P2 fault system.

offset the Mesozoic bedrock areas group into the wide N-NNW – S-SSE and WNW – ESE trending sectors (Fig. 8D). The fault strikes of the two sectors spread about 30° and 50° respectively with the exception of a single narrow maximum striking 100°-110°. However, the fault scatter narrows considerably as the Mesozoic subareas are viewed separately (Fig. 12). The rose diagrams of the three main Mesozoic fault blocks, the Rønne Graben block, the Arnager-Sose block, and the Nyker block, illustrate individual fault trends with narrow maxima; the fault pattern of the Bøsthøj and Holsterhus blocks follow the trend of the Nyker block. The Rønne Graben block exhibit two maxima around the N-S direction striking 161°-170° and 1°-10°; the Arnager-Sose block has a single maximum trending NW-SE, and the Nyker block has two maxima, one trending WNW-ESE and a second maximum striking around N-S. The intersept angle between the maxima is 70° in the Nyker block, and 20° in the case of the Rønne Graben block.

The onshore parts of the Rønne Graben and Arnager-Sose blocks are "open" to the west and southwest respectively (Fig. 12); i.e. within the study area, only the limiting faults to the east and northeast are available for detailed observation. The subsidence of the Nyker block and the Bøsthøj block was down towards the Cretaceous package from all sides; these blocks are limited by faults on three or four sides forming individual "closed" halfgraben or graben blocks.

The onset of Mesozoic faulting varied between the fault blocks: The Rønne Graben and Arnager-Sose blocks are longlived fault blocks that suffered repeated subsidence. The break down of the Bornholm area up through the Mesozoic was initiated in the Rønne Graben in the Early Triassic; the disintegration then moved into the Arnager-Sose block in the Early Jurassic (Fig. 7.2). The rifting and subsidence of the Nyker and Bøsthøj blocks was associated with the break down of the central Bornholm block during the late Late Cretaceous. The established fault pattern signatures of the Mesozoic blocks change with age, each step identified by a new geometry of the Mesozoic rifting (Fig. 12). It is therefore suggested that the changing fault patterns may reflect changes of the tectonic regime up through the Mesozoic.

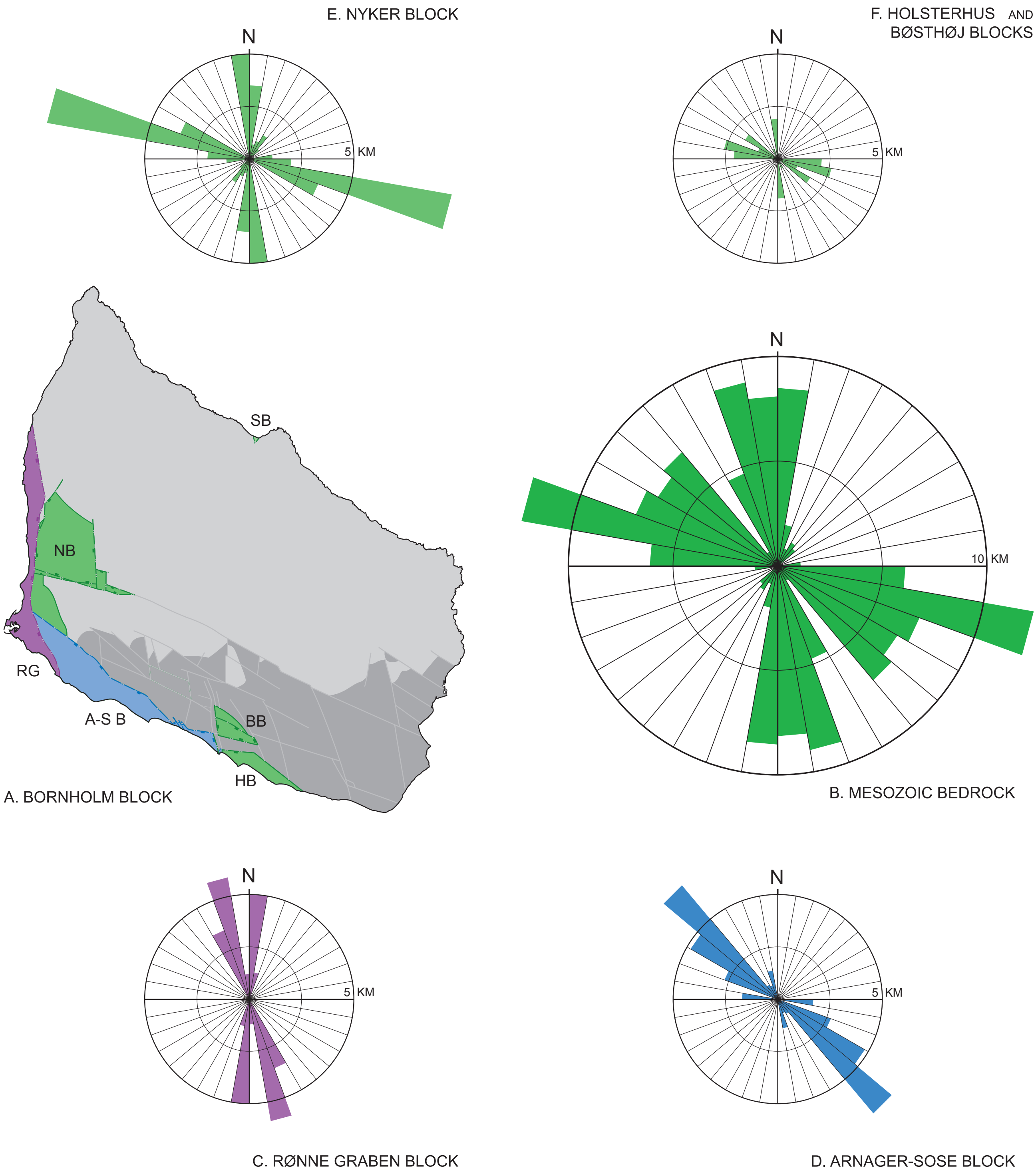


Fig. 12. Map and rose diagrams of the Mesozoic fault blocks of Bornholm where Mesozoic sediments are preserved. A: Mesozoic faulting was initiated in the Rønne Graben in the Triassic; in the Jurassic, faulting was extended onto the Arnager-Sose block, and in the Cretaceous, the faulting was extended into the Nyker, Bøsthøj, Holsterhus and Salene blocks. (RG: Rønne Graben block; A-SB: Arnager-Sose block; NB: Nyker block; BB: Bøsthøj block; HB: Holsterhus block; SB: Salene block). B: Rose diagram of the faults limiting the Mesozoic bedrock of Bornholm. C: Rose diagram of the Rønne Graben faults onshore Bornholm. D: Rose diagram of the Arnager-Sose block onshore Bornholm. E: Rose diagram of the Nyker block. F: Rose diagram of the Bøsthøj and Holsterhus blocks.

Mesozoic faulting of the Palaeozoic area

The Læså Graben and the Øle Å block complex

The Late Palaeozoic P1 and P2 fault systems established in the Lower Palaeozoic core area to the east (Figs 10, 11) are discontinued as you move into the Øle Å block complex and the Læså Graben to the south and west (Fig. 13A). In contrast to the unidirectional southwesterly subsidence of both the P1 and P2 fault block systems, the Læså Graben and the Øle Å block complex are limited by multidirectional fault systems. The downfaulted areas are fenced by faults with subsidence towards the east, south and west. The Læså Graben is embedded within the Cambrian rock suite of the western Palaeozoic area (Fig. 1); the graben subsidence is emphasized by the occurrence within the graben of the younger Ordovician interval, that is otherwise only outcropping further east. The youngest Palaeozoic rocks on Bornholm are from the Silurian, and they are only preserved in the Boderne block and in the downfaulted Øle Å block complex.

The Øle Å complex and the Læså Graben were cut out of the faulted and eroded Palaeozoic platform; the superposed fault complexes were separated by the platform footwall block extending to the south (Fig. 13A). The trend of the Læså Graben is around N-S; the graben is *c*. 2 km wide and narrows towards the north to around 1 km. There is a stepwise subsidence along the eastern margin, and internal transverse faults across the graben.

The Øle Å block complex has a wider east-west range and exhibit a stepwise incision into the Palaeozoic platform. The fault blocks of the Øle Å complex are outlined to the east and west by NNW-SSE striking faults and to the north by faults striking WNW-ESE. The NNW-SSE striking faults are continuous with the faults established during the P1 faulting. However, the subsidence of the western Øleå fault block complex is down-to-the-east, i.e. opposite of the movements associated with the P1 fault blocks to the north (Fig. 13A). The reversed subsidence polarity underline the superposed charcter of the Øle Å fault block complex onto the P1 fault system.

Regarding the relationship between the WNW-ESE trending faults of the Late Palaeozoic P2 system and those of the Øle Å complex and the Læså Graben, there is a *c*. 10˚ deviation between the orientation of the P2 system dominated by strikes in the 111˚-120˚ sector and the faults associated with the northern termination of the Øle Å complex and the Læså Graben that are striking in the 101˚-110˚ sector (Fig. 13A).

The structural and stratigraphic differences between the multi-directional subsidence of the Øle Å fault block complex and the Læså Graben and those of the uni-directional subsidence of the P1 and P2 fault systems support the interpretation that the Læså Graben and the Øle Å complex were superimposed onto the P1 and P2 fault block systems.

Age of the Læså Graben and the Øleå block complex

The lack of synrift sediments preserved in the downfaulted Læså Graben and the Øleå block complex render the age question to be estimated from structural relationships. A minimum age of the Øleå complex can be established at the southwest corner of the complex, where the western Øleå blocks are superseded by the Lower Cretaceous Rabekke Formation of the Holsterhus block with an angular unconformity at the base (Figs 1, 13B).

To the north, the Cretaceous Bøsthøj block occupy a hangingwall block position between the the Øleå complex and the Læså Graben (Fig. 13B). In the Cretaceous, the Øleå and the Læså fault block complexes were thus converted to footwall blocks while they originally were established as hangingwall block complexes during a pre-Cretaceous faulting and subsidence. Both the Øleå complex and the Læså Graben are therefore assigned with a Jurassic minimum age.

The WNW-ESE fault strikes of both the Øleå block complex and the Læså Graben have maxima in the 101˚-110˚ sector that parallels the maximum stike of the Mesozoic bedrock faults (Figs 12, 13A); the orientation of these maxima in addition have a 10˚ deviation from the WNW-ESE trend of the Late Palaeozoic P2 fault system (Figs 8C-D, 13A). The relationships between the fault directions are therefore interpreted in favour of a Mesozoic age of the superposed pre-Cretaceous graben systems.

Graben subsidence in the Triassic was associated with the Rønne Graben and the Risebæk Graben (Figs 2, 15.1, 16.1), while the central Bornholm block was not invaded untill the Late Triassic, when the Kågerød Formation was laid down as a relatively uniform cover over the entire Bornholm region (Figs 7.1, 14.1) (Graversen 2004b). The Læså Graben and the Øle Å complex are therefore interpreted to postdate the Kågerød Formation, i.e. assigned with a post-Triassic age. In conclusion of the age discussion, the Læså Graben and the Øle Å block complex that were superposed onto the faulted and eroded Palaeozoic platform are interpreted to be of Jurassic age (Fig. 14.2, 15.2, 16.2).

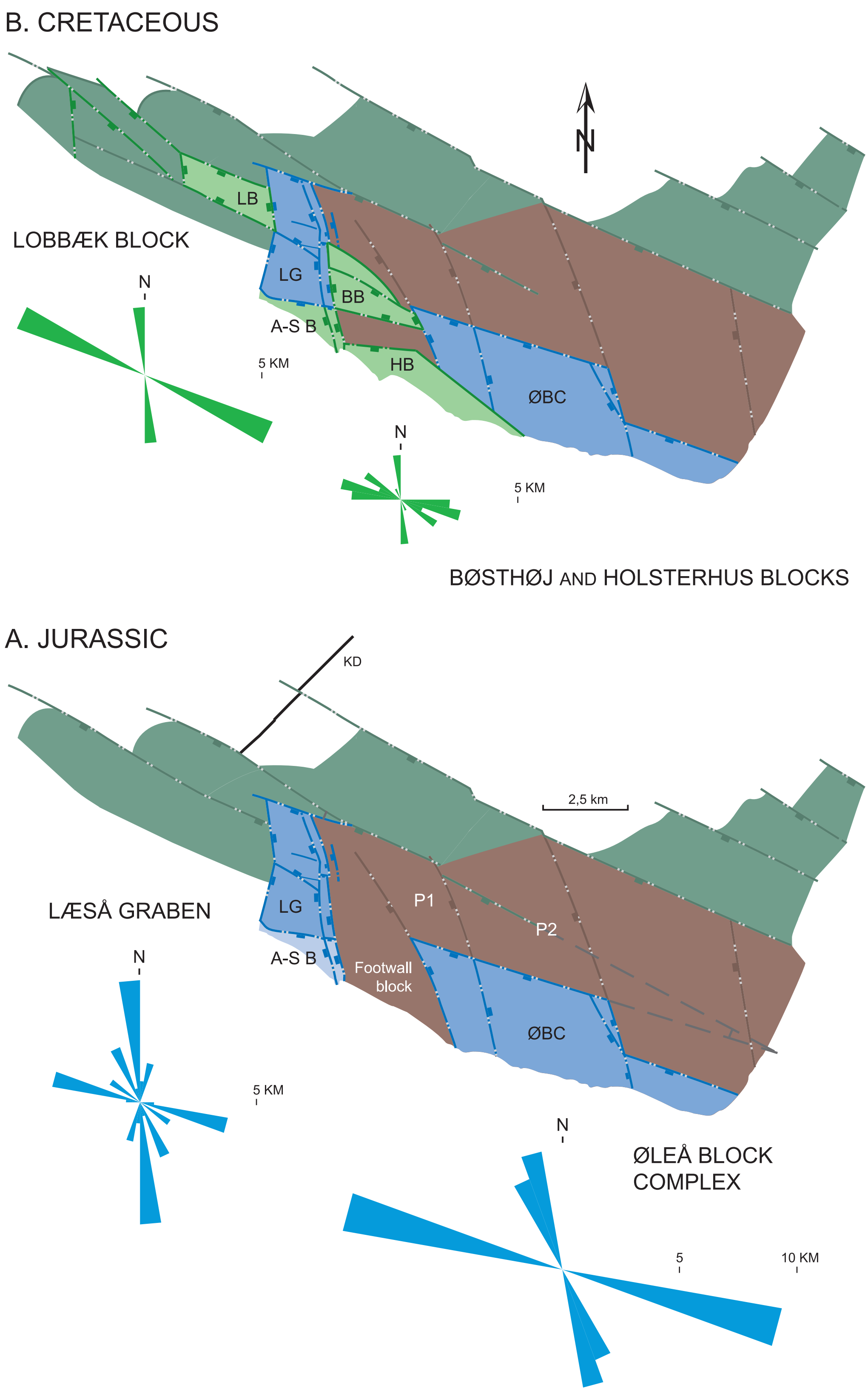


Fig. 13. Jurassic and Cretaceous fault blocks interpreted within the Palaeozoic bedrock outside the present distribution of the Mesozoic sediments. A: Jurassic – Map and rose diagrams of the Læså Graben and the Øleå block complex. A-S B: Arnager-Sose block; LG: Læså Graben; ØBC: Øleå block complex; KD: Keldseå dyke. B: Cretaceous – Map and rose digrams of the Lobbæk block (LB) and associated fault blocks with Cretaceous sediments preserved. A-S B: Arnager-Sose block; BB: Bøsthøj block; HB: Holsterhus block.

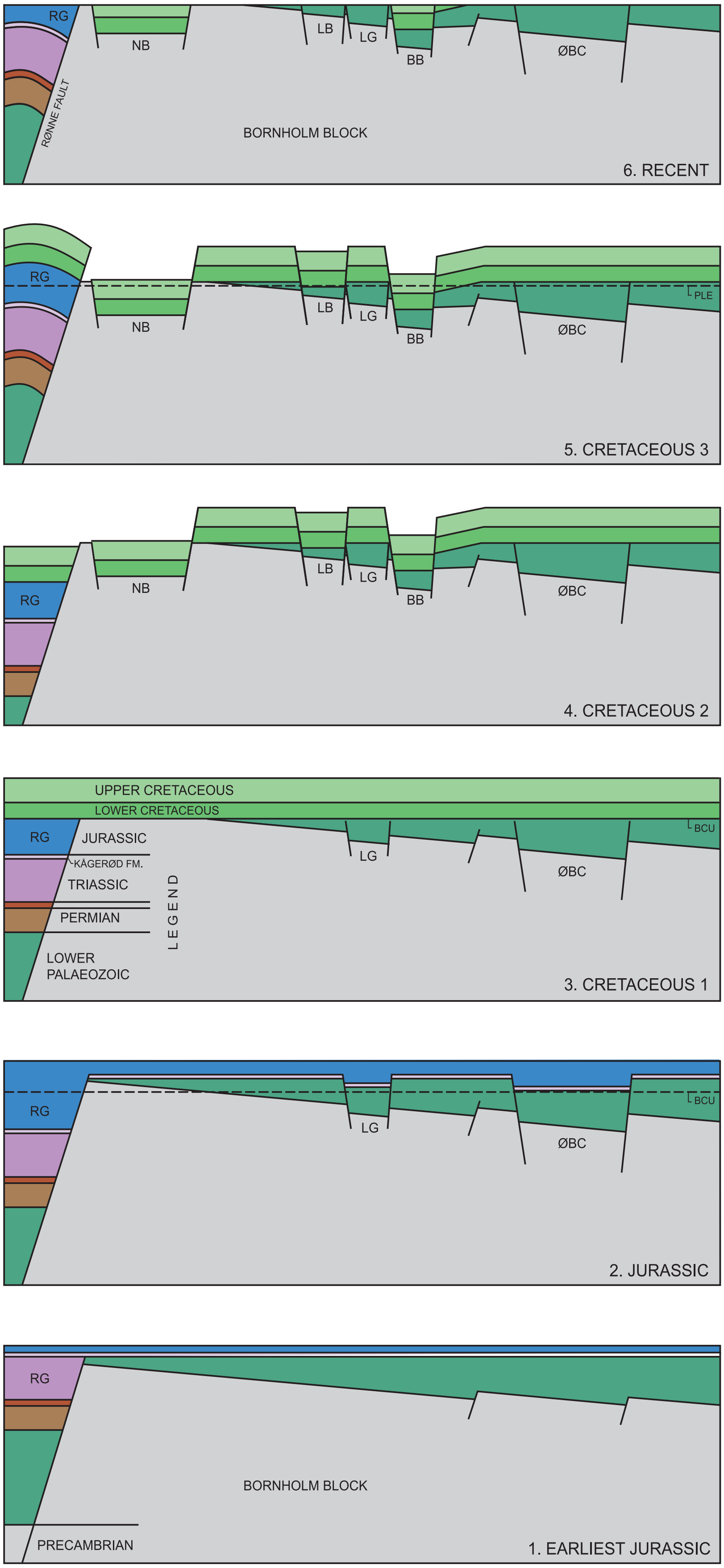


Fig. 14. Schematic reconstruction of the structural evolution across southwest Bornholm during the Mesozoic. RG: Rønne Graben; NB: Nyker block; LB: Lobbæk block; LG: Læså Graben; BB: Bøsthøj block; ØBC: Øle Å block complex; BCU: Base Cretaceous unconformity; PLE: Present level of erosion.

The Lobbæk block

The footwall barrier between the Læså Graben and the Øle Å complex was disintegrated by faulting in the Late Cretaceous. Differential fault block movements is outlined by the Bøsthøj and Holsterhus blocks, where the downfaulted Cretaceous sediments are preserved (Figs 1, 13B). The rectangular Bøsthøj block is closed by NNW-SSE and WNW-ESE trending faults with subsidence towards the hangingwall block from all directions.

A rectangular fault block similar to the Bøsthøj block is encountered on the Lower Palaeozoic stratigraphic level in the Lobbæk hangingwall block to the west of the Læså Graben (Figs 1, 13B). The subsidence of the Lobbæk block does not conform with the established Palaeozoic fault systems, and the occurence of an isolated fault block with subsidence from all directions towards the hangingwall block has only been observed in association with faulting of the Cretaceous cover. The subsidence of the Lobbæk block is therefore correlated with the Late Cretaceous faulting (Figs 14.4, 15.3, 16.3). The Cretaceous cover, however, is now removed by erosion from the Lobbæk block (Fig. 14.5-6).

The Bøsthøj and Lobbæk hangingwall blocks subsided to the east and west of the Læså Graben that acted as part of the footwall block in the Late Cretaceous (Figs 15.3, 16.3). The change of the hangingwall-footwall block relationship of the Læså Graben from the Jurassic to the Late Cretaceous was accompanied by a reversal of the fault subsidence polarity along the NNW-SSE trending faults of the Bøsthøj and Lobbæk blocks.

Additional Mesozoic faults of the Palaeozoic bedrock area

In addition to the Mesozoic fault systems interpreted above within the Palaeozoic bedrock (Fig. 13) a number of faults along the northern margin of the Early Palaeozoic bedrock area deviate in orientation and/or subsidence direction from the established orientations of the Late Palaeozoic P1 and P2 fault systems (Figs 1, 11). Faults with northwest to northerly strikes dipping to the southwest, west and east are parallel with major Mesozoic fault trends and the associated fault block subsidence directions; the age of these solitary faults are interpreted to be of Jurassic and Cretaceous age according to their orientation being parallel to either the Jurassic or the Cretaceous subsidence patterns (Figs 15.2-3).

WNW-ESE striking faults dipping to the north, i.e. opposite the established P2 fault system, are encountered close to Aakirkeby and to the southwest of Nexø. The fault at Aakirkeby offsets the N-S striking westdipping fault, and the WNW-ESE striking fault must therefore be simultaneous with or younger than the N-S striking fault of supposed Cretaceous age. The northdipping WNW-ESE striking faults are suggested to be of Cretaceous age (Fig. 15.3).

Rose diagrams of the Palaeozoic and Mesozoic faults

The rose diagrams of the cumulative fault directions measured in the Palaeozoic and Mesozoic bedrock areas (Fig. 8 C, D) may now be revised according to the established age relationship of the Mesozoic faults superposed onto the Palaeozoic bedrock. The faults of the Læså Graben and the Øle Å fault block complex and the interpreted additional Mesozoic faults of the Palaeozoic area are thus subtracted from the Palaeozoic bedrock area leaving the remaining faults to be of Palaeozoic age (Fig. 8E); as a consequence the faults of the Læså Graben and the Øle Å block complex are added to the Mesozoic faults (Fig. 8F).

Basement-cover relationships

The faults/fractures and the dykes of the Precambrian basement are dominated by strikes distributed in the NE-SW quadrants (Figs 8A-B, 9), while the basement fault directions are only sparsely represented in the Phanerozoic fault patterns (Figs 8C-D, 15). This implies that the NW-SE to WNW-ESE striking faults that dominates the fault patterns of the cover rocks are almost absent from the basement. There is, however, some examples of overlap between basement faults and fault offsets of the cover rock. In the Palaeozoic bedrock, at the southern end of the Keldseå dyke, the Palaeozoic was downfaulted towards the southeast along the dyke, a fault direction that is not encountered elsewhere in the cover (Figs 1, 9A). In the Mesozoic, positive correlation is found between the 26°-38° and 163°-180° basement fault groups and the limiting faults of the Salene block, and some of the fault segments of the Nyker and Rønne Graben blocks (Fig. 9C). Parallelism between Mesozoic faults and the 26°-38° basement fault group has not been identified elsewhere.

The contrasting fault/fracture interference patterns of the basement and the cover are displayed in Figs 1, 9. The fault pattern anomaly between the basement and the cover section is underlined by the observation that almost none of the fault groups continue across the boundary between the basement and

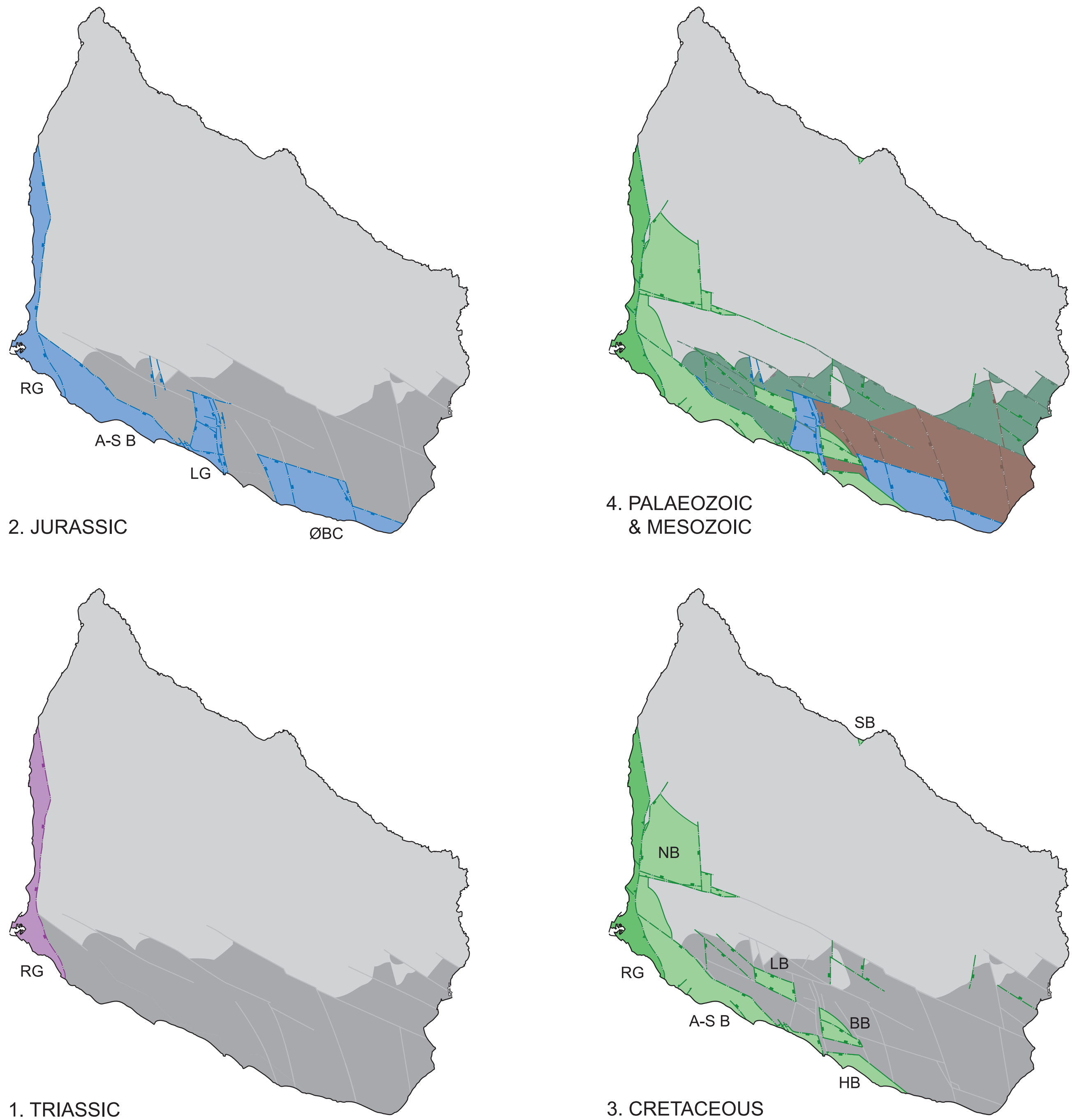


Fig. 15. 1-3: Triassic through Cretaceous fault block patterns of Bornholm. 4: Superposed fault block patterns of the Palaeozoic and Mesozoic cover. The distribution of the Palaeozoic fault systems is based on Fig. 11C, E. RG: Rønne Graben; A-SB: Arnager-Sose block; LG: Læså Graben; ØBC: Øle Å block complex; NB: Nyker block; LB: Lobbæk block; BB: Bøsthøj block; HB: Holsterhus block; SB: Salene block.

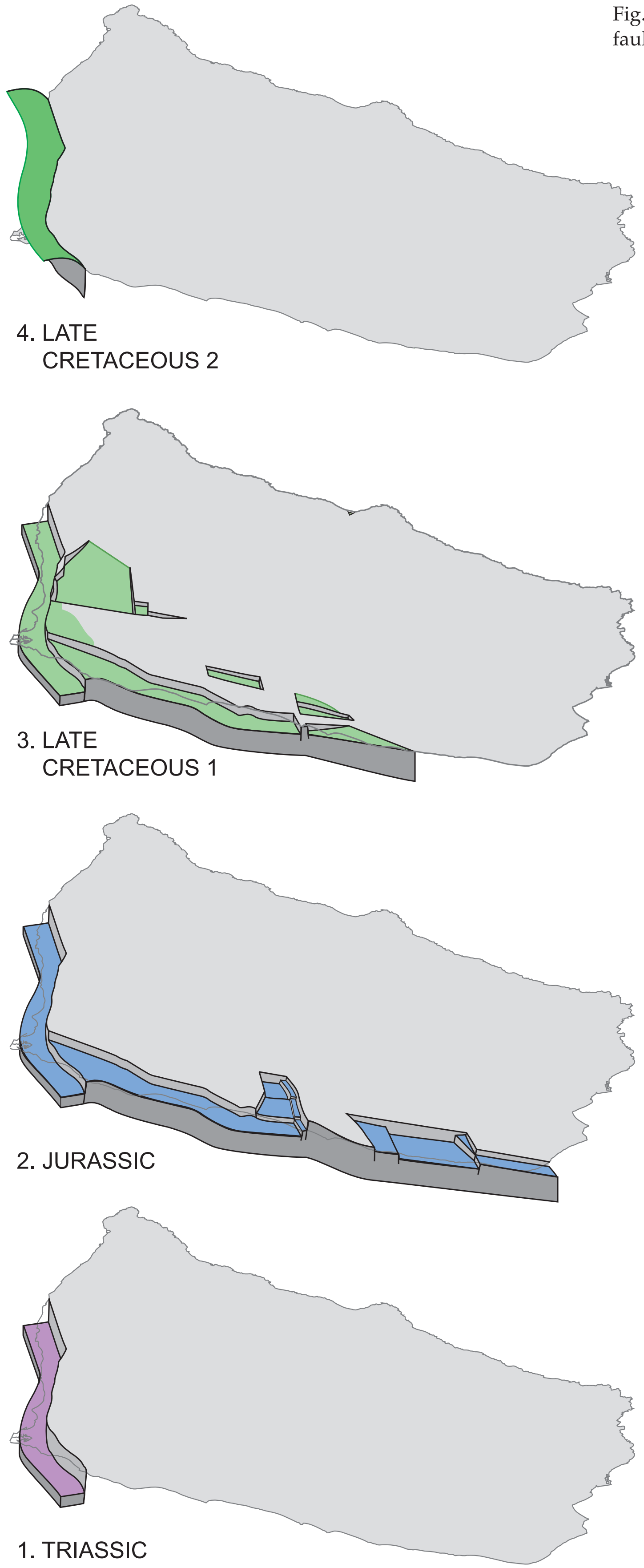


Fig. 16. 1-4: Block diagrams of the Triassic through Cretaceous fault blocks of Bornholm.

the cover rocks. The only exception is the limited 116°-134° basement fault/fracture group that is restricted to the vicinity of the Palaeozoic area in continuation of the Late Palaeozoic P2 fault system (Fig. 9B). The P2 fault system is characterized as a unilateral extensional fault system with a staircase trajectory and extension towards the SSW (Figs 10, 11). The continuation of the P2 fault system into the basement (Fig. 9B) may thus indacate that the 116°-134° basement fault group was superimposed onto the basement during the Late Palaeozoic faulting. The limited extension towards the westnorthwest of the joined P2—116°-134° fault/fracture group may then illustrate, that the break down of the Palaeozoic platform into the km-scale stairs (Figs 10-11) may have been arrested close to the present distribution of the Lower Palaeozoic cover rocks? The central and northern basement area, to the north of the WNW-ESE striking throughgoing fault across Bornholm, may thus have been established as part of a single continuous Late Palaeozoic fault block.

Many of the ~N-S trending fault zones of the Mesozoic fault blocks display a combination of NNW and NNE striking fault sections, i.e. parallel with the 1°-10° and 163°-180° basement fault groups (Figs 9C-D); examples are encountered along the Rønne Graben block, the western Nyker block and in the Læså Graben (Figs 12, 13). However, a similar fault combination of the two fault groups has not been identified in the fault/fracture pattern of the basement (Fig. 1); integration of the two fault directions is thus a characteristic only of the Mesozoic faulting.

The restricted fault/fracture correlation between the basement and the cover rocks indicates that reworking of the basement faults during the Phanerozoic was limited. Likewise, with the P2 fault group as the only exception, impact of the Phanerozoic faulting on the basement outside the present Phanerozoic cover has not been identified.

Evaluation of the Phanerozoic palaeostress fields

Two basic models have been established to explain the development of faults to accommodate for strain boundary conditions during deformation of the upper brittle crust: The Anderson (1951) model of conjugate fault sets that accommodates for two-dimensional plane strain, and the model by Reches (1978, 1983) that accommodates three-dimensional strain along two sets of intersecting conjugate fault systems (Fig. 17). The principal stress and strain axes are ideally arranged in an orthogonal coordinate system with the axes oriented parallel with and perpendicular to the earths surface. In the two-dimensional fault system there is extension parallel to sigma 3, shortening parallel to sigma 1 and no change of dimension parallel to sigma 2; in the three-dimensional system there is extension in two directions parallel both to sigma 2 and sigma 3, and shortening parallel to sigma 1. To analyse the palaeostress field of a fault system, the fault surfaces are plotted as great circles in a stereonet, where the position of the principal stress and strain axes can be constructed.

The fault data of the present analysis are drawn from the macroscopic scale of observartions represented in the geological map (Fig. 1). The available data consists of the strike orientations and the associated dip directions of the faults; information of the dip angles and fault movement directions are not available. The Arnager-Sose and Rønne Graben blocks have not been included in the analysis as only a small part of these blocks are encountered on Bornholm.

The data plotted in the stereograms are extracted from the fault strike maxima of the rose diagrams, the dip directions from the geological map, while the dip angles are chosen arbitrarily to 60° to illustrate standard steep conjugate fault sets. As a result of the use of standard fault dips, the orientation of the stress and strain axes are oriented parallel with and perpendicular to the earths surface; this is an ideal situation, and expected minor tilting of the axial coordinate system can not be detected. However, comparison with palaeostress fields in the Tornquist Zone in Skåne based on full fault measurements show that tilting of the coordinate systems does not exceed *c.* 10° (Bergerat *et al.* 2007); the present simplification of the Bornholm data is therefore not expected to have a significant influence on the established palaeostress fields.

Contrasting development of the Palaeozoic and Mesozoic stress fields

The Palaeozoic P1 and P2 fault systems are characterized by unilateral fault block subsidence along parallel faults towards the WSW and SSW respectively (Figs 10-11). Both fault systems display a monoclinic fault geometry illustrated by the great circles representing the unidirectional fault planes in the stereographic projections (Fig. 18). The fault systems are interpreted to represent a special case of Anderson's (1951) conjugate fault system (Fig. 17A) dominated by a single fault set developed in the present working area. Maximum extension parallels the sigma 3 axis, striking ENE-WSW during the P1 deformation and NNE-SSW during the P2 deformation. The shift of the Palaeozoic palaeostress field from the P1 to the P2 fault system

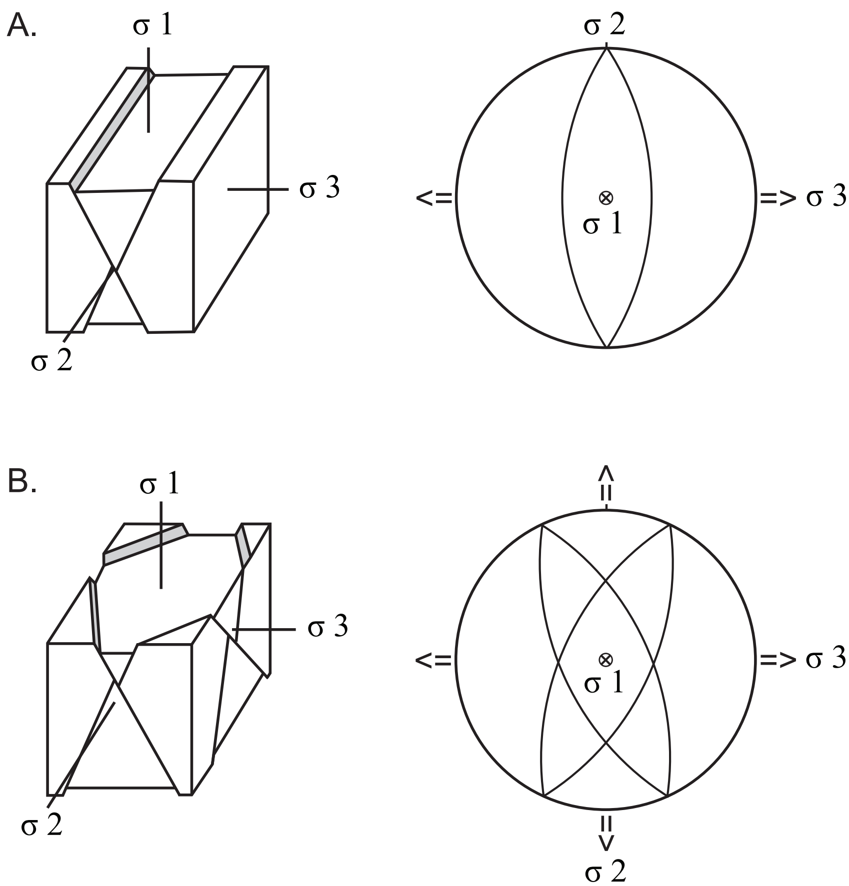


Fig. 17. Conjugate fault systems of two- and three-dimensional strain. A: Two-dimensional plane strain (Anderson 1951) and the associated conjugate fault set with the position of the stress- and strain axes illustrated in a block diagram and stereographic projection. Sigma 2 = 0; sigma 1 and sigma 3 ≠ 0. B: Three-dimensional strain (Reches 1978, 1983) and the associated intersecting conjugate fault sets with the position of the stress- and strain axes illustrated in a block diagram and stereographic projection. Sigma 1, sigma 2 and sigma 3 ≠ 0. The figure is based on Reches (1983).

was associated with an anticlockwise rotation around a vertical axis. The observed change of the palaeostress field follow the previously established age relationship between the P1 fault system of supposed early-middle Carboniferous age and the younger P2 system associated with lithospheric stretching in the Tornquist Zone during the Late Carboniferous-Early Permian.

The Jurassic and Cretaceous fault block patterns onshore Bornholm are characterized by multidirectional fault systems. The fault blocks are limited by two fault sets striking around WNW-ESE and NNW-SSE (Figs 12, 13). Parallel fault sets are dipping in opposite directions towards each other and down towards the hangingwall block (Fig. 18). The "closed" hangingwall fault blocks established in the Cretaceous Bøsthøj and Lobbæk blocks and in the northern block of the Jurassic Læså Graben illustrate almost ideal examples of brittle deformation predicted to take place under three-dimensional stress conditions (Fig. 17B). The minimum and intermediate principal stress and strain axes, i.e. the subhorisontal extension directions, were oriented NE-SW (sigma 3) and NW-SE (sigma 2) in both the Jurassic and the Cretaceous fault block areas (Fig. 18).

Correlation of palaeostress fields in Bornholm and Skåne

Interpretation of palaeostress fields based on fault analysis from field measurements in the Skåne section of the Bornholm-Skåne segment (Fig. 4) have resulted in the establishment of a series of major tectonic episodes since the Permian (Bergerat *et al.* 2007). The extensional stress fields in Skåne of interest for the present study are the NE-SW extension associated with the intrusion of the Late Carboniferous-Early Permian dykes, and the Mesozoic faulting with a dominant NE-SW extension and a contemporaneous secondary extension trending NW-SE. The Palaeozoic P2 palaeostress field in the Bornholm area is correlated with the faulting associated with the Permo-Carboniferous dyke injection in Skåne. The sigma 3 azimuth during the dyke intrusion in Skåne was about 30° (Obst & Katzung 2006), while the azimuth of the sigma 3 axis associated with the P2 fault system in Bornholm was trending 28° (Fig. 18). The older P1 palaeostress field established on Bornholm has no equivalent in Skåne, as there is no observations in Skåne of palaeostress fields prior to the dyke event (Bergerat *et al.* 2007).

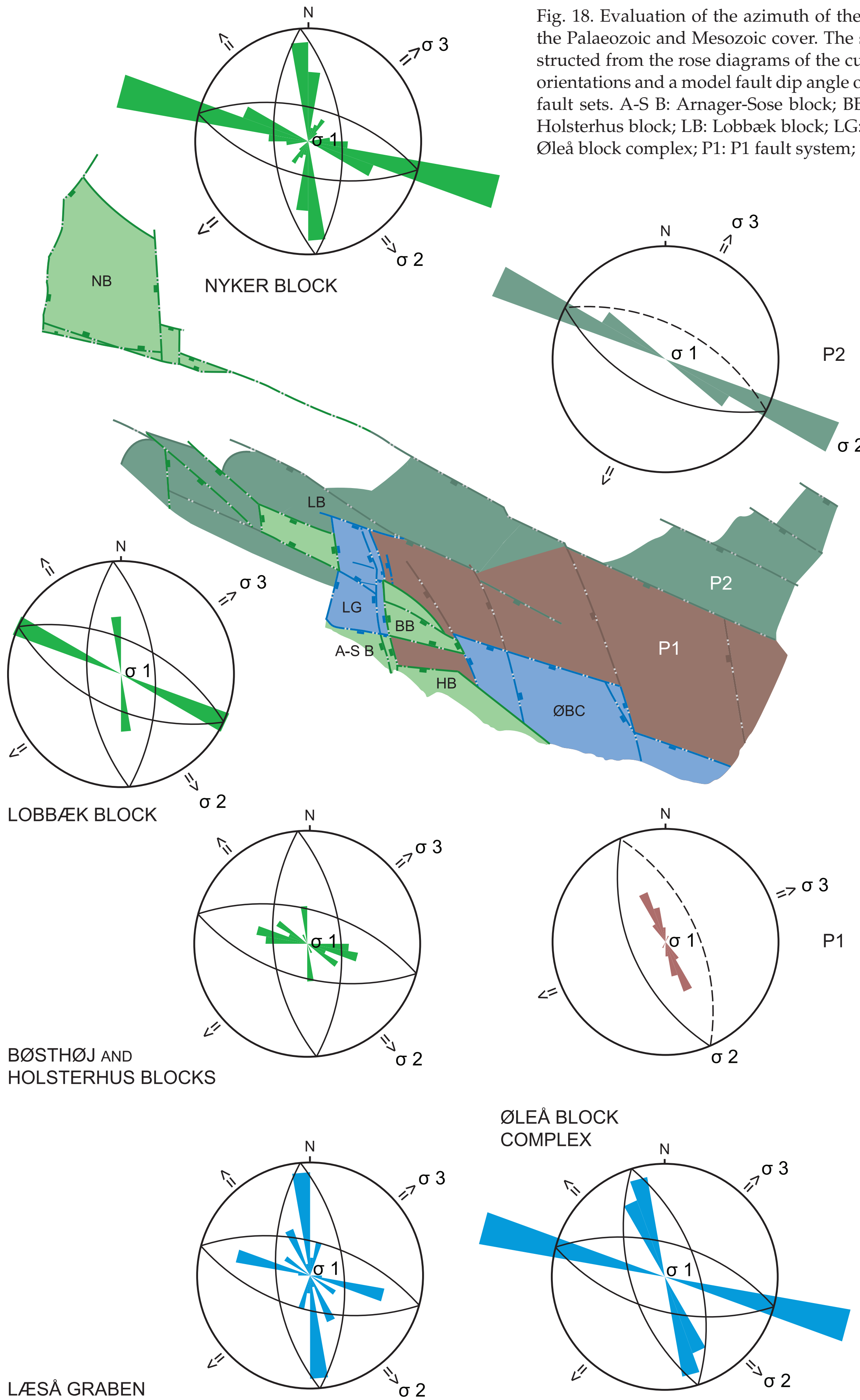


Fig. 18. Evaluation of the azimuth of the palaeostress axes of the Palaeozoic and Mesozoic cover. The stereograms are constructed from the rose diagrams of the cumulative fault strike orientations and a model fault dip angle of 60° of the conjugate fault sets. A-S B: Arnager-Sose block; BB: Bøsthøj block; HB: Holsterhus block; LB: Lobbæk block; LG: Læså Graben; ØBC: Øleå block complex; P1: P1 fault system; P2: P2 fault system.

The Jurassic and Cretaceous extensional palaeostress fields on Bornholm with maximum extension along the sigma 3-axis trending NE-SW is in good agreement with the dominant NE-SW extension up through the Mesozoic in Skåne (Bergerat *et al.* 2007). The secondary NW-SE extension in Skåne may then be correlated with the subordinate extension parallel with the intermediate sigma 2-axis trending NW-SE on Bornholm.

Palaeostress fields of the Bornholm-Skåne segment in a plate tectonic context

The Palaeozoic stress fields were characterized by the developmment of a two-dimensional plane strain deformation in the Variscan foreland. The Palaeozoic faulting developed during the continent-continent collision between Gondwana and Laurussia and the closure of the Rheic ocean during the amalgamation of the Pangea supercontinent (Torsvik *et al.* 2002).

The Mesozoic stress fields were associated with faults created in a three-dimensional stress field. The fault evolution of the Bornholm-Skåne segment took place along with the widespread fracturing and break-up of the Pangea continent. The three-dimensional stress field may be explained as an interference pattern between the two extensional palaeostress fields: The NE-SW trending primary extensional stress field and the secondary stress field trending NW-SE. The NE-SW oriented extension may have been associated with the fracturing and opening of the North Atlantic striking NW-SE, while the perpendicular NW-SE oriented extension may have been related to extension and faulting along the NE-SW striking future spreading zone of the Norwegian-Greenland Sea (Lundin 2002; Torsvik *et al.* 2002).

The change from two-dimensional stress fields in the Late Palaeozoic to the three-dimensional stress fields in the Mesozoic may thus have been related to the transition from constructive processes leading to the build-up of the Pangea supercontinent during the Late Palaeozoic to the extensional destructive processes initiated in the the early Mesozoic ending with the break-up of Pangea.

Conclusions

Bornholm is established as a major horst block belonging to the Bornholm-Skåne segment that in the present paper is separated as a new subunit of the Sorgenfrei-Tornquist Zone. The structural analysis of the fault patterns of Bornholm have enabled the distinction of a number of superposed fault systems in the Precambrian crystalline basement and in the Phanerozoic cover. The strikes of the Precambrian faults/fractures are distributed in the NE-SW quadrants while WNW-ESE and NNW-SSE trending maxima characterize the Palaeozoic and Mesozoic fault systems (Fig. 8). The Late Palaeozoic faulting was superposed onto the Early Palaeozoic Baltica platform, while the Mesozoic evolution was characterized by an active tectonic environment in the Tornquist Zone where subsidence and deposition alternated with uplift and erosion.

Two Late Palaeozoic fault systems, P1 and P2, have been established on southeast Bornholm (Figs 10, 11, 18). The fault systems are characterized by two-dimensional plane strain and unidirectional extension and subsidence towards the WSW (P1) and SSW (P2).

In the Mesozoic three-dimensional strain with multidirectional contemporaneous subsidence along the WNW-ESE and NNW-SSE striking fault sets took over. The subsidence was towards the E(NE) and W(SW), and the NNE, SSW and SW (Figs 12, 13).

Mesozoic faulting started in the Triassic in the Rønne Graben that cut into the western edge of the onshore Bornholm block (Figs 15.1, 16.1). In the Jurassic, faulting and subsidence of the Rønne Graben continued, and new fault block complexes were cut into the Bornholm block from the south (Figs 13A, 14.2, 15.2, 16.2). The Jurassic fault systems are represented in the Arnager-Sose block, and in the Læså Graben and the Øle Å block complex established in the present paper. The southern Jurassic fault block complexes were superimposed onto the faulted and eroded Early Palaeozoic platform. The Bornholm block was uplifted and eroded in the Late Jurassic, and there are no Mesozoic sediments preserved in the Læså Graben nor in the Øle Å block complex.

In the Late Cretaceous, following upon transgression and deposition up through the Cretaceous, isolated "closed" fault blocks punctured the Cretaceous basement of the Bornholm block along with renewed subsidence of the Arnager-Sose block (Figs 13B, 14.4, 15.3, 16.3). The Cretaceous sediments are preserved in the downfaulted Nyker, Bøsthøj and Holsterhus blocks. The Lobbæk hangingwall block is associated with the Late Cretaceous isolated fault blocks, but no Cretaceous sediments are preserved in the fault-bounded basin. Following the Late Cretaceous fault block subsidence, the Rønne Graben underwent structural inversion in the late Late Cretaceous (Figs 14.5, 15.3, 16.4).

The Late Palaeozoic faulting was the result of two-dimensional plane strain deformation governed by ENE-WSW (P1) and NNE-SSW (P2) extension. The Bornholm area was situated in the Variscan foreland, and the deformation was associated with the build-up of the Pangea supercontinent. The Mesozoic faulting of the Bornholm-Skåne segment of the Tornquist Zone was governed by three-dimensional strain composed from superposed stress fields trending NE-SW and NW-SE. The Mesozoic palaeostress fields were established during the break down of the Pangea continent.

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