Metasedimentary rocks, associated intrusions and tectonic features of the Precambrian in eastern Bamble, South Norway : an interpretative study

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Based on the results of mapping progammes and map compilation work carried out by the author in recent years, a subdivision of the bedrock geology of the easternmost part of the Bamble Sector into two domains is proposed – the Kragerø and Portør domains, separated by a major fault zone. These domains show contrasting sedimentary and magmatic histories, particularly in their earlier phases. In the Portør domain, a large, elongate body of diorite to granodiorite is identified but not yet dated isotopically. It has no equivalent in the Kragerø domain where the Levang Granite Gneiss Dome (LGGD) is a dominating feature. The latter is assessed in terms of synplutonism and its relationship to adjacent metasedimentary rocks and their fold patterns. The significance of existing isotopic age data in relation to field data is also considered. The existence of an early developed trough or half-graben into which clastic sediments of the Kragerø domain were deposited is envisaged.

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Introduction

The area of study extends from Risør northeastwards in the direction of Kragerø and beyond as far as the border with the Oslo Rift (Figs. 1A and 1B). The rocks within this rhomb-shaped area form part of the Bamble Sector and are of Precambrian age, except for a few, non-metamorphosed dolerite dykes believed to be of Permian age, and have clearly a long and complex evolutionary history.

Geological field data, published and unpublished, have recently been assembled by the author in map compilations at scales of 1:250,000 (Arendal bedrock map) and 1:50,000 (Tvedestrand 1612.1, Risør 1712.3, Gjerstad 1612.1, Kragerø 1712.4 and Langesund 1712.1). The relation of the 1:50,000 sheets to the area of study is shown in Fig. 1B.

The purpose of the present paper is to identify and describe various metasedimentary sequences and focus attention on some of the structural, metamorphic and intrusive events which have affected them. Some of the major intrusions present in the area are shown in Fig. 2. The conclusions reached are primarily based on field observations but also incorporate the results of the few isotopic age studies so far carried out on the rocks of the area. It is clear, however, that further isotopic age studies are necessary to determine not only the depositional age and if possible the source of the sediments, but also subsequent tectonic and metamorphic events. Hopefully, this paper will serve to focus attention on relationships and events in need of further geological and geochronological study.

For purposes of description it is convenient to divide the area into two parts, known hereafter as the Kragerø and Portør domains (Fig. 3). These differ in both their sedimentary record and the type of intrusions which have affected them. The two domains are separated by a major fault complex, referred to hereafter as the Haslumkilen-Langholmen Fault Zone (HLFZ), now partially intruded by mafic rocks.

Regarding mafic rocks, the term *diabase* is used in this article for those having an intrusive origin (dykes and sills) and which have undergone thermal metamorphism or tectonic deformation, or both. The term dolerite is reserved for mafic dykes or sills, the mineralogy and texture of which are little affected by later thermal and tectonic events.

The Kragerø domain

The metasedimentary rocks: general features

The existence of rocks of undoubted sedimentary origin in the Bamble Sector has long been recognized (Brøgger 1934, Bugge 1965, Morton 1970, 1971, Starmer 1976, 1978). They are invariably intruded by magmatic rocks and affected by tectonic movements reflecting post-depositional events in the evolution of the Sector. They normally represent the first recognizable event (e.g., Starmer 1991, p 119) though little is said, or known, about the basement on which they accumulated.

In the present area of study, metasedimentary rocks are well represented (Fig. 4), particularly in the Kragerø domain. They are normally recrystallized with the development of metamorphic minerals and textures (Fig. 5) but there can be no doubt as to their sedimentary origin. The commonest types present are quartzites, micaceous quartzites and pelitic (argillaceous) gneisses. Here, as elsewhere in the Bamble Sector, carbonate rocks are hardly present at all. So

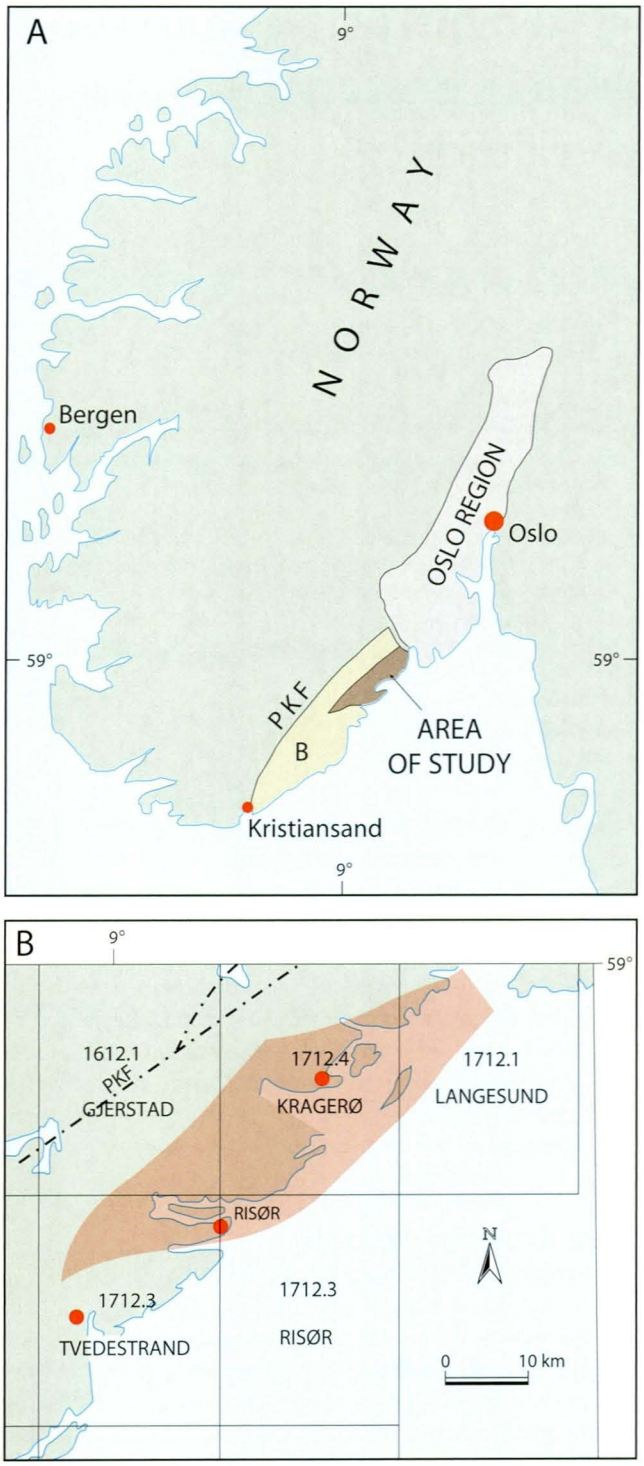


Fig 1. Maps showing location of the area of study in southern Norway; (A) its location in the Bamble Sector. B – Bamble Sector, PKF - Porsgrunn-Kristiansand Fault Zone; (B) relation to the 1:50,000 bedrock map-sheets.

far, no attempt has been made to establish a stratigraphic succession for the domain, thus opening the way for paleogeographic, provenance and other studies. One reason for this is a lack of reliable structural data, another the paucity of data concerning primary depositional features.

One exception to this is on Arøy (Fig. 2) and on the nearby Jesper islands in the easternmost part of Kragerø´s skjærgård. Here, quartzitic outcrops show abundant signs of cross-bedding (Morton 1971). Though somewhat deformed the ´way up´ of the beds, both here and in the near vicinity (present author´s observations), can be determined. Collectively, these observations indicate overfolding and some thrusting of the beds to the SSE. There is an abrupt line of contact between the metasedimentary rocks here and diverse gneissic rocks possibly belonging to an older basement (See also the section on the Skåtøy triangle, p. 00) At Røsholmen (Fig. 4), the line of contact is also partially marked by a remarkable conglomerate. This is markedly polymictic and was described by Morton (1971, plate 2) as a metapyroclastic breccia. It may form part, possibly the lowermost part, of the local stratigraphic succession. After unravelling the local fold structure Morton concluded that the quartzitic sedimentary rocks on Arøy were deposited by currents flowing from the northwest.

Perhaps the greatest thicknesses of quartzitic rocks are to be found southwest of Kragerø. Here, several thick units make up the NW flank of a major antiformal structure (the Mørjeheia Dome) and have been commercially exploited for many years at Litangen and Snekkevik (Fig. 2). A similar large quarrying operation was located in a thick quartzite unit on Bærøy (Figs. 2 and 4), 1.5 km east of Kragerø. In both areas, recrystallization is extreme and no sedimentary structures have yet been reported.

A large area occupied by metasedimentary rocks including quartzites, micaceous quartzites and mica schists occurs in the western part of the study area, more specifically on and around the mountain Heiberg (Figs. 2 and 4). Field data and map compilations by Starmer (1976, 1978) give a fairly good picture of the geology and have been used in the compilation of the 1:50,000 map-sheet Gjerstad 1612.1 (Padget 1993c). There are, unfortunately, few data which can be used to establish an order of succession, possibly due to the present highly metamorphosed nature of the rocks. Field relations involving certain conglomeratic and quartzitic rocks 1.5 km southeast of the summit of Heiberg (Starmer 1978, pp. 52-53) can be interpreted to indicate younging of the beds to the northeast. This, in conjunction with a study of the regional folding in the area, means that the local stratigraphical sequence is one where the main quartzite overlies a sequence of sillimanite-bearing paragneisses. No basement can be identified to the latter but the quartzites seem to be equivalent to those of the Mørjeheia Dome (Fig. 4) mentioned above.

Metasedimentary rocks encircle most of the Levang peninsula (Fig. 4) and seem to dip outwards towards the surrounding sea areas. An important lithological unit exposed on the south side of the peninsula is a well banded, somewhat micaceous quartzite with a minimum thickness of about 15 metres. It is here termed the Rapen Quartzite (Fig. 6) and at one place displays cross-bedding indicating younger beds southwards towards Stølefjorden (Fig. 2). It is probably overlain here by sillimanite-bearing metasedimentary rocks which occupy a major synform (Fig. 4) offshore.

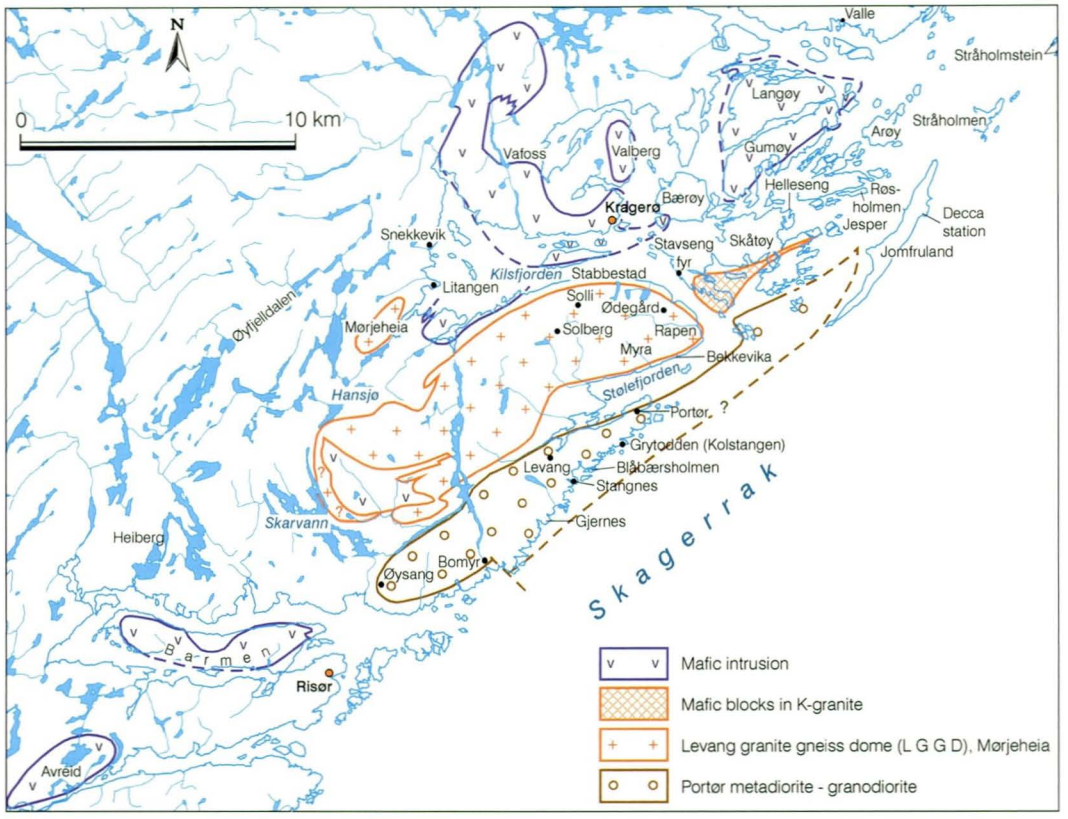


Fig 2. Map of the area of study showing the main intrusions and place names referred to in the text.

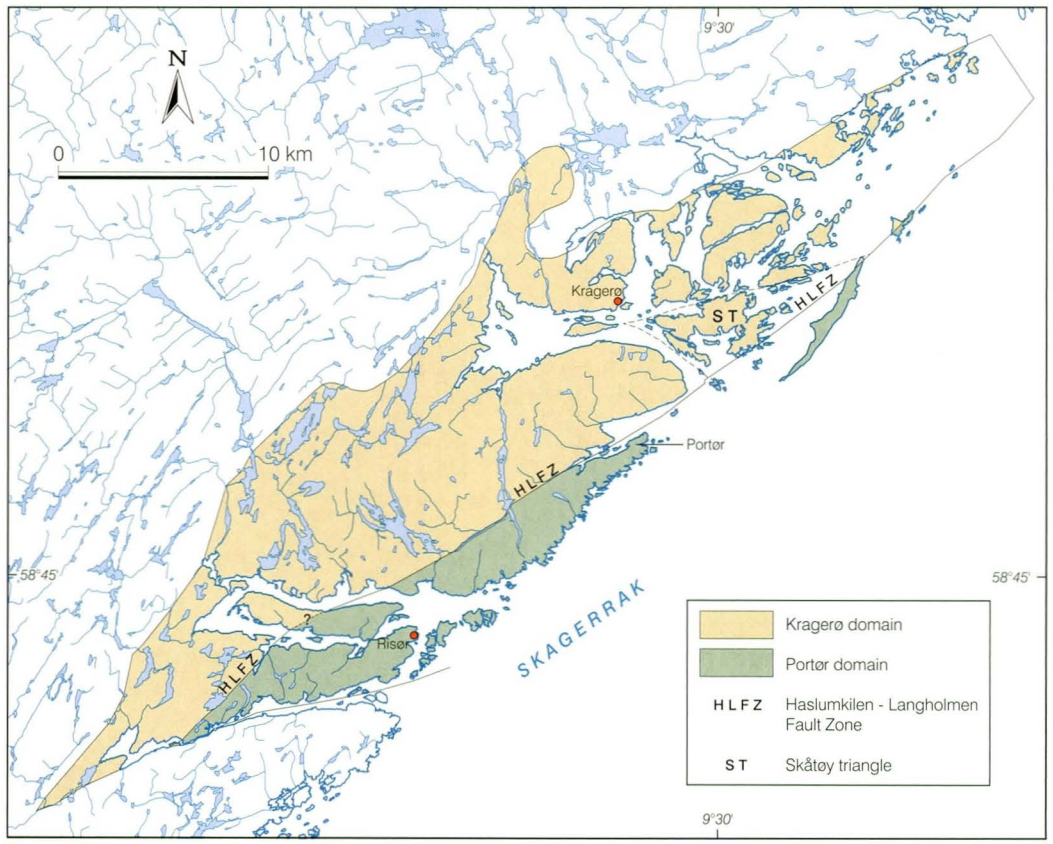


Fig 3. Location of the Kragerø and Portør domains and the fault zone (HLFZ) separating them.

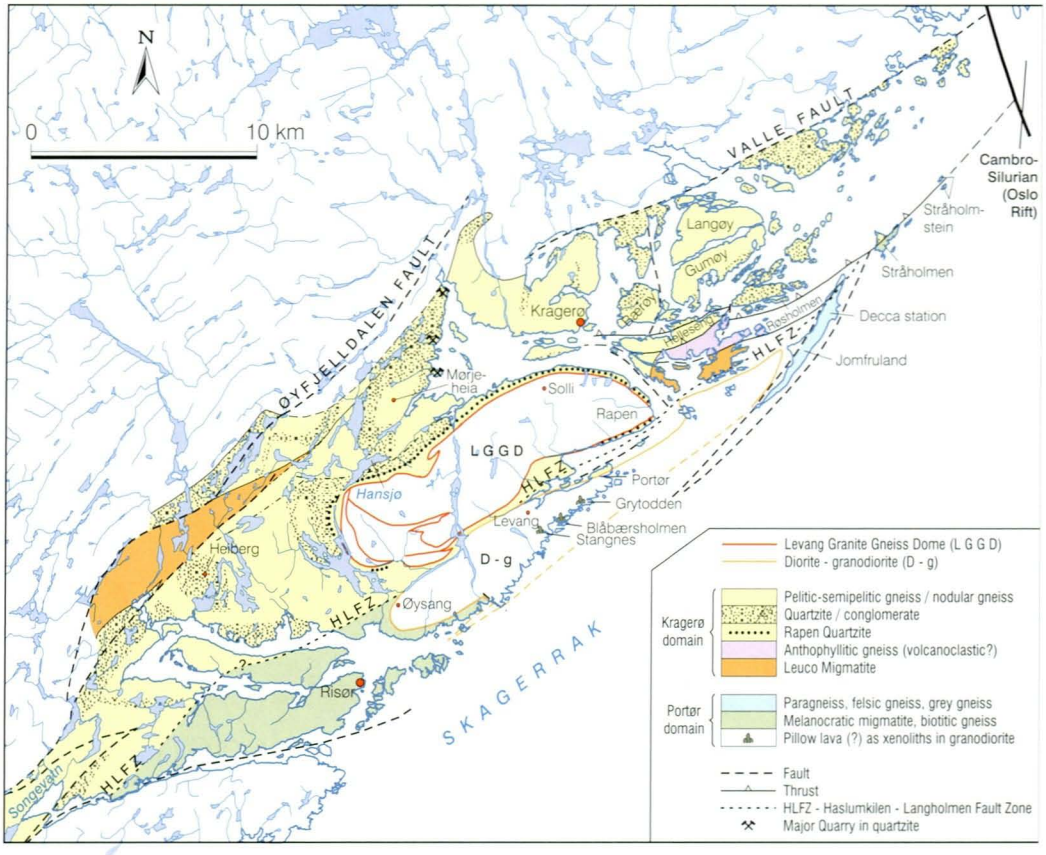


Fig 4. Distribution of the main metasedimentary rock formations in the Kragerø and Portør domains. The major mafic intrusions are omitted.

The quartzite here is steeply dipping and terminates a short distance from the coastline, against a thick, variegated amphibolite which has partly intruded it. No further metasedimentary rocks have been detected on the opposite, i.e. northern side of the amphibolite. The quartzite, which is conglomeratic in a few places, can be traced on Hofseth´s map (1942) along the whole length of the north coast of the Levang peninsula as far as Hansjø (Fig. 4). On the

Fig 5. Pelitic gneiss showing quartz-sillimanite nodules arranged in a fold with a subhorizontal/-gently dipping fold axis. The long axes of the nodules tend to be parallel with the fold axis. Location: 700 metres north of Stavseng fyr, Skåtøy (Kragerø domain). Lens gives scale.

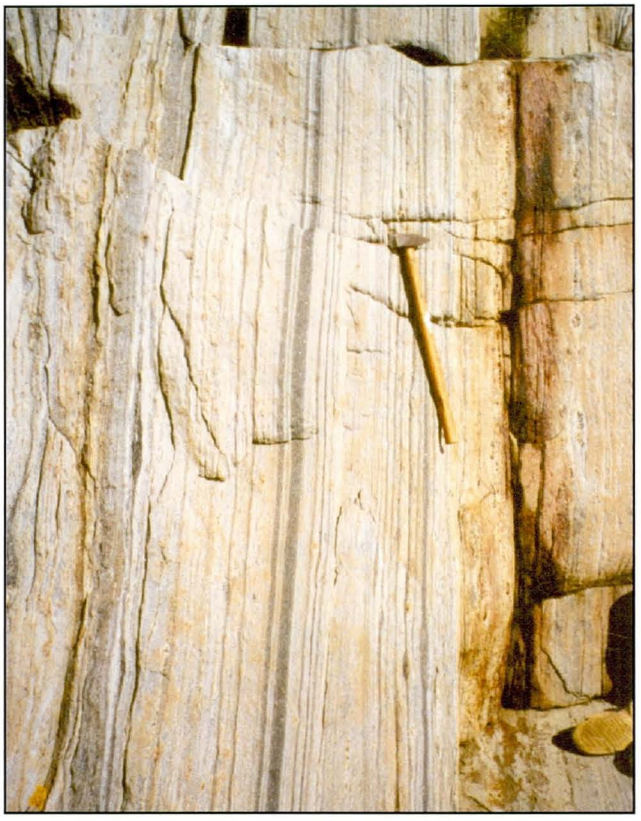


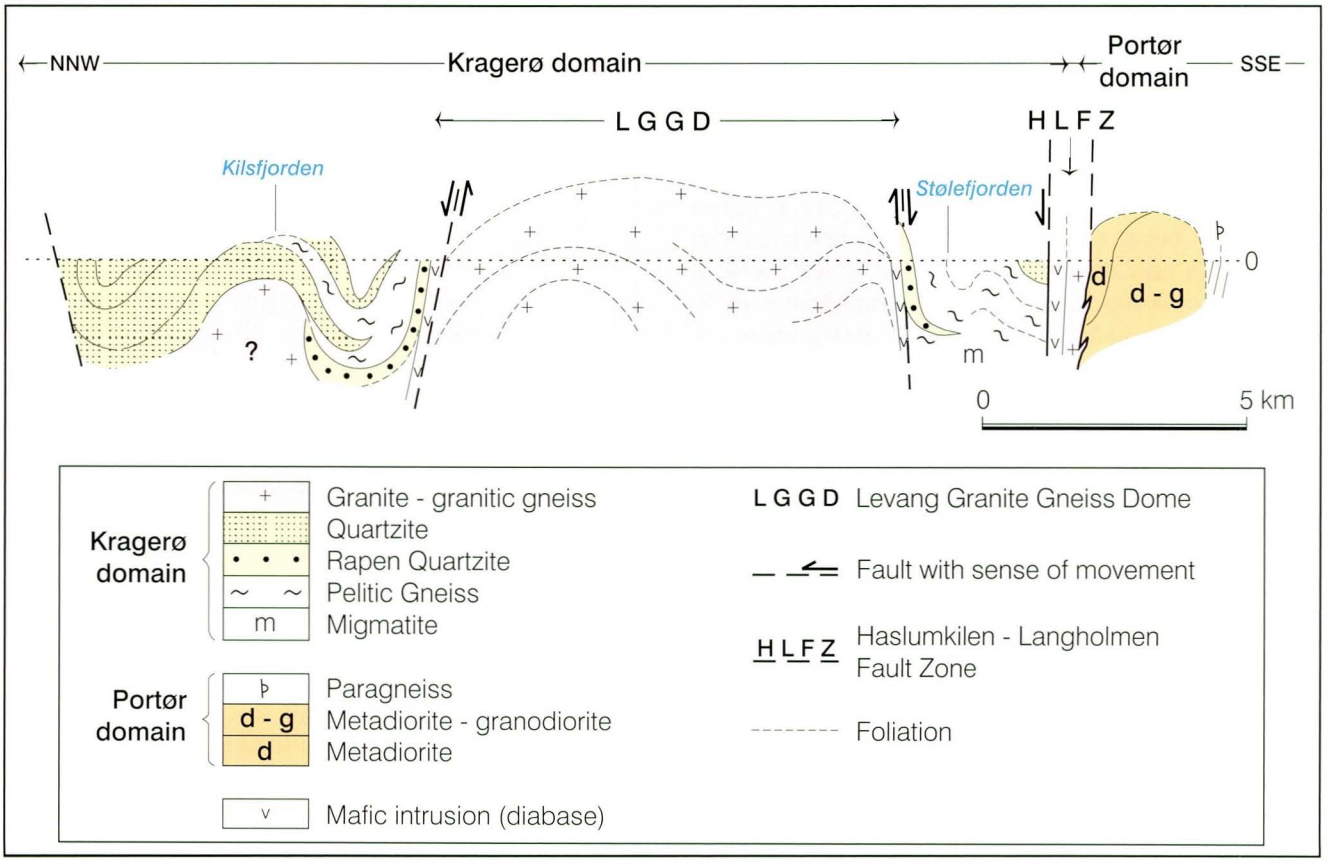
Fig 6. The Rapen Quartzite. Steeply dipping, well banded layers of quartz(light) and biotitic gneiss (dark). Coastal exposure on the Levang peninsula, 900 metres northeast of Bekkevika (Kragerø domain).

south coast, however, 350 metres west-southwest of Bekkevika (Fig. 2), a dark, micaceous gneiss unit intervenes between the quartzite and the amphibolite and is probably stratigraphically lower than the former.

Clearly, additional observations of primary sedimentation features such as cross-bedding are needed to confirm (or refute) the conclusions reached so far regarding the order of stratigraphic succession, both here and elsewhere in the area of study.

Meanwhile, one may conclude from the map compilations (Fig. 4, this article), (Padget 1993a, 2000a, 2001) that the greatest thicknesses of quartzite are located towards the northwest and extend along strike northeastwards from Songevatnet as far as Valle and the boundary with Cambro-Silurian sedimentary rocks of the Oslo Rift (Fig. 4), a distance of nearly 50 km. They terminate to the northwest rather abruptly against a series of faults (the Valle Fault, for example). Southeastwards they are less prominent and are thought to thin out or are replaced by more pelitic, sillimanite-bearing gneisses (facies change). From this it is thought that deposition took place in an elongate trough trending NE-SW and possibly fault-bounded on its northwest margin

Fig 7. Cross-section (schematic) over the Levang Granite Gneiss Dome and associated rocks of the Kragerø and Portør domains showing some of the main structural features. Note the folding of the foliation planes in the granite gneiss and steeply inclined marginal faults. The latter may be an indication of some upward, diapiric rise of the granite gneiss body.



(Fig. 7). The present faulted margin of the metasedimentary unit is younger in age but this is probably a rejuvenative effect.

The lack of continuity between the main outcrops of metasedimentary rock demonstrates the magnitude of subsequent events, particularly the emplacement of large igneous bodies.

Intrusions

The Levang Granite Gneiss Dome

The general features of the Levang Granite Gneiss Dome (LGGD) were first outlined by Hofseth (1942) who went on to conclude that the granitic gneiss represented a synkinematic intrusion in an antiformal structure. The concordant and sharply defined contact between the granitic gneiss and the enclosing rocks, recrystallization of the mineral components and widespread development of foliation seemed to support this view. Burrell (1964) and Elder (1964) carried out more detailed studies of the Dome, the latter concentrating particularly on the chemical composition and structure of the granitic gneiss. He made good use of aerial photo coverage to identify apparent fold structures and went on to confirm their existence by detailed field studies involving measurement of foliation surfaces, fold axes and lineations. He concluded that the granitic rocks were formed "synkinematically through the transformation of a pre-existing series of supra-crustal rocks by processes of metasomatic granitization". This conclusion was almost certainly influenced by current thinking at the time of writing."

The present author has carried out reconnaissance studies of the area and can confirm the existence of folded foliation planes, but there is no sign of supracrustal rocks of undoubted sedimentary origin within the area of granitic gneiss. Otherwise, the gneiss is recrystallized to various degrees, a feature marked by increased grain size and diffuse grain boundaries. This makes any primary magmatic features difficult to discern. However, xenoliths occur at two places, one being a metre-long block of metadiorite at Ødegaard, a now derelict farm 800 metres northwest of Rapen, the other a block of granite, now somewhat gneissic, in granitic gneiss at Rapen itself. Veins of microgranite, partially invaded by the surrounding granite, are also present at Rapen . Leucocratic veining is common towards the southern margin of the granitic gneiss and is also foliated. However, Elder (1964) records the existence of a patch of quartz-rich granite gneiss near Solli (Fig. 2) and, close by, a sizeable body of amphibolitic greenstone. The latter is still inadequately mapped but is veined by granite and clearly incorporated in the granite gneiss and must pre-date the latter. These observations indicate to the present author that the granitic gneiss of the LGGD was originally an intrusion.

The present elongate, ellipsoidal shape of the granitic gneiss may reflect the former existence of an ENE-WSW-trending `crack´ or mega-fracture in basement rocks up which granite magma could ascend. A possible configuration of the granitic body at depth, with an associated access channel through basement rocks, is shown schematically in Fig. 8. This channel could be fault-defined. inviting comparison with the Main Donegal Granite, Ireland (Hutton 1982), for which an elaborate model was developed relating emplacement to fault tectonics. However, the configuration of the granitic gneiss of the LGGD at depth is thought to be pear-shaped to accord better with the steeply dipping nature of the contacts observable in surface outcrops.

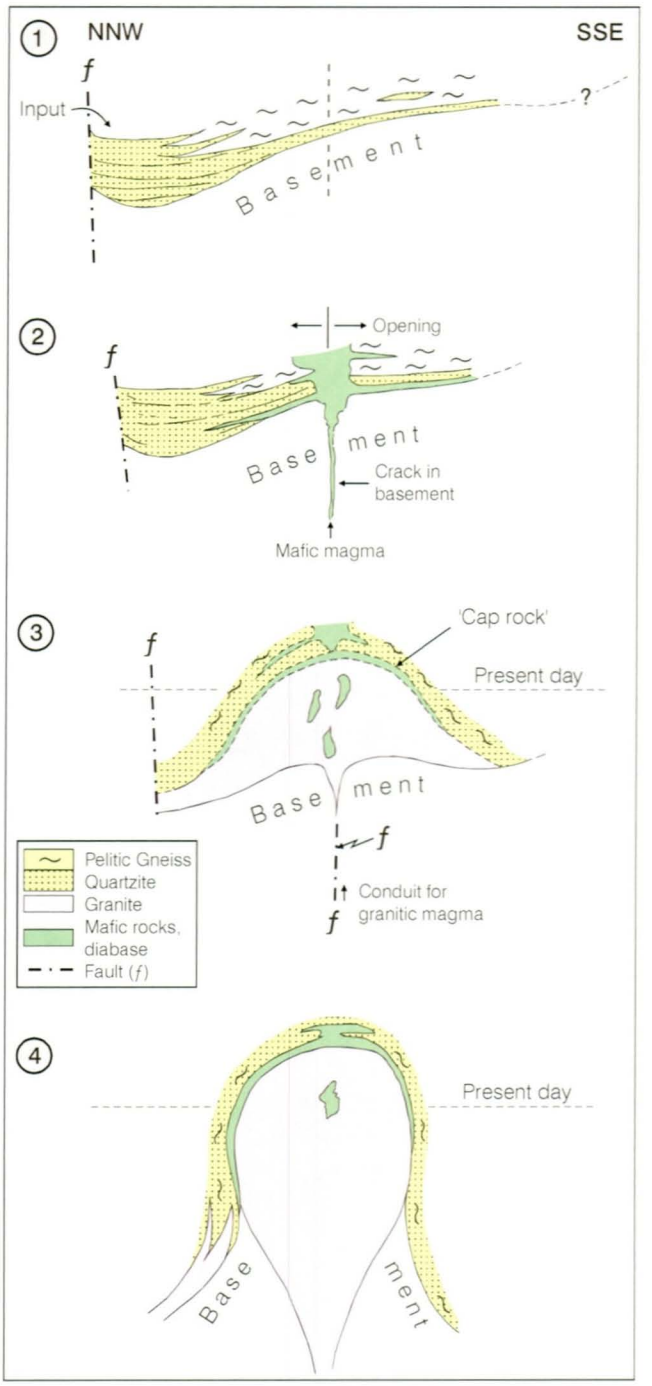


Fig 8. Schematic drawings to demonstrate the early evolution of the Levang Granite Gneiss Dome. 1) depositional phase, 2) intrusion of mafic magma, 3) main granite intrusion. The configuration of the granite at depth is uncertain, 4) a more pear-shaped form, narrowing downwards, is also possible.

A calibration of this intrusive event and later disturbances is clearly desirable. A U-Pb zircon date of 1587 ± 6 Ma was obtained by Råheim (unpublished data in Lamb et al. 1986) for the granite (now orthogneiss) and is considered to be a minimum age for its emplacement. Earlier studies by O´Nions et al. (1971) gave a Rb-Sr whole-rock isochron of 1616 ± 38 Ma for a metamorphic event affecting granitic rocks of the LGGD. An alternative age of 1582 ± 37 Ma by the Rb-Sr method is cited by Starmer (1991, p.122), presumably for the same event. More precise age determinations are needed here, focusing on the age of emplacement of the granite. This is important since field studies indicate clearly that the granite has intruded the metasedimentary rocks (and associated mafic intrusions) and therefore must be younger than these. The metasedimentary rocks themselves must be significantly older than recent U-Pb zircon dating studies on other metasedimentary rocks in the Bamble Sector indicate. One of these is for a quartzite from the vicinity of Kragerø (Åhäll 1998) which gave a depositional age not older than 1499 Ma. Other ages from the Sector (Knudsen et al. 1997) indicate deposition in the interval 1500 to 1370 Ma. This apparent difference in the depositional age of the sedimentary rocks of the LGGD and those elsewhere in the Bamble Sector needs further investigation. One explanation may be that the age of the granite is as old as indicated but its intrusive contacts are the result of remobilization, thus opening the way for a basement/cover interpretation of the field relationships. There is, however, no evidence to support this at the present time.

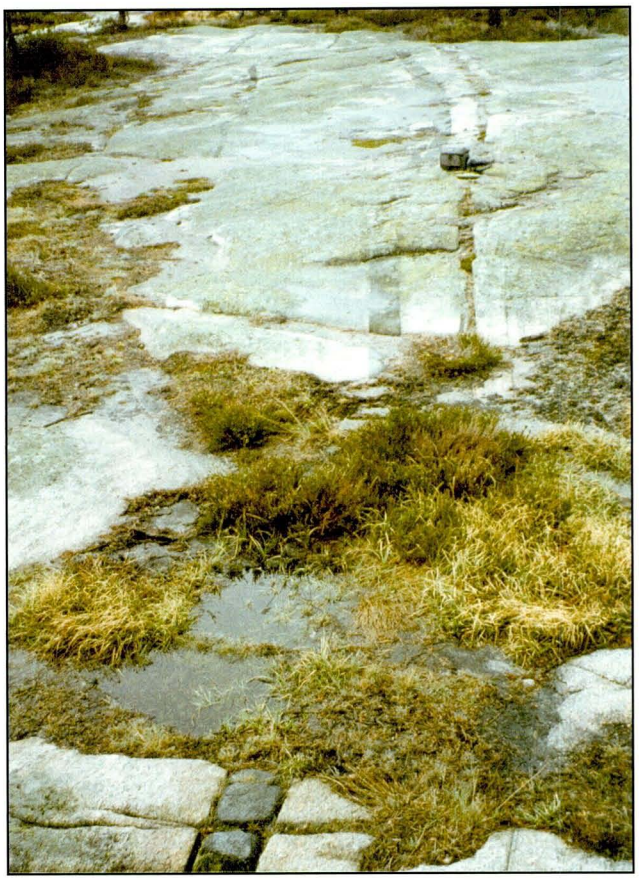


Fig 9. Steeply dipping diabasic dykes (synplutonic) intruded into granitic gneiss. Rapen, Levang peninsula (Kragerø domain). Camera bag gives scale.

Basic intrusions

These include dykes, mega-dykes, small- to medium-sized gabbros and lopoliths as on Gumøy-Langøy. They intrude the metasedimentary rocks and are characteristic for the whole domain. A few (meta)peridotites in association with metagabbro are known from exposures on the coast south of Rapen (Fig. 4). They probably intruded at various stages and helped to maintain high heat levels in this part of the crust over long periods of time. Some idea of the complexity and abundance of these intrusions may be gained from map compilations by Starmer (1969) in the Risør area and in later papers (1985, 1991, see reference list). Morton et al. (1970, pp. 21-28) were impressed by the number of separate intrusions and their general concordance with the strike of the rocks in easternmost Bamble. There is little published geochemical data on these rocks.

In the absence of geochronological data the intrusive ages of these rocks can only be viewed in a relative way, that is, in relation to each other and to their host rocks. Factors such as degree of metamorphism and deformation must also be taken into account.

In the present study, attention is confined to mafic dykes in the LGGD. In the granitic gneiss, for example, they occur in swarms (Fig. 9), are commonly concordant with the outer contact zone and with the internal structure of the gneiss. Intrusion may have been facilitated by the presence of (? cooling) joints in the granite. The dykes are now metamorphosed but only rarely stretched to the point of being segmented. These intrusions are considered to be synplutonic and intruded at some stage during the consolidation of the granitic body.

A rather similar pattern of mafic intrusions seems to be present in the Mørjeheia Dome, southwest of Kragerø, judging from map compilations on the Kragerø map-sheet (Padget, 2000a). Here, a series of steeply dipping, diabase intrusions occurs. These are concordant or near-concordant with the host quartzites, and therefore sill-like in their mode of occurrence. Intrusion seems to have followed bedding and/or foliation planes in the quartzites.

One particular intrusion lies between quartzitic rocks and the granite core. It is normally 5 to 15 m thick, somewhat variegated as regards internal structure and can be followed around most of the Levang peninsula. It intrudes the quartzitic rocks (Rapen Quartzite) in a sill-like manner and hence has an almost stratigraphic mode of occurrence. It is considered to have been intruded into the metasedimentary rocks before intrusion of the granite (See also p.00 regarding its significance in an evolutionary sense).

A number of mafic dykes, around a metre or so in thickness, intrude the above-mentioned mafic intrusion as well the metasedimentary rocks surrounding the granite gneiss.

These show various degrees of metamorphism, some being rich in porphyroblastic garnet, others merely fine- to medium-grained metamorphosed diabases (metadolerites). Cross-cutting relationships are commonly observed between these dykes indicating repeated intrusion of mafic magma, possibly over a long time interval. The metamorphism may be related to the impact of the Sveconorwegian orogeny.

Structural features in the Kragerø domain

The domain is contained within two major fault zones, represented by the Valle and Øyfjelldalen Faults to the northwest and the Haslumkilen-Langholmen Fault Zone (HLFZ) to the southeast (Fig. 10). The former is responsible for abrupt terminations of metasedimentary formations to the northwest (Fig. 4) and is marked by strong mylonitization in the Valle area, and northeastwards as far as the boundary with rocks of the Oslo field. The HLFZ is a complex zone, up to 500 m wide in which quartzitic rocks are highly deformed with the development of sillimanite and micaceous minerals. This zone was intruded at a later date by diabase (metadolerite), now amphibolitized. Between these two zones the LGGD is a major domal feature which, in a way, seems to deflect fold axes in the surrounding metasedimentary succession (Fig. 10). These axes have the normal NE-SW Bamble trend and are termed F1 in this study. Mineral lineations and minor fold axes are near horizontal in the northeast (Arøy area) but plunge southwesterly around the LGGD.

Interpretation of air photos and field studies show that foliation surfaces in the granitic gneiss of the LGGD are folded, the most convincing expression of which is the Myra dome (Fig. 10). This antiformal structure, and other less well defined folds, have axes roughly parallel with the long axis of the granitic gneiss, and foliation surfaces concordant with its contacts. Despite having the same general F1 trend of other fold axes in the area of study, it is not certain they belong to the F1 phase in time, but could have been formed later in connection, for example, with the domal uprise of the LGGD.

Southwest of the LGGD, the two fault zones converge and the F1 folds in between are affected by a later set of folds here termed F2. The result is a superimposed fold pattern. This pattern is further complicated, if not accentuated, by folds (antiforms) thought to be due to the rise of mafic magma, e.g., Barmen (Figs. 2 and 10), though this intrusion may be, to some extent, fault-controlled. The LGGD is surrounded by synforms (rim synforms). These may be a consequence of the upward intrusion of the granitic magma, further accentuated by diaparism of the solidified magma at a later stage. The schematic cross-section (Fig. 7) through the Kragerø and Portør domains demonstrates some of these structural features.

Finally, certain larger intrusions such as the mafic Gumøy-Langøy and possibly the Valberg bodies (Fig. 2) now occupy synformal or basin-like structures and can be termed lopolithic. These could be due to the loading effect of the bodies themselves causing a passive downwarp of the crust and are probably independent of any specific fold phase.

The Skåtøy Triangle

An area of special interest lies to the east of the LGGD. Here, a triangular area of ground, largely coincident with the island Skåtøy, is limited on three sides by faults (Fig. 3) and consists of various formations of a gneissic character (Figs. 2 and 4). The ENE-WSW- trending boundary can be traced through the islands Stråholmen and Stråholmstein (Fig. 4) and is interpreted as a basal thrust to a package of metasedimentary rocks overfolded to the southeast. The southerly boundary of the triangle is part of the HLFZ fault zone, locally marked by an intrusion of amphibolitic diabase. The third side trends NW-SE and occupies the channel between Skåtøy and the Levang peninsula. It is considered to be a high-angle fault of some magnitude judging from the strongly deformed nature of the rocks observable on the Skåtøy side of the channel.

The rocks present in the triangle include migmatites, granitic gneiss and anthophyllite gneiss. There is also an area where large blocks of amphibolitic diabase are embedded in a younger potassic granite (Fig. 2), the whole having an agmatitic appearance. Tangential to this is a vertical `wall´ of granite, 20 m thick, and extending east-west for a distance of nearly 2 km. It is thought to have been intruded along a crustal fracture, possibly a fault. These intrusive features are thought to be the result of extensional stresses set up in connection with faulting between Skåtøy and the eastern part of the Levang peninsula. The whole triangle is considered to be a fragment of an older basement sequence, predating the metasedimentary succession described earlier. The rocks seem to be akin to those of the Portør domain.

Evolution of the Kragerø domain

On the basis of field studies it is now possible to envisage some of the main events in the evolution of the Kragerø domain. These are depicted schematically in Fig. 8.

1) Initial sedimentation on a basement of unknown character but probably containing a high percentage of crystalline, felsic rocks. Input of waterlain, clastic sediments from the northwest into a sinking trough or semi-graben. More argillaceous sediments to the southeast.

2) Mega-fracture in basement arising from tensional forces allowing upward rise and lateral intrusion of mafic magma into a thick sequence of sediments.

3) Forceful intrusion of granitic magma from a deep level in the basement causing updoming of the metasediments (LGGD and Mørjeheia Dome). Upward and outward limit to the intrusion marked by a thick diabasic intrusion (`cap rock´ effect) and break-up of pre-existing mafic rocks, now represented by xenoliths in the granitic gneiss (LGGD).

4) The immediate post-intrusional phase is marked by cooling, crystallization and the development of joints. In this phase, diabase (metadoleritic) dykes were intruded into the granitic core of the LGGD. These are considered to be synplutonic and not xenoliths from a pre-granitic terrane.

(5) The final major episode in the evolution of the domain was undoubtedly one of deformation and regional metamorphism. The development of foliation surfaces in

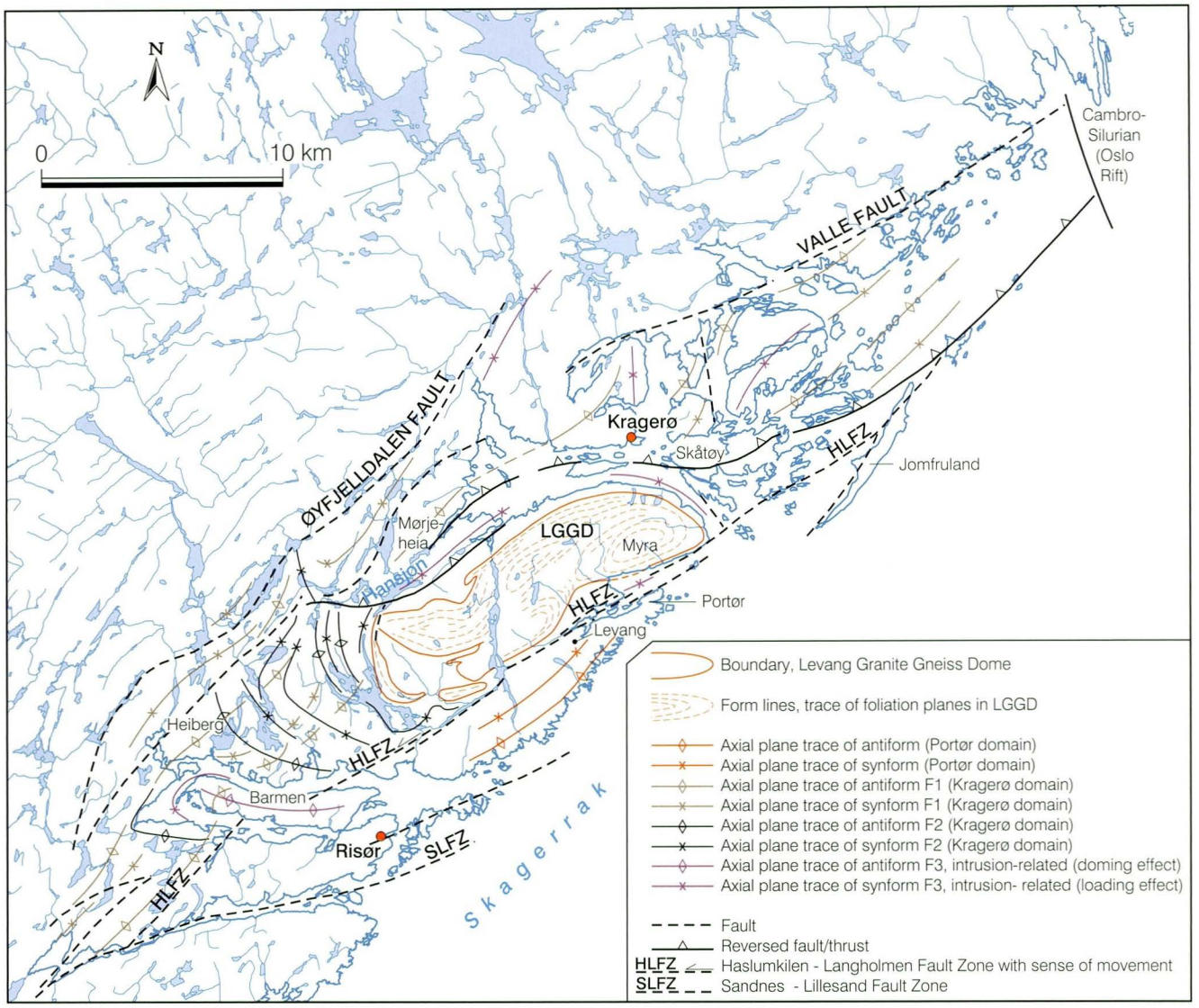


Fig 10. Map showing the main structural elements present in the area of study.

the granite probably belongs to this episode but their apparent folding could be a reflection of F1 folding already imprinted on the metasedimentary rocks which formed the roof of the intrusion. The steep, marginal, contact zones to the granitic gneiss of the LGGD (Fig. 7), together with a more pear-shaped configuration of the granitic gneiss at depth (Fig. 8), may reflect a diapiric movement related to compressional forces. This final episode can possibly be related to the Sveconorwegian orogeny which was most active during the 1100-1200 Ma interval.

(6) Stabilization. The long period extending from the Early Neoproterozoic into the Phanerozoic is marked by cooling, brittle faulting and the intrusion of pegmatites and dolerite dykes. The latter are markedly discordant to pre-existing bedrock structures and one representative, traceable for 500 m in the Rapen area (Fig. 4), penetrates granitic gneiss. It is vertical, non-metamorphic and in sharp contact with the host gneiss. A Permian age for this and other dolerite dykes seems most likely though a Vendian age cannot be excluded.

Joints in the metasedimentary succession are commonly at high angles to most structural surfaces and sometimes have quartz-carbonate veining. In a few cases, brittle faulting can be seen.

Pegmatites are also common in the Kragerø domain as elsewhere in the Bamble Sector. Good examples are to be found in the Rapen area where they are typically non-metamorphic and generally concordant with the structure of the rocks into which they are emplaced, though cross-cutting relationships are also observed. They show little or no differentiation except for poorly defined quartz cores. A Neoproterzoic age for the pegmatites is possible.

In a few places, folded pegmatites are present but these are thought to belong to an earlier, possibly Svecofennian, episode. The not too distant Fen intrusive complex is represented by a lamprophyric (damtjernite) dyke on Skåtøy. This

has been dated by the $^{40}Ar/^{39}Ar$ method to 588 ± 10 Ma (Meert et al. 1998).

The Portør domain

This lies seaward of the Kragerø domain and more specifically between two major fault zones, the Haslumkilen-Langholmen Fault Zone (HLFZ) and the Sandnes-Lillesand Fault Zone (SLFZ, Fig. 10).

Metasedimentary and other layered rocks

These include: (i) paragneisses with associated orthogneisses on Jomfruland (Decca station area, Fig. 4), (ii) biotite gneisses and migmatitic rocks in the Risør and Stråholmen-Stråholmstein areas (Kragerø´s skjærgård), (iii) a possible pillow lava formation preserved as xenoliths in granodiorite in coastal exposures south of Portør (Fig. 4).

(i) The rocks exposed on Jomfruland are largely intrusive but some interlayered gneisses probably have a sedimentary origin. Outcrops of the latter in the Decca station area

Fig 11. Paragneisses (?metasediments) of uncertain origin, invaded by diabasic dykes (dark in photo). The parallelism achieved is broken by minor transverse faults. Coastal exposures on the SE shore of Jomfruland, close to the Decca station. (Portør domain).

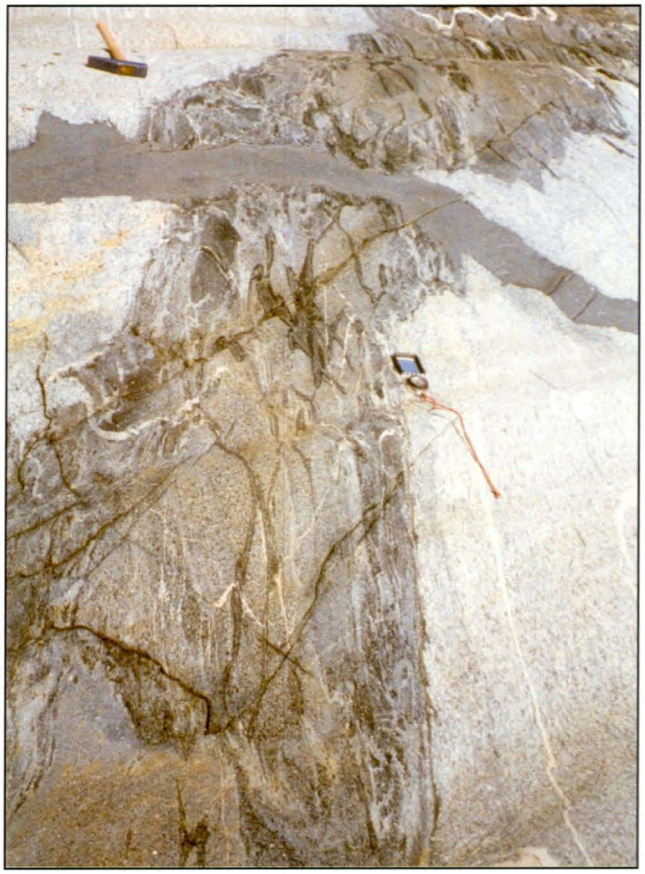


Fig 12. Coastal exposure at Grytodden, 1.1 km southwest of Portør showing possible pillow lavas (dark) in a xenolith in granodiorite. A younger (Precambrian) diabasic dyke cuts both gneiss and xenolith. Compass gives scale. (Portør domain)

are interlayered with mafic and felsic rocks (Fig. 11). The mafic rocks are considered to represent deformed sills and dykes intrusive into a pre-existing terrane consisting of quartzitic and arkosic sedimentary rocks which in a few places show primary clastic features and traces of cross-bedding. There are also a number of rather indeterminate gneisses characterised by a significant content of biotite. They seem to be more akin to gneisses exposed in an enclave in larvikites at Løvall to the north-northeast (see the Langesund map-sheet, Padget 2000b). The whole sequence is one representative of high strain, marked by strong shearing, pronounced ductile deformation and rotation which transposed all rocks into parallelism.

(ii) In the island chain (Stråholmen, Stråholmstein, etc.) northeast of Jomfruland (Fig. 4), outcrops of dark, biotite-rich gneiss, in places epidote-bearing, are clearly of a different nature. They are also penetrated by mafic (amphibolitic) dykes and sills as well as being folded in a complicated manner. Outcrops are relatively small and do not allow far-reaching conclusions to be drawn. The relationship of the biotite-rich gneisses to the rocks on Jomfruland is unknown due to lack of exposure (sea covered).

In the extreme southwest of the Portør domain, around

Risør, dark mica schists and gneisses are common and generally exist as xenoliths in later intrusions (Starmer 1969). Migmatitic rocks are also widespread in the same area and have been described as melanomigmatic by Starmer (1969), presumably on account of the abundance of dark mineral components such as biotite and hornblende.They are folded into an antiform of regional dimensions east of Risør (Padget 1993b) and are in faulted contact with metasedimentary rocks of the Kragerø domain to the north (Fig. 4) and with a major lineament, the SLFZ (Fig. 10), to the south and southeast (cf. Padget 2000a, Fig. 2). A possible connection with paragneisses as far to the northeast as Jomfruland is suggested. Though the intermediate area is sea-covered, a northeasterly trend, concordant with the Portør granite-granodiorite body on the nearby land area, seems reasonable. Elsewhere in the domain, certain gneisses are particularly quartz-rich and may have sedimentary origins. One example is a quartz-rich gneiss on Fengesholmen (Stølefjorden), 2 km northeast of Portør. Its stratigraphic and structural relationships cannot be ascertained.

(iii) Finally, mention can be made of certain amphibolitic rocks which occur within well exposed granodiorite on the coast at Stangnes and at Grytodden (600 metres east of Kolstangen, Fig. 2)), south and southeast of Levang (Fig. 4). They are typically angular, xenolithic blocks of varying shape and size and are usually in sharp contact with the enclosing granodiorite (Fig. 12). They exhibit foliation, shearing and veining, features which clearly pre-date their enclosure in the granodiorite. There is also a considerable re-distribution of the dark and light mineral components giving the rock a semi-banded appearance. The author is of the opinion that these rocks could be somewhat deformed and metamorphosed pillow lavas and hence belong to a supracrustal formation as yet unrecognized elsewhere in the domain. The lighter coloured amphibolite is considered to represent the pillows and the darker, melanocratic amphibolite the matrix. So far, the characteristic pillow shape seen in undeformed, non-metamorphic pillow lavas has not been seen. Rather similar rocks are reported from the Fiskenæsset region, Southwest Greenland (Myers 1984, p.101), where a transition to less deformed, indisputable pillow lavas can be followed in outcrop.

Intrusive rocks

Rocks of intrusive origin make up a large part of the Portør domain. A mega-unit in this respect is a foliated diorite-granodiorite body (Fig. 2), well exposed in the region of the Portør community where it is intruded by granitic veins (Fig. 13). It continues into the sea area west of Jomfruland where the same rocks and relationships can be observed on several small islands. On Jomfruland itself, at the west coast landing-pier, metadioritic and amphibolitic rocks probably belong to the same intrusion.

On the mainland, quartz dioritic to granodioritic rocks are in contact with the metadiorite and occupy large areas to the southwest in the direction of Risør. The contact relationships between these various types of diorite are not yet known in detail though some seem to be transitional. Mafic dykes, now amphibolitic, and less regular bodies of amphibolite intrude the dioritic rocks and are both folded and sheared on a regional scale.

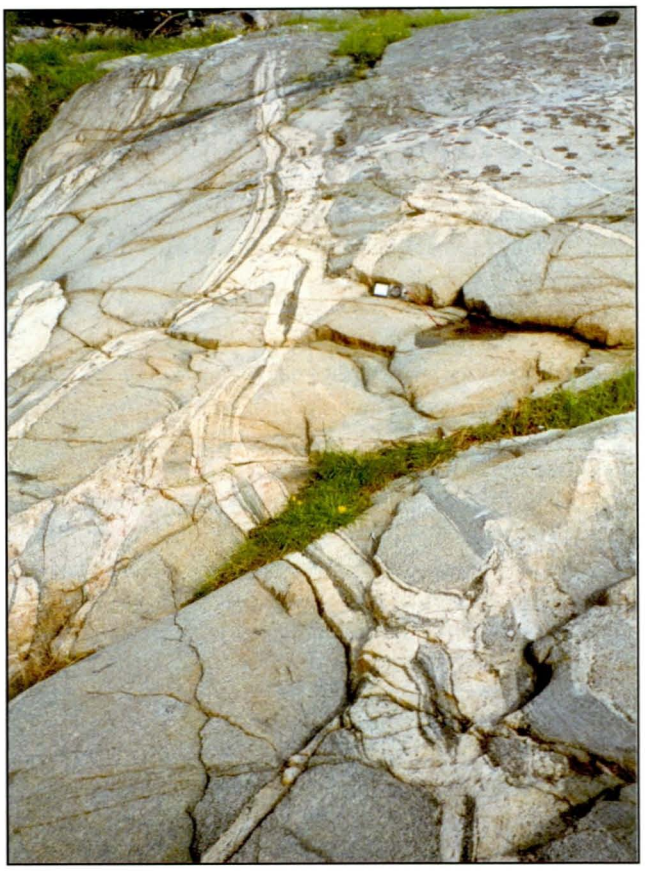


Fig 13. Granitic veins invading metadiorite along a pre-existing fault system. 600 metres WSW of Portør. Portørenga. Compass mirror gives scale. (Portør domain)

In good exposures, as on Blåbærsholmen (Bersundholmen), a small, elongate island 1.6 km east-southeast of Levang (Fig. 4), several phases of dyke intrusion can be seen, the younger mafic ones being both narrower and less deformed than the older ones (Wegmann & Schaer 1962). A fragment of the inferred pillow lava mentioned above is also present at this locality, representing an earlier, pre-dyke phase. A later generation of granitic or felsic dyke intrusion is also evident in many of these and other outcrops in the domain, a feature which seems to increase in importance to the northeast. Near Øysang (Fig. 2) at the extreme southwestern end of the intrusion, the metadioritic-granodioritic rocks are folded and can best be described as melanocratic orthogneiss.

All in all, there is strong evidence for the intrusion of dioritic and granodioritic magmas into a rather mixed assemblage of layered rocks, the true nature of which is still not satisfactorily resolved. Subsequently, diverse magmas of mafic, felsic and granitic composition invaded these rocks in several episodes. All the rocks show evidence of regional metamorphism and ductile deformation.

Structural features of the Portør domain

The whole domain is characterized by a marked structural trend varying between 060° and 065°. This is particularly evident on air photos and is the result of the intersection of foliation and bedrock surfaces (B-tectonites). It is, however, possible to identify 2 folds of regional extent south of Levang, a synform and a complementary antiform (Fig.10). Linear features such as mineral orientations and fold axes show a consistent plunge towards 245°. A complicated pattern of jointing is superimposed on the folds.

Geochronology in the domain

Isotopic dating of certain granitic rocks in the Portør domain using the Rb-Sr whole-rock method (O´Nions et al. 1971) gave a poorly constrained age of 1167 ± 50 Ma. This age is difficult to interpret but may indicate an intrusion age for certain granitic rocks related to the Sveconorwegian orogeny. The age of emplacement of the metadiorite in the domain has not yet been satisfactorily determined in the author´s opinion. It seems to be a distinct intrusion without any obvious connection with, for example, the granitic gneiss of the LGGD. Dating of the metasedimentary rocks has not yet been undertaken.

Dolerite dykes and fault breccias transect the Precambrian rocks at many places and though minor features they represent later episodes in the geological evolution of the domain, probably extending into the Phanerozoic. Many of the mafic dykes are most probably related to the development of the Oslo Rift in the Permian.

The inter-domain contact zone

The contact between the two domains (Fig. 3) is readily discernible on map compilations at all scales and can be traced for nearly 40 km. It is particularly clear over the central section (map-sheet 1712.4 Kragerø, and in Fig. 1B) where it is marked by migmatitic rocks, together with strongly deformed quartzites. Here, there is a steep northwesterly dip. To the southwest the contact is less clear due to the presence of large, cross-cutting intrusions of (meta)gabbro, now largely amphibolitic, such as the Barmen and Avreid bodies.The line of contact is really a zone, up to 0.5 km in width, of ductile faulting, here termed the Haslumkilen-Langholmen Fault Zone (HLFZ) and has been invaded by both mafic and felsic rocks. The sense of movement is not clear but the F2 folds west of the LGGD (Kragerø domain) may be related to a sinistral movement along this fault zone.

Conclusions

The area of study is an important part of the Bamble Sector in the southern part of Norway. Recently completed map compilations have brought to light a number of geological features of a regional nature providing the basis for interpretation studies. These include the recognition of two fault-defined domains, referred to as the Kragerø and Portør domains. These are separated by the Haslumkilen-Langholmen Fault Zone (HLFZ). Gneissic rocks in the Skåtøy area are of Portør-domain type but make up a triangular, fault-bounded enclave in the Kragerø domain. Major faults and fault zones delimit the area of study to the north (Øyfjelldalen and Valle Faults) and to the south (Sandnes-Lillesand Fault Zone).

Metasedimentary rocks are present in both terranes but differ in type as well as in degree of deformation and metamorphism. No satisfactory order of stratigraphic succession has been worked out for these sedimentary sequences but most of the clastic and associated sediments in the Kragerø domain are thought to have been deposited in an elongate trough or half-graben. Certain mafic rocks in the Portør domain are interpreted as possible pillow lavas.

Intrusions, both mafic and felsic, penetrate the metasedimentary rocks of both domains. In the Kragerø domain, the Levang Granite Gneiss Dome (LGGD) is thought to have an intrusive granite core which post-dates the host metasedimentary rocks and most of their associated mafic intrusions. This precludes a simple basement/core relationship. At the same time the relative high intrusion age for this granite of 1616 ± 38 Ma (first reported by O'Nions et al. 1971) means that the immediate host rocks must be even older. The latter are then significantly older than similar rocks elsewhere in the Bamble Sector (Knudsen et al. 1997 and Åhäll 1998) deposited in the 1500 to 1370 Ma interval. It also means that the Kragerø domain, as defined above, contains two sedimentary sequences of different ages.

Some idea of the episodic development of this terrane is depicted schematically in Fig 8.

The major, post-sedimentary intrusions in the Portør domain are dioritic to granodioritic and these are, in turn, invaded by granitic rocks of probable Sveconorwegian age. The intrusion of mafic rocks (diabases, gabbros) traditionally dated to the 1200-1100 Ma interval (Starmer 1985), affects both domains but took place in several phases over a long period of time. Doleritic dykes and pegmatites are common in late Precambrian (Neoproterozoic) time.

From the above, it is clear that there is a great need for additional isotopic dates to clarify the evolution of this part of the Bamble Sector.

Finally, these rocks and particularly those of the Portør domain are of some interest since a recently published compilation (Sigmond 2002) shows them to be part of an extensive area of supposed Precambrian gneisses in the inner part of the Skagerrak, a conclusion based on interpretations of geophysical data (e.g., Flodén 1973). The nearest outcrops which can be inspected are, in fact, those in the Portør domain and in the enclave of Precambrian rocks in Permian vulcanite at Løvall, 1.2 km east of Nevlunghavn (Padget 2000b).

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used by the present author in the map-sheet compilations on which the present study is partially based.
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References

Brøgger, W.C. 1934: On several Archean rocks from the south coast of Norway. Nodular granites from the environs of Kragerø. *Det norske videnskaps-akademi i Oslo 1933, 1. Matematisk-Naturvidenskapelig klasse, 2.* 97 pp.

Bugge, A. 1965: Iakttagelser fra rektangelbladet Kragerø og den store grunnfjellsbreksje. *Norges geologiske undersøkelse 229*, 115 pp.

Burrell, D.C. 1964: *The geology of the country west of Levang peninsula, south Norway.* Unpublished Ph.D. thesis, Univ.of Nottingham.

Elder, T.G. 1964: *A petrological and structural study of the Levang Gneiss Dome, southern Norway.* Unpublished Ph.D. thesis Univ.of Durham. 240 pp.

Flodén, T. 1973: Notes on the bedrock of eastern Skagerrak with remarks on Pleistocene deposits. *Stockholm Contributions in Geology 24*, 79-102.

Hofseth, B. 1942: Geologiske undersøkelser ved Kragerø, i Holleia og Troms. *Norges geologiske undersøkelse 157*, 11-46.

Hutton, D.H.W. 1982: A tectonic model for the emplacement of the Main Donegal Granite, NW Ireland. *Journal of the Geological Society of London 139,* 615-631.

Knudsen, T-L., Andersen, T., Whitehouse, M.J. & Westin, J. 1997: Detrital zircon ages from southern Norway – implications for the Proterozoic evolution of the southwestern Baltic Shield. *Contributions to Mineralogy and Petrology 130*, 47-58.

Lamb, R.C., Smalley, P.C. & Field, D. 1986: P,T conditions for the Arendal granulites, southern Norway: implications for the roles of P,T and CO_2 in deep crustal LILE depletion. *Journal of metamorphic geology 4,* 143-160.

Meert, J.G., Torsvik, T.H., Eide, E.A. & Dahlgren, S. 1998: Tectonic significance of the Fen province, S. Norway: constraints from geochronology and paleomagnetism. *Journal of Geology 106, 553-564.*

Morton, R.D., Batey, R. & O´Nions, R.K. 1970: Geological investigations in the Bamble Sector of the Fennoscandian Shield, south Norway. 1.The geology of eastern Bamble. Norges geologiske undersøkelse 263, 72 pp.

Morton, R.D. 1971: Geological investigations in the Bamble Sector of the Fennoscandian Shield, S. Norway. 2. *Norsk Geologisk Tidsskrift 51*, 63-83.

Myers, J.S. 1984: Archaean tectonics in the Fiskenaesset region of southwest Greenland. In: Krøner, A & Greiling, R. (eds) 1984: *Precambrian Tectonics Illustrated.* E.Schweitzerbart´sche Verlagsbuchhandlung. Stuttgart, 95-112.

O´Nions, R.K. & Baadsgaard, H. 1971: A radiometric study of polymetamorphism in the Bamble region, Norway. *Beiträge zur Mineralogie und Petrologie 34*, 21 pp.

Padget, P. 1990: Tectonic and lithostratigraphic relationships in the Bamble sector, south Norway: an interpretative view. *In:* Gower, C.F. Rivers,T. & Ryan, A.B. (eds.). *Mid-Proterozoic Laurentia-Baltica.* Geol. Assoc. Canada, Special Paper 38, 307-316.

Padget, P. 1993a: Tvedestrand. Berggrunnskart 1612.1- 1:50 000, foreløpig utgave. *Norges geologiske undersøkelse.*

Padget, P. 1993b: Risør Berggrunnskart 1712.3- 1:50 000, foreløpig utgave. *Norges geologiske undersøkelse.*

Padget, P. 1993c: Gjerstad Berggrunnskart 1612.1- 1:50 000 foreløpig utgave. *Norges geologiske undersøkelse.*

Padget, P. 2000a: Notes to accompany preliminary map sheet Kragerø 1712.4. Bedrock 1:50 000. *Norges geologiske undersøkelse. Report 2000.009*, 38 pp.

Padget, P. 2000b: Notes to accompany map sheets Langesund 1712.1 and Stavern 1812.4. Bedrock 1:50000. *Norges geologiske undersøkelse. Report 2000.008*, 24 pp.

Padget, P. 2001: Arendal 1611.4. Notes to accompany the map compilation (preliminary) of 1997 with revisions year 2000. *Norges geologiske undersøkelse. Report 2000.010*, 56 pp.

Sigmond, E.M.O. 2002: Geological map, Land and Sea Areas of Northern Europe 1:1 million. *Geological Survey of Norway.*

Starmer, I.C. 1969: The migmatite complex of the Risør area, Aust-Agder, Norway. *Norsk Geologisk Tidsskrift 49*, 33-56.

Starmer, I.C. 1969: Basic plutonic intrusions of the Risør-Søndeled area, south Norway: the original lithologies and their metamorphism. *Norges Geologisk Tidsskrift 49,* 403-431.

Starmer, I.C. 1976: The early major structure and petrology of rocks in the Bamble Series, Søndeled-Sandnesfjord, Aust-Agder. *Norges geologisk undersøkelse 327,* 77-97.

Starmer, I.C. 1978: The major tectonics of the Bamble Series between Søndeledfjord and Kilsfjord (Aust-Agder and Telemark). *Norges geologiske undersøkelse 338,* 37-58.

Starmer, I.C. 1985: The evolution of the south Norwegian Proterozoic as revealed by major and mega-tectonics of the Kongsberg and Bamble sectors. 259-290. *In*: Tobi,A.C. & Touret, J.L.R.(eds.): *The deep Proterozoic Crust in the North Atlantic Provinces*, Nato ASI Series, Ser. C. 158. D. Reidel 259-290..

Starmer, I.C. 1991: The Proterozoic evolution of the Bamble sector shear belt, southern Norway: correlations across southern Scandinavia and the Grenvillian controversy. *Precambrian Research 49,* 107-139.

Wegmann, C. E. & Schaer, J.P. 1962: Chronologie et deformations des filons basiques dans les formations precambriennes du sud de la Norvège. *Norsk Geologisk Tidsskrift 42*, 371-387.

Åhäll, K. I. 1998: Ion probe zircon dating of metasedimentary units across the Skagerrak: new constraints for early Mesoproterozoic growth of the Baltic Shield. *Precambrian Research 87*, 117-134.