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Metasedimentary rocks in the Bamble terrane, Norway: their lithological expression, possible correlations and depositional scenarios.

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REPORT

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Summary: The paper presents the results of a study of metasedimentary rocks in the Bamble Terrane, S. Norway. These are of Mesoproterozoic age and were deposited in an early phase in the evolution of the Terrane judging from deformational features, cross-cutting intrusive rocks and widespread metamorphism. Lithologically speaking, the main sedimentary units consist of quartzites (former sandstones), meta-pelites (former slamstones, argillaceous sediments, some partially quartz-bearing) and occasionally, calcsilicate beds. Small amounts of marble (former carbonate-rich sedimentary rocks) occur often in association with the meta-pelitic beds. Some meta-greywacke beds (possibly pyroclasts of volcanic origin) are also reported (Morton 1971).

These layered rocks have a SW-NE strike and are grouped into two main metasedimentary units, possibly separated by a fault. The area northwest of this fault consists of metasediments of a major clastic unit (dated at 1700 Ma) which grades laterally along strike into gneissic units. These two units then dip to the SE and constitute stratigraphically a Lower series. No well defined basement to this series has so far been found. SE of this fault the metasedimentary rocks consist of a more varied series of meta-pelites and quartzites collectively referred to here as the Upper series. One quartzite in the latter is dated from the 1700 -1250 Ma interval. Beds of the two series are possibly separated from each by the fault the existence of which first became apparent during cartographic compilation when quartzitic units of the Upper series were seen to terminate abruptly to the northwest. The fault trace (Fig. 4) deduced also coincided with strongly deformed beds SW of the lake Rore (near Landvik, 4 kms west of Grimstad) and is thought to be a south-westerly continuation of the Valle fault. The scale and sense of movement along this fault are unknown, but some down-faulting of the Upper series in relation to the Lower series seems most likely. Generally speaking, there is no evidence from field studies in the part of the Bamble Terrane discussed here that major inversions of the lithological sequences have taken place, either by overfolding or thrusting or both.

Separate from the above, occur conglomerates at two localities. Field relationships indicate they are of limited extent, are discordant to the aforementioned metasediments and hence represent a late-stage event in the sedimentological process, at least older than 989 Ma, being the Neoproterozoic age of the Grimstad granite which intrudes one of these conglomerates and the 920 Ma age of the Herefoss granite which intrudes the other. There are no geochronological data as yet to indicate more specifically the depositional age of the conglomerates but they show little or no signs of having undergone regional metamorphism.

A number of quartzite bodies, recorded on regional map compilations but otherwise isolated from other metasedimentary units by post-depositional intrusions and erosion, are also tentatively correlated with similar units in the Lower and Upper series. This allows an integrated picture of the various metasediments in the Bamble Terrane to be formulated despite subsequent tectonic deformation and magmatic intrusion and at the same time forms a framework to which these later events can be related.
Some tentative conclusions can also be drawn regarding depositional aspects of some of the formational units utilising primary depositional features (where available) as well as the configurations of individual units. This in turn opens for speculation regarding the direction of transport and provenance of the clastic material, the source areas of which are thought to lie to the north or northeast, possibly in the Telemarkia terrane (Bingen et al. 2008) and well outside the Bamble Terrane boundary. Further support for some of the conclusions offered regarding the depositional processes involved has also been sought in articles describing situations in analogous, but better exposed and less deformed terrains.

Keywords: Bamble	Quartzites	Metasediments

INTRODUCTION

The Bamble Terrane, also termed `Sector' in many previous publications, is a well known feature of the Precambrian bedrock geology of southern Norway with its distinctive regional NE-SW strike direction and evolutionary history giving it a tectonostratigraphic appearance, possibly due to its position in a collision zone between the Telemarkia and Idefjorden Terranes (Bingen et al. 2008). The part dealt with in this article extends northeast parallel to the Skagerrak coastline over a distance of 130 kms (Fig. 1). A possible continuation of the Terrane in the Modum area to the north is not considered here.

It has long been known that layered rocks of undoubted sedimentary (now metasedimentary) origin are important elements in the Bamble Terrane, their deposition being among the earliest discernible events in its evolutionary history (e.g, Starmer 1990). However, little has so far been done to establish a stratigraphy for the terrane as a whole or to detail the types of sediment present. Attention has rather been focused on later events such as intrusion of magmas, structural disturbances and metamorphism. These events were often severe making elucidation of the primary stratigraphy and nature of the early sedimentation processes difficult to resolve. In addition, episodic erosion over a long period of time has reduced the aerial expression and volume of all the rocks, not least those of sedimentary origin. Despite this, an attempt is made in this report to show the distribution of the various lithologic units in map form (Figs 2 and 4) with suggestions as to their possible stratigraphic arrangement and correlation (Fig. 3). At the same time the report puts on record field observations relevant for building up a picture of these early depositional events and also includes suggestions regarding possible depositional scenarios. The latter, though admittedly speculative in many cases, can form starting points for future field studies as well as sampling for geochronological studies (cf. Bingen et al. 2008).

For descriptive purposes this large area is divided into two parts referred to as the Nidelva area (southwest) and Kragerø area (northeast). The line of division is shown in figure 2 and is duly referred to in appropriate places in the text.

Database

Relevant data on the bedrock have recently been assembled in map compilations at scales of 1:250 000 (Arendal sheet, colour printed) and at 1:50 000 (13 sheets, preliminary only but now digitized). Eleven of the latter cover a major part of the Bamble Terrane, in particular that covering the area of the present study between Lillesand in the southwest and Langesund (Cambro-Silurian boundary) in the northeast, a distance of 130 kms. (Fig. 1). Digitization of all relevant geodata has recently been completed enabling printouts of selected areas, themes etc. to be produced. An overview map at a scale of 1:130 000 (Padget & Gjelle 2005) showing, for example, all quartzitic units served as a base map for the present study. Use has also been made of unpublished data, mainly map data, in the archives of the Geological Survey of Norway (NGU).

Age determinations

In recent years dating of sediments by U-Pb isotope technology has been much in focus. Published studies so far carried out in the Bamble Terrane (e.g. Knudsen et al. 1997) conclude that deposition of certain quartzites among the metasediments cannot be older than 1500 Ma and most probably took place in the 1500-1250 Ma interval (i.e. Mesoproterozoic). A similar conclusion was reached by Åhäll (1998) for a quartzite localized rather vaguely as `west of Kragerø'. This is at variance with a conclusion reached more recently by Nijland et al. (2000) for quartzites (Nidelva quartzite, see below) exposed near the lake Blengsvann. Here alkaline dykes which intrude the quartzites belong to a period of incipient rifting dated at around 1500 Ma using the Sm-Nd method. Deposition of the host quartzites is therefore considered to be older. The quartzitic material could then have been derived by erosion and fluviatile transportation from a crustal batholith belonging to the 1900-1750 Ma interval (Paleoproterozoic). The explanation for this apparent discrepancy in age could be that quartzites of two distinct ages are present, an older one belonging to the *Lower series* of this article and a younger one to the *Upper series*. This conclusion at least accords well with the arrangement of the lithostratigraphic units presented in Fig. 3 though the geochronological evidence is still meagre (Knudsen et al. 1997, Bingen et al. 2008) and needs further substantiation.

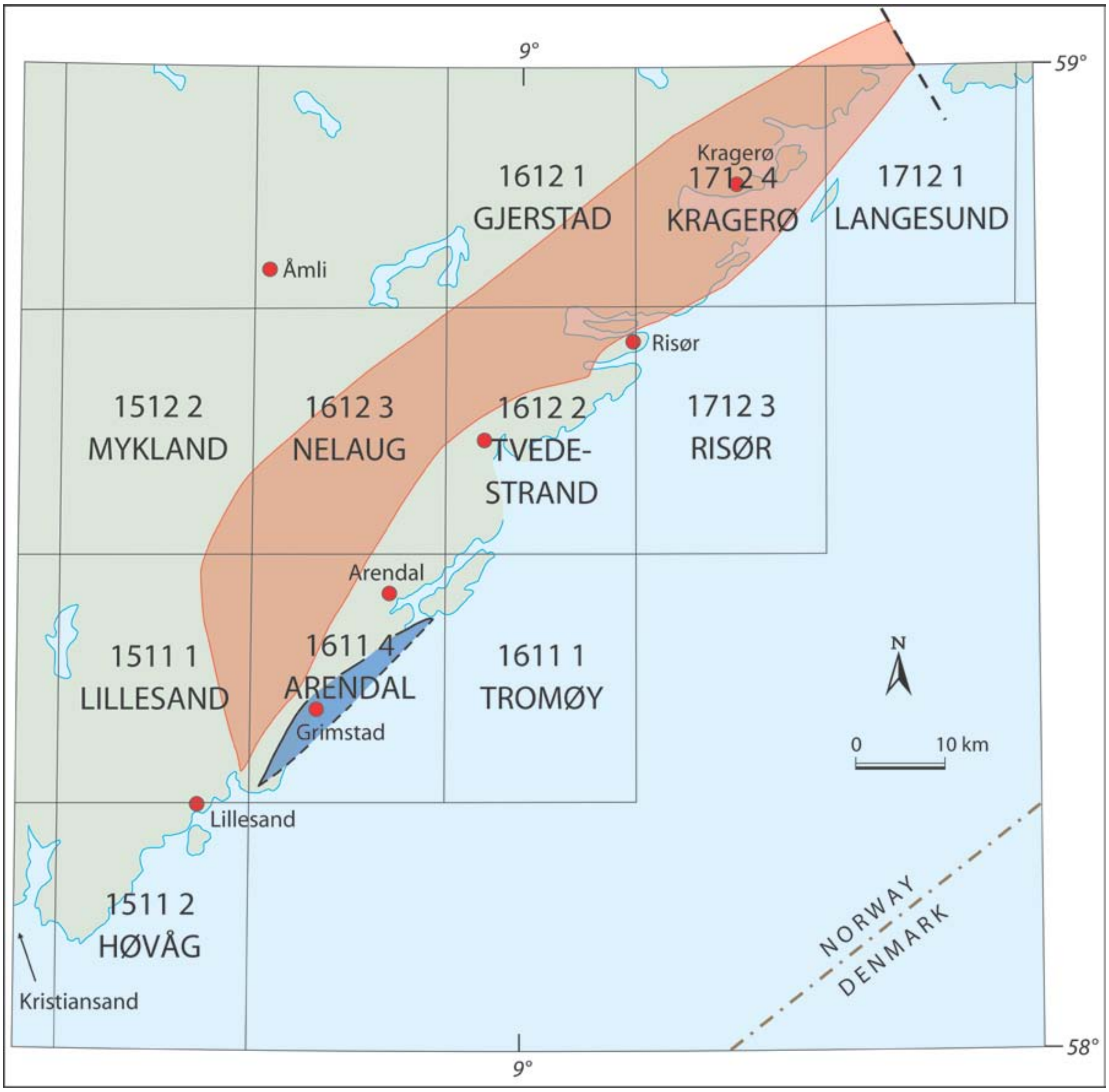

Fig. 1. Map showing location of area of study within the Bamble Terrane, southern Norway and its relation to 11 1:50 000 map sheets for which preliminary compilations of the bedrock have been made by the author. Bamble tract in brown, Merdøy tract in blue.

Regional lithology (Overview).

This study deals with metasedimentary rocks present in two main tracts within the Bamble Terrane, the main Bamble tract and the smaller Merdøy tract (Fig. 1). In the former, the regional lithology is considered in two major areas, hereafter referred to as the Nidelva area in the west or southwest and the Kragerø area in the northeast (Fig. 2). In each area quartzites are prominent among the layered rocks and are important for correlation studies. At the same time, all the sediments are much invaded by granitic and mafic intrusions and hence often exist as relict bodies in the latter displaying moderate to high grades of metamorphism and recrystallization. The same is true of metasedimentary rocks present in the smaller though separate Merdøy tract. Depositional features exist in the metasedimentary rocks of both tracts (Fig. 2) but are, regrettably, few and far between or of inferior quality for diagnostic purposes.

The main lithologic units identified in this study are shown in the correlation chart (Fig. 3) where they are grouped into two series, a *Lower series* in the south and southwest consisting of the Nidelva quartzite which passes laterally to the northeast into a variety of gneisses collectively referred to here as the Sundebru gneisses, including the Selås gneisses (Touret 1968), and an *Upper series* consisting of a number of separate depositional systems, hereafter referred to as the Heiberg, Litangen, Stølefjorden and Kragerø archipelago (or `skjærgård') depositional systems (Fig. 4). There is, however, mapping evidence to suggest that collectively these systems rest on a substrate of meta-pelitic rocks, often sillimanite-bearing, which is in practice the uppermost lithological unit of the *Lower series.* This unit is referred to as the Stavseng (meta-) pelite in the NE and the Rore (meta-) pelite in the SW (Figs 2 and 3) and consisted originally of argillaceous material possibly deposited in a shallow, water-filled basin. Its approximate limits and relationships to later deposited quartzites are evident from the map compilation (Fig. 2). Furthermore, three units (Fig. 2), as yet undated isotopically, are thought to represent units of the *Upper series* further southwest. These include the Mesel quartzite which rests on the locally developed Rore (meta-) pelite, and the Øynesvann quartzite as well as a not insignificant area of meta-pelitic rocks in the Eikeland area, east of the Øynesvann quartzite thought to be an extension of the meta-pelitic formations mentioned above. Quartzite may once have overlain this (meta-) pelite also but has later been eroded away or incorporated into upwelling granitic magmas.

Conglomerates and sandstones of limited extent locally overlie the Mesel quartzite (at Krokelia) and the Nidelva quartzite (at Stemvannet) and are the uppermost, probably the youngest rocks of sedimentary character known in this part of the Bamble Terrane, younger in fact than units of the *Upper series* mentioned above but older than 989±9 Ma, being the intrusion age of the Grimstad granite (Kullerud & Machado 1991). For descriptive purposes they are grouped together as a *late-stage* unit.

The much smaller, semi-parallel Merdøy tract, also contains metasedimentary rocks. These now apparently occupy a separate, fault-defined basin and include the Merdøy quartzite which appears to be younger towards the southeast though isoclinal folding could complicate this interpretation. If correct, associated interlayering with micaceous meta-pelitic rocks should also young in this direction. Below the quartzite a variety of meta-pelites occur as well as some bodies of marble (in Grosfjorden). Correlation of these meta-pelites, and the associated marbles, with the Rore meta-pelite seems to be a reasonable assumption to make, the overlying Merdøy quartzite then possibly being correlative with the Mesel quartzite (Fig. 3). A former pre-erosive physical connection between the two is shown tentatively by the dotted signature in Fig. 2.

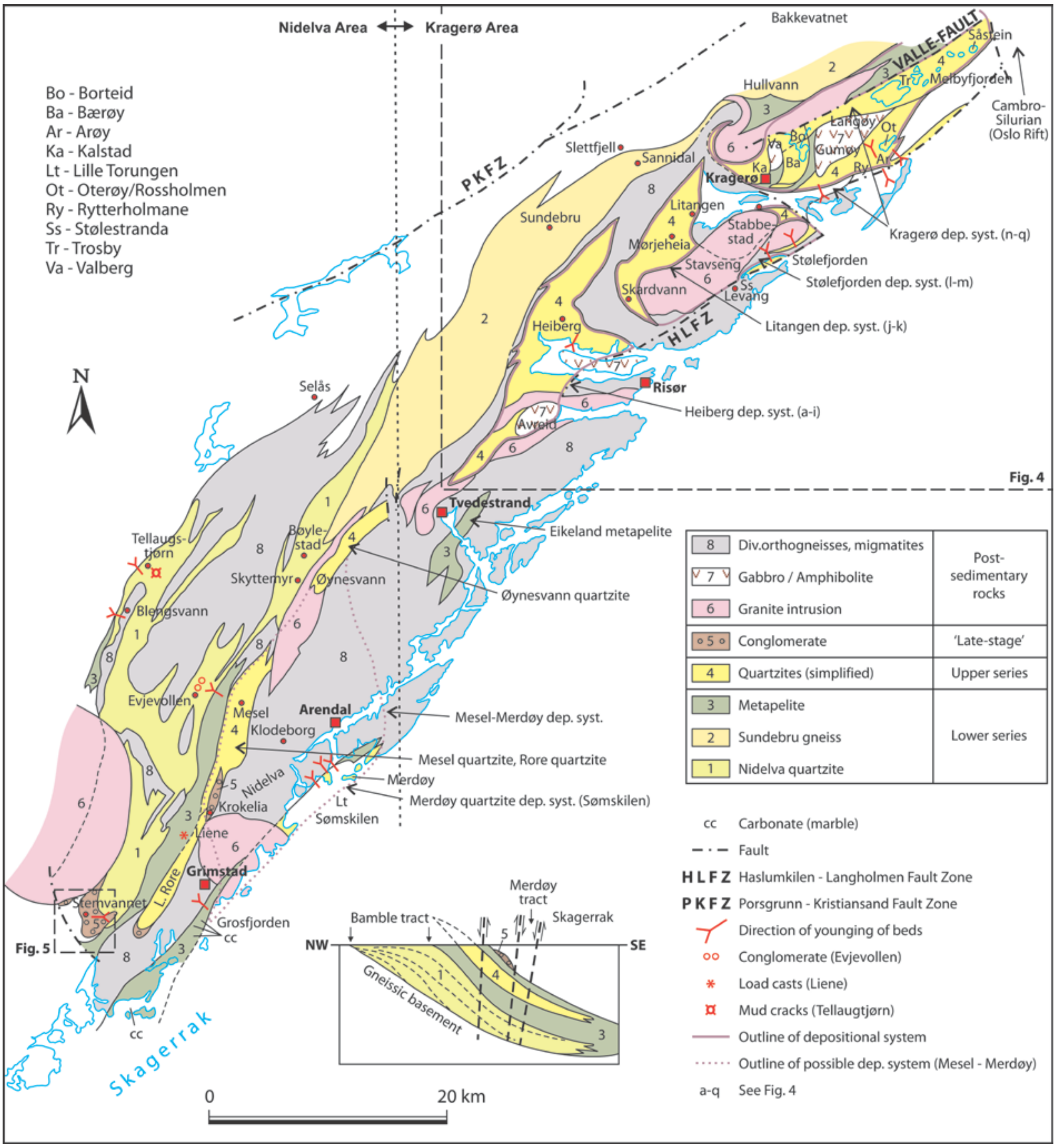

Fig. 2. Map of the area of study showing the main lithostratigraphical units preserved from an early depositional stage in the evolution of the Bamble Terrane. The figure also includes an idealized cross-section over the southernmost part of the Terrane to demonstrate the basic stratigraphy before the onset of major disruptive faulting, shearing and magmatic intrusion. Dashed lines in the quartzite denote possible stages of progradation to the southeast. A few rocks of intrusive character are also shown.

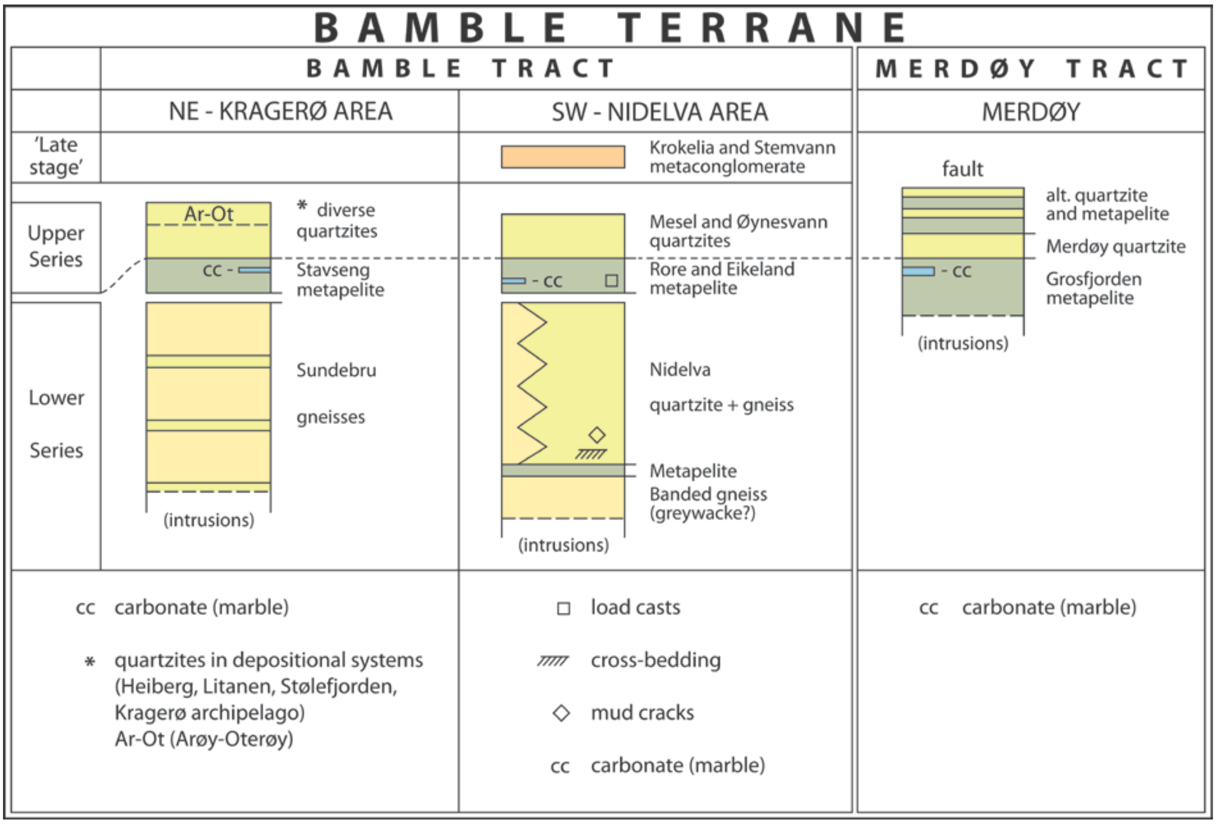

Fig. 3. Correlation chart showing the main lithological units present in the Bamble and Merdøy tracts, those of the former being further subdivided into northeasterly and southwesterly areas. Thickness of formations schematic.

It should be noted here that the metasedimentary rocks present in the two main tracts, and discussed in further detail below, may formerly have had continuations outside their present limits where they are now represented by paragneisses and migmatites. This means that the original distribution of the rocks as sediments extended beyond their present-day limits. The map (Fig. 2), however, shows only the distribution of the lithological units within the two tracts as they appear today. Tectonic deformation has almost certainly affected the sediments in post-depositional time, for example, in connection with the Sveconorwegian Orogeny (1140-900 Ma) and contributed to a changed lithological aspect. There is, however, no field evidence to indicate the existence of major inversions of the metasedimentary succession and without evidence to the contrary, such as high quality geochronological data for example, the three-fold subdivision of the meta-sedimentary rocks presented in Fig. 3 is considered to be essentially chronostratigraphic and gives a fair and comprehensive picture of the early sedimentational and associated tectonic phase in the evolution of the Bamble Terrane.

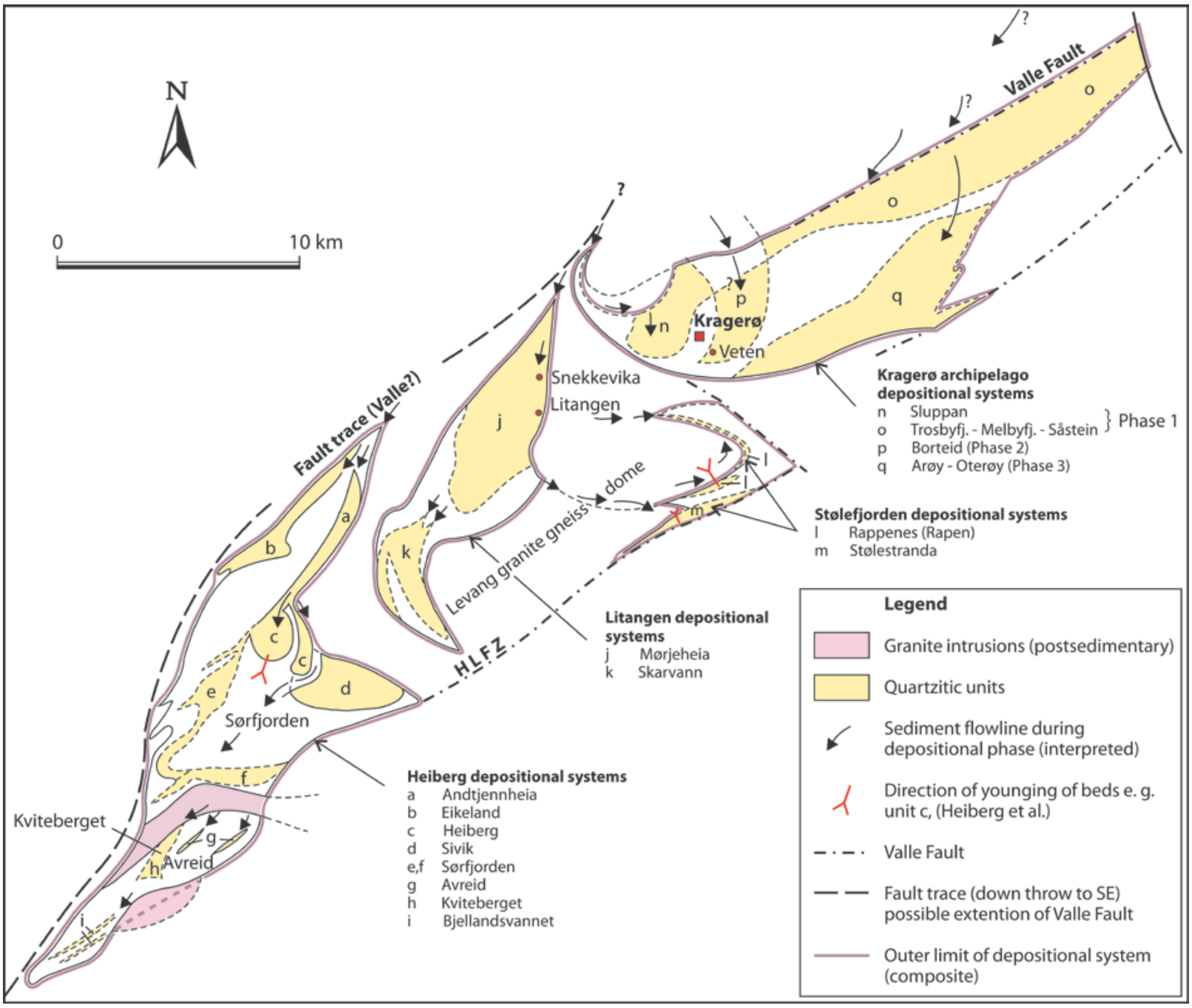

Fig. 4. Map showing quartzitic rocks (lettered `a´ to `q´) of the Upper series and their location in the Heiberg, Litangen, Stølefjorden and Kragerø archipelago depositional systems (outlined). Arrows indicate possible entry points for sedimentary input and also subsequent flow-lines within and between systems (interpreted). Bamble tract, Kragerø area (See also Fig. 2.) Boundary faults collectively showing incipient graben arrangement.

Bamble tract

Lower series

Description of lithological units

Nidelva quartzite

As can be seen from the map a large body of quartzite is present on the western side of the Nidelva area, hereafter named the Nidelva quartzite replacing the term Nidelva Quartzite Complex in an earlier publication (Padget 1990). Judging from the outcrop width and dip (about 50 degrees to the southeast) of the main quartzite component a maximum thickness of the order of 1000 metres is thought to be present, at least in its central part, but thins to the northeast. Southwards, the quartzitic rocks maintain their thickness before terminating abruptly against a large body of amphibolitized gabbro (`Hisåsen’ in Fig. 5) thought to be intruded along an early NNW trending fault downthrowing to the east. This supposed fault then marked the limit of clastic deposition in a southerly direction and may have been active

during the depositional process if only to explain the enhanced thickness of quartzite and its abrupt termination along this fault line.
In the same area a small but distinctive patch of conglomerate, about 4 square kms in area, overlies the Nidelva quartzite. Known as the Stemvannet conglomerate (Fig. 5) it belongs to a later period of sedimentation and seems to fill, partially at least, a small basin. Further details are given below.

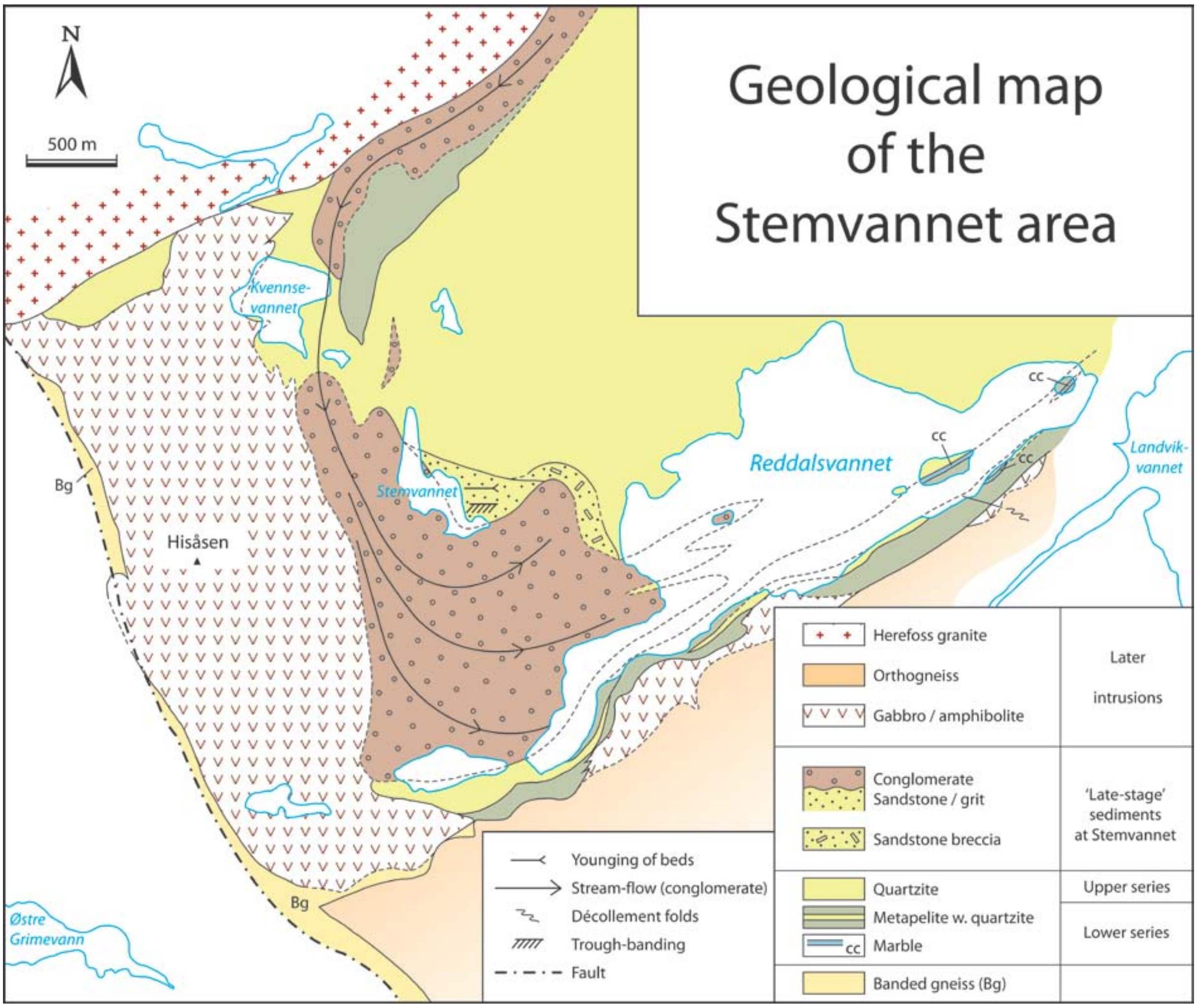

Fig. 5. Geological map over the Stemvannet area, Bamble tract, (Nidelva area) based on field mapping carried out by H. Breivik (1988-1989). Location: see Fig. 2.

The Nidelva quartzite overlies diverse banded gneisses concordantly to the north and northwest. The actual contact is poorly known but apparently conglomerate-free and undramatic. The nature of the banded gneiss in terms of its original sedimentary component (palaeosome) is uncertain but may represent greywacke type formations. These gneisses terminate against the Porsgrunn-Kristiansand Fault Zone (PKFZ) to the NW. No other rocks of layered character are known.

The quartzites are normally recrystallized and rarely show depositional features but an exception to this is found in the Barlindåsen area (Nijland et al. 1993). Here, at Tellaugtjørn (Fig. 2), near the base of the Nidelva quartzite, large-scale cross-bedding features with some slump structures occur on beds dipping to the SE. Not far away, ripple-marks are evident on

some bedding planes and can be described as sinuous and intersecting. These features indicate shallow water conditions, possibly in basins of limited extent. At other places in the vicinity mud cracks are evident on bedding surfaces indicating drying out conditions, possibly as a result of a temporary fall in water levels or overbank situations. Close examination of some of the aeolian cracks shows them to be tapering downwards indicating the beds to be right way up. Such clear-cut features have not been found elsewhere in the quartzite apart from a few cases of ripple-marks on bedding surfaces at Syråsen, close to Tellaugtjørn.
Further east at Evjevollen and higher in the succession, several metres of conglomerate occur as a distinct unit in a quartzite lens. Though much deformed the pebbles are clearly quartzitic, vary somewhat in colour and are probably the result of erosion of pre-existing sandstone/quartzitic beds in the vicinity. (The outcrop was kindly shown to the author by Kees Maijer, leader of a Utrecht-based research group in Norway).

Towards the northeast, extensions of the Nidelva quartzite occur in the form of elongate, somewhat sinuous bodies of quartzite now separated from each other by granitoid intrusions. The latter are frequently gneissic, elongate, concordant to semi-concordant with the strike of the quartzites and probably intruded a once more or less continuous cover of quartzite/sandstone. The latter became progressively replaced by non-quartzitic sediments before being transformed into banded gneisses and other gneisses of uncertain origin to the northeast. The southernmost part of the Nidelva quartzite is the thickest and most homogeneous part. Here the beds apparently young to the east and can have accumulated by successive phases of progradation into a subsiding basin.
Some idea of the lithological relationships can be seen along the southeastern shore of Reddalsvannet (Fig. 2) where quartzite, probably the uppermost part of the Nidelva quartzite, is overlain by the Rore meta-pelite. In a transition zone between the two a few metre-thick beds of marble occur. A somewhat idealized cross-section (in Fig. 2) demonstrates the basic lithology here at an early stage in the orogenic evolution, before major disruptive faulting and shearing took place.

Mention should also be made at this point of brown-weathering sulphidic zones reported from quartzites at a few places. The best known of these are at Skyttemyr and Bøylestad in the uppermost part of the Nidelva quartzite (Fig. 2) and have formed the basis for ore prospecting campaigns. One such campaign (Robyn et al. 1985) concluded that the mineral occurrences are stratabound and of exhalitic character.

Sundebru gneisses.

The second main formation present in the *Lower series* includes a variety of gneissic rocks here known collectively as the Sundebru gneisses and includes the Selås gneisses studied in more detail by Touret (1968). These seem to be, partially at least, lateral equivalents to the Nidelva quartzite. Separate quartzitic units of the latter become thinner and are apparently replaced by banded gneisses towards the northeast. These gneisses now occupy an extensive area in the central and northeastern parts of the Bamble Terrane (See map Fig. 2) where a few thin quartzites are still discernible. A somewhat larger body of quartzite occurs south of Slettfjell, near Sannidal (Fig. 2).
The base of the Sundebru gneisses is taken somewhat arbitrarily at one of these quartzites. Indentations in the line of contact are due to the presence of later granitoid intrusions.

The Sundebru gneisses have been studied in detail in the Selås area by Touret (1968) who concluded that some were altered turbiditic greywackes. He detected the presence of rhythmic banding and identified extensive areas of migmatite. He also showed the rocks to be often graphite-bearing, especially where close to quartzitic units.

A general problem concerning the Sundebru gneisses is to determine the nature of their palaeosomes. This aspect was taken up from a geochemical point of view by Beeson (1975) who pointed out that bulk analyses showed the rocks to be Mg-rich and not strictly comparable with any known sedimentary rock. Metasomatic processes are thought to have affected these rocks after their deposition, the end-product being rocks of amphibolitic and orthogneissic appearance involving some metasomatism. One can speculate as to whether or not the original sediments were enriched in Mg due to increments of volcanic ash.

Whatever their sedimentary origin it is not yet possible to establish a meaningful stratigraphy for the Sundebru gneisses. In the Sundebru area itself there are some thin quartzites near which graphite-bearing gneisses as well sulphidic and calc-silicate zones occur. Outside these zones migmatites are common and have palaeosomes with an argillaceous rather than a siliciclastic component.

The Sundebru gneisses continue in a northeasterly direction into the Hullvann and Bakkevatnet areas where the beds are more clearly definable as quartzites and (meta-)pelites and where a few sulphidic horizons also occur, the most well known of which occur in layered rocks just south of Slettfjell. Here a rather curious rock described as siliceous, cherty gneiss with some albite, is present. It continues to the ENE as a distinct sulphide-bearing horizon 3 kms long and supposedly of exhalative nature (Pedersen, 1984). If the rock identifications are correct they suggest that a special form of chemical sedimentation in a volcanic environment took place here.

Metapelites.

Along the lake Rore the Rore metapelite overlies the Nidelva quartzite more or less conformably and can be traced over a length of 20 kms. It crops out on islands in the lake and along the eastern shore-line where it consists typically of thin-bedded metapelitic and semi-meta-pelitic beds thought to represent silty clays. At Liene, the degree of metamorphism is relatively weak and thin-bedded strata display excellent load cast features (Fig 6) on a number of bedding surfaces (map reference: 647150/47480). Contact of these meta-pelites with the underlying quartzite can be seen around the western end of Reddalsvannet (Fig. 5) where in a temporary road cutting close to the lake (map reference: 6464990/46970), small-scale deċollement folds observed on bedding surfaces are believed to be synsedimentary (cf. Boggs 2001, p.108) and interpretable as foreset beds belonging to a delta-front facing SE.

The Stavseng meta-pelite crops out in the innermost part of Stølefjorden and also west of the Levang peninsula (Fig. 2) where it is now represented by quartz-mica schists and sillimanite-bearing schists and gneisses, sometimes with nodular structure (Burrell 1964). These rocks also extend in an almost continuous northeasterly trending zone overlying the Nidelva quartzite and Sundebru gneisses. The line of contact with the underlying formations provides a useful reference horizon to which quartzitic units of the *Upper series* can be related. The latter formations then likely extended over a large part of the Levang peninsula at one time, i.e. before the uprise of the Levang granite gneiss dome (Padget 2004), a possible Sveconorwegian event. The original sediments are thought to have been essentially argillaceous and were deposited in a rather broad basin with a NE-SW orientation.

The Eikeland metapelite occupies an irregular area 2 to 3 kms SE of the metapelitic formations mentioned above (Fig. 2). It is considered, on the basis of its supposedly argillaceous, now metapelitic character, to be of the same age as the latter but is now infolded in the prevailing felsitic gneiss terrain. It can be looked upon as a southerly extension of the Heiberg depositional system (see below) to the north but without an overlying quartzite. The latter may have been deposited but has been removed by erosion in post-depositional time.

Fig. 6. Load casts on bedding surface of the Rore meta-pelite, Liene (eastern shore of the lake Rore). Location: `Li´on Fig. 2. The pen-point (illuminated) gives the scale. Photo: H. Breivik.

Upper series (Kragerø area, Fig.2). Description of lithostraphic units.

Quartzites.

These, formerly arkosic sandstones, are represented by a number of separate bodies as distinct from those of the *Lower series*, are aligned SW-NE and rest on a substrate of metapelite (Rore-metapelite in the southwest) and its continuation to the northeast as the Staveng metapelite.The series begins with quartzite, here represented by a number of separate bodies aligned roughly in SW-NE direction and resting on the Rore and Stavseng metapelites. There is no evidence of angular unconformity at the base of the quartzitic rocks but this may have been eliminated or subdued by later deformation or may be just an expression of near-concordant deposition. Individual bodies are typically deformed and recrystallized and often contain micaceous layers. Furthermore, they can be grouped into one or two or more systems reflecting their depositional mode of deposition. The latter are lettered from a to q (Fig.4) and named accordingly below.

Depositional systems in the Upper series

The above-mentioned quartzitic lithologies can, in the author's opinion, be arranged in a number of depositional systems. Those in the northeastern part of the Bamble tract (Kragerø area, Fig. 4) are as follows:

* Heiberg depositional system with quartzitic units a to i.
* Litangen depositional system with quartzitic units j to k.
* Stølefjorden depositional system with the Rapen (l) and Stølestranda (m) quartzites.
* Kragerø archipelago depositional system with quartzitic units n to q.
* In the southwestern part of the Bamble tract the Mesel and Øynesvann quartzites (Fig. 2) lie in direct continuation with the above-mentioned systems and are possibly parts of a large depositional system extending into the Merdøy tract (See below).

The quartzites and related rocks of the Heiberg depositional system make up the largest clearly defined depositional system of the *Upper series.* The configuration of this system (shown somewhat schematically in Fig. 4) includes a number of now separate quartzitic bodies which collectively seem to indicate deposition along a general line of flow starting about 8 kms NW of Kragerø and bifurcating, deltaic fashion, at Andtjennheia (a) and Eikeland (b). Narrow "shoestring"-like deposits of quartzite are tentatively interpreted as distributary channels. Sizeable, circumscribed bodies of quartzite at Heiberg (c) and Sivik (d) were once probably one and the same body later separated in some way, for example by stream and river erosion, exposing pelitic rock which probably underlies both quartzite bodies. Their slightly arcuate form as well as a V-shaped, probably flat-lying deposit (e and f) south of Sørfjorden are reminiscent of sand bars, and may reflect a southwesterly flow direction in a shallow, aqueous environment. Material in (e and f) may have been derived from (c) and (d). On the south side of the Heiberg massif Starmer (1978) reported coarse conglomeratic rocks grading upwards into less coarser ones. The former are here interpreted as locally developed basal members of the Heiberg quartzite succession. The direction of younging of the beds is shown in Fig. 2 and in Fig. 4, unit c.

Further south, the (meta-)sedimentary succession is invaded by granitoid rocks but garnetiferous quartzites (g) are clearly discernible as inclusions in and adjacent to the Avreid mafic intrusional complex (Starmer 1969). Two elongate zones of quartzite are present, both originally probably parts of a larger body. The Kviteberg quartzite (h) is known for its coarsely crystalline texture, high silica content and refractory nature. It differs markedly from all other quartzites mentioned in this paper. This may be due to heating brought about by the adjacent Avreid gabbro though there is some uncertainty regarding its sedimentary origin.

Finally, at Bjellandsvannet, south of the Avreid Complex, a zone of quartzitic gneisses (i), in the otherwise granitic terrane, is thought to represent the downslope termination or `toe' of the depositional system, the total distance from apex to toe being of the order of 36 kilometres.

The configuration (Fig. 4) proposed for the Litangen depositional system also includes a number of quartzite bodies and these seem to be part of a linked system starting about 6 kms WNW of Kragerø as a narrow channel. This opens out southwards into the large Litangen deposit (j) which extends over much of Mørjeheia. Mapping suggests that the deposit is apparently thicker along its eastern margin, the enhanced thickness incidentally making it more attractive for commercial exploitation, e.g. quarrying at Litangen and Snekkevika. Foliation surfaces are common but no certain depositional features are known. It is possible this eastward thickening is due to the development of a north-south trending basin during sedimentation. A synsedimentary fault related to early rifting may have played some part in this basinal development.

Possible extensions of this depositional system may be represented by elongate quartzite deposits in the Skarvann area (k) in the western part of the Levang peninsula. These appear to die out before reaching the important domain boundary marked by the Haslum-Langholmen Fault Zone (HLFZ). No sedimentary structures are known but the quartzite may represent shallow basinal infillings or, more likely, are the result of folding of one or more formational unit(s). The present configuration of the quartzites, however, is partly a reflection of their position around the eastern termination of the Levang granite gneiss dome (Fig. 4).

Collectively, the quartzites present in the Heiberg and Litangen depositional systems are considered to be separate, linked systems of aqueous transport and deposition, the latter taking place in shallow basins. On the map (Fig. 4) a tentative attempt is made to show specific flow lines or channels indicative of aqueous transport within the systems as well as entry points for sedimentary input. Indeed, the general pattern shows distinct resemblances to patterns recently deduced from seismic and borehole data in the offshore North Sea area (Dreyer et al. 2004, Bullimore et al. 2005). Generally speaking, however, the numerous quartzitic units of the *Upper series* detailed in the present report, are probably the basal parts of these depositional systems and hence are relict features following prolonged erosion in post-depositional time.

Following this line of thought, the Stølefjorden depositional system is a smaller system present on the easternmost part of the Levang peninsula and adjacent Stølefjorden (Fig 4). It is characterized by narrow zones of quartzite 10 to 20 metres thick, and schistose, mica-rich layers some of which can be shown to replace the former by lateral transition. One of these, the Rapen quartzite (Padget 2004), is well exposed and has some cross-bedding indicating younging of beds to the SSE. Traces of a second quartzite about 40 metres below this quartzite can just be discerned in the marginal part of the Levang granite gneiss dome. Further into this domal area some basic dykes occasionally contain thin layers of quartzite. This quartzite was presumably `captured' by the basic magma from a more deeply lying quartzite on its way upwards demonstrating the originally more extensive nature of quartzite in this area before intrusion of the granite.
Well developed ripple-marks are evident in road side exposures near Stabbestad school (Fig. 7) in weakly metamorphosed pelites localized within the aureole of the granite gneiss dome.

Another quartzite with at least two examples of cross-bedding indicating younging of beds to the south, is present at Stølestranden (Fig. 2) close to the Haslum-Langholmen Fault Zone (Padget 2004). Early movements on this fault zone can be envisaged allowing for the accumulation of clastic material in a shallow basin.

Collectively, these quartzites and associated schistose units are thought to be parts of a single depositional system and like the other systems mentioned above had a substrate of Stavseng (meta-)pelite, which at the time probably covered much of the central part of the Levang peninsula judging from a number of mica-rich relicts present at certain places within the Levang granite gneiss dome area (See map in Hofseth 1942). Even so it is thought that a fluidal system, possibly sourced in the Litangen depositional system (Mørjeheia, unit j for example), transported and deposited siliciclastics into a shallow basin or basins covering at least the easternmost part of the present day peninsula area and now represented by the Rapen and Stølefjorden quartzites (in Fig. 4). One may speculate as to whether these sediments may even represent a `spillover' effect from the Litangen basin. It is also possible that the

Stølefjorden and Litangen systems are really parts of one large depositional system with a lobate form (Fig. 4), the disconnected nature of the quartzitic elements in both being due to extensive erosion of a more continuous cover of clastic and other rocks in the area now occupied by the Levang granite gneiss dome.

Fig. 7. Ripple-marks on vertical bedding surface of meta-pelite (Stølefjorden depositional system). Road-side exposure near school, Stabbestad. Location: `Sb´ on Fig. 2. Ruck sack, below to the right, gives scale.

The Kragerø archipelago depositional system in the most northeasterly part of the Bamble tract is represented by four quartzite-dominated units. Designated n,o,p,q. (Fig. 4) they are now separated from one another by sizeable intrusions of mafic rocks (Valberg, Gumøy-Langøy) responsible for significant metamorphism and recrystallization of the host rocks the separate units of which include quartzites in the Sluppan area west of Kragerø (n), the Borteid area immediately east of the town (p), a long narrow zone in the archipelago area proper between Trosbyfjorden, Melbyfjorden and Såstein (o), and possibly in the Arøy area (q) to the south of the latter. They are all considered to be parts of one major depositional system, though possible fluvial channels responsible for material transport are not as evident, i.e. preserved, as for the other depositional systems (e.g. Heiberg and Litangen). The first two (n and p) have lobate configurations, presumably indicating input from the north, (q) is somewhat deltaic but its configuration possibly indicates a northerly source too. Units n and o may belong to one and the same unit, the linear NE-SW trend being reminiscent though distinct from the Nidelva quartzite and suggestive of deposition in a fairly shallow open sea environment. They lie, however, above the Stavseng metapelite and therefore belong to the *Upper series* of this report.

The Sluppan quartzite (n) (Fig. 4) and other metasedimentary rocks which occur in the Sluppan and Kalstad areas 1 to 2 kms west of Kragerø, are much invaded by intrusive rocks and it is difficult to understand fully their primary relationships. However, a manuscript map in the archives of NGU (Fredrickson, A.F. 1951-1952) shows clearly a fan-like array of quartzite with an apparent shallow overall dip to the SE. The SW part of this array turns into a more northerly direction, and though reduced in thickness the quartzite here can be traced partially round an antiformal structure (cored by a later granite intrusion). This thickness reduction could either mark a flow channel by which clastic material was transported into the Sluppan area, or be merely the result of deformation. To the NE, the quartzite seems to terminate against the Valberg gabbro but reappears east of the latter to connect with quartzite(o) in the Trosbyfjorden, Melbyfjorden and Såstein areas. The author has also considered the possibility that the Sluppan quartzite represents the distal part of a small deltaic depositional unit separate from the other quartzites but confirmation of this requires more detailed mapping.

For the record, the ion probe zircon dating study made on quartzite west of Kragerø (Åhäll 1998) indicates that it could not be older than 1500 Ma. The material may have come from erosion of the Sluppan quartzite mentioned earlier in this report.

The quartzites (o) in the Trosbyfjorden, Melbyfjorden and Såstein areas (and associated metasedimentary and associated migmatitic rocks) form a broad, parallel-sided tract extending northeast as far as Rognsfjorden where they are unconformably overlain by Cambro-Silurian strata of the Oslo rift. Little is known regarding the initial sedimentary nature of these quartzitic rocks which are now significantly metamorphosed and recrystallized. Meta-pelitic rocks, an extension of the Stølefjorden meta-pelite, form a distinct zone parallel to the quartzites to the northwest and seem to dip to the SE beneath the latter (Fig. 2) though this relationship is complicated by the presence of the Valle Fault. In pre-fault times, however, the basin to which these quartzites (o) apparently belong most probably extended north of the present day fault line for an unknown distance, the existing outcrops south of the fault representing merely distal parts of the depositional system as a whole. A possible configuration of this system is outlined in Fig. 4. Arrows indicate likely flow lines and transport of clastic material from northeast to southwest.

The Borteid quartzite (p), east of Kragerø, is well exposed on the northern part of the island of Bærøy, on the peninsula to the north (Borteid), and is most likely present in the sea area immediately to the west. No primary features of deposition are known. Occasional darker, micaceous bands occur but these are movement planes of tectonic rather than sedimentary origin. The present outcrops collectively indicate the presence of a quite sizeable depocentre here. This centre was probably fault-defined at an early stage being located more specifically at the intersection of an early north-south trending (?growth) fault marking its eastern boundary and a WSW trending fault marking its northerly limit. A basin produced by the ensuing fault system was then filled up by clastic material introduced from the north (Fig. 4), most likely by fluvial systems as yet unidentified. The southerly and southwesterly limits of the quartzite probably mark the limits of progradation in these directions and here more mica-rich beds alternate with quartzites (Elliot & Morten 1965, fig. 1). An E-W oriented body of quartzite forms the northern part of the island Veten, close to Kragerø, and is now an enclave of unknown extent contained within a mafic intrusion. It may be either part of the main Borteid depocentre or a possibly, but less likely, a westward continuation of the Arøy quartzite (see below).

The sediments in the Borteid depocentre are exceptionally well recrystallized due in large measure to the close proximity of large, subjacent intrusive bodies of gabbro and can now best be described as quartz-rich micaceous gneisses. Linear and planar features are probably of tectonic rather than sedimentary origin.

Fig. 8. Cross-bedding in semi-clastic rocks (meta-arenites) and interbedded schistose (sillimanitic) layers, eastern part of Arøy, Kragerø archipelago. Younger beds upwards in the photo. Lens cover gives scale.

Fig. 9. Conglomerate (in shadow) with partially deformed clasts in metasedimentary sequence exposed on SW shore line of Arøy, Kragerø archipelago. Photo: H. Breivik. Pencil gives scale.

The Arøy-Oterøy depositional system (q) is located on the southeast side of the major Gumø-Bærø gabbroic body. It is well exposed on 3 islands, Arøy, Oterøy and the smaller Røssholmen and these have been well described by Morton et al. (1970), and Morton (1971).

Morton's map of the islands shows well bedded metasedimentary rocks most of which are clastic, now metamorphosed to quartzite together with alternating layers of sillimanite-bearing schists. Some of the quartzitic rocks display excellent cross- and trough-banding (Fig. 8) on well-washed and ice-polished outcrops. A distinctive, now somewhat deformed conglomerate (Fig. 9) is also present in the sequence exposed on Arøy. There are also lesser though conspicuous units of micaceous schists as well as a fragmental rock (Fig. 10) interpreted as pyroclastic and indicative of a contemporaneous volcanic episode during deposition of the sediments. The latter event is clearly evident on Røssholmen (Røsholm) as shown by Morton (1971). Otherwise, the metasedimentary rocks indicate a high-energy regime in an aquatic environment. The remarkably well preserved nature of the metasedimentary rocks on Arøy and Oterøy with only moderate degrees of structural deformation and regional metamorphism (development of muscovite and sillimanite) could possibly suggest they form a separate stratigraphical unit, younger than other units described from the *Upper series* and shown accordingly in the stratigraphic table in Fig. 2.
Correlation with the late-phase conglomerates of this article (Fig. 2) can also be envisaged but cannot be otherwise substantiated.
Finally, Morton (1971) went so far as to conclude that the metasediments were derived from a source located to the northwest based on palaecurrent directions. Further study of the individual cross-bedding elements and measurement of their down dip directions may further substantiate this.

Fig. 10. Meta-agglomerate with trondhjemitic (?)fragments exposed on south shore of Røssholmen, SW for Oterø, Kragerø archipelago. Lens cover gives scale.

Within the Kragerø archipelago depositional system as a whole it is possible that deposition took place in two phases, the first represented by the Sluppan quartzite and quartzites in the Trosbyfjorden, Melbyfjorden and Såstein areas, the second by the Borteid and Arøy quartzites. The tongue-like configuration of the Borteid unit (map compilation) and apparent discordant relationship to the quartzites in Trosbyfjorden, Melbyfjorden and on Såstein would support this conclusion. The relatively weak metamorphism and deformation of the quartzite on Arøy as well as similar sediments on Oterøy point in the same direction though degree of metamorphism, as is well known, is a doubtful criterion for correlating formational units.

The Mesel and Øynesvann quartzites (Nidelva area, Fig.3).

The Mesel quartzite (Fig 2) is a distinct unit lying above the Rore pelite and in direct line with the Heiberg and Litangen depositional systems described above.
It is partly interlayered with schistose units though the geology here is confusing due to the intrusive effects of mafic intrusions, and is in need of revision. No features of primary depositional nature are known. Some much sheared quartzite and a little conglomerate (possibly Krokelia conglomerate, see below) can be traced for a further 10 kms south-southwest of the Grimstad granite pluton.

The Øynesvann quartzite (Fig 2) to the NNE of the Mesel quartzite is an elongated body of which little is known in detail. It is now separated from the Mesel quartzite by a `wall' of granite. No features of primary deposition have been recorded. It is not known to rest on pelitic rocks but is nevertheless equated here with the Mesel quartzite and hence with other quartzitic units of the *Upper series.*

The possibility that these two quartzites may be parts of a larger depositional unit embracing quartzite as far away as the Merdøy tract (Fig. 2) is further explored later in this report.

To conclude, the depositional systems of the *Upper series* shown in Fig. 4 (Kragerø area) seem to indicate a multifluvial transport of sediment sourced in the northeast and introduced at several points into an elongated basin with the NE-SW Bamble trend and a width varying between 5 to 10 kms. This basin most likely continued southwestwards to encompass both the Øynesvann and Mesel quartzites (Nidelva area) but at the present level of erosion is much reduced in area in this direction due to the intrusion of magmatic rocks and the development of migmatites (Fig. 2). Nevertheless, the basin, which is now fault-defined (Valle Fault and Haslum-Langholmen Fault Zone) and possibly of graben type, may have originated by movements, possibly of tensional character, on faults active before or during the sedimentation process.

`Late-stage´.

Krokelia and Stemvannet conglomerates.

These are the youngest known rocks of sedimentary character in the Bamble tract (Nidelva part) and are well exposed in the vicinity of the hamlet Krokelia, just north of the Grimstad granite pluton. Here, a distinctive conglomerate, named the Krokelia conglomerate, lies upon Mesel quartzite of the *Upper series.* This relationship is well seen in an enclave located in the marginal zone of the pluton itself. The conglomerate has a N-S strike at Krokelia and is clearly polymict and consists of cobble-sized, weakly supported clasts which have a tendency to parallel alignment of their long axes (Fig. 11). It can be followed southwards at intervals for a further 8 kms along a somewhat sinuous course but with much reduced pebble size. Local erosion and short-lived transport may explain its present depositional features.

The Stemvannet conglomerate (Fig. 5) consists of two units: coarse-grained clastic sediment and conglomerate. The former rests on the Nidelva quartzite in the vicinity of Stemvannet. Here, excellent exposures of coarse-grained gritty sandstone show trough-bedding with steep foresets clearly indicating progradation from east to west. There are also ripple-marks on a few bedding surfaces close to the lake. In the same zone 1 km to the east a special type of rock is present. It consists of locally derived tabular clasts or laths of sandstone up to 15 cms in length embedded in a matrix of gritty sandstone. These clasts seem to indicate erosion of

pre-existing sandstones in the vicinity followed by short-lived transport and rapid deposition giving rise to a fragmental, breccia-like sedimentary rock. The contact between these beds and the underlying Nidelva quartzite is probably unconformable but this is difficult to see in the field.
The Stemvannet conglomerate, however, certainly overlies these clastic beds, its general configuration suggesting transport from the northeast with deposition taking place by fanning out into a shallow basin (Fig. 5). It is noteworthy that the sedimentary beds comprising the Stemvannet conglomerate are only weakly metamorphosed and deformed, except where in contact with the younger (920 Ma) Herefoss granite.

Fig. 11. Krokelia conglomerate with ill-sorted pebbles in outcrop at entrance to boat-building yard, Krokelia, Nidelva, See Fig. 2 (about 2 km south of Sundsåsen). Photo: Padget (1986). Hand lens in upper centre of photo gives scale.

The two conglomerates represent the uppermost and probably the youngest stratigraphical units in this part of the Bamble tract. It is tempting to think they may have been connected with each other at one time but this has not been established in the field. They represent, however, a late episode of erosion, fluvial transport and deposition post-dating deposition of the other sedimentary formations described above but pre-dating intrusion of the $989^{+16}/_{-27}$ Ma Grimstad (Kullerud, & Machado 1991) and 920±9 Ma Herefoss (Andersen et al. 2002) granite plutons.

Merdøy tract

Lithostratigraphic units

Quartzite.

A major lithological unit, here known as the *Merdøy quartzite*, occupies a 23 km long portion of the Skagerrak coast, more specifically between Grosfjorden and the Sømskilen archipelago

(Fig. 2). It has a maximum outcrop width approaching 2 kms and occupies a basin, now fault-defined, SE of the Bamble tract and completely separate from the latter. The central portion has been intruded by the Grimstad granite pluton (989±9 Ma, Kullerud & Machado 1991) but northeast of this intrusion quartzitic rocks occur on a number of islands, Merdøy, for example, as well as on the nearby mainland. The present author has found cross-bedding features at three locations all of which indicate younging of beds to the southeast. The most seaward outcrops of bedrock, on Lille Torungen for example, show strongly deformed quartzite as well as interbedded mica-schists suggesting the near presence of an important fault disturbance which in turn marks the southeast limit of this tract as a whole. Knudsen (1996) reported the existence of pelitic schists in metre-thick layers on several islands and also a mafic granulite on Merdøy interpreted as a possible ashfall deposit. Interlayering of quartzite and meta-pelite is common on islands in the present day offshore zone.

These rocks reappear southwest of the Grimstad granite pluton though the quartzitic unit here is much reduced in thickness but one outcrop shows cross-bedding indicating younging of beds to the southeast.

Grosfjorden metapelite

In the area of Grosfjorden and for some distance to the southwest rocks of originally argillaceous character occur and are referred to here as the Grosfjorden meta-pelite. Towards the northwest they are limited by intrusions, a continuation of those separating the Merdøy and Bamble tracts, and to the southeast are in contact with the Merdøy quartzite mentioned above and probably lie beneath it. A continuation of the Grosfjorden meta-pelite 7 kms to the southwest is also evident as is a limited outcrop at the northeast termination of the main outcrop of the Merdøy quartzite. There is thus a similar stratigraphic relation here to that described for the *Upper series* in the Bamble tract with quartzite lying above pelitic rocks. In addition, a layer (or layers) of carbonate (marble) in the upper part of the meta-pelites suggests correlation with marble occurrences in the Stemvannet/Reddalsvannet area (Fig. 5) to the northwest. Here, the marble is much thinner and is located close to the quartzite/metapelite interface. These relationships strongly suggest that the Merdøy quartzite can be correlated with the Mesel quartzite (See Fig. 3) thus providing a means of correlating the layered rocks of the Bamble and Merdøy tracts. In other words, in *Upper series* time there was possibly lithological continuity between the two tracts, the Mesel, Øynesvann and Merdøy quartzites being remnants of one and the same depositional system. A tentative outline of such a system is shown in Fig. 2 (dotted signature) the lobate configuration of which can be interpreted to mean that the main transport or flow direction was from NNE to SSW. The clastic material for these quartzitic units could then have been derived from the same distant northerly source.

In this connection, the Eikeland pelite (this paper), if continued to the southwest, would be the pelitic substrate for such a depositional system as is the Stavseng meta-pelite for quartzites of the Upper series in the Kragerø part of the Bamble tract (Fig. 3).

North of the Merdøy tract and east of the Bamble tract, i.e. in the direction of the Skagerrak coast, both paragneisses and orthogneisses make up most of the bedrock. Here, the Eikeland metapelite (Fig. 2) now occupies a synform \`cradled´ as it were between two later intrusions of granite. The possibility that other lithostratigraphic units occur in this area cannot be discounted: banded iron ore and associated carbonate beds at Klodeborg, 4 kms west of Arendal, for example, are deemed sedimentary (Bugge 1978, for relevant references) and possibly form part of an early stratigraphic unit pre-dating the *Lower series* of this report.

Identification of such a unit is, however, beyond the scope of the present study but could have economic, i.e. ore-geological significance.

Conclusions

1.The metasedimentary rocks dealt with in this paper occupy two NE-SW trending tracts, the Bamble tract and the lesser Merdøy tract both within the Bamble Terrane. Both are characterized by having quartzitic rocks of sedimentary origin (recrystallized sandstones) as well as rocks originally of more pelitic (argillaceous), semi-pelitic or even greywacke character.

2. The main stratigraphical conclusion which can be drawn is that *two* main periods involving deposition of clastics has occurred, one represented by the Nidelva quartzite in a *Lower series*, and one represented by several quartzitic units in an *Upper series*. Finally, a late-phase or *late-stage* of erosion, transport and deposition of conglomerate is evident in the southerly part of the Bamble tract (Nidelva area) and may be of Neoproterozoic age.

3. Meta-pelitic rocks occur as formational units, above the Nidelva quartzite and Sundebru gneisses, and form a substrate on which the fluviatile depositional systems of the *Upper series* rest.

4. Quartzites and associated (meta-)sediments of the *Upper series* are grouped into 4 depositional systems (Heiberg, Litangen, Stølefjorden, and parts of the Kragerø archipelago). These are thought to be erosional relics of once more continuous depositional lobes. The latter, together with inferred avenues of sediment supply, are shown in Fig. 4. Deposition in a fault-defined basin (graben?) is envisaged. A possible fifth and more widespread depositional lobe common to both the Bamble and Merdøy tracts is tentatively shown in Fig. 2.

5. All sediments of the two series are thought to have been deposited in aquatic environments belonging to widespread epeirogenic seas and at a time probably not much younger than 1500 Ma, i.e. they are Mesoproterozoic in age. Some basin development, possibly involving proto-rifting may also have taken place at an early stage in the evolution of the Bamble Terrane. This may explain some apparent thickness differences in the lithological sequences, e.g. the Nidelva quartzite.

6. The depositional scenario for the Nidelva quartzite of the *Lower series* is considered to be part of a shelf system in a fairly open, elongate seaway deepening to the southwest. A possible analogue is to be found in other sand-rich shelf systems such as the Utsira Formation (Miocene) in the North Sea Basin (Galloway 2002, Fig.18).

7. The source areas for the clastic material are still unknown but configurations shown by the quartzite deposits (i.e. constructed depositional lobes) (Fig. 4) as well as the few mineral dates available point to areas well outside the present NW boundary of the Bamble Terrane. A common source dominated by deeply eroded granitoid rocks, possibly with calc alkaline affinities, seems necessary for both the Nidelva quartzite and quartzites of the *Upper series*. Zircon isotope technology may help throw further light on the respective ages of these quartzites and the provenance of their clastic material.

8. The Merdøy quartzite lies in the Merdøy tract, now a one-sided graben parallel to the Skagerrak coast. This quartzite is correlated with the Mesel and Øynesvann quartzites on

lithologic grounds and as such provides a basis for correlating the stratigraphy of both the Bamble and lesser Merdøy tracts.

9. Thus, despite the paucity of primary sedimentary, depositional features and the magnitude of post-depositional events (intrusions, metamorphism, tectonism, erosion) all is not lost. The scheme of lithostratification offered here enables details concerning the early evolutionary history of the terrane to be worked out. This includes not only sedimentation but also some measure of contemporary, tensional faulting. Grouping of quartzites in the *Upper series* into separate units and configurations allows some conclusions to be drawn regarding provenance, mode of transport and depositional regimes of the clastic material. A few conclusions are also drawn regarding the morphology of the landscape during deposition, gradients of the terrain for example, and identification of possible basinal, i.e. potential depositional areas.

10. To conclude, the map compilation (Fig.2) shows the Upper series to consist of several units of meta- sedimentary rocks which collectively are interpreted to represent a major sedimentological event involving riverine flow from NE to SW with deposition of the sedimentary load in a number of locations, deltaic fashion. These have been partially modified by later events but not sufficiently so as to eradicate completely primary features of deposition. It also means that the various units belong to approximately the same stratigraphic horizon. This in itself is a unique feature in this otherwise tectono-stratigraphic terrain. An alternative to the above is to interpret the various meta-sedimentary units exclusively as products of metamorphism or deformation or both. Nevertheless, both interpretations are in need of further field work to substantiate the one or the other. Whatever the final consensus, it must be remembered that many features are only partly preserved either due to extensive felsic intrusion or, in the last instance, to widespread subaerial erosion.

11. The study has not revealed any hitherto unknown mineral deposits with economic potential but at least focuses attention on the occurrence and possible size of quartzitic bodies, the exploitation of which has a long tradition in southeast Norway.

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