Lithostratigraphy and Facies Analysis of the Ringerike Group of the Oslo Region

P. TURNER

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The Ringerike Group is a late Silurian red bed succession confined to the Oslo Graben of southern Norway. At Ringerike, the type area, it contains the Sundvollen Formation (500 m) below and the Stubdal Formation (750 m). The sediments of the Sundvollen Formation consist mostly of sandstones and siltstones, whereas those of the Stubdal Formation are nearly all sandstones. In the Kolsås area, 20 km SE of Ringerike, the Group is only 500 m thick and the Sundvollen Formation (100 m) consists mostly of red siltstones and mudrocks. In the Holmestrand area, about 60 km south of Oslo, the Group is made up by the Holmestrand Formation which is a series of distinctive sandstones and conglomerates. The Holmestrand Formation is thought to be broadly laterally equivalent to the Stubdal Formation. Evidence from vertebrate faunas indicates that the age of the Ringerike Group ranges from lower Ludlovian (Sundvollen Formation) to Downtonian (top of the Holmestrand Formation).

Detailed facies analysis of the Ringerike area is used to determine depositional environments in the Sundvollen and Stubdal Formations. This concentrated on vertical facies sequences which were analysed using standard matrix techniques. In the Sundvollen Formation fining-upwards cyclothems of restricted grain size show that sedimentation was in a meandering fluviatile environment, probably on a coastal alluvial plain. Frequent high-energy conditions are indicated by the presence of massive beds of sandstone which were deposited from suspended-load in river channels. The occurrence of fossiliferous calcarenites at the base of several cyclothems shows that marine tidal conditions were not uncommon. In the Stubdal Formation sandstones deposited in channels from both bed-load and suspended-load make up most of the succession. These are interpreted as the deposits of braided rivers but the fine grain size suggests a distal alluvial complex rather than steeply sloping mountain rivers.

P. Turner, School of Physics, Department of Geophysics and Planetary Physics, The University, Newcastle–upon–Tyne, England

Introduction

The Ringerike Group is the name given to a late Silurian red bed succession which outcrops in a number of areas, the remnants of a once continuous sheet, within the Oslo Graben of southern Norway (Fig. 1). In the type area of Ringerike, 25 km NW of Oslo, the Group reaches its maximum thickness of about 1250 m; here it outcrops on the eastern side of Steinsfjorden and Tyrifjorden below the steep Krokskogen escarpment. The area is thickly wooded but exposures are generally good and easily accessible. A large outcrop is centred on Kolsås hill, 20 km SE of Ringerike. This area is well known for the Permian sediments and lavas which overlie the Ringerike Group. The outcrop west of Drammen is very poorly exposed but the outcrops north of Holmestrand and at Jeløya are both well seen, particularly in coastal sections. The most southerly outcrop of the Ringerike Group is just east of Skien, about

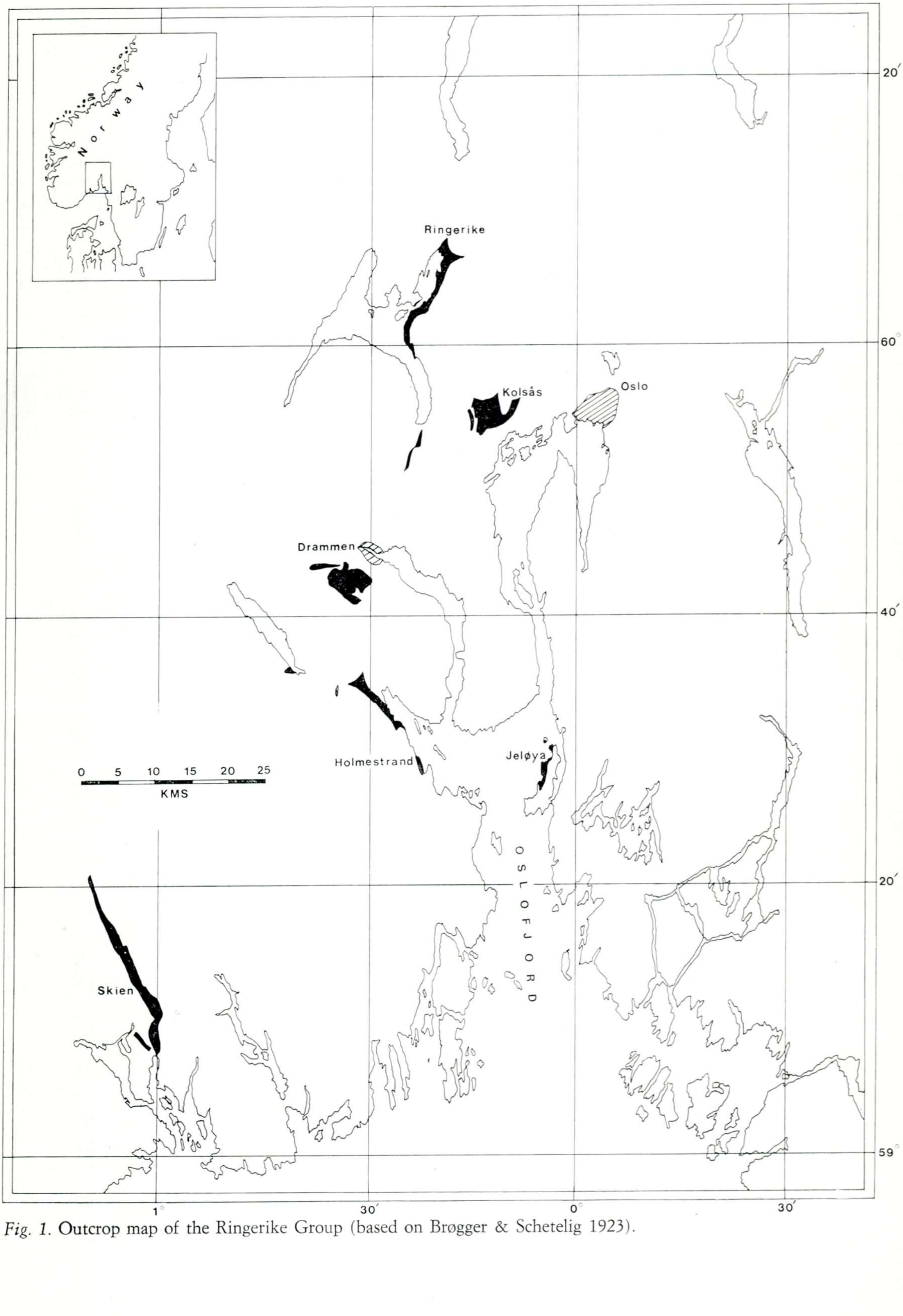


Fig. 1. Outcrop map of the Ringerike Group (based on Brøgger & Schetelig 1923).

STRATIGRAPHIC UNIT		LITHOFACIES	THICKNESS	AGE	CHARACTERISTIC FOSSILS
Stubdal Fm		sandstones & intra-formational conglom.	750 m	Upper Ludlow - Downton?	
Sundvollen Fm		sandstones, red siltsts & mudrocks, thin limestones	500 m	Lower-Middle Ludlow	Logania taiti Ateleaspis robustus, Pterolepis nitidus, Dictyocaris sp, Hughmilleria norvegica,
'Stage' 9	g	thin lsts & shales	250 m	Wenlock	Leperditia norvegica
	f	limestone			
	e				Howellella sp.
	d	"			Leperditia phaseolus
	c	limestone & shale			Atrypina angelina
	b	" "			
	a	" "			
'Stage' 8	d	limestone & shale	135 m	Wenlock	Leperditia baltica
	c	" "			Rhynchotreta cuneata
	b	calcareous siltst. & shales			Leperditia hisingeri, Palaeocyclus porpita
	a	" "			Cyrtia exporrecta
'Stage' 7	c	red mudstones & lst.	130 m	Llandovery	Costistricklandia lirata
	b	limestone			Pentamerus oblongus
	a	"			Pentamerus borealis
'Stage' 6	c	calcareous sst & shales	115 m	Llandovery	Rhynchotreta decemplicata
	b	calcareous sst.			Camarotoechia weaveri
	a	calcareous sst. & shales			Leptocoelia hemisphaerica

Fig. 2. A summary of the Silurian stratigraphy of the Ringerike area.

100 km SSW of Ringerike. The rocks here, however, have suffered intense thermal metamorphism by the nearby Permian igneous complexes.

The stratigraphical setting is the same in all these areas. The clastic sediments of the Ringerike Group lie conformably on Silurian marine limestones and shales and are overlain by Permian sediments and lavas. Tectonically the sediments are, at most, mildly deformed, despite having been subjected to Caledonian folding. The large Permian igneous intrusions have, however, thermally metamorphosed the sediments in a number of places. These include: northern part of Ringerike, Drammen, parts of the Kolsås area and the Holmestrand and Skien areas.

Much of the previous work on the Ringerike Group was inspired by the vertebrate and arthropod faunas discovered by Kiær (1911, 1924). These faunas, which come from near the base of the Ringerike Group, are now believed to be lower Ludlow or even upper Wenlock in age (Heintz 1969). A summary of the whole Silurian stratigraphy of the Ringerike area is shown in Fig. 2.

Lithologically, the Ringerike Group is comparable with the Old Red Sandstone which outcrops around the margins of the north Atlantic and is mostly Devonian in age. Like the Old Red Sandstone it is a late orogenic sequence which was deposited mostly in fluviatile environments. Although early workers fully appreciated the similarity of the Ringerike Group to the Old Red Sandstone of Great Britain no detailed stratigraphical work was done, particularly in the areas outside Ringerike. At Ringerike Kiær (1911, p. 8) noted that, 'it seems natural to divide this huge series of sandstone into a *lower part* rich in shales and an *upper part* poor in shales'. Whitaker's (1966) more detailed stratigraphical work divided the Group into lower (10a), middle (10b), and upper (10c) 'Ringerike Sandstone Series'. His research concentrated on the marine Silurian of Ringerike and these divisions were regarded as being rather arbitrary. The present study is based on detailed work in the Ringerike area and all the other outcrop areas within the Oslo Graben.

Lithostratigraphy

The name Ringerike Group is introduced to replace the variously used 'Ringerike Sandstone Series' (Whitaker 1966), 'Ringerike Formation' (Spjeldnæs 1966), and 'Ringerike Sandstone' (Heintz 1969). The Group contains three Formations: Sundvollen Formation, Stubdal Formation and Holmestrand Formation. The Stubdal Formation overlies the Sundvollen Formation but the boundary between them is likely to be diachronous. The sediments of the Holmestrand Formation form a distinct sedimentary province which is not mappable with the other two formations. For this reason the sequence has been raised to the rank of Group since it falls outside the definition of a Formation. Moreover the lithological variation and thickness warrant the application of Group status to the sequence.

RINGERIKE

Since it is the area of maximum development, of greatest historical significance and is easily accessible, Ringerike is naturally selected as the type area. The area around Steinsfjorden and Tyrifjorden was mapped on a scale of 1 : 15,000 using aerial photographs and topographical base maps. Fig. 3 is a map of the area based on this work. The Ringerike Group in this area has been divided into a lower Sundvollen Formation and an upper Stubdal Formation.

The Sundvollen Formation

This takes its name from the small town of Sundvollen between Steinsfjorden and Tyrifjorden (Fig. 3). The type section is along the E68 highway on the west side of Kroksund, to Sundvollen and from there to the toll hut on Dronningveien, the road to Kleivstua. The thickness exposed in this section is estimated at 500 m. The Sundvollen Formation maintains this thickness throughout the length of its outcrop from Åsa in the north, to the very south of the area near Kløvik. For the greater part of its outcrop the lower boundary is covered by Steinsfjorden or Tyrifjorden and is only well-exposed in the type section. Here thinly bedded grey limestones and green shales of 'Zone' 9g pass rapidly into the red beds of the Sundvollen Formation. The sediments of the Sundvollen Formation consist mostly of sandstones and siltstones, approximately in equal proportions. The sandstones are red, grey or grey-green in colour and contain a wide varity of sedimentary structures characteristic of fluviatile deposition. The siltstones are nearly always red in colour and show many structures including ripple marks, cross-lamination, mud-cracks, mud-crack diapirs (Whitaker 1964) and pseudo-nodules. Carbonate concretions are common at many horizons. Trace fossils in the form of crustacean and

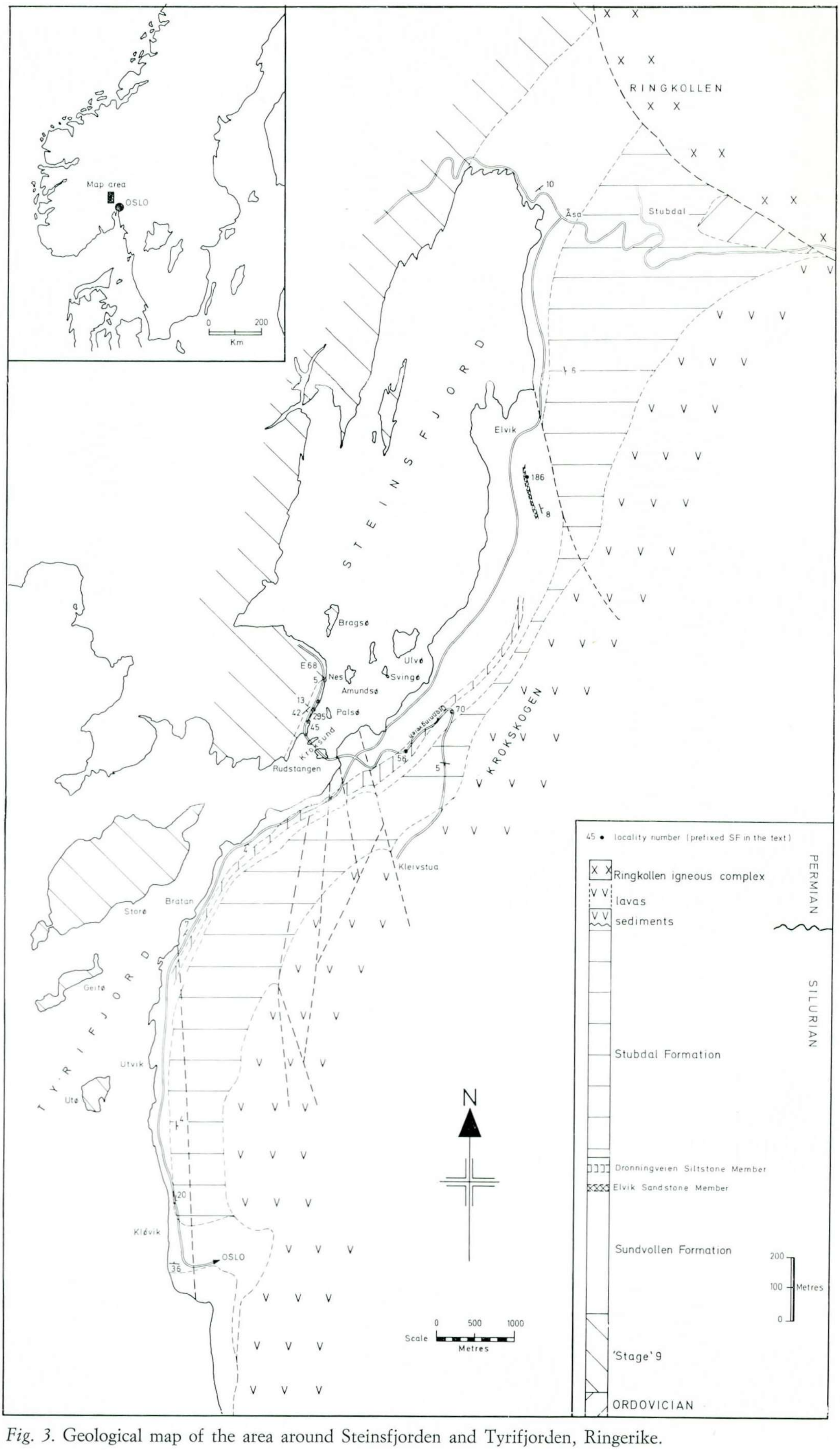


Fig. 3. Geological map of the area around Steinsfjorden and Tyrifjorden, Ringerike.

eurypterid trails are characteristic of the siltstones. No body fossils, apart from from a few fragmental bryozoans, have been found in the clastic rocks of the Sundvollen Formation.

The sandstones and siltstones are usually arranged in fining-upwards cyclothems (Allen 1970) similar to those described from the Old Red Sandstone by Friend (1965), Allen & Friend (1968) and Allen (1970). Towards their base these cyclothems often contain mud-flake or carbonate-concretion intra-formational conglomerate but no extra-formational conglomerate of any type has been seen at Ringerike. Cross-stratified, medium and coarse grained calcarenites averaging 0.5 m in thickness occur at the base of a number of cyclothems, particularly in the northern part of the area. These calcarenites contain a variety of fragmental marine fossils including: bryozoa, ostracodes, trilobites, echinoderms and thelodonts.

In the basal part of the type section on the west side of Kroksund the beds are dipping steeply at 45–60° SE. The lowest beds of the Sundvollen Formation are referable to the *Nes Limestone–Mudrock Member.* It is well exposed on the main E68 highway near Nes at the base of the type section (Loc. SF5). The base is drawn at the top of a 0.5 m thick sequence of grey limestones and mottled red and green shales. The member is 3 m thick and consists of thin wavy and lenticular bedded limestones rarely more than 5 cm thick intercalated with red shales and siltstones. Structures include mud-cracks, small scale symmetrical ripple marks and animal burrows.

Above the Nes Member comes 15 m of greyish-red, micaceous siltstones with thin beds of red mudrock and shales. Structures include cross-lamination, ripple marks, pseudo-nodules, convolute lamination, mud-cracks, burrows, trails and bioturbated horizons up to 15 cm thick. These features are consistent with sedimentation in an inter-tidal environment.

These siltstones are overlain by the sandstone–siltstone cyclothems which constitute the major part of the Sundvollen Formation. In this part of the section the sandstone beds are fine to very-fine grained, rarely exceed 2 m in thickness, and are mostly massive or flat-bedded. Cross-stratified sandstones only appear higher up in the section (Loc. SF45) about 90 m above the base.

An important calcarenite horizon, the *Kroksund Calcarenite Member,* outcrops on the E68 road section (Loc. SF295) about 80 m above the base of the Sundvollen Formation. Here the strike is almost parallel to the road and the beds are dipping 45° SE. The grey calcarenite is cross-stratified, coarse-grained and persists laterally for about 55 m. It is about 30 cm thick and both upper and lower boundaries are clearly visible. It was from this horizon that Størmer (1954) recorded the presence of the thelodonts *Thelodus parvidens* and *Thelodus scoticus* and suggested that it might be correlated with the Ludlow Bonebed in Britain. Subsequent research, however, has shown that the *T. parvidens* of Størmer is probably *T. laevis,* whilst revision of *T. scoticus* by Gross (1967) has shown that it consists of several species whose range extends well below that of the Ludlow Bonebed. The thelodont fauna from this horizon is more consistent with a Ludlovian age (Turner 1973).

Shortly after this point the E68 crosses Kroksund and the section continues from Sundvollen up Dronningveien. The *Dronningveien Siltstone Member* is a massive, coarse red siltstone up to 25 m thick. It is the most laterally persistent and distinctive marker horizon within the Sundvollen Formation and can be traced with little apparent change in thickness 4 km to the south and 3 km to the north of Sundvollen. In many places the siltstones have a distinctive pock-marked appearance due to the weathering of small carbonate concretions. Beds of nodular carbonate concretions (usually calcite, but occasionally dolomite) occur at several horizons in this siltstone member. The base of the Dronningveien Siltstone Member is only poorly exposed but the top is well-seen at the first sharp left-hand bend on Dronningveien (Loc. SF56). Here a 4 m thick grey sandstone lies on an erosional surface cut into the siltstone. Channelling, cross-stratification and flat-bedding can be traced laterally in the sandstone for a short distance. This horizon is more or less parallel to Dronningveien and shortly below the toll hut (Loc. SF70) the Dronningveien Siltstone Member outcrops again.

Above the toll hut only 1 cyclothem (4 m of sandstone and 8 m of siltstone) is present before siltstones become virtually absent and sandstones dominate the succession. This boundary between the Sundvollen and Stubdal Formations is drawn at the top of the siltstone and is shown on Fig. 3.

The type section is wholly typical of the Sundvollen Formation, with only two exceptions. The first is the northern part of the area near Åsa where the Formation is characterized several calcarenite horizons similar to the Kroksund Calcarenite Member. These calcarenites have been described by Turner (1974). Their significance is described later in this paper. The second is the *Elvik Sandstone Member* a 20 km thick sandstone unit which outcrops for about 0.5 km parallel to the N–S road which leaves the Sundvollen–Åsa road just south of Elvik (Loc. SF186). It is unusual not only because of its thickness but because it contains the only medium-grained sandstones found in the Sundvollen Formation and also because some of the cross-stratified sets are unusually thick (up to 2 m). Moreover the sandstones occasionally contain a few, scattered, well-rounded quartz grains and they could be aeolian in origin. The relationships within the Sundvollen Formation are summarized in Fig. 4.

The Stubdal Formation

The Stubdal Formation is named after the small village of Stubdal in the northern part of the area where the Formation reaches its maximum thickness of about 750 m. Siltstones are virtually absent and the succession is dominated by fine-grained sandstone and intra-formational conglomerate. The latter commonly occur as thin beds of mud-flake conglomerate up to 1 m in thickness and laterally impersistent, occupying broad, shallow channels and depressions in erosion surfaces. Many of the sandstones appear massive but flat-bedding, cross-stratification and cross-lamination are common sedimentary structures. Some of the cross-stratified sandstones tend to be slightly coarser and occasionally reach medium grain size.

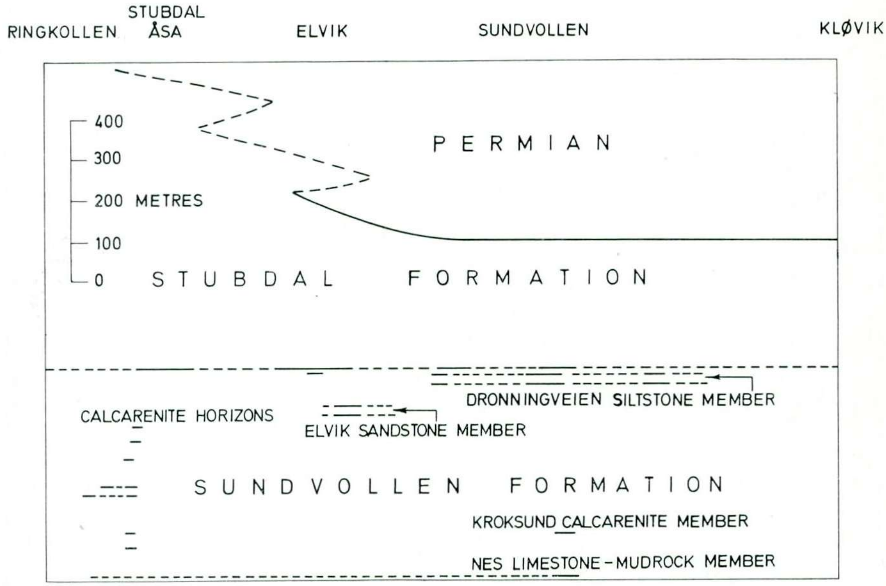


Fig. 4. Summary of the stratigraphical relationships within the Sundvollen Formation at Ringerike.

When traced southwards the exposed thickness of the Stubdal Formation rapidly decreases because of the increased cover of the overlying Permian lavas. South of Sundvollen, where the lavas are dominantly red in colour, very fine grain size is most abundant and flat-bedding is by far the commonest structure. The upper boundary of the Stubdal Formation is very rarely seen because of the steep screes at the foot of the Krokskogen escarpment. When seen it is unconformably overlain by the Permian sediments which underlie the thick sequence of lavas.

The Sundvollen and Stubdal Formations are notable for their fine grain size and complete absence of extra-formational conglomerate. Petrologically the sandstones of both Formations are quite similar. They are frequently micaceous or calcareous, usually sub-angular and quartzose, feldspathic, or lithic wacke and arenite in composition (Okada 1971).

KOLSÅS

There is a large outcrop of the Ringerike Group in the Kolsås area about 20 km SE of Ringerike. Most of the studies in this area have been made around the well-known Kolsås hill where the best exposures occur. A map of the area is shown in Fig. 5. The stratigraphy is broadly similar to that in the type area; lateral extensions of both the Sundvollen and Stubdal Formations can be recognized, although the whole succession is only about 500 m thick.

The Sundvollen Formation

The Formation is poorly exposed but forms a distinct valley which can be traced from Hauger NE to Gothaab, a distance of 3 km (Fig. 5). The thickness

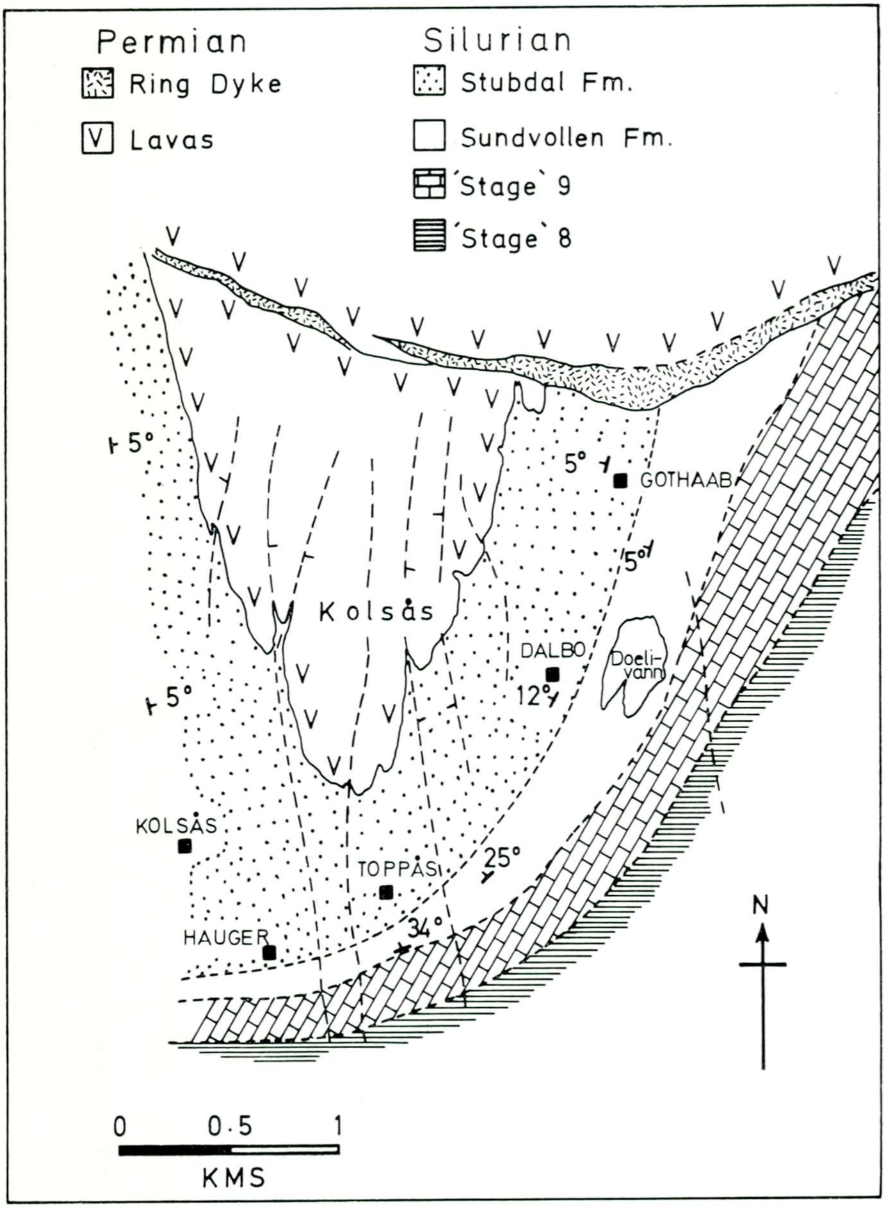


Fig. 5. Geological map of the Kolsås area.

is estimated at 100 m. The base is exposed in the stream section immediately south of Kolsås hill and east of Toppåsveien. The sediments from this locality have been described by Spjeldnæs (1966). Thinly bedded green shales and grey limestones pass upwards into a variable sequence of red mudstones and micaceous siltstones with calcareous laminae, which are often graded and intensely burrowed. Green shales and grey limestones typical of 'Zone' 9g occur at three higher horizons and 12 m above the base there is grey calcareous mudstone with fragmental trilobites, ostracodes and echinoderms. Evidently the change from marine to non-marine conditions took place more gradually in the Kolsås area.

Above this horizon come the massive red siltstones characteristic of the Sundvollen Formation. Cross-lamination, ripple marks and mud-cracks are common, as are eurypterid trails of a type similar to those at Ringerike. Carbonate concretions are also common and in some beds form aggregates of flattened nodules 4 or 5 cm in length. Spjeldnæs (1966) noted that the number of carbonate concretions tended to increase upwards and this generally seems to be the case, the most densely packed beds of carbonate concretions occurring at the top of the Sundvollen Formation. Sandstones have been found at only two horizons and fining-upwards cyclothems like those at Ringerike have not been seen. The top of the Sundvollen Formation at Kolsås is marked by a carbonate pebble conglomerate which can be seen at Hauger station and and in the NE of the area (Dons & Gyøry 1967).

The Stubdal Formation

The boundary between the Sundvollen and Stubdal Formations, although nowhere seen, is apparently conformable. The thickness of the Stubdal Formation is estimated at 400 m. It consists mostly of fine and very fine grained red, grey and grey-green sandstones with scoured surfaces, channels and intraformational conglomerate. The most common structures are flat-bedding and cross-stratification but cross-lamination and ripple marks occur.

On the whole, the sandstones of the Kolsås area are petrologically similar to those of Ringerike. Notable exceptions are the occurrence of quartzose arenites low down in the Stubdal Formation and some very micaceous sandstones a little higher up, Locally, the sandstones are colour banded and contain abundant pyrite and epidote, effects which have been produced by thermal metamorphism from the nearby Permian igneous complexes.

HOLMESTRAND AND JELØYA

These areas are about 60 km south of Oslo (Fig. 1) on the western and eastern banks of Oslofjorden. The base of the deposits corresponding to the Ringerike Group is covered by the fjord but the top is again marked by the steep escarpment of Permian lavas. The total thickness of the sediments in this area is estimated at 600 m, of which about 400 m is covered by Oslofjorden. The character of these sediments is considerably different from that of the Ringerike Group in the type area and a new Formation, the Holmestrand Formation, is named.

The Holmestrand Formation

This Formation takes its name from the town of Holmestrand on the west side of Oslofjorden. It includes the rocks which outcrop around and to the north of Holmestrand and those on the small island of Jeløya on the east side of Oslofjorden. The type section is along the E18 highway between Engenes and

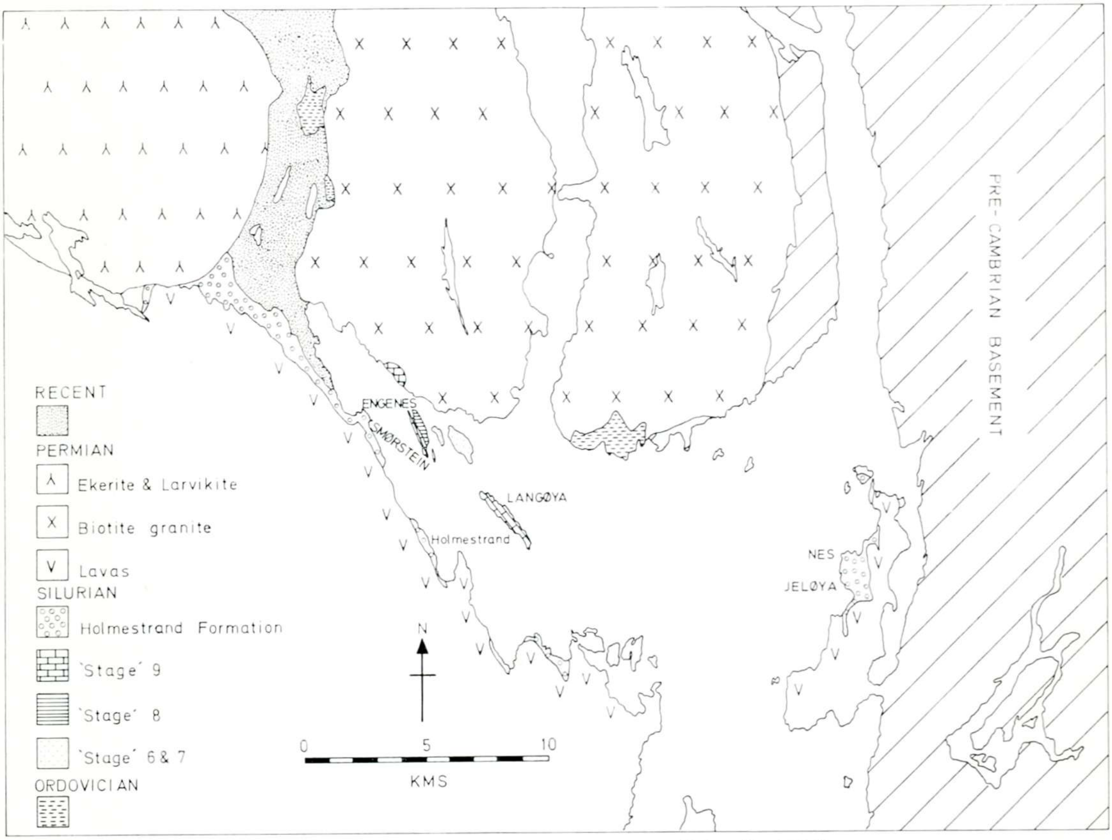


Fig. 6. Geological map of the Holmestrand area (based on Brøgger & Schetelig 1926).

Smørstein. The beds dip at about 20° SW in this area and there are numerous good roadside exposures. A map of the area is shown in Fig. 6.

The Formation consists dominantly of medium-grained sandstones but fine- and coarse-grained sandstones are quite common. Their colours range through grey, grey-green, buff, red and orange-red. Many of the sandstones, particularly in the Holmestrand area, are colour banded and this is apparently due to the thermal metamorphism which they have suffered. Metamorphic epidote, zoisite and clinozoisite, is common in thin section and is partly responsible for variations in colour. A characteristic feature is the presence of extra-formational conglomerates. These occur as thin beds or as scattered well-rounded pebbles and cobbles. They are mostly grey or liver-coloured quartzites but pebbles of acid and basic igneous rocks, arkose and other clastic sediments occur. Many of these pebbles are of rock-types which outcrop today along the eastern front of the Caledonian mountains and are mostly Eocambrian in age.

There is a wide range of sedimentary structures including channels and erosion surfaces, cross-stratification, flat-bedding and ripple marks. Deformed cross-stratification (Allen & Banks 1972) occurs at several localities.

The petrology of the Holmestrand Formation is also distinct from that of the Sundvollen or Stubdal Formation. The sandstones contain much less feldspar and are mostly quartzose arenite or lithic arenite in composition.

No fossils were found in the Holmestrand Formation but Heintz (1939) recorded the presence of *Hemicyclaspis kiaeri* Heintz from Jeløya. This horizon is near the top of the Holmestrand Formation and the similarity of *H. kiaeri* to *H. murchisoni* indicates a possible lower Downtonian age. Thus the Holmestrand Formation can be roughly correlated with the Stubdal Formation.

Facies Analysis

DATA COLLECTION AND TECHNIQUES

Detailed vertical sections were measured in both the Sundvollen and Stubdal Formations. The data were recorded on a printed form so that a continuous record of lithology, colour, grain size, sedimentary structures and palaeocurrent measurements could be made. Most of the measured sections are relatively short, being less than 40 m, but they are well exposed and continuous. They are spread both laterally and vertically throughout the area and are thought to represent the two Formations fairly. The unit of measurement in the sections has been the *set*, defined by McKee & Weir (1953). The character of like sets or lithofacies has been defined in essentially the same manner as by Krumbein & Sloss (1963). 'The physical, mineralogic and petrographic characteristics of sedimentary rocks are expressed in terms of *lithologic aspects* which result in the delineation of *lithofacies*'.

A good method of comparing the facies content and variation in a stratigraphic unit is by constructing *facies profiles* as described by Selley (1968). This involves reorganizing all the data from the measured sections into a single profile which illustrates graphically the facies content of that stratigraphical unit and enables it to be compared with another. Facies profiles have been constructed for the Sundvollen and Stubdal Formations.

An important property of the facies not conveyed in the facies profiles is their set thickness. Therefore as a supplement to the facies profiles cumulative frequency distributions of set thickness have been plotted on log-probability paper for all the facies. These plots summarize the available data and allow rapid comparison of set thickness distributions, both within and between Formations.

The main part of this section, however, is concerned with the vertical relationships between facies and their sedimentological interpretation. These are of crucial importance in the interpretation of cyclic sedimentation and depositional environments. A number of authors have suggested ways in which these vertical relationships can be objectively assessed. Carr et al. (1966), Krumbein (1967), Potter & Blakely (1968), and Allen (1970) have all used the transition probability matrix, a square matrix which records the probability of upward facies transition from any one facies to another. It is calculated by summing each row of a matrix recording the total number of transitions from one facies to another, the tally matrix, to unity. This enables a ready assessment of the probability of one facies being succeeded by another, and allows any vertical patterns of sedimentation to be elucidated without any prior decision as to what may constitute each cyclothem or where it may begin. From the transition probability matrix, a facies relationship diagram can be constructed which graphically illustrates the main facies transitions and the relationships between the sequence of facies. Selley (1970) has advanced these techniques a little further in an attempt to study the variation in the matrix more closely. From the tally matrix, which he termed the data array, Selley calculated the number of times that different facies could be expected to pass into each other if the depositional process was random. This was done by cross-multipying the row and column totals of the matrix and dividing by the total number of transitions. The matrix obtained in this way, the predicted data array was then subtracted from the data array to produce a matrix which showed the differences between the observed number of transitions and those predicted using a random model of deposition (the residual data array). From this matrix Selley was able to construct a corrected facies relationship diagram which showed the upward transitions which occurred most frequently for each facies, after allowing for the number expected had the depositional process been random. This corrected facies relationship diagram is a useful tool in interpretation because it records those transitions produced by the process which controlled the depositional sequence.

The advantage of preparing data in this way is that they can be used as a basis for statistical tests. The tests can be used to determine whether the sedimentary sequence was generated by an *independent trials process* or a *Markov process* (Carr et al. 1966). The first order Markov process (Markov–1) is the simplest case. In it, the nature of an event is dependent to some degree on the nature of the preceding event, but independent of all previous events. It is said to have a one-step memory. A Markov–1 process can be recognized by testing the observed tally matrix against an independent events prediction. The test applies a χ^2 distribution either by the method of Anderson & Goodman (1957) or by treating the matrices as contingency tables (Potter & Blakely 1968, Read 1969, Doveton 1971). In this case the expected values are found by cross-multiplication of the row and columns total and dividing by the grand total. The statistic for testing with χ^2 is then found in the normal manner using the formula:

$$\sum (O-E)^2 / E$$

This has $(m-1)^2$ degrees of freedom where m is the number of facies in the matrix. The method of Anderson & Goodman (1957) is described in the computer program TESTMARK (Krumbein 1967). It is based on an application of the χ^2 test for regular transition matrices and the conditions of the test are that the transition probability matrix is stationary and that events occur at equally spaced intervals in time (an approximation is made by having transitions spaced at regular vertical intervals). The tally matrix and the transition probability matrix are both used in the test, which has the sample statistic:

$$-2 \log_e \lambda = 2_{ij}^{m} n_{ij} \log_e (p_{ij} / p_j)$$

where $-2 \log_e \lambda$ for m facies is asymptotically distributed as with $(m-1)^2$ degrees of freedom and where:

n_{ij} is the tally in the n_{ij} th cell of the matrix
p_{ij} is the transition probability in the same cell
p_j is the marginal probability for the column.

In both the methods described, if the calculated statistics are larger than the tabulated value for $(m-1)^2$ degrees of freedom and the required significance level, then the null hypothesis of an independent events prediction is rejected and the observations are said to represent a Markov–1 process.

FACIES ANALYSIS OF THE SUNDVOLLEN FORMATION

Facies description

In the Sundvollen Formation 444 m of strata, comprising 26 sections ranging from 5–75 m in thickness, have been used in the analysis. Seven facies were delineated as follows:

1. Cross-stratified sandstone facies
2. Massive sandstone facies
3. Flat-bedded sandstone facies
4. Massive siltstone facies
5. Cross-laminated siltstone facies
6. Mudrock facies
7. Calcarenite facies

Cross-stratified sandstone facies

This facies is represented dominantly by red, grey, and grey-green very fine- and fine-grained sandstones of feldspathic wacke and arenite and quartzose wacke and arenite composition (Okada 1971). The sandstones are frequently calcareous. Solitary and grouped sets (cosets) of cross-strata occur and alpha, beta, gamma, epsilon, zeta, pi, and omikron types of Allen (1963) have all been recognized. Set thickness averages 0.41 m and intra-formational conglomerate may be concentrated towards the base of some sets. Analysis of foreset dip azimuths indicates essentially a unidirectional flow pattern characteristic of fluviatile deposits (Turner 1974).

Massive sandstone facies

Many sandstone sets, dominantly grey, calcareous, and fine-grained reveal no visible structure in the field. The thickness of these sets averages 1.14 m and they commonly lie on a scoured erosion surface with a concentration of intra-formational conglomerate towards their base. Absence of sedimentary structure in this facies poses a problem. The X-ray photographic technique did reveal structures in some sandstones but the majority showed no apparent structure and appear to be truly massive. In view of the fine grain size it is possible that these massive beds represent deposition from suspension load under high-energy conditions. Such massive beds have been described from fluviatile deposits by Visher (1972).

Flat-bedded sandstone facies

Flat-bedded, red and grey, fine- and very fine-grained sandstones are widespread in the Sundvollen Formation. Composition ranges from feldspathic wacke and arenite to quartzose wacke and arenite and the sandstones are frequently micaceous. Sets average 1.20 m in thickness and often rest on scoured erosion surfaces. Intra-formational conglomerate is present as stringers or concentrations towards the base of sets. Many representatives of this facies have good bedding planes, the surfaces of which often reveal parting lineations indicating deposition within the upper flow regime (Allen 1964).

Included in this facies are laminated sandstones which consist of alternating laminations of pinkish or buff, fine- or very fine-grained sandstone and darker, purplish, more matrix-rich siltstone. The laminations are in the order of 0.20 cm to 4.00 cm thick and the coarse units show a crude grading in thin section. This facies may have been produced by very low amplitude sand waves similar to those described by Smith (1971) from the Rio Grande, and Coleman (1969) from the Brahmaputra. The laminae tend to lens out within the space of 0.10 m to 1.00 m, unlike those in the more homogeneous type of flat-bedding, which are laterally persistent. Bedding planes in the laminated facies do not usually show well-developed parting lineation, but parallel linear troughs with orientated micas and intra-formational conglomerate do occur.

Massive siltstone facies
Thick sets of massive, pinkish red siltstone constitute what is quantitatively the most important facies in the Sundvollen Formation. Set thickness averages 2.82 m. Bedding features are often absent or obscure and a vertical prismatic jointing is sometimes developed. The dominant sedimentary structures are mud-cracks, which may occupy several metres of strata and are occasionally defined by small calcite crusts. Small cm scale carbonate concretions, usually calcite, are often scattered throughout the facies and sometimes are concentrated in thicker bands which have a distinct knobbly appearance. X-ray diffraction analysis has shown that these may be composed of calcite or dolomite.

Other sedimentary structures include ripple marks, cross-lamination and pseudo-nodules. Grain size is dominantly coarse silt although thin partings of red mudrock and very fine sand occur. Compositionally this facies is noteworthy for its high proportion of calcite cement and red argillaceous matrix. Similar distinctive siltstones have been described by Allen (1970) from the Old Red Sandstone of Great Britain and North America, and by Friend & Moody-Stuart (1970) from the Wood Bay Formation of Spitsbergen.

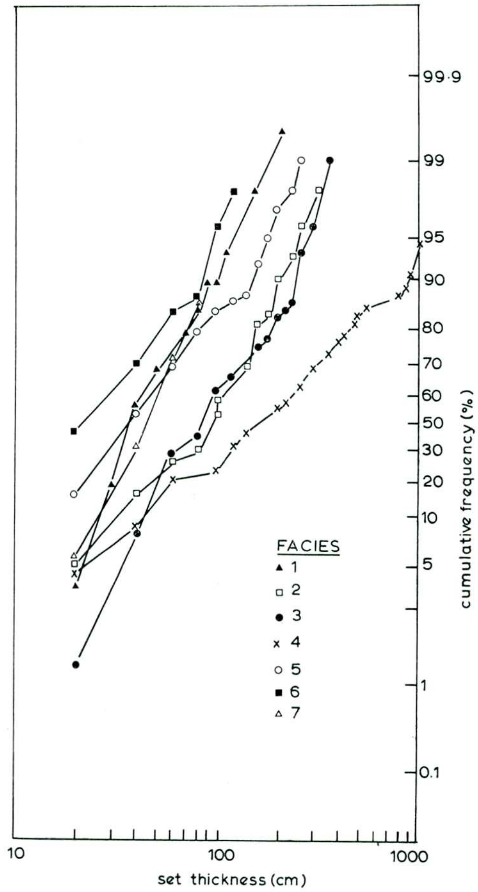
Cross-laminated siltstone facies
Siltstones, very fine-grained sandstones and rarely fine-grained sandstone, with cross-lamination as the dominant sedimentary structure, are attributed to this facies. The siltstones are grey, buff or red in colour but on the whole less strikingly red than the massive siltstone facies. This facies is distinctly less argillaceous than Facies 4 and usually less calcareous. Siltstones, and very fine sandstones particularly, are often micaceous. Set thickness averages 0.63 m. Most set boundaries are gradational but occasionally small channels are seen and bases may rest on an erosional surface lined with intra-formational conglomerate.

Trough cross-lamination and climbing ripple cross-lamination are the commonest structures. Others include ripple marks, pseudo-nodules, mud-cracks and mud-crack diapirs (Whitaker 1964).

Intercalated in the cross-laminated sets in proportions ranging from 0 to 50% are thinner beds of finer-grained red shales or silty shales (mudrocks) which also often show cross-lamination. When these form a high proportion of this facies they form rapid alternations, on a scale of 0.10 m to 0.20 m, very similar to the *alternating beds* facies of Allen (1970). However, since there is continuous variation from thick sets of cross-laminated siltstone to the alternating beds, they have not been considered as a separate facies.

Mudrock facies
This facies comprises a variety of fine-grained argillaceous rocks, the most common of which are red shales and silty shales in very thin sets. More rarely they are green or grey-green in colour. These mudrocks are often micaceous and have a well-developed flat-lamination which gives the shaly sets a marked

Fig. 7. Set thickness distributions for the Sundvollen Formation.



fissility. Carbonate is common in the form of calcite, both as nodular concretions and thin films on bedding planes. A scarce lithology which is included in this facies is a massive, red, calcareous mudrock, showing animal burrows and bioturbation. At one locality (SF13) it includes fragmental calcareous fossils, of which bryozoa have been definitely identified.

Sedimentary structures in this facies include small-scale ripple marks, cross-lamination and mud-cracks as well as the more abundant flat-lamination.

Calcarenite facies

Thin sets of cross-stratified, medium- to coarse-grained calcarenite, averaging 0.50 m in thickness occur at several horizons throughout the Sundvollen Formation. The calcarenites are red, greenish-red or grey in colour and often rest on an erosion surface with a concentration of intra-formational conglomerate towards their base. Compositionally the calcarenites are intrasparites and fossiliferous intrasparites containing fragmental bryozoa, trilobites, ostracodes, echinoderms, molluscs and thelodonts. Cross-stratification is commonly of the pi or omikron style of Allen (1963) and analysis of foreset dips azimuths has yielded a bipolar palaeocurrent pattern characteristic of tidal deposits (Turner 1974).

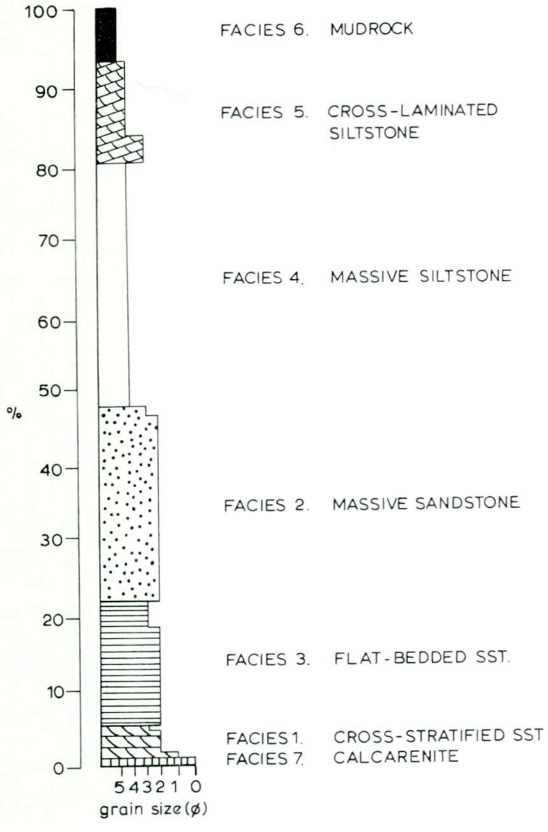


Fig. 8. Facies profile for the Sundvollen Formation.

Set thickness distribution

The set thickness distributions of Facies 1–7 are shown in Fig. 7. The results are plotted on a logarithmic scale and probability ordinate and are recorded in frequency per cent. In general the distributions show a tendency to be log-normal. A similar tendency has been noted by Pettijohn (1957) for a wide range of facies and Allen (1970) noted it for similar Old Red Sandstone sediments from Great Britain and North America.

Facies profile

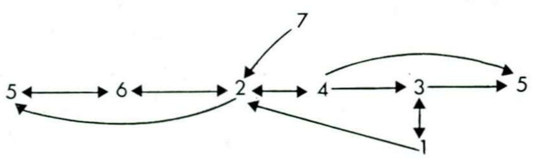
The facies profile is shown in Fig. 8. The bulk of the Formation (92%) is made up of sandstone and siltstone in almost equal proportions. The remainder is made up of 7% mudrock facies and 1% calcarenite facies. It has not been possible, because of the lack of exposure, to collect enough data from the same stratigraphic horizon to allow construction of facies profiles for different parts of the Ringerike area. However, study of over 400 localities, and inspection of the measured sections, suggest that there is no significant variation in facies content throughout the Ringerike area. The only possibly exception is an abundance of calcarenite horizons in the northern part of the area. At the same time, it has not been possible to correlate any of the sections because of

	Facies 1	2	3	4	5	6	7
1	1	7	7	1	2	3	1
2	2	6	8	13	18	15	1
3	10	5	2	4	10	5	3
4	2	8	7	1	8	6	0
5	2	11	8	11	17	31	0
6	5	22	7	6	23	4	0
7	1	2	1	0	1	0	0
							308

A. Tally Matrix for the Sundvollen Formation.

	Facies 1	2	3	4	5	6	7
1	0.05	0.32	0.32	0.05	0.09	0.14	0.05
2	0.03	0.10	0.13	0.21	0.29	0.24	0.02
3	0.26	0.13	0.05	0.10	0.26	0.13	0.08
4	0.06	0.25	0.21	0.03	0.25	0.19	0.00
5	0.02	0.14	0.10	0.14	0.21	0.39	0.00
6	0.07	0.32	0.10	0.09	0.35	0.06	0.00
7	0.20	0.40	0.20	0.00	0.20	0.00	0.00

B. Transition Probability Matrix for the Sundvollen Formation.



Facies
1 Cross-stratified sandstone
2 Massive sandstone
3 Flat-bedded sandstone
4 Massive siltstone
5 Cross-laminated siltstone
6 Mudrock
7 Calcarenite

C. Facies Relationship Diagram for the Sundvollen Formation (P>0.2).

Fig. 9. Facies relationships in the Sundvollen Formation.

the absence of marker horizons, and considerable lateral variation between the various facies is thought to exist.

An important feature illustrated by the facies profiles is the extreme restriction of grain size for a clastic sequence of this type. Medium sandstone is very rare and coarse sandstone and extra-formational conglomerate are completely absent.

The only fossils found in the Sundvollen Formation come from the calcarenite facies and certain members of the mudrock facies. The nature of the fossils suggests a marine environment in both cases. The absence of fossils and the nature of the facies in the greater part of the Sundvollen Formation suggests deposition in a non-marine environment.

Vertical facies relationships

The tally matrix showing the number of upward facies transitions for the Sundvollen Formation is shown in Fig. 9 A. The corresponding transition probability matrix, Fig. 9 B, was calculated using the computer program TESTMARK described by Krumbein (1967). The positive elements in the main diagonals of the two matrices record the transition of a facies into itself. Read (1969) and Selley (1970) both recorded such multi-storey lithologies from a variety of sedimentary sequences. The two facies with important positive elements in the main diagonal are Facies 2 (massive sandstone) and Facies 5 (cross-laminated siltstone). In the former the set boundaries are erosion surfaces. In Facies 5, colour, grain size variation and erosion surfaces all mark the boundaries of different sets.

A facies relationship diagram has been constructed for transitions which have a probability of greater than 0.2 (Fig. 9 C). The starting state of the diagram is Facies 5 and it can be seen that a variety of paths lead back to the same facies state, indicating that the overall arrangement is cyclic. When traced, the paths of these cycles can be seen to include one or more of the sandstone facies and one or more of the siltstone facies. In fact, the three sandstone facies are all closely associated, as are the three siltstone facies. The calcarenite facies is closely associated with the sandstone facies but there is only a very low probability of transition to calcarenite from any of the facies. In the sandstone association Facies 2 and Facies 3 may be alone or associated with Facies 1, which is never alone. In the siltstone association, Facies 5 and 6 are closely associated, whereas Facies 4 is likely to be alone, but may be associated with Facies 5. Clearly the vertical organization of facies in the Sundvollen Formation is very complex. In order to indicate where variation in the facies transitions lies, a predicted data array and residual data array (Fig. 10 A & B) were calculated. The residual data array shows which transitions are most likely to occur after allowing for the number had the depositional process been random. A corrected facies relationship diagram (Fig. 10 C) graphically illustrates the most likely transitions for each facies. Two basic sequences emerge, one involving Facies 3 and 1 with Facies 5 and 4, and another involving Facies 2, 4 and 6. Either of these sequences may contain Facies 7 within the sandstone part of the cyclothem.

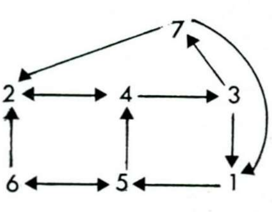
Although we are able to detect cyclic sedimentation from the facies relationship diagrams they do not tell us whether the controlling process was of

	Facies						
	1	2	3	4	5	6	7
1	1.6	4.3	2.8	2.6	5.5	4.5	4.5
2	4.6	12.2	8.0	7.4	15.8	13.1	1.8
3	2.9	7.6	5.0	4.6	9.8	8.1	1.1
4	2.4	6.4	4.2	3.9	8.3	6.8	0.9
5	5.9	15.7	10.3	9.5	20.4	16.8	2.3
6	5.0	13.2	8.7	8.0	17.1	14.1	1.9
7	0.6	1.5	1.0	0.9	2.0	1.6	0.2

A. Predicted Data Array for the Sundvollen Formation.

	1	2	3	4	5	6	7
1	+0.6	-2.7	-4.2	+1.6	+3.5	+1.5	-0.4
2	-2.6	-6.2	0.0	+5.6	+2.2	+1.9	-0.8
3	+7.1	-2.6	-3.0	-0.6	+0.2	-3.1	+1.9
4	-0.4	+1.6	+2.7	-2.9	-0.3	-0.8	-0.9
5	-3.9	-4.7	-2.3	+1.5	-3.4	+14.2	-2.3
6	0.0	+8.8	-1.7	-2.0	+5.9	-10.1	-1.9
7	+0.4	+0.5	0.0	-0.9	-1.0	-1.6	-0.2

B. Residual Data Array for the Sundvollen Formation.



Facies
1 Cross-stratified sandstone
2 Massive sandstone
3 Flat-bedded sandstone
4 Massive siltstone
5 Cross-laminated siltstone
6 Mudrock
7 Calcarenite

C. Corrected Facies Relationship Diagram for the Sundvollen Formation.

Fig. 10. Corrected facies relationships in the Sundvollen Formation.

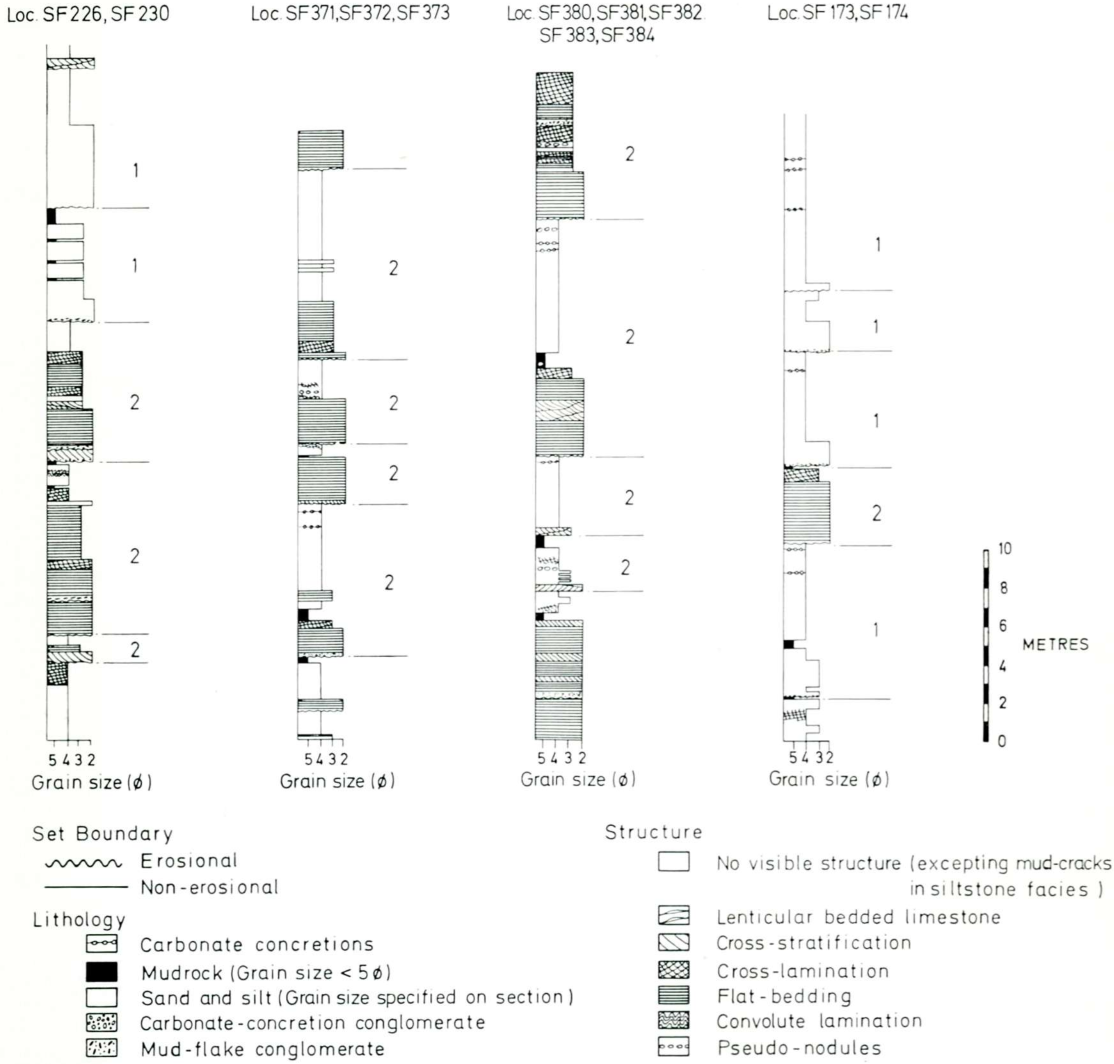


Fig. 11. Measured sections from the Sundvollen Formation illustrating the occurrence of Type–1 and Type–2 fining upwards cyclothems.

the independent trials or Markov type. This has been achieved by application of the test as described in an earlier section. In the first case the tally matrix was treated as a contingency table. The null hypothesis of an independent trials process was rejected because the χ^2 obs of 94.04 exceeded the χ^2 0.05 of 50.90 for 36 degrees of freedom. In the second case a regular transition matrix was prepared as input for TESTMARK. Two runs were made based on transitions every 1.0 and 0.5 m recorded from the same measured sections. The effect of this, however, was to create large positive elements in the main diagonals, and the χ^2 obs of 845.3 and 2053.6, respectively, strongly rejected the null hypothesis. The evidence suggests that more reliable results in testing for the Markov–1 property are obtained by using the tally matrix as a contin-

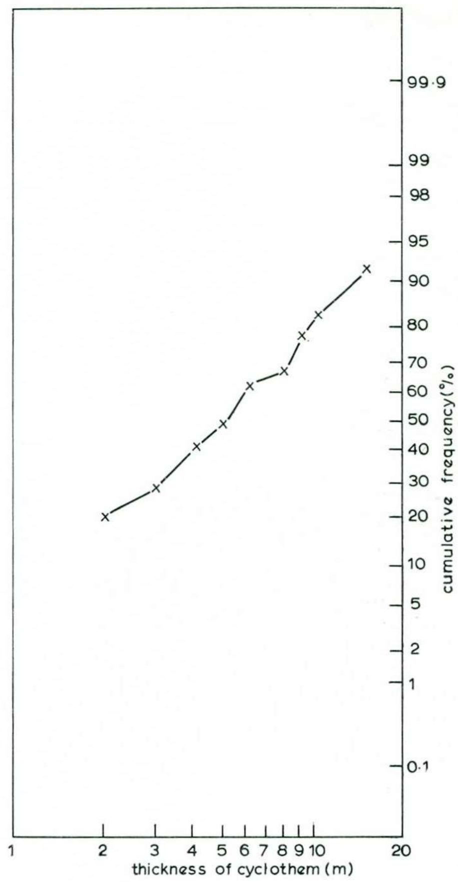


Fig. 12. Thickness distribution of fining upwards cyclothems (without calcarenite facies) in the Sundvollen Formation.

gency table. Division of the measured sections into regular vertical intervals creates large positive diagonals in sequences of this type and may lead to χ^2 obs values which are unrealistically large.

Interpretation and discussion of the results

The results indicate that a process of the Markov–1 type was important in generating the sequence of facies in the Sundvollen Formation. The corrected facies relationship diagram indicates that a large number of cyclic sequences may be found. Essentially the cyclothems are of two types. The first (Type–1) contains only Facies 2 (massive sandstone) in association with Facies 4 (massive siltstone). The second (Type–2) contains Facies 1 (cross-stratified sandstone, Facies 3 (flat-bedded sandstone), Facies 5 (cross-laminated siltstone) and Facies 6 (mudrock). Either type of cyclothem may be modified by the presence of calcarenite. Fig. 11 illustrates both Type–1 and Type–2 cyclothems.

Both types of cyclothem are very similar to the sedimentary units described by Allen (1965, 1970), Allen & Friend (1968) and Friend (1965) as fining-upwards cyclothems. Three basic features are common to all these cyclothems:

1. a basal erosion surface, often laterally persistent,
2. a lower coarse member consisting of cross-stratified and flat-bedded sandstones, often with a basal zone of intra-formational conglomerate,
3. an upper fine member consisting mostly of siltstones.

The thickness distribution of these cyclothems (without calcarenite facies) is shown in Fig. 12. The mean thickness of 5.64 m compares very closely with 6.46 m quoted by Allen (1970) for Old Red Sandstone cyclothems from Great Britain and North America. The thickness of the Wood Bay Formation cyclothems is much greater, averaging 12.0 m (Friend 1965).

By comparison with the deposits of Recent rivers (Allen 1965) these fining-upwards cyclothems are generally considered to be the deposits of meandering streams. The coarse members are bed-load sediments which were deposited in the river channel and on point bars. The siltstones were deposited on levees and the river floodplain. The cross-laminated siltstone facies, with its evidence of repeated submergence and emergence, probably represents deposition on levees. The massive siltstone facies, with its mud-cracks and calcification, represents deposition on the river flood-plain.

The sedimentological significance of Type–1 and Type–2 cyclothems remains to be demonstrated. Type–2 cyclothems are typical fining-upwards cyclothems like those previously described. Type–1 cyclothems, however, are unusual in that they have coarse members of massive fine-grained sandstone. Since this facies is interpreted as a suspension-load deposit it follows that the cyclothems were deposited from suspension-load probably under high-energy conditions. Massive beds have been described from braided fluviatile deposits (Visher 1972) and these may have originated in a similar way. Other features which are unusual in the cyclothems are the extreme restriction of grain size and the occurrence of calcarenites in some of the coarse members (Turner 1974). These features are taken to indicate that the rivers of the Sundvollen Formation were a relatively long distance from their source area. The calcarenites are thought to show that the river channels were occasionally within the reach of tidal currents, which deposited carbonate sediments, derived from the seaward side, at the mouths of the river estuaries.

FACIES ANALYSIS OF THE STUBDAL FORMATION

Facies description

In the Stubdal Formation 120 m of strata, comprising 14 sections ranging from 5–20 m in thickness, have been used in the analysis. Five lithofacies were delineated as follows:

1. Intra-formational conglomerate facies
2. Cross-stratified sandstone facies
3. Massive sandstone facies
4. Flat-bedded sandstone facies
5. Siltstone facies

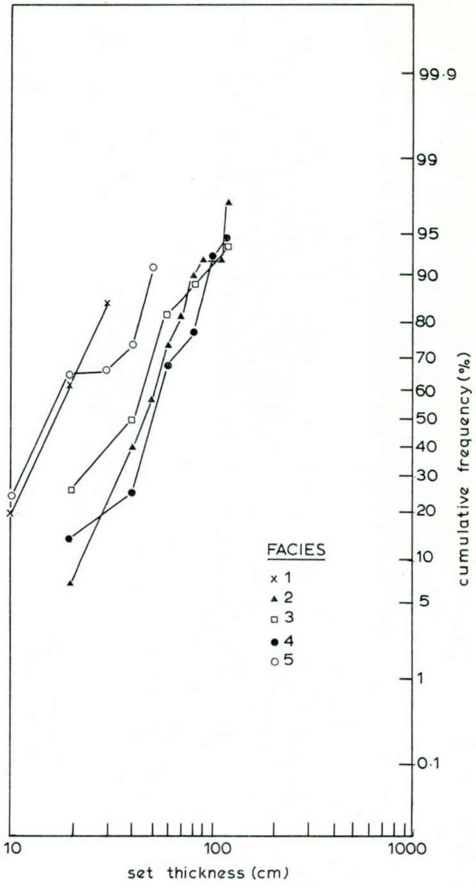


Fig. 13. Set thickness distributions for the Stubdal Formation.

Intra-formational conglomerate facies

In contrast to the Sundvollen Formation sets of intra-formational conglomerate are quantitatively important in the Stubdal Formation. They consist predominantly of well-rounded, oblate, mud-flake pebble conglomerates with occasional cobble-sized clasts. Sub-angular to rounded pebble conglomerates consisting mostly of carbonate fragments (calcite and/or dolomite) also occur. These conglomerates are similar to the concretion clast conglomerates described by Friend & Moody-Stuart (1970) from the Wood Bay Formation of Spitsbergen, and also to the conglomeratic cornstone described by Allen (1960) from the Old Red Sandstone of the Welsh Borders. Set thickness averages 0.17 m.

Cross-stratified sandstone facies

This facies is essentially the same as in the Sundvollen Formation. Pi and omikron cross-stratification tends to be more abundant and the average set thickness is slightly less (0.39 m).

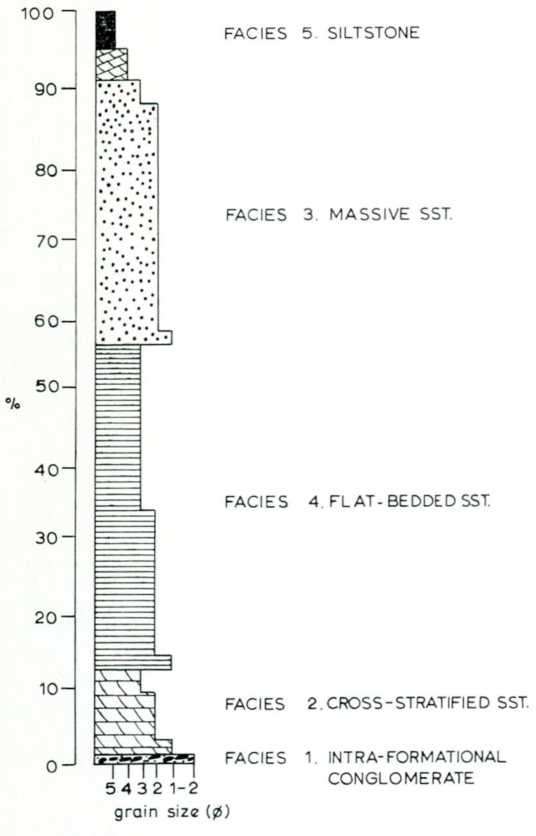


Fig. 14. Facies profile for the Stubdal Formation.

Massive sandstone facies
This is essentially the same as in the Sundvollen Formation except that the mean set thickness is less (0.72 m).

Flat-bedded sandstone facies
This is quantitatively the most important facies in the Stubdal Formation, comprising over 40% of all measured sets. Flat-bedded fine- and very fine-grained sandstone often occupy several metres of strata, being interrupted only by erosion surfaces. Colours range from brownish-red through buff to grey, which is most abundant. Both types of flat-bedding occur, that with parting lineations and that with sand-silt laminations, which were described for the Sundvollen Formation.

Siltstone facies
Red siltstone and mudrocks are rare in the Stubdal Formation and for convenience are considered as one facies. Sedimentary structures include cross-lamination, ripple marks, mud-cracks and pseudo-nodules.

Erosion surfaces
Scoured erosion surfaces are abundant in the Stubdal Formation. In view of their obvious importance in depositional processes they have been considered

as a separate facies state. The erosion surfaces are flat, laterally extensive and lack steep sides. They are often lined with intra-formational conglomerate and frequently show cross-cutting relationships.

Set thickness distribution

The set thickness distributions of Facies 1–5 are shown in Fig. 13. As in the Sundvollen Formation, set thickness shows a tendency to be log-normally distributed. However, both flat-bedded and massive sandstone facies are markedly thinner than their counterparts in the Sundvollen Formation.

Facies profiles

The facies profile of the Stubdal Formation is shown in Fig. 14. Comparison of this with Fig. 8 shows the main differences from the Sundvollen Formation. The Stubdal Formation consists of over 85% fine- and very fine-grained sandstones. Siltstones and mudrocks form less than 10% of the measured sets and calcarenites are totally absent. Intra-formational conglomerates are present as discrete beds making up about 1% of the measured sets. As in the Sundvollen Formation, coarse sands and extra-formational conglomerates are completely absent.

Vertical facies relationships

The tally matrix and corresponding transition probability matrix for the Stubdal Formation are shown in Fig. 15 A, B. A facies relationship diagram (Fig. 15 C) has been constructed for $P > 0.15$. This reveals a large number of cyclic sequences. Every facies may pass into Facies 4 or Facies 6 (erosion surfaces) but there are only three paths out of Facies 6 (Facies 1, 3, and 4) and two paths out of Facies 4 (Facies 4 and 6). In order to isolate the variation a predicted data array and residual data array were calculated (Fig. 16 A, B). A corrected facies relationship diagram (Fig. 16 C) illustrates graphically the most likely transitions to take place after allowing for those expected had the depositional process been random. There are a large number of possible cyclic sequences. In contrast to the Sundvollen Formation, however, most of these only involve the sandstone facies and erosion surfaces, with siltstones playing only a minor role.

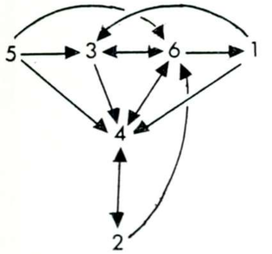
Treatment of the tally matrix as a contingency table yielded a χ^2 obs of 68.79 against a χ^2 0.05 of 37.65 with 25 degrees of freedom. The null hypothesis of an independent trials process was therefore rejected. Data were again prepared as input for TESTMARK based on transitions spaced at regular vertical intervals of 1.0 m and 0.5 m. This had the same effect as in the Sundvollen Formation, creating large positive elements in the main diagonal, and the χ^2 obs of 132.4 and 190.6 strongly rejected the null hypothesis. It must be concluded therefore, that a process of the Markov–1 type was important in controlling the depositional sequence which we see in the Stubdal Formation.

	Facies						
	1	2	3	4	5	6	
1	0	2	4	6	0	0	
2	0	0	2	7	1	7	
3	0	2	3	7	4	19	
4	0	7	2	4	2	20	
5	0	0	4	2	1	4	
6	12	6	16	15	2	0	
							161

A. Tally Matrix for the Stubdal Formation.

	Facies					
	1	2	3	4	5	6
1	0.00	0.17	0.33	0.50	0.00	0.00
2	0.00	0.00	0.12	0.41	0.05	0.41
3	0.00	0.06	0.08	0.19	0.11	0.56
4	0.00	0.19	0.06	0.11	0.08	0.59
5	0.00	0.00	0.36	0.18	0.09	0.36
6	0.23	0.12	0.32	0.30	0.04	0.00

B. Transition Probability Matrix for the Stubdal Formation.



Facies
1 Intra-formational conglomerate
2 Cross-stratified sandstone
3 Massive sandstone
4 Flat-bedded sandstone
5 Siltstone
6 Erosion surfaces

C. Facies Relationship Diagram for the Stubdal Formation (P>0.15).

Fig. 15. Facies relationships in the Stubdal Formation.

Interpretation and discussion of the results

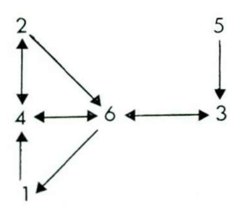
The results indicate that a process of the Markov–1 type was important in controlling the depositional sequence. In contrast to the Sundvollen Formation, the corrected facies relationship diagram indicates that the cyclothems of the Stubdal Formation contain only two basic elements:

	Facies					
	1	2	3	4	5	6
1	1.5	1.7	2.7	3.6	1.0	4.6
2	1.9	2.1	3.4	4.6	1.2	5.8
3	3.6	4.0	6.5	8.6	2.3	10.9
4	3.6	4.0	6.5	8.6	2.3	10.9
5	1.3	1.4	2.4	3.1	0.8	3.9
6	5.2	5.8	9.4	12.5	3.3	15.8

A. Predicted Data Array for the Stubdal Formation.

	Facies					
	1	2	3	4	5	6
1	-0.5	+0.3	+1.3	+2.4	0.0	-3.6
2	-0.9	-1.1	-1.4	+2.4	-0.2	+1.2
3	-2.6	-2.0	-3.5	-1.6	+1.7	+8.1
4	-2.6	+3.0	-4.5	-4.6	-0.3	+9.1
5	-0.3	-0.4	+1.6	-1.1	+0.2	+0.1
6	+6.8	+0.2	+6.6	+2.5	-1.3	-14.8

B. Residual Data Array for the Stubdal Formation.



Facies
1 Intra-formational conglomerate
2 Cross-stratified sandstone
3 Massive sandstone
4 Flat-bedded sandstone
5 Siltstone
6 Erosion surfaces

C. Corrected Facies Relationship Diagram for the Stubdal Formation.

Fig. 16. Corrected facies relationships in the Stubdal Formation.

1. a basal erosion surface
2. a sequence of sandstone facies

The characteristic fine members of siltstones and mudrocks seen in the Sundvollen Formation are absent, and fining-upwards cyclothems, as such, are also absent. The erosion surfaces record the cutting of channels under strong current conditions whilst the cross-stratified and flat-bedded sandstones record deposition in the channels from bed-load. The massive sandstone facies indicates that energy conditions were often sufficiently strong for deposition

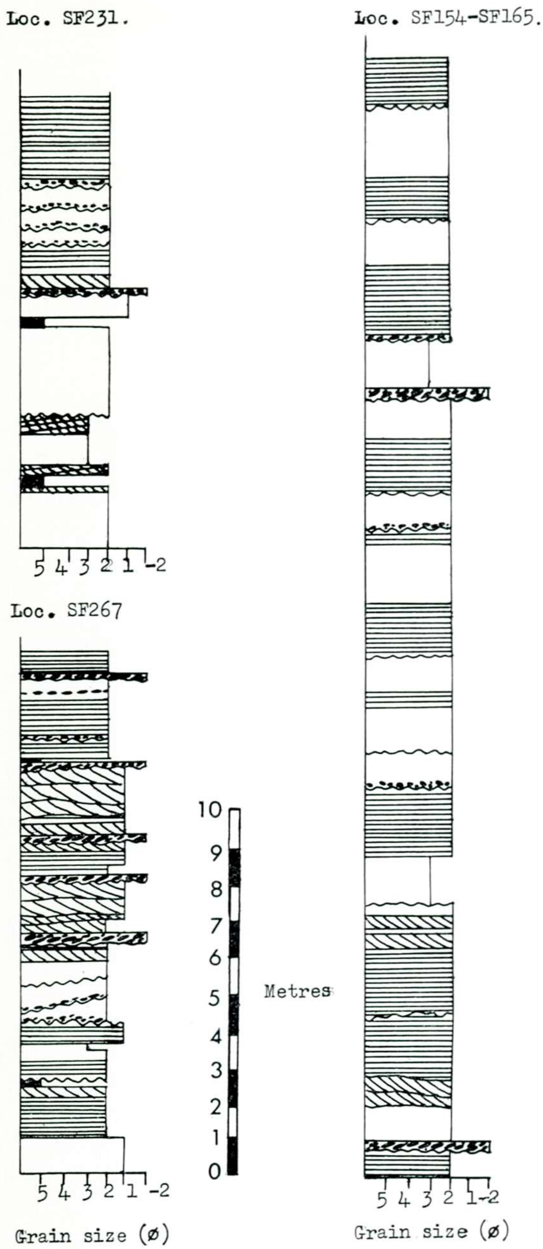


Fig. 17. Measured sections from the Stubdal Formation.

from suspension-load to take place in the river channels. Assuming erosion surfaces to be the starting state of the cyclothems, sequences which record deposition under waning current conditions play an important role in the sedimentation of the Stubdal Formation. These sequences include:

1. erosion surface → intra-formational conglomerate → flat-bedded sandstone → erosion surface

2. erosion surface → flat-bedded sandstone → cross-stratified sandstone → erosion surface
3. erosion surface → massive sandstone → siltstone

Such sequences, recording erosion followed by bed-load or suspension-load deposition are repeated many times throughout the Stubdal Formation. Measured sections illustrating them are shown in Fig. 17.

Overall, the features of the Stubdal Formation are thought to fit a braided stream depositional model (Doeglas 1962, Allen 1965, Williams & Rust 1969, Smith 1970). Here the river channel wanders across its flood-plain, cutting channels and depositing sands in the channels and on sediment bars. Fine-grained overbank deposits have thus very little chance of being preserved and bed-load deposits form the bulk of the succession.

Many recent braided rivers are very powerful and carry coarse sand and conglomerates. These are largely confined to mountainous areas, however, and Chien (1961) and Coleman (1969) have both described major braided rivers (Yellow and Brahmaputra rivers respectively) which carry mostly very fine and fine sand. The braided rivers of the Stubdal Formation are thought to have been of this type. What brought about the change from meandering rivers in the Sundvollen Formation to braided rivers in the Stubdal Formation is not clear. The processes which bring about braiding are complex and not yet fully understood. One of the important features of the Yellow and Brahmaputra rivers is their high sediment load, which causes the rapid filling and abandonment of channels. It may be that uplift in the Caledonian mountain source area to the north brought about an increase in sediment load which contributed to the change from meandering to braided fluviatile sedimentation.

Conclusions

In the type area, collection of data in measured sections has enabled the sedimentation of the Sundvollen and Stubdal Formations to be represented by transition probability matrices and facies relationship diagrams. Treatment of these matrices by statistical techniques has enabled the isolation of vertical facies sequences after allowing for the random transitions; also the Markov–1 property has been recognized in both the Sundvollen and Stubdal Formations. The advantage of using mathematical techniques is that variations in the sedimentary sequence, otherwise unseen, can be revealed, isolated, and quantitatively assessed. The Sundvollen Formation has been shown to consist of fining-upwards cyclothems, of two types, which formed under different energy conditions. The fine grain size of the bed-load deposits of the cyclothems and the presence of tidal calcarenites within some coarse members suggest that the meandering streams formed a coastal alluvial plain.

In the Stubdal Formation erosion surfaces overlain by sandstones deposited from bed-load and suspension-load make up the succession. The mathematical techniques show that sequences deposited under waning current conditions are an important feature of the sedimentation. These are interpreted as the deposits of braided rivers. The fine grain size of the sandstones and the conformable passage from the Sundvollen to Stubdal Formation suggests large alluvial braided rivers rather than those characteristic of mountain areas.

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