A PETROGRAPHIC STUDY OF SOME EOCAMBRIAN SEDIMENTARY ROCKS FROM THE LAKE MJØSA AREA, SOUTHERN NORWAY, AND THE TANAFJORD AREA, NORTHERN NORWAY

By

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CONTENTS.

LIST OF TABLES

Abstract. Grain size and composition were measured in about 50 samples from Eocambrian rocks near Lake Mjøsa and Tanafjord. The sparagmites in the Lake Mjøsa area vary widely in composition, but the average compositions of the formations are similar. The grain size distributions of the various formations are different, but consistent within each formation. Composition and grain size are treated statistically to evaluate differences among the samples. Grain size distribution does not appear to be a valid criterion for the correlation of the tillites studied. The Moelv tillite and the Tanafjord tillites show different patterns of grain size variability, suggesting that their modes of origin may have been different. Composition is related to grain size.

Introduction.

PURPOSE OF THE INVESTIGATION.

The petrographic study of Eocambrian rocks described in this paper was undertaken for the purpose of providing data on their composition, grain size, and petrology for comparison with rocks of similar age in other parts of the world, especially in North America. The study included preliminary work in samples from the pre-Cambrian Torridonian formation of Scotland; a comparison of these rocks with the sparagmites will be the subject of a later paper.

SCOPE OF THE WORK.

Mapping of Eocambrian formations is now being carried on by the Norwegian Geological Survey, and it was felt that no significant contribution could be made to this work during a single summer. Therefore, field work was confined to sampling and examination of outcrops. Thin-sections of sandstones, conglomerates, and tillite-like rocks were examined and subjected to various measurements with the aid of a petrographic microscope. The limitations of microscopic examination confined the work to grain sizes between 0.005 mm (very fine silt) and 8.00 mm (fine gravel).

ACKNOWLEDGEMENTS.

I would like to express thanks to the Institutt for Geologi, Oslo, and to Professor Trygve Strand, for providing facilities for carrying out petrographic work during part of 1960 and 1961. Space for special studies was made available at the Mineralogisk Museum, Oslo, by Professor T. F. W. Barth and Dr. H. Neumann. Most of the excellent thin sections were made by Hr. Fjellet of the Mineralogisk Museum.

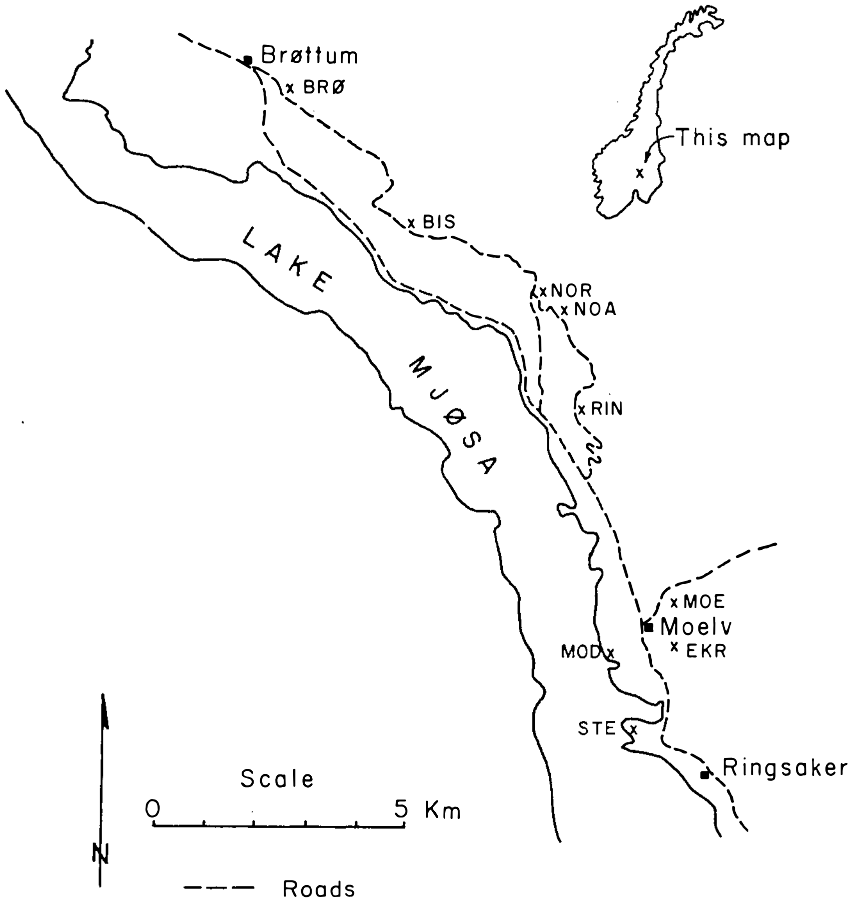

Fig. 1. Sample localities, Lake Mjøsa area.

Ian Maycock of the University of Reading, England, kindly accompanied me to Scotland in November, 1960, and is wholly responsible for an enjoyable and successful week in the field near Loch Torridon. Financial support was provided by a NATO post-doctoral fellowship. administered by the National Science Foundation, Washington, D. C.

LOCALITIES.

Samples were collected from outcrops near Lake Mjøsa in southern Norway (Hedmark) and Tanafjord in northern Norway (Finnmark). At Lake Mjøsa, the classical area for sparagmite exposures, the out-

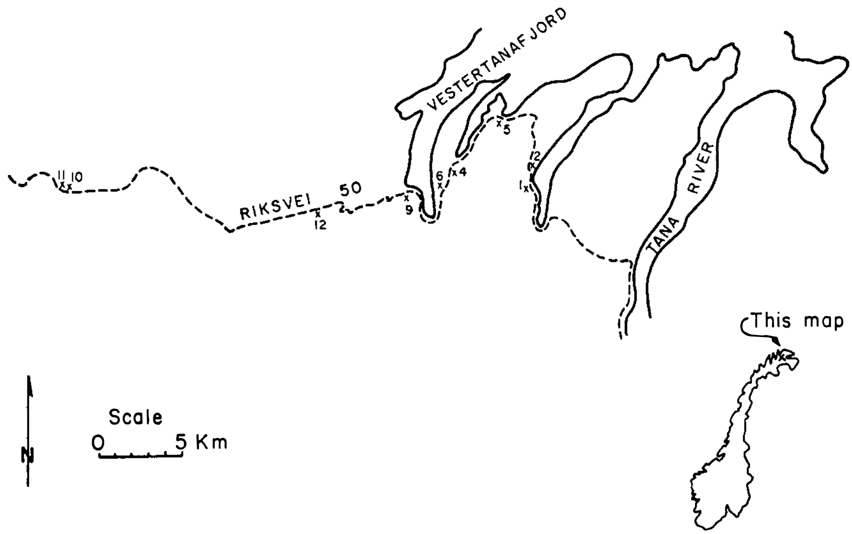

Fig. 2. Sample localities, Tanafjord area.

crops were located along Riksvei 50, along the road from Kjøs to Brøttum on the hillside east of the lake, along the lake shore, and at several places near Moelv (Fig. 1). At Tanafjord, the samples were taken from outcrops along the shore and from roadcuts along Riksvei 50 between Varangerfjord (Karlbotn) and Ifjord (Fig. 2). A few rocks were collected from outcrops at the head of Porsangerfjord.

SAMPLE NUMBERS.

The sample numbers used in this investigation consist of a three-letter prefix in capitals designating the sample locality, followed by a number showing the sample sequence at that locality, and ended by a suffix in lower case letters designating the formation from which the sample was taken (Table 1).

PREVIOUS WORK.

GOLDSCHMIDT's description (1908) of the sparagmite area between Ringsaker and Brøttum east of Lake Mjøsa has provided the basis for all subsequent work in that locality. Later work in the area includes structural and stratigraphic studies by HOLTEDAHL (1922) and VOGT (1924, 1952). HOLTEDAHL (1918) and FØYN (1937) studied and de-

TABLE 1.

Sample Number Prefixes.

BIS	—	roadcuts on the west side of Biskopaasen, Lake Mjøsa.
BRØ	—	roadcuts between Biskopaasen and Brøttum, Lake Mjøsa.
EKR	—	outcrops on the hillside near the railroad overpass at Ekredalen, Lake Mjøsa.
KAR	—	outcrops along the shore north of Karlbotn, Varangerfjord.
MOD	—	outcrops along the east shore of Lake Mjøsa at Modalen.
MOE	—	roadcuts on the hillside east of Moelv, Lake Mjøsa.
NOA	—	roadcuts south of the road intersection at Nordberg, Lake Mjøsa.
NOR	—	roadcuts at Nordberg, Lake Mjøsa.
POR	—	outcrops at the head of Porsangerfjord .
RIN	—	roadcuts and outcrops near Ringhotellet east of Lake Mjøsa.
STE	—	outcrops along the east shore of Lake Mjøsa at Sten.
TAN	—	roadcuts and outcrops along Riksvei 50 between Tanafjord and Ifjord.

Sample Number Suffixes.*

bi	—	Biri formation.	oec	—	older Eocambrian (Finnmark)
br	—	Brøttum formation.	ri	—	Ringsaker quartzite.
lc	—	lower Cambrian.	t	—	tillite (Karlbotn, Finnmark).
lt	—	lower tillite (Finnmark).	ut	—	upper tillite (Finnmark).
m	—	Moelv formation.	vl	—	Vardal sandstone.
mt	—	Moelv tillite.	yec	—	younger Eocambrian (Finnmark).

* F and C were used in the suffixes of TAN-10 and TAN-11 to distinguish between finer-grained and coarser-grained rocks found at the same place.

scribed the Eocambrian rocks of Finnmark. A summary of the geology of Eocambrian rocks has recently been made by HOLTEDAHL (1960). Guidebooks prepared for excursions during the International Geological Congress in 1960 describe the sparagmite region in southern Norway (HENNINGSMOEN and SPJELDNÆS) and the Eocambrian rocks of Finnmark (HOLTEDAHL, FØYN, and REITAN).

Point-counting.

The composition of the rock samples was determined by point-counting. The theory of this technique has been described by CHAYES (1954, 1956) and will not be considered here. A mechanical stage provided with a click-stop device (ratchet wheel) on the horizontal traverse control wheel was fitted to the microscope stage. The vertical control wheel was unmodified.

A preliminary study of eight thin sections representing various rock types and major localities in Norway was made to determine the optimum number of points required to provide stable estimates of composition. The counting was done in traverses of 50 contiguous points parallel to the long edge of the thin sections. Each preliminary trial consisted of three or more groups of ten traverses (500 points per group). 1500 points were counted in samples BRØ—3br, KAR—11t MOE—1m, RIN—2m, TAN—11Fyec, and TAN—12ut. 2000 points were counted in BIS—5bi, and 2500 points in BIS—7bi. The results of these preliminary counts indicated that 500 points per thin section would be sufficient to provide stable estimates of composition.

Point-counting was carried out on fifty thin-sections.

Measurement of grain size.

Grain size was measured in thin-section by using a Leitz grid insert in the ocular of the microscope. The grid was calibrated with a 2 mm stage micrometer divided into 10-micron intervals. The long axis of selected grains was measured. The long axis is defined to be the straight line determined by the two points that are farthest apart on the grain, and does not necessarily lie entirely within the grain boundaries. The selection of grains to be measured was made by choosing the grain under the crosshair after every interval of five click-stops on the point-counter. Ten traverses, each consisting of ten grains, were made in each thin-section, for a total of 100 grains per thin-section. Measurements were made in 46 samples from Norway, omitting some conglomerates because of large grain size and some quartzites because of uncertain grain boundaries.

Rock Descriptions.

Descriptions of the rocks as they occur in outcrop are to be found in the literature. Table 2 shows the sections at Lake Mjøsa and in Finnmark. The following remarks pertain specifically to features seen in thin-sections of conglomerate, sandstone, and pebbly mudstone collected during the present investigation. Carbonate rocks and shales have not been investigated in this study. The rock names given in the descriptions follow the usage of DAPPLES, KRUMBEIN, and SLOSS (1953) which was modified after KRYNINE (1948) and PETTIJOHN (1948).

TABLE 2.*

Eocambrian Stratigraphy.

Lake Mjøsa Area.

formation	*thickness* m
Fossiliferous Lower Cambrian etc.	
Thin quartz conglomerate.	
Ringsaker quartzite } "Quartz	
Vardal sparagmite (grey) with quartz conglomerate } sandstone"	200
Ekre (red and green) shale	50
Moelv conglomerate, tillite	10—20
Moelv sparagmite, mostly red, coarse, often conglomeratic	350
Biri limestone and shale	100
Biri congl., largely coarse, water-worn	150
Brøttum limestone and shale, thin.	
Brøttum sparagmite, dark grey, with arenacous shale	600
Base not seen.	

Tanafjord Area.

formation	*thickness* m
Light-colored quartzite with pipe structures in upper part. Digermul formation	500
Green siltstone etc. Breivik formation	1 100
Red quartzitic sandstone and greenish shale	175
Blue-green and red-violet shale	315
Dark shale and light-colored sandstone	60
Upper tillite. Mainly crystalline rocks. (max)	60
Reddish-brown sandstone etc. Material coarser to the south. Nyborg formation (max)	400
Lower tillite, rich in dolomite boulders except near southern border (max)	60
(Slight angular unconformity in N-S direction)	
Shale and dolomite (at Porsangerfjord thick dolomite with stromatolites)	50
White quartzitic sandstone. Vagge quartzite	150
Dark arenaceous shale. Vagge shale	50
Light-colored quartzitic sandstone	300
(Here pre-tillite denudation surface at head of the Tanafjord.)	
Alternating quartzite and dark shale	300
Siltstone. Stangenes formation	185
Quartzitic sandstone with fine-grained conglomerate	100
Quartzitic sandstone and arenaceous shale	35
Base not seen.	

* Taken directly from Plate 6, N. G. U. No. 208, compiled by Olaf Holtedahl.

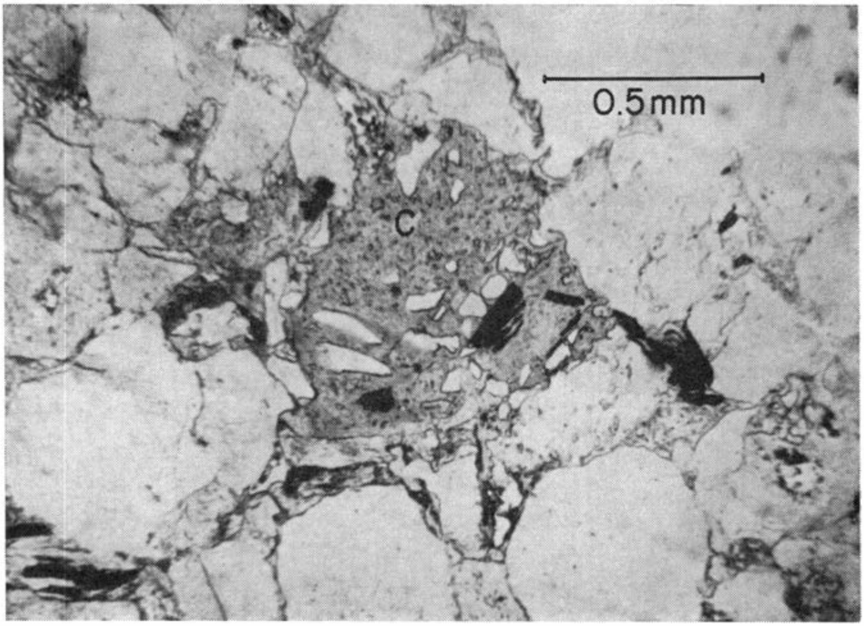

Fig. 3. Possible collophane containing silt fragments in Brøttum sandstone.

Brøttum formation.

The Brøttum sandstone at locality BRØ is a medium-grained, poorly sorted, dark gray-brown graywacke with a clay matrix.

The quartz grains are mostly angular and subangular, with irregular grain outlines caused by incomplete quartz overgrowths. Some of the grains appear to have been rounded before the formation of the overgrowths. Extinction is mainly undulose, but sometimes patchy. Metaquartz (internally granulated) is present in small amounts. Surfaces of inclusions and disseminated inclusions are present in most of the grains.

The microline is commonly fresh, but some grains are extensively altered, and a complete gradation exists between fresh and weathered grains. The fragments are angular and subangular, with irregular boundaries. Internal fractures are sometimes filled with limonite and limonite-stained clay.

An isotropic yellow to brown mineral with a refractive index higher than quartz, and containing small angular fragments of quartz and

Fig. 4. Outcrop of Biri sandstone and conglomerate on Biskopaasen showing inclined bedding and possible channeling in the sandstone. Scale in cm.

feldspar, occurs in two specimens (Fig. 3). The mineral is probably collophane, and if so, the size, composition and internal morphology of the grains suggest the possibility that they are fecal pellets.

Biri formation.

The Biri formation at locality BIS ranges from a siltstone through very coarse-grained very poorly sorted gray arkose to a conglomerate containing rounded boulders up to 25 cm or more in diameter. Sedimentary structures such as channels and inclined bedding are sometimes visible on weathered surfaces of Biri sandstone (Fig. 4). Compaction structures are present at times in sandstone underlying conglomeratic beds. A silty limestone occurs in the formation at other nearby localities.

The quartz grains range from angular to rounded; most are subangular with irregular boundaries. Extinction varies from normal to undulose and patchy; it is mostly undulose. Overgrowths are rare and may be inherited from a previous episode of lithification. Surfaces of inclusions and disseminated inclusions are commonly present within the grains. A little metaquartz is present in most of the samples.

Microcline occurs in all degrees of alteration from very fresh to completely weathered. The grains range from rounded to angular; most are subangular. Twinning boundaries are displaced within a few grains.

Calcite has been deposited in the interstices of some of the rocks, and in a few cases it replaces feldspar. Detrital calcite occurs in BIS—6bi.

Moelv formation.

The Moelv formation at locality RIN consists of a coarse-grained, poorly sorted gray arkose which weathers red, and conglomerate containing well rounded quartz and feldspar pebbles.

The quartz grains, most commonly subround, range from angular to rounded with smooth to irregular boundaries. The irregular boundaries appear to be associated with the formation of overgrowths. All degrees of undulose extinction are present, and some grains have patchy extinction. Contact undulosity is a common phenomenon, sometimes associated with mutual interpenetration of the grains. This feature is believed to be an early stage in the deformation of the quartz grains (BAILEY, BELL, and PENG, 1958). The deformation would later pass through a stage of granulation characteristic of the Valdres sparagmite to complete recrystallization as a quartz schist. In a few cases the strained crystal structure at grain contacts seems to control the pattern of emplacement of inclusions (Fig. 5). Inclusion surfaces and disseminated inclusions are common.

The microcline is usually quite fresh, but a relatively small number of badly weathered grains is present. The grains are mostly subround or subangular, with irregular surfaces. Microcline grains, in spite of typical feldspar cleavage, are not as susceptible to pressure as quartz and usually show little or no reaction to relatively severe pressure even in such rocks as the Valdres sparagmite, where they are commonly associated with thoroughly granulated quartz. In contrast, plagioclase grains in the Moelv sandstone are often internally disrupted and display bent or broken lamellae.

Clay matrix occurs in most specimens. At the RIN locality, the matrix is characterized by microchlorite in the lower parts of the formation, but higher parts appear to be sericitic, and contain little or

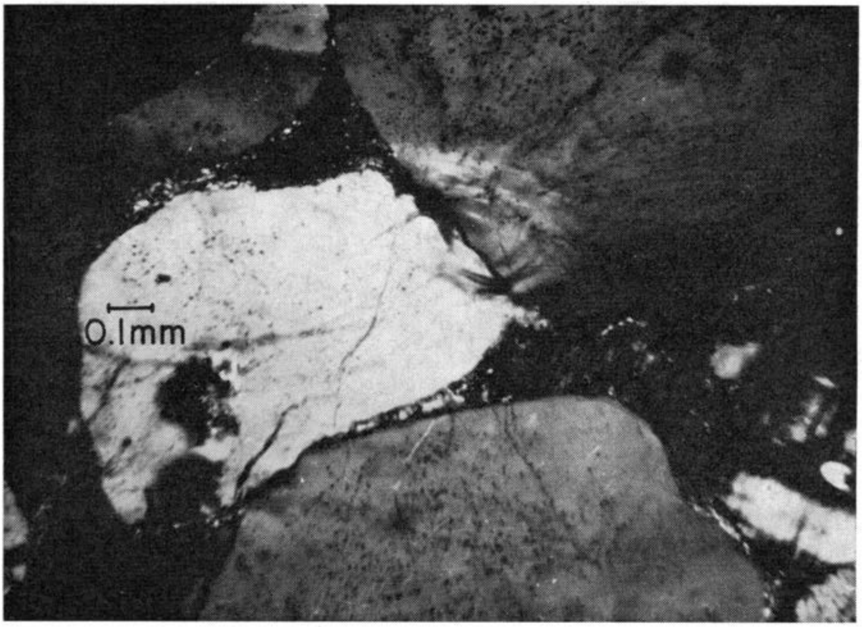

Fig. 5. Contact undulosity produced by strained crystal structure which may also have controlled the emplacement of the radiating inclusions.

no microchlorite. In cases where both clay and overgrowths of quartz are present, the overgrowths appear to postdate the clay (Fig. 6). Certain clay clots may be altered grains of feldspar. Iron oxide minerals are very common in the interstices between grains and in fractures within the grains; emplacement predates the quartz overgrowths. Some specimens contain nests of authigenic titanium-bearing accessory minerals, principally leucoxene. The occurrence and composition of leucoxene as an authigenic mineral in sedimentary rocks is discussed by TEODOROVICH (1958).

Trains of inclusions traverse several specimens, cutting across as well as around the grains. These have proved to be veinlets of quartz, containing impurities, which have filled small fractures (see Fig. 8 illustrating this feature in older Eocambrian quartzite from Tanafjord). The quartz in the veinlets has crystallized in optical continuity with adjacent quartz grains. TUTTLE (1949) discusses the various theories about the emplacement of inclusion planes.

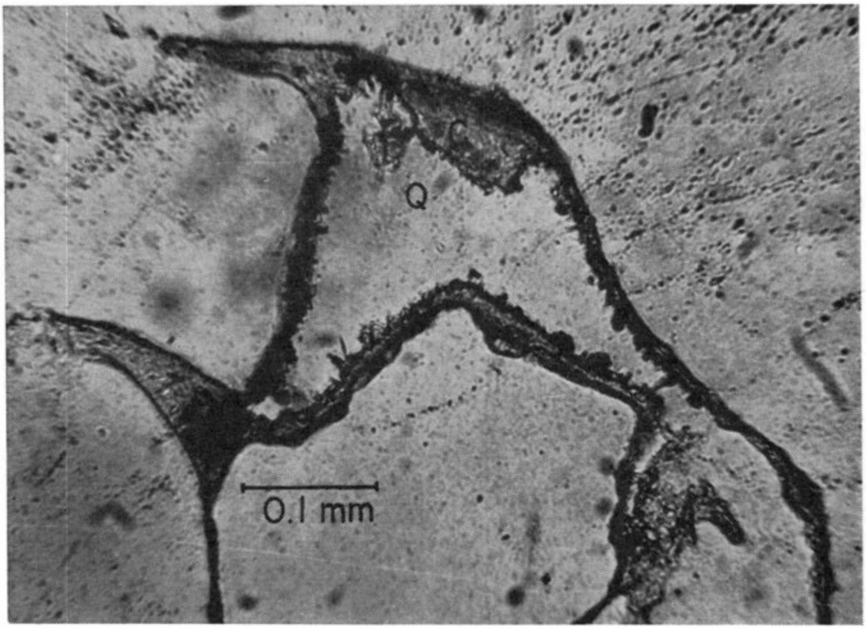

Fig. 6. Authigenic clay and quartz cement in Moelv sandstone.

Moelv tillite.

At the EKR and MOD localities, the Moelv tillite is an extremely badly sorted brown pebbly mudstone containing boulders up to half a meter in diameter (Fig. 7). The quartz ranges from rounded in large grains to subangular and angular in small grains, with normal to undulose extinction. Inclusion planes are common. Metaquartz is present, along with rare pieces of vein quartz (comb structure). The microcline is quite fresh; the grains are rounded to subangular and angular, commonly with irregular boundaries. The matrix consists of clay, often iron-stained, and finely comminuted quartz, feldspar, and megamicas.

Vardal sparagmite.

The Vardal sparagmite at the MOE and MOD localities is a medium to coarse-grained, very poorly sorted, gray subgraywacke. The quartz grains are subround and subangular with somewhat irregular boundaries and undulose extinction. Meta-quartz is common, and a few

Fig. 7. Outcrop of Moelv tillite at Modalen.

grains have been granulated. Planes of inclusions are common in the quartz, but do not appear to transgress grain boundaries. The microcline grains are round to subround with irregular boundaries. They are virtually unweathered. Distortion of lamellae is a common feature, and a few grains have been smashed. Specimens containing granulated quartz and smashed microcline may have been taken from zones close to minor faults.

Ringsaker quartzite.

At the STE locality the Ringsaker is a coarse-grained, very well sorted gray quartzite. The grains appear to have been round and subround. Extinction is normal to slightly undulose, and extends to the overgrowths. Cementation took place by the formation of quartz overgrowths, which postdate the small amount of iron oxide present. The formation of the overgrowths was accompanied by microstylolitic intergrowths. Subsequent shearing is marked by narrow zones of granulation, and by healed fractures.

Older Eocambrian.

At locality POR the older Eocambrian consists of dolomite, shale, and fine-grained or medium-grained poorly sorted to well sorted gray quartzite. The quartz grains are round to subangular with undulose extinction. Metaquartz is common and vein quartz is present in small amounts. The rock is completely cemented by quartz overgrowths, which also have undulose extinction. The overgrowths predate the major portion of any clay that may be present. Microcline occurs in small quantities; it is fresh and rounded to subround. Accessory minerals, especially zoisite, are present in unusual numbers in some specimens, and may be the result of metasomatism rather than sedimentary concentration.

At locality TAN the older Eocambrian consists of shale and medium-grained to coarse-grained well sorted light gray and maroon subgraywacke. The quartz grains are round and subround, with undulose extinction. Quartz overgrowths with undulose extinction cement the rock. The overgrowths postdate a small quantity of clay that coats many of the grains, and also postdates the iron-rich and manganese-rich coatings that are found near Torhop. Rounded grains of fresh microcline occur in some of the specimens; only a few weathered grains are present. Trains of inclusions commonly transgress grain boundaries (Fig. 8).

Younger Eocambrian tillites.

The lower and upper tillites at locality TAN are extremely poorly sorted bluish- or greenish-gray pebbly mudstones containing pebbles of many different kinds of rocks. Some of the pebbles are quite similar to the tillite itself and may indicate that erosion of till was taking place at the same time as its deposition in a nearby area. The quartz grains range from angular to round. Overgrowths on a few grains may be inherited from previous sedimentary rocks. Feldspar is rare. The matrix consists of clay minerals and finely comminuted quartz, feldspar, and megamicas. Clay rims surround the feldspar grains. A large quantity of secondary calcite is present in the lower tillite. The platy clay minerals are parallel to adjacent grain boundaries, but show an overall tendency toward parallelism when viewed with the gypsum plate and crossed nicols (SITLER and CHAPMAN, 1955).

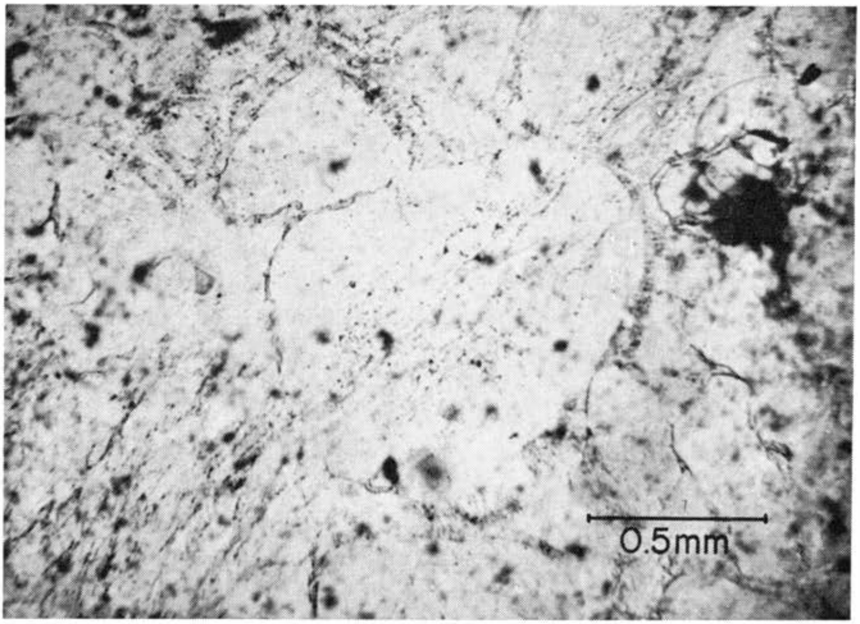

Fig. 8. Inclusion trains transgressing quartz grains in older Eocambrian quartzite.

Younger Eocambrian quartzite.

The younger Eocambrian quartzite between Vestertanafjord and Ifjord ranges from a green siltstone to red or white fine-grained well sorted subgraywacke. The quartz grains are round and subround, with undulose extinction. Cementation took place by the formation of quartz overgrowths, which also have undulose extinction. The overgrowths postdate limonitic accretions on the grains, but appear to predate most of the clay minerals. Feldspar is rare. When present, matrix consists of clay minerals together with finely comminuted quartz and megamicas. Shear zones are common, and one specimen contains veins filled with clay minerals and chorite.

Composition.

Operational definitions of compositional categories.

In cases where a large number of analyses must be made, it is usually not feasible to make mineral identifications which are in exact agreement with the strict mineralogical or chemical definitions of the minerals. It is therefore necessary to set up operational definitions of compositional categories which can be quickly and reliably identified with the microscope (GRIFFITHS, 1960). The following definitions are based on a preliminary examination of the thin-sections of Eocambrian rocks from Norway. In all cases involving monomineralic categories, the optical characteristics used in the investigation are those given by ROGERS and KERR (1942).

Quartz — includes all varieties (normal, undulose, patchy, granulated, etc.) except recognizable fragments of detrital orthoquartzite.

Microcline — feldspar with characteristic grid twinning or spindle twinning.

Untwinned feldspar — fragments recognizable as feldspar due to cleavage, characteristic weathering pattern, etc., but *without visible twinning*. A large number of such fragments may be orthoclase, but undoubtedly a large number are also pieces of microcline or plagioclase.

Matrix — fragments less than 20 microns in maximum dimension, regardless of composition.

Other: ***Plagioclase*** — recognizable albite twinning.

Biotite — mica, dichroic in shades of green or brown.

Muscovite — mica with high interference colors when cut across the cleavage.

Chlorite — green mica with low interference color .

Calcite cement — characteristic high interference color, cleavage, and twinning; may at times be dolomitic or ankeritic; usually sparry.

Quartz cement — overgrowths and interstitial quartz (probably also overgrowths).

Limonite cement — brown to red-brown and orange grain coatings and interstitial filling; isolated grains are not included in this category.

Accessories — mostly minerals with high relief that are usually studied as "heavy minerals"; common accessories are zircon, rutile, tourmaline, epidote, garnet etc.

Rock fragments — recognizable fragments of pre-existing sedimentary, igneous, or metamorphic rocks. In practice, coarse-grained fragments of granitic or gneissic rocks were counted by their constituents, not as rock fragments, because in the sparagmites, as in most rocks, the difference between such a rock fragment and a grain of quartz or feldspar the same size is purely fortuitous.

Opaque — any grain not penetrated by light in thin-section; commonly magnetite, ilmenite, leucoxene, pyrite and limonite.

Microperthite — characteristic microperthitic intergrowths.

Etc. — anything else, including myrmekite and collophane.

Results of the point-count.

The results of point-counting 49 samples from the Eocambrian of Norway are summarized in Table 3. In addition, one sample of lower Cambrian from locality STE is included for comparison with the underlying Ringsaker quartzite. Figure 9 shows the results in graphical form, using a triangular diagram slightly modified after DAPPLES, KRUMBEIN, and SLOSS (1953). In this diagram the percentages have been calculated by setting quartz + feldspar + matrix + micas = 100%. The Eocambrian rocks range in composition from pure quartzite (STE—1ri) to graywacke (BIS—3bi) and somewhat impure arkose (RIN—5m). The average composition of each formation has been plotted, and the rock names have been assigned on the basis of these averages. The tendency of the Mjøsa sparagmites to occur in a closely-spaced group near the junction of the graywacke-arkose-subgraywacke categories indicates their basic similarity, and should induce a great deal of caution n the use of the rock names — the formations do not differ among themselves as much as the rock names might suggest, and this fact provides a certain justification for the use of an inclusive term such as "sparagmite" to characterize them.

Several distinguishing features of the triangular diagram are notable: a) with only two exceptions, the Mjøsa sparagmites contain more than 10% feldspar, b) the Eocambrian samples from Finnmark contain less than 10% feldspar, and c) the younger Eocambrian tillites contain more than 65% matrix while all the other tillite samples contain less than 40% matrix.

Statistical analysis of composition.

It would be absurd to expect identical results from repeated point-counts of the same samples. Such results never occur even in successive trials by a single experimenter, and when two or more operators are

TABLE

Compo

Percentages based on 500-W

Sample	Quartz	Micro-cline	Un-twinned Feldspar	Plagio-clase	Matrix	Quartz Cement	Calcite Cement
BIS—1bi	55	19	9	1	14	1	
BIS—2bi	51	21	7		16		
BIS—3bi	18	3	1		72		2
BIS—4bi	48	31	7	1	9	Tr	2
BIS—5bi	49	32	4	Tr	6	1	4
BIS—6bi	49	16	8	2	20	1	1
BIS—7bi	44	26	11	1	15	Tr	Tr
BRØ—1br	29	15	19	3	25		
BRØ—2br	35	22	14	4	21	Tr	
BRØ—3br	57	9	5	Tr	29		
EKR—1mt	43	10	7	Tr	39		
EKR—2mt	40	16	4	Tr	39		Tr
KAR—1t	65	1	1	1	30	1	
KAR—2yec......	64	5	1		17	4	9
MOD—2vl	62	14	4	Tr	20		
MOD—4mt	54	11	5	1	28		
MOE—1m	57	22	6		14	Tr	
MOE—2vl	68	18	3		10	1	
NOA—1m	52	25	6	1	15	Tr	
NOR—1bi**	83	10	1		6		
NOR—2bi	53	19	6	Tr	17		
POR—1oec	41	2	Tr	1		31	
POR—3oec	69				17	8	6
POR—4oec	82	2	1		9	6	
RIN—1m	61	15	7	Tr	16	1	
RIN—2m	52	20	6	Tr	20	1	
RIN—3m	58	12	7	Tr	21	1	
RIN—4m	56	16	8	Tr	15	3	
RIN—5m	51	27	7	Tr	13	1	
RIN—6m	56	24	8		10	1	
RIN—7m**	80	8	4		7		
RIN—8m	53	22	4	Tr	18		
RIN—10m	55	25	4	Tr	14	1	Tr
RIN—11m	54	24	7	2	10	2	
RIN—12m	56	23	6	2	10	2	
RIN—13m	58	25	4	Tr	11		
RIN—14m	54	25	5	1	14		
STE—1ri	77					22	
STE—21c	60				9	17	
TAN—1oec	74		Tr		3	23	
TAN—21t	26	2	Tr		72		Tr
TAN—4oec	72	5	1		Tr	22	
TAN—5oec	79	1	2		Tr	4	
TAN—61t	24	2	1	1	56	Tr	15
TAN—9ut	30	1	1		66	Tr	
TAN—10Cyec ...	56		Tr		24	18	
TAN—10Fyec....	19	1	Tr		80		
TAN—11Cyec ...	71	Tr			9	20	
TAN—11Fyec....	70				12	18	
TAN—12ut	13	1	1	Tr	82		

* Tr = less than 1%: VRF = volcanic rock fragment: SRF = sedimentary rock fragment.

** Conglomerate.

3

*sition.**

counts per thin-section							
Limonite Cement	Biotite	Chlorite	Musco-vite	Micro-perthite	Accessory Minerals	Opaque	Etcetera
	1			Tr	Tr	Tr	Tr (myrmekite)
	2	Tr		1	1	1	
	3	Tr	Tr		1		
				2	Tr	Tr	
	Tr			2			2 (VRF)
	2			Tr	1	Tr	
	1	1		Tr	1	Tr	
8	1		Tr	Tr			Tr (SRF)
	Tr	Tr	Tr	1	1	2	
		Tr	Tr		Tr	Tr	
					Tr	1	Tr (myrmekite)
	Tr			Tr	Tr	1	
		1			Tr	Tr	Tr (VFR)
	Tr					Tr	
		Tr		Tr	Tr	Tr	
				1	Tr	Tr	Tr (VRF)
						1	
	Tr	Tr		1	Tr		
	Tr					Tr	
	1	4		Tr			
	Tr		18		7		
			Tr		Tr		
					Tr		Tr (VRF)
						Tr	
			Tr	Tr	Tr	1	
				Tr		1	
				1		1	
						1	
	Tr		Tr		Tr	1	
				1	Tr	Tr	
Tr		Tr	Tr	1	1	1	
Tr					Tr	1	Tr (SRF)
				1		Tr	
			Tr	1	Tr	Tr	
	1			1	Tr	Tr	
				1	Tr	Tr	
						1	
						14	
						Tr	
	Tr						
					Tr	Tr	
14							Tr (chert)
	Tr	1				Tr	
	Tr					1	1 (SRF)
					Tr	2	
						Tr	
			Tr			Tr	
		Tr					
	1	Tr	Tr		Tr	1	1 (SRF)

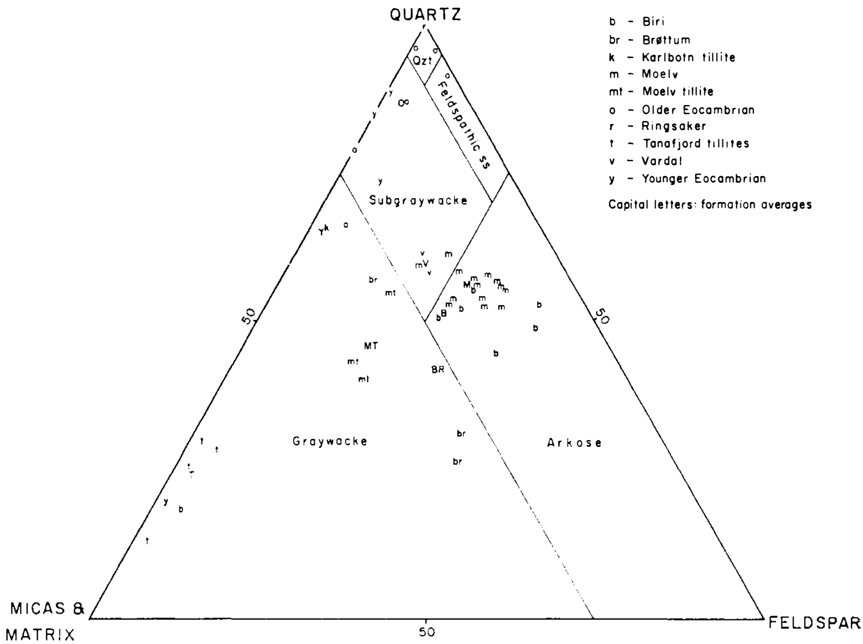

Fig. 9. Triangular diagram showing composition of samples.

involved the differences are striking (GRIFFITHS and ROSENFELD, 1954). It is therefore desirable to make use of some rational basis for evaluating the differences among experimental results: do the differences actually exist, or are they merely the result of natural variability inherent in the experiment? In the present instance we wish to know whether there are real differences in composition among the Eocambrian formations. Certain simple and well-known statistical techniques provide the rational basis for making the decisions.

The variable selected for testing is quartz-counts-per-traverse, which is proportional to the quartz content of the sample (it will be recalled that the point-counting was carried out by counting ten traverses of fifty contiguous points in each thin-section). This variable provides a large number of occurrences, and quartz is relatively easy to identify with consistent dependability, hence it is a convenient and reliable quantity to test. This does not imply that one or more of the other components would not provide suitable quantities for comparison, and indeed in an exhaustive preliminary analysis all of the quantities would probably be analyzed to find the one that is most diagnostic for the type of analysis to be carried out. For example, feldspar-counts-per-traverse is compared with quartz-counts-per-traverse in an analysis dealing with composition and grain size in a later section of this paper.

For each statistical analysis, the hypothesis to be tested is stated in a form known as the "null hypothesis". The results of the test are reported in terms of the probabilities of obtaining certain values for the statistical quantities computed. These probabilities are given in tables in statistics texts and books of mathematical tables. The following statement holds good for all the cases considered in this study: if the value of the probability is less than 0.05, the null hypothesis is rejected, with a chance equal to or less than 1 in 20 that the rejection is an error. If the null hypothesis were true, this result ($p \leq 0.05$) would occur by chance alone in one case or less out of twenty. This result is sufficiently unusual to cast doubt on the validity of the null hypothesis, so the hypothesis is rejected as being untrue. However, this could be the one case in twenty, therefore there is at most a chance of 1 in 20 that the rejection of the null hypothesis is an error. In the present case, this is considered to be an acceptable level of risk. If the probability exceeds 0.05, then the null hypothesis is not rejected, and no conclusions are drawn. Note that "not rejected" does not mean "accepted". It is simply analogous to the well-known Scottish verdict of "not proven". The explanation of the reason for the distinction between "not rejected" and "accepted" is far beyond the scope of this paper, and can be found in any standard textbook on mathematical statistics such as the one by HOEL (1954).

The following terms and formulas will be used in subsequent paragraphs:

mean — the first moment of the frequency distribution.

$$\overline{X} = \frac{\sum_{i=1}^{n} x_i}{n}$$

variance — the second moment about the mean of the frequency distribution.

$$s^2 = \frac{1}{n-1} \sum_{i=1}^{n} (x_i - \bar{x})^2 = \frac{1}{n-1} \left[\sum_{i=1}^{n} x^2_i - \frac{\left(\sum_{i=1}^{n} x_i\right)^2}{n} \right]$$

The latter part of the formula is a convenient computational form.

standard deviation — the square root of the variance.

$F = \frac{S_L^2}{S_S^2}$ where L stands for "larger" and S for "smaller".

$$t = \left| \bar{x}_1 - \bar{x}_2 \right| \sqrt{\frac{(n_1 + n_2 - 2)(n_1 n_2)}{(n_1 s^2_1 + n_2 s^2_2)(n_1 + n_2)}}$$

degrees of freedom = df = one less than the number of observations used in computing the quantity in question = $n - 1$.

An asterisk (*) means that the result is significant, ($p \leq 0.05$). and the null hypothesis is rejected.

NS means that the result is not significant, ($p > 0.05$), and the null hypothesis is not rejected.

The differences between formation means of quartz-counts-per-traverse can be tested with Student's "t" test (Moroney, 1956, p. 227 and following). One of the assumptions underlying the use of this procedure is that the samples (in this case traverses) are drawn from populations with identical variances, so it is necessary to test for equivalence of variances by using Snedecor's "F" test (Moroney, 1956, p. 233 and following) before proceding with "t". The null hypothesis for the "F" test is that both sets of samples were drawn from populations with identical variance, and any difference between the sample variances is due to chance. If "F" is significant, the variances of the sample populations are probably different, and the "t" test can not legitimately be made. If "F" is not significant, then (at the level of rejection that has been selected) there is no reason for differentiating between the sample populations on the basis of variance, and the "t" test can be made. The null hypothesis for the "t" test is that both sets of samples were drawn from populations with identical means, and any difference between the sample means is due to chance. In the following series of tests, tabulated in Table 4, each formation is compared to adjacent or similar formations simply to see where real differences in quartz-counts-per-traverse exist.

TABLE 4.

"F" and "t" tests: quartz-counts-per-traverse.

Formations compared	F	t
Biri .... Brøttum................	1.14 NS	1.25 NS
Biri .... Moelv	1.67*	
Brøttum................ Moelv	1.47 NS	6.61*
Moelv .... Moelv tillite.............	1.54 NS	4.80*
Moelv .... Vardal	1.37 NS	2.79*
Moelv tillite............. Lower tillite	2.55*	
Moelv tillite............. Upper tillite	1.12 NS	3.55*
Moelv tillite............. Karlbotn tillite	1.43 NS	5.49*
Moelv tillite............. Vardal	1.12 NS	6.56*
Lower tillite .... Upper tillite	2.85*	
Lower tillite .... Karlbotn tillite	1.78 NS	14.53*
Upper tillite .... Karlbotn tillite	1.60 NS	11.40*

* Significant at 5% level or less.
NS — not significant.

TABLE 5.

Analysis of variance: quartz-counts-per-traverse.

Formation	Source	Degrees of Freedom	Sum of Squares	Mean Square	F
Design	Thin-sections (m)	m − 1	$\sum_1^m \left(\sum_1^n x\right)^2 \Big/ n - CT$	$SS_m / m-1$	MS_m / MS_n
	Traverses (n)	m(n − 1)	$SS_{total} - SS_m$	$SS_n / m(n-1)$	
	Total	mn − 1	$\sum_1^{mn} x^2 - CT$		
	Correction term = CT = $\left(\sum_1^{mn} x\right)^2 \Big/ mn$				
Biri	Thin-sections	6	2274	379.00	12.94*
	Traverses	63	1846	29.30	
	Total	69	4120		
	Correction term = 35034				
Brøttum	Thin-sections	2	1098	549.00	35.37*
	Traverses	27	419	15.52	
	Total	29	1517		
	Correction term = 12161				
Moelv	Thin-sections	14	1614	115.29	4.20*
	Traverses	135	3702	27.42	
	Total	149	5316		
	Correction term = 120757				

(*continued on next page.*)

This series of tests indicates that there are real differences in quartz-counts-per-traverse among the formations, with a single exception (Biri sandstone has not been shown to differ significantly from Brøttum sandstone in quartz-counts-per-traverse). In cases where "t" is significant, the difference probably reflects a reciprocal relationship between quartz grains and matrix. In the cases involving the Karlbotn tillite, the difference may also be increased due to the fact that almost

TABLE 5 (continued).

Formation	Source	Degrees of Freedom	Sum of Squares	Mean Square	F
Moelv Tillite	Thin-sections	2	294	147.00	10.47*
	Traverses	27	379	14.04	
	Total	29	673		
	Correction term = 15550				
Upper Tillite	Thin-sections	1	361	361.00	49.25*
	Traverses	18	132	7.33	
	Total	19	493		
	Correction term = 2226				
Lower Tillite	Thin-sections	1	2	2.00	< 1 NS
	Traverses	18	171	9.50	
	Total	19	173		
	Correction term = 3150				

* Significant at 5% level or less.
NS — not significant.

all of the grains in this rock are quartz, in contrast to the other tillites which contain feldspar and micas in appreciable amounts.

The consistency of quartz content in samples of each formation can be investigated with a technique known as "analysis of variance", usually called simply ANOV (Moroney, 1956, p. 371 and following). ANOV is a test which allows the total sample variability to be apportioned to the various sources of variability in the experiment. In this test a quantity called the "mean square" is computed. The mean square can be considered as the variance associated with a given source variability. Ratios of mean squares are therefore equivalent to "F", and tables of "F" are used to test the significance of differences between mean squares in ANOV. The use of ANOV in geological experiments has been described by Krumbein and Miller (1953). In the present case, we wish to find out whether the variability in quartz-counts-per-traverse among thin-sections in a formation is significantly greater than the variability among traverses within thin-sections. If the variability among traverses within thin-sections were greater than the variability among thin-sections, it would indicate a) the need for caution in ascribing geological significance to the variability among thin-sections, and b) the need for more traverses within each thin-section in order to form a more stable estimate of the composition of each sample. The ANOV is carried out in Table 5.

The results are fairly consistent; in all but one case they indicate greater variability among the thin-sections of a formation than among the traverses within thin-sections. The variability of quartz-counts-per-traverse in the younger Eocambrian lower tillite has not been shown to differ significantly between thin-sections and traverses within thin-sections. The results suggest the use of a greater number of samples in each formation in order to provide a greater measure of control over the variability of composition within the formations. This would not necessarily result in an increase in the labor of point-counting, since it has also been demonstrated that the variability within thin-sections is relatively over-controlled (except in the case of the lower tillite), and reduction of the number of points counted per thin-section to 200 or even 100 would probably not seriously affect the consistency of the estimates of composition.

Grain size in thin-section.

Implications of the method.

Exclusive use of the petrographic microscope in the examination of thin-sections confined the study to grains ranging in size from fine silt to fine gravel. It must be kept in mind, therefore, that the statistical parameters and size distributions considered in the following paragraphs apply only to grain sizes between 6 microns and 8 mm.

The method, previously described, of choosing the grains to be measured is analogous to choosing the grains to be counted in point-counting. This implies that the results constitute a volumetric estimate of grain size — so much volume of grains of a given size range, rather than so many grains of a given size range. Nevertheless, the method does not afford a directly proportional comparison with data obtained from sieving, as demonstrated by ROSENFELD, JACOBSEN, and FERM (1953).

A large volume of literature concerning the measurement of grain size in thin-section has accumulated (KRUMBEIN, 1935; CHAYES, 1935

TABLE 6.

mm	*phi*	*Wentworth class*
8	− 3	fine gravel
4	− 2	granules
2	− 1	very coarse sand
1	0	coarse sand
1/2	1	medium sand
1/4	2	fine sand
1/8	3	very fine sand
1/16	4	coarse silt
1/32	5	medium silt
1/64	6	fine silt
1/128	7	very fine silt
1/256	8	

1951; GREENMAN, 1951a, 1951b; ROSENFELD, JACOBSEN, and FERM, 1953). Attempts to find an unbiased correction factor for converting grain size in thin-section to actual grain size have not been an unqualified success. This should occasion no doubts as to the usefulness of the thin-section method. CHAYES (1951, p. 275) says, "The observed distribution of x contains just as much information as that of kx, and in dealing with it, one is much less likely to overestimate the importance of small differences." GREENMAN (1951a, p. 274) points out the salient factor: "At the present stage of the science of sedimentology every technique of size analysis requires the setting-up of an arbitrary definition of size to fit the procedure used and the computations based on such procedure. The thin-section method is no more guilty in this respect than is any other method."

Units of measurement.

The results of the grain size measurements are reported here in millimeters, and also in phi units. The phi scale was originated and formalized by KRUMBEIN (1936).

$$\Phi = -\log_2 \mathrm{mm}$$

Lognormal size distributions of sedimentary particles are commonly observed (KRUMBEIN, 1938). Recognition of this factor is implicit in the use of exponential grade-size classes in classifications such as WENTWORTH'S (1922). Table 6 shows the simple correspondence between the phi scale and Wentworth's scale.

TABLE 7.

Grain size parameters.

Based on measurement of 100 grains in each thin section.*

Sample	$\bar{x}_{mm}$	Range (mm) Smallest	Range (mm) Largest	s_{mm}	$\bar{x}_{\Phi}$	Range (Φ) Smallest	Range (Φ) Largest	s_{Φ}
BIS—1bi	0.43	0.01	2.92	0.48	1.93	6.64	— 1.61	1.53
BIS—2bi	0.41	0.02	3.02	0.45	1.91	5.32	— 1.59	1.38
BIS—3bi	0.05	0.005	0.20	0.04	4.91	7.64	2.28	1.33
BIS—4bi	1.71	0.01	6.11	1.70	0.35	6.64	— 2.16	2.21
BIS—5bi	1.42	0.005	5.98	1.66	0.97	7.64	— 2.58	2.42
BIS—6bi	0.34	0.005	1.32	0.30	2.29	7.64	— 0.40	1.67
BIS—7bi	0.47	0.005	3.14	0.50	1.93	7.64	— 1.65	1.78
BRØ—1br	0.37	0.01	1.32	0.31	2.03	6.64	— 0.40	1.48
BRØ—2br	0.56	0.03	2.80	0.50	1.35	5.05	— 1.49	1.27
BRØ—3br	0.32	0.005	0.98	0.23	2.11	7.64	0.02	1.41
EKR—1mt ...	0.34	0.005	1.26	0.35	2.27	7.64	— 0.33	1.57
EKR—2mt ...	0.44	0.01	5.56	0.73	2.30	6.64	— 2.48	1.88
KAR—1t	0.42	0.005	5.38	0.65	2.21	7.64	— 2.43	1.92
KAR—2yec ..	0.08	0.01	0.16	0.04	3.79	6.64	2.64	0.93
MOD—2vl	0.48	0.06	1.92	0.27	1.27	3.94	— 0.94	0.83
MOD—4mt ...	0.37	0.01	2.08	0.38	2.05	6.64	— 1.06	1.44
MOE—1m	1.29	0.04	4.42	0.75	— 0.07	4.64	— 2.14	1.00
MOE—2vl	0.90	0.01	3.74	0.62	0.49	6.64	— 1.91	1.18
NOA—1m	0.73	0.06	3.74	0.62	0.87	4.05	— 1.91	1.02
NOR—2bi	0.31	0.005	0.78	0.16	2.09	7.64	0.36	1.38
POR—3oec ...	0.14	0.005	0.31	0.08	3.20	7.64	1.69	1.17
POR—4oec ...	0.43	0.02	0.98	0.21	1.45	5.32	0.03	0.88
RIN—1m	0.87	0.04	4.62	0.67	0.55	4.83	— 2.21	1.12
RIN—2m	0.94	0.06	4.04	0.79	0.56	4.05	— 2.02	1.20
RIN—3m	0.33	0.05	0.80	0.17	1.78	4.32	0.31	0.84
RIN—4m	0.63	0.05	1.56	0.27	0.84	4.32	— 0.64	0.86
RIN—5m	0.85	0.01	3.54	0.64	0.66	6.64	— 1.83	1.29
RIN—6m	0.99	0.02	3.50	0.89	0.59	5.32	— 1.81	1.40
RIN—8m	0.74	0.005	3.50	0.63	1.00	7.64	— 1.81	1.43
RIN—10m ...	0.83	0.08	4.80	0.66	0.55	3.55	— 2.26	0.96
RIN—11m ...	0.98	0.20	4.72	0.66	0.29	2.28	— 2.24	0.86
RIN—12m ...	1.05	0.18	4.02	0.75	0.29	2.43	— 2.01	1.03
RIN—13m ...	0.87	0.04	3.20	0.65	0.57	4.64	— 1.86	1.14
RIN—14m ...	0.88	0.04	3.26	0.70	0.65	4.83	— 1.71	1.22
STE—1ri	0.77	0.22	1.86	0.32	0.52	2.21	— 0.90	0.64
TAN—1oec ...	0.61	0.20	1.28	0.26	0.85	2.35	— 0.36	0.67

TABLE 7 (continued).

Grain size parameters.

Based on measurement of 100 grains in each thin section.*

Sample	$\bar{x}_{mm}$	Range (mm)		s_{mm}	$\bar{x}_{\Phi}$	Range (Φ)		s_{Φ}
		Smallest	Largest			Smallest	Largest	
TAN—21t	0.11	0.005	0.61	0.15	4.49	7.64	0.71	1.99
TAN—4oec ...	0.23	0.06	0.50	0.08	2.17	4.05	1.00	0.59
TAN—5oec ...	0.31	0.10	0.60	0.10	1.75	3.39	0.72	0.48
TAN—61t	0.19	0.005	3.94	0.45	3.67	7.64	— 1.98	1.80
TAN—9ut	0.17	0.01	1.22	0.23	3.79	6.64	— 0.29	2.03
TAN—10Cyec	0.08	0.02	0.24	0.04	3.73	5.64	2.02	0.74
TAN—10Fyec	0.02	0.005	0.10	0.02	5.71	7.64	3.39	1.01
TAN—11Cyec	0.10	0.03	0.18	0.03	3.41	5.05	2.43	0.58
TAN—11Fyec	0.09	0.02	0.20	0.04	3.65	5.32	2.35	0.71
TAN—12ut ...	0.08	0.005	1.29	0.15	4.69	7.64	— 0.37	1.44

* Measurements confined to range between 0.005 mm and 8.00 mm.

TABLE 8.

Grain size mode and mean range.

Formation	Midpoint, Modal 0.5Φ class	Mean Range, mm	Mean Range, Φ
Biri ss	2.25	2.92	8.68
Brøttum ss	1.75	1.68	7.07
Moelv ss	0.75	3.49	6.26
Moelv tillite	1.25	2.96	8.26
Ringsaker ss	0.25	1.64	3.11
Vardal ss	0.75	2.80	6.72
Older Eocambrian ss...............	1.75	0.66	3.95
Younger Eocambrian ss	3.25	0.16	3.49
Tanafjord tillite	5.25	1.76	7.87

The measurements were originally made in units corresponding to the grid-insert in the microscope ocular, and these were converted directly to millimeters, both scales being linear and therefore directly proportional. The mean and standard deviation for each sample were calculated in millimeters with the aid of the formulas given in the

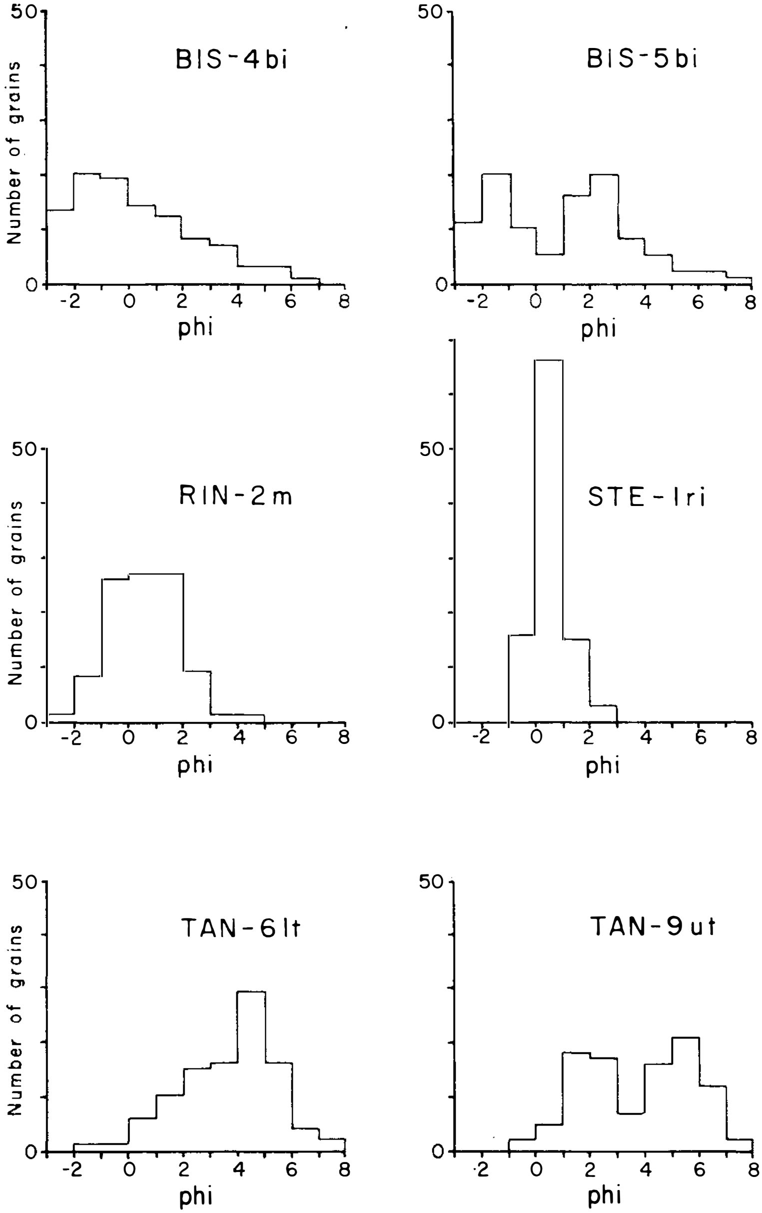

Fig. 10. Size-frequency histograms illustrating the wide range in grain-size distributions among the samples.

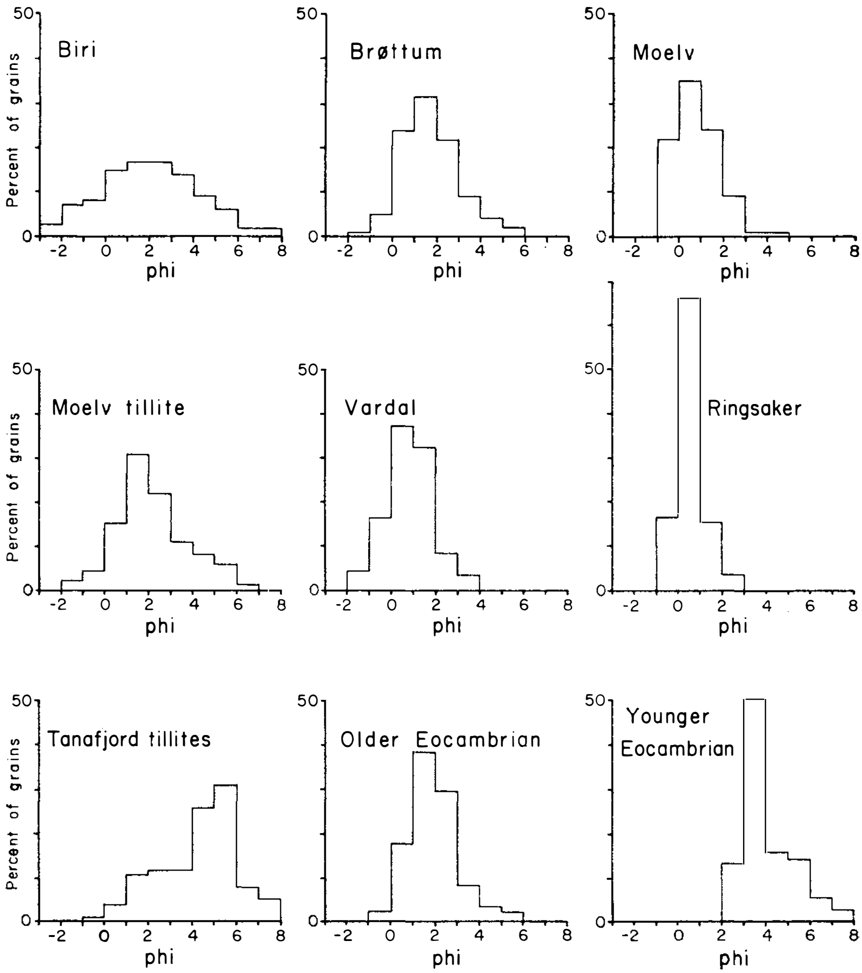

Fig. 11. Cumulative size-frequency histograms for the various formations.

section on composition. To carry out the same calculations in phi units would mean the conversion of each measurement to units of phi. Although tables exist for this conversion (PAGE, 1955; GRIFFITHS and MCINTYRE, 1958), the large number of measurements in each thin-section made it possible to use a tabulation method described in all textbooks on statistics (MORONEY, 1956, p. 66 and following). Calculation of the mean and standard deviation in phi units was therefore carried out by a tabulation method, using classes of width 0.5Φ from — 3Φ to 8Φ.

Table 7 shows the mean, standard deviation, and range of grain size in millimeters and in phi units for each sample. The mode (phi class in which the greatest number of measurements occur) and mean range of grain size for each formation are given in Table 8. Individual samples showed a wide range of distributions, as illustrated in Figure 10, but Figure 11 shows that the cumulative formation distributions were, as might be expected, not so widely divergent.

TABLE 9.

"F" and "t" tests; grain size in thin-section.

Formations compared	F	t
Biri .... Brøttum	4.43*	
Biri .... Moelv	3.12*	
Brøttum .... Moelv	1.42*	
Moelv .... Moelv tillite	1.87*	
Moelv .... Vardal	1.21 NS	13.26*
Lower tillite .... Upper tillite	1.15 NS	0.80 NS
Moelv tillite .... Tanafjord tillites	1.31*	
Moelv tillite .... Karlbotn tillite	1.37*	
Moelv tillite .... Vardal	2.26*	
Tanafjord tillites .... Karlbotn tillite	1.04 NS	2.88*

* Significant at 5% level or less.
NS — not significant.

Statistical analysis of grain size.

In the analysis of grain size data, the "F" and "t" tests were used to discover which formations differ significantly in grain size. All but two of the combinations have significant variance ratios (implying different variabilities in grain size), and hence the "t" test could be applied only in two cases. Of these, the younger Eocambrian lower tillite was not shown to differ from the upper tillite, so they are combined in all subsequent calculations. The younger Eocambrian tillite (lower and upper tillites combined) from Tanafjord can then be shown to differ significantly in grain size from the Karlbotn tillite. The results of the "F" and "t" tests are shown in Table 9.

In its grain size variability the Brøttum sparagmite is more like the tillites than the other sparagmites, but this comparison is not really valid because the variability of the Brøttum arises through the alternation of thin beds of different grain size, whereas the variability of the tillites arises from a wide range of grain sizes in fairly homogeneous rock bodies. This difference between the Brøttum and the tillites can be investigated by using analysis of variance. The calculations are made in phi units. It was previously mentioned that individual measurements were not converted to phi units; this would ordinarily make it impossible to calculate the necessary sums of squares in the ANOV investigation. However, the experimental design is so simple in this case that it was possible to compute the necessary sums of squares by utilizing the phi means and standard deviations calculated by the tabulation method, together with the formulas for the mean and standard deviation, according to the following equations:

$$\sum_1^n x = n\bar{x} \quad \ldots\ldots\ldots\ldots\ldots\ldots \text{derived from } \bar{x} = \frac{\sum_1^n x}{n}$$

$$\sum_1^n x^2 = (n-1)s^2 + n\bar{x}^2 \quad \ldots \text{ derived from } s^2 = \frac{1}{n-1}\left[\sum_1^n x^2 - \frac{\left(\sum_1^n x\right)^2}{n}\right]$$

The ANOV is shown in Table 10. The results lead to the following conclusions:

1) There is significantly greater variability in grain size among samples than among grains within samples in the Brøttum, as expected.

TABLE 10.

Analysis of variance: grain size in thin-section (phi units).

Formation	Source	Degrees of Fredom	Sum of Squares	Mean Square	F
Design	Thin-sections (m)	m − 1	$\sum_{1}^{m}\left(\sum_{1}^{n} x\right)^2 / n - CT$	$SS_m / m - 1$	MS_m/MS_n
	Grains (n)	m(n − 1)	$SS_{total} - SS_m$	$SS_n/m(n-1)$	
	Total	mn − 1	$\sum_{1}^{mn} x^2 - CT$		
	Correction term = CT = $\left(\sum_{1}^{mn} x\right)^2 / mn$				
Brøttum	Thin-sections	2	34.88	17.44	9.04*
	Grains	297	573.35	1.93	
	Total	299	608.23		
	Correction term = 1004.67				
Moelv Tillite	Thin-sections	2	3.73	1.86	< 1 NS
	Grains	297	799.22	2.69	
	Total	299	802.95		
	Corretion term =				
Tana-fjord Tillites	Thin-sections	3	76.68	25.56	7.26*
	Grains	396	1326.07	3.52	
	Total	399	1402.75		
	Correction term = 6922.24				

* Significant at 5% level or less.
NS — not significant.

2) There is no particular reason for assigning more variability to either samples or grains within samples in the Moelv tillite, indicating homogeneity in the distribution of grain sizes throughout the rock even though there is a wide range of grain size.
3) There is significantly greater variability in grain size among samples than among grains within samples in the tillites from Tanafjord.

TABLE 11.

Analysis of variance: grain size in thin-section (phi units), Tanafjord tillites.

Formation	Source	Degrees of Freedom	Sum of Squares	Mean Square	F
Design	Formations (f)	f − 1	$\sum_{1}^{f}\left(\sum_{1}^{mn} x\right)^2 \Big/ mn - CT$	$SS_f/f - 1$	MS_f/MS_n
	Thin-sections (m)	f(m − 1)	$\sum_{1}^{fm}\left(\sum_{1}^{n} x\right)^2 \Big/ n - SS_f - CT$	$SS_u/f(m-1)$	MS_m/MS_n
	Grains (n)	fm(n − 1)	$SS_{total} - SS_f - SS_m$	$SS_n/fm(n-1)$	
	Total	fmn−1	$\sum_{1}^{fmn} x^2 - CT$		
	Correction term = CT = $\left(\sum_{1}^{fmn} x\right)^2 \Big/ fmn$				
Tana-fjord Tillites	Formations	1	2.56	2.56	< 1 NS
	Thin-sections	2	74.12	37.06	11.06*
	Grains	396	1326.07	3.35	
	Total	399	1402.75		
	Correction term = 6922.24				

* Significant at 5% level or less.
NS — not significant.

The latter result was unexpected in the light of the results of the "F" and "t" tests. Examination of the data from the tillites in question leads to the suspicion that the non-significance of the "F" and t"" tests must have been due to compensating differences between samples within formations. ANOV of modified design confirmed this idea (Table 11). Variability is greatest among thin sections, whereas no significant difference has been shown to exist between the upper tillite and the lower tillite.

The difference between the variability of the tillites from Finnmark and the ones from Hedmark may simply be a reflection of the well-known fact that glacial deposits as a whole represent a wide variety of depositional conditions ranging from fluviatile to lacustrine and ice-plastered. On the other hand, the results indicate that texture (as represented by grain size and sorting) does not form a valid basis for the correlation of these tillites, and in fact does indicate that they are significantly different. The contrast between the homogenity of the Moelv tillite and the heterogeneity of the Finnmark tillites suggests strongly that their modes of origin are different, in spite of the similarity of their ages and, superficially, their lack of sorting. Previous work on this type of rock has been conducted by many workers, notably CROWELL (1957), NEWELL (1957), and FLINT, SANDERS, and RODGERS (1960).

Comparison between grain size and composition.

The existence of an association between two unlike quantities such as grain size and mineral composition can be tested with a chi-square contingency table (MORONEY, 1956, p. 246 and following). The table is constructed by placing the observed number of occurrences in the separate categories, and then calculating the "expected value" for each category by multiplying the associated marginal totals and dividing the product by the grand total. The value of chi-square is calculated by taking the sum of the quantities

$$\frac{(\text{observed value} - \text{expected value})^2}{\text{expected value}}$$

and its significance is evaluated by referring to standard tables of chi-square probabilities. In the present case, we are testing for an association between mean grain size in thin-section and quartz or feldspar counts per thin-section. The null hypothesis is that the proportion of thin-sections in the various size categories is the same in all composition categories. The calculations and results are shown in Table 12. The rejection of the null hypotheses implies that the proportion of quartz and feldspar in the rocks increases as mean grain size increases, a conclusion entirely in accord with what might be expected.

Summary of results.

Individual units of the sparagmite formations of the Lake Mjøsa area show a wide range of composition (Table 3), but the majority of the samples cluster near the junction of the graywacke-arkose-sub-

TABLE 12.

*Chi-square contingency tables; mean grain size in thin-section versus quartz- and feldspar-counts-per-traverse.***

		Quartz-counts-per-traverse						Row Totals
		0–129		130–259		260–389		
	0.00	0		6		18		24
	1.99	2.73	2.73	0.00	6.00	0.49	15.27	
$\bar{x}_\Phi$	2.00	1		5		10		16
	3.99	0.37	1.82	0.25	4.00	0.00	10.18	
	4.00	4		0		0		4
	5.99	28.01	0.45	1.00	1.00	2.55	2.55	
Column Totals		5		11		28		44

4 degrees of freedom.
Chi-square = 35.40*.

		Feldspar-counts-per-traverse						Row Totals
		0–79		80–159		160–239		
	0.00	4		13		8		25
	1.99	3.60	10.00	0.90	10.00	1.80	5.00	
$\bar{x}_\Phi$	2.00	10		5		1		16
	3.99	2.02	6.40	0.31	6.40	1.51	3.20	
	4.00	4		0		0		4
	5.99	3.60	1.60	1.60	1.60	0.80	0.80	
Column Totals		18		18		9		45

4 degrees of freedom.
Chi-square = 16.14*.

** In each square the observed values (o) are in the upper left, the expected values (e) are in the lower right, and $(o - e)^2/e$ is in the lower left.

graywacke categories on the triangular diagram (Fig. 9). The sparagmites differ in quartz content, with two exceptions, among themselves. The Biri sandstone and the Brøttum sandstone have not been shown to differ significantly in quartz content (Table 4). Analysis of variance indicates that quartz content is in general more variable among thin-sections from each formation than it is among point-count traverses within thin-sections (Table 5). This means that variability in quartz content is relatively undercontrolled among thin-sections within formations, and is relatively overcontrolled among traverses within thin-sections, suggesting that future work along these lines should utilize more thin-sections per formation and fewer traverses per thin-section.

Grain-size measurements were confined to the interval from fine silt to fine gravel. Grain-size distributions and parameters vary widely among samples (Fig. 10, Table 7), but are relatively consistent for each formation (Fig. 11, Table 8). Most of the Eocambrian formations differ from each other in grain-size variability (Table 9). Statistical comparison of grain-size variability in the Brøttum formation, the Moelv tillite, and the Eocambrian tillites from Finnmark gave the following results (Table 10): 1) The variability in the Brøttum formation arises from the alternation of homogeneous beds of different grain size; 2) the Moelv tillite shows widely variable grain sizes evenly distributed; and 3) the tillites from Tanafjord show homogeneous units which differ significantly from each other but in such a way that no difference has been demonstrated between the upper tillite and the lower tillite. The latter result (3) was unexpected and should be investigated further. Grain size and sorting do not appear to be useful criteria for the correlation of tillites in Norway, although their use has been more successful in other areas (SHEPPS, 1953). The different patterns of grain size variability among the Tanafjord tillites and the Moelv tillite suggest that they may have different modes of origin.

Predictably, the proportions of quartz and feldspar in the rocks studied tend to increase as grain-size increases (Table 12).

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