Depositional History and Geochemical Composition of Lower Palaeozoic Epicontinental Sediments from the Oslo Region

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Two hundred samples of Lower Palaeozoic sediments from the Oslo Region have been analysed for major elements (including P_2O_5 and organic carbon) and 10 trace elements (Ba, Rb, Mn, Sr, Ni, Cr, V, Cu, Zn and S). Mineralogical analyses have been carried out on all samples using X-ray diffraction and thin section examination. These data are used to interpret the depositional and diagenetic history of the about 1000 m thick Cambro–Silurian sequence. Calcite is by far the predominant carbonate mineral in the limestones. In the marly shales, however, dolomite is rather common. Sr content exceeds 1000 p.p.m. in Upper Ordovician impure limestones and marly shales. The black Cambrian alum shale consists of illite, fine grained quartz and diagenic feldspar. Carbon and sulphur contents reach 10–12% and uranium values about 150 p.p.m.

Shales stratigraphically above the Ceratopyge limestone (Arenigan) also contain chlorite in addition to illite and are grey in colour due to low carbon and sulphur contents. Comparison with analyses of geosynclinal sediments from the Trondheim Region indicates that in Cambrian times sediments from the two areas differed strongly in composition. Middle Ordovician to Silurian sediments in the Oslo Region, however, approach the composition of the sediments of the Trondheim Region, with their higher MgO and Na_2O contents suggesting a derivation from the geosynclinal part of the Caledonian geosyncline. The weighted average composition of sediments from the Oslo Region is calculated and compared with the composition of sediments on the Russian platform.

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Introduction

The present paper is an attempt to describe the Lower Palaeozoic sediments of the Oslo Region sedimentologically and geochemically in order to interpret some major aspects of their depositional and diagenetic history. A detailed study of one section of Middle Ordovician rocks from Bygdøy (K. Bjørlykke 1965) convinced the author that a general and much less detailed survey of the whole Cambro–Silurian sequence should be carried out in order to establish the main trends prior to further detailed studies of sections.

The object of the present paper is to present and interpret the data from such a general survey. The first part of this article is an interpretation of the depositional history based on earlier work on the stratigraphy of the sediments of the Oslo Region and the author's own observations and petrographic and geochemical analyses. Very few geochemical or petrographical data on these sediments have been published prior to this investigation. Aspects of the geochemistry and sedimentology of the shaly sediments of the Oslo Region have been published separately in another article (Bjørlykke 1974). Papers on the origin of the limestone nodules and on the occurrence of diagenetic barium feldspars have also been published separately (Bjørlykke & Griffin 1973; Bjørlykke 1973).

The present paper discusses the petrology and geochemistry of carbonate sediments in the Oslo Region on the basis of X-ray diffraction data and chemical analyses. A summary of the geochemistry of each element is then presented.

Finally the geochemistry and petrology of the sediments of the Oslo Region are compared with data from the Trondheim Region (Wolff 1973) and from Wales (Bjørlykke 1971), in an attempt to assess the difference in chemical composition in relation to the evolution of the Caledonian geosyncline.

The geochemical and petrographical data obtained from this investigation are too voluminous to be included in this paper and are therefore reproduced separately in a *data appendix* which can be obtained from the author or The Geological Survey of Norway (NGU) on request.

SAMPLING

The Lower Palaeozoic marine sequence from the Oslo Region totals about 1000 m shale and limestone and was, except in the southwestern part, folded during the Caledonian orogeny and later intersected by Permian faults. Because of this deformation, and the poor exposures in many parts of the Oslo Region, no continuous section is available covering the whole Cambro–Silurian sequence. Samples for this survey were therefore collected from a number of different localities and sections where the stratigraphic position could be determined from previous descriptions or from available guide fossils.

To simplify data-processing and presentation of the analytical data the author has subdivided the Cambro–Silurian sequence into 25 units, which are indicated in all figures. A summary of the stratigraphy of the Oslo Region has been published by Henningsmoen (1960).

Samples were collected from six different districts following the subdivision of the Oslo Region proposed by Størmer (1953), Fig. 1.

	District	Symbols used on samples
I.	Oslo–Asker	A
II.	Krekling (Sandsvær–Eiker)	K
III.	Skien–Langesund	S
IV.	Toten	M
V.	Nes–Hamar	
VI.	Ringsaker	R

Most emphasis has been placed on getting representative samples from the Oslo–Asker District in order to study the stratigraphic variation in the composition of these sediments; 114 of a total of 200 samples were collected from the Oslo–Asker District. The Krekling District provides good sections particularly from the Cambrian to Lower Middle Ordovician and 34 samples were collected here, mainly from the section near Krekling station.

Samples from the districts around Lake Mjøsa (Toten, Nes–Hamar and Ringsaker) have been collected to see if major stratigraphic variations in the Oslo–Asker District persist into the northern part of the Oslo Region and to study sedimentary facies that are not developed in the Oslo–Asker District, i.e. the Mjøsa Limestone. Only a few samples of limestone and shale have been collected from the Skien–Langesund District.

Samples have also been collected from one section outside the Oslo Region, at Hallingskarvet. The section here, which was first described by Brøgger (1893) and later reinvestigated by Naterstad, runs from black schists into a limestone which is correlated with the Orthoceras Limestone (Brøgger 1893). The limestone is overlain by green metavolcanic sediments. A complete list of all samples analysed in this project, their localities, and their stratigraphic positions is found in the data appendix referred to above.

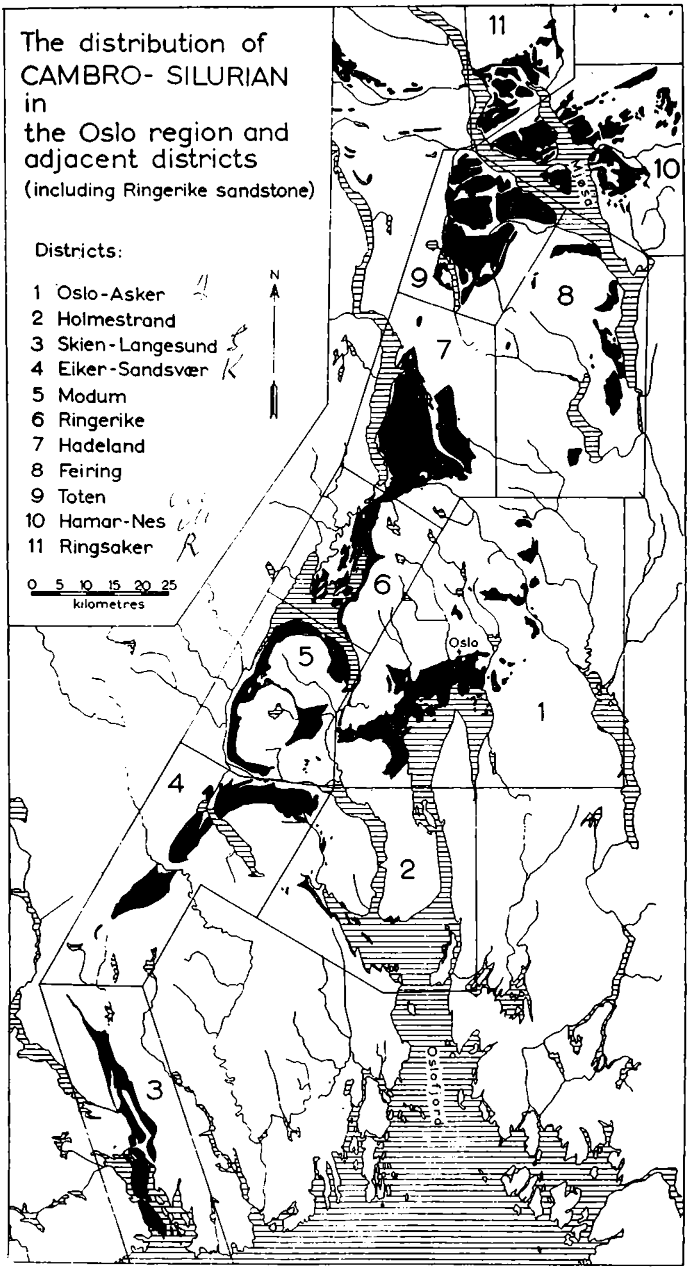

Fig. 1. The distribution of Cambro–Silurian rocks in the Oslo Region and adjacent districts. (Størmer 1953).

CHEMICAL ANALYSES

Two hundred and eight samples of Lower Palaeozoic sediments were analysed by X-ray fluorescence using a semi-automatic Siemens spectrograph at the Department of Geology, University of Oslo.

The samples were crushed finer than 60μ in a steel disc mill. For analyses of major elements, samples were mixed with lithium tetraborate 1:9 and fused.

Calibration curves for the major elements were based on international rock standards. By using propane gas in the counter and pulse height analysis, good results were also obtained for sodium using 4 minutes counting time.

For trace element analyses undiluted pressed pellets were used. Limestones and shales have rather different adsorption characteristics, so separate calibration curves for trace elements were made for shale and limestone by adding known concentrations of trace elements to a composite limestone and composite shale. Such calibration curves were made for Rb, Sr, Ba, V, Zn, Cu and S, and compared with international standards. Ni and Cr are less dependent on the matrix and calibration curves were based on international standards only. Attempts to analyse Pb failed because of peak interference from As, which is rather abundant in sulphide-rich shales. Organic carbon was analysed with a Leco induction furnace and gravimetric carbon determinator. Prior to these analyses carbonate was dissolved from the samples using hydrochloric acid.

X-RAY DIFFRACTOMETER ANALYSES

All chemically analysed samples (208) were also run on the X-ray diffractometer for identification of mineral phases and semiquantitative determination of the mineral composition. For semiquantitative analyses unoriented rock powder ($< 60\mu$) was mounted on glass slides with vaseline. Oriented samples were precipitated onto glass slides from suspension.

Illites proved to be largely non-expandable after glycol treatment. After HCl treatment 7Å reflections were completely destroyed, indicating that this reflection was only due to chlorite and that kaolinite was not present in detectable quantities. No attempt has been made here to convert X-ray diffraction intensities into mineral percentages as this is subject to considerable error. Instead, the relative intensities of the characteristic reflections for each mineral are calculated. There is still no generally accepted method of measuring peak intensities. Gavish & Friedmann (1973) claim that measurements of peak height are more reproducible than peak areas for certain carbonate rocks. Peak intensities are also affected by grinding. Milliman & Bornhold (1973), however, argue that measurement of peak area, although time-consuming, gives the most reproducible results. The present author has preferred to calculate the peak area measured as the peak height multiplied by the width at half height, following Norrish & Taylor (1962). Errors in drawing the base line of the peaks are then somewhat reduced. The quantitatively most important minerals in the Lower Palaeozoic sediments of the Oslo Region are quartz (4.26Å), illite (10Å), chlorite (7Å), feldspar (3.18Å, 3.23Å), calcite (3.03Å), and dolomite (2.88Å). Sulphides are important in some black shales.

The relative intensity of each mineral is calculated as the percentage of the sum of the intensities of characteristic peaks of these minerals or as ratios between the intensity of two peaks (i.e. I 7Å/I 10Å).

In the discussions of the mineralogical data conclusions are drawn only from major differences in composition between rocks of different stratigraphic units. Because of the thick and variable section that has been sampled, the statistical sampling error is probably often greater than the analytical precision in the semiquantitative mineral determinations.

Stratigraphy and palaeoenvironment of the Lower Palaeozoic Sediments from the Oslo Region

THE CAMBRIAN

The Lower Cambrian in the northern part of the Oslo Region

The Lower Cambrian rocks are only present in the northern part of the Oslo Region around Lake Mjøsa north of Hamar. Fossiliferous Lower Cambrian beds (Holmia Series) here overlie the Late Precambrian/Eocambrian sparagmite sequence (Hedmark Group) (Bjørlykke et al. 1967) which includes glacial conglomerates (Moelv tillite) (Spjeldnæs 1964). The regional geology and stratigraphy of this area have been described by Skjeseth (1963).

The Hedmark Group, which includes about 3000 m of sediments, was deposited in restricted, mainly fault controlled basins on the Precambrian Shield (Bjørlykke 1966, 1973; Englund 1966, 1972).

The youngest formation in the Hedmark Group, the Vangsås Formation, is developed as a feldspathic sandstone (Vardal Sparagmite) in the lower part, and as an orthoquartzite in the upper part (Ringsaker Quartzite). At Ringsaker (north Mjøsa) the cross-bedded Ringsaker Quartzite is overlain by a thin granule-conglomerate, often only 10–20 cm thick, which defines the base of the Holmia Series (Lower Cambrian) (Skjeseth 1963). This conglomerate contains quartz and quartzite fragments and is enriched in durable heavy minerals such as zircon (Vogt 1924). Phosphorite and glauconite grains are also common in this conglomerate. In the very topmost bed of the Ringsaker Quartzite borings of the *Skolithos* and *Diplocraterion* type occur in the autochthonous facies to the south (Skjeseth 1963). The transition between the Vangsås Formation and the Lower Cambrian is indicative of a break in sedimentation, but may not involve a great deal of time (Kiær 1916, Holtedahl 1953, p. 180, Skjeseth 1963).

The thin conglomerate at the top of the Vangsås Formation represents a very important marker horizon indicating the beginning of the Lower Cambrian transgression and deposition of the Holmia Series. As pointed out by Kiær (1916) and Vogt (1924) the conglomerate marks the change from deltaic or fluvial environment into a shallow marine facies.

In early literature (for summary see Vogt 1924 and Skjeseth 1963) the sparagmites were also included in the Lower Cambrian. Brøgger (1900) introduced the term ‘Eocambrian’ for the sedimentary sequence below the fossiliferous Lower Cambrian sediments (Holmia Series). Kiær (1916, p. 103) considered the fossiliferous Lower Cambrian of the Ringsaker District to correspond to the upper part of Lower Cambrian in N. America and regarded the ‘Sparagmite Formation’ as a continental facies of the Lower Cambrian. Vogt (1924), however, thought that the unconformity at the base of the Holmia Series represented a longer period of time which at least includes the lower part of the Lower Cambrian as developed in N. America, and that the sparagmites consequently were true Precambrian formations. Holtedahl (1953) and Skjeseth (1963) considered the same unconformity to represent only a minor break, but the sparagmites are not normally included in the Cambrian sequence (Henningsmoen 1960). Holtedahl (1961) suggested that only the upper part of the sparagmite sequence should be included in the term Eocambrian, the base being defined by the base of the tillites. He felt that the Eocambrian should be included in the Cambrian System as its lowermost unit. However, no international agreement has yet been made to define the base of the Cambrian. This work is now in progress through the Commission on Stratigraphy, I.U.G.S. The lower part of the Holmia Series consists of dark muddy sandstones which yield *Mobergella holsti* (1aα_2) (Skjeseth 1963). On the eastern side of Lake Mjøsa at Flagstad river a thin limestone (Bruseter Limestone 1aα_1) with *Holmia schmidtiellus* is found in the basal part immediately above the conglomerate, but these beds appear to be missing at Ringsaker (Skjeseth 1963). The sandy beds with *Mobergella* (*Discinella*) (Bråstad Sandstone (1aα), Skjeseth 1963) are overlain by shale yielding *Volborthella tenuis* (Bråstad shale 1aβ) and then by the Holmia Shale (*Holmia kierulfi* 1bα). Two thin limestone beds (0.20 m) yielding *Strenuella linnarssoni* (1bβ) mark the top of the Lower Cambrian (Kiær 1916, Strand 1929). This limestone is a trilobite biomicrite containing whole shells of trilobites in a micritic matrix.

The Lower Cambrian rocks of the Mjøsa District make up a sedimentary cycle starting with a marine transgression and carbonate sedimentation on top of the Vangsås Formation, which is probably deltaic or fluviatile. These thin carbonate beds (Brennsæter Limestone) were partly eroded prior to the deposition of the Lower Cambrian sandstone (Bråstad) Sandstone). The sediments then become gradually more fine-grained upwards into the Holmia Shale, reflecting a decreasing rate of clastic sedimentation. The Strenuella Limestone at the top of the Lower Cambrian succession was deposited as carbonate mud in a low energy environment with little supply of clastic sediments.

The Middle Cambrian (Paradoxides Series)

The base of the Middle Cambrian is marked by a conglomerate in the *Paradoxides oelandicus* zone (1cα), which indicates a break in the sedimentation and considerable erosion. In the Flagstad river section (Skjeseth 1963, p. 38) both the Strenuella Limestone (1bβ) and the Holmia Shale (1bα) are eroded and the Oelandicus Conglomerate rests on the Bråstad (Volborrella) Shale (1aβ). This conglomerate contains phosphorite and glauconite. Analyses published by Vogt (1924, p. 88) showed that pure phosphorite fragments contain up to 18% P_2O_5, while fossiliferous limestone fragments contained 0.42% P_2O_5. Limestone fragments from the same conglomerate (see Data appendix, Table 8) analysed by the present author contained 0.25% P_2O_5.

The regression indicated by the Oelandicus Conglomerate is followed by a transgression in the southern part of the Oslo Region. In the Oslo–Asker

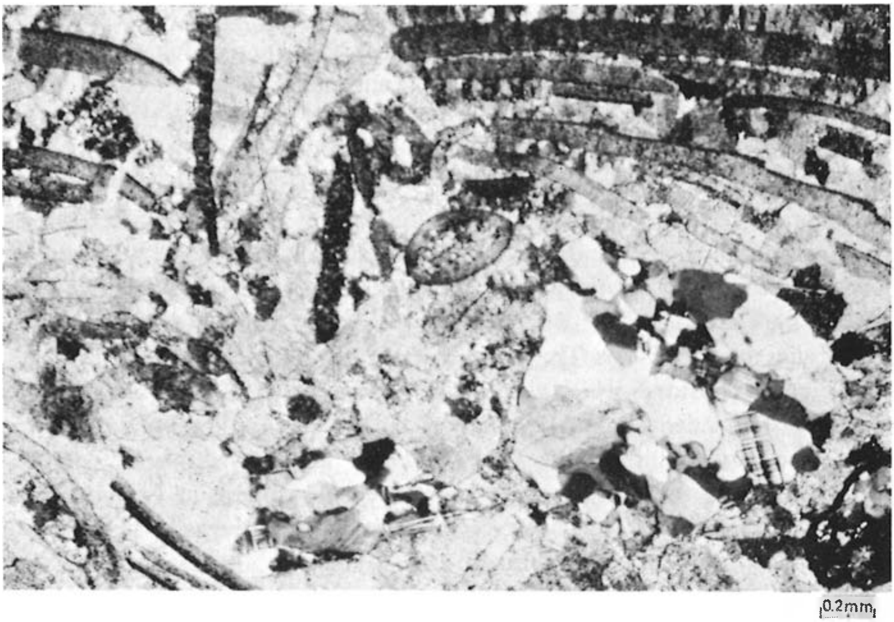

Fig. 2. Middle Cambrian (1c) trilobite biosparite with clasts of microcline gneiss (1.2 mm). Loc. Slemmestad. Crossed nicols.

District, thin limestone beds containing *Ptychagnostus gibbus* (1cβ) rest directly on the crystalline Precambrian basement (Spjeldnæs 1955). The basal limestone has a sparry matrix with trilobite fragments, mainly Paradoxides. Thin section examination of this limestone also reveals angular fragments of basement rocks up to 3–4 mm containing fresh microcline feldspar and quartz. This suggests that the Paradoxides Limestone was deposited in a rather high energy environment and that small islands of Precambrian basement were exposed, supplying fresh basement detritus to the sea floor. Spjeldnæs (1955) has described sections from Asker where the *Hypagnostus parvifrons* zone of the Middle Cambrian (1cγ) rests directly on the basement, suggesting that these areas were exposed or eroded in 1cβ to 1cγ time. A probable hiatus in the Middle Cambrian sequence at Slemmestad, indicated by a missing trilobite zone (*Ptychagnostus atavus*, 1cγ) and the occurrence of the thin arkose bed, was detected by Spjeldnæs (1962).

There is thus considerable evidence that sedimentation in Middle Cambrian times in the Oslo Region took place periodically in a shallow, relatively high energy environment accompanied by erosion and breaks in sedimentation. Spjeldnæs (1955) attributes the irregular basement topography to contemporaneous faulting following the same zones of weakness as later in Permian times. Another possible explanation may be that the Precambrian basement had considerable relief prior to the Middle Cambrian transgression. Periods of regression would then expose and erode basement heights. Exposure of islands of Precambrian basement would increase the turbulence and the conditions on the sea floor would be more oxidizing, thus encouraging an abundant fauna.

Fig. 3. Upper Cambrian Limestone with thin trilobite exoskeletons (Olenides). Loc. Slemmestad. Plane polarized light.
Note the dense packing of the exoskeletons and that the matrix consists of both micrite and sparry calcite.

Beds of biosparites and calcarenites (Fig. 2) with basement fragments were deposited during these periods.

The Middle Cambrian shales are usually included in the term 'alum shale' but they have considerably lower contents of sulphur and carbon than Upper Cambrian shales (see Table 1 and Appendix). The sulphur content may reach about 3% and the carbon content is about 1–2%. The Upper Middle Cambrian shales (1d) include beds which are lighter grey in colour and contain correspondingly less carbon and sulphides (Appendix Table 4) (Fig. 24). In the Middle Cambrian sucession black shale occurs in direct contact with the basal conglomerates and carbonate beds deposited in a relatively high energy environment (Spjeldnæs 1955). The Middle Cambrian transgression probably covered most of the Baltic shield; the evidence pointed out above suggests that shallow conditions must have prevailed for some time after the transgression. It is therefore necessary to assume that the Middle Cambrian alum shale was at least partly deposited in very shallow water.

The Upper Cambrian

The Upper Cambrian sequence in the Oslo Region totals about 45 m and consists of black shales interbedded with thin limestones beds and nodules. The limestone nodules vary in size from about 10 cm to 1–2 m and occur in distinct horizons in the shale. In the opinion of the present author these nodules are not concretions in the ordinary sense but dissolution relicts of

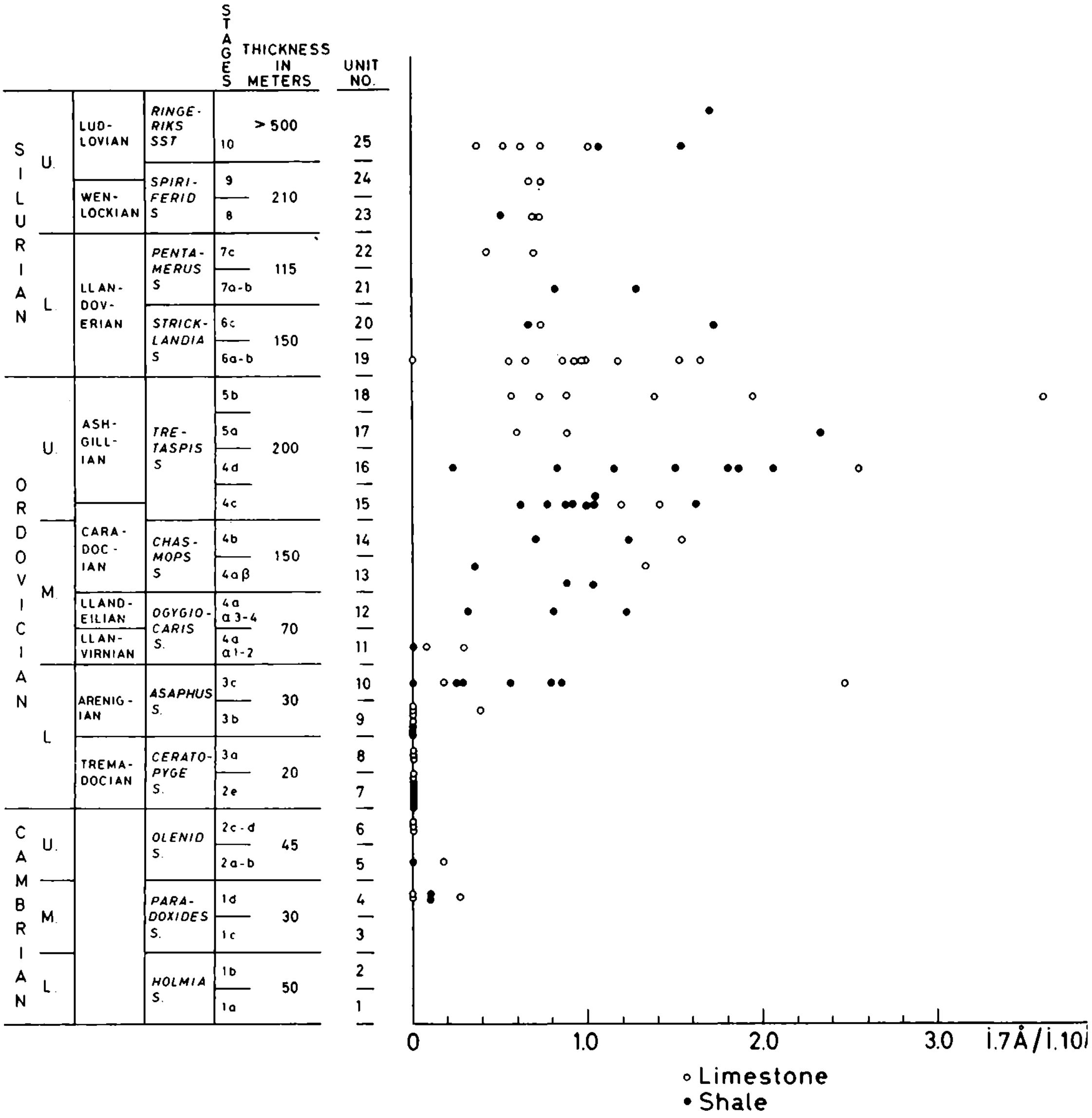

Fig. 4. X-ray diffraction analyses of chlorite/illite ratios in 114 samples of limestones and shales from the Oslo–Asker District expressed as I 7Å/I 10Å.

continuous limestone beds (Bjørlykke 1973). Secondary sparry calcite (anthraconite) is often found around the nodules. Both the limestone beds and the nodules consist of pure carbonate with a $CaCO_3$ content exceeding 90%. The dolomite content is always very low and is normally not detectable by X-ray diffraction. Some of the nodules are totally recrystallized, probably in connection with early diagenetic subsolution and precipitation, while others have well preserved primary textures. The fauna, mainly trilobites of the family Olenidae (Henningsmoen 1957), is often abundant in the nodules, but rarely preserved in the shales. Upper Cambrian limestones often consist of a grain-supported structure of trilobite exoskeletons. The matrix between the exoskeletons may however consist of both lime mud and sparry calcite (Fig. 3).

There is little sign of reworking by waves or currents in the Upper Cambrian limestones. The very thin Olenid exoskeletons are well preserved in large pieces, probably deposited as they were shed by the trilobites. Any reworking or transportation of these exoskeletons would probably have produced smaller fragments. Studies of the orientation of trilobite shields (Henningsmoen 1957, p. 72) also suggest quiet water during the accumulation of the Upper Cambrian limestones. The small amounts of lime mud in many of the Upper Cambrian limestones may be due to deposition in an environment where the sea water was undersaturated with respect to calcium carbonate. In this environment production of lime mud from algae would have been small and dissolution could take place (Alexanderson 1972).

The absence of fragments of basement rocks in the limestones in the Upper Cambrian suggests that the islands of Precambrian basement that were exposed in Middle Cambrian times were buried in Upper Cambrian times. A gradual decrease in chlorite content in Middle Cambrian times and the absence of this clay mineral in the Upper Cambrian shales in the Oslo Region and Sweden (Armands 1972b), have been interpreted by the present author (Bjørlykke 1974) as a result of decreasing supply of clastic chlorite from basement highs as these were drowned by the Middle Cambrian transgression (Fig. 4).

The Upper Cambrian shales have carbon contents (up to 10–12% C) and sulphur contents (10–12% S) significantly higher than those of the Middle Cambrian shales. Hydrocarbons have to a large extent been distilled off during Caledonian folding and low-grade metamorphism. Vanadium is found in concentrations up to 700–800 p.p.m. The highest uranium concentrations are also found in the Peltura Shale (2d) (Skjeseth 1958). Radiometric determination of uranium of two samples of Upper Cambrian shale from the Oslo–Asker District gave values of 144 and 154 p.p.m. U. respectively (Table 3, Appendix).

Conclusions on the Cambrian sedimentation in the Oslo Region

The Lower Cambrian rocks, which only occur in the northern part of the Oslo District, are distinctly different in appearance and in chemical and mineralogical composition from the Middle and Upper Cambrian shales and limestones (Table 2, Appendix). The low content of organic carbon and sulphides (Table 9) of the Holmia Series is due to deposition in a moderately oxidizing environment. The Lower Cambrian sediments were deposited in a basin which in S. Norway only represented a limited transgression out of the area where the sparagmites of the Hedmark Group were deposited. Clastic sediments were therefore derived from nearby sources in the Precambrian basement, probably mainly by fluvial erosion. The presence of chlorite indicates that the Precambrian basements were not deeply weathered (Bjørlykke 1974).

Following the Middle Cambrian transgression the sedimentary environment changed drastically as a result of the drowning of most of the available source areas on the Baltic Shield. Chlorite is only present in small amounts in the lower part of the Middle Cambrian and the shales are indicative of predominantly stagnant conditions. In the Middle Cambrian times water depths have most probably been very shallow and the basal limestones above the Precambrian basements are biosparites with basement fragments indicative of high energy environment. Also in the upper part of the Middle Cambrian there is evidence of relatively high energy and more oxidizing conditions. In the Upper Cambrian, however, more permanent stagnant conditions prevailed in probably somewhat deeper waters.

Upper Cambrian clastic sediments are very fine-grained ($< 10\mu$) probably derived from very distant source rocks. Sedimentation rates were in the order of 1 mm/1000 yrs. and the clastic grains may have been transported in suspension both in water and by wind.

Middle and Upper Cambrian shales are often grouped together and referred to loosely as alum shale. The present investigation has shown that both lithologically and geochemically (see Table 2, Fig. 24) the Middle Cambrian sediments differ significantly from those of the Upper Cambrian in many important respects such as carbon, sulphur, and trace element contents, particularly those of vanadium and uranium.

THE ORDOVICIAN

The Dictyonema Shale (2e)

The black shale facies of the Upper Cambrian Peltura beds continues into the lowermost Ordovician, and the Tremadocian shales contain layers with abundant graptolites. The stratigraphy of the transitional beds between the Cambrian and the Ordovician system has recently been discussed by Henningsmoen (1973). These highly fossiliferous shales have a relatively high carbon content (8–9% C) (see Fig. 24) but have a much lower sulphide content (0.3–1.5% S) than the Upper Cambrian shales. These shales must have been deposited as a very fine-grained mud, and thin section studies indicate that the maximum size of clastic grains was less than 10μ. The high carbon content in these shales as accompanied by vanadium concentrations up to 1500 p.p.m. (see p. 61). Alternating grey and black laminated shale suggests that these beds were deposited under conditions varying from strongly reducing to moderately ventilated conditions. The *Dictyonema* Shale contains higher barium concentrations than the Upper Cambrian shales, and reaches 1.5% Ba at Krekling.

The Ceratopyge Shale

The Ceratopyge Shale (Upper Tremadocian) is developed as a dark to grey shale with isolated limestone nodules. Alternating black and grey shale laminae are more common than in the Dictyonema Shale. The Ceratopyge Shale and also the Lower Didymograptus Shale contain graptolites, while trilobites are less abundant. Størmer (1938) presented evidence that gas bubbles were forming on the stagnant sea floor while the upper water layers were probably more oxygen-rich. High barium concentrations are found in the Ceratopyge Shale of the Oslo–Asker District (Bjørlykke & Griffin 1973). Thin limestone beds have probably been deposited during periods of more oxidizing conditions. The author (Bjørlykke 1974) has interpreted these limestone nodules as being remains of continuous limestone beds which were partly dissolved by sea water unsaturated with respect to calcium carbonate.

Assuming that barium is precipitated as barite, this requires sufficiently oxidizing conditions for sulphur to be present as SO_4. (At PH 8, Eh > -0.3, Garrels & Christ 1965.) Barite has probably become unstable and dissolved due to subsequent reducing conditions during diagenesis and barium has been available to enter the silicate phase, forming authigenic barium feldspar and possibly also illite (Bjørlykke & Griffin 1973). The Ceratopyge Shale also contains frequent 'anthrakonit' nodules (Brøgger 1882), which may exceed 1 m. The coarse crystalline 'anthrakonit' is secondary sparry calcite precipitated around more fine-grained nodules.

The Ceratopyge Limestone

The Ceratopyge Limestone (3aγ) consists of a lower grey micritic bed and an upper brown calcarenite bed separated by a thin layer of calcareous shale. The total thickness in the Oslo–Asker District is about 1 m. The transition from the Ceratopyge Shale to the Ceratopyge Limestone is marked by the occurrence of a thin layer of dark limestone nodules. A detailed study of the fauna and the lithology of the Ceratopyge Limestone has been carried out by Fjelldahl (1966). The upper part of the Ceratopyge Limestone consists of calcarenite, which usually has a brown weathering colour due to dolomite. Thin section studies show that this is a fine- to medium-grained intrasparite. Towards the top of the Ceratopyge Limestone green glauconite-like sand grains occur. These 'glauconite' grains, however, are grey to colourless in thin section, and X-ray diffraction analyses indicate only the presence of illite. X-ray identification of the 'glauconite' pellets carried out by S. Bergstøl at the Geological Museum, University of Oslo, indicates the presence of 1 M illite (Fjelldahl 1966).

Some 'glauconite' grains have been partly or wholly silicified and are replaced by sulphides and silica. Dolomite rhombs can also be seen replacing the 'glauconite' grains. It seems probable that the glauconite has been diagenetically altered to illite. This process may have accompanied the silification and dolomitization that has affected this bed.

The Tremadocian/Arenigan unconformity

In the Oslo Region there is no evidence of an angular unconformity at the top of the Ceratopyge Limestone. The intra sparite and 'glauconite' beds in the upper part of the Ceratopyge Limestone are indicative of shallow water and most probably a period of non-deposition.

In the Skien–Langesund District, however, practically the whole of the Lower Ordovician (2e–3b) sequence is missing (Størmer 1953). The Orthoceras Limestone (3c) here overlies the Upper Cambrian shale without any apparent erosional relief. The basal part of the Orthoceras Limestone consists of a conglomeratic calcareous sandstone. This break in sedimentation and relative uplift of parts of the shield in Lower Ordovician times have been referred to by Størmer (1967) as the Pre–Arenig disturbance. Similar breaks in sedimentation in Arenigan/Tremadocian times are also absent in different parts of Sweden (Tjernvik 1956). The significance of this disturbance and its correlation with the Trondheim Region has been discussed by Bjørlykke (1974).

The Lower Didymograptus Shale (3b)

The basal part of the 3b shale or Tøyen Formation (Erdtmann 1965) consists of grey shale interbedded with dolomitic limestone. This is the Hagastrand Member of the Tøyen Formation (Erdtmann 1965). According to Erdtmann (1965) the lowermost 7–8 m of the 3b shale yield virtually no fossils. Pyrite concretions are common in these beds and about 1–2 m above the Ceratopyge Limestone pseudomorphs after crystals, 1 m in size, occur particularly well exposed at Bjerkåsholmen in Asker. These crystals attracted the attention of Reusch (1884), who interpreted them as being pseudomorphs after gypsum because twinned crystals resembling 'swallow tails' occur. Antun (1967), however, reinterpreted these as being pseudomorphs after barite, and the present author detected a high concentration of barium in these layers (see p. 54). The crystals are replaced by calcite, pyrite, and quartz. Microprobe analyses have shown that barium is present as barium feldspar (Bjørlykke & Griffin 1973). If the pseudomorphs were after gypsum they would be evidence of evaporite conditions. Since these crystals most probably are pseudomorphs after barite, they can no longer be regarded as evidence of saline conditions. Barite may form in sediments with high SO_4-concentration caused by oxidation of sulphide-rich mud. No reliable indications of evaporite conditions are found in the Lower Palaeozoic of the Oslo Region.

The Middle part of the Lower Didymograptus Shale (Galgeberg Member of the Tøyen Formation, Erdtmann (1965)), consists of dark graptolitic shale. Skjeseth (1952) demonstrated that the black shale facies in the Oslo Region makes up the deeper parts of an embayment surrounded by grey shales and limestone facies. The longest axis of the embayment has a NE–SW trend and this axis of maximum subsidence controls the patterns of sedimentation up to Upper Silurian times (Størmer 1967). The upper 2–3 m of the Didymograptus Shale (Slemmestad Member) consist of lighter grey shale indicative of more ventilated conditions as one approaches the overlying Orthoceras Limestone (3c). Laminae of black shale in this grey shale suggest that an oscillation between reducing and moderately oxidizing conditions has taken place.

The Orthoceras Limestone (3c)

The Orthoceras Limestone consists of a lower Megistaspis Limestone (3cα) (1.5 m), a middle marly shale with limestone nodules (Asaphus Shale 3cβ (3 m)) and an upper Endoceras Limestone (3cγ) (3–4 m) (Skaar 1972). This lithology can be recognized in much of the Oslo Region.

The Orthoceras Limestone increases in thickness and has a higher clay content in the northern parts of the Oslo Region. In the Ringsaker District the Stein Limestone, which is the lithostratigraphic name of this northern facies of the Orthoceras Limestone, attains about 40 m (Skjeseth 1963). The sediments north of the Solbergåsen Horst are probably tectonically transported relatively to those south of the horst (Skjeseth 1963). A reticulate facies similar to the Stein Limestone is also found south of the Solbergåsen Horst, but the Orthoceras Limestone there has a smaller thickness (Skaar 1972).

Detailed studies of the lithology and geochemistry of the Orthoceras Limestone carried out by Skaar (1972) have provided evidence that the shape of the basin in 3c-time was about the same as outlined by Skjeseth (1952) for the 3b-time. The Oslo District was probably in the deeper parts of the basin, and the occurrence of oolites in the lower part of the Orthoceras Limestone at Helgøya (Lake Mjøsa) points to shallower water to the north. While there is a relatively sharp boundary between the Orthoceras Limestone and the overlying Upper Didymograptus Shale in the Oslo–Asker District, there is a transitional zone of limestone at the top of the Orthoceras Limestone in the Lake Mjøsa area, indicating that carbonate sedimentation persisted longer in that area.

The Middle Ordovician

An introduction to the stratigraphy of the Middle Ordovician rocks of the Oslo Region was published by Størmer (1953). This introduction has been followed by a large number of publications describing the fauna and the biostratigraphy in the Middle Ordovician of the Oslo Region.

The Upper Didymograptus Shale (4aα 1–2) is developed as a black or dark shale often with an abundance of graptolites. Lithologically the Upper Didymograptus Shale looks very similar to the Lower Didymograptus Shale, but the latter contains significantly higher concentrations of chlorite and magnesium than the former (Bjørlykke 1965). The present investigation has confirmed this difference in composition. A well documented upwards increase in chlorite content through the Orthoceras Limestone which is sandwiched between these two shales (Skaar 1972) adds to the evidence of a steady increase in chlorite/illite ratio from the Lower Ordovician to the Middle Ordovician. The Lower Didymograptus Shale may contain isolated limestone nodules but is mostly non-calcareous. The overlying Ogygiocaris Shale (4aα 3) is more calcareous and contains a varied trilobite fauna. The so-called bronni beds (4aα 4) (Trinucleus bronni) are characterized by a thin basal bed of fine calcareous silt and sand. This bed, which is often only 10–15 cm thick, has well developed convolute lamination structures (Fig. 5). The size of the carbonate grains is 0.1–0.2 mm, which is ideal for the early thixotropic deformations that may cause the formation of convolute lamination. The remaining part of the bronni beds in the Oslo–Asker District consists essentially of grey calcareous shale with limestone nodules. Some limestone beds are fine-grained calcarenites showing micro cross lamination, but they are

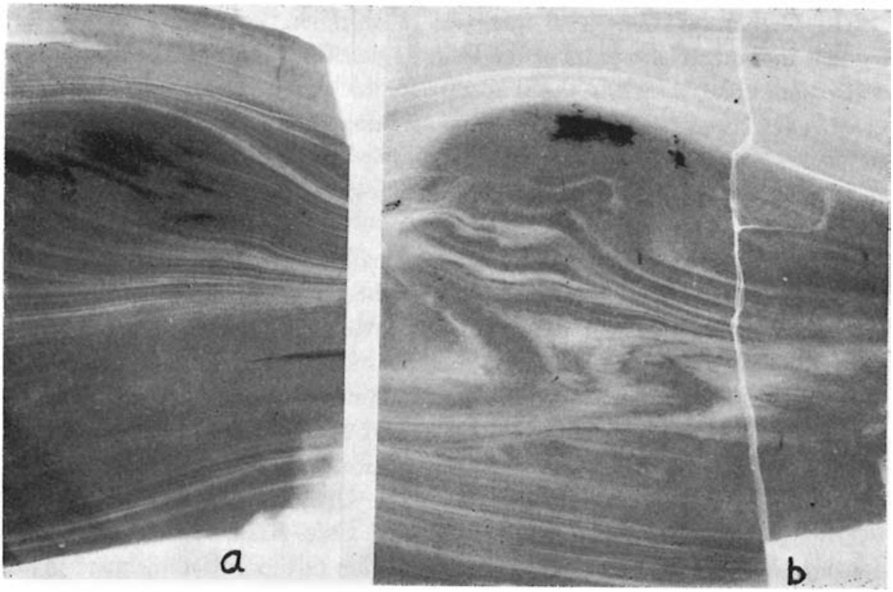

Fig. 5. X-ray radiography of Middle Ordovician ($4a\alpha_4$) calcareous siltstone beds
a) Foreset laminae with pyrite concretions.
b) Convolute lamination.
Loc. Huk, Bygdøy. Natural scale.

mostly micritic limestone without any lamination. The fact that the size of extrabasinal fragments (quartz) does not exceed 30–40µ indicates that they do not represent an influx of clastic material but local uplifts and reworking of sediments within the basin. In the opinion of the present author too much importance has been attached to these very thin calcarenite beds. These beds have been interpreted by Seilacher & Meischner (1964) as turbidites, but show few of the characteristic features of turbidites as described by Bouma (1962). No graded beds corresponding to unit A in Bouma's terminology occur in the bronni beds. There is a rapid literal change in character and thickness of the bronni beds over some hundred metres or a few kilometres. At Slemmestad the current bedded bronni beds are missing; in the Ringerike District 40–50 km to the NW of Oslo the bronni zone is entirely missing and a sedimentary breccia suggests erosion during that period (Hamar 1964). This area may then be one possible source of the fine grained calcarenite sand flowing into the Oslo District. Sole markings at the base of the calcarenite beds at Huk indicate transport from SW to NE but this may be due to currents flowing parallel to the axis of the basin. Similar current directions can be observed in several of the younger formations in the Oslo–Asker District (se p. 24). Some palaeocurrent measurements in the Lower Palaeozoic of the Oslo Region have been done by Seilacher & Meischner (1964). The cross-bedding and convolute laminae observed in the basal parts of the bronni zone may have been formed by currents generated by storms in a relatively shallow sea. The irregular distribution of the calcarenite beds seems to preclude deposition by turbidity currents along long basin slopes, which in any case probably would have been too gentle for turbidites to form.

Størmer (1967) has emphasized the influx of sand in the Oslo District in bronni time and connected this with the approximately contemporaneous Robergia beds on the northern part of the Oslo Region (Holtedahl 1909, Skjeseth 1963). It is, however, important to distinguish between calcarenite sand, which represents a redistribution of sediments formed in the basin, and clastic sediments transported in from areas of exposed basement rocks. In the Oslo–Asker District there are no coarse sand-sized clastic sediments in Middle Ordovician rocks.

The Ampyx Limestone (4aβ)

The Ampyx Limestone is a nodular limestone not unlike that of the bronni beds. The beds with limestone nodules occur at regular intervals and suggest rhythmic sedimentation. In the Ampyx Limestone two superimposed rhythms can be observed. These two cycles have an average thickness of approximately 10 cm and 40 cm. Assuming an average sedimentation rate of 7 mm/1000 yrs (see Fig. 13), the cycles may represent approximately 15,000 yrs and 60,000 yrs. The actual sedimentation rate of these beds, however, may be higher than average sedimentation rate allowing for periods of non-deposition and considerable variation in sedimentation rate. Possible correspondence between these cycles and astronomically controlled climatic changes has been discussed by O. A. Christophersen (unpublished manuscript).

The Chasmops Series

A detailed description of a section through the Chasmops Series at Steilene in the Oslofjord worked out by N. Spjeldnæs has been published by Størmer (1953). The Chasmops Series consists of shales (Lower and Upper Chasmops Shale 4bα, 4bγ) with limestone nodules; limestones (Lower and Upper Chasmops Limestone 4bβ and 4bδ) consist of nodular limestone with a higher nodule/matrix ratio than the shales. Some more massive limestone beds, probably deposited in shallow water, occur towards the top of the Upper Chasmops Limestone. Most of the Chasmops Limestone consists of micrite except in thin layers in the upper part, which show evidence of reworking.

The Mjøsa Limestone in the north and the Encrinite Limestone in the Skien District to the south is developed as a coral–stromatoporoid–algal limestone facies and is thought to be contemporaneous with the upper part of the Chasmops Series in the Oslo District (Størmer 1967). We can see that in a broad way the basin morphology that Skjeseth (1952) reconstructed for the Lower Ordovician also persisted in the Middle Ordovician times.

The Middle Ordovician of the Mjøsa Region

The Middle Ordovician of the Mjøsa District has been described by Holtedahl (1909), Størmer (1953), and Skjeseth (1963). From these descriptions it is evident that the Mjøsa district represents an even shallower facies than the contemporaneous deposits in the Oslo District. Differences in sedimentary facies between the Mjøsa District and the Oslo–Asker District, pointed out for the Lower Ordovician by Skjeseth (1952), become more pronounced in Middle Ordovician times. The Robergia Beds (Størmer 1953) or Hovindsholm Shale (Skjeseth 1963) are silty shales and limestones. Fossils in these beds are rare (Holtedahl 1909). These beds are indicative of a relatively rapid supply of clastic sediments due to uplifts during the Pre–Caradocian Disturbance (Størmer 1967, p. 208). However, in the approximately corresponding bed in the Oslo–Asker District (Bronni Beds 4aα 4) there is little evidence of an increased supply of clastic sediments. The Pre–Caradocian Disturbance has only led to a very limited and local erosion and resedimentation of calcareous sediments (see p. 17). In the Furuberg Formation, which comprises the Coelosphaeridium Beds and the Cyclorinus Beds, sediments become more calcareous (Kiær 1897, Holtedahl 1909, Størmer 1953).

In the upper part of the Middle Ordovician, corals, stromatoporoids, and green algae become more and more common and on top of the Chasmops Series we have the Mjøsa Limestone, which contains true reef structures (Størmer 1953, Skjeseth 1963) and Holtedahl (1909) correlated the Mjøsa Limestone with the Tretaspis Shale (4c) of the Oslo District. Raymond (1916, p. 244), however, later put the Mjøsa Limestone at the boundary between the Chasmops Series and the Tretaspis Series of the Oslo Region (4bδ) and 4cα). The same correlation was made by Størmer (1945, 1953). Recent work by Hamar (in preparation) on the conodont fauna in the Ordovician Limestones of the Oslo Region may suggest that the top of the Mjøsa Limestone is slightly younger than the age proposed by Raymond. Kiær (1921, 1927) suggested that the break in sedimentation indicated by the phosphorite conglomerate near the base of the Tretaspis Shale is to be correlated with the regression following the deposition of the Mjøsa Limestone in the Mjøsa District.

A possible explanation of short breaks of this nature and oscillatory sea level changes may be the accumulations of ice in the polar regions. Evidence made available in recent years shows that we had an important period of glaciation in Middle to Upper Ordovician times (Beuf et al. 1971). In Hoggar in North Africa, which at that time was near the South Pole, continental glacial deposits are overlain by Ashgill sediments, indicating a Caradocian age for the glaciations. Records of this glaciation in Normandy show that the glaciation was not restricted to the polar regions. The Oslo Region was then in a low-latitude position (Spjeldnæs 1961). From Quaternary periods we know that during the period of maximum glacial advance the sea level is lowered about 200 m and that the present extent of the ice corresponds to about 50 m lowering of the sea level. As the Quaternary regression left the present epicontinental seas dry, one would also expect the Ordovician glaciation to affect the sedimentation in the Ordovician epicontinental seas. The sea level oscillations during the deposition of the Chasmops Series and the unconformity at the base of the Tretaspis Series are within the possible time range for the

Ordovician glaciation in Africa. Transgression and regression caused by accumulations of ice could become an important tool in an Ordovician chronostratigraphy.

If the break in sedimentation near the base of the Tretaspis Series in the Oslo District is due to a eustatic sea level change, this should also be recorded in the Mjøsa Limestone if the top of the Mjøsa Limestone is younger than the base of the Tretaspis Shale. Some evidence of solution (karst structures) has been found near the top of the Mjøsa Limestone (Skjeseth 1963), but it is difficult to make any correlation on this basis. The Mjøsa Limestone is followed by a break including the Upper Ordovician (Ashgillian and Lower Llandoverian) up to 6c, a period which in a broad sense corresponds to the Ekne disturbance of the Taconic fold phase (Vogt 1929, 1945).

The Upper Ordovician

The Upper Ordovician rocks, which total about 200 m in the Oslo District correspond to the Tretaspis Series, including the Tretaspis Shale and Limestone (4c), the Gastropod Limestone (5a), and a Calcarenitic Sandstone (5b).

The Tretaspis Shale

Overlying the Upper Chasmops Limestone the dark grey Tretaspis Shale (4cα) follows, representing a rather abrupt change in facies. The Tretaspis Shale is dark grey in colour and may look like a black shale, but has a relatively low content of sulphur and carbon compared with the Cambrian shales. In contrast to the Middle Ordovician limestones and shales, the Tretaspis Shale contains abundant clastic quartz and feldspar grains up to fine-grained sand size (0.06–0.10 mm) (see Fig. 13). Well sorted sand beds are also present. The fauna from the Tretaspis Shale has been described by Størmer (1945).

In the Oslo District a phosphorite conglomerate occurs in the basal part of the Tretaspis Shale. Palaeontological evidence indicates that the basal part of the Tretaspis Shale in the Oslo District was deposited at the same time as carbonate sedimentation was still continuing further west in the Asker District (Størmer 1953, p. 68). This is in accordance with the general morphology in early and Middle Ordovician times, where the Oslo District still represented the deepest part of the basin.

The phosphorite conglomerate, which is only a few cm thick, contains fragments of phosphorite and of micritic limestone in a matrix of fine grained quartz sand (0.1 mm). The limestone fragments may represent fragments eroded from thin limestone beds in the basal part of the Tretaspis Shale. The phosphorite conglomerate does not indicate any subaerial exposure but a period of break in the sedimentation, erosion, and possibly also subsolution of carbonate beds.

At Lunner in Hadeland, Lauritzen (1973) described an intraformational conglomerate which also occurs near the transition between stages 4b and 4c. Here, however, this conglomerate is overlain by about 0.5 m of limestone before passing up into the Tretaspis Shale facies. Lauritzen placed the boundary

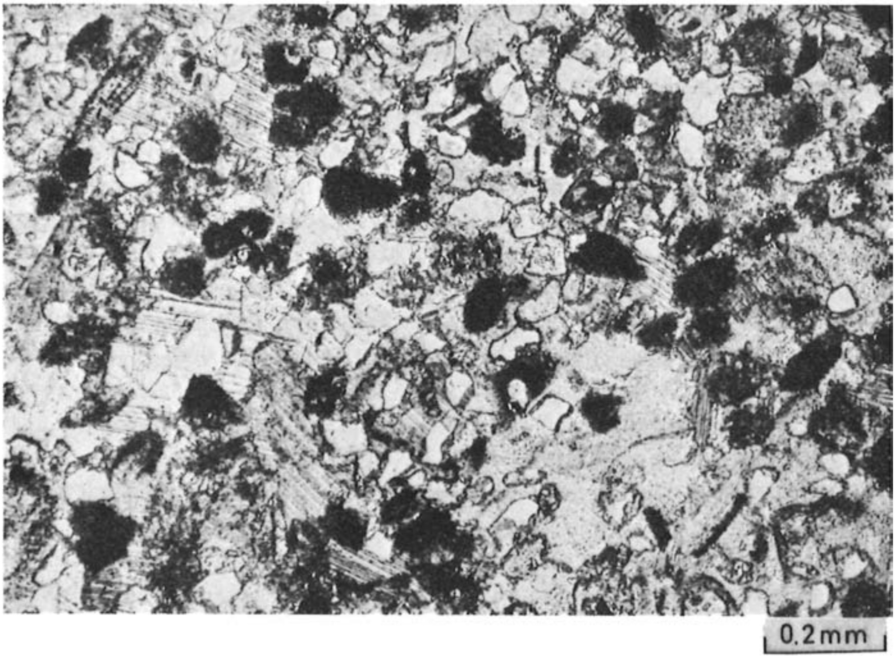

Fig. 6. Upper Ordovician (5b) fine-grained sandstone with pellets. Jongskollen, Bærum. Note similar grain size between faecal pellets and quartz grains. Plane polarized light.

between 4b and 4c above the limestone for palaeontological and lithological reasons. If, however, this conglomerate is synchronous with the conglomerate from the Oslo area described above, then carbonate sedimentation prevailed longer in Hadeland to the NW than in the Oslo District. Størmer (1945), however, considered that the beds above the Chasmops Limestone at Hadeland may have been deposited in a period corresponding to the hiatus in the basal 4c in the Oslo District.

Vogt (1929) has correlated this break in sedimentation with the Ekne Disturbance, which is included in the late Ordovician (Taconic) orogeny in the Trondheim Region. The Tretaspis Shale contains an early invasion of clastic sediments, which persist and become more coarse-grained towards the top of the Upper Ordovician (5b). The Tretaspis Limestone (4cβ) is a nodular limestone with smaller nodules (5 cm) than the common size in the Chasmops Series. The Upper Tretaspis Shale (4cγ) is lighter grey and more calcareous than the Lower Tretaspis Shale.

The Isotelus Beds (4d) are developed as a nodular limestone with silty calcareous layers, particularly in the upper part. A high quartz/clay ratio and high SiO_2/Al_2O_3 ratio (see Fig. 15) in these sediments may suggest winnowing, most probably by shallow currents. Current ripple lamination also occurs in the Isotelus Beds. An excellent section through the Upper Ordovician from the 4d to the 5b is exposed at Ringeriksveien near Sandvika. This section and other Upper Ordovician outcrops in the Bærum District have been described by Lervik (1970).

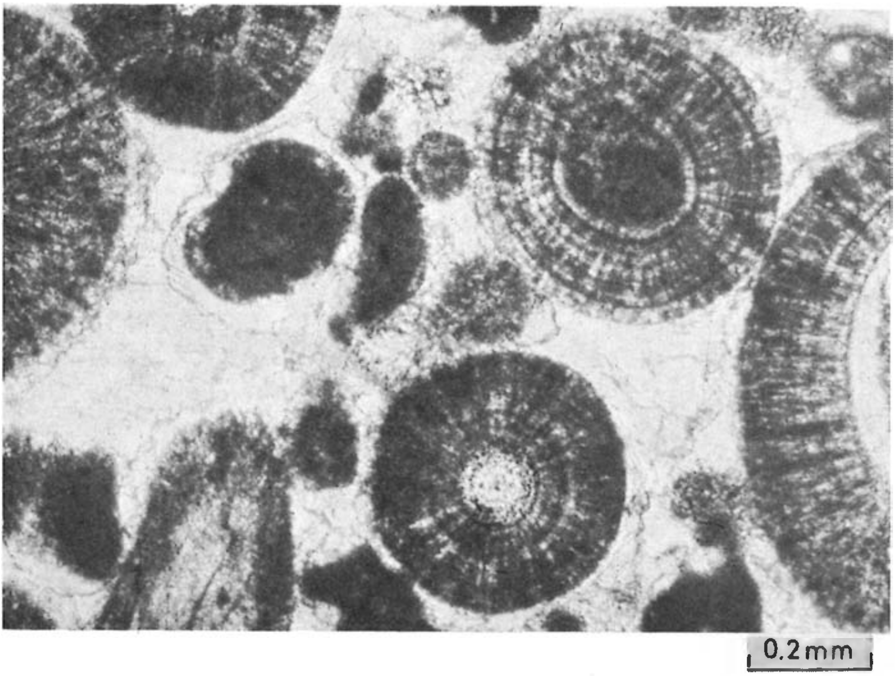

Fig. 7. Upper Ordovician (5b) oosparite with some smaller faecal pellets. Loc. Jongskollen, Bærum. Plane polarized light.

The upper part of the Upper Ordovician (stage 5) in the Asker District has been the subject of relatively detailed studies by Kiær (1901). Algae including Palaeoporella are abundant in the Gastropod Limestone. Parallel lamination of fine-grained calcarenite alternating with impure micritic limestone, locally showing grading, is common in the 5a beds. A possible origin of these beds is by sedimentation of suspended material after storms in a shallow sea (Reineck & Singh 1972). Near the transition between 5a and 5b fine-grained sandstones with small pellets (0.05 mm) occur (Fig. 6). Further up the section to the top of the Upper Ordovician the grain size increases gradually to coarse sand, consisting of oolites and quartz grains of about 0.5–1 mm in the uppermost part. Cross-bedding is common in the upper part of 5b and the sandstones are well sorted and have a sparry matrix (Fig. 7). The oolites and the sand grains are well sorted and have approximately the same diameter.

The Upper Ordovician beds are in places cut by erosion, which may reach down into the Isotelus Limestone (4b) (Lervik 1970) so that the Silurian rests on different horizons. Spjeldnæs (1957) suggested that the Cambro-Ordovician sequence was folded by the Teconic fold phases prior to erosion and deposition of the Silurian sediments. Lervik (1970), however, failed to find any direct evidence for this. The top of the Ordovician succession contains strong evidence of very shallow water. Algae appear in 5a and isolated corals and small coral patches are found in 5b (Lervik 1970). Cross-bedded oolite beds are sometimes overlain by parallel laminated sandstone, which may

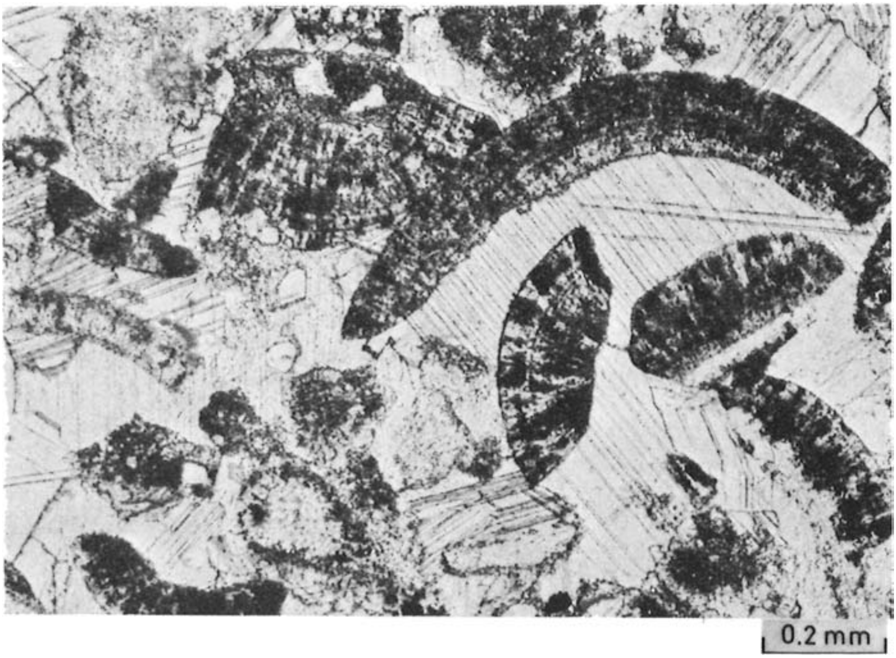

Fig. 8. Fractured ooids in sparry matrix in the topmost part of the Upper Ordovician (5b). Loc. Jongskollen. Plane polarized light.

have been deposited in a high energy beach environment. In the topmost part of these beds, the sand grains may be made up of fractured oolites (Fig. 8). The oolites are clearly mechanically fractured prior to deposition.

In the conglomerates in the top of the Upper Ordovician sequences (Spjeldnæs 1957), one finds that the largest blocks (1–2 m) consist of oosparite (see also Lervik 1970). These blocks must have been cemented at the time of deposition. This suggests that the oolitic sandstones were cemented as beach rocks due to exposure to fresh water.

If the uppermost Ordovician sandstones, which include both oolite and quartz sand, were cemented as beach rocks or later due to exposure during a regression, they would then form a hard crust on top of soft sediments. During subsequent erosion these cemented beds would break off and drop into the channels. This process can explain the occurrence of large (4–5 m) blocks of sandstone with cross-bedding indicating that they have been overturned (Spjeldnæs 1957, p. 361, Seilacher & Meischner 1964, p. 605).

From Lervik's (1970) description of sections in Bærum (Oslo–Asker District), it is apparent that channels were cutting into the Upper Ordovician beds at a rather high angle. The conglomerate at the base of the Silurian is found resting upon the 5b beds at short distances from sections where 4d is the youngest bed below the conglomerate. Large corals facing upside-down are common in these conglomerates. This suggests that a rising sea floor of carbonate sediments with some coral patches was intersected by erosion producing steep channels cutting through beds of stages 5b and 5a. It seems likely that during the process, the sediments were subject to subaerial exposure.

Conclusions on Ordovician sedimentation in the Oslo Region

The black shale facies continues from the Upper Cambrian into the Lower Ordovician with a high carbon content but with a lower sulphur content in the Dictyonema Shale. Dark to light grey laminae in the Ceratopyge Shale indicates oscillation between reducing and oxidizing conditions up to the Ceratopyge Limestone. High barium concentrations in these shales and the overlying Lower Didymograptus Shale (3b) may be due to precipitation of barite (Bjørlykke & Griffin 1973). The Ceratopyge Limestone represents in the author's opinion a very important marker horizon in the Lower Palaeozoic stratigraphy of the Oslo Region. Although there is little direct evidence of an unconformity at the top of the Ceratopyge Limestone in the Oslo–Asker District it may represent a period of non-deposition, which can be correlated with unconformities in other parts of the Oslo Region and in Sweden. Chlorite is introduced above the Ceratopyge Limestone in the 3b shale and the significance of this, relating to organic movements, has been discussed by Bjørlykke (1974).

Very small amounts of coarser clastic sediments were introduced into the Oslo Region in Lower and Middle Ordovician times. Palaeogeographical reconstructions (Skjeseth 1952, Størmer 1967, and Skaar 1972) indicate that for most of this period the Oslo–Asker District was located in the central and slightly deeper part of an epicontinental sea.

The Pre-Caradoc disturbance (Størmer 1967) seems to mean very little in terms of supply of clastic sediments in the Oslo–Asker District in Llandeilian time, while the equivalent beds in the Mjøsa District (Robergia Beds) contain sandy beds of somewhat uncertain thickness due to poor exposure.

In the Middle Ordovician sediments up to the top of the Chasmops Series there is evidence of oscillatory depth conditions becoming very shallow in the upper part with reef facies in the Mjøsa District and in the Skien–Langesund District. The transition between the Chasmops Limestone and the Tretaspis Shale indicates a very important change in sedimentation.

The phosphorite conglomerate near the base of the Tretaspis Shale suggests erosion, and a break in sedimentation, but there is no evidence of subaerial exposure. However, this conglomerate may be approximately time-equivalent to the regression which caused the unconformity above the Mjøsa Limestone to the north. Peak values in chromium due to clastic chromite, probably derived from the rocks of the Trondheim Region, are found in these beds close to the Middle/Upper Ordovician boundary. In contrast to the Middle Ordovician beds the Upper Ordovician shales and limestones contain sand sized clastic sediments. After a probable initial subsidence in the beginning of the Upper Ordovician there is evidence of a continuing shallowing up to the Ordovician/Silurian unconformity. The occurrence of boulders of oolitic limestone in the Upper Ordovician channels suggests that early diagenesis has taken place prior to erosion. It is, however, difficult to estimate the duration of this break. Sedimentation rates during Upper Ordovician times were probably considerably higher than in the lower parts of the Ordovician period (Fig. 13). This agrees well with palaeontological evidence published earlier (Størmer 1930, 1945,) (Strand 1934).

THE SILURIAN

The basal Silurian beds (6aα) above the Ordovician/Silurian unconformity, consist of rapidly accumulated sand with a sparse fauna (Kiær 1908, p. 465). The thickness of this lower unit varies from about 50 m in the east at Malmøya to about 20 m in the western part of the Oslo Region. The variable thickness and development of the basal Silurian beds reflect the filling in of the irregular topography that resulted from the erosion of the Upper Ordovician beds. Kiær recognized that the subsidence in the east was stronger than in the west. Throughout most of the Silurian, the eastern Malmøy facies represents a deeper water environment than the Bærum–Asker Region, only 15–20 km to the west. Kiær (1908, p. 477) also points out that there was a first period of subsidence when the 6aα beds were deposited, followed by gradual shallowing up to 6b and a renewed subsidence and supply of sand in 6c.

In a recent study of stage 6 at Malmøya, Worsley (1969) has studied the palaeoecology of brachiopod communities, which may be sensitive indicators of depth, wave, and current energy. Worsley considered that the maximum depositional depth at Malmøya occurred in 6b time becoming shallower towards stage 7. Petrographically the basal Silurian beds of the eastern facies are developed as feldspathic sandstone with about 20% carbonate having a high dolomite content (Fig. 9). Fresh clastic microcline grains show that the erosion following the Taconic orogeny must have cut into sparagmites or Precambrian basement rocks. A possible source for these feldspars is granitic rocks, which are found together with the gabbroic rocks of the Jotun Nappe, or possibly from the Telemark land in the west. Palaeocurrent indicators such as groove casts give a consistent pattern of transport from the south-west, following the approximate basin axis. This is in agreement with palaeocurrent measurements by Seilacher & Meischner (1964) and Worsley (1969). Broadhurst (1968) has described large scale ripples from stage 6 in the Skien–Langesund District. He interpreted these as being due to strong currents probably of tidal origin mainly because some cross-laminations indicate reversed transport relatively to the dominant direction. In the opinion of the present author a storm or storm-generated tide currents could well be responsible for these structures.

Major (1946) studied the Lower Silurian sandstones (stage 6) from Hadeland to Gjøvik in the north-west part of the Oslo Region. On the basis of a northward wedging-out of the sandstone from about 100 m at Hadeland to less than 10 m at Gjøvik and an increasing grain size in the same direction, he inferred that the sand was derived from the north. The sand here contains predominantly potash feldspar suggestive of a granitic source. As pointed out

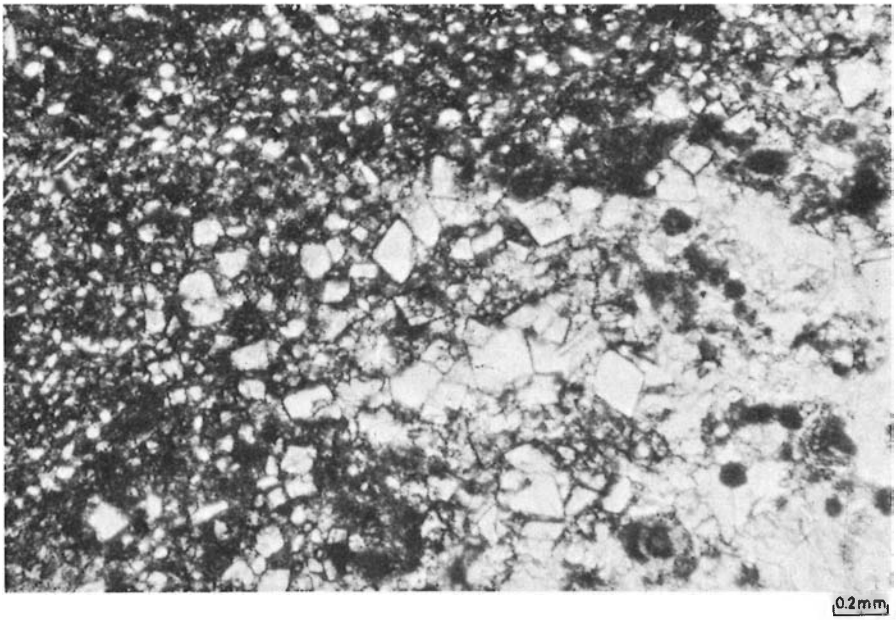

Fig. 9. Dolomite rhombs in Lower Silurian (6a) calcareous sandstone. Bærum. Dolomite rhombs have probably formed during late diagenetic dolomitization.

by Major (1946) the concentration of potash feldspar could be the result of a selective weathering of the plagioclases. The Jotun Nappe includes granitic rocks along with the quantitatively more important gabbroic rocks.

The Pentamerus Series (Stage 7, Upper Llandovery)

The Pentamerus Series in the Asker–Bærum District contains massive limestones in the lower part (7a–b) followed by more marly sediments in the upper (7c). The Pentamerus Limestone is built up mostly by brachiopod shells, Pentamerus borealis at the base (7a) and Pentamerus laevis in the upper (7b) (St. Joseph 1938). The matrix is partly sparry calcite; partly micrite often with terrigenous mud containing quartz of silt and fine sand size. The limestone is often intersected by wedges enriched in clastic material suggesting subsolution of carbonate. There is much evidence of reworking, probably by wave action, and formation of intraclast conglomerates. The basal limestone (7a) is developed as a nodular marly limestone at Malmøya (Kiær 1908) and it seems also that during this period the eastern facies represented a somewhat deeper environment than the shallow western facies. The same situation is reflected in the upper part of the Pentamerus Series, where the marly shale with the numerous crinoid stems (7c) in Asker–Bærum, has a strong red colour, indicative of an oxidizing environment, while the equivalent shale at Malmøya remains grey. The red shale (7c) is interbedded with calcareous beds (7cβ) rich in corals and the shale contains intrasparite breccias which support the above interpretation.

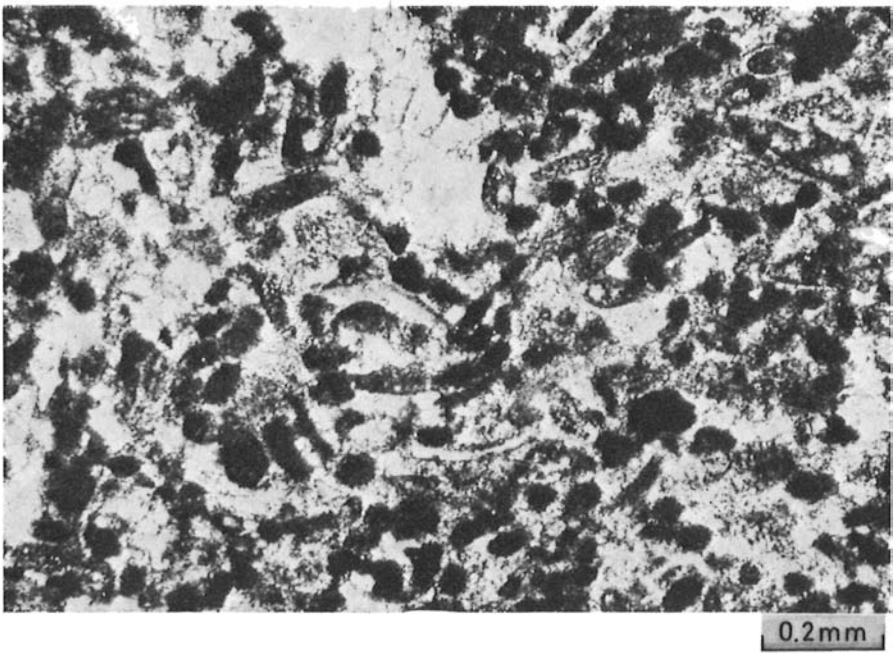

Fig. 10. Pellets in Upper Silurian limestone (9c). Bærum. The pellets occur in a dominantly sparry matrix.

The Spiriferid Series (Stage 8 and 9, Wenlockian) of the Oslo Region

The basal beds of the Spiriferid Series of the Oslo Region, consisting of the Monograptus Shale (8a–b) are a finely laminated calcareous siltstone totalling about 80–90 m. Carbonate sedimentation prevails in the upper part of stage 8 (c–d). The thickness of the upper calcareous units corresponding to the Rynchonella zone (8c) and the Malmøy Limestone is in the eastern facies (Malmøya) about 20 m and in Bærum about 40 m (Kiær 1908). This is the beginning of the last phase of carbonate sedimentation in the Lower Palaeozoic of the Oslo Region. The Chonetes and Leperditia limestones are mostly micritic limestones with nodular beds. The Leperditia Beds are in Bærum overlain by finely laminated calcareous sandstones (stage 9 a–c) with thin sorted and graded beds of pellets and quartz with diameters around 0.05–0.10 mm (Fig. 10). The matrix consists partly of sparite but also of clay minerals. This pelletal facies must have been deposited in high subtidal or intertidal facies. Holtedahl (1920) has reported mud cracks in sediments from approximately the same stratigraphical horizon (9b–c) at Kolsås. Størmer (1942) has reported mud cracks at Ringerike in beds of an even lower stratigraphic position (8b), which adds to the evidence that very shallow conditions prevailed in Upper Silurian times. The uppermost part of the stage 9 limestone (9f) is largely composed of favositid corals.

The coral-rich facies of stage 9f is overlain by red or grey calcareous shales (9g), which may have been deposited in the tidal zone of an estuary (Spjeldnæs 1966). Spjeldnæs also described evidence that marine fossils were transported into a brackish water environment by bottom currents going up the estuary. At the transition to the overlying Ringerike Sandstone a thin intraformational conglomerate occurs (Spjeldnæs 1966, p. 504).

The Ringerike Sandstone contains many sedimentary structures indicative of deltaic and fluvial environment. Oscillation ripple marks and mudcracks (Holtedahl 1920) are common. Mudcrack diapirism has been described by Whitaker (1964).

The Silurian of the Mjøsa District

In the Mjøsa District the Helgøya Quartzite (6c) rests unconformably on the Mjøsa Limestone (Kiær 1908, Skjeseth 1963) (Fig. 12). After a long period of erosion and non-deposition including most of Upper Ordovician and basal Silurian this area was covered with a transgressive sandstone wedging out to the north (Major 1946). Karst structures and erosion furrows in the Mjøsa Limestone (Skjeseth 1963) are clear indications of subaerial exposures during this break. The Pentamerus Limestone represents shallow carbonate shelf conditions, as in the Oslo District. The overlying graptolite shale (Ek Shale 7c) contains bentonites (Hagemann & Spjeldnæs 1955, p. 38). The Ek Shale yields graptolites (Monograptus sp.) and represents the same facies as developed in the Oslo District in stage 8a–b (Monograptus Shale).

The Ek Shale is succeeded by the Bruflat Sandstone, which is the youngest Silurian formation exposed in the Mjøsa District (Kiær 1908, 1922, and Skjeseth 1963). The Bruflat Sandstone consists of fine-grained calcareous sandstone with grading and ripple cross-lamination, interbedded with a silty mudstone. The carbonate content may be up to 20% with a high dolomite/calcite ratio. These relatively fine-grained sandstones probably represent a delta slope environment with deposition of distal turbidites.

The late Silurian regressive sequence

The Bruflat Sandstone represents the first occurrence of deltaic facies in the Oslo Region since early Cambrian times, indicating the emergence of a rising mountain chain in the late orogenic stage. As pointed out by Skjeseth (1963, p. 82) the Bruflat Sandstone can be regarded as an early parallel to the Ringerike Sandstone. Spjeldnæs (1966) has presented evidence that the basal beds of the Ringerike Formation are younger at Kolsås than at Ringerike (26 km to the north-west) and still younger at Jeløya to the south of Oslo. Størmer (1967) distinguishes between an early Wenlock disturbance giving rise to the Bruflat Sandstone and a late Ludlow period of land rise producing the Ringerike Sandstone, separated by a quiet period. The sections from the Upper Silurian from Lake Mjøsa to the Oslo District and Jeløya farther south (Fig. 11) seem to indicate, however, a possibility for assuming a continuing prograding delta sedimentation to the south from early Wenlock to late Ludlow. This period can be estimated to be about 5–10 million years long. Deltaic sedimentation, however, probably continued into Downtonian times and therefore probably lasted 10–20 m.y., which is comparable to the period of Miocene molasse sedimentation in the Alps.

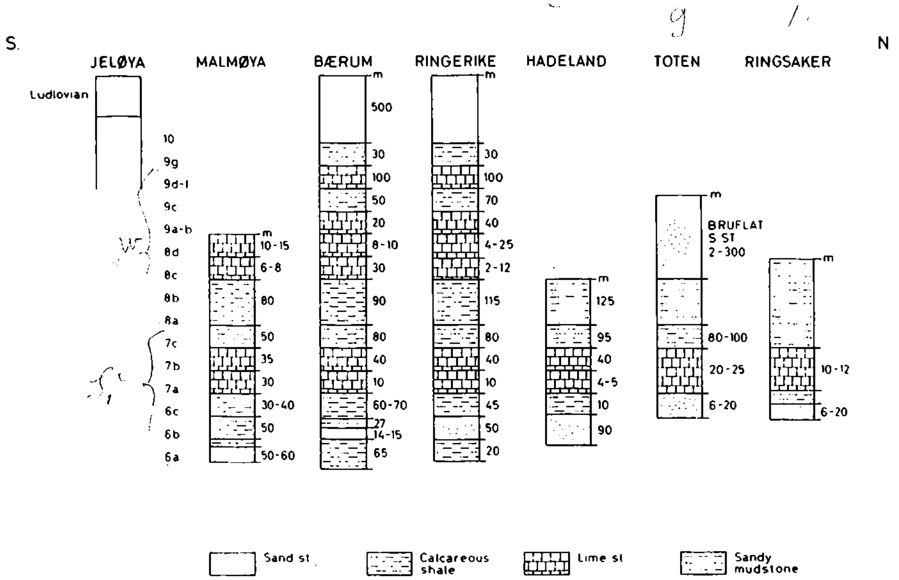

Fig. 11. Stratigraphy of the Silurian rocks of the Oslo Region, mainly based on data from Kiær (1908).

The accumulation of a considerable thickness of Ludlovian sediments in the Oslo Region and other occurrences of Ludlow with similar thicknesses in Skåne and in the Baltic (Christensen 1971) suggests deposition in an elongated trough or syneclise (Størmer 1967). The outline of this trough is still quite uncertain owing to the lack of exposures and boreholes. It seems, however, probable that relatively rapid sedimentation occurred in a geotectonic depression in the Baltic Shield in Ludlovian times. The Ludlow sediments of the Skåne Region and Baltic consist of marine mudstones with graptolites representing a facies rather different from the deltaic facies of the Ludlow of the Oslo Region. The fact that the Lower Palaeozoic sediments of the Oslo Region are preserved only in the faulted Permian Oslo graben makes it difficult to estimate the extent of the Late Silurian deltaic sedimentation. The Ringerike Sandstone of the Oslo Region consists mostly of silty and fine sand, often with a high mud content (Whitaker 1965) reflecting a mature relief around an estuary migrating into a shallow continental shelf. Coarse clastic grains or conglomerates are rare or absent. As a contrast to this environment, early Devonian molasse sedimentation in the more central part of the Norwegian Caledonides in western South Norway is conditioned by large scale faulting, producing thousands of metres of conglomeratic sediments (Bryhni 1964).

To understand late orogenic sedimentation in the Oslo Region it may be useful to look for similar modern environments. The river Po flows into the Adriatic Sea, which is a very shallow sea particularly in its inner parts. The innermost 300 km is nowhere deeper than 100 m. The tidal range is very low in the Adriatic Sea and that may also have been the case in the shallow epicontinental sea on the Baltic Shield in Silurian times. The sedimentation in the Po delta has recently been described by Nelson (1970). According to

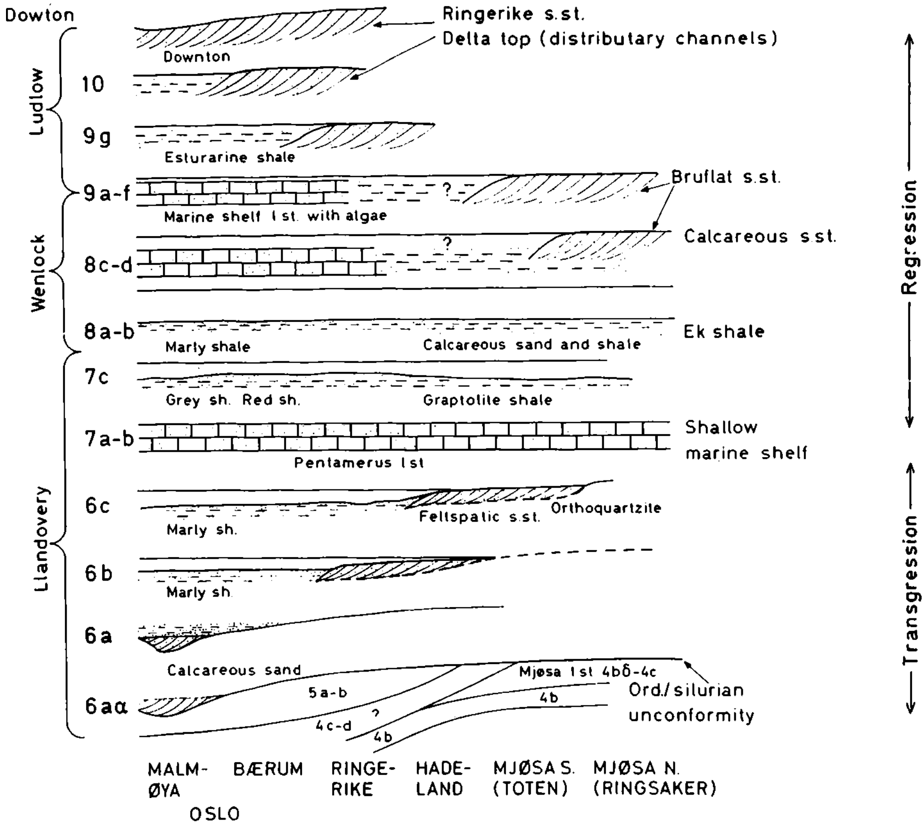

Fig. 12. A simplified interpretation of stratigraphic data from Fig. 11 showing an early Silurian transgressive sequence and a late Silurian regressive sequence.

his description, the water near the delta is brown to green due to suspended sediments. However, 50 km from the river mouth, the water is blue and contains virtually no sediments or plankton (Nelson 1970, p. 182). If the conditions in the Oslo Region were comparable to this, deltaic sedimentation could take place in the Hadeland–Mjøsa District (50–100 km) to the north of the Oslo Region at the same time that clear water sedimentation prevailed in the Oslo District in Upper Silurian (Wenlockian/Ludlovian) times. The rocks of the Mjøsa District were deposited further apart from the Oslo District than they are situated at present; the distance has been shortened by later folding. The shape of the Adriatic Sea, a sedimentary basin running at an angle to the Alpine mountain chain from which the sediments are derived, resembles the late Silurian syneclise continuing to the south of the Oslo Region, as described by Størmer (1967). The gradual prograding deltaic sedimentation in the Adriatic Sea and change from shallow marine to deltaic and fluvial environment may serve as a model for the transition from marine to fresh water sediments in the Upper Silurian of the Oslo Region.

Summary on Silurian Sedimentation

Our knowledge of Silurian stratigraphy and fauna is still to a very large extent based on Kiær's (1908) work on the Silurian of the Oslo Region. Biostratigraphic correlations with Silurian sections in Britain and within the Oslo Region have been published by Basset & Richards (1971). Fig. 11 is a compilation of stratigraphic data on Silurian sediments in different parts of the Oslo Region, mainly from Kiær (1908).

The Upper Ordovician regression is followed by a Lower Silurian transgression. Kiær (1908) and later Major (1946) were able to establish that gradually younger beds of stage 6 overlie the Ordovician/Silurian unconformity northwards to the Mjøsa District (Fig. 12). Kiær also recognized a relatively deeper-water facies in the eastern part of Malmøya compared to Asker–Bærum Districts and western parts of the Oslo Region. The fact that algae (Girvanella) suggesting shallow water have been found in the stage 6 of the Asker–Bærum District and not at Malmøya (Worsley & Lauritzen, personal communication) supports Kiær's interpretation.

The Lower Silurian transgression in the Oslo Region is approximately contemporaneous with transgressions of Llandovery age in Britain. If, however, the transgression was largely due to eustatic rises of sea level one would expect to find equal depth during the deposition of stage 6 above the Ordovician/ Silurian unconformity. The evidence of differences in depth, and the gradual transgression to the north, suggest that this transgression was largely controlled by subsidence which took place at rates which have varied in different parts of the Oslo Region. The facies distribution during Silurian sedimentation, which shows a deeper part in the Oslo District becoming shallower to the north and west, is very similar to that of Ordovician times.

The Lower Silurian transgression is accompanied in the Oslo–Asker District by evidence of gradually more shallow conditions from stage 6 to 7 (Kiær 1908, Worsley 1969). It is therefore necessary to assume that we had a relatively rapid initial subsidence but that sedimentation later was faster than the subsidence. The basal Silurian beds of Malmøya (Oslo) 6aα contain sandy layers and sandy sediments are found in gradually higher stratigraphic positions to the north (Fig. 11). In the Mjøsa District stage 6 consists only of a thin (6–20 m thick) well-sorted sandstone above the unconformity, probably corresponding to 6c (Major 1946). Major concluded that transport was from the north. There is, however, no suggestion of deltaic sedimentation in stage 6. The thin well-sorted sandstone of stage 6 at the Mjøsa District corresponds well to a transgressive shoreline sand body (Visher 1972).

The Pentamerus Series consists mostly of nodular or massive limestones indicative of clear water sedimentation in a period of relatively slow supply of clastic sediments. Micritic limestones alternating with sparry limestones suggest that the Pentamerus Limestone was deposited below normal wave base but that the sediments were partly sorted by storm waves.

The Pentamerus Limestone in the Mjøsa District is overlain by a graptolite shale (7c), which passes upsection into sandy shale and then into the Bruflat

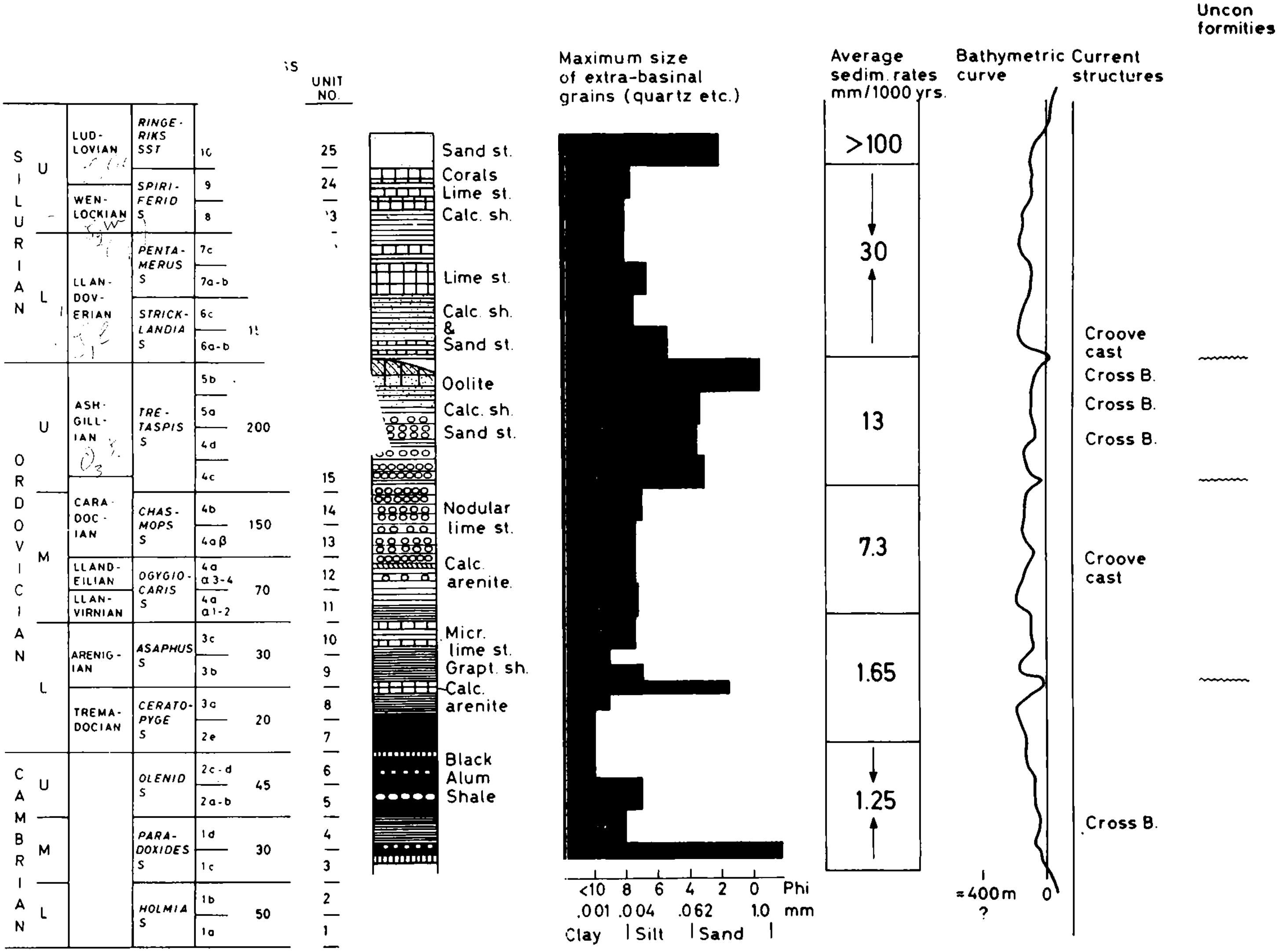

Fig. 13. Simplified stratigraphic Table of the Lower Palaeozoic sequence of the Oslo–Asker District. Measurements of maximum size of extrabasinal grains are based on thin sections of 200 samples collected by the author supplemented by available thin sections in the collections of Department of Geology, University of Oslo.
Average sedimentation rates are calculated by dividing stratigraphic thickness by the estimated duration of the geologic periods. The bathymetric curve represents an interpretation of the relative depositional depth.

Sandstone, which represents a true deltaic facies. The presence of deltaic sediments in the Mjøsa District dates the formation of a tectonic land to the northwest, produced by orogenic uplifts. The age of the Bruflat Sandstone is not very well defined but corresponds most probably to Wenlock (stage 8) (Skjeseth 1963). The Bruflat Sandstone represents the initiation of a period of delta sedimentation, which gradually filled up the shallow sea with clastic sediments. The Ringerike Sandstone represents a continuation of this process but we have no means of telling if this process was completely gradual or if the Bruflat Sandstone was deposited during an early phase of uplift followed by a period of lower supply of sediments before the deposition of the Ringerike Sandstone.

Palaeocurrent measurements in Silurian sections from the Oslo–Asker District and in the Ringerike District carried out by Whitaker (1965) indicate that currents were dominantly flowing from the west-southwest to the east-northeast, which is a pattern rather similar to that recorded in Ordovician sediments. In the Ringerike Sandstone, however, one finds cross-bedding, indicating transport from the north-northwest (Whitaker 1965).

TECTONIC CONTROL OF LOWER PALAEOZOIC SEDIMENTATION IN THE OSLO DISTRICT

Lower Palaeozoic marine sedimentation in the central part of the Oslo Region (Oslo–Asker District) starts in Middle Cambrian and continues with only minor breaks until Upper Silurian (Ludlovian). This period of time can be estimated to be about 140 m.y. Total thickness of the marine sediments is about 1000 m; the overlying deltaic Ringerike Sandstones is not included in this figure. For the marine sequence this means an average sedimentation ratio of about 7 mm/1000 yrs. In Cambrian and Lower Ordovician times, however, sedimentation rates were close to 1 mm/1000 yrs (Fig. 13). One can observe a rapid increase in the sedimentation rate from the black Cambrian and Lower Ordovician shales up to the Upper Ordovician and Silurian more oxidized calcareous sediments, where sediment rate is about 30 mm/1000 yrs.

The Lower Palaeozoic sediments in the Oslo Region and equivalent sediments present as scattered remnants in Sweden are typical examples of epicontinental sedimentation on a Precambrian shield with low relief and a very slow supply of clastic sediments.

Subsidence of the shield during sedimentation has generally been slow since there is considerable evidence of shallow water environment in the sediments. Rates of subsidence have varied in different parts of the shield. Palaeographic reconstructions (Skjeseth 1952, Størmer 1967) indicate that a zone of maximum subsidence (deeper water) ran from the Lake Mjøsa District through the Oslo–Asker District, continuing southwards west of Skåne. This trend corresponds in a broad way to the direction of the Permian graben. Outside this zone of maximum subsidence, along the western margin of the Oslo Region and eastwards into Sweden, there is evidence of smaller average sedimentation rates, or higher carbonate/shale ratios and more frequent breaks in sedimentation, as would be expected in a more shallow water environment. Breaks in sedimentation, such as those observed in the Skien–Langesund District (Lower Ordovician) and in the Mjøsa District (Upper Ordovician–Lower Silurian) may be due t the formation of highs on the sea floor that received no sediments and t only periodically exposed.

In Ordovician times m tic Shield was covered by fine-grained muddy sediments. Invasion o c quartz or feldspar grains in Upper Ordovician times therefore ind e of magmatic or metamorphic rocks, or the late Precambrian spara hat the energy of the environment was high enough to transport diments. A study of the distribution of the maximum size of clasti grains (Fig. 13) shows that sand was introduced into the Oslo Re ds corresponding to orogenic episodes in the Caledonian geosyncline, rather similar to that described by Størmer (1967). The stratigraph st occurrence of sand-sized quartz grains above the thin shale is at t Ceratopyge Limestone (Tremadocian/Arenigan), which contains a v unt of clastic quartz grains in a thin calcarenite bed. This non-ang nity may correspond in time with the early Ordovician Trondhe e indicated by the Stokkvola Conglomerate in the Trondheim Region kke 1974). The facts that Cambrian and Tremadocian shales are generally devoid of chlorite and that this mineral occurs in the sediments above the Ceratopyge Limestone have been interpreted as evidence of emerging island arc systems (Gale & Roberts 1972) in the eugeosynclinal regions to the north-west (Bjørlykke 1974). The Middle Ordovician sediments of the central part of the Oslo Region (Oslo–Asker District) are very fine-grained, containing practically no sand-sized clastic grains (Fig. 13). In the northern Mjøsa District, however, the Robergia Beds (basal Caradocian) contain cross-bedded sandstones in their upper parts (Skjeseth 1963, p. 74). The Tretaspis Shale at the base of the Ordovician, however, includes sandy beds and a conglomerate with phosphorite and carbonate fragments. In the upper part of Upper Ordovician (5a–5b) there is evidence of increasingly shallow conditions towards the top of the Ordovician succession, where coarse oolite and quartz sandstones are found below the Ordovician/Silurian unconformity.

The Upper Ordovician uplift and the increased supply of coarser clastic sediments correspond in time with the Ekne Disturbance and the Horg Disturbance (Vogt 1945) of the Taconic phase in the Trondheim Region. The Lower Silurian transgression in the Oslo Region was probably due to a slow crustal subsidence. During the deposition of the upper part of stage 6 and stage 7 sedimentation was faster than the subsidence, resulting in increasingly shallow conditions. In sediments of stages 8 and 9 mudcracks are found in some localities, suggesting periods of subaerial exposure. Late organic molasse-type sedimentation starts in the northern parts of the Oslo Region (Lake Mjøsa District) in early Wenlockian times with the deposition of the Bruflat sandstone. As the late orogenic uplift of the Caledonides progressed, the shallow marine sediments of the Oslo Region were succeeded by deltaic sediments. The Ringerike sandstone was deposited during a southward progressive filling up of the shallow marine sea in Ludlovian times.

Geochemistry

INTRODUCTION

The chemistry of sediments can be used to characterize and classify sedimentary environments. Chemical data are, however, only one kind of information relevant for the interpretation of sedimentary environments. The geochemistry of sediments helps to interpret the provenance and the physical chemistry of the environments but is rarely sufficient for an environmental interpretation. Sedimentary structures, textures and palaeontological evidence also provide important information, which sometimes may apparently contradict conclusions drawn purely on the basis of chemical evidence. In the author's opinion a purely statistical treatment of geochemical data as presented by Vine (1966, 1969) and Vine & Tourtelot (1969) without any information on the mineralogy of the sediments or on the sedimentary environment has severe limitations.

In the present paper the author will not attempt to classify the sediments purely on the basis of their geochemistry alone but will use geochemistry as a line of evidence in addition to those available from sedimentological, stratigraphical and palaeontological studies.

Armands (1972b), following Vine & Tourtelot (1969), distinguished 5 fractions in sedimentary rocks: (1) clastic, (2) organic, (3) authigenic, (4) sulphide, and (5) carbonate fractions.

The sediments in the Oslo Region can naturally be divided into 3 main groups:

1) Carbonates
2) Grey shales
3) Black shales

The petrology and geochemistry of the carbonate sediments will be discussed separately, and Mg and Sr analyses will be used to interpret depositional environment and diagenesis.

Grey shales consist predominantly of clastic minerals but also contain some authigenic silicate minerals, such as feldspar. Considering that the clay minerals are essentially clastic in origin (Bjørlykke 1974), the composition of shales is controlled largely by the source rock and the climatic and erosional environment in the source area. The major element composition of shales will be discussed in relation to clay mineral content and sand/clay ratios. The distribution of each trace element analysed will then be discussed in relation to stratigraphy and environment. The petrology of the black shales (alum shales) is discussed on the basis of carbon, sulphur, and trace element distribution.

PETROLOGY AND GEOCHEMISTRY OF LOWER PALAEOZOIC CARBONATE ROCKS OF THE OSLO REGION

Literature on Lower Palaeozoic carbonate rocks from the Oslo Region has largely been devoted to descriptions of the fauna and discussions of stratigraphic relationships. Relatively little has so far been published on the mineralogical and chemical composition of these sediments. Holtedahl (1912) published some carbonate analyses as a part of a survey of limestones of potential economic interest in the Oslo Region. His data, mostly obtained from relatively pure limestones, showed very low MgO contents, commonly below 1% and rarely above 2%. It was therefore natural to assume that dolomite did not occur in any significant quantities in the limestones of the Oslo Region. Dolomite was first identified from the Mjøsa Limestone by Jørgensen & Spjeldnæs (1964) and later by Antun (1967) from Lower Ordovician calcareous shales at Asker. X-ray diffraction analyses of more than 200 shale and limestone samples from the Oslo Region carried out by the present author indicate that dolomite is a relatively common mineral in the Lower Palaeozoic sediments of the Oslo Region. Dolomite is, however, most prominent in the calcareous shales and impure limestones. The pure limestones contain little or no dolomite, which explains why Holtedahl (1912) failed to detect any magnesium carbonates. Although dolomite is a relatively common mineral it is quantitatively not very important. Analyses from the Oslo District (Fig. 14) show that only calcareous shales with less than 20% $CaCO_3$ have a high dolomite/calcite ratio (I 2.88Å/I 3.03Å).

Dolomitization

In order to interpret the observed pattern of dolomite distribution in the limestones of the Oslo Region, it is important to distinguish between early and late diagenetic dolomitization. The conditions required for early diagenetic dolomitization are now well understood, through studies of modern carbonate environments (for summary see Bathurst 1971). It is apparent from these studies that dolomite is formed by replacement of aragonite or calcite in an environment of high Mg^{++}/Ca^{++} ratio (7–12) (Müller 1970). Since the Mg^{++}/Ca^{++} ratio is about 5 in normal sea water, dolomite does not form in contact with open sea water. In environments of restricted circulation and evaporation, precipitation of calcium salts, mainly aragonite and gypsum, may increase the Mg^{++}/Ca^{++} ratio above 7. Aragonite will then react with sea water and dolomite will form. Early diagenetic dolomite is therefore of great environmental significance.

Late diagenetic dolomitization occurs when water circulates through the sediments after relatively deep burial and reacts with calcium carbonate to form dolomite. Garrels et al. (1960) have shown that the Mg^{++} concentration required to form Mg carbonates (dolomite, huntite and magnesite) is dependent upon the degree of hydration of the Mg^{++} ion. At increasing temperatures the hydration of the ions becomes weaker and the Mg^{++} and Ca^{++} ions occur essentially naked. At 80° dolomite may form by interaction

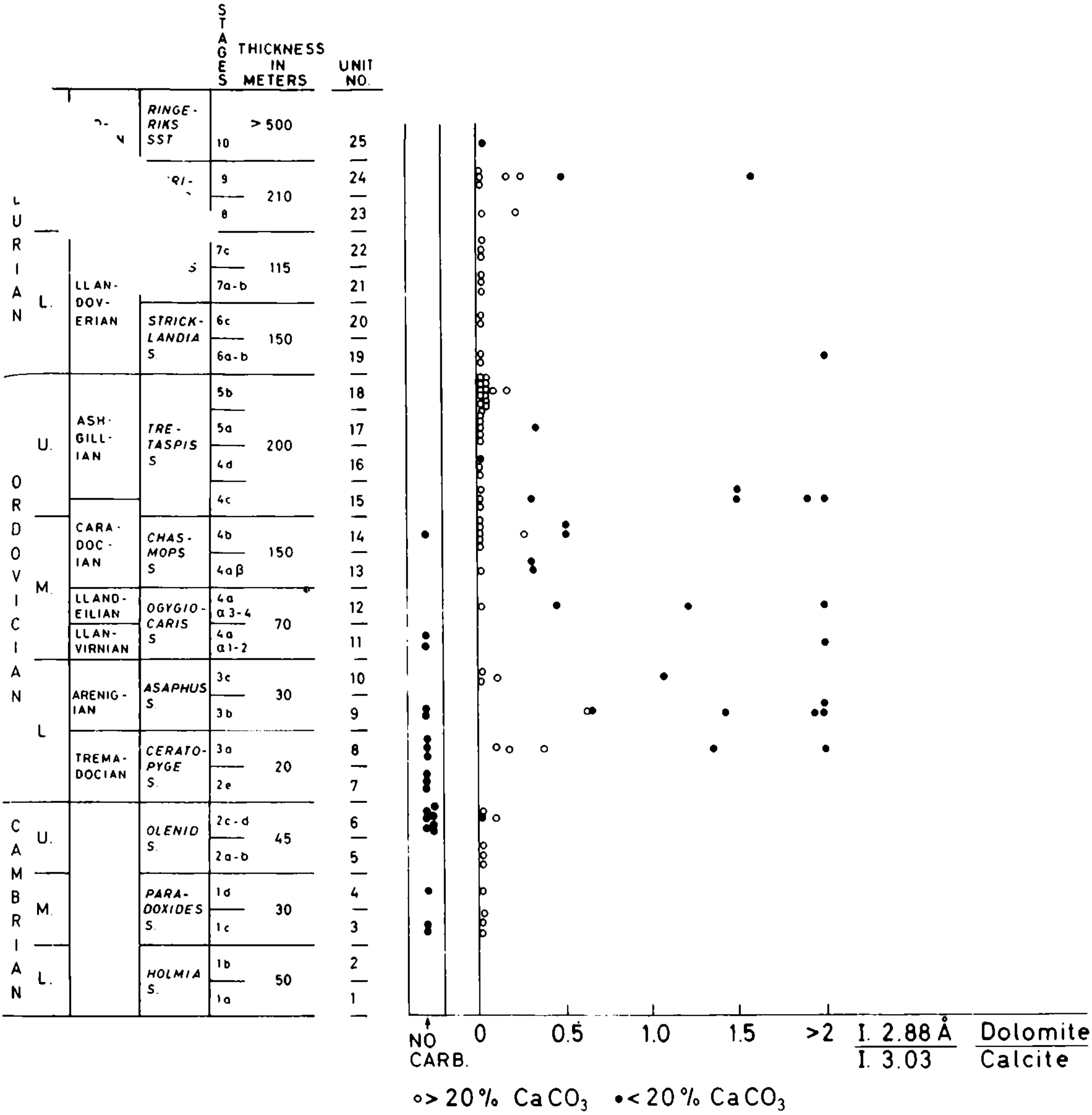

Fig. 14. Dolomite/calcite ratios expressed as I 2.88Å/I 3.03Å in 114 samples of limestones and shale from the Oslo–Asker District.

between calcite and water with Mg^{++}/Ca^{++} as low as 0.20 (Usdowski 1968). During late diagenesis, temperatures may reach 50–80° and dolomitization may take place in contact with water with very low Mg^{++}/Ca^{++}. The low content of dolomite in the limestones of the Oslo Region indicates that conditions were rather unfavourable for both types of diagenetic dolomitization.

Cambrian limestones

The Lower Cambrian in the Ringsaker District consists mainly of sandstones and shales. In the topmost part of the Lower Cambrian succession, however, thin limestone beds occur (Strenuella Limestone, see p. 7). This is a micritic limestone containing about 70% $CaCO_3$. Dolomite is not present and the total MgO content is very low (0.63% MgO). The limestone is light grey in colour with low organic carbon (0.24% C) and sulphur (0.1% S) contents, suggestive of a relatively oxidizing environment.

The Middle Cambrian limestones (Paradoxides Limestone) of the Oslo–Asker District near the Precambrian basement are developed as trilobite biosparites consisting of a grain-supported structure of trilobite tests and occasional sand-sized fragments of basement rocks (Fig. 2). The carbonate content is about 90% and no dolomite has been detected. These limestones have probably been deposited as carbonate sand in a relatively high energy environment. In the upper part of the Middle Cambrian (1d) fine-grained calcarenites occur in cross-laminated carbonate layers. These beds are associated with grey shales deposited in a more oxidizing environment, probably in shallow water.

The Upper Cambrian limestones consist of trilobite tests in a micritic matrix. The amount of matrix is, however, so low that the tests commonly form a grain-supported structure (Fig. 3). The thin tests of the family Olenidae are well preserved in almost whole pieces, suggesting very quiet water (Henningsmoen 1957). The depositional depth may not have been very great, but the low content of matrix suggests that the production of carbonate mud was very small. In modern carbonate environments, carbonate mud is mostly produced by algae (Bathurst 1971) and the small amounts of carbonate mud in the Upper Cambrian limestones suggest that the environment in this period was rather unfavourable for algal growth. This agrees well with the assumption that the Upper Cambrian limestones were deposited in an environment which most of the time was undersaturated with respect to calcium carbonate (Bjørlykke 1973). The Upper Cambrian limestones are also generally very pure (90% $CaCO_3$) and are devoid of dolomite.

The fact that the Cambrian limestones in the Oslo Region contain no dolomite (Fig. 14), indicates that these limestones were deposited in an environment where there was little post-depositional increase of the Mg^{++}/Ca^{++} ratio. Although the Cambrian shales were deposited in a stagnant environment, the limestone beds were most probably accumulated in periods of ventilated conditions with increased circulation of the sea water (see p. 9). Conditions were therefore probably unfavourable for the formation of early diagenetic dolomite in the Cambrian. There is no evidence of the evaporite conditions necessary to produce reflux of water with high Mg^{++}/Ca^{++} ratio that could cause late diagenetic dolomitization as described by Adams & Rhodes (1960). Limestone beds may also have been sealed off from circulating water by the surrounding black mud of low permeability during later stages of diagenesis.

Lower Ordovician limestones

Some limestone beds and nodules occur in the Ceratopyge Shale. The overlying Ceratopyge Limestone consists of a lower micritic limestone and an upper calcarenite with sand-sized (0.5 mm) quartz and 'glauconite' grains (see p. 13). Quartz and dolomite occur in and around the glauconite grains and have partly grown at the expense of glauconite. Carbonate grains and matrix have also been partly dolomitized. This evidence from thin section studies indicates that the topmost part of the Ceratopyge Limestone has been subjected to late diagenetic dolomitization and silicification. It is significant that only the upper part of the limestone, which probably had a high primary porosity and permeability, has been dolomitized, while the less permeable lower micritic limestone has not been affected.

The hiatus in the Skien–Langesund District (see p. 13) and similar breaks in sedimentation in Sweden, in Tremadocian/Arenigan times, suggest that the Oslo District may have been surrounded by areas of land at this time. Although this land probably had a modest elevation above sea level it might have produced a hydraulic gradient sufficient to circulate sea water with high Mg^{++}/Ca^{++}, concentrated in the near shore environment, through permeable beds in the surrounding sediments. The basal part of the overlying Lower Didymograptus Shale (3b) also contains dolomitic carbonate beds, in which pseudomorphs after barite are found (Bjørlykke & Griffin 1973).

The Orthoceras Limestone consists of two relatively massive biomicritic limestones (3cα and 3γ) separated by a nodular limestone (3cβ) (see p. 14). In his detailed geochemical and mineralogical study of the Orthoceras Limestone, Skaar (1972) detected dolomite in the Oslo–Asker District. Dolomite is, however, usually subordinate to calcite except in the very topmost layer (Skaar 1972). The present author also found small amounts of dolomite in the Orthoceras Limestone at Ottestad in the southernmost part of the Lake Mjøsa District. However, dolomite occurs mainly in the central part of the Oslo Region, probably corresponding to the deepest part of the basin (Skjeseth 1963, Skaar 1972). Thirteen samples from the Orthoceras Limestone analysed by the present author contain an average of 37% CaO (66% $CaCO_3$). In the Lake Mjøsa District and the Skien–Langesund District a higher than average value was found, while the Oslo–Asker and Krekling Districts have lower carbonate contents. The MgO content was low in all areas, generally below 2% MgO.

Middle Ordovician limestones

Middle Ordovician limestones are biomicritic with the exception of a few thin calcarenite beds (see p. 16). Their chemical and mineralogical composition differ very little from those of the Orthoceras Limestone. The MgO content may reach 3–4% but this is mostly due to an increased chlorite content in the clastic fraction (see p. 15). The Middle Ordovician sections in the Oslo Region contain the most typical development of nodular limestones. The Middle Ordovician limestones commonly contain a rich fauna including trilobites and brachiopods, but the fossils always occur in a mud-supported texture. Both texturally and chemically there seems to be little difference between the composition of the limestone nodules and the continuous limestone beds. The author (Bjørlykke 1973) has interpreted these limestone nodules as remains of continuous carbonate beds partly dissolved by subsolution prior to burial. It is significant that the nodular limestone beds are commonly present at transitions between shaly facies and homogeneous limestones. Thirty chemical and mineralogical analyses from Middle Ordovician shales and limestones (*Trinucleus bronni* Zone $4a\alpha_4$) have been published by Bjørlykke (1965).

In the upper part of the Chasmops Series ($4b\delta$) more thick-bedded limestones occur. Following the arguments put forward explaining the origin of the nodular limestones (Bjørlykke 1973), the more massive topmost part indicates continuous carbonate sedimentation in a shallow-water environment uninterrupted by periods of subsolution. These beds may be correlated with major reef developments in the Mjøsa Limestone to the north and in the Skien District to the southwest (Størmer 1953, 1967).

Dolomite in Ordovician calcareous shales

As is apparent from Fig. 14, dolomite occurs mainly in beds stratigraphically above the Ceratopyge Series. Dolomite is, however, mostly present in the shales and very little dolomite is found in the purer limestones. We know from the works of Skjeseth (1952) and Størmer (1967) that accumulation of siliceous mud took place in slight depressions in the floor of an epicontinental sea, surrounded by shallow water where carbonate sedimentation took place. Accumulation of carbonate in areas with restricted circulation would result in a depletion in Ca^{++} relatively to Mg^{++}. This slightly more saline water might flow from the shallow sea into the somewhat deeper parts of the shield, and dolomite could form in the pores of the siliceous mud. Dolomite is found in modern lake sediments where the water has had high Mg^{++}/Ca^{++} ratios (Müller et al. 1972). A study of these lakes suggests that at Mg^{++}/Ca^{++} between 7–12 high-Mg calcite is the primary carbonate mineral. Dolomite may then form diagenetically at the expense of high-Mg calcite. Müller et al. (1972) concluded that carbonate formation is controlled only by the Mg^{++}/Ca^{++} ratio in both marine and non-marine environments. In marine environments high Mg^{++}/Ca^{++} ratios will most likely develop in a near-shore tidal environment in association with evaporites ,while in lakes with restricted circulation the Mg^{++}/Ca^{++} ratio will increase from the shore into deeper water. In an epicontinental sea with restricted circulation, particularly in the deeper parts, the lacustrine model may be more suitable, and may explain the concentration of dolomite in the shales deposited in the deepest part of the 'Oslo basin'.

X-ray diffraction data suggest that the dolomite in the Ordovician shales is not stoichiometric. Using NaCl as an internal standard, following Blatt et al. (1972 p. 478), the 104 reflection was found to be 2.903 Å, which is a significant deviation from the 2.88 value of an ideal dolomite and corresponds approximately to $Ca_{55}Mg_{45}(CO_3)_{100}$. This may suggest that dolomite is still present as protodolomite, as has been found in younger carbonate sediments.

The Mjøsa Limestone

The Mjøsa Limestone ranges in composition from pure calcite to dolomite. The distribution of dolomite does not always follow the primary lithological boundaries and is therefore probably of late diagenetic origin. The Mjøsa Limestone consists of reef or coralgal facies. In thin section dolomite can be observed as scattered rhombs in a calcite matrix, or in some beds as sucrose dolomite, typical of late diagenetic dolomitization. Dolomitization has probably taken place at some depth. In cores drilled through a modern atoll (Funafuti) in the Pacific (Bathurst 1971, p. 356) dolomite was recorded at a depth of about 200 m. It is conceivable that hypersaline conditions existed in a back reef facies to the north of Lake Mjøsa District, producing an evaporite reflux.

The present investigation included 17 whole-rock samples from the Mjøsa Limestone indicating an average of 41% CaO (73% $CaCO_3$) and 4.2% MgO (9% $MgCO_3$). Minor amounts of magnesium are present in silicate minerals.

Thirty-five samples from the Mjøsa Limestone from Eriksrud, Toten (N.G.U. report) contained an average of 83% $CaCO_3$ and 6.4% $MgCO_3$ in acid soluble carbonate.

The MgO content of the Mjøsa Limestone, as well as that of the limestones in the Oslo Region as a whole, is negatively correlated with the CaO content or the total carbonate content (Fig. 18). The fact that samples of Mjøsa Limestone from Eriksrud have a higher total carbonate content and a lower MgO content than the author's samples is consistent with this pattern. Field evidence also suggests that sand and silty beds with high contents of clastic material are preferentially dolomitized. This may be due to higher permeability in the beds having a high content of clastic minerals.

The Upper Ordovician limestones

The lower part of the Upper Ordovician contains nodular limestones and shales rather similar to those of the Middle Ordovician. In the Tretaspis Limestone, however, nodules are smaller (<5 cm) than the Middle Ordovician ones. Larger nodules occur in the Isotelus Limestone (4d). The Upper Ordovician limestones, unlike the Middle Ordovician ones, commonly contain sand-sized clastic grains, mainly quartz and some feldspars. The 5a zone, particularly the lower part, consists of algal (palaeoporella) limestones, while the upper part is developed as a nodular limestone.

The clay mineral content of the limestones is comparatively lower in the Upper Ordovician limestones, particularly in the topmost part (upper part of 5b). (Fig. 15).

The lower part of 5b also consists of nodular limestone with beds of fine-grained calcarenites. Faecal pellets about 0.1 mm in diameter occur in some horizons together with angular quartz and feldspar grains of the same size. In the upper part of stage 5b we have cross-bedded oolitic sandstones. Oolites and quartz grains occur together in widely different proportions but are of relatively uniform size. The quartz grains are well rounded and no

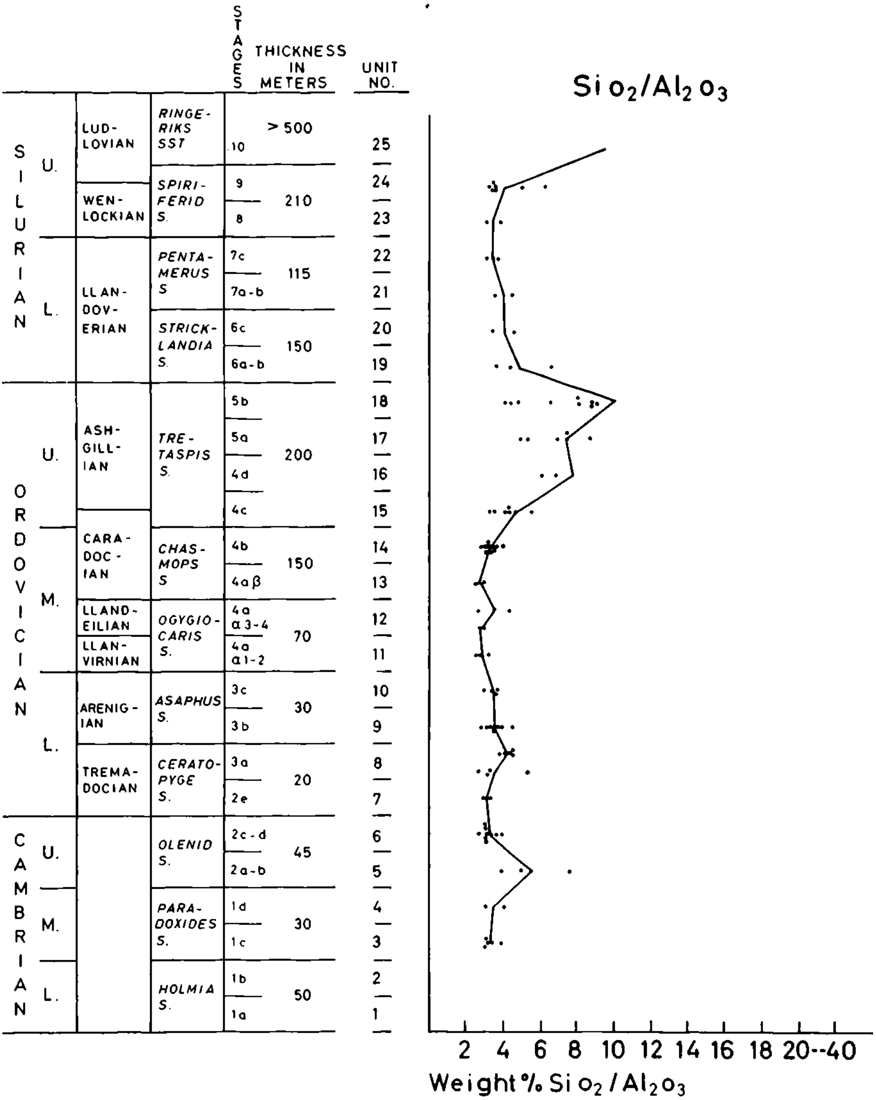

Fig. 15. SiO_2/Al_2O_3 ratios in 114 samples of shale and limestone from the Oslo-Asker District. This ratio is largely controlled by the relative quartz and clay mineral content and is therefore essentially a geochemical expression of sorting.

feldspar occurs in this facies. The matrix consists of sparry calcite. The topmost beds include limestones consisting essentially of oolite fragments in sparry matrix. Oolitic sediments form today in very shallow seas at only a few (1–5) metres depth (Bathurst 1971). The Upper Ordovician limestones (stages 5a–5b) are pure calcite with very little dolomite. It is consistent with the theories referred to earlier that no early diagenetic dolomite is formed in this shallow subtidal environment (see also Müller et al. 1972, p. 163), where there is no evidence of evaporite formation.

The Silurian limestones

The Lower Silurian (stage 6) consists of calcareous shales which may contain some dolomite, particularly in the lower part of stage 6, but the dominant carbonate mineral is calcite. Coarse secondary dolomite rhombs (Fig. 9) suggest a late diagenetic origin.

The Pentamerus Limestone (7a–b) and overlying crinoid shale (7c) are essentially devoid of dolomite. Partial chemical analyses carried out by Oslo Materialprøve Anstalt (N.G.U., unpublished analyses) indicate very small concentrations of Mg-carbonate. The average $CaCO_3$ content of 48 samples was 75.6% with 2.4% $MgCO_3$. The highest Mg content recorded was 3.6% $MgCO_3$. Very pure Pentamerus Limestone at Ringerike (Holtedahl 1912, p. 44) contains 52.5% CaO (94% $CaCO_3$) and only 0.74% MgO. Holtedahl (1912) also refers to similar CaO and MgO values from the purest parts of the Pentamerus Limestone in the Oslo District. Analyses of the Pentamerus Limestone (only 2 samples) carried out by the author are consistent with these findings.

The Upper Silurian (stages 8 and 9) limestones and shales frequently contain dolomite. Seven out of 9 samples contained dolomite but mostly in relatively small concentrations. The increase in dolomite content from stage 7 to stages 8 and 9 coincides with a change in environment from open carbonate shelf to shallow coralgal facies with periods of intertidal and subtidal environment.

MAJOR ELEMENT COMPOSITION OF SEDIMENTS FROM THE OSLO REGION

In the present chemical survey of the sediments of the Oslo Region, shales have been arbitrarily defined as fine-grained sediments containing less than 10% CaO (about 18% $CaCO_3$) (Tables 1–4). Sediments with higher CaO contents are all for this purpose grouped together as limestones and marly shales. Very little calcium is present in minerals other than carbonate, and non-carbonaceous shales contain very small amounts of calcium. The advantage of treating the carbonaceous sediments and the siliceous sediments separately is that the trace element distribution in the later can be discussed without too much interference from the dilution effect of a carbonate matrix.

Dolomite contents are generally so small that MgO present as dolomite contributes only small amounts to the total carbonate content. For each stratigraphic unit the average compositions of 'shales' and 'limestones' have been calculated. These averages and their standard deviations are listed in the data appendix. These stratigraphic units are then grouped together and weighted averages of larger units (Middle Cambrian–Upper Silurian) are calculated based on the relative thickness of the stratigraphic units (see Appendix and Tables 1–2). In the same way the average Cambrian, Ordovician, and Silurian shales are calculated. The Middle and Upper Cambrian shales are grouped together excluding the Lower Cambrian, which is restricted to the very northernmost part of the Oslo Region and which also represents

Table 1. Composition of Lower Palaeozoic shales (CaO < 10%). Weighted averages for stratigraphic units

	Thickness in m	No. of Analyses	SiO_2 %	TiO_2 %	Al_2O_3 %	Fe_2O_3* %	MnO %
Lower Cambrian	50	(5)	65.63	0.87	16.58	6.93	0.08
Middle Cambrian	30	(9)	61.25	1.13	19.14	3.14	0.03
Upper Cambrian	45	(16)	53.78	0.92	16.64	4.73	0.01
Average M.–U. Cambrian		(25)	56.76	1.00	17.64	4.09	0.02
Lower Ordovician	50	(21)	58.38	0.95	18.17	3.32	0.03
Middle Ordovician	220	(33)	54.52	0.77	16.80	7.37	0.06
Upper Ordovician	200	(9)	58.82	0.61	11.65	4.92	0.06
Average Ordovician		(63)	56.86	0.71	14.66	5.83	0.06
Lower Silurian	270	(5)	57.91	0.74	14.20	5.71	0.06
Upper Silurian	310	(2)	50.97	0.71	14.05	6.26	0.09
Average Silurian		(7)	54.89	0.73	14.13	5.95	0.07
Average M. Cambrian–Upper Silurian Shale		(95)	55.87	0.73	14.63	5.76	0.062

* Iron calculated as Fe_2O_3. Iron is mostly present as ferrous iron, which gives high totals for the analyses. Samples from the Ringerike Sandstone and the Bruflat Sandstone are not included in this calculation.

Table 2. Composition of Lower Palaeozoic shales (CaO < 10%). Weighted averages for stratigraphic units

	No. of				Trace elements (ppm)					
	Analyses	Ba	Rb	Sr	V	Ni	Cr	Zn	Cu	S
Lower Cambrian	(5)	432	188	35	223	69	124	105	30	321
Middle Cambrian	(9)	1023	204	25	331	57	138	86	99	7685
Upper Cambrian	(16)	1701	144	50	587	125	141	86	107	37994
Average M. Cambrian–U. Cambrian	(25)	1430	168	40	484	98	140	86	104	25870
Lower Ordovician	(21)	11068	165	157	429	65	129	81	63	7026
Middle Ordovician	(33)	1256	146	185	215	147	274	122	52	4476
Upper Ordovician	(9)	484	123	311	161	152	482	113	45	5742
Average Ordovician	(63)	2003	137	237	214	141	350	113	50	5322
Lower Silurian	(5)	571	163	276	204	125	340	100	37	5537
Upper Silurian	(2)	412	140	170	156	98	112	113	24	394
Average Silurian	(7)	501	153	230	183	113	240	106	31	3301
Average M. Cambrian–U. Silurian	(95)	1265	147	220	219	125	284	108	45	5851

Table 3. Composition of Lower Palaeozoic limestones and marly shales (CaO > 10%). Weighted averages for stratigraphic units

	No. of				Major elements (%)	
	Analyses	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MnO
Lower Cambrian	(1)	19.20	0.21	4.83	3.01	0.52
Middle Cambrian	(8)	9.72	0.08	2.12	1.20	0.11
Upper Cambrian	(9)	4.87	0.04	0.92	0.34	0.15
M. Cambrian–U. Cambrian	(17)	6.81	0.06	1.40	0.68	0.13
Lower Ordovician	(26)	20.97	0.28	5.39	3.23	0.13
Middle Ordovician	(23)	15.60	0.21	4.10	2.65	0.19
Upper Ordovician	(25)	34.27	0.31	4.48	2.27	0.06
Average Ordovician	(74)	24.49	0.26	4.41	2.55	0.13
Lower Silurian	(5)	28.92	0.37	7.31	2.94	0.12
Upper Silurian	(7)	17.28	0.24	4.50	1.85	0.04
Average Silurian	(12)	23.86	0.31	6.09	2.46	0.09
Average M. Cambrian–U. Silurian	(103)	22.93	0.25	4.98	2.37	0.11

ble 1 continued.

MgO %	CaO %	Na_2O %	K_2O %	P_2O_5 %	Loss on ign.	Total
1.83	0.39	0.66	4.24	0.13	3.53	100.87
1.54	0.19	0.90	5.30	0.03	7.92	100.57
1.28	0.39	0.84	4.42	0.06	17.39	100.46
1.38	0.31	0.86	4.77	0.05	13.60	100.48
1.84	2.41	0.88	4.90	0.15	7.86	98.81
3.96	4.28	1.23	4.42	0.11	6.76	100.28
3.47	7.55	1.30	2.74	0.12	8.24	99.48
3.47	5.52	1.22	3.75	0.12	7.54	99.75
3.85	6.01	1.27	3.24	0.05	6.81	99.85
5.25	7.62	1.30	3.28	0.14	10.75	100.39
4.46	6.71	1.28	3.26	0.09	8.52	100.08
3.78	6.12	1.26	3.60	0.10	8.43	100.34

ble 3 continued.

MgO	CaO	Na_2O	K_2O	P_2O_5	Loss on ign.	Total
0.63	39.03	0.40	0.77	0.08	31.37	100.05
1.74	47.51	0.28	0.26	0.23	36.49	99.74
1.65	50.35	0.28	0.16	0.50	40.32	99.58
1.69	49.21	0.28	0.20	0.39	38.79	99.64
2.10	35.41	0.53	1.33	0.30	29.91	99.58
2.73	39.13	0.43	1.00	0.06	33.10	99.20
1.98	29.35	0.69	1.13	0.02	25.00	99.56
2.33	34.37	0.56	1.09	0.06	29.15	99.40
2.17	29.73	0.63	1.89	0.03	26.36	100.47
2.75	38.37	0.49	1.29	0.02	32.29	99.12
2.42	33.49	0.57	1.63	0.03	28.94	99.43
2.33	35.02	0.54	1.28	0.07	29.74	99.62

Table 4. Composition of Lower Palaeozoic limestones and marly shales (CaO > 10%). Weighted averages for stratigraphic units

	No. of Analyses	Trace elements (ppm) Ba	Rb	Sr	V	Ni	Cr	Zn	Cu	S
Lower Cambrian	(1)	68	55	205	19	36	26	14	5	1189
Middle Cambrian	(8)	74	36	265	23	36	24	52	16	3256
Upper Cambrian	(9)	158	12	463	26	35	14	69	32	6436
Average										
M. Cambrian–U. Cambrian	(17)	144	22	384	25	35	18	62	26	5164
Lower Ordovician	(26)	692	62	563	81	49	44	66	22	4492
Middle Ordovician	(23)	336	35	493	71	57	66	44	13	4332
Upper Ordovician	(25)	182	61	1021	60	98	216	53	24	4898
Average Ordovician	(74)	307	50	716	67	74	136	50	19	4601
Lower Silurian	(5)	331	101	498	141	56	69	55	13	2049
Upper Silurian	(7)	197	51	678	61	41	34	50	18	3183
Average Silurian	(12)	273	79	576	106	50	54	53	15	2542
Average M. Cambrian–										
U. Silurian	(103)	280	61	581	82	60	89	52	18	3685

a very different environment. These averages are again used to calculate the average Cambro–Silurian shale. The same calculations are carried out for the limestones (see Tables 3–4). By estimating the percentage of limestones and shales in the Cambrian, Ordovician, and Silurian sequences, one can arrive at a weighted average for the Cambro–Silurian sediments of the Oslo Region (Tables 5 and 6).

Samples from deltaic sediments (Ringerike Sst. and Bruflat Sst.) have been excluded from this compilation. Lower Cambrian sediments are also left out from the final calculation of the average Cambro–Silurian sediment since they only occur in the northern part of the Oslo Region. The calculated average is therefore an estimation of the composition of epicontinental sediments deposited in the Oslo Region from the Middle Cambrian to Upper Silurian time.

The average Cambro–Silurian Shale of the Oslo Region does not differ a great deal in composition from an average of 277 shales taken from the literature (Wedepohl 1970a). A relatively high calcium content (6.12% CaO), however, corresponds to a carbonate content of about 10%. This carbonate matrix dilutes the siliceous matrix, which may explain why the SiO_2 (55.87%) and Al_2O_3 (14.63%) contents are lower than those of the average shale (58.9% SiO_2 and 16.7% Al_2O_3).

Sodium and potassium contents are also very similar to the average shale

Table 5. Composition of Lower Palaeozoic sediments in the Oslo Region. Weighted averages for stratigraphic units (%)

	No. of Analyses	% Carbonates	SiO_2	TiO_2	Al_2O_3	Fe_2O_3
M. Cambrian–U. Cambrian	(42)	10%	51.77	0.91	16.02	3.75
Ordovician	(137)	50%	40.61	0.49	9.54	4.19
Silurian	(19)	60%	36.27	0.48	9.31	3.86
Average M. Cambrian–U. Silurian	(198)		39.39	0.52	9.90	4.01

le 6. Composition in Palaeozoic sediments of the Oslo Region in ppm. Weighted averages of stratigraphic units

	No. samples	% Limestone	Trace elements Ba	Rb	Sr	V	Ni	Cr	Zn	Cu	S
Cambrian–U. Cambrian	(42)	10% carbonates	1301	153	74	436	92	128	84	96	23799
ovician	(137)	50% "	1155	94	477	141	108	243	82	35	4962
rian	(19)	60% "	364	109	432	137	75	128	74	21	2845
rage Cambrian–U. Silurian	(198)		798	105	427	160	98	181	78	33	5325

(Table 1). The shales of the Oslo Region, however, have significantly higher magnesium contents, 3.78% MgO to 2.60% MgO in an average shale. This is mainly due to the high chlorite content in the Middle Ordovician to Silurian shales and to a lesser extent to small amounts of dolomite. The Cambrian and Lower Ordovician shales have MgO contents about 1.28–1.84% because of the low chlorite/illite ratio; this is only 40–60% of the values for an average shale.

Variations in the concentration of the two most important clay mineral groups (Fig. 4), illite and chlorite, are accompanied by a corresponding change in potassium and magnesium contents (Bjørlykke 1974). In some shales dolomite also contributes to the magnesium concentration. However, since the total carbonate content in these shales is relatively low, the magnesium distribution, which is stratigraphically conditioned (see p. 43), is largely controlled by the chlorite content. Similarly the highest potassium values are found in the illite-rich shales. Alumina and silica occur in quartz, feldspar, and clay minerals. Since aluminium is mainly controlled by the clay mineral content and to a lesser extent by feldspar, the SiO_2/Al_2O_3 ratio is well correlated with grain size and sorting in sediments (Pettijohn 1957). In high-energy environments we get well-sorted quartz sand or calcarenite with small amounts of clay minerals and a correspondingly high SiO_2/Al_2O_3 ratio. The shallowing of the basin and the increase in energy level from the base to the top of the Upper Ordovician is well expressed by the increasing SiO_2/Al_2O_3 ratio. (Fig. 15). Feldspar occurs both as a clastic mineral and an authigenic phase (see p. 46).

Cambrian and Lower Ordovician black shales are very fine-grained and contain practically no feldspar visible in the microscope. X-ray diffraction analysis, however, (Fig. 16), shows that they contain rather high concentrations of feldspar. This feldspar is probably entirely diagenetic in origin. The

ble 5 continued.

nO	MgO	CaO	Na_2O	K_2O	P_2O_5	Loss on ign.	Total
.03	1.41	5.20	0.80	4.31	0.08	16.12	100.40
.10	2.90	19.95	0.93	2.42	0.09	18.35	99.47
.08	3.24	22.78	0.85	2.28	0.07	20.77	99.95
.086	2.95	20.21	0.88	2.49	0.08	19.31	99.83

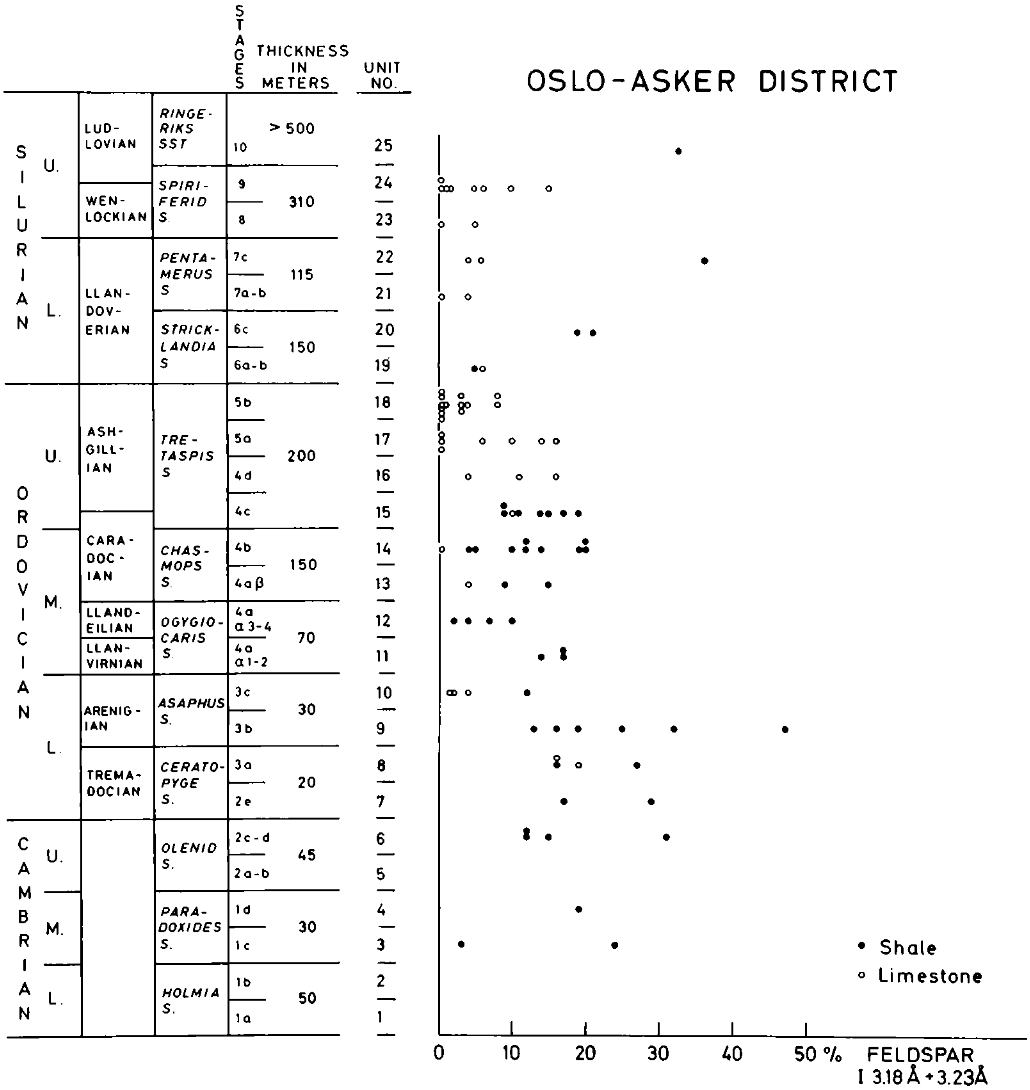

Fig. 16. Distribution of diagenetic and clastic feldspar in 114 samples from the Oslo–Asker District expressed by the intensity of I 3.18Å and I 3.23Å.

occurrence of barium-rich feldspars formed from dissolving barite (Bjørlykke & Griffin 1973) proves that diagenetic formation of feldspar has taken place. These black shales were probably very mature sediments containing very little detrital feldspar. In the Upper Ordovician and Silurian rocks detrital feldspar can be observed in many sandy or silty beds. The increasing Na_2O content (Table 1) and decreasing K_2O/Na_2O ratio (Fig. 27) from Lower Ordovician to Middle and Upper Ordovician times are probably expressions of an increasing content of sodium feldspar.

Iron is present in sulphides and chlorite but only in minor amounts, mostly dioctahedral, in the illite. Sulphide-rich (10% S) Upper Cambrian shales

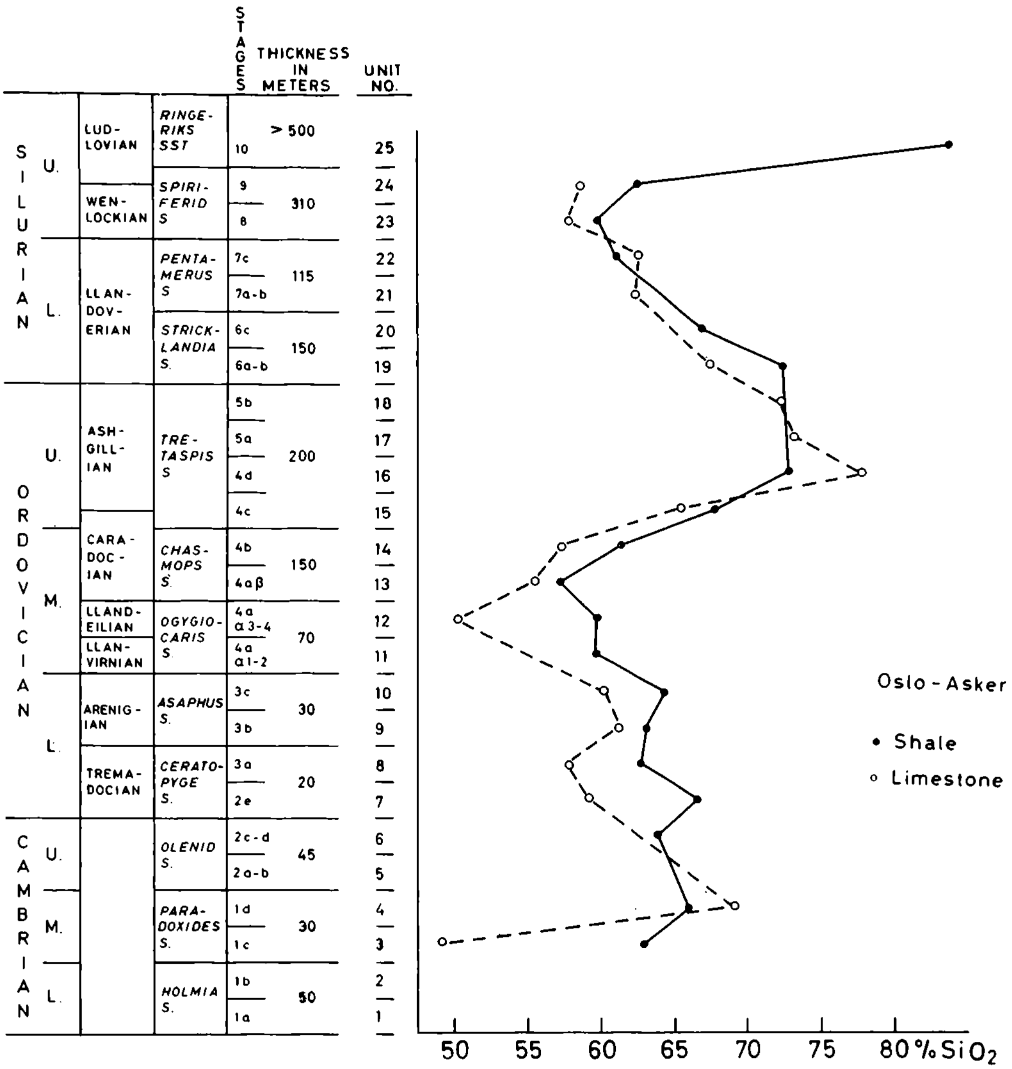

Fig. 17. Average SiO_2 contents in recalculated 'clastic residue' (CaO and loss on ignition subtracted) based on 114 samples of limestones and shales from the Oslo-Asker District.

(Alum shale) contain up to 12% iron as Fe_2O_3. In the shales with low sulphur contents (<1% S), however, iron contents are closely related to chlorite concentrations. Cambrian and Lower Ordovician shales with little pyrite (low S) contain only 1–2% Fe_2O_3, while Middle Ordovician shales contain 8–9% Fe_2O_3. Iron values in Silurian shales are somewhat lower (6–7%) corresponding to a drop in the MgO values (see p. 42). Since both magnesium and iron are present primarily in chlorite in shales with low pyrite contents, and Middle Ordovician shales contain between 8–9% Fe_2O_3 and 4–5% MgO, one arrives at an Fe_2O_3/MgO ratio of about 2 or slightly less. The MgO content in the pure illite shale is about 1% and the MgO contribution from illite in the Middle Ordovician shales can therefore be assumed to be about 0.5% MgO, provided the composition of the illite is approximately constant.

Chemical analyses have been recalculated after subtracting carbonate, sulphide, and carbon (CaO + loss on ignition) (data appendix). It is then possible to get a picture of the composition of the silicate phase in sediments with variable contents of non-detrital phases. It is apparent that the silicate fraction of limestones and calcareous shales differs relatively little from the shales in the same stratigraphic horizon. Some of the high Mg contents in the recalculated values are due to dolomite, which is not subtracted in this recalculation.

Fig. 17 shows that the SiO_2 content of the non-carbonate phase of the sediments varies in a rather systematic manner. The Upper Ordovician carbonate sediments are very siliceous; this is due to a high quartz/clay mineral ratio and confirms the pattern apparent from the SiO_2/Al_2O_3 distribution (Fig. 15).

DISTRIBUTION OF TRACE ELEMENTS

The following trace elements have been analysed by X-ray fluorescence: Sr, Mn, P, Ba, Cr, Ni, Zn, Cu, and V. Radiometric determinations of Th and uranium have been carried out on 9 samples only. A complete list of all the analytical data on which the following discussion is based is printed in a separate data appendix which is available on request from the author. This data appendix also includes Tables of average element content in each stratigraphic unit and calculated standard deviations and also Tables with a correlation matrix for the elements analysed.

In the following chapter the distribution of each trace element is discussed separately. The average trace element contents in the sediments of the Oslo Region are compared with data from an average shale (Wedepohl 1970a) and other Palaeozoic sediments.

STRONTIUM

Strontium in sedimentary rocks is mainly substituting for calcium in carbonate minerals. Cambrian shales, which are generally devoid of carbonate minerals, are characterized by Sr values below 50 ppm, the average of the Lower and Middle Cambrian shales being 40 ppm. This value agrees well with the average Sr content of non-carbonaceous shales (Tonschiefer) which is 39 ppm Sr (Wedepohl 1970b). In the Middle Ordovician to Silurian shales, which usually contain some carbonate, a pronounced increase in Sr contents can be observed. The average Ordovician shale contains 237 ppm and the average Silurian shale 230 ppm Sr. The CaO contents are 5.52% and 6.71% respectively (Table 1). These correspond to Sr/Ca ratios of $6.0 \cdot 10^{\div 3}$ and $4.8 \cdot 10^{\div 3}$, which are comparable to the Sr/Ca ratio of an average shale ($6 \cdot 10^{\div 3}$) (Turekian & Kulp 1956).

The strontium contents are, as expected, higher in the limestones than in the shales. The Sr content does not, however, increase proportionally

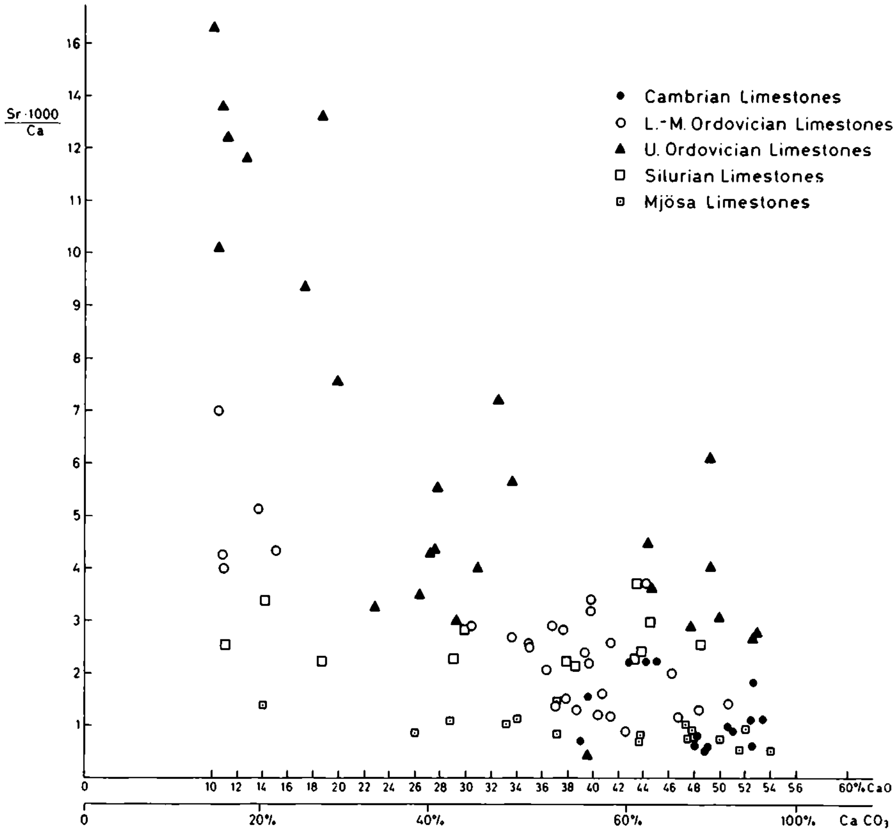

Fig. 18. Sr/Ca ratios in limestones and marly shales (CaO > 10%) plotted against carbonate content.

with the CaO content (Fig. 18). The distribution of Sr in the Lower Palaeozoic limestones is also stratigraphically controlled. The strontium content of the Lower Palaeozoic limestones increases from an average of about 265 ppm in the Middle Cambrian to 1021 ppm in the Upper Ordovician. Silurian limestones have intermediate values (498 ppm Lower Silurian, 678 Upper Silurian).

The weighted average of 581 ppm Sr for the Lower Palaeozoic limestones of the Oslo Region is somewhat higher than average values for limestones reported elsewhere. Averages from North American limestones are 490 ppm Sr and from Scotland 420 ppm (Graf 1962, p. 851). Carbonate rocks on the Russian Platform average 477 ppm Sr (Vinogradov & Ronov 1956b). The comparatively high average Sr values from the Oslo Region are to a large extent due to very high values in the Upper Ordovician limestones.

Modern carbonate sediments contain 7000–10000 ppm Sr depending upon their mineralogical and biological composition (Kinsman 1969, Bathurst 1971). Lithified limestones, however, normally have Sr values about 10% of those in recent sediments. This is due to expulsion of Sr from the crystal lattice into solution during diagenesis and due to the aragonite → calcite transformation. Dolomitization and also dedolomitization will lead to a decrease in Sr content (Shearman & Shirmohammadi 1969). The Sr content in sediments may therefore serve as an indicator of the degree of recrystallization of the limestone. It is notable that the Middle Cambrian Paradoxides limestones, which are biosparitic, have significantly lower Sr content (265 ppm Sr) than the Upper Cambrian limestones (463 ppm Sr), which have a micritic matrix. A sparry matrix precipitated between the bioclasts will normally have a lower Sr content than carbonate mud. Sparites will also have a higher primary porosity, allowing increased circulation of fluids to carry away expelled Sr.

Plotting the $\frac{Sr \cdot 1000}{Ca}$ ratios against % CaO or $CaCO_3$ (Fig. 18) one finds that certain limestones have Sr contents which are approximately proportional to the carbonate contents. This is the case with the Mjøsa Limestone, which also has very low $\frac{Sr}{Ca}$ ratios. The Upper Ordovician limestones, on the other hand, are characterized by a strong negative correlation between $\frac{Sr}{Ca}$ ratio and carbonate content. This means that the Sr content does not vary much as a function of the carbonate content. In shales (<10% CaO) Sr has a positive correlation coefficient (0.722) with CaO. In the limestones and marly shales, however, Sr is negatively correlated with CaO (coefficient ÷ 0.206). Turekian & Kulp (1956) also observed a negative slope of 45° in plots of Sr/Ca ratio against log CaO in shales, showing that Sr contents are independent of carbonate content. Turekian & Kulp (1956) considered this relation to be wholly fortuitous, since calcium occurs both in the carbonate matrix and bound on the clay particles. Such Sr/Ca distributions may, however, be explained by assuming that the degree of recrystallization decreases with increasing clay mineral/carbonate ratio. Carbonate minerals in calcareous shales will occur mostly in small spaces between clay minerals. This is likely to reduce recrystallization and a higher proportion of the expelled Sr will be absorbed to the clay minerals. Campbell & Lerbekmo (1965) have shown that Sr expelled from the reef-facies limestones during dolomitization may be absorbed on the clay minerals in the surrounding shales, which will thus be characterized by high Sr/Ca ratios.

The Mjøsa Limestone has been partly dolomitized and has a very low Sr/Ca ratio. The present material of 17 samples of Mjøsa Limestones from different localities and stratigraphic positions suggests that there is no simple relation between degree of dolomitization and Sr content, as found in the French Jura by Shearman & Shirmohammadi (1969), and Bathurst (1971, p. 264). This may suggest that the Mjøsa Limestone has been evenly recrystallized but that the pore water passing through the sediments has only partly had Mg/Ca ratios sufficient to lead to dolomitization. Usdowski (1968) has estimated that there is an 87% probability that the most commonly occurring pore solution at a temperature of 80° would cause dolomitization. Although dolomitization in the Mjøsa Limestone is probably late diagenetic, it has probably not occurred at very great depth since it is followed by an unconformity and a rather thin Silurian sequence. Lower diagenetic temperatures would lead to lower frequency of dolomitization because of the higher incidence of hydrated Mg^{++} ions as temperature decreases. The possibility of Sr depletion during weak regional metamorphism and folding, however, should not be excluded. This would also explain why the distribution of Sr is not correlated with dolomite content.

One of the most notable results of the present survey of Sr distribution in these sediments is the high Sr/Ca ratios observed in the Upper Ordovician limestones and calcareous shales. The strontium concentrations remaining in limestone after diagenesis are a function of a complex process and it is difficult to explain this high concentration. The Upper Ordovician limestones are locally oolitic, but high Sr contents are not restricted to these beds. Since Sr/Ca ratios in these beds seem to be a function of the clay and silt content of the limestone the Sr distribution can be said to be an expression of how much Sr is trapped in the sediment. One would here naturally assume that in environments with relatively high sedimentation rates the inversion of aragonite to calcite will take place at greater depths and exchange between pore fluid and sea water will be reduced. The Middle Ordovician rocks and lower units have probably been subjected to subsolution and to some extent to concretionary processes, and in an environment with slow sedimentation rates and very shallow burial depth. One would expect that these conditions would favour a more effective exchange of Sr and precipitation of a calcite with relatively low Sr content.

MANGANESE

Manganese may be present in sea water both as divalent and as quadrivalent ions. Divalent manganese is relatively soluble, while 4–valent manganese may precipitate as MnO_2; oxidation to Mn^{4+} takes place at Eh + 0.45 volt in sea water, pH 8 (Carvajal & Landergren 1969). Sediments deposited in reducing environments will therefore be characterized by low manganese contents, while more oxidized sediments may have generally much higher values.

The present data (Fig. 19) show that the Cambrian and Tremadocian black shales are characterized by very low manganese contents (0.01–0.03% MnO). Analyses of Cambrian alum shale from Sweden also indicate very low manganese content (0.01–0.02% Mn) (Carvajal & Landergren 1969, Armands 1972b). The average value for North American black shales (Vine & Tourtelot 1970) is 0.015% Mn. An increase in MnO content can be observed from the Lower Didymograptus Shale (3b) to the top of the Ogygiocaris Series (4aα 3–4) (0.06%). Upper Ordovician and Silurian shales have relatively constant contents of about 0.05–0.07% Mn. Limestones in the Oslo Region generally have higher contents of manganese than do the black shales, because they have been deposited in a more oxidizing environment where Mn has precipitated as MnO_2. Mn is probably also present as $MnCO_3$ in the limestones (Cambrian–L. Ordovician) deposited in a reducing environments (Fig. 19).

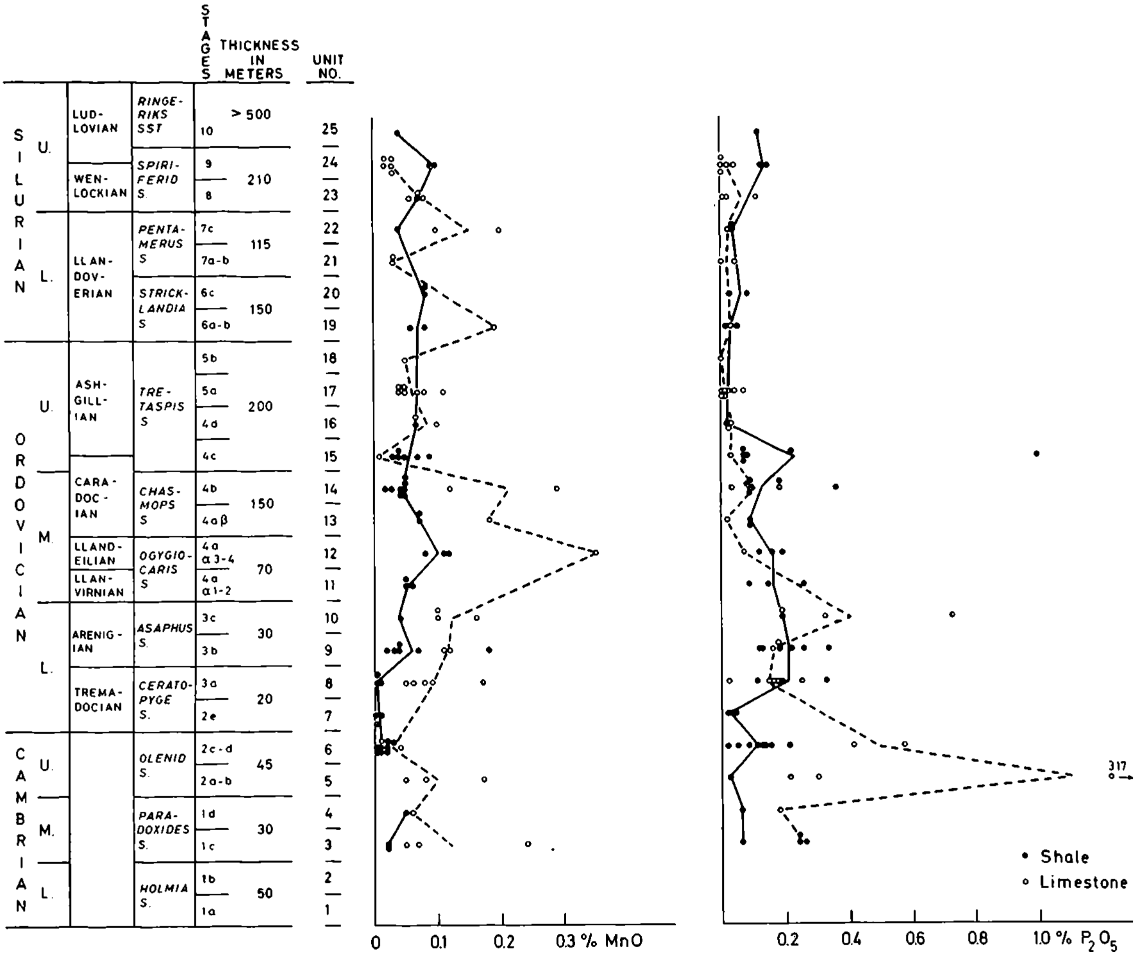

Fig. 19. Distribution of manganese and phosphorus in 114 samples from the Oslo–Asker District.

The highest manganese contents are found in the Middle Ordovician limestones and marly shales (average 0.19% MnO). The regular alternation of shales and nodular limestones in the Middle Ordovician suggests that these sediments were deposited under conditions oscillating between reducing and oxidizing (Bjørlykke 1973). The Upper Ordovician limestones are indicative of more constant shallow oxidizing conditions where the manganese content in the sea water remains low and there would be little supply of manganese. The lower concentrations of manganese (0.06% MnO) in the Upper Ordovician Limestone are therefore consistent with the hypothesis presented above.

The distribution of manganese in sediments on the Russian Shield has been studied in great detail by Ronov & Ermishkina (1959). Four hundred and four composite samples from sediments ranging in age from the Precambrian to the Quaternary averaged 0.063% MnO. These authors also studied the distribution of manganese in relation to sedimentary facies and inferred palaeoclimate. Manganese was shown to be enriched in a coastal facies compared to pelagic and continental/lagoonal facies. However, the MnO content varied mostly within 0.05–0.08% MnO. Manganese was also claimed to be enriched in pelagic sediments of the humid zone. These conclusions, however, depend heavily upon a correct interpretation of the palaeofacies, which may be difficult, particularly in pelagic environments.

Data from the Oslo Region presented here suggest that the MnO content in these sediments is controlled largely by Eh conditions during sedimentation, and by sedimentation rates. The coastal facies of Ronov & Ermishkina (1959) probably corresponds to environments with Eh fluctuation between reducing and further oxidizing, and favouring precipitation of MnO_2 due to oxidation of Mn^{++} to Mn^{4+} (Berner 1971). Deeper-water facies usually represent more constantly reducing conditions and continental and lagoonal facies are more oxidizing. In both cases the MnO contents are relatively lower than in the coastal facies. This agrees well with the observed pattern for the MnO distribution in the Oslo Region.

The average manganese content of the Lower Palaeozoic shales of the Oslo Region is 0.062% MnO, which is somewhat lower than for an average shale (0.085% MnO) (Wedepohl 1970a). This is probably due to the fact that the shales of the Oslo Region have been deposited under generally more reducing conditions than the average shale. The whole of the Lower Palaeozoic sequence (Table 5), including the carbonates, however, gives an average of 0.086% MnO.

PHOSPHORUS

A number of occurrences of phosphorite have been described from the sediments of the Oslo Region. Nystuen (1970) has described phosphorite conglomerates from the basal Cambrian sections at Ena in Trysil. Phosphorite conglomerates also occur in the Lower Middle Cambrian (Oelandicus Zone) from the Mjøsa District (Strand 1929). Higher concentrations of phosphorus are in most cases due to phosphorite layers or conglomerates in association with small unconformities. In addition to the occurrence mentioned above, a phosphorite conglomerate occurs in the Tretaspis Shale (unit 15) 1 m above the Upper Chasmops Limestone (Størmer 1953, p. 68). A sample from this conglomerate contains 1% P_2O_5.

Phosphorus is known to be enriched in hard-grounds formed during periods of non-deposition (Bathurst 1971, p. 409). Practically all occurrences of phosphorites in the Lower Palaeozoic sequence in the Oslo Region are found in beds where there is other evidence of non-deposition, erosion, and possibly also corrosion.

This applies to the basal conglomerate of the Holmia Series, the basal Middle Cambrian Oelandicus Zone, and to the conglomerate in the basal part of the Tretaspis Series. High phosphorus values in the Upper Cambrian limestones and partly also in the Orthoceras Limestone may be related to many small breaks in sedimentation and a generally low sedimentation rate causing enrichment of phosphorite.

The present survey of the sediments of the Oslo Region indicates an average P_2O_5 content of 0.07% in limestones and marly shales and 0.10% P_2O_5 in the shales (Tables 1,3). These values agree well with data from the Russian Platform (Ronov & Korzina 1960), which gave average values of 0.068 and 0.102% P_2O_5 for limestone and shale respectively. The average shale according to Wedepohl (1970a) has, however, a higher P_2O_5 content (0.16%).

The only previous systematic geochemical survey of the Lower Palaeozoic sediments of the Oslo Region was confined to the element phosphorus (Holtedahl 1927). One hundred and twenty-two analyses published by Holtedahl (1927) gave an arithmetic average at 0.126% P_2O_5. The present figure, however, is a weighted average based on the relative thickness of the different stratigraphic units.

In the black shale facies (Middle Cambrian to Lower Ordovician) phosphorus contents are very low, generally 0.03–0.06% P_2O_5. The shales in the Middle Ordovician to Silurian beds, which are usually somewhat calcareous, average from 0.10–0.15% P_2O_5 (Table 1). Phosphorus from organisms will usually go into solution and may precipitate around nuclei such as skeletons to form phosphorite nodules (Ronov & Korzina 1960; Wolff et al. 1967). In the black shale facies carbonate fragments have been dissolved (Bjørlykke 1973) and phosphorus will not precipitate. Phosphorus will therefore be concentrated in the carbonate beds in the black shale facies, which explains its high concentration in Cambrian limestones. In the more oxidizing environment which prevailed during carbonate sedimentation in Middle Ordovician to Silurian times, organic remains will be oxidized except for their hard parts and will therefore contain less phosphorus. The shales have probably been deposited in a slightly more reducing environment and contain concentrations of phosphorus.

BARIUM

The present investigation shows high Ba concentrations in some samples, up to 6–7% Ba in the Lower Ordovician shales of the Oslo Region. In the Oslo–Asker District the highest values are found in the Ceratopyge Shale (unit 8) and in the 3b shale right above the Ceratopyge Limestone. In the Krekling District high values (about 1.5% Ba) also occur in the Dictyonema Shale. Relatively high barium concentrations are also found in some Ordovician limestones, particularly in the Middle Ordovician sediments of the Mjøsa District (Appendix). These analytical data show that high barium values occur in sediments ranging from black shales to light limestones. There are several reports of barite in the Lower Palaeozoic sediments of Scandinavia. Callisen (1914) has described barite crystals in the Cambrian alum shale of Bornholm, and Hadding (1938) has reported several occurrences of barite in Cambrian and Ordovician sediments in Sweden. Hadding also notes that the barite crystals are frequently corroded and in some cases completely dissolved and replaced by marcasite, pyrite, and calcite. 'A secondary formation of barite crystals by the crystallization of the disintegrated and removed material has not been observed anywhere in the series of strata' (Hadding 1938, p. 100).

In the Oslo Region barite crystals from the Lower Middle Ordovician Ogygia Shale at Hovindsholm in the Mjøsa District have been described by Holtedahl (1909). In the Oslo–Asker District the basal part of the 3b shale contains pseudomorphs of about 1 m long crystals which were first interpreted as pseudomorphs after gypsum (Reusch 1884) because they seemed to have swallow-tail twins similar to those of gypsum. Antun (1967), however, has shown that these pseudomorphs are formed after barite.

The present author searched the heavy fraction from beds containing pseudomorphs, but failed to detect any barite. It was natural then to assume that barium was present in the silicate phase, and analytical work with the electron probe indicated the presence of feldspars containing up to 15% BaO (Bjørlykke & Griffin 1973). The electron probe analyses also indicate that barium is present in the clay fraction, but the mineral grains are too small for quantitative analyses. It is significant that in the black or grey shales barium is present in the silicate phase, while barium occurs as barite in Ordovician limestones. This supports the conclusion reached by Bjørlykke & Griffin (1973) that barite becomes unstable due to reduction by organic matter during diagenesis.

CHROMIUM

The distribution of chromium in the Lower Palaeozoic sediments of the Oslo Region shows interesting stratigraphic variations. In the Cambrian shales concentrations are about 140 ppm Cr. In the Ordovician sequence there is an increase in Cr contents up to the Middle Ordovician/Upper Ordovician boundary, and Ni follows a similar trend.

Cr does not enter sulphides to a large extent and Cr is therefore not enriched in the Upper Cambrian sulphide-rich beds as much as is Ni. Cr may, however, be reduced and precipitated as hydroxide. In the Cambrian shales Cr is probably largely present in illite substituting for Al^{3+}. Cr may also be a trace element in chlorites and the observed increase in Cr content in the Middle to Upper Ordovician rock takes place approximately parallel with an increase in chlorite/illite ratio. However, while the 3b shale contains significant amounts of chlorite (Fig. 4) the Cr values are not higher than those of the Cambrian shales (Table 2). The increase in Cr content occurs first in the shales of stage 4a, which indicates exposure of serpentinites in the Trondheim Region (see p. 74).

Very high concentrations of chromium, up to 1200 ppm, occur in some samples of the Tretaspis Shale (4c) and the Chasmops Limestone (4b). These values are too high to be accounted for by the amounts present in chlorites. Electron microprobe examination of heavy fractions proved that chromite grains were present in these samples (Bjørlykke 1974). Cr is positively correlated with Ni (correlation coefficient 0.526) because both elements are enriched in chlorite-rich sediments, but Cr does not follow Ni in

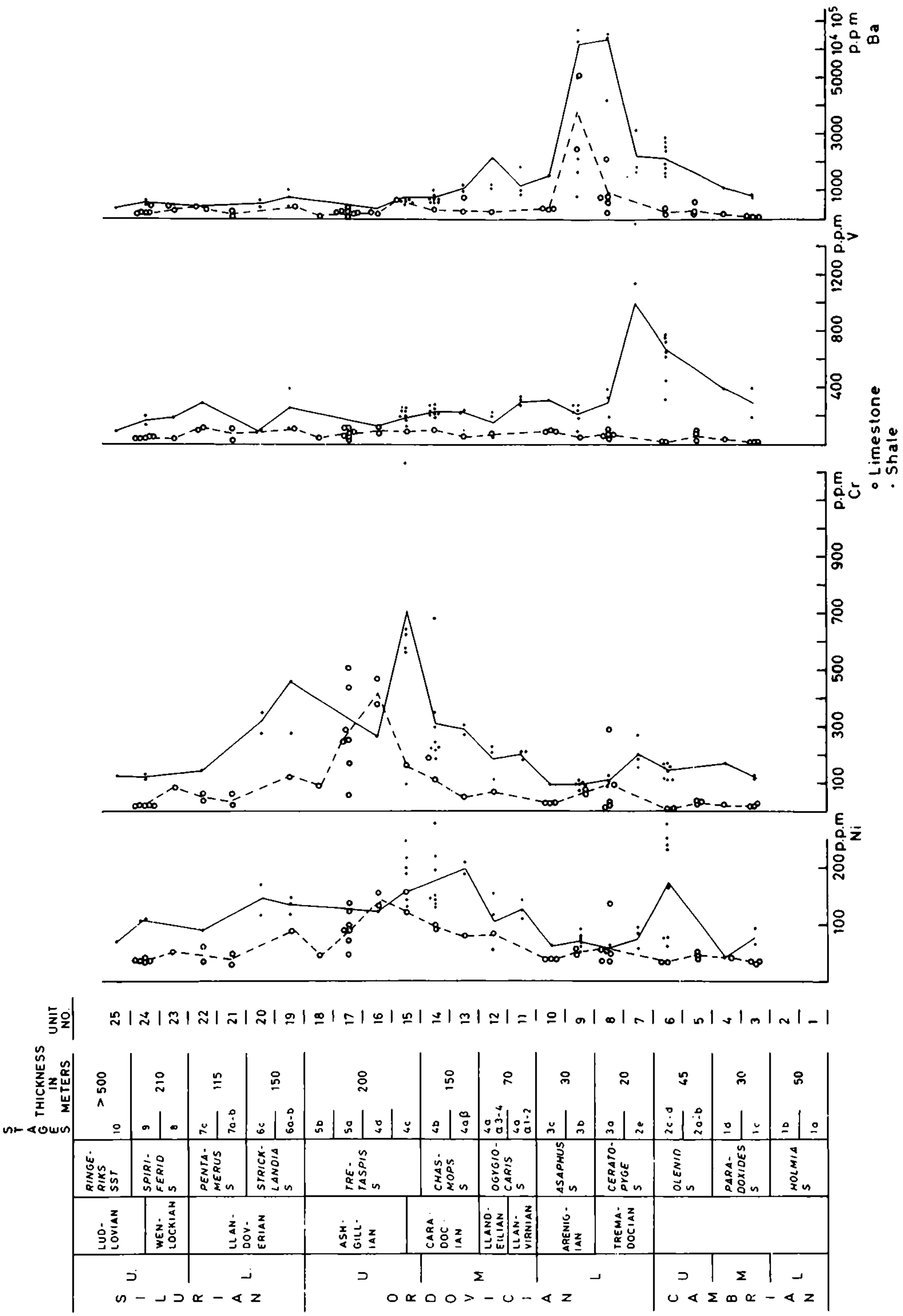

Fig. 20. Stratigraphical distribution of Ni, Cr, V, and Ba in 114 samples of limestone and shale from the Oslo-Asker District.

the sulphide phase, which explains why the correlation coefficient is not higher. Systematic heavy mineral analyses have not yet been carried out and it is possible that small amounts of chromite also exist in shales with lower Cr contents.

The calculated average Cr content for the Lower Palaeozoic shales of the Oslo Region is 284 ppm Cr which is considerably higher than for the average shale (90 ppm) (Wedepohl 1970a). This is mainly due to the high values in the Ordovician and L. Silurian shales.

NICKEL

Nickel is present both in the silicate phase, mainly in chlorites, and in the sulphide phase. In the section through the Lower Palaeozoic sediments of the Oslo Region the Ni distribution has two peaks (Fig. 20). The one in the Upper Cambrian alum shale (unit 6) corresponds to the maximum sulphide content. Four samples of alum shale with sulphur contents between 8–10% S contain between 230–275 ppm Ni. The rest of the Cambrian and Lower Ordovician shales contain 50–70 ppm Ni (Table 2), comparable to an average of 68 ppm (Wedepohl 1970a). In the Middle Ordovician the Ni values climb from 100–120 ppm in Lower Ordovician to about 200 ppm in the Chasmops Series (unit 13). The shales of the upper part of the Chasmops Series (14) and the lower part of the Tretaspis Series (unit 15) show a great spread in the Ni values, ranging from 62 ppm to 275 ppm (Table 2). The X-ray data indicate that there is a positive correlation between the chlorite content and the Ni values in these beds (Table 2). The limestones have generally rather low Ni contents, around 50 ppm or below, but in the impure Middle Ordovician limestones samples with more than 10% CaO contain up to 150 ppm Ni. The Upper Ordovician limestones have a low average clay mineral content; particularly in the upper part they are cleanly washed and therefore contain only small amounts of Ni (Table 4). The Lower Silurian shales (units 19,20) contain between 115 and 168 ppm Ni and higher up in the Silurian succession one finds values around 100 ppm.

RUBIDIUM

Rubidium does not form its own minerals but is always found substituting for potassium and therefore is related to potassium bearing minerals such as feldspar and mica (Goldschmidt 1954, Heier & Adams 1964). The highest rubidium concentrations are found in the Cambrian shales, which have average values about 180–200 ppm. The highest value, 269 ppm Rb, is found in the basal shales of the Paradoxides Zone (unit 3) in the Oslo Region near the Precambrian basement. This is probably due to a high content of clastic mica in sediments deposited immediately after the transgression. The rubidium content of the Upper Cambrian shales (unit 6) is lower (140–150 ppm) than those of the Middle Cambrian, but this is due to dilution by higher content of sulphides and carbon. Higher values around 200 ppm are found in the Dictyonema Shale (unit 7) in the Oslo Region, while the concentration at

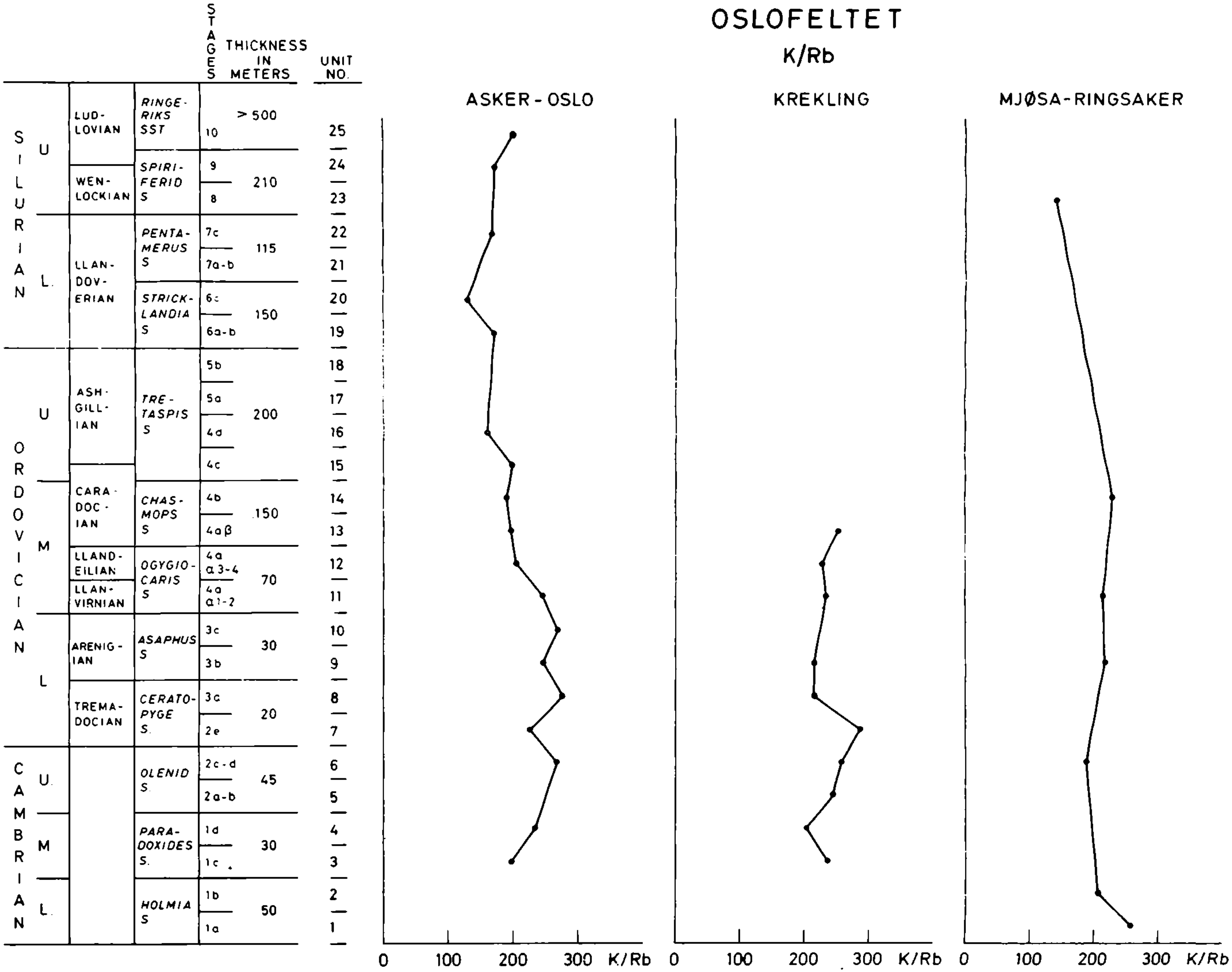

Fig. 21. K/Rb ratios in shales from the Oslo Region.

Krekling is about 160 ppm. The rubidium content in the overlying Ordovician shales averages around 140–150 ppm (Fig. 21). This is a normal Rb content for shales; a compilation of 277 shales from the literature (Wedepohl 1970a) gave an average Rb content of 140 ppm. In the Silurian some higher Rb values are found, but the data here are too sparse to show any trend. The K/Rb ratio in the Cambrian and Lower Ordovician shales (with the exception of unit 3) is higher than in the Middle Ordovician and the Silurian (Fig. 21). It appears from Tables 1 and 2 that this is not due to a higher rubidium content but to a decrease in potassium content from the Lower to the Middle Ordovician beds. From the X-ray data (Fig. 16) one can observe a drop in the intensities of the 3.18 and 3.23Å reflections from the Lower Ordovician (unit 9) to the Middle Ordovician. The coarser-grained siltstones and sandstones in Middle and Upper Ordovician and Silurian contain clastic feldspar clearly visible in the microscope. In the black shale facies the feldspar which is recorded by X-ray is often too fine-grained to be observed in the microscope, and the detection of high-barium feldspars in these shales (Bjørlykke & Griffin 1973) indicates that significant quantities of feldspar were formed diagenetically. It is possible that these diagenetic feldspars formed from pore solutions having a high K/Rb ratio, corresponding to that of sea water (K/Rb=3160; Wedepohl 1970a). This would account for the high K/Rb ratio in the black shales compared to the coarser, more oxidized sediments.

COPPER AND ZINC

Copper concentrations are generally low in the grey shales of the Oslo Region, since copper is closely related to the sulphide content. Average Cu values for Cambrian shales are about 70 ppm. From Fig. 22 one can see that the average content of Cu declines from about 50–60 ppm in the Middle Ordovician to about 20–30 ppm in the Silurian, probably as a response to the more oxidizing environment. These values are very near to the average composition of 227 shales as reported by Wedepohl (1970a). It will appear from Wedepohl's compilation of shales and modern clay sediments that moderately oxidized sediments contain 30–50 ppm Cu. In the limestones the Cu content is lower (Fig. 22), mostly 15–30 ppm. The average Cu content for Lower Palaeozoic limestones is 18 ppm (Table 4). For the whole Lower Palaeozoic sequence the average is 33 ppm Cu (Table 6).

The zinc distribution in the shales does not follow that of copper. Zinc is not much enriched in the alum shale. Cu is more concentrated in the sulphide phase than Zn. This is also indicated by the fact that Cu is well correlated with S (correlation coefficient 0.670) while the correlation coefficient between Zn and S is only 0.131. The average value of unit 6 is 110 ppm, only slightly higher than the average shale (95 ppm) (Wedepohl 1964). The highest concentration of zinc is found in the basal beds of the Middle Ordovician near the Precambrian basement, probably a secondary enrichment. Antun (1967) has observed traces of sphalerite in the alum shale of the Oslo Region, and this survey confirms that Zn sulphides must occur in very small

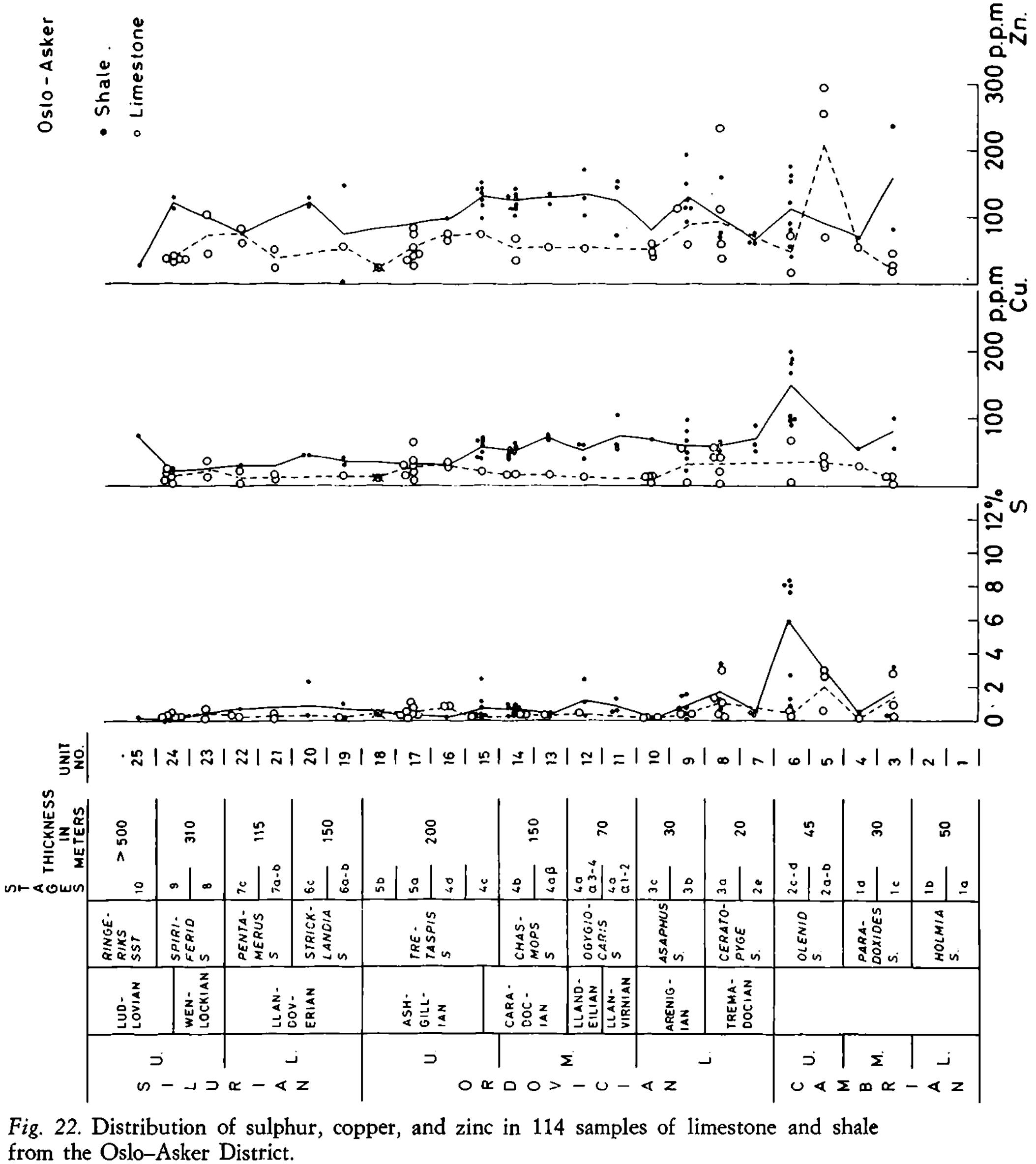

Fig. 22. Distribution of sulphur, copper, and zinc in 114 samples of limestone and shale from the Oslo–Asker District.

amounts. High Zn values are found in lower Upper Cambrian limestones (unit 5) (250–300 ppm Zn).

The maximum Cu concentrations (150–200 ppm Cu) are found in the Peltura Beds (2d) in shale with a high sulphide content (8–10% S). Analyses of Cambrian shales from Billingen, Sweden, suggest that the copper content in the alum shales is significantly higher in Sweden than in the Oslo Region. The average of 53 Upper Cambrian shales published by Armand (1972b) is 190 ppm, which corresponds closely to the highest concentrations found in the Peltura beds of the Oslo Region. The estimated average of 16 Upper Cambrian shales from the Oslo Region is 107 ppm Cu (see Table 2).

Both in Sweden and in the Oslo Region Middle Cambrian shales have somewhat lower copper values.

Microprobe analyses of pyrites from the Cambrian shales at Billingen (Armands 1972b) have demonstrated that Ni, Cu, Zn, and other chalcophile trace elements do not occur in higher concentration than about 100 ppm–500 ppm in these pyrites. This is insufficient to account for the observed concentration of these elements. These trace elements must therefore also be present in the silicate minerals and/or as separate sulphide phases.

In the Oslo Region the Zn content is lower in the Middle and Upper Cambrian shales (86 ppm) than in the Ordovician and Silurian calcareous shales, where average concentrations are between 100–120 ppm Zn. Zinc is therefore not associated with sulphides in these shales and may be assumed to be present to a large extent in the detrital minerals and carbonate.

VANADIUM

Vanadium has a relatively simple distribution pattern in the analysed samples. There is a strong enrichment of V in the Upper Cambrian and Lower Ordovician black shales. The highest values, up to 1500 ppm, are found in the Dictyonema Shale (2e, unit 7), but some horizons in this shale also have low V values (A7 145–278 ppm). The Dictyonema Shale has a relatively low pyrite content, corresponding to a sulphur content of 0.5–1% S, and relatively high carbon content (5–10%). In the Upper Cambrian shales the V values are lower (6–700 ppm). V values in the shales of other stratigraphic horizons vary between 100–300 ppm.

These values agree well with analyses by Goldschmidt (1954) of 18 Ordovician phyllites of the Stavanger District (Norway), which had an average V content of 200 ppm. Goldschmidt (1954) reports that the Dictyonema Shale in Norway and Sweden contains 1000–3000 ppm V, also in agreement with the present data. The geochemistry of vanadium is now relatively well understood and in the Oslo Region the vanadium content is also closely related to the content of organic carbon.

Low Cr/V ratios are frequently used as indicators of reducing depositional environment (Ernst 1970). The assumption is that Cr contents are relatively constant in the clastic fraction, while vanadium is enriched in the organic fraction. In the Oslo Region, however, Cr has been shown to vary within wide ranges. Extremely high Cr/V ratios are found in the Upper Ordovician limestones and shales, where a very oxidizing environment with low V content coincides with large amounts of Cr in the clastic fraction (Fig. 23).

URANIUM AND THORIUM

Uranium and thorium have only been analysed in 9 samples (Table 7). The distribution of these elements and their relative abundance have been studied in some detail by Adams & Weaver (1958). It is apparent from their work that the Th/U ratio is of great environmental significance. Uranium is highly mobile and is easily leached during weathering. It may then be absorbed to

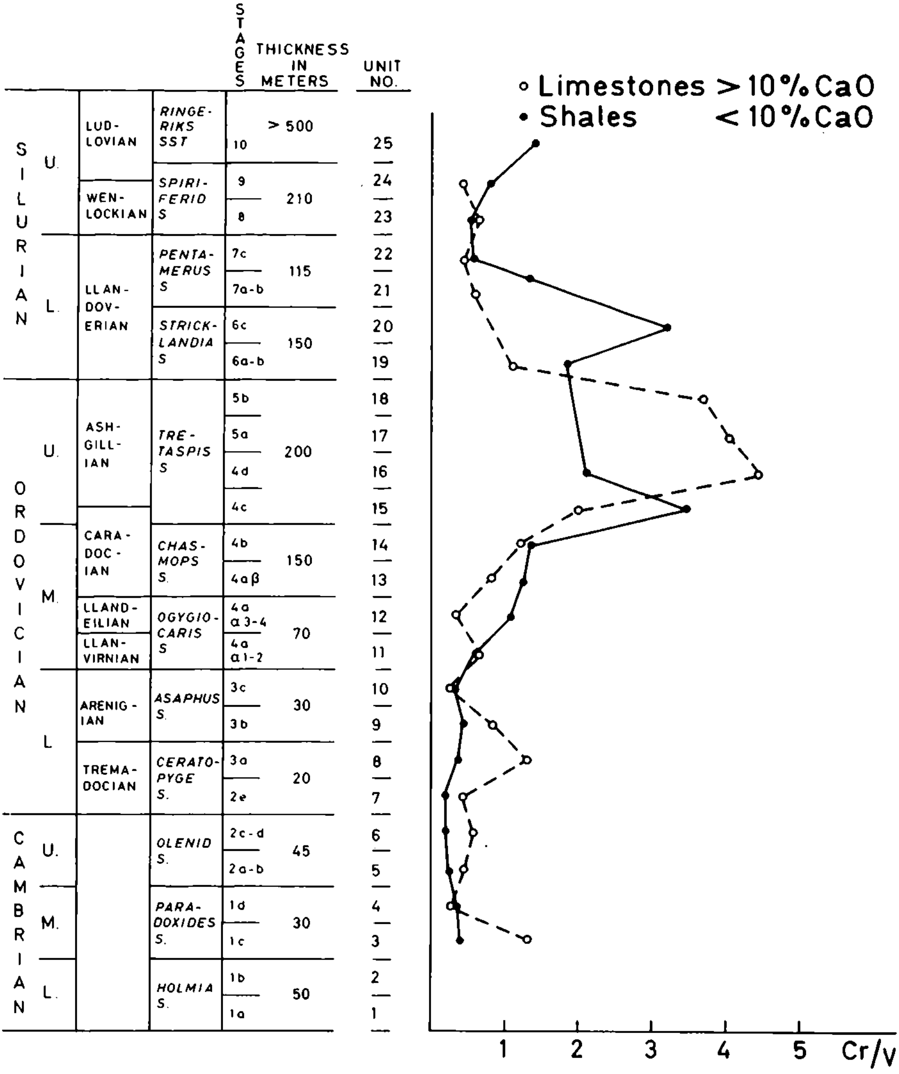

Fig. 23. Average stratigraphic distribution curve for Cr/V ratios.

the organic phase of black mud in reducing environments. Thorium is concentrated in certain minerals such as zircon and monazite in resistate sediments.

Th/U ratios lower than 2 are characteristic of black shale facies (Adams & Weaver 1958, p. 429) while marine grey-green shales have values between 2 and 6. Two samples from the Alum shale (2d) have very low Th/U ratios (0.08 and 0.10) and uranium contents around 150 ppm (Table 7). A sample from the Middle Cambrian Shale contains considerably less uranium (23.7 ppm U), which is also in agreement with the result obtained from uranium prospecting (Skjeseth 1958) and earlier determinations (Strøm 1948).

Another sample from the Lower Ordovician black shale facies (Ceratopyge Shale) also shows a considerably lower uranium concentration (10.4 ppm).

Table 7. Radiometric determinations of uranium and thorium analyses of a selected number of shales and limestones from the Oslo–Asker District

Sample no.			Th (ppm)	U (ppm)	Th/U
A 20 165	(6c)	Silurian, calcareous shale	9.4	2.1	4.48
A 17 164	(5a)	U. Ordovician " "	1.6	0.7	2.29
A 9 171	(3b)	L. Ordovician shale	14.5	2.8	5.18
A 9 163	(3b)	" " "	13.5	2.4	5.63
A 8 161	(3a)	" " "	16.6	10.4	1.60
A 6 162	(2d)	U. Cambrian limestone	0.5	12.5	0.04
A 6 160	(2d)	" " shale	14.0	144.0	0.10
A 6 159	(2d)	" " "	12.0	154.0	0.08
A 3 158	(1c)	M. Cambrian shale	14.3	23.7	0.60

The analyses have been carried out by the Geological Museum, Oslo, under the supervision of A. O. Brunfelt using gamma spectrometer, Na-iodide scintillation detector. Analyst G. Råde.

Four samples from stratigraphically higher units including 3b shale, Upper Ordovician and Silurian shales contained less than 3 ppm uranium and have Th/U ratios between 2 and 6, which is typical for normal marine shales (Adams & Weaver 1958). Thorium concentrations are relatively constant irrespective of facies, except in calcareous shales and limestones, where the concentration is lower. As shown by Adams & Weaver (1958) the thorium concentrations in calcareous sediments are often approximately proportional to the percentage of insoluble residue. Higher uranium contents (400 ppm) are found in the Upper Cambrian alum shale in the autochthonous sequences of South Sweden (Armands 1972b) and of the Caledonian front (Armands 1972a, Gee 1972).

BLACK SHALES

Parts of the Lower Palaeozoic sequence in the Oslo Region have relatively high carbon contents (Fig. 24) (see separate data appendix). The highest values are found in the Upper Cambrian shales which contain an average of about 10% carbon. In the overlying Dictyonema shale carbon contents are more variable. Carbon contents about 8–10% are found in the zones with abundant graptolites, particularly in the Krekling District, while the samples from the Oslo Region contain about 4–5% carbon. Because of the rapid alternations between black and dark-grey shales in the Dictyonema Shale the present data are not sufficient to conclude anything about stratigraphic or regional trends within the Dictyonema Shale.

In the Middle Cambrian the Paradoxides Shale (1c) contains 2–5% carbon, while the Upper Middle Cambrian contains light-grey shales with carbon contents generally below 1%. This shows that the Middle Cambrian shales, which usually are grouped with the Upper Cambrian shales and referred to as 'alum shale', contain beds which have been deposited in a moderately oxidizing environment.

In the Lower Ordovician shales there is a general decrease in carbon

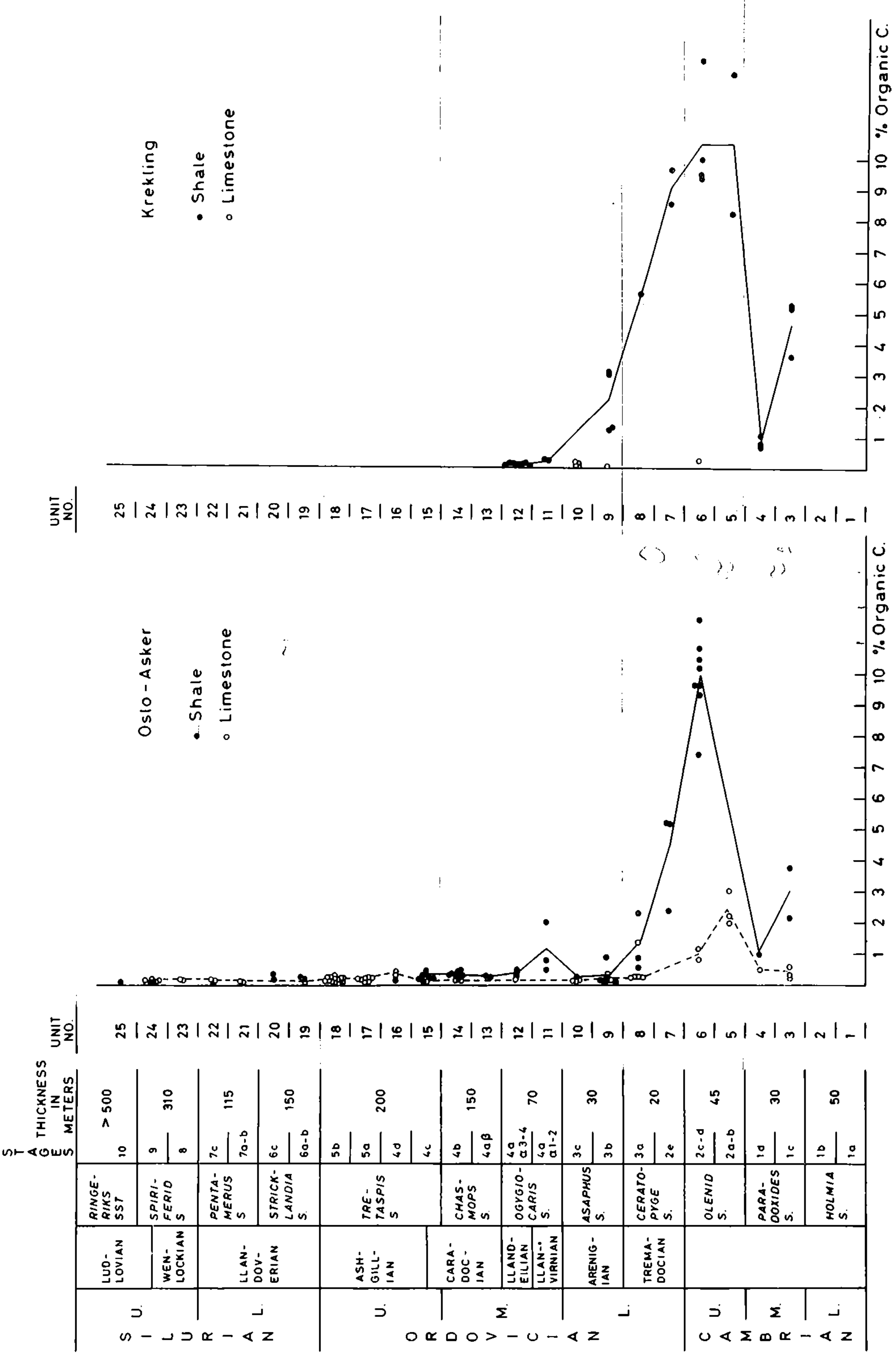

Fig. 24. Distribution of organic carbon in 114 samples from the Oslo–Asker District and 34 samples from the Krekling District.

contents in the sediments toward the upper part. In the Krekling District the Lower Didymograptus Shale (3b) contains up to 3% carbon, while in the Oslo–Asker District carbon contents are generally below 1% C. Carbon contents exceeding 1% may also be found in the Upper Didymograptus Shale but samples from the whole of the overlying Ordovician and Silurian sequences have carbon contents generally between 0.10 and 0.40%. The Tretaspis Shale, which often has been referred to as black shale facies, has generally low carbon contents ($<$ 0.50% C).

Sulphides, mainly pyrite, are important constituents of black shales (Antun 1967). Minor amounts of pyrrhotite, which may cause serious geotechnical problems (Bastiansen et al. 1957), have been formed by secondary alteration of pyrite in the contact metamorphic aureole around igneous intrusions in the Oslo Region (Antun 1967). The amount of pyrite is most accurately measured by the sulphur content (Fig. 22) rather than by X-ray diffraction data. Pyrite is irregularly distributed and occurs partly as nodules, which often makes estimation of average pyrite content difficult. Since both carbon and sulphur are indicative of reducing conditions they have a relatively similar distribution. The highest values of sulphur (8–10%) are found in the Peltura beds. The overlying Dictyonema beds, however, contain only about 0.5–1.3% S, while carbon values are high. This suggests that the Dictyonema Shale was deposited in an environment of high organic production, probably due to the appearance of abundant planktonic organisms such as graptolites.

Relatively low sulphur content in the Middle Cambrian shales compared to Upper Cambrian shales (Fig. 22, Table 2) support the evidence from the carbon analyses that conditions were less reducing in Middle Cambrian than in Upper Cambrian times. M. Ordovician to Silurian grey shales have average sulphur values around 0.5% S.

A voluminous literature has been published on the geochemistry of the black shales. A bibliography with abstracts covering literature from 1930–1965 has been published by Tourtelot (1970). In early literature the black shale facies was usually taken as evidence of deep water environments in basins comparable to the present Black Sea. Later, however, it was realized that very shallow water conditions must have existed during the deposition of several black shales. The German 'Kupferschiefer', which has been subjected to many detailed studies (Wedepohl 1964), was probably deposited in a sea with a maximum depth of 50–100 m (Rentsch 1964). Similarly, Armands (1972b) concluded that the Swedish alum shale was deposited in relatively shallow water. In the Oslo Region the Middle Cambrian shales were probably deposited in very shallow water since they finger into beach conglomerates. Although the Upper Cambrian and lowermost Ordovician shales show little evidence of sorting by waves or currents the depositional depth was probably still rather small (Henningsmoen 1957, Bjørlykke 1974).

Even if the depositional depth was small one must assume that a stagnant bottom layer of water existed below more oxidized water near the surface, separated by a stable pycnocline. Reducing water containing H_2S may precipitate heavy metals as sulphides. Krauskopf (1956), however, demonstrated that the concentrations of these metals in black shales do not correspond to the solubility of the sulphides and concluded that this process could not be the important one in the concentration of metals in black shales. Some elements, particularly Ni, V, and U, are controlled by organic reactions. Wedepohl (1964) has shown that the observed trace element concentrations in the 'Kupferschiefer' cannot have been derived from normal sea water. Similarly, Brongersma-Sanders (1965, 1966) has stressed the importance of a supply mechanism for trace elements, in addition to the removal by precipitation.

TRACE ELEMENTS IN BLACK SHALES

The present analyses of black shales from the Oslo Region indicate that the analysed heavy metals do not occur in very high concentrations.

	Upper Cambrian Alum Shale Oslo Region	Upper Cambrian Alum Shale Sweden (Armands 1972)	Average Shale (Wedepohl 1970a)
Ni ppm	125	160	68
Zn –»–	141	150	95
Cu –»–	107	190	45
Cr –»–	141	94	99
V –»–	530	680	130
U* –»–	150	206	37

* See Table 7.

The Table above shows that Ni, Zn, Cu, and Cr are enriched 2.–3.5 times compared to an average shale (Wedepohl 1970a). Vanadium and uranium, however, have a higher enrichment factor. The Upper Cambrian shales in Sweden (Armands 1972b) show consistently higher values for these metals. The alum shales both in Sweden and in the Oslo Region have high contents of authigenic feldspar (Fig. 16, Armands 1972b). Armands (1972b) found that uranium was not very strongly correlated with organic carbon (correlation coefficient 0.39), but was well correlated with Na–K and K–feldspar. On the basis of statistical calculations and analyses of acid leachable uranium, Armands (1972b) concluded that uranium was associated with several mineral phases including authigenic K–feldspar, phosphorite, organic carbon, sulphur, and detrital minerals such as zircon and titanite.

Microprobe analyses of samples of Dictyonema Shale (Armands 1972b) indicated that vanadium is finely distributed and that sulphides have low V contents, suggesting that vanadium is associated with the organic fraction, which agrees well with the present data. Autoradiographs (Fig. 25) of Upper Cambrian alum shale show that the distribution of uranium follows the primary lamination.

Fig. 25. Autoradiography of hornfelsed alum shale (2d) from Vestfossen. The picture which is negative shows the distribution or uranium as detected by using Kodak A R 10 stripping film. Exposure time 1 month.

SUMMARY ON TRACE ELEMENT DISTRIBUTION

From the discussion of the individual elements it is apparent that some elements have a rather simple distribution pattern, occurring mainly in one fraction of sediments (see p. 33), while other elements occur in two or more fractions.

The distribution of copper is largely controlled by the sulphide phase, and oxidized sediments including limestones have consistently low values. Zinc has a more complex distribution; it occurs partly in the sulphide phase, but is is also enriched in some Cambrian and Lower Ordovician limestones, which represent a carbonate phase in a generally reducing environment. In the Middle Ordovician and Silurian sediments Zn is clearly relatively enriched in the clastic fraction, probably substituting for iron in chlorite. Vanadium and uranium are concentrated in the black shales but while uranium reaches its highest values in the Upper Cambrian beds, the highest concentrations of vanadium are found in Lower Ordovician Dictyonema Shale. While Cu, V, and U are concentrated in black shales with the highest sulphur and carbon content, indicating a very reducing environment, Ba is strongly enriched in the transitional beds between strongly reducing and moderately oxidized sediments, indicated in the Lower Ordovician sequence by alternating grey and black shales. Barite requires periods of sufficiently oxidizing conditions for SO_4^{--} anions to form, but may dissolve due to reducing conditions during diagenesis and enter the silicate phase. Ni occurs in both the clastic silicate phase and in the sulphide phase and has consequently two peaks in its stratigraphic distribution curve. One peak occurs in the Upper Cambrian shales (in the sulphide phase) and a second and higher peak in the Middle and Upper Ordovician shales is due to the presence of Ni substituting for Fe^{++} in chlorites. Cr is not significantly enriched in the sulphide phase (negative correlation –0.09 with S), but its distribution seems to be largely controlled by the chlorite distribution (Fig. 4). Very high Cr values in Middle/Upper Ordovician shales have been shown to be partly due to the presence of detrital chromite (Bjørlykke 1974).

Rubidium substitutes for potassium in illite and in both clastic and authigenic potash feldspar. In carbonate sediments rubidium concentrations are closely related to the percentage of clastic fraction.

Manganese occurs in very low concentrations in black shale facies but is enriched in carbonate beds in the black shale facies and in mainly grey Ordovician shales. Carbonate beds deposited under oxidizing conditions are characterized by low manganese values. Sr/Ca values vary within wide ranges in the carbonate sediments of the Oslo Region, and the highest values are found in Upper Ordovician impure limestones and marly shales. In the limestones Sr/Ca ratios are negatively correlated with CaO content.

Composition of the Lower Palaeozoic sediments in relation to the evolution of the Caledonian geosyncline

Geochemical classification of the sediments

The first attempt to classify Lower Palaeozoic sediments chemically in a systematic manner was by Vogt (1927). On the basis of a maturity index $(K_2O + Al_2O_3)/(MgO + Na_2O + CaO)$ he distinguished between an eastern facies with high maturity and a western facies with low maturity. Bjørlykke (1965), however, demonstrated that the stratigraphic variation between Lower and Upper Ordovician in the Oslo Region covered the same range in geochemical variation as the regional ones observed by Vogt (1927). In expressing the maturity of the sediment, Bjørlykke (1965) preferred to leave out CaO because calcium present in carbonates could easily confuse the classification of the clastic components.

Englund & Jørgensen (1973) proposed the following two parameters for expressing the maturity of sediments:

$$M_1 = \frac{FeO + MgO + Al_2O_3}{K_2O + Na_2O + CaO} \text{ and } M_2 = \frac{Al_2O_3}{FeO + MgO}$$

The facts that iron may be largely present in authigenic minerals such as iron sulphides, and that MgO and CaO could be present in carbonates may, however, reduce the value of these parameters as indicators of maturity. In Englund & Jørgensen's (1973) triangular diagram with end members $(K_2O + Na_2O + CaO)$, $(FeO + MgO)$ and (Al_2O_3), black shales are not easily differentiated from other shales because low MgO values due to small amounts of chlorite may be compensated by high iron contents due to iron sulphides.

The elements potassium, sodium, and calcium are all released by the weathering of feldspars. Potassium may, however, be partly retained in the sediments as illite in environments with high K^+/H^+ ratio (Garrels & Christ 1965). This may be the case particularly in arid or poorly drained environments. Calcium and sodium from the weathering of silicates will normally go into solution more readily than potassium so that the K_2O/Na_2O ratio may be indicative not only of the initial stages of weathering but also of provenance. In sediments with little or no kaolinite, such as those of the Lower Palaeozoic in the Oslo Region, potassium will belong to the stable elements and may conveniently be grouped with aluminium, as proposed by Vogt (1927). Sodium and magnesium are mostly present in albite and chlorite, respectively, in the sediments of the Oslo Region. In the Trondheim Region magnesium is also present in actinolite and small amounts of pyroxenes. Dolomite rarely contributes very significantly to the bulk MgO content of the shales.

The index used in the present paper, $M = (K_2O + Al_2O_3)/(Na_2O + MgO)$, is modified from Vogt (1927), and in the present author's opinion is the best way of classifying the Caledonian sediments, though it may be less useful for other types of sediments. Mineralogically this equation expresses the illite + K–feldspar content relative to the chlorite + albite content. The relative abundances of these minerals are dependent partly on provenance and partly on weathering in the source area. As pointed out by Bjørlykke (1974), chlorite is not stable during continental weathering and forms only in regions of cold climates and/or rapid erosion. Detritus from basic volcanic and plutonic rocks of the Trondheim Region will be rich in chlorite and albite. Precambrian basement rocks on the continental shield will generally have more acid compositions but may produce sediments with relatively high chlorite contents, as seen in the Late Precambrian and Lower Cambrian sediments. When weathering is faster than erosion, however, sediments will be almost devoid of chlorite, which is the case on continents at low altitudes today (Bjørlykke 1974).

The maturity index introduced above ($M = (Al_2O_3 + K_2O)/(MgO + Na_2O)$) is therefore indicative of both maturity and provenance.

MINERALOGICAL AND CHEMICAL COMPOSITION OF SEDIMENTS AS A FUNCTION OF TIME

Vinogradov & Ronov (1956a, b) and Ronov & Migdisov (1971) have compiled large amounts of geochemical data from the sediments on the Russian Platform. When plotting the relative concentrations of elements as a function of time they observed certain trends in element distribution in sediments from the Precambrian to the Quaternary. Some of these trends could also be found in sediments from other continents, e.g. N. America (Schwab 1972). When comparing the composition of older sediments with Mesozoic, Cenozoic, and modern equivalents, it should always be borne in mind how much smaller a percentage of the sediments deposited in the earlier geological

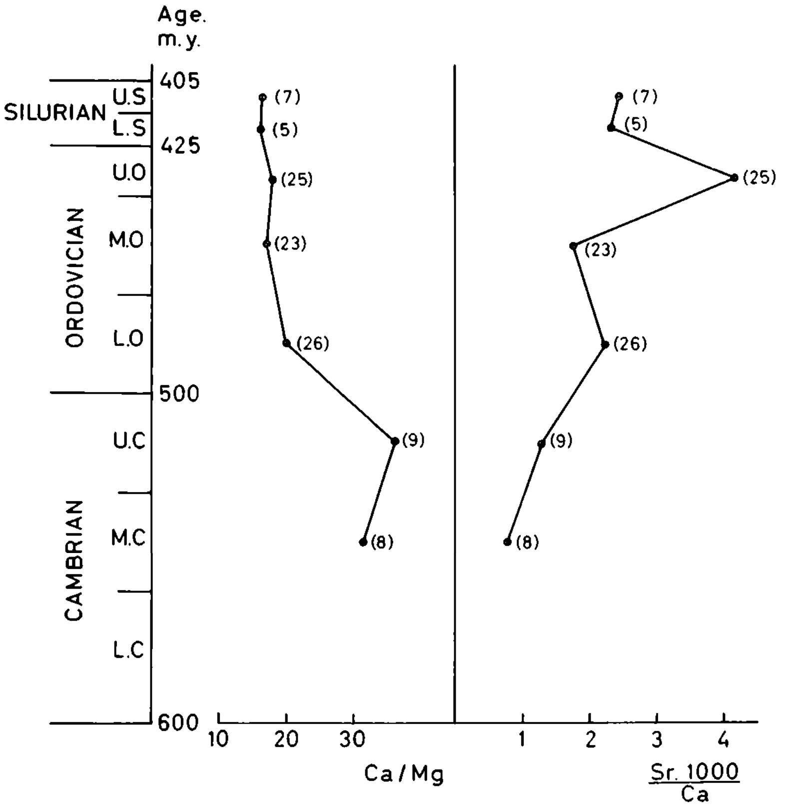

Fig. 26. Distribution of average weight per cent Ca/Mg and Sr/Ca ratios in limestones and marly shales from the Oslo Region. The number of analyses in each stratigraphic unit is indicated in parentheses.

periods is preserved. In the interpretation of the average composition of sediments as a function of their age, distinctions should be made between the results of changes in environment with time and what could be due to the survival factor.

It is important to remember that what is preserved of sediments from older geological periods is probably not representative of what was deposited at that time. As pointed out by Garrels & Mackenzie (1971, p. 297) there is no evidence that the composition of sea water should have changed a great deal since late Precambrian times. The most important changes are probably due to biological factors such as the introduction of plant cover in late Palaeozoic time. An observed decrease in Ca/Mg ratios with time in carbonate sediments on the Russian Shield (Vinogradov & Ronov, 1956b, p. 542, Ronov 1972) has been interpreted by these authors as reflecting a radical change in the conditions of carbonate formation from the Precambrian to the present. The carbonates of the Lower Palaeozoic of the Oslo Region, however, contain very little dolomite and have Ca/Mg ratios between 30 and 40 in the Cambrian and 15 and 20 in the Ordovician and Silurian (Fig. 26). On the Russian platform such high average Ca/Mg ratios are only found in Cretaceous and younger rocks.

Epicontinental sediments of early Palaeozoic age, however, are not likely to be preserved over large areas and the small thicknesses of these sediments make them quantitatively less important than geosynclinal sediments deposited in continental troughs. As mentioned earlier, conditions for dolomitization of epicontinental sediments are not favourable if evaporite facies are not developed. Limestones deposited in sedimentary basins may, however, be more frequently subjected to late diagenic dolomitization due to penetration of pore fluids at higher temperatures (see p. 35) (Usdowski 1968).

Carbonates in such down-faulted or down-warped basins are probably more frequently preserved on continental shields than other sediments deposited at the same time. Obviously the probability of late diagenetic dolomitization increases with time after deposition.

According to Ronov (1956, 1972) an increase in Ca/Mg ratio with time, as observed for carbonate rocks, exists for all sedimentary rock on the continents. The Ca/Mg ratio of clastic sediments will, however, be strongly influenced by small amounts of carbonates. Furthermore, geosynclinal sediments are likely to have higher MgO contents than other sediments because of their frequent association with basic volcanism. The relative frequency of geosynclinal sediments to other preserved sediments probably increases with age.

Problems relating to the MgO content of clastic sediments have been discussed earlier (p. 47) and in other papers (Bjørlykke 1971, 1974). The present author does not advocate the theory that the average composition of sediments or sea water has not changed with time, but would argue that this cannot be adequately proven by the statistical approach presented by Ronov (1972).

COMPOSITION OF LOWER PALAEOZOIC SEDIMENTS

Data on the composition of Lower Palaeozoic sediments are still too few to allow a detailed picture of the geochemical facies to be drawn. However, the fact that the sediments in the different parts of the Caledonides vary in composition within very wide ranges, makes it possible to draw some general conclusions even without a very large statistical basis. A marked increase in MgO content from Lower to Middle Ordovician shales was first observed by Goldschmidt (1926) and this conclusion was further substantiated by Bjørlykke (1965).

In Fig. 27 the present data from the Oslo Region together with analyses published by Wolff (1973) are plotted as a function of the maturity index M and the K_2O/Na_2O ratio. The stratigraphic control and coverage in the eastern Trondheim Region is not as good as in the Oslo Region, but the stratigraphy and the approximate age are known from the Meråker District where the samples have been collected (Wolff 1973).

The index $M = (Al_2O_3 + K_2O)/(Na_2O + MgO)$ for the Cambrian of the Oslo Region is characterized by values close to 10 for the Middle and Upper Cambrian, while values for the Lower Cambrian are somewhat lower, prob-

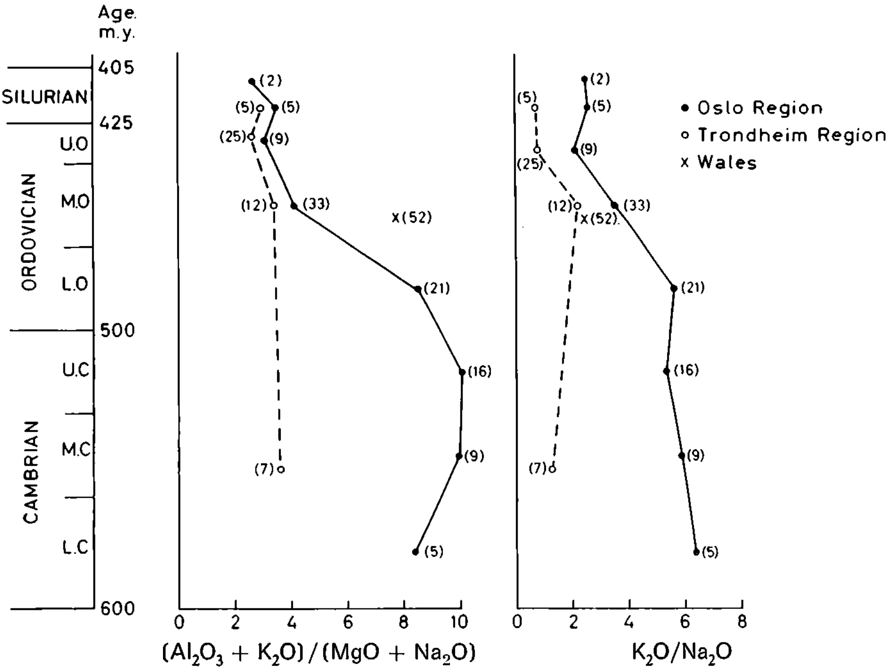

Fig. 27. Average ratios of $(Al_2O_3 + K_2O)/(MgO + Na_2O)$ and K_2O/Na_2O ratios for sediments in different stratigraphic positions from the Oslo Region (present data) from the Trondheim Region (Wolff 1973) and from Wales (Bjørlykke 1971).

ably because these shales contain some chlorite. A very notable decrease in the value of M is observed from the Middle Ordovician to Upper Ordovician and Silurian, as pointed out by Bjørlykke (1965, 1974).

In the sediments of the Meråker area of the eastern Trondheim Region there is only a relatively moderate drop in the value of M from the Cambrian Sonvass Group (Table 8) to the Ordovician Sulåmo Group and from the Kjølhaug Group to the Silurian Slågån Group.

While the compositions of the sediments in the eastern Trondheim and Oslo Regions contrasted strongly in Cambrian and L. Ordovician times they are geochemically rather similar in Middle Ordovician to Silurian times. The higher sodium content in the sediments of the Trondheim Region, however, is very noticeable throughout Lower Palaeozoic times, as expressed by the K_2O/Na_2O ratio (Fig. 27).

Analyses of samples from a Lower to Middle Ordovician autochthonous sediments from Hallingskarvet indicate an important change in composition of the sediments from Lower to Middle Ordovician times (Table 8a–b). The black shales below the limestone, which is probably stratigraphically equivalent to the Orthoceras Limestone, are similar in composition to the L. Ordovician and Cambrian shales in the Oslo Region (Tables 9–10). The green phyllite and volcanic ash above the limestone are characterized by high Fe_2O_3 and MgO contents similar to Ordovician rocks of the Trondheim Region (Table 7). The autochthonous sediments at Hallingskarvet (Hardangervidda) were

Table 8. Average composition of Lower Palaeozoic sediments (mainly phyllites and greywackes) from the Trondheim Region, calculated from analyses published by Wolff (1973)

	Sonsvass gr. (Cambrian)	Sulåmo gr. (M. Ordovician)	Kjølhaug gr. (U. Ordovician)	Slågån gr. (L. Silurian)
No. Samples	(7)	(12)	(25)	(5)
SiO_2 %	64.10	60.60	59.71	54.60
TiO_2 -»-	0.79	0.74	0.78	0.80
Al_2O_3 -»-	13.43	15.60	13.22	16.00
Fe_2O_3 -»-	8.15	6.91	6.39	7.20
MnO -»-	0.23	0.07	0.12	0.13
MgO -»-	2.75	4.26	3.55	5.00
CaO -»-	4.73	1.63	5.08	4.30
Na_2O -»-	1.73	1.36	2.10	1.84
K_2O -»-	2.25	2.86	1.84	2.51

probably deposited in an intermediate position between an epicontinental sea on the shield and the eugeosyncline to the north–west. It is important to note that up to early Ordovician times there is no supply of volcanic sediments or chlorite-bearing clay from the north–west to the Hardangervidda Region.

As long as the volcanicity in the Trondheim Region was largely submarine very little volcanic material seems to have been brought into suspension (Bjørlykke 1974).

Lower Palaeozoic sediments in the Oslo Region and also in southern Sweden have a high degree of lateral lithological and geochemical continuity. Vertical changes in mineralogical and geochemical composition, however, are often abrupt. This agrees well with the expected distribution pattern for an epicontinental facies model where sedimentation rates are slow and the sediments are supplied from distant sources.

Wales, on the other hand, represents a facies model strongly contrasting the epicontinental model of the Oslo Region. Lower Palaeozoic sediments in Wales have been deposited in a number of fault-controlled basins accompanied by acid volcanism (see Bjørlykke 1971). Here the sources of the sediments are near and sedimentation rates higher than in the Oslo Region. In Wales, therefore, each basin has had its separate development and there is little lateral continuity in the composition of sediments from one sedimentation basin to the next (Bjørlykke 1971).

The low frequency of basic source rocks in Wales has resulted in low MgO content (average 1.40% MgO), while the high incidence of sodium-rich volcanic rocks has resulted in low K_2O/Na_2O ratios comparable to the Trondheim Region (Fig. 27).

PROVENANCE OF CLASTIC SEDIMENTS IN THE OSLO REGION

From the various evidence presented above, it has been shown that the character of the sediments of the Oslo Region has been strongly influenced from Lower/Middle Ordovician times up to the Silurian, by the developing

Table 9. Chemical analyses of Lower and Middle Ordovician samples from Hallingskarvet

		Major elements							
	Sample no.		SiO_2 %	TiO_2 %	Al_2O_3 %	Fe_2O_3 %	MnO %	MgO %	CaO %
Middle Ordovician	C 17	green shale and volc. above limestone	43.18	0.69	15.31	8.43	0.19	7.70	9.64
	C 16		43.76	1.46	12.01	15.35	0.28	6.97	9.98
	C 15		63.38	0.75	15.62	7.97	0.12	3.68	0.35
Lower Ordovician	C 14	Limestone (3C?)	9.59	0.16	2.72	1.16	0.04	1.44	46.67
	C 13	black shale below limestone	81.67	0.60	10.31	0.50	n.d.	1.10	0.11
	C 12		67.56	0.09	18.16	0.69	n.d.	1.72	0.16

Table 10. Chemical analyses of Lower and Middle Ordovician samples from Hallingskarvet

			Trace elements ppm								
	Sample no.		Ba	Rb	Sr	V	Ni	Cr	Zn	Cu	S
Middle Ordovician	C 17	green shale above limestone	11	6	239	223	132	407	71	99	168
	C 16		n.d.	19	82	431	64	86	124	61	1175
	C 15		1231	105	91	236	56	188	106	60	1322
Lower Ordovician	C 14	limestone 3C?	139	30	369	34	33	24	29	14	2765
	C 13	black phyllites below limestone	2683	139	18	211	36	76	38	45	1144
	C 12		4175	197	34	358	37	115	65	47	1719

eugeosyncline far to the north-west. The comparison of the geochemistry of sediments from the eastern Trondheim Region with that from the Oslo Region has also confirmed this general trend. The identification of chromite grains, similar to those in the serpentinites of the Trondheim Region, in upper Middle Ordovician shales and limestones around Oslo suggests that material was transported from exposed horizons in island arc complexes within the eugeosyncline, south-eastwards into the Oslo Region. The usefulness of clastic grains of chromite as a tracer of sediment transport from serpentinite source rocks has also been demonstrated by Iijima (1964), in this case for Quaternary sediments in Japan.

There is little evidence that large parts of the Precambrian Shield around the Oslo Region were exposed or served as an important source of supply

Table 9 continued.

Na_2O %	K_2O %	P_2O_5 %	Loss on ignition %	Total %
3.31	0.30	0.06	10.83	99.76
1.97	0.38	0.15	6.92	99.32
2.30	3.02	0.13	3.28	100.81
0.26	0.89	0.00	36.68	99.68
0.26	3.32	0.05	3.63	101.87
0.45	5.35	0.09	4.90	99.67

of sediments during Lower Palaeozoic sedimentation in the Oslo Region. Where Cambro–Silurian sediments are preserved on the Precambrian basement their character indicates that the basement itself cannot be a possible source rock for these sediments. Certain areas of Precambrian basement without any cover of younger sediment could, however, represent possible source areas. Skjeseth (1962) has demonstrated that erosion of late Precambrian sparagmites occurred in early Ordovician times in the Østerdalen district. This may have been of a local nature since Cambrian sediments are preserved in many of these areas.

In the Telemark Region to the west of the Oslo Region a series of Precambrian supracrustal rocks includes both acid and basic lavas and tuffs (Dons 1960). It cannot be excluded that this area was periodically exposed during Ordovician times, but there is no evidence that the area supplied any great quantity of sediments to the Oslo Region. Lower Ordovician sediments of the western part of the Oslo Region (i.e. the Krekling District) are indicative of a shallow water environment and have higher carbonate/shale ratios than those in the Oslo District (Skjeseth 1952), yet there is no increase in the thickness or grain-size of the clastic sediments to the west. The fact that chlorite first appears in the Lower Ordovician sediments in the 3b shale at the Lake Mjøsa (Ringsaker) and is first recognized at Krekling only in 3c/4a time suggests transport from the north rather than from the west (Bjørlykke 1974).

To the west of the Telemark District on Hardangervidda the Cambro–Silurian cover contains quartzites of probable early Ordovician age (Brøgger 1893). The author agrees with Vogt (1929) that if these clastic sediments were derived from the Telemark District their maturity is indicative of a very low relief in the source area. The autochthonous black shales of probable Cambrian and Lower Ordovician age on Hardangervidda are geochemically very similar to the black shales of the Oslo Region (Tables 9 and 10). If the Telemark basement rocks were exposed and eroded, one would expect chlorite and coarser clastic grains of quartz and feldspar to occur in the Cambrian and Lower Ordovician sequence in the Oslo Region and at Hardangervidda. It therefore seems most probable that these sediments were deposited in a stagnant sea that continued across the Telemark Region. The autochthonous Middle Ordovician sediments at Hardangervidda consist to a large extent of volcanic tuffs (Table 9; Naterstad, personal communication), and are geochemically similar to the sediments of the Trondheim Region (Table 8). The supply of sediments to the Oslo Region was probably by ash fall (as evidenced by the bentonite beds), and by the reworking of volcanic rocks exposed in the island arc region.

The Precambrian rocks are mostly of basic composition as in the Jotun nappe, but they also include granitic rocks. Clastic feldspars in the Upper Ordovician and Lower Silurian sediments of the Oslo Region may have been derived from such rocks; Major (1946) has observed mesoperthites typical of the rocks of the Jotun kindred in these sandstones. A more direct attempt to identify the clastic minerals in the sediments of the Oslo Region and to relate these to different source rocks will be a natural extension of the present research programme. The usefulness of the microprobe in such studies has already been demonstrated by the identification and analysis of chromite grains (Bjørlykke 1974).

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