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ASTRID ANDERSSON, BERTIL DAHLMAN,
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Bertil Dahlman

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Bertil Dahlman spent most of his professional life investigating the Swedish alum shales. An inorganic chemist and mineralogist by training with an initial research interest in mineral chemistry, he joined the Geological Survey of Sweden in 1949 and participated in a wide-ranging prospecting programme focussed on the alum shales of central and southern Sweden. This work led to the identification and development of the Ranstad area in Västergötland. Dahlman was responsible for a large number of unpublished reports on the alum shales, most of which were done under contract and treated as confidential until the 1970s; they remain an important source of information on the shales.

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The Baltoscandian Platform, from Finnmark in northern Norway to Skåne in southern Sweden, was an area of great stability during the Late Cambrian, with deposition of a thin (c. 10–60 m) shale facies along with large amounts of organic matter. This shale deposition started in many areas in the Middle Cambrian and continued in some areas into the earliest Ordovician (Tremadoc). The content of organic matter is commonly in the order of 10 %, locally over 20 % and very occasionally up to nearly 30 %. In areas such as Närke, Östergötland and Kinnekulle, that have not been influenced by temperatures in excess of 100 °C, the brown shales yield significant amounts of oil (Fischer assays of 6–7 %). In other areas, oil-yields are lower or absent; the shales are darker in colour, the organic matter varying in maturation from bituminous to semi-anthracitic or even anthracitic and graphitic towards the interior of the Caledonides. These organic-rich shales, composing the Alum Shale Formation, are remarkable for their syngenetic concentration of a variety of trace elements, in particular, U and V, but also Mo and Ni. Throughout Scandinavia, uranium contents are highest in the *Peltura scarabaeoides* zone reaching a maximum of 306 ppm over a thickness of 3.6 m in the Ranstad area of the Billingen-Falbygden outlier. Vanadium contents generally (Jämtland excepted) do not exceed 1000 ppm in the Upper Cambrian but rise rapidly to 2000–3000 ppm in the *Dictyonema* zones of the Tremadoc. Even in areas where the general level of these trace elements is lower, the variation in their concentrations is closely related to the stratigraphy. This may also be the case further to the south and southwest where black shales of similar age occur in Poland, in the Anglo-Welsh area, and in eastern Canada on Avalon and in the Maritime Provinces.

The Alum Shale Formation contains Sweden's most important reserve of fossil energy; oil yields are significant and greatly increased by retorting in hydrogen under pressure. The formation contains the largest uranium resource in Europe, the uranium-rich unit of the Billingen-Falbygden outlier alone containing about a million tonnes of this element. In the Caledonides, tectonically repeated alum shale successions, several tens of metres thick, contain a combination of unusually high trace element concentrations (200–240 ppm U, 350–400 ppm Mo, 1500–2000 ppm V). The Alum Shale Formation has considerable economic potential.

Introduction

Black shales of Middle and Late Cambrian and locally of earliest Ordovician age are developed extensively in Scandinavia. This shale facies composes a characteristic formation that can be recognized from Finnmark in northernmost Norway to Skåne (Scania) in southernmost Sweden (Fig. 1). In general, the unit is about twenty metres thick; however, greater thicknesses (up to nearly one hundred metres), occur in the southernmost areas in Skåne and around Oslo and also in the Caledonides, where tectonic repetition locally plays an important role. The unit represents a long period of very slow marine deposition and reflects an interval of great stability during the Early Palaeozoic history of the Baltoscandian Platform.

The term alum shale was introduced over three hundred years ago to refer to particular parts of this black shale formation from which the alum salt, $K\,Al\,(SO_4)_2 \cdot 12\,H_2O$ was extracted. The name Alum Shale Formation is used for the entire lithostratigraphic unit throughout Scandinavia. No type section has yet been defined for the formation among the well-preserved outliers on the platform; formation names have been introduced locally in parts of the Caledonides and on Öland.

The formation is dominated by black shales with an organic carbon content ranging up to c. 20 %; it contains subordinate grey shales and silts, particularly in the lower part. Thin, fine sandstone interbeds occur locally, in the lowermost (Middle Cambrian) and uppermost (Lower Ordovician) parts. Bituminous limestone (stinkstone) lenses and discontinuous beds are a characteristic and generally subordinate component; in most areas the carbonate in the formation is concentrated in these stinkstones and the shales generally contain only 1–2 % $CaCO_3$. Small lenses of organic matter (kolm) occur locally at particular levels in the Upper Cambrian stratigraphy. Iron sulphides compose nodules and thin bands and also occur disseminated throughout the formation. General similarity of the formation over Fennoscandia is accompanied by small differences in facies in the various isolated areas of occurrence, allowing local subdivision of the formation into constituent members. In some areas stinkstones are more abundant; in others, thin grey shale

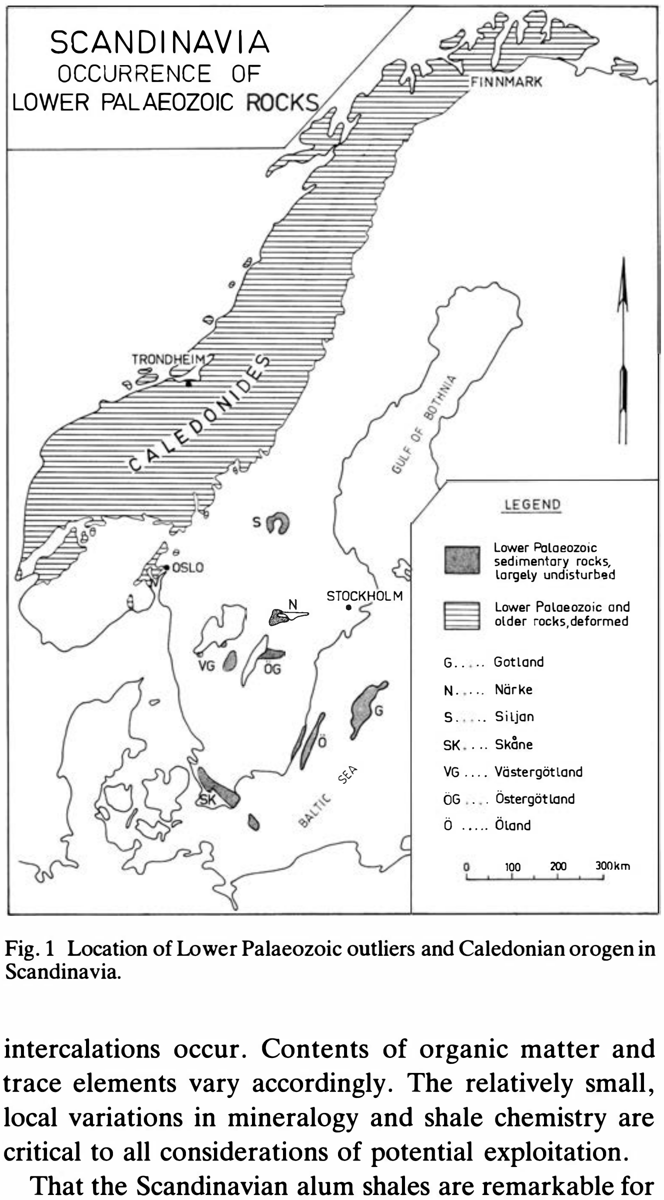

Fig. 1 Location of Lower Palaeozoic outliers and Caledonian orogen in Scandinavia.

intercalations occur. Contents of organic matter and trace elements vary accordingly. The relatively small, local variations in mineralogy and shale chemistry are critical to all considerations of potential exploitation.

That the Scandinavian alum shales are remarkable for their content of uranium has been known since the turn of the century. The local occurrence within the shales of kolm lenses containing up to c. 5 000 ppm U was reported by Nordenskiöld (1893). More recently the shales have been shown to contain unusually high concentrations of other trace elements, particularly vanadium, molybdenum and nickel and some rare earth elements. Table 1 compares particular units of the alum shales with general shale and black shale geochemistry. The presence of the trace elements, along with a high organic carbon content provides the basis for exploitation. That the highest concentrations of the various components of economic interest are seldom enriched together in the same stratigraphic unit in the formation or within any one area is a major frustration to exploitation. The possibility of finding more favourable combinations of trace elements than those known today presents one of the chief incentives for further prospecting.

The development of the black shale facies in the areas of southern and central Sweden in relation to the fossil zones is summarized in Fig. 2. The stinkstone lenses are usually highly fossiliferous, allowing the establishment of a detailed biostratigraphy (Westergård 1922, 1947a, Henningsmoen 1957, Martinsson 1974) and accurate correlation between the different areas of development. In general, the chemistry of the shales is related regionally to the biostratigraphy. Uranium contents are systematically higher in the Upper Cambrian and are highest in the lower part of the *Peltura scarabaeoides* zone. Vanadium is highest in the Lower Ordovician (*Dictyonema* zones). Organic carbon content is generally highest in the Upper Cambrian; in areas where kerogen (organic matter capable of yielding oil on destructive distillation) is present, the oil content is greatest in the zones of *Leptoplastus* and *Protopeltura praecursor*. These and other correlations of chemistry with time of deposition illustrate the extent to which small regional variations in the Cambrian sedimentary environment occurred simultaneously over substantial areas of the Baltoscandian Platform.

Much of the existing information on the Swedish shales is contained in unpublished SGU and company reports. These are extensively cited in Hessland & Armands (1978) and in Andersson *et al.* (1983). Dahlman & Eklund (1953, unpublished report) contains an earlier overview of information available thirty years ago.

Geological setting

The crystalline basement to the Baltoscandian Platform, generally of Svecokarelian (c. 1800 Ma) to Dalslandian (c. 1000 Ma) age is overlain with major unconformity by shallow marine quartz sandstones (Thorslund 1960, Martinsson 1974, Bergström & Gee in press). In central Sweden, these are a few tens of metres thick; they thicken both southwards into the Skåne trough (>94 m, Bergström & Shaikh 1982) eastwards towards the Baltic (126 m at Filehajdar, Gotland, Thorslund & Westergård 1938) and westwards in the Caledonides (up to at least c. 300 m) where they are intercalated with a variety of siltstone and shale members. In westernmost areas, they

TABLE 1. Comparison of the chemistry (wt %) of some Swedish black shales with an average shale and average black shale. Note that Armands (1972) referred to the shales in the Upper Member of the Alum Shale Formation at Billingen (below) as "Upper Cambrian" and the Middle and Lower Members (below) as the "Middle Cambrian" (cf. Fig. 6). The figure of 8 ppm U for average black shales is tak en from Swanson 1961, who suggested that "shallow" marine black shales contain an average of 20 ppm U.

Element	Uranium-rich black shale, Southern Storsjön Area, Jämtland (Gee & Snäll, 1981)	Uranium-rich alum shale, Ranstad, Västergötland (Andersson _et al_. 1983)	Average alum shale, Upper Member, Billingen (Armands 1972)	Average alum shale, Middle and Lower Members, Billingen (Armands 1972)	Average black shale (Vine & Tourtelot 1970)	Average shale (Turekian & Wedepohl 1961)
Al	6.3	6.6	6.5	8.2	7.0	8.0
Fe	3.4	6.0	7.1	6.8	2.0	4.72
Mg	0.58	0.49	0.5	0.8	0.7	1.5
Ca	2.3	0.7	0.7	0.5	1.5	2.21
Na	0.06	0.21	0.17	0.12	0.7	0.96
K	3.8	4.0	3.6	4.0	2.0	2.66
C_{org}	14.2	15.5	13.7	6.1	3.2	-
C_{carb}	0.62	0.2	0.43	0.17	0.33	-
Ti	0.39	0.35	0.4	0.5	0.2	0.46
Mn		0.025	0.02	0.02	0.015	0.085
Ag			0.00014	-	<0.0001	0.000007
B		0.011	0.012	0.011	0.005	0.01
Ba		0.05	0.05	0.05	0.03	0.058
Be			0.0005	-	0.0001	0.0003
Co		0.0025	0.005	-	0.001	0.0019
Cr	0.0112	0.032	0.0094	-	0.01	0.009
Cu	0.0138	0.011	0.019	0.018	0.007	0.0045
Ga		0.0022	0.0017	-	0.002	0.0019
La		0.005	-	-	0.003	0.0092
Mo	0.046	0.034	0.027	0.007	0.001	0.00026
Ni	0.044	0.02	0.016	0.009	0.005	0.0068
Pb		0.0014	0.014	0.008	0.002	0.002
Sc		0.0009	-	-	0.001	0.0013
Sr		<0.01	0.004	0.004	0.02	0.03
V	0.16	0.075	0.068	0.045	0.015	0.013
Y		0.004	0.004	0.005	0.003	0.0026
Zn	0.027	0.013	0.015	-	<0.03	0.0095
Zr		0.01	0.011	0.018	0.007	0.016
S	4.4	7.0	6.7	4.5		0.24
P		0.082	0.074	0.053		0.07
U	0.0245	0.030	0.0206	0.001	0.0008	0.00037
Ce		0.021	0.017	0.018		0.0059
Rb		0.011	0.014	0.024		0.014
As	0.016	0.011	0.0017	-		0.0013
Sb		0.0005	0.002	-		0.00015
Ge			0.00016	-		0.00016
Bi			0.00013	-		-
Sn		<0.001	0.002	-		0.0006
In			0.00007	-		0.00001
Cd	0.0007	0.00022				
Hg	0.0003	0.000031				
Ra^{226}		$9.5.10^{-9}$				
Rare earth elements		0.041				

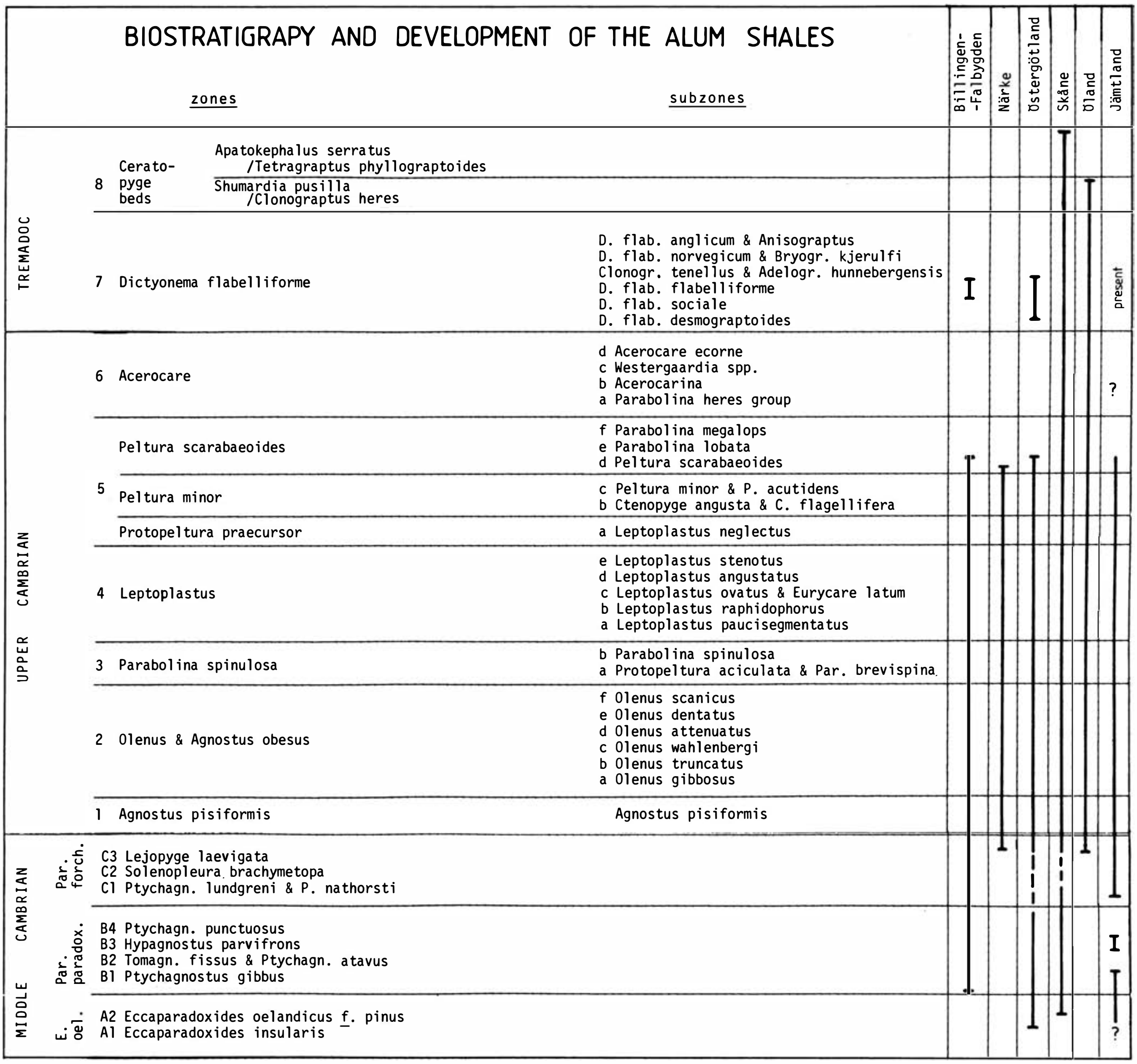

Fig. 2 Middle and Upper Cambrian and Lower Ordovician biostratigraphy (based on Westergård 1922 and 1953 with minor modification by J. Bergström, pers. comm.) and development of the alum shale facies in Sweden (based on Dahlman & Gee 1977 and Bergström J. 1980).

are underlain by tillites and other Late Proterozoic sediments. This sandstone formation is of Early Cambrian and, in areas of thicker development in the Caledonides, also of Vendian age. It is usually glauconitic and phosphatic in its upper part, and is, in some areas, overlain by grey green siltstones and shales of Middle Cambrian age. These pass transitionally, or with sharp contact and development of a thin conglomerate, into the Middle Cambrian black shale facies of the Alum Shale Formation.

The alum shales are generally overlain by a few decimetres of sandy, glauconitic, phosphatic limestone of Late Tremadoc (*Ceratopyge* limestone) or Early Arenig age. These are overlain either by Ordovician limestones or grey shales and the shale and limestone dominated sequences continue through the Ordovician into the Silurian. Only in western areas, in the Caledonides, does the Ordovician carbonate facies pass laterally westwards into thick greywackes.

The structural history of much of central and southern Sweden after the Early Palaeozoic deposition has been relatively simple. The sequences are characterized by very gentle dips. Vertical faulting is frequent and, in several cases, partly accounts for the preservation of the outliers. In Skåne, an important northwest trending fracture-zone, the Tornquist zone (Pegrum 1984), showing evidence of both Palaeozoic and post-Palaeozoic movement, has resulted in a more complex structural geometry. This pattern, essentially involving differential vertical movement, contrasts with that in the Caledonian Front where the structure is dominated by thrust nappes. There, alum shales have played an important role in the frontal décollement, providing an incompetent unit in which detachment occurred and over which the lowermost nappes were displaced.

The maturity of the alum shales varies considerably from area to area. This variation is apparently related both to the subsequent depositional history and, locally, to the intrusion of Permo-Carboniferous dolerites. Deposition of an Old Red Sandstone facies may have occurred over much of Sweden during the Mid-Late Silurian and Devonian, comparable in thickness with the Ringerike sandstones (c. 1 000 m) in the Oslo graben. Thereafter, central Sweden remained an area of general stability with little or no subsequent deposition. Kerogen is preserved in these areas (e.g. Närke and Östergötland). In southern Sweden (Skåne), thicker Ordovician and Silurian (together 1000–1500 m, Regnéll & Hede 1960, Bergström *et al.* 1982) and Mesozoic (up to c. 2000 m) sequences, along with the widespread intrusion of Permo-Carboniferous dykes has resulted in general coalification of the kerogen to semi-anthracitic grades. Likewise in the Caledonides, sub-greenschist facies metamorphism (Kisch 1980) of the autochthon and lower nappes has resulted in dispersal of hydrocarbons and the organic matter in the shales passes from semi-anthracitic in the thrust front to graphitic in greenschist facies environments further west, towards the border with Norway.

History of exploitation

The discovery over three hundred and fifty years ago that the hydrated salt, potassium aluminium sulphate could be prepared from the alum shales led to the development of one of Sweden's earliest major industries (Rinman 1788). Mining started in 1637 at Andrarum, in Skåne, and this was followed by the establishment of mining and extraction industries in a number of other areas. The shale was roasted; thereafter the salt was leached out with warm water and precipitated. During the early years, the burning of the shale was achieved with the help of wood; it was not until the end of the eighteenth century, probably due to a limited local supply of timber, that particular shale units were identified to contain sufficiently high concentrations of fossil energy to burn by themselves and ovens were constructed for this purpose. The extraction of the alum salt continued in southernmost Sweden until the beginning of this century. During the most expansive years, annual production reached c. 250 tonnes, the salt being used in the preparation and preservation of skins, in the textile industry for the fixing of colours and pharmaceutically as an astringent, to name but a few of its many early applications.

The presence and potential usage of the kerogen content of the alum shales was recognized towards the end of the last century and various attempts were made at the beginning of this century to extract and refine the hydrocarbons. Using conventional retorting methods, oil yields are significant only in Kinnekulle (Västergötland), Närke and Östergötland (Westergård 1941, 1944a and b). Production at a pilot plant at Kinnekulle reached about 500 tonnes of petroleum a year and this capacity was expanded during World War II, largely for military purposes (Statens offentliga utredningar, SOU 1956:58). Whilst mining and extraction continued at Kinnekulle, plans were laid for expansion in the Närke area and the centre of activities was transferred there at the beginning of World War II. Production started in 1942. However, with the renewed import of oil after the war, the project ceased to be economically viable and production decreased in the late fifties and finally ceased in 1966. About 50 million tonnes of shale were mined during this period.

The alum shales provide Sweden's main source of fossil energy; (minor quantities of oil have been pumped up on Gotland in recent years and thin coal seams occur in Skåne). Estimation of the country's reserves of alum shales containing more than 10 % organic carbon have been published in a government report (SOU 1956:58) and in Hessland & Armands (1978). In Table 2, data are presented from SOU 1956:58 together with new information from the Caledonides (Gee *et al.* 1982, unpublished report). An estimate of the oil yield obtainable by conventional retorting techniques is also presented, based on the Fischer Assay data.

TABLE 2. Quantities of shale, organic matter and oil in alum shales containing more than 10 % organic matter (based on SOU 1956:58 and Gee *et al.* 1982, unpublished report).

Area	Shale billion tonnes	Organic matter %	Organic matter million tonnes	Oil %	Oil million tonnes	Oil billion MJ	Energy in gas and coke billion MJ	Total energy billion MJ
Närke								
East Närke	1	20	200	5.5	55	2 300	5 000	7 300
West Närke	0.7	20	140	4.5	30	1 200	3 800	5 000
Östergötland	12	14	1 600	3.5	400	16 800	41 900	58 700
Västergötland								
Billingen-Falbygden	12	13	1 600	1.5	200	8 400	46 100	54500
Halle- and Hunneberg	1	13	100	0	0	0	3 400	3 400
Kinnekulle	1	14	140	3.4	20	1 200	3 800	5 000
Öland	6	12	700	2.7	170	7 000	18 000	25000
Skåne	15	11	1 600	0	0	0	58 600	58 600
Jämtland								
Southern Storsjön Area	26	12	3 200	0	0	0	117 200	117 200
Total	75		9 280			36 900	297 800	334 700

The identification of high concentrations of uranium in the kolm lenses (Nordenskiöld 1893) led to mining activities in the Stolan area of Billingen, Västergötland, activities that quickly proved unsuccessful due to the erratic distribution of the lenses. The subsequent discovery of radium resulted in new abortive attempts to utilize the kolm. In 1904, Landin (referred to in Eklund 1946) showed that the alum shales themselves contain unusually high concentrations of uranium; however, it was not until after World War II that systematic exploration started, in particular in the Västergötland and Närke areas, the investigations being carried out by the Geological Survey of Sweden on behalf of the Swedish Oil Shale Company (Svenska Skifferoljeaktiebolaget) and, later, the Atomic Energy Company (Atomenergi AB). These investigations established that some parts of Närke and Västergötland contain units at least 3 m thick with more than 200 ppm uranium. In the middle of the 1950s an area (Ranstad) was identified (Dahlman 1962, unpublished report) on the south side of Billingen, Västergötland, to contain c. 300 ppm uranium over a thickness of about 3.5 metres and the centre of the uranium extraction activities was concentrated there. Previous attempts to extract uranium had been carried out in association with the petroleum plant at Kvarntorp in Närke. The Ranstad mill was built in the early 1960s with a nominal capacity of 120 tonnes of uranium per year. The plant was in operation from 1965–1969 but only at about half this capacity because of the low market prices and lagging domestic demand. The open-pit production of shale during this period was 0.4–0.5 million tonnes per year. Various techniques (Peterson 1967, Oskarsson & Sjöberg 1977, Carlsson 1980) were tested and a method established for uranium extraction (the so-called Atomic Energy Company Process) which involved milling of the shales, separation of the stinkstone component and acid leaching. Recovery of c. 67 % of the uranium was achieved by this method; subsequent improvements increased this figure to 80 %.

The presence of unusually high concentrations of vanadium in the *Dictyonema* alum shales in Skåne was established in 1940 (Brundin, unpublished reports), and led to various attempts to extract the element. The techniques involved roasting of the shales and subsequent leaching with sulphuric acid. Due to the low organic carbon content (about 5–8 %) and calorific value of these shales it was necessary to introduce oil into the roasting furnace. Small amounts of vanadium pentoxide were produced together with potassium and ammonium aluminium sulphate during World War II.

During the last two centuries, the alum shales have been used in a variety of other processes, of which two have lasted until recent years. Both have involved taking advantage of the high content of organic carbon by burning the alum shales together with limestone in open "field ovens". In one case, lime was produced for agricultural usage; in the other, the method was used as the basis for the production of a light porous building stone. The alum shales and limestones, in approximately equal proportions, were burnt together. Subsequent addition of small amounts of aluminium oxide resulted in release of hydrogen and production of a porous product that could be steam hardened. "Breeze-blocks" produced in this way were used extensively in the building industry in Sweden until it was recently demonstrated that houses built of such material were liable to accumulate unacceptably high concentrations of radon (Ds Jo 1979:9, SOU 1983:6).

Whereas all previous exploitation of the alum shales has been concentrated to obtaining one particular product, development of techniques during the 1970s concentrated on extracting all usable components. (Lilljha 1980). Since 1969, the Ranstad mill has been used exclusively for research and development activities, awaiting political decisions regarding the extent to which the reserves of the black shales should be utilized. The research programme included development of suitable processes for an expansion of the uranium production capacity as well as methods for the recovery of other valuable substances from the shale material. In the short term, these would be by-products of the uranium process; in the long term, however, an integrated process is envisaged for recovery of uranium, fossil energy, sulphur, fertilizer products (K, Mg etc.), steel alloy metals (V, Mo, Ni) and aluminium products. The rapid rise in the price of oil has naturally led to a renewed interest in exploitation of the kerogen (Fahlström 1979, Hellestam 1981, 1983, DsI 1983:20).

The chemical data available on the alum shales reflects the previous preoccupation with extraction of individual products. Thus a large volume of published and unpublished information exists on the content and character of the organic matter (including the hydrocarbons), the calorific value of the shales, and the contents of uranium and vanadium. The level of the other components in the various areas of development of the shale is little known and the subject of on-going research. An appendix (pp. 43–50) provides information on drillcores from each of the main areas of occurrence. The data allow comparison of lithologies and contents of organic matter (and/or calorific value), oil yield (Fischer Assay, F.A.), uranium and vanadium.

Areal development

The main areas of development of the Alum Shale Formation in Sweden, shown on Fig. 3, are supplemented by offshore occurrences which are probably extensive in the southern Baltic (Fig. 4). The shales thin northwards on Öland, are present beneath a part of Gotland and may also occur in the Gulf of Bothnia (Winterhalter 1972). Of those occurring on land, the development in the Billingen-Falbygden area of Västergötland and in Närke, further north-east, have been the most extensively studied. It is in these areas that the highest contents of both kerogen and uranium are thought to occur (Andersson *et al.* 1983). The main centre of activities has been concentrated in recent years in Ranstad in south Billingen and the descriptions that follow draw extensively on evidence from that area. Thereafter, short comparative treatments of the other areas are given.

The Alum Shale Formation in the different areas can locally be conveniently subdivided on a lithostratigraphic basis into constituent members. Comparison of sequences in the different areas is facilitated first and foremost by reference to the biostratigraphy (Fig. 2).

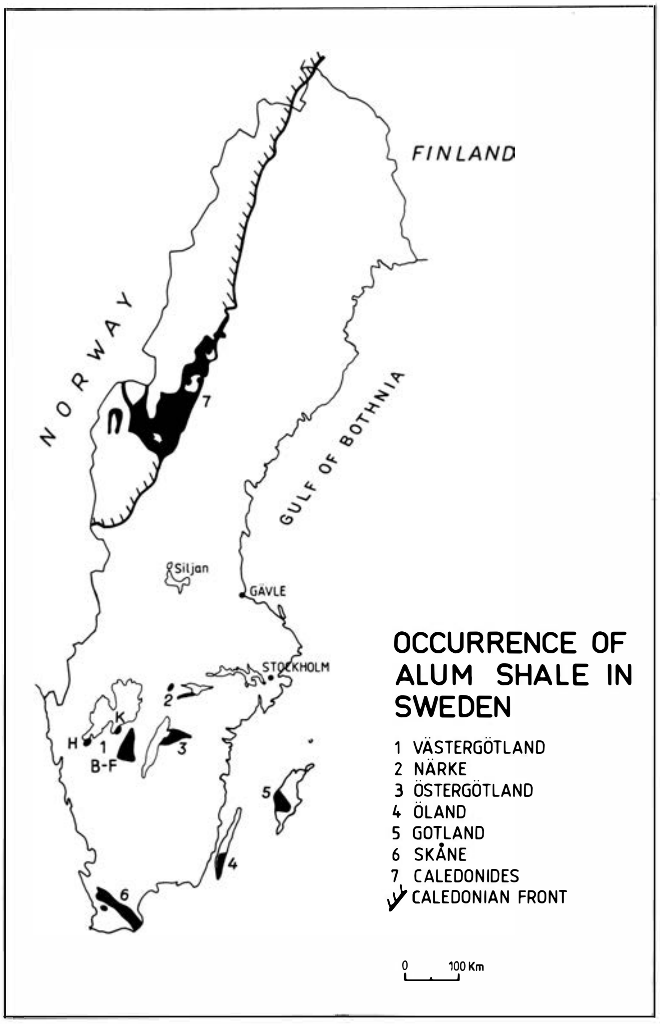

Fig. 3. Alum shale occurrences in Sweden (B-F = Billingen-Falbygden, H = Hallberg-Hunneberg, K = Kinnekulle).

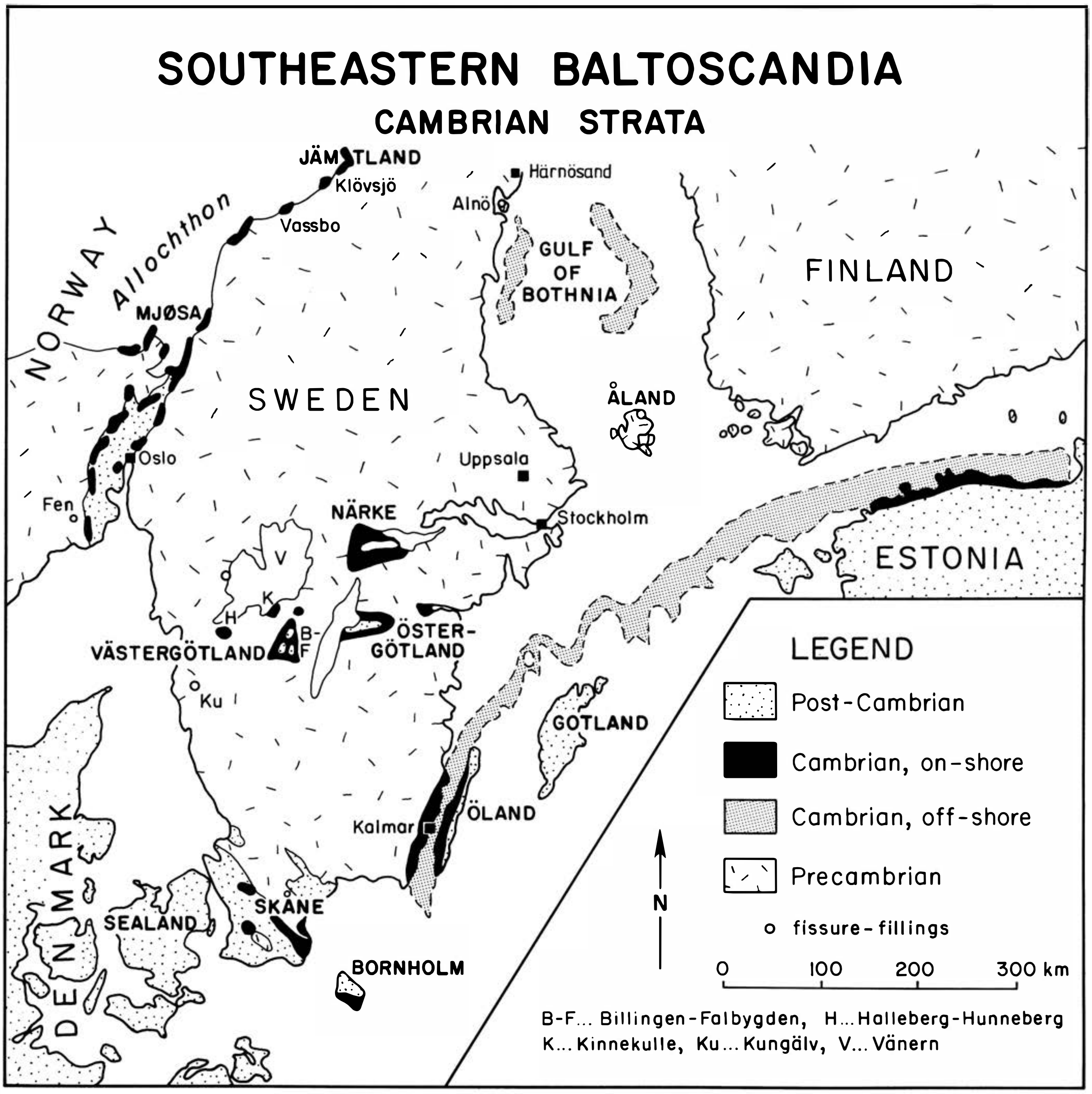

Fig. 4. Cambrian deposits of southeastern Scandinavia (from Bergström & Gee, in press).

Billingen-Falbygden, Västergötland

The pre-Quaternary geology of the Billingen-Falbygden area is illustrated in Fig. 5, which is based on Munthe *et al.* (1928), Hörnsten *et al.* (1974) and Andersson *et al.* (1983). The nearly flat-lying Lower Palaeozoic sedimentary sequence, resting on a gneissic crystalline basement, reaches up into the Lower Silurian and is capped by a thick Permo-Carboniferous diabase sill. Subsequent faulting along the western and southern sides of the outlier, together with the capping of the diabase, account for the preservation of the sediments. The latter, some 150–160 m thick, comprises four formations, a basal sandstone (30–35 m), followed by the alum shales (22–24 m), then limestones (c. 50 m), locally with up to 3 m of shale (*Didymograptus*) at the base, and finally a passage

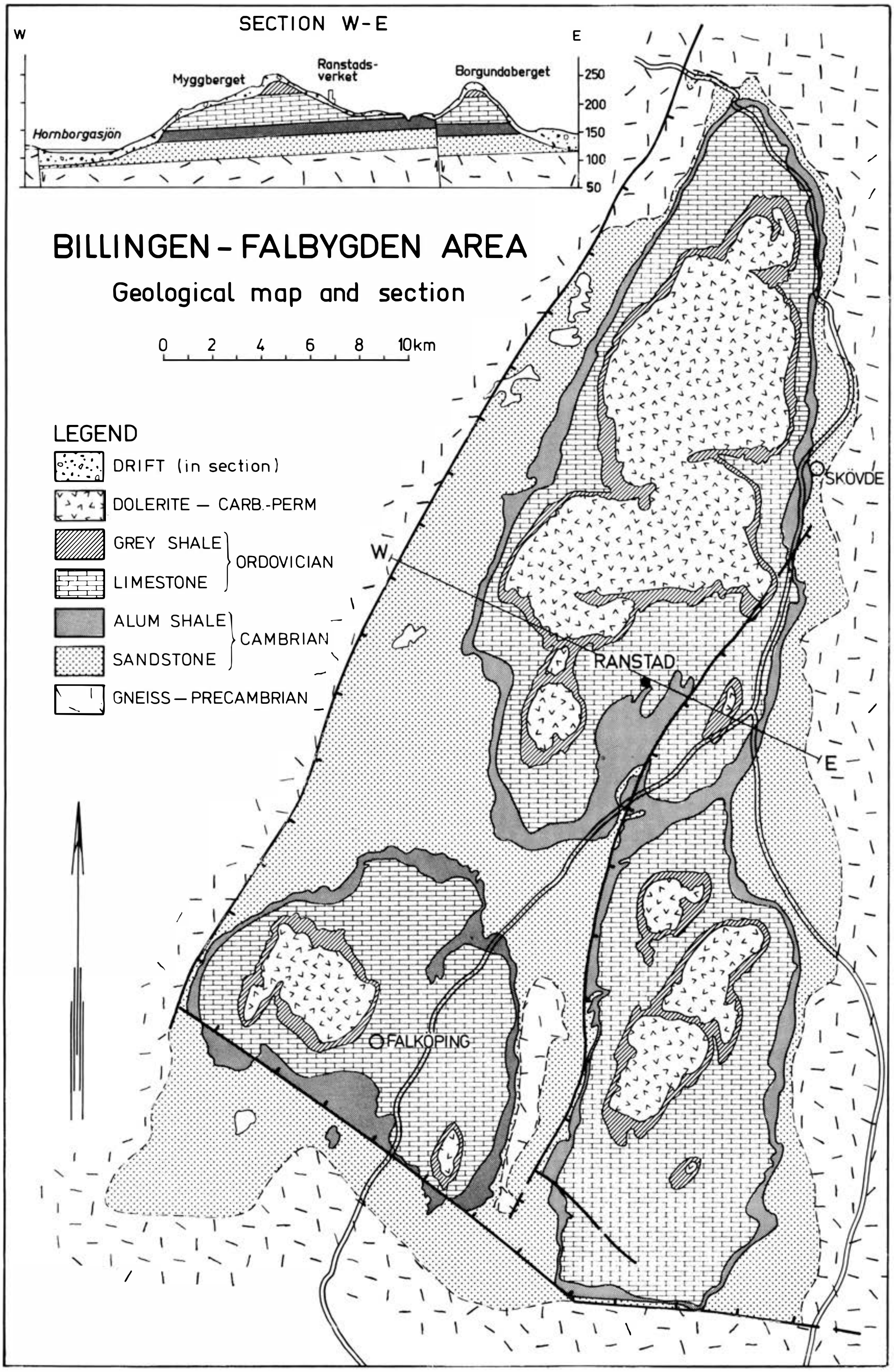

Fig. 5 Bedrock geology of the Billingen-Falbygden outlier, Västergötland.

transitionally upwards into grey and subordinate reddish shales (up to 50 m thick). The competent massive sandstones, limestones and diabase units dominate the outcrop pattern; shales are recessive, implying that the alum shales, in general, are accessible only locally to open-cast mining.

Typical of other areas of development, the Alum Shale Formation in Billingen-Falbygden is composed of two dominant lithologies: black shales and stinkstones. The majority of the stinkstones occur as sporadic lenses, but two levels of more or less persistent bands occur (the lower "*Exporrecta*" and the upper "Great Stinkstone" band) and these have been used to divide the formation into three members (Dahlman & Gee 1977, Andersson *et al.* 1983). Of these, the *Peltura scarabaeoides* zone of the upper unit is excellently exposed in the Ranstad open pit. This member has been penetrated by over 100 drillholes and is referred to as the Ranstad Member; the other two are called, informally, the Middle and Lower Members. The base of the Ranstad (Upper) Member is taken at the top (cf. Andersson *et al.* 1983, p. 200) of the Great Stinkstone band; the base of the Middle Member at the base of the *Exporrecta* stinkstone.

The mineralogy of the shales at Ranstad is illustrated in Fig. 6 (based on Armands 1972). The fine grain-size (<10 μm) prevented direct modal analysis and the proportions of the different minerals, identified by X-ray diffraction methods, were calculated from the whole rock chemical analyses. The shales are composed of three main categories of components, silicates, organic matter and sulphides.

Organic carbon clearly increases systematically from the Lower Member (average 4–5 %) through the Middle Member (7.5–9.5 %) to the Ranstad Member (c. 14 %). Only low oil yields (c. 1–2 %, F.A.) have been reported (Holmberg 1930). In this context it is of interest to note that there is good general correlation of the regional alteration of the organic material in the alum shales in the different Lower Palaeozoic outliers, as reflected in the presence of hydrocarbons, and their thermal histories as recorded in the study of conodont colour alteration indices (CAI) by Bergström S.M. (1980).

The content of pyrite varies in a similar manner to that of the organic matter, increasing from c. 8 % in the Lower Member to c. 12 % in the Middle and Ranstad Members. However, its appearance may be more erratic than is shown in Fig. 6 due to its presence both disseminated throughout the shale and as thin bands and nodules. Increase in sulphides and organic matter towards the top of the formation is accompanied by a corresponding decrease in silicates. This is achieved principally by a systematic decrease in quartz, illite and chlorite, the last of these being present only in the Lower Member and in the lowermost parts of the Middle Member. Armands (1972) reported that small (<0.5 %) amounts of kaolinite have been detected in the uppermost shales of the formation. Potash feldspar is higher near the base of the formation and in the Ranstad Member; the former probably represents a detrital component whereas the latter is, at least partly, of diagenetic origin. The carbonate content in the shales is very subordinate (c. 2 %) throughout the formation; occasional very thin laminae of $CaCO_3$ are also present in addition to the stinkstones. The "remainder" is mostly composed of small amounts of apatite, zircon and sphene. No uranium mineral has as yet been identified. Uranium occurs finely disseminated in the shale, mostly associated with the organic matter; some preferential enrichment in phosphorite and zircon grains has also been observed.

The bituminous limestones (stinkstones) are composed of calcium carbonate in varying degrees of purity; most lenses do not contain more than c. 20 % of the shale mineralogy. The lenses are often partly recrystallized marginally to a pure, coarsely crystalline, radial, sparry aggregate; the latter is often preferentially developed in the upper parts of the lenses, the very fine-grained, dark, bituminous character, along with some primary stratification and the fossils, being preserved in the central and lower parts.

Within the Ranstad Member, kolm lenses and thin (<10 cm) bands occur. They are generally confined to two levels (e.g. in the Billingen area) but three may appear (e.g. in Västra Falbygden). As in Närke, these kolm lenses are restricted to the zone of *Peltura scarabaeoides* and contribute to the most uranium-rich part of the Alum Shale Formation. The kolm lenses are black and coaly, commonly exhibiting a conchoidal fracture. They have organic carbon contents of 30–70 % and uranium concentrations of 2000–5000 ppm. Other components are present in approximately the same proportions as in the shales.

Very occasional chert bands and phosphorite nodules have been reported from the Billingen-Falbygden alum shales. Thin (<10 cm) fractures filled with a vanadium-rich organic matter occur locally. Glauconite has been reported from some concretions particularly at the *Exporrecta* level and is conspicuous in the green shales at the base of the Lower Member.

Stratification in the shales occurs as a fine parallel lamination. Cross-lamination, ripples, etc. have not been recorded. The stratification passes laterally into the stinkstones and also wraps around the latter, a result of

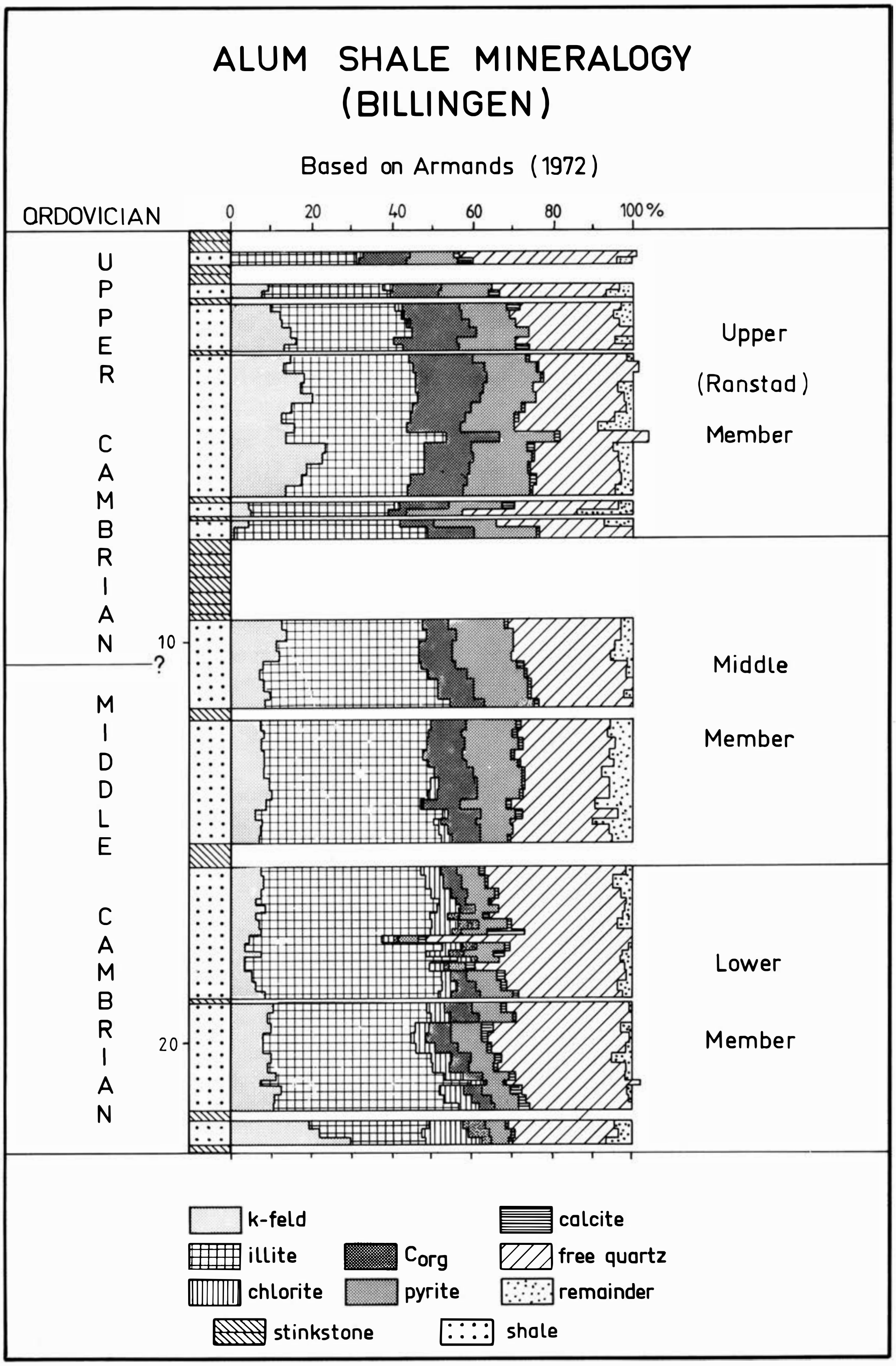

Fig. 6. Mineralogy of the Alum Shale Formation in the Billingen area based on Armands 1972. (Note that the boundary between the Middle and Upper Cambrian is not exactly defined).

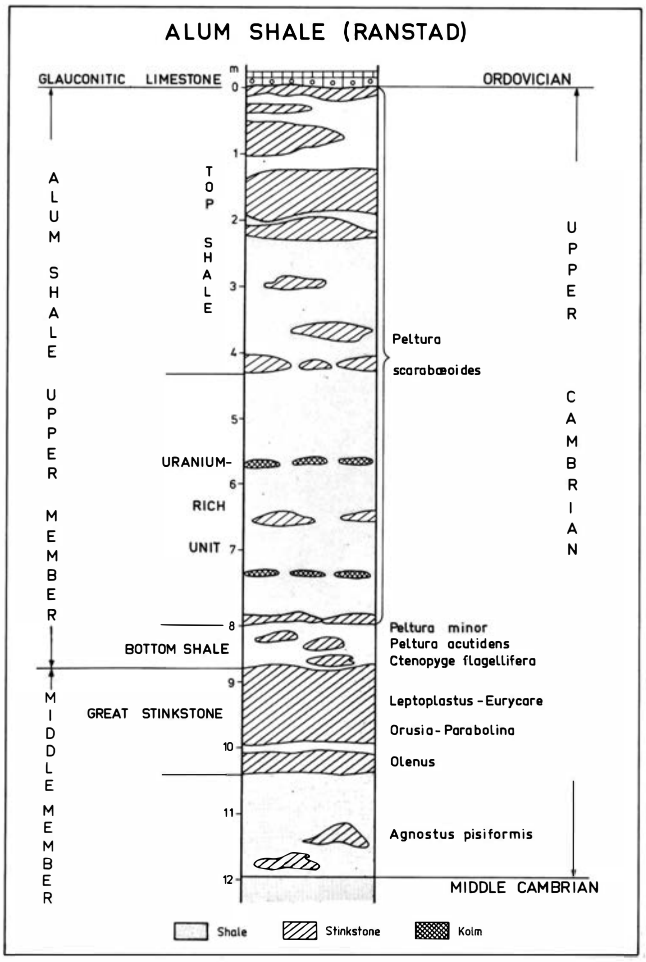

Fig. 7. The Ranstad Member of the Alum Shale Formation in the Ranstad area (from Dahlman & Gee 1977).

later compaction. The stinkstones are occasionally conglomeratic, being composed of usually angular, but sometimes rounded fragments of bituminous limestone in a limestone matrix. These conglomerates testify to early diagenetic lithification. They may contain both glauconite and phosphorite and very occasional foreign rock fragments have been reported.

As is apparent from the foregoing description of the formation in the Billingen-Falbygden area, it is the Ranstad Member that is of greatest economic interest. This member can conveniently be divided into three parts, a top shale, a uranium-rich unit and a bottom shale, as shown in Fig. 7, overlying the Great Stinkstone.

Exploration during the 1950s (see Andersson *et al.* 1983 for reference to unpublished reports) demonstrated that a part of the formation above the Great Stinkstone was particularly uraniferous. Within this upper part of the formation, the uranium-rich unit increases from a thickness of c. 2 m in the north of the Billingen-Falbygden outlier (Stolan) to c. 4–5 m in the southwest (Västra Falbygden). The highest concentrations of uranium occur locally in southeastern areas (Östra Falbygden–365 ppm over 3.4 m). Relationships between thickness and uranium concentrations are shown on Fig. 8, where it should be noted that neither the thickness of the stinkstones nor the erratic presence of the uraniferous kolm lenses are included. Drilling of the Ranstad area has shown that the uranium-rich unit (including kolm, but not the stinkstones) contains a weighted mean of 306 ppm U over 3.6 m.

In addition to the thousands of uranium analyses of the uranium-rich unit, three continuous sections have been analysed through the entire Alum Shale Formation. Armands (1972) reported the results of the analysis for 24 major, minor and trace elements from a drillcore (Dbh. 1a-65) from the western part of the Ranstad concession. Andersson (1977, unpublished report and in preparation) analysed two drillcore sections, one from the Ranstad open pit and the other from a locality on Sydbillingen some 6.5 km to the north, for the following elements: C (organic and inorganic), Al, Fe, Ca, K, Mg, Mn, Na, P, S, Mo, Ni, Rb, U, V and Y. There proved to be a good general agreement between the analyses of these elements from the different areas. One set of results is presented in Table 3, where the analyses have been combined for specific parts of the formation, namely: the top shale, the uranium-rich unit and the bottom shale of the Ranstad Member, the Great Stinkstone, the middle shale unit and the *Exporrecta* stinkstone of the Middle Member and the upper shale unit and lowermost glauconitic shale of the Lower Member. This particular core (No. 65/77) contains somewhat more stinkstone than is normal (4–8 %) for the uranium-rich unit in the Ranstad area; it also lacks kolm. Otherwise it illustrates well the variation of chemistry throughout the formation. The variation of eight important elements, C_{org}, U, V, Mo, S, Fe, Al and K is illustrated in Fig. 9.

The distribution of the different elements and their correlation has been treated by Strahl (1958), Armands (1972) and Edling (1974), with particular reference to U, V, and Mo. Some aspects are commented on below in the discussion of the depositional environment of the formation.

The total area of development of the full thickness of the Alum Shale Formation in the Billingen-Falbygden outlier is c. 490 km^2. Obviously, the uranium reserve in

TABLE 3. Chemical analysis of the Ranstad drillcore 65/77 (from Andersson 1977, unpublished report).

Ordov. Lst.	Analysis of shale (SH) and stink-stone (ST) in	Depth below Ordovician limestone in metres	Thickness in metres Total	SH, ST	Lith-ology	C_{org} %	Al %	Fe %	Ca %	K %	Mg %	Mn %	Na %	P %	S %	Mo ppm	Ni ppm	Rb ppm	U ppm	V ppm	Y ppm	CO_2 %	$CaCO_3$ %
Upper member	Top shale	0 – 2.30	2.30	1.61	SH	14.0	5.6	5.9	0.82	2.7	0.5	0.025	0.05	0.07	6.7	260	175	100	155	563	≤20	0.8	
				0.69	ST	2.4	0.95	2.8	29.0	0.39	0.25	0.10	0.02	0.48	3.2	106	72	20	89	126	<20	31.9	72.5
	Uranium-rich shale	2.30– 6.10	3.80	2.73	SH	15.7	6.4	6.6	0.65	3.9	0.5	0.03	0.15	0.09	7.5	300	240	105	337	797	40	0.6	
				1.07	ST	2.4	0.57	0.56	35.9	0.27	0.30	0.11	0.02	0.17	0.6	31	45	20	106	79	<20	39.8	90.5
	Bottom shale	6.10– 8.22	2.12	1.30	SH	12.1	7.1	7.4	0.77	3.8	0.5	0.02	0.09	0.12	8.4	257	248	120	151	717	–	0.6	
				0.82	ST	1.7	0.68	1.1	34.4	0.30	0.25	0.11	0.02	0.04	1.0	29	44	20	78	79	<20	38.3	87.2
Middle member	Great stinkstone	8.22– 8.85	0.63	0.02	SH	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	
				0.61	ST	2.3	0.78	0.89	34.5	0.39	0.29	0.12	0.02	1.01	1.1	491	45	20	64	71	<20	35.2	80.0
	Shale	8.85–14.70	5.85	5.27	SH	8.5	7.9	7.2	0.4	4.2	0.7	0.025	0.15	0.05	7.4	142	165	150	44	610	30	0.4	
				0.58	ST	1.4	1.0	1.1	33.9	0.43	0.26	0.25	0.02	0.02	1.1	24	39	20	15	67	<20	37.4	85.0
	Exporrecta stinkstone	14.70–15.50	0.80	0.01	SH	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	
				0.79	ST	1.1	1.4	1.4	31.7	0.65	0.41	0.085	0.02	0.31	1.2	18	40	20	13	50	<20	34.7	78.9
Lower member	Shale	15.50–22.40	6.90	6.63	SH	4.6	8.3	6.0	0.6	4.2	0.8	0.03	0.07	0.07	4.6	52	98	209	15	306	40	0.8	
				0.27	ST	4.4	2.4	3.3	15.4	1.44	0.35	0.22	0.03	0.68	2.2	55	30	70	19	78	60	16.3	37.1
	Glauconitic shale	22.40–23.08	0.68	0.68	SH	0.2	4.4	12.7	2.8	4.8	1.1	0.06	0.03	0.25	3.5	7	30	225	7	81	40	3.0	

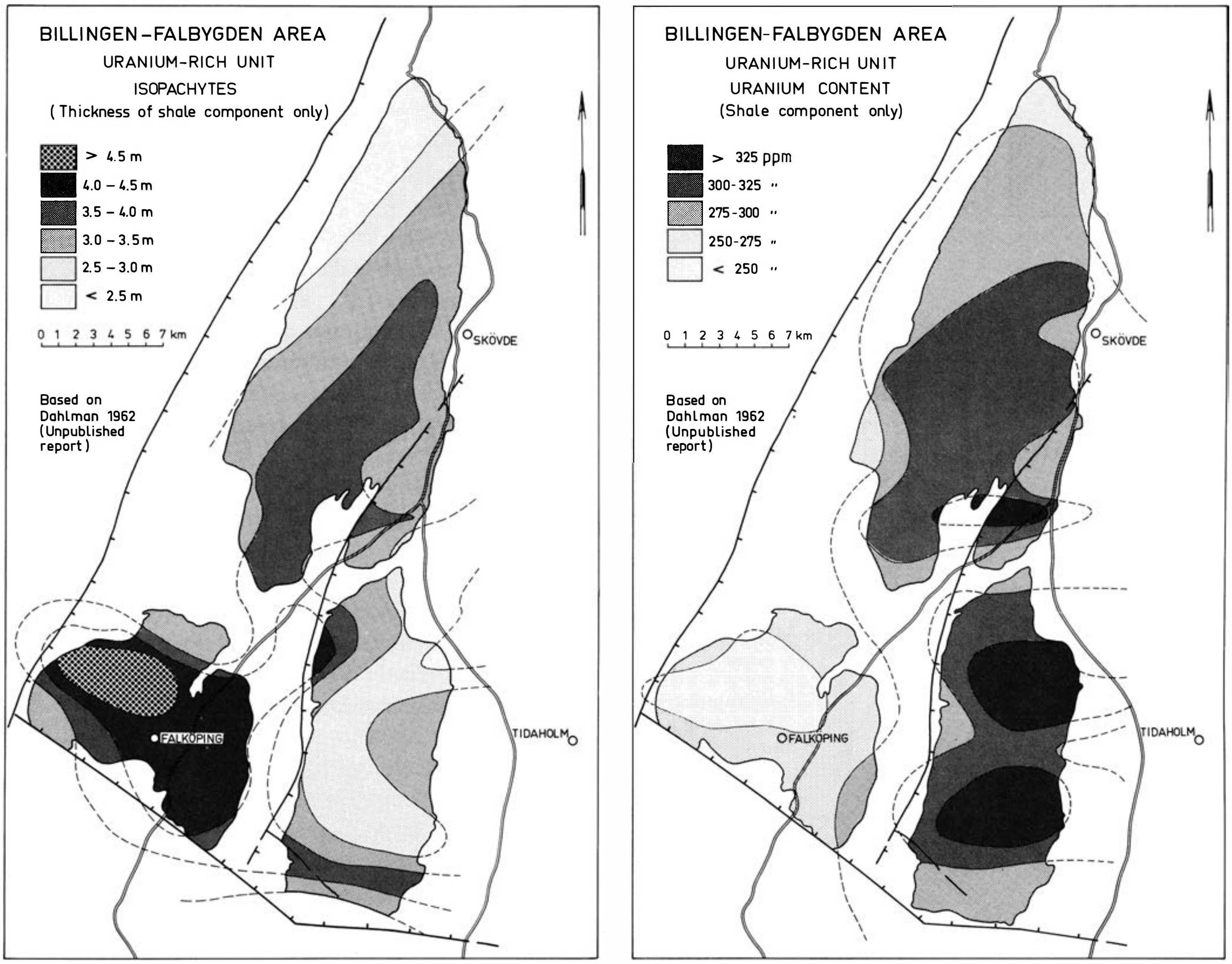

Fig. 8. Relationship between uranium concentration and shale-thickness in the uranium-rich unit of the Ranstad Member of the Alum Shale Formation in the Billingen-Falbygden outlier, Västergötland (from Dahlman & Gee 1977).

the area is vast; in the uranium-rich unit alone it is estimated to be about one million tonnes (Table 4). Only a small proportion of this area is accessible to open cast mining.

TABLE 4. Quantities of shale and stinkstone and resources of uranium and kerogen in the Upper Member of the Alum Shale Formation in the Billingen-Falbygden area, Västergötland (from Andersson *et al.* 1983). The tonnages are metric.

Units in Upper Member of Alum Shale Formation	Shale (excluding kolm and stinkstone)					Stinkstone	
	Shale (billion tonnes)	C_{org} %	Kerogen (billion tonnes)	Uranium ppm	Uranium million tonnes	Wt %	billion tonnes
Top shale	2.2	14.5	0.35	167	0.37	42	1.6
Uranium-rich unit	3.4	15.5	0.6	292	0.99	8	0.3
Bottom shale	2.6	12.0	0.35	150	0.39	33	1.3
Total	8.2	14	1.3	213	1.7	28	3.2

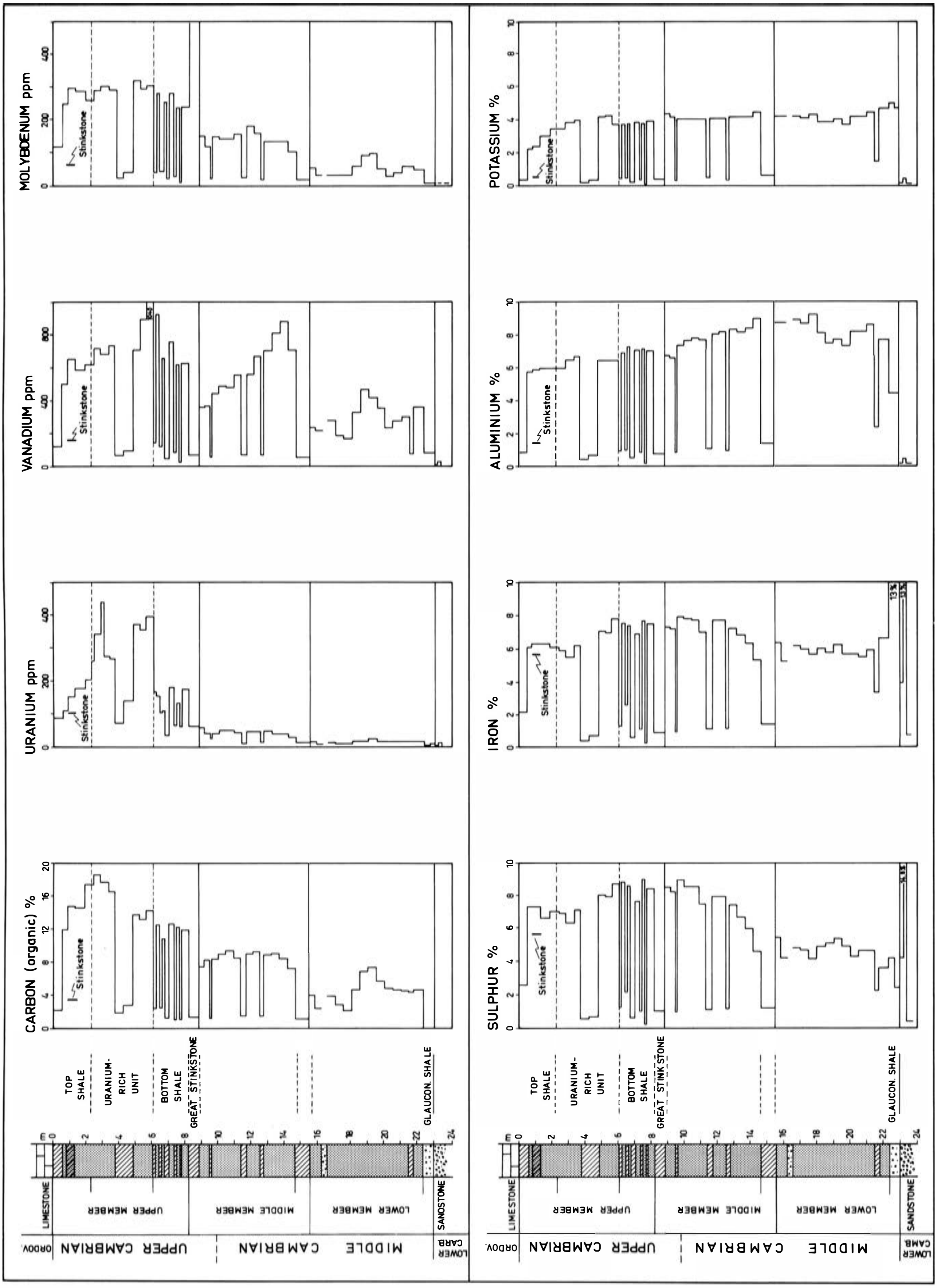

Fig. 9. Variation in concentrations of C_{org}, S, Fe, Al, K, Mo, V and U in the Alum Shale Formation of the Ranstad area (from drillcore DBH 65/77 in Andersson 1977, unpublished report).

Kinnekulle and Halleberg-Hunneberg, Västergötland

A variety of localities occur in Västergötland, west of the Billingen-Falbygden area, where Lower Cambrian strata are preserved as fissure fillings in the Precambrian basement. In addition, three important outliers of Lower Palaeozoic rocks occur, of which two are shown on Fig. 3 (Kinnekulle, Fig. 10 and Halleberg-Hunneberg, Fig. 11). The third, Lugnås, is too small (c. 5 km^2) to be represented and contains a stratigraphy that does not reach above the zone of *Parabolina spinulosa* (Thorslund 1960). Both the main outliers mentioned above are capped by dolerites; in the case of Halleberg-Hunneberg, the intrusion cuts gently upwards from the north (Halleberg), where it rests on the Lower Cambrian sandstones, to the south (Hunneberg), where the succession passes up through alum shales into Lower Ordovician shales and limestones.

At Kinnekulle (Eklund & Thorslund 1942, unpublished report) the relationships are similar to those in the Billingen-Falbygden outlier, with preservation of a Cambro-Ordovician sedimentary sequence that passes up into the Lower Silurian. The Alum Shale Formation is of similar thickness to that in Billingen-Falbygden and can likewise be divided into three members. However, there are marked differences in development of the formation, the Upper Cambrian section being thicker on Kinnekulle, where the *C. flagellifera* and *P. acutidens* subzones are better represented. These zones provide the higher oil yields. The Upper Member contains a higher percentage of stinkstones than in the Billingen-Falbygden area; they increase to about 50 % of the unit in the western part of the outlier. This Upper Member at Kinnekulle contains younger Cambrian shales (zone of *Parabolina heres*) than are present in Billingen-Falbygden (Westergård 1943).

Dolerite intrusion in the Halleberg-Hunneberg area baked the alum shales, producing thin coaly layers and fracture fillings often rich in vanadium. As at Billingen-Falbygden, lighter hydrocarbons were driven off during this Permo-Carboniferous intrusion. By contrast, Kinnekulle's alum shales are much less influenced by the basic intrusions and have retained some of the highest contents of hydrocarbons recorded in the Swedish alum shales (Sundius 1941). These were mined prior to and during World War II.

As in the Billingen-Falbygden area, the contents of kerogen and uranium in the Kinnekulle shales increases upwards in the formation (Westergård 1943, Dahlman & Eklund 1953, unpublished report). The Lower Member

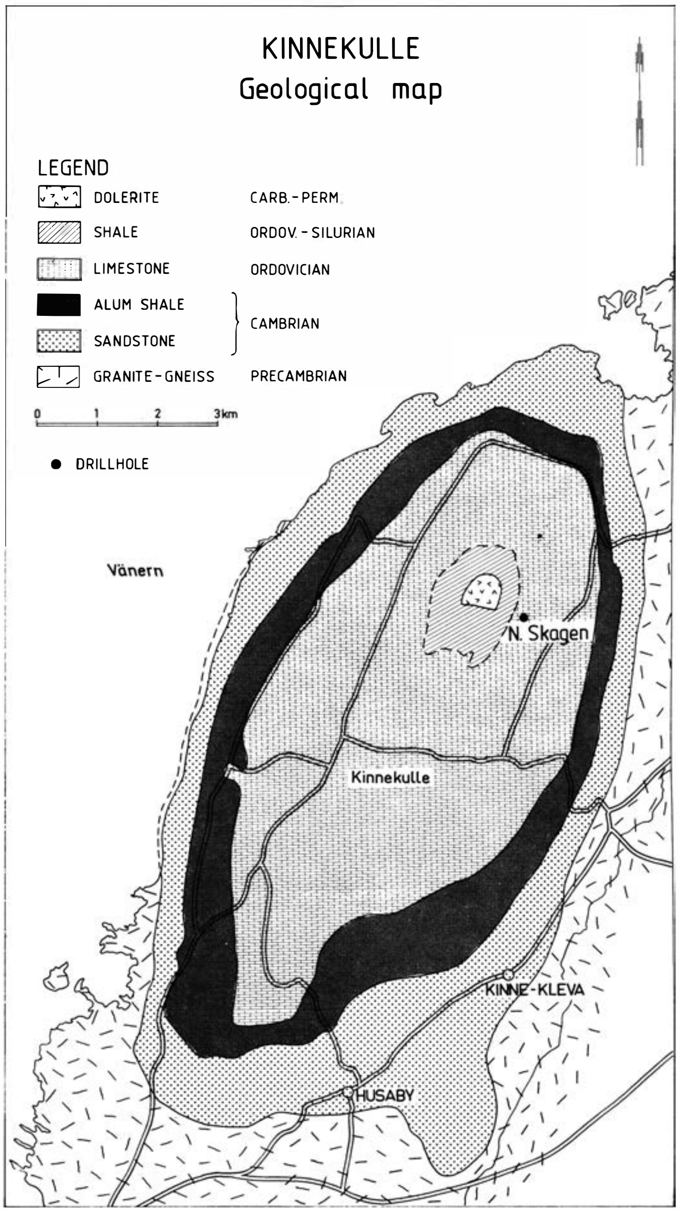

Fig. 10. Bedrock geology of the Kinnekulle outlier (from Westergård 1943).

(3.5 m) contains 0.9–2.6 % oil (F.A.) and 18–24 ppm U, the Middle Member (6.2–6.8 m) 3.4–4.4 % oil (F.A.) and 31–44 ppm U. In the Upper Member, both oil and uranium contents are considerably higher. Oil reaches a maximum in the shales immediately above the Great Stinkstone, with thicknesses of 3 m containing 6.0–6.5 % (F.A.). In the overlying shales, the Fischer Assay drops to c. 4 %. By contrast, uranium-contents increase from the oil-rich unit (110–125 ppm U) to a local maximum (160 ppm over 2.0 m at Per Månsgården) in the overlying shales, only to fall off again in the uppermost part of the member to about the same level as in the oil-rich unit.

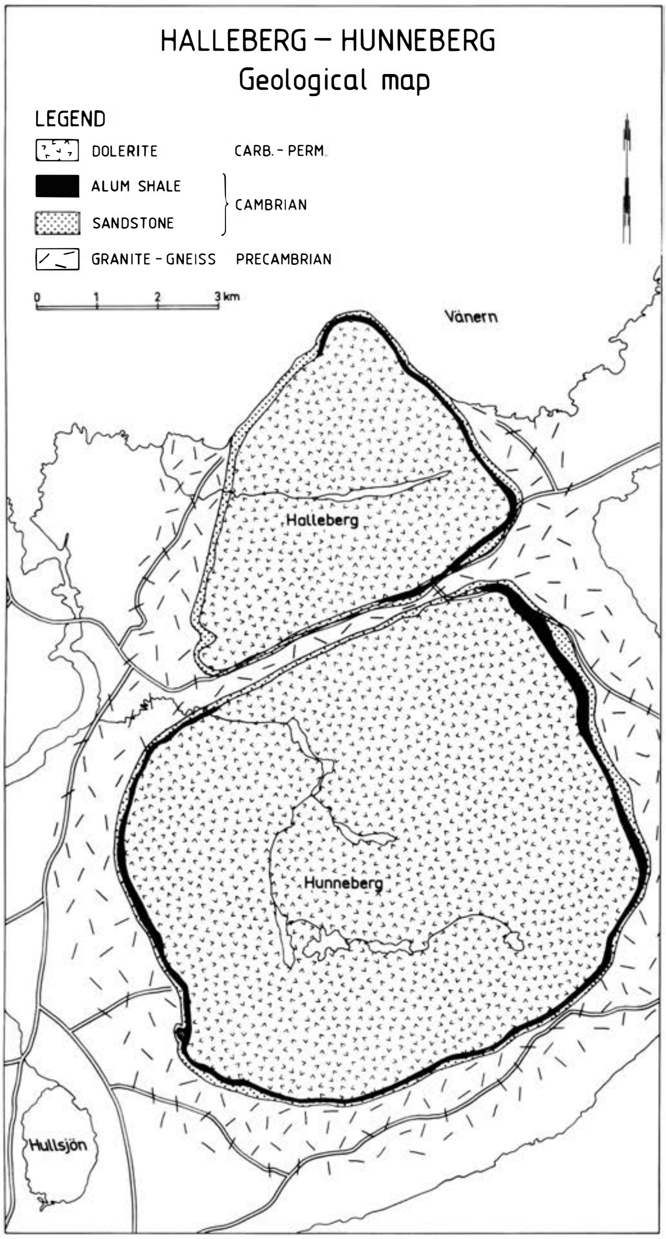

Fig. 11 Bedrock geology of the Halleberg-Hunneberg outlier (from Sidenbladh 1870).

Within the unit with the highest uranium content, kolm has been reported locally. It is of interest to note that the most uraniferous unit occurs in the zone of *Peltura scarabaeoides* whereas the highest oil yields are obtained from the shales underlying stinkstones with *Peltura minor* and overlying the Great Stinkstone, the latter including the subzone of *Olenus gibbosus* in its upper part. The higher oil yields in the Kinnekulle area (by comparison with Billingen-Falbygden) are probably related both to the differences in Upper Cambrian stratigraphy mentioned above and the greater stratigraphic separation of the Alum Shale Formation from the Permo-Carboniferous dolerites (180 m on Kinnekulle, 100 m on Billingen).

The small size of the Kinnekulle outlier makes further exploitation in the area improbable in the foreseeable future. Mining must be largely underground. Transfer of the oil extraction plant from Kinnekulle to Närke after World War II was influenced by this factor and the presence in Närke of shales with only slightly lower oil contents and containing less stinkstone.

Närke

Within the Närke outlier (Fig. 12), complete sections through the alum shales occur in two areas lying to the west and south of the town of Örebro. The outliers preserve a stratigraphy extending from the Lower Cambrian sandstones into the Lower Ordovician limestones. This sequence is faulted along the western and southern margins and influenced by several other subordinate E–W and N–S fractures; it is generally flat-lying and otherwise little disturbed tectonically. The area has been described by Eklund (in Eklund *et al.* 1961) and Dahlman (1962, unpublished report) and in a variety of map-sheet descriptions (Lundegårdh & Fromm 1971 and Lundegårdh *et al.* 1972, 1973).

The Alum Shale Formation varies in thickness from c. 12 to 19 m in Närke and has a maximum thickness (at Hynneberg) of 19.3 m in the eastern outlier. It is very largely of Late Cambrian age, only the lowest part (<1 m) being represented by the *P. forchhammeri* stage of the Middle Cambrian. The formation as a whole is notable for having a relatively low content of stinkstones (c. 15 %) and a relatively high content of organic matter (up to c. 28 %, Dahlstrand 1961 and with an average of c. 20 %, Eklund in Eklund *et al.* 1961).

In the East Närke outlier, the complete Alum Shale Formation occurs over an area of c. 30 km^2, overlain by Lower Ordovician limestones, generally less than 15 m thick. The Upper Cambrian zones (Westergård 1947a) of *Ctenopyge flagellifera* and *augusta*, *Peltura acutidens*, *minor* and *scarabaeoides* are well represented; the uppermost Cambrian and Tremadocian zones are absent (Fig. 13). The lowermost (1.5–2 m) parts of the formation are dominated by stinkstones. The intervening shales have contents of organic matter ranging from c. 18 % to c. 23 % (Eklund in Eklund *et al.* 1961) and can be divided into a lower, Oil Shale unit (up to 10 m thick) with a Fischer Assay of 6–8 % oil and 135 ppm U, and an upper, Uraniferous Shale unit (6–8 m in thickness) in which the oil content drops to 4–5 % (F. A.) and the uranium con-

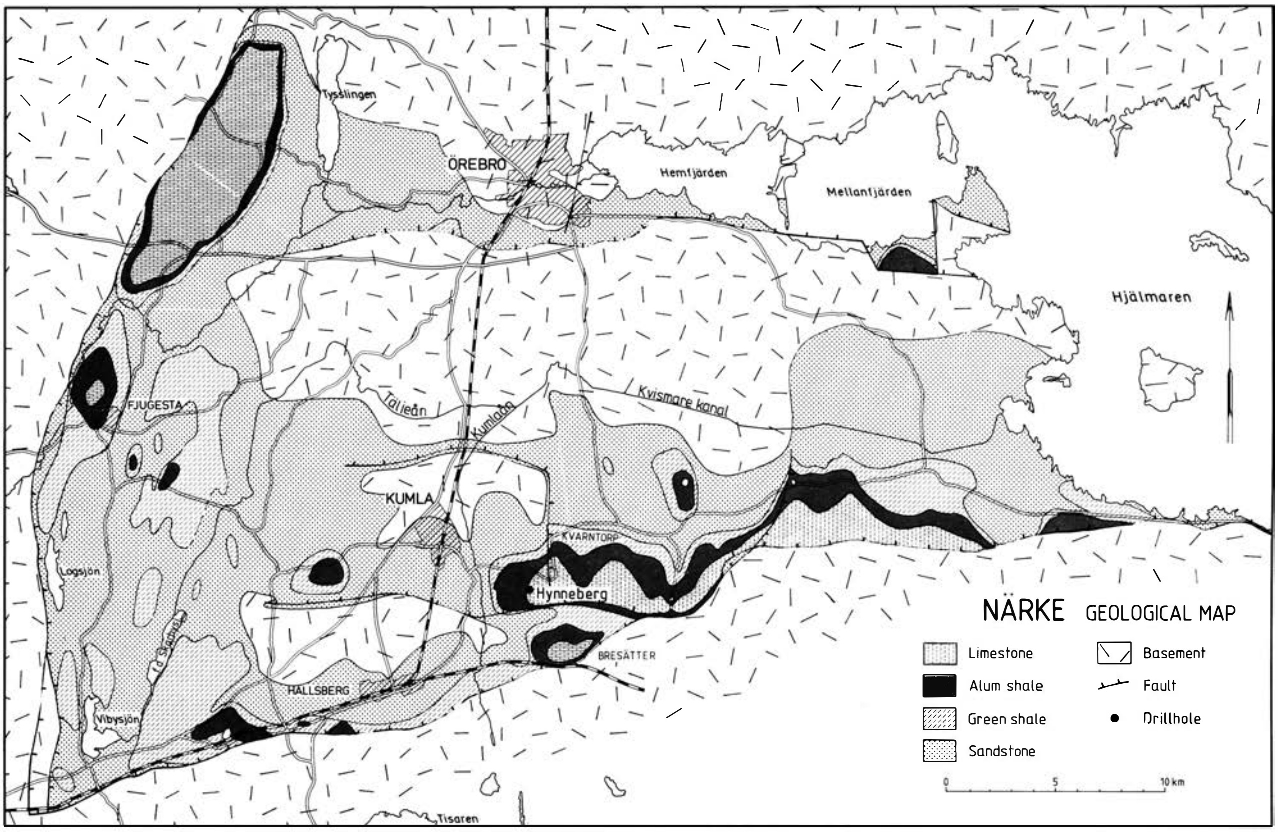

Fig. 12. Bedrock geology of the Närke area (from Eklund *et al.* 1961, Dahlman 1962, unpublished report, Lundegårdh & Fromm 1971 and Lundegårdh *et al.* 1972, 1973). The alum shales occur in two main outliers, referred to as East and West Närke.

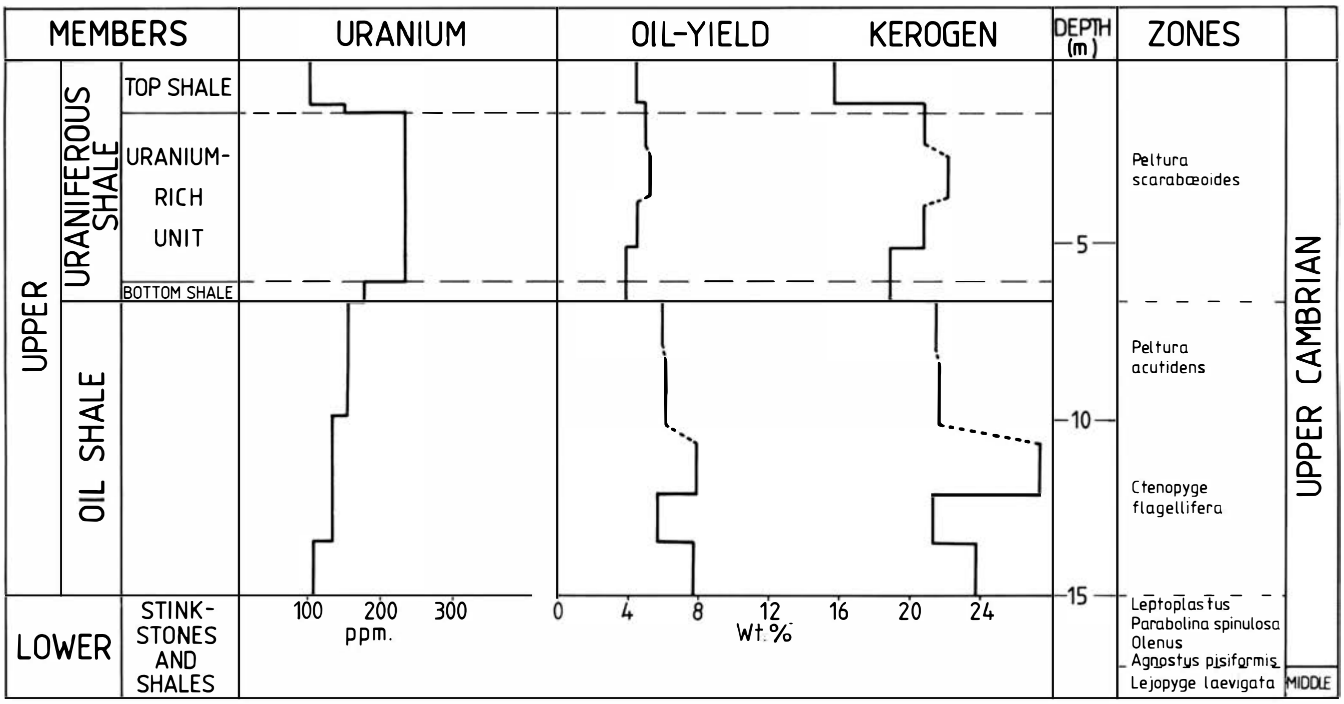

Fig. 13. Variations in the oil yield (Fischer Assay) and contents of uranium and kerogen in the western part of the East Närke outlier (from Andersson *et al.* 1983). Uranium data are averaged from the Alaborg area (Dahlman 1962, unpublished report), oil yield data derive from the Norrtorp drillcore (Westergård 1941) and kerogen contents have been calculated from the calorific values also provided in Westergård (1941).

tent rises to 245 ppm over thicknesses of 4.5 m in the middle of the unit (Andersson *et al.* 1983).

There are considerable differences in thickness of the Oil Shale unit in East Närke; these largely account for the variation in thickness of the formation (from 12 to 19 m) as a whole. The subzones of *C. flagellifera* and *P. acutidens* are better represented in the western part of the East Närke outlier. It was the thicker development of the Oil Shale in the western parts, that led to the concentration of mining in the Kvarntorp area during and after World War II.

In the West Närke outlier, the entire Alum Shale Formation is also developed over an area of c. 30 km^2 of which probably only a minor part is accessible to open pit mining due to the greater thickness of the overlying limestones (20–30 m, Lundegårdh *et al.* 1972). The formation varies in thickness from 12 m in the northern part to 18 m in the south. In general, both the Uraniferous and the Oil Shale units are more variable in thickness and quality than in East Närke, with the former locally containing up to c. 230 ppm U over 3 m and the latter up to c. 5.5 % oil (F.A.) over 7 m.

The Närke alum shales, with their content of kerogen higher than in the Billingen-Falbygden area, are particularly attractive for renewed exploitation. Although the total reserves (Table 5) are considerably less than in Västergötland, there is a greater accessibility to opencast mining, particularly in the eastern area. Here the Uranium-rich unit alone, with an average of 235 ppm U, c. 20 % kerogen and c. 4 % oil (F.A.) over 4.5 m represents an important energy and uranium reserve. The limited data available on other elements in the Närke shales suggests that they are generally comparable with those in Ranstad, Västergötland.

TABLE 5. Quantities of shale and stinkstone and resources of uranium and kerogen in the Upper Member of the Alum Shale Formation in the Närke area (from Andersson *et al.* 1983) The tonnages are metric.

Units in the Upper Member of Alum Shale Formation		Shale (excluding kolm and stinkstone)				Stinkstone	
		Shale (billion tonnes)	Kerogen (billion tonnes)	Uranium		Wt %	billion tonnes
				ppm	million tonnes		
Uraniferous Shale	Top and bottom shales	0.32	0.06	145	0.05	30	0.14
	Uranium rich unit	0.54	0.11	245	0.13	11	0.07
Oil Shale		0.79	1.18	135	0.10	13	0.11
Total		1.65	0.34	175	0.28	16	0.32

Östergötland

In the vicinity of Motala on the eastern side of lake Vättern, the alum shales occur in an E–W trending faulted syncline, occupying an area of about 450 km^2 (Fig. 14). The southern limb of the syncline dips gently northwards to an axial zone running just north of Motala where the thickness of the Ordovician and Silurian limestones and shales overlying the alum shales reaches a maximum of about 150 m. The geology of this outlier has been described by Thorslund (1960). More recently 1:50 000 map-sheets and descriptions have been published over part of the area (Gorbatschev *et al.* 1976, Persson *et al.* 1981 and Wikman *et al.* 1980, 1982).

The Alum Shale Formation increases in thickness from c. 14 m in the east to c. 20 m in the west with a maximum of 24 m in the vicinity of Vadstena. The formation passes transitionally down into grey and green shales and the base is usually taken in the upper *P. forchhammeri* stage of the Middle Cambrian where the black shale facies becomes completely dominant. The sediments below the upper part of the *P. forchhammeri* stage (Fig. 2) are irregularly developed as green glauconitic shales with subordinate dark shales. In the western part of the outlier, the dominating black shale facies commences in the *E. oelandicus* stage. The base of the formation is generally glauconitic and phosphoritic. By contrast with areas described previously, the black shale facies of the Upper Cambrian passes up into the Tremadocian *Dictyonema* zones. They are overlain by Lower Ordovician (Hunneberg stage) limestones, the latter being glauconitic and phosphatic in their basal beds.

The formation in Östergötland can be subdivided into three members. As in the previously described areas, the Great Stinkstone is well developed (1–3 m) embracing locally even the lowermost zone of the Upper Cambrian (*Agnostus pisiformis*). The variable development below and including this bituminous limestone bank composes the Lower Member (c. 5–8 m). Black shales overlying the Great Stinkstone make up the Middle Member (c. 4–8 m). The Upper Member (up to c. 9 m) is characterized by black shales and very thin sandstones, the thickest sandstone (c. 1.5 m) being developed at the base. The Middle Member is entirely of Late Cambrian age; the Upper Member is of Tremadoc age (*Dictyonema* zones). The general, eastward thinning of the formation is accompanied by an increase in the amount of stinkstones, the latter often being conglomeratic and phosphoritic.

Analyses of the more interesting components of the alum shales (Dahlman & Eklund 1953, unpublished

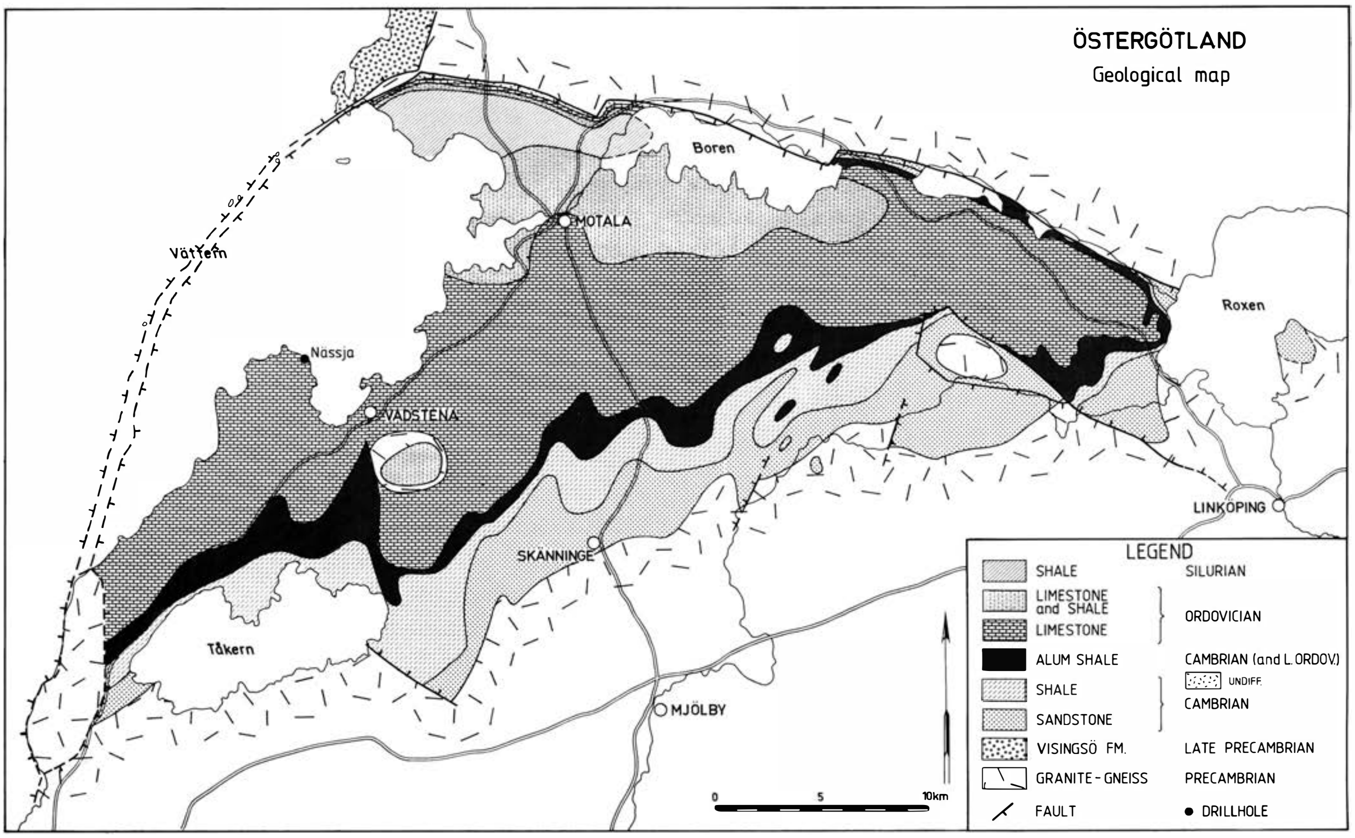

Fig. 14. Bedrock geology of the Östergötland outlier (from Thorslund 1944, Gorbatschev *et al.* 1976, Persson *et al.* 1981 and Wikman *et al.* 1980, 1982).

report; Dahlman 1962, unpublished report) indicate that the area has less economic potential than both Närke and Billingen-Falbygden. As in these areas, it is the upper part that contains the most interesting chemistry. The content of oil in the shales varies from 3 to 6 % (F.A.) in the upper two members. Uranium is highest in the Middle Member, with a maximum of 260 ppm in the 0.6 m of *Peltura scarabaeoides* zone shales; it seldom reaches 200 ppm over a thickness of 2 m. Up to 190 ppm U over 1 m has been recorded locally in the Upper Member, a value that is unusually high for Tremadoc shales. Vanadium increases upwards in the Middle Member to c. 1000 ppm and reaches a local maximum of 2000 ppm over c. 6 m in the Upper Member. Sulphur is highest in the lower part of the Middle Member (7–8 %), particularly in those areas with the highest oil contents.

Skåne (Scania)

Most of southeasternmost Sweden is occupied by Lower Palaeozoic and Mesozoic strata. Lower Palaeozoic rocks (Regnéll & Hede 1960, Norling & Skoglund 1977) occur in a NW–SE trending fault trough over an area of some 2000 km^2. Their presence elsewhere beneath the Mesozoic has been locally demonstrated in recent wells drilled in connection with exploitation for oil; thus Cambrian black shales have been recorded at a depth of 2000 m at Haslöv near Malmö.

Within the main trough of Lower Palaeozoic rocks, Silurian strata comprise most of the exposures, Ordovician and Cambrian sediments occurring only locally along the margins (Fig. 15). Although it is possible that the Alum Shale Formation underlies the entire area of the trough, the existing drill-hole data are inadequate for making a confident assessment of the central parts, where the Cambrian successions occur beneath a cover of up to c. 1000 m of younger Lower Palaeozoic sediments. At six localities along the margin of the trough, drilling has sampled the shales. Only in the southeast (Bergström 1977), in an area of c. 500 km^2 lying to the east of a north–south line through Andrarum, are the Cambrian strata known to occur extensively at shallow depths and it

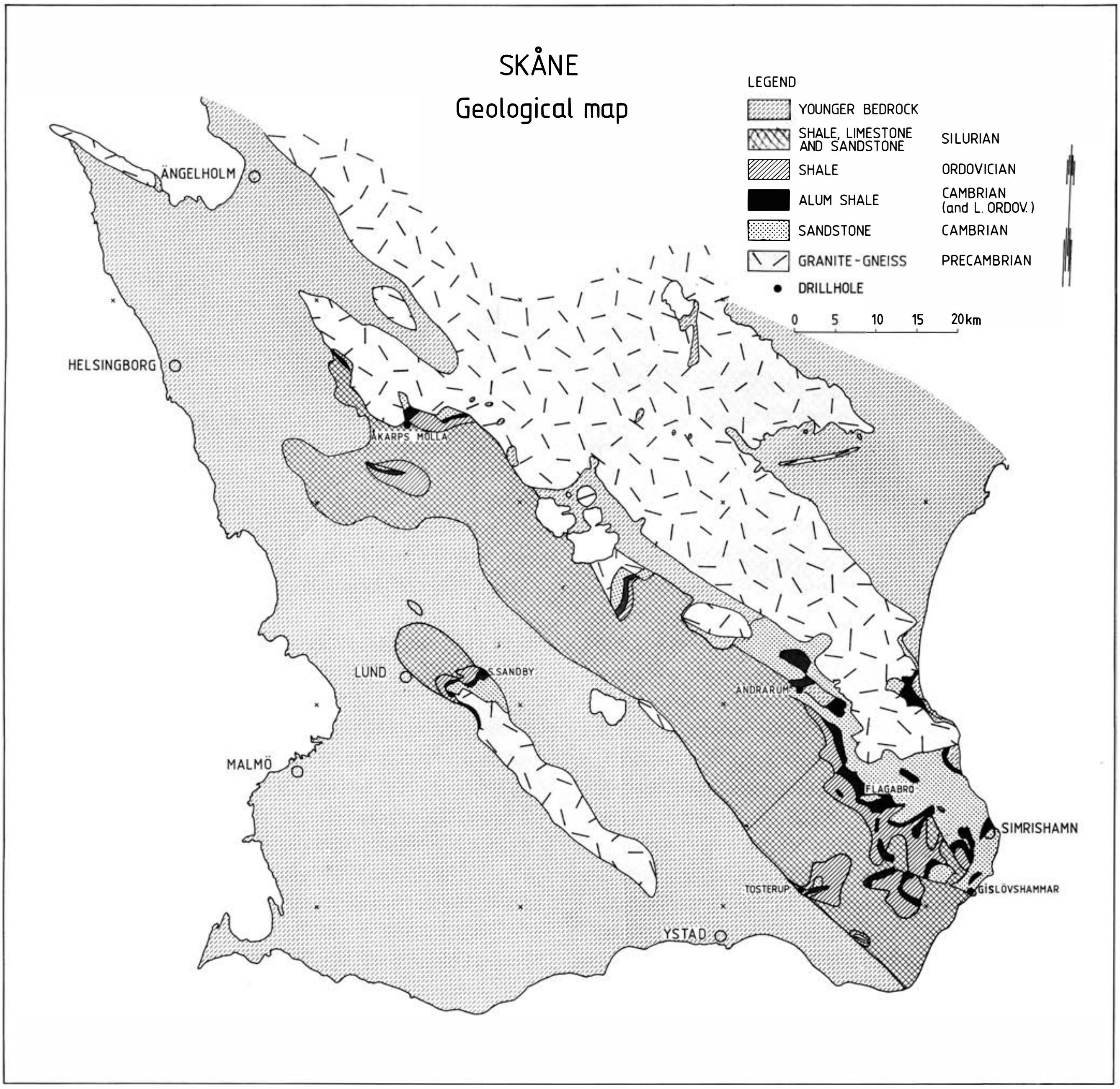

Fig. 15. Bedrock geology of Skåne. The distribution of the alum shales has been taken from Bergström & Shaikh (1980, 1982).

is from here that most of the data on the shales in Skåne are derived (Westergård 1944b).

During their post-depositional history, the alum shales in Skåne have been buried to substantially greater depths than all the other alum shale occurrences east of the Caledonian Front in Scandinavia. The combined influence of deep burial and the intrusion of a Mesozoic dyke swarm has resulted in general coalification of the organic matter and the grade has been identified as semi-anthracitic. Bergström S.M. (1980) recorded high CAI values (4.5–5.5) in the Skåne area. The relative importance of burial depth and dyke intrusion on the organic matter remains unassessed and the possibility exists that lighter hydrocarbons may still be preserved in localities where the intrusions are few or lacking.

The thickness of the alum shale in Skåne is greater than elsewhere in central and southern Sweden and the zonal succession is more complete. A maximum development of 95 m has been recorded (at Tosterup) in which most of the fossil zones occur, from the upper part of the *E. oelandicus* stage of the Middle Cambrian to the top of the Tremadocian. The Alum Shale Formation in Skåne (Dahlman 1962, unpublished report) contains substantially less stinkstone and somewhat more non-bituminous limestone than has been recorded elsewhere; the carbonate content (c. 6 %) in the shale matrix is somewhat higher than in other areas. The lower part of the formation (c. 20 m) composing the Middle Cambrian, contains up to c. 5 % C_{org}, 20–30 ppm U and 100 ppm V (cf. Appendix and Dahlman & Eklund 1953, unpublished report). The Upper Cambrian alum shales (c. 50 m) contain more organic matter (up to a maximum of 15 % C_{org}) with some units, 10–15 m thick, containing 10–12 % C_{org}. The shales also contain higher uranium, particularly in the upper half, with a local maximum of 180 ppm and a best average of c. 130 ppm over 6 m (Tosterup) in the zone of *Peltura scarabaeoides*. The vanadium content (c. 1000–1500 ppm) in the Upper Cambrian increases rapidly upwards into the Upper Member of the formation. The latter, of Tremadoc age, contains the highest values (3500 ppm) in the middle *Dictyonema* zones. Thicknesses of c. 5 m generally contain 2500–3000 ppm; the best area, however, (Södra Sandby, Westergård 1944a) contains 2800 ppm over 9.6 m (or 3700 ppm over 4.0 m). Uranium (c. 40–60 ppm) is lower than in the Upper Cambrian as is the content of organic matter (c. 6–7 % C_{org}).

The data presented above indicate that the Skåne black shales are characterized by substantially lower contents of organic matter and uranium than the other areas of Sweden. However, the tonnages of these "low grade" shales are considerable; they represent an important reserve. Vanadium, as on Öland (see below), is exceptionally high, but occurs in shales with lower organic carbon contents. It needs emphasis that the Skåne alum shales are inadequately explored; areas may well exist with higher contents of the interesting components than those mentioned above, areas where dyke frequency is low and the ubiquitous high-angle faulting is subordinate.

Öland

Although the Alum Shale Formation underlies the Ordovician limestones throughout Öland (Westergård 1944b, 1947b), its thickness is insignificant (<2 m) in the northern part of the island where stinkstones dominate; it increases in a southeasterly direction reaching nearly 24 m in the southern extremity of the island (Fig. 16). It is readily divisible into two members, an upper unit (c. 10

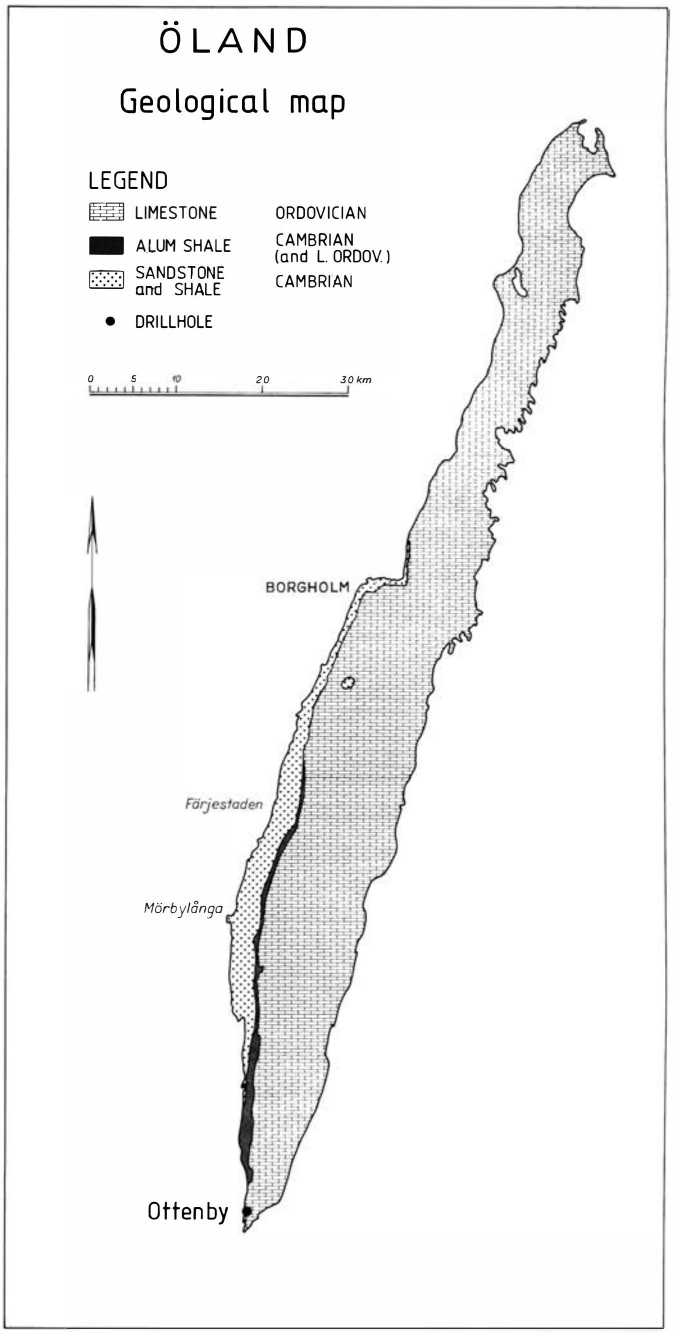

Fig. 16. Bedrock geology of the island of Öland (Hedström & Wiman 1906 and Dahlman 1977, unpublished report). In the northern part of the island the formation containing the alum shales is thin (<2 m) and dominated by stinkstones. It increases in thickness in southern Öland to a maximum of c. 23 m.

m) of black shales with very subordinate stinkstones and a lower unit (c. 14 m) of black shales with a high frequency of stinkstones (25–35 %) particularly in the upper part. The formation dips very gently (c. 1°) southeastwards. It outcrops along the western side of the island and is overlain by Ordovician limestones which reach a thickness of 35 m in the extreme southeast. Deposition of the black shale and stinkstone facies started in the late Middle Cambrian (*P. forchhammeri* stage) and continued through the Late Cambrian into the Tremadoc.

The black shale facies reaches into younger units (*Ceratopyge* zone) on Öland than elsewhere in Sweden. The Upper Member is almost entirely of Ordovician age and the Lower Member of Middle and Upper Cambrian age. *Dictyonema* zones of the Tremadocian are well developed (up to c. 8 m) in black shale facies; much of the Upper Cambrian is composed of stinkstone and the *Peltura scarabaeoides* zone is poorly represented (c. 1 m).

Information about the Öland alum shales has been compiled recently by Dahlman (1977, unpublished report). The Öland alum shales are notable for their unusually high contents of sulphur (in the Lower Member, generally about 10 % and up to nearly 14 %; in the Upper Member c. 2.5–3 %). In general, the shales in both members have a uranium content of c. 50 ppm with the concentration rising to c. 100 ppm in the Upper Cambrian units. Vanadium contents of 2000–3000 ppm have been recorded from the Lower Ordovician shales. Oil-yield is generally between 2 and 3 % (F.A.) and the organic carbon ranges from 9 to 12 %.

Gotland

The island of Gotland is entirely composed of Silurian sediments, largely limestones and shales. Deep drilling in the context of an oil-prospecting programme has identified a limited area (Fig. 3) in the southern part of the island in which alum shales are preserved at a depth of 450–500 m below sea level. Elsewhere, the Lower Ordovician limestones rest directly on Lower and Middle Cambrian sandstone and shales. The alum shales vary in thickness up to 4.5 m and, at least locally, are of both Late Cambrian and Tremadoc age. The zones with *Agnostus pisiformis, Ctenopyge flagellifera* and *Dictyonema* have been identified, and as in Gävlebukten (see below) cross-bedded sandstones occur in the Tremadoc black shales. Stinkstone conglomerates are also present, the fragments of limestone occurring in a sandy matrix. Analyses of a single *Dictyonema* bearing shale (Drillhole Wiklau, 382.74–382.90 m) yielded 8.6 % C_{org}, 219 ppm U and 1867 ppm V. The Upper Cambrian shales contained 9–14 % C_{org}, 60–80 ppm U and 300–400 ppm V (Geological Survey of Sweden, unpublished data).

Baltic Sea and Gulf of Bothnia

The Alum Shale Formation probably occurs off-shore in the southern Baltic Sea. As noted above, the formation increases in thickness southwards on Öland; its gentle easterly dip implies that it thus probably underlies a substantial area between Öland, Skåne and Bornholm (Denmark) and further to the east.

North of Stockholm, in the southern part of the Gulf of Bothnia between Gävle and Härnösand (Fig. 4), an area of flat-lying Lower Palaeozoic rocks, largely composed of Ordovician limestones, has been identified (Winterhalter 1972), up to some 200 m thick. Black shales and sandstones, up to 1 m thick and of Tremadoc age, have been recognized (Thorslund & Axberg 1979) in a drillhole near Gävle and it remains possible that the formation may occur below the extensive Ordovician limestones further east. These Tremadoc shales contain high concentrations of both uranium (190–240 ppm) and vanadium (1700–2100 ppm). No black shales have been recorded in the material sampled from the sea-bed but the presence of stinkstone (Axberg 1980) and oil-impregnated sandstone boulders (Thorslund, pers. comm. 1979) in the glacial drift along the coast north of Gävle may be taken to favour the occurrence of alum shales off-shore.

Caledonides

Lithofacies development in the Cambrian of the Caledonian Front (Fig. 1) is broadly similar to that in central and southern Sweden. Lower Cambrian sandstones pass up via phosphorite-bearing conglomerates through a grey-green siltstone facies into upper Middle and Upper Cambrian black shales. The latter locally extend into the Lower Ordovician, to be overlain by limestones and shales. The Cambrian lithologies can be traced far west from the Caledonian Front autochthon beneath the nappes and via the various windows into coastal Norway. In the central part of the mountain belt, the black shale facies has been traced 200 km west of the front to Tømmerås in Trøndelag (Gee 1980), where it is still characteristically highly radioactive. This evidence implies that the Cambrian shelf environment extended over the vast areas of western Scandinavia which are now overridden by the Caledonian allochthon (Bergström & Gee in press).

Over much of the Caledonian Front, the autochthonous alum shales provide the detachment zone for the lowermost allochthon. In zones of high strain between the thrust sheets, most of the fossil evidence has been destroyed; the sporadic occurrence of a fauna and the generally low content of uranium (<100 ppm) suggests that the Upper Cambrian part of the formation is only locally preserved. In southern areas (Oslo Graben and central Jämtland), however, the formation occurs both in the autochthon and in the overriding nappes. The shales are often highly disturbed and thicknesses are much influenced by local tectonic thinning and repetition. Sequences of over 300 m are known from some areas (e.g. Tåsjöberget, in northernmost Jämtland, Asklund 1938, Gee 1972).

Oslo Graben

The main area of occurrence of alum shales in Norway is within the Oslo graben. As in Sweden, the black shale facies, with associated stinkstones (up to 50 %), was developed during both the Middle and Late Cambrian and extended into the Tremadoc (Henningsmoen 1957). The formation has a total thickness of c. 80–90 m. Only in the Oslo area are the Tremadoc shales extensively developed.

Investigation of the uranium content of the alum shales in southern Norway commenced locally immediately after World War II (Rosenqvist 1948) and was supplemented in the mid-fifties by regional prospecting (Skjeseth 1958). Nineteen drillcores were logged and analysed, interest being concentrated on the varying uranium content and supplemented by a few analyses for sulphur, organic carbon and vanadium. Subsequently, Bjørlykke (1974), in a general investigation of the geochemistry of the Lower Palaeozoic sequence in the Oslo region, provided supplementary data on the distribution of these and some other elements in the Alum Shale Formation. He reported high sulphur contents (10–12 %) in the Upper Cambrian shales along with an average of c. 10 % C_{org}; subordinate units occur locally with organic carbon up to 14 %. Occasional higher values have been noted in environments influenced by tectonic or metamorphic processes. Thus, from the Caledonian thrust front of the Mjøsa area, near Gjøvik, Foslie (1919) reported very high organic contents (40–50 %) in anthracitic alum shales beneath an allochthonous quartzite. Rosenqvist (1948) commented on the lack of kolm in the Oslo alum shales. Uranium contents are highest in the *Leptoplastus* and *Peltura* zones, reaching a local maximum (in 10–15 cm thick units) of 170 ppm and a general average of 50–150 ppm over thicknesses of 5–15 m (Skjeseth 1958). Vanadium in these units is at a level of about 600–700 ppm and rises to a maximum of 1500 ppm in the overlying *Dictyonema* shales (Bjørlykke 1974). This increase in vanadium is accompanied by a concomitant decrease in uranium (10 ppm), organic carbon (8–9 %) and sulphur (c. 1 %).

Recently, Lindahl (1983), referring to an unpublished report by Olerud (1982), reported tectonically repeated (c. 150 m) successions from the vicinity of Elsjø. Thin units contain up to 240 ppm U; thicker sections (10–20 m) provide a general average of 150 ppm. Vanadium contents reach a maximum of 2000 ppm but generally average c. 800 ppm. Lindahl (1983, p. 131) also mentioned that the previous analyses of uranium content in alum shales from the Oslo area were "too low".

It can be concluded from this summary that the general geochemistry of the alum shales of the Oslo region compares most closely with that of the Skåne shales in Sweden. A systematic reinvestigation, particularly with regard to the chemical and mineralogical variation in relation to the biostratigraphy of the units with the highest organic carbon contents, would be necessary to allow a closer comparison with Swedish occurrences. North of the Oslo region, data are conspicuously lacking from areas of greater structural complexity; as in Jämtland, the latter can locally be a positive factor for prospecting.

Caledonian Front in Jämtland

An investigation of the Jämtland alum shales (Fig. 17) has located extensive areas with development of relatively thick Upper Cambrian units in the vicinity of Storsjön, near Östersund (Gee *et al.* 1982, unpublished report).

In the area (Fig. 18) south of Storsjön, tectonic repetition of the alum shales in the core of a major antiform (Fig. 19) has been identified. In this structure organic-rich Upper Cambrian black shales with thicknesses of 150–180 m contain c. 10 % C_{org}, 1500–1600 ppm V and 180 ppm U. Subordinate units in the order of 20–30 m in thickness, contain c. 11–12 % C_{org}, 1500–2000 ppm V, 200–240 ppm U and 350–400 ppm Mo. Thinner sections (comparable in thickness to the uraniferous units in the Billingen-Falbygden and Närke areas) are marginally richer in these components (c. 12–13 % C_{org}, 1500–2000 ppm V, 225–250 ppm U and 400–450 ppm Mo).

These Jämtland alum shales occur in the lower nappes of the Caledonian allochthon. The shales are more penetratively deformed than in the other areas of preservation in Sweden, described above, and have been subject to metamorphic temperatures of c. 200 to 300 °C (Kisch 1980, Bergström S.M. 1980, Snäll in prep.). The semi-anthracitic to anthracitic grade of maturity of the organic material is comparable with that of the alum shales in Skåne.

Stinkstones are sporadically preserved in these Jämtland shales, and are often extensively recrystallized. Nevertheless, it has proved possible (Bergström J. 1980) to identify a number of Middle and Upper Cambrian zones and establish that the chemistry referred to above occurs in shales containing the zones of *Parabolina spinulosa, Leptoplastus* and *Peltura.* No detailed analysis of the inter-relationships of the trace element chemistry and the biostratigraphy has yet been possible.

The remarkable thickness and relatively high concentrations of the various interesting components of the Jämtland alum shales imply the presence of a very large reserve of both fossil energy and trace metals. Whereas all previous planning of the exploitation of the alum shales in Sweden has concentrated on open-cast mining of a relatively thin unit, the new data from Jämtland requires a radically different approach that as yet remains unassessed.

Caledonian Front in Västerbotten and Norrbotten Counties

The Jämtland alum shales can be traced northwards into the counties of Västerbotten and Norrbotten. They are present in the autochthon, the lower nappes and occur locally at some higher tectonic levels. In the north, in Norrbotten (Fig. 20) the occurrences are sporadic and the shales are generally thin and highly deformed. Further south in the mountain front of Västerbotten (Fig. 21), the Alum Shale Formation thickens and is better preserved both in the autochthon and lower nappes. As in northern Jämtland, great thicknesses are preserved locally.

Caledonian Windows

Black phyllites and schists are present in several windows within the mountain belt, generally occurring as thin units in association with quartzites and marbles, overlying parautochthonous basement. In some cases, such as the Grong-Olden Culmination, it has been possible to follow these occurrences eastwards into lower grade environments where the fossil content has allowed correlation with the Cambrian alum shales. The chemical signature, at least with respect to uranium and vanadium, apparently is retained in units subject to high greenschist facies metamorphism. The better preserved phyllites of probable Cambrian age occur in windows along the Swedish-Norwegian border, such as in Olden (Gee 1980), Nasafjäll (Thelander *et al.* 1980) and Rombak (Kulling 1964). However, similar associations with radioactive black schists occur in the Tømmerås (Gee 1977) and Høgtuva Windows and are also reported from Rendalsvik (Skjeseth & Sørensen 1953, Lindahl 1983) where uranium contents reach c. 180 ppm (average 45 ppm) and vanadium 3000 ppm (average 450 ppm). These are also probably correlatives of the Alum Shale Formation.

Köli Nappes

The higher Caledonian nappes, composed of volcano-sedimentary eugeoclinal associations (the Köli Nappes), contain a variety of black phyllite units at different levels in the tectono-stratigraphy. One of these, occurring near Nordaunevoll in eastern Trøndelag was shown by J.H.L. Vogt (1889), Th. Vogt (1941) and Størmer (1941) to be of Tremadoc age, based on the presence of a *Dictyonema* fauna. Trace element analysis of these highly graphitic units (Gee 1981) demonstrated uranium and vanadium concentrations very similar to those which are characteristic of the Tremadoc shales on the platform. At Nordaunevoll, the graphitic shales occur together with pillow basalts and are intruded by dolerite dykes. This particular unit has been reported (Wolff 1976, 1979) to extend along strike at least 100 km through eastern Trøndelag south of the Grong-Olden Culmination. North of this culmination at a similar tectonic level in the Köli Nappes of southern Lappland, a graphitic phyllite unit in association with the Stekenjokk volcanites has a similar geochemical signature (Sundblad and Gee, in press) and is also inferred to be of Tremadoc age.

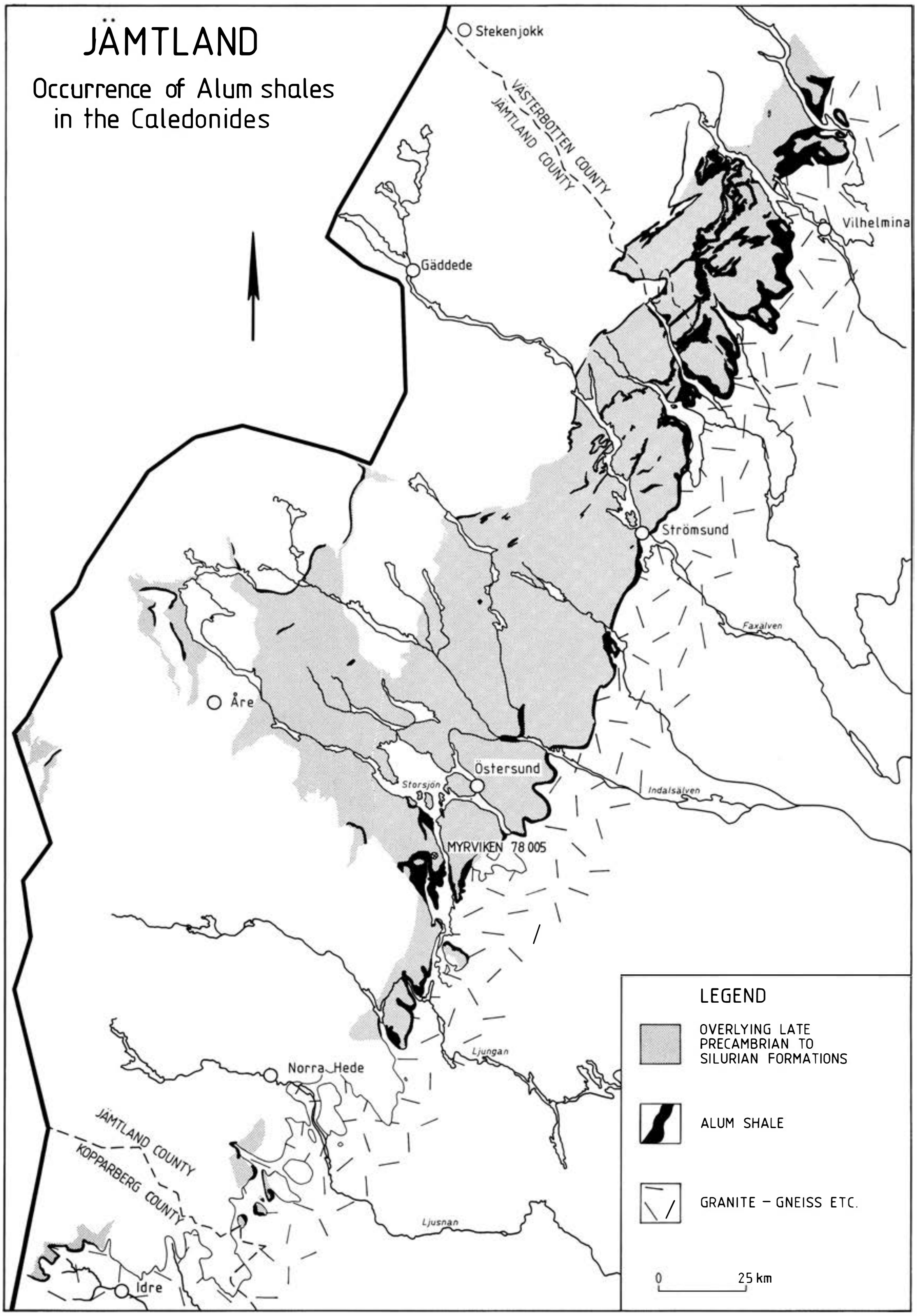

Fig. 17. Distribution of the alum shales in western Jämtland, northernmost Kopparberg and southernmost Västerbotten Counties. Areas are also marked where the alum shales are covered by Ordovician and Silurian strata and/or thrust sheets of Upper Proterozoic/Lower Cambrian sandstones and quartzites. The alum shales probably also occur further west at greater depths beneath the higher nappes (based on a compilation for Radonutredningen 1979 by T. Thelander, Ds Jo 1979:9, Appendix 2:2).

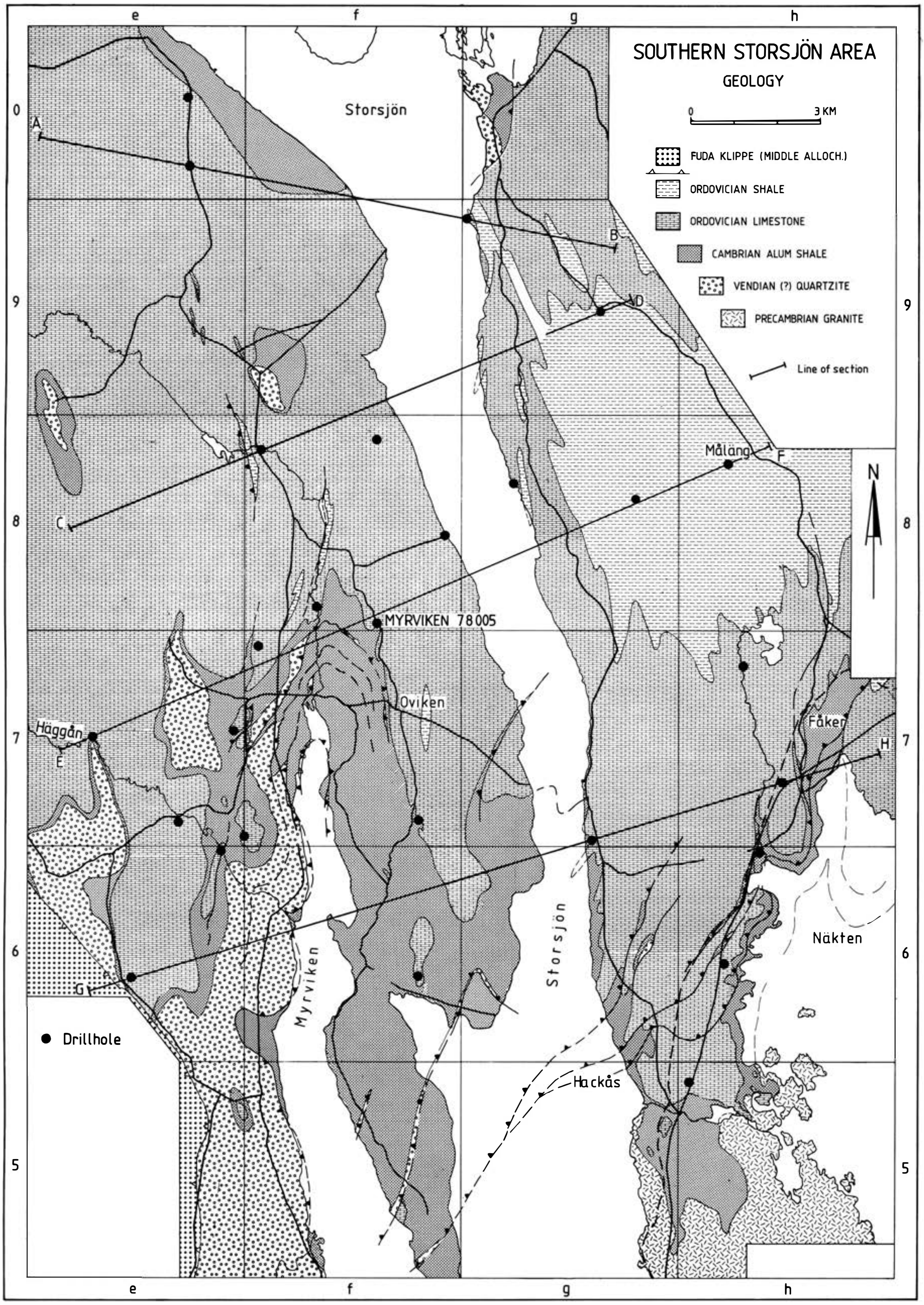

Fig. 18. Bedrock geology of the area of southern Storsjön, Jämtland (based on Gee *et al.* 1982, unpublished report). The Lines A–B, C–D, E–F and G–H mark the profiles in Fig. 19.

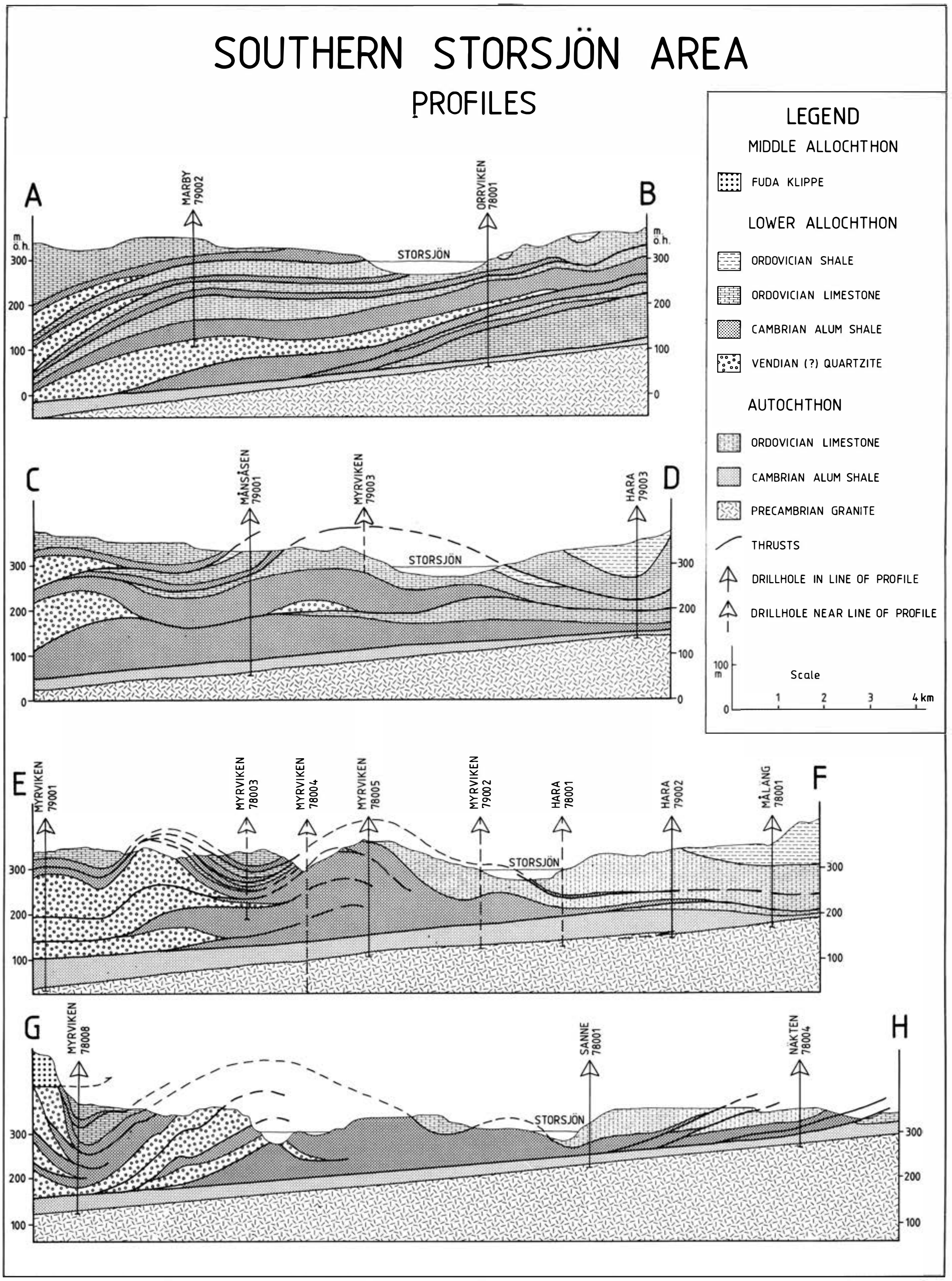

Fig.19. Sections through the southern Storsjön area, Jämtland, (taken from Gee *et al.* 1982 unpublished report) illustrating the thick development of the alum shales where they are tectonically repeated in the core of the Myrviken Antiform. Note that the allochthonous cover of sedimentary rocks is thrust over a passive largely undisturbed autochthon of Cambrian shales (locally with Lower Ordovician limestones) and underlying Precambrian crystalline rocks.

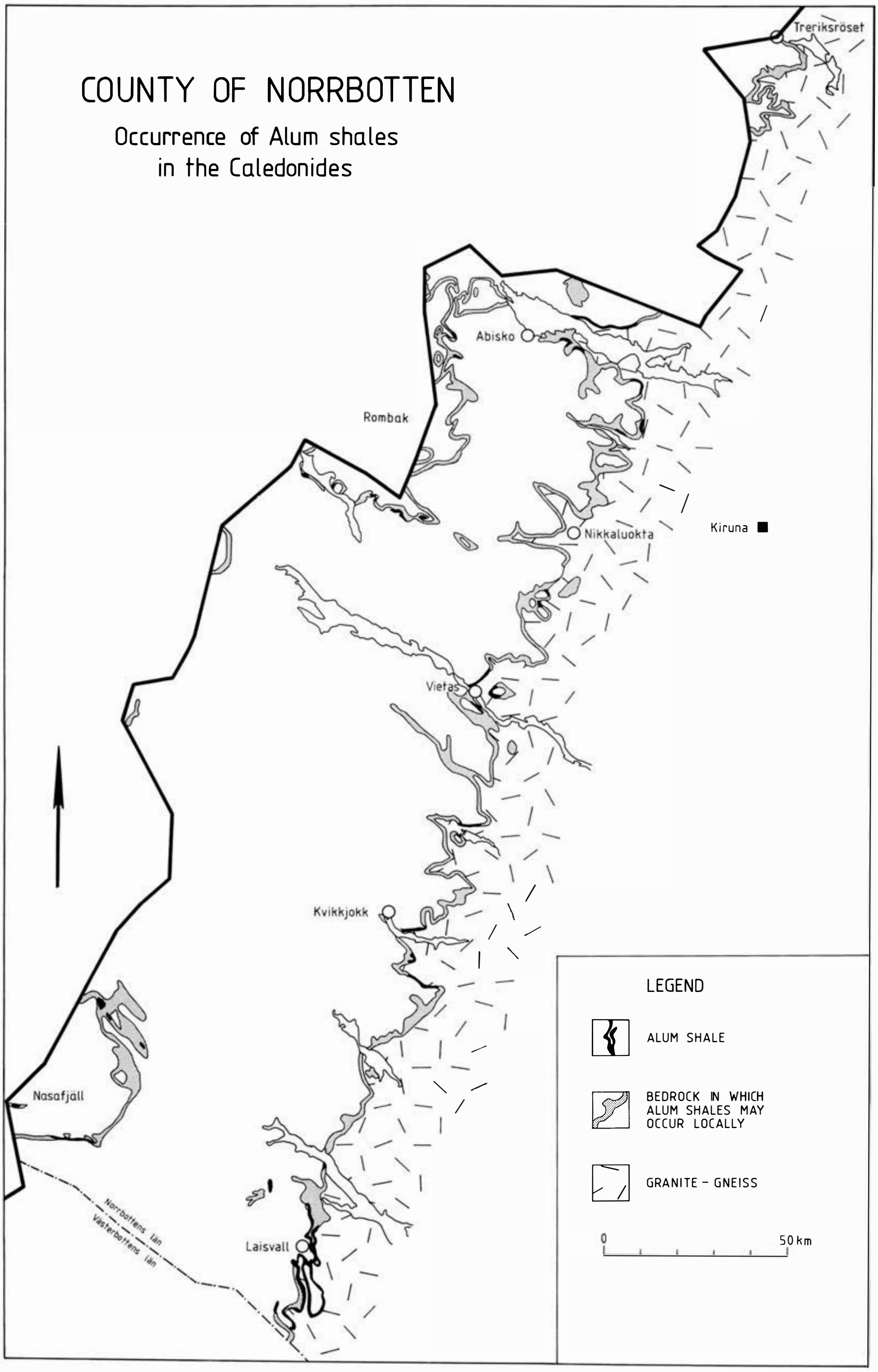

Fig. 20. Distribution of the alum shales in western Norrbotten County. The formation occurs sporadically in the autochthonous sedimentary rocks of the Caledonian Front, in the lower nappes and in the parautochthonous and lower allochthonous cover strata of the windows (based on a compilation for Radonutredningen 1979 by T. Thelander, Ds Jo 1979:9, Appendix 2:2).

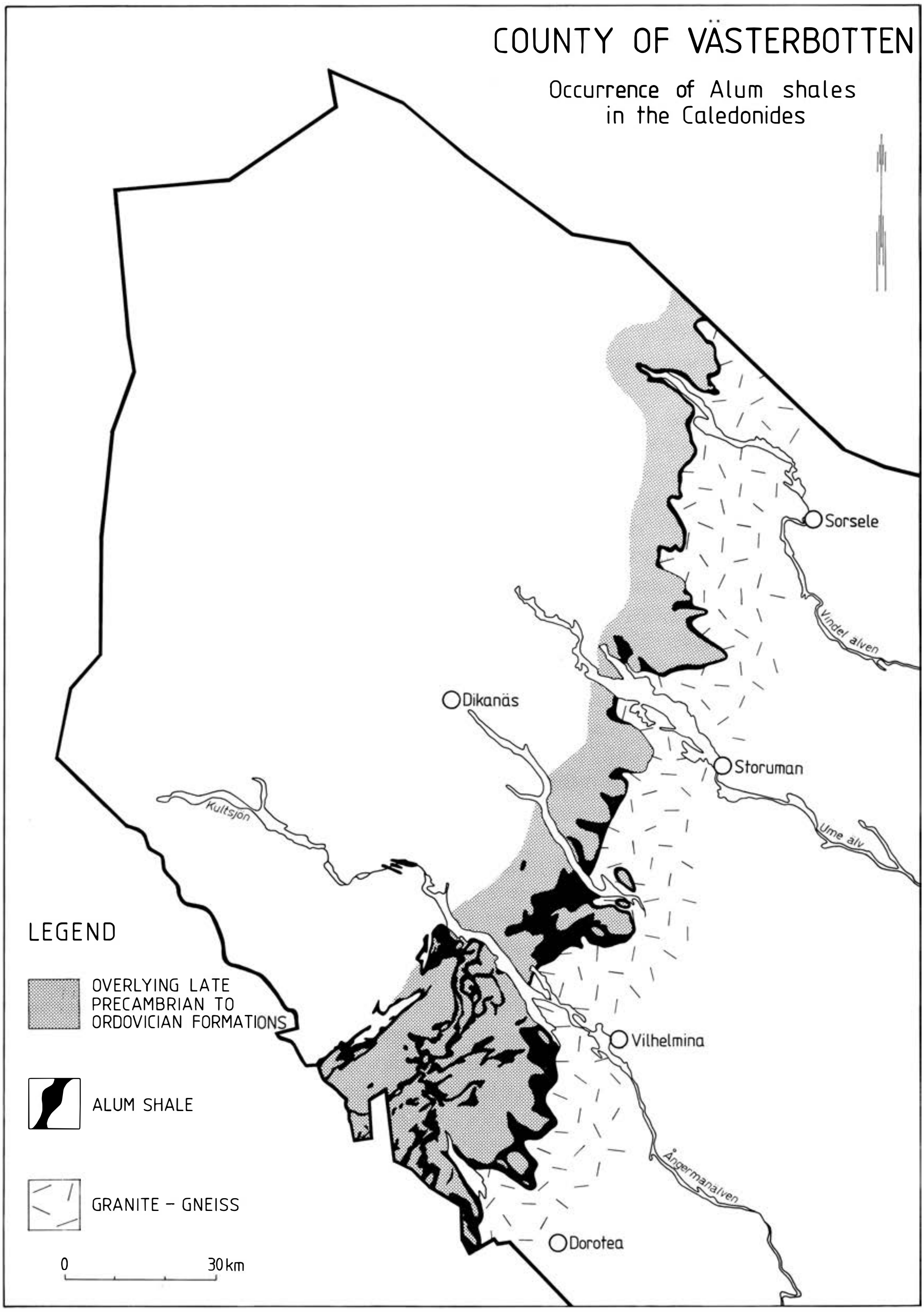

Fig. 21. Distribution of the alum shales in western Västerbotten County. The formation occurs in the autochthonous sedimentary rocks of the Caledonian Front, in the lower nappes and in the parautochthonous and lower allochthonous cover strata in the windows. Areas are also marked where the alum shales are covered by Ordovician strata or thrust sheets of Upper Proterozoic and Lower Cambrian sandstones and quartzites. The alum shales probably also occur at greater depths beneath the higher nappes (based on a compilation for Radonutredningen 1979 by T. Thelander, Ds Jo 1979:9, Appendix 2:2).

Elsewhere

Similarity in the development of the Middle and Upper Cambrian shale facies from Scandinavia, via the Anglo-Welsh region of Great Britain to the Avalon zone of Eastern Newfoundland and Cape Breton Island has been referred to by many authors. Outside Scandinavia, the sequences are generally thicker, siltier and more calcareous. However, somewhat condensed black muds were deposited during at least part of the Upper Cambrian in all these areas (Fig. 22).

In the Anglo-Welsh area, the black shale facies is largely confined to the *Parabolina spinulosa, Leptoplastus* and *Peltura* zones, being usually underlain and overlain by dark shales and subordinate sandstones. Taylor & Rushton (1971) correlated the Monks Park black shales (Warwickshire) with the Dolgelly Beds of North Wales, the White-Leaved-Oak shales of the Malvern Hills, and the Shoot Rough Road shales and Black shales of Shropshire. These successions, at least locally, are strikingly similar to those of the same age in Scandinavia, a good example being the c. 4 metres of *Peltura minor* black shales and stinkstones of the Dolgelly Beds in the Bentleyford Brook section of Shropshire (Stubblefield 1930, Rushton 1974). Ponsford (1955) reported the results of a study of the radioactivity of these and other sediments. Although the Upper Cambrian pyritized carbonaceous black shales were markedly enriched in uranium by comparison with black shales of other ages, no single unit was found to contain more than 39 ppm U. Ponsford commented (p. 27) on the highest uranium contents in the units occurring "not in the blacker beds, but in the innumerable thin, light-grey bands". Gamma-ray logging of the Warwickshire boreholes (in Taylor & Rushton 1971) likewise demonstrated higher radioactivity in the Upper Cambrian succession and particularly the Monks Park shales, confirmed this correlation with colour, and identified a peak occurring near the base of the Upper Cambrian, equivalent to c. 150 ppm U.

The Upper Cambrian successions of eastern Newfoundland (Hutchinson 1962), Cape Breton Island (Hutchinson 1952) and New Brunswick (Hayes & Howell 1937) are generally developed in grey and black shale facies; dark shales also occur locally in the Middle Cambrian. All these successions – the Elliot Cove and Hardcourt Groups of Newfoundland, the MacNeil Formation of Cape Breton Island and the Agnostus Cove, Black Shale Brook and Narrow Formations of the St. John's Group in southern New Brunswick are relatively thick units by comparison with their Scandinavian time-equivalents. Very little information is as yet available on their geochemistry. An understanding of the origin of the anomalous Scandinavian black shales would undoubtedly be enhanced by more chemical and mineralogical data on the shales of similar facies and age occurring elsewhere in Europe and in North America.

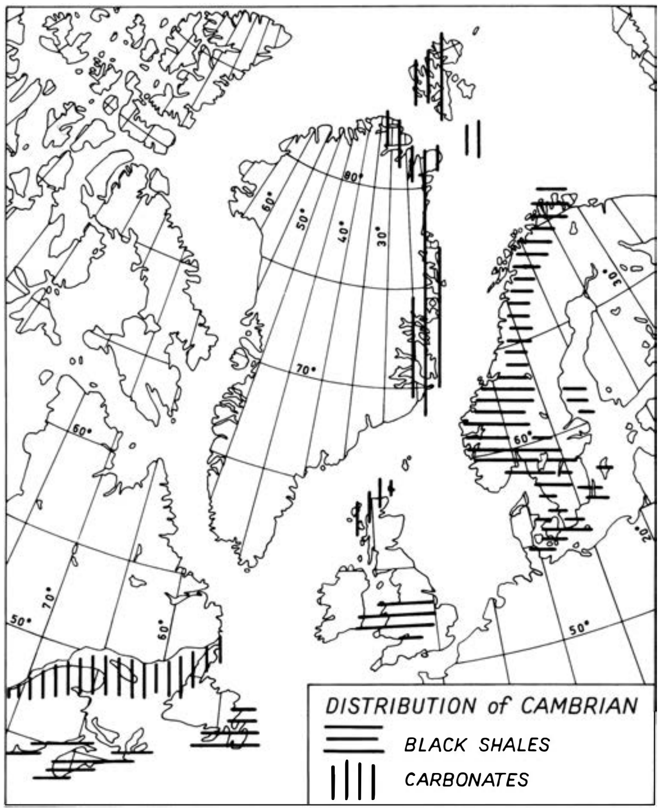

Fig. 22. Late Palaeozoic reconstruction of the Caledonian-Appalachian orogen showing the distribution of the Cambrian black shale and limestone facies (from Gee *et al.* 1974).

Discussion

Depositional environment

Regional relationships

Late Cambrian black shales, occurring on the Baltoscandian Platform, in the Anglo-Welsh area of the British Isles and in easternmost North America, accumulated along the southern margin of the Caledonian – Appalachian geosyncline (Fig. 22). There is an increasing volume of evidence (Wilson 1966) favouring the existence, during the Early Palaeozoic, of a major ocean basin–the Iapetus Ocean of Harland & Gayer (1972) – separating this southern continental margin (probably located at moderate to high latitudes), from the more equatorial Laurentian margin (Scotese *et al.* 1979). In the shallow marine, epicontinental environments of the latter area, a Lower Cambrian sandstone facies onlapped westwards and was succeeded by a monotonous carbonate bank (Swett & Smit 1972) extending at least from east Greenland via north Scotland to the western front of the Appalachians in North America (Rodgers 1968) and lasting from the Middle Cambrian into the Middle Ordovician.

The Cambrian faunal communities of these two contrasted epicontinental environments are markedly dissimilar (Cowie 1974). This evidence has led to various estimates of the size of the Iapetus Ocean (McKerrow & Cooks 1976); it probably had a width of a few thousand kilometres during the Late Cambrian, prior to Ordovician and Silurian closure. Within the Caledonian-Appalachian orogen, the various allochthonous ophiolitic associations and subduction-related volcanic rocks provide a fragmented record of the opening and closing of the ocean (Roberts & Gale 1978). Relationships along the Baltoscandian margin (Gee 1975) favour the existence of a passive Atlantic-type development at least during the Early and Middle Cambrian, the epicontinental areas giving way oceanwards to deeper shelf and then ocean floor. Subduction-related processes, with the development of a Baltoscandian volcanic island arc associated with closure of the ocean (Stephens and Gee, in press) are thought to have occurred in the Early Ordovician and may have started in the Late Cambrian.

Rifting, related to initial separation of Baltoscandia and Laurentia and early development of Iapetus started in the Late Proterozoic. An Iapetus sea-floor was probably in existence during or shortly after the intrusion of the extensive tholeiitic dyke swarms now preserved in the Scandinavian Caledonian allochthon (Särv Nappes) i.e. at c. 650–700 Ma B.P. An irregular Late Precambrian topography along the northwestern margin of the continent was subject to a long period of erosion and peneplanation which, after the Varanger glaciation, was followed by cycles of regional transgression and regression leading to gradual submergence of much of the Baltoscandian Platform. Peneplanation and submergence reached its culmination in the Late Cambrian with the regional development of the black shale facies.

Baltoscandia

Various attempts have been made to reconstruct the changing Baltoscandian palaeogeography during the Cambrian (Hansen 1945, Thorslund 1960). It has been suggested that Early Cambrian deposition occurred principally in two areas, a northeast trending land-ridge about 150 kilometres wide, separating a Caledonian front depositional area from an area embracing the Baltic, central and southern Sweden and regions to the southeast. This central "torso" (Asklund 1960) is thought to have persisted throughout the Cambrian, becoming progressively submerged in the southwest and resulting, in the latter part of the Middle Cambrian and the Late Cambrian, in the connection of the two depositional areas. The presence of only very thin alum shales of Tremadoc age in the Siljan area (Thorslund 1960) has provided support for this hypothesis.

The basis for this interpretation of the distribution of land and sea during the Middle and Upper Cambrian is somewhat conjectural. In the Alum Shale Formation, the fossils are usually excellently preserved in the stinkstones and absent in the shales; only in Skåne and the Oslo area is the shaly facies notably fossiliferous. Identification of the presence of particular zones is thus dependent on a subordinate and laterally impersistent lithology; thus the apparent lack of particular zone fossils need not imply non-deposition or even deposition and subsequent erosion. Sequences dominated by shales have been referred to as basinal; lateral passage into stinkstone conglomerates (e.g. the change from Billingen to Kinnekulle in the Late Cambrian) has been interpreted to imply proximity to a coastline towards the northwest. However, the areas of greater stinkstone frequency may well represent intrabasinal highs rather than evidence of emergence or proximity to land. Local development of monomict stinkstone conglomerate testifies to the early diagenetic consolidation of the sediments and subsequent disturbance, possibly by storms.

The black shale facies and the fauna clearly indicate a tranquil, marine environment of deposition for the formation. The shales are parallel laminated; cross-lamination, grading, scouring and other evidence of current activity have not been recorded. In areas of apparently continuous deposition, such as Skåne or Oslo, maximum thicknesses of the Upper Cambrian in the order of 45–55 metres suggest depositional rates of less than 2 metres/m.y. Thinner sequences are generally interrupted and contain a higher volume of stinkstones; they may, but do not necessarily, imply even slower rates of deposition. On the basis of the associated stinkstones, etc., referred to above, depth of water is generally assumed to have been shallow (Westergård 1922), but, nevertheless, deposition is thought to have occurred below wave-base. The latter may have been substantially shallower than is normal in shelf-seas today (Keulegan & Krumbein 1949).

The change from the shallow marine, intertidal deposition of grey shales, silts and sands in the early Middle Cambrian into the black shales was transitional in some areas, providing evidence of the lateral passage from ventilated littoral to stagnant basinal environments. In areas such as Östergötland, where there is evidence that the black shales were deposited in western parts during the early Mid Cambrian, simultaneously with greenish shales further east, it can be concluded that great variations in water depth cannot have existed. The minor irregularities in the basement surface, controlling these facies changes in the Middle Cambrian, were gradually eliminated and, by the Late Cambrian, the black shale facies was completely dominant. On Gotland and in the vicinity off-shore of Gävle, the presence of coarse, cross-bedded feldspathic sandstones in the black shales and the sandy matrix of the stinkstone conglomerates likewise implies a relatively shallow marine environment. It seems very unlikely that such local facies changes involved variations in water depth of more than a few metres to tens of metres.

The often very perfect preservation of the fossils in the Alum Shale Formation, with the survival of delicate olenid exoskeletons (Henningsmoen 1957), implies a depositional environment undisturbed by bottom currents. The specialization of the Acadian and Baltic trilobites and their provincialism suggests particular adaptation to this tranquil, partly stagnant environment. The trilobite fauna was probably not benthonic, except for the asaphids (Bergström J. 1980); brachiopods probably were. However, they occur only at a few stratigraphic levels; there is thus only limited evidence of life on the bottom (Bergström J. 1980). Henningsmoen (1957) entertained the possibility that the olenids may have adapted to life in a nearly anaerobic environment. However, he observed that the presence of vast numbers of the trilobites at particular levels suggests that the fauna was not tolerant to complete lack of oxygen and was occasionally overwhelmed by the toxic waters. The olenids probably migrated between the bottom waters and the surface, occupying the former for short intervals when they were not completely depleted of oxygen.

This evidence influences any consideration of the reasons for concentration of uranium and other anomalous components in the alum shales. The deposition was exceedingly slow, the environment tranquil and undisturbed by currents, yet the dominantly foul bottom was periodically flushed out and exchanged for oxygenated water. The oxidation-reduction boundary, normally occurring in the water column, repeatedly descended to near the sediment-water interface, and then migrated gradually upwards again to a level probably approximately coincident with wave-base.

Present evidence thus favours the deposition of the alum shales on an exceedingly stable epicontinental margin. Inferred land areas had very low relief. There is no direct evidence of contemporaneous volcanicity in Baltoscandia; taken along with the evidence for the development of the Iapetus Ocean, this suggests that large distances separated the mid-ocean volcanics from the continental margin.

Concentration of trace elements, sulphur and organic carbon

The remarkable correlation of shale chemistry with biostratigraphy, apparent from the areal descriptions, indicates that the trace element concentrations were essentially syngenetic, occurring in response to small regional changes in the depositional environment. Secondary redistribution is apparent locally, e.g. in the Caledonides, where some elements are concentrated in zones of high strain. Local evidence for the influence of Permian contact metamorphism has been observed in the Oslo Graben.

Rate of sedimentation probably exercised an important control on the concentration of some trace elements.

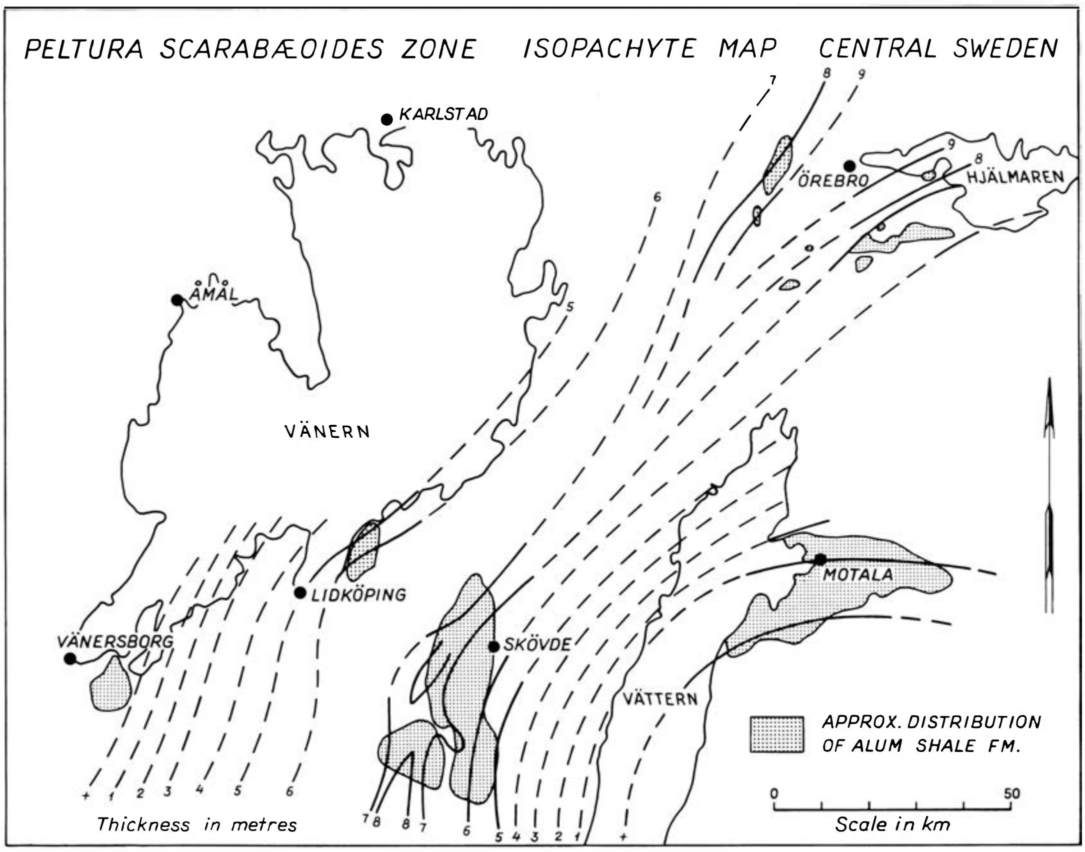

Fig. 23. Variations in thickness of the *Peltura scarabaeoides* zone in the Närke, Östergötland and Västergötland outliers.

This is apparent when rock chemistry can be compared with variation in thickness of particular zones (cf. Appendix). Thus, in areas where the *Peltura scarabaeoides* zone is apparently complete there is an inverse relationship between the thickness of the uraniferous unit (Fig. 8) and the uranium content. Comparison of the Billingen-Falbygden and Närke areas (Fig. 23) also favours the same inverse relationship.

The chemical data from Ranstad, Västergötland, presented in Table 3 and Fig. 8, is in general comparable with that provided by previous studies of the alum shales (Bates *et al.* 1958, Strahl 1958, Armands 1972). The content of organic carbon increases upwards in the formation from 4.6 % in the Lower Member to 8.5 % in the Middle Member and 14.3 % in the Upper Member. This trend is accompanied by an increase in sulphur from 4.6 % to a maximum of 8.4 % and is followed by general increase in the contents of the trace elements, molybdenum, nickel, uranium and vanadium. Vanadium deviates from this general trend by showing unusually high concentrations also in the lower part of the Middle Member. It is of interest to note here that, in the case of vanadium in other areas, e.g. Skåne, the transition into the *Dictyonema* shales occurs with a three- to four-fold increase in vanadium accompanied by a marked decrease in organic carbon.

Closer study of the distribution of the elements Mo, U and V, organic carbon and sulphur reveals significant irregularities in the general correlation. Table 6 provides a simple comparison of the variation in concentration of these elements throughout the formation by taking the content in the Lower Member as unity and expressing the content in the overlying units relative to this. The behaviour of uranium is particularly interesting. Whilst showing a general correlation with organic carbon, its enrichment in the Upper Member is anomalously high and its very high concentration (300 ppm U) in the uranium-rich unit is accompanied by only a very small increase of organic carbon and a slight fall in the level of sulphur. Thus, whilst the two components thought to reflect both the rate of deposition and the character of the anoxic sea bottom remained more or less constant, the rate of uranium fixation doubled; some other factor(s) clearly played a decisive role.

TABLE 6. Relative enrichment of C_{org}, S, Mo, U and V in the alum shales at Ranstad.

	Lower Member	Middle Member	Upper (Ranstad) Member Bottom Shale	U-rich Unit	Top Shale
C_{org}	1	1.8	2.6	3.4	3.0
S	1	1.6	1.8	1.6	1.5
Mo	1	2.7	4.9	5.8	5.0
U	1	2.9	10.0	22.0	10.0
V	1	2.0	2.3	2.6	1.8

A variety of hypotheses have been presented for the unusually high concentration of such trace elements as uranium in particular black shales. Although some trace element enrichment is common in black shales in general, a small minority, including the Chattanooga Shale and the Alum Shale, contain very high concentrations. These particularly anomalous levels have led some authors to appeal to the influence of special external factors for their origin, such as the local erosion of granitic terrains (Brown 1956, Eklund *in* Eklund *et al.* 1961) or contemporaneous volcanicity (Brown 1956). The increase in concentration upwards in the formation suggests the possibility of derivation of the uranium by erosion of Middle Cambrian units during Late Cambrian deposition. Other workers (e.g. Swanson 1960, 1961) felt that these and other possible mechanisms for increasing the amount of uranium available during black shale deposition, were not necessary. Swanson (1961) concluded that the particular anoxic environment, accompanied by exceedingly slow rates of deposition (McKelvey *et al.* 1955) were adequate to account for the derivation of the uranium from normal seawater (containing c. 3 ppb U) by processes of precipitation or sorption from solution.

Comparison of the Upper Devonian, Gassaway Member of the Chattanooga Shale in Tennessee (Conant & Swanson 1961) and the Upper Cambrian part of the Alum Shale Formation in Scandinavia reveals many similarities. In both cases, deposition probably occurred in a stable shallow marine epicontinental environment more extensive than any existing today; neighbouring land areas had very low relief; the highest concentration of the trace elements accumulated during the most extensive submergence of these terrains; current and wave action were inadequate to significantly disturb the accumulation of the black muds; deposition was exceedingly slow (probably in the order of 1–2 metres/m.y.); a large amount of organic matter was available during deposition. However, important differences in the character of the organic matter are implied by the lack of land plants in the Upper Cambrian and their abundance in the Devonian (Gray & Boucot 1978).

In recent years high uranium concentrations (up to 50 ppm) have been reported from Quaternary sapropels in the Mediterranean (Mangini & Sigl 1977, Mangini & Dominik 1979). Green algae are known to concentrate various trace elements including uranium. Adsorption occurs on the surfaces of cells of dead algae. This evidence and the remarkable restriction of the highly uraniferous shales to the Upper Cambrian suggests the possibility that concentration was significantly influenced by biological processes, perhaps peculiar to Cambrian-Early Ordovician seaweeds.

Resources summarized

Sweden's resources of fossil energy, as they occur in the Alum Shale Formation, are vast. If one only takes into account shales with more than 10 % organic matter, the resources have been estimated to c. 50 billion tonnes of shale containing 6 billion tonnes of kerogen (SOU 1956:58). These figures included an estimate for Skåne that was based on the restricted occurrence of the shales near the surface. They did not include the vast resources discovered recently in Jämtland. Finally, they took no account of the possible off-shore development of the formation (Hessland & Armands 1978). It can be concluded that the resources are considerably greater than those presented in Table 2. Moreover, it is clear that the application of new techniques can radically influence exploitation. Thus, recent experiments suggest that a notable increase in oil-yield can be obtained by pyrolysis of the shales in an atmosphere of hydrogen under pressure (Fig. 24).

Estimates of the quantities of uranium in the shales (one million tonnes in the Billingen-Falbygden area) take into account only the richest units in the formation (c. 290 ppm U over 2–4.5 m). A fifty ppm lower cut-off would imply inclusion of greater thicknesses in the Billingen-Falbygden area and also allow exploitation of units in both Närke and Jämtland, vastly increasing this figure.

It is apparent from this summary of the various areas of development of the alum shales in Sweden, that our information is of very variable character. Prospecting for

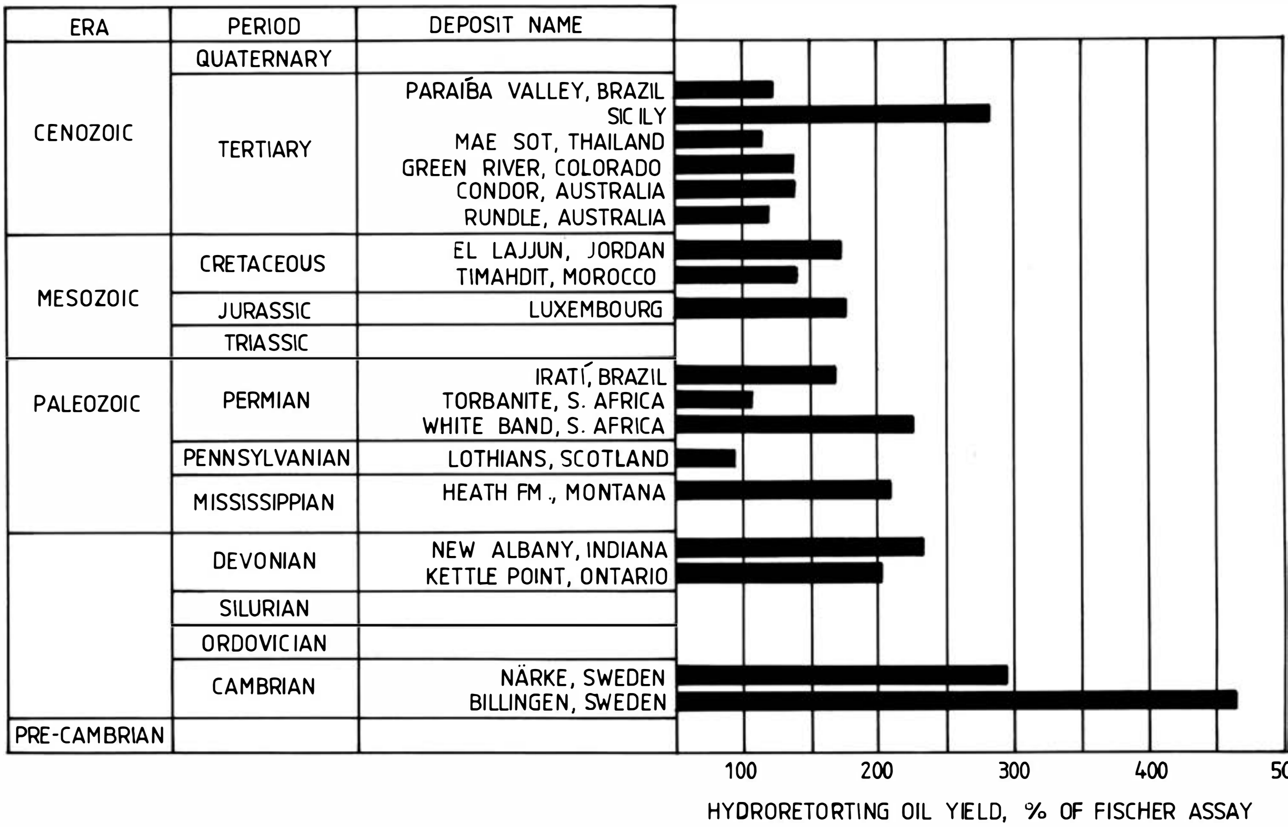

Fig. 24. Hydroretorting assay test results (from Janka & Rex 1984). The Närke and Billingen samples (Fischer assays of 4.4 % and 1.5 %, respectively) yielded 134 litres/tonne and 73 litres/tonne oil, respectively, when retorted in an atmosphere of hydrogen under pressure (7 MPa).

alum shales with high organic and trace element contents is far from complete. With regard to the information about the organic material, it can be concluded that the data available provide a good basis for comparing the different areas; however, the variation within the areas needs closer assessment. There remains a need for modern analyses of the kerogen and new investigation (Fischer Assays, Rock-Eval, Hydroretorting) of the variations in oil-yield. In Skåne, where the shales apparently do not yield oil by conventional retorting methods, the six analysed drill cores do not provide an adequate basis for assessing the regional variations in distribution and character of the organic component. In the Caledonides, no oil can have survived the deformation and metamorphism but recent investigations suggest that areas may well exist where very thick sequences contain higher concentrations of organic material than have so far been identified.

With regard to the distribution of trace elements in the shales, there is a considerable general need for further documentation, particularly with regard to the concentrations of U, V, Mo, Ni and REE. The recent prospecting in Jämtland has demonstrated the presence of very thick successions with relatively high trace element concentrations. It can be concluded that there are good chances of finding thick successions in the Caledonides with trace element concentrations at least as high as in the richest units in areas further to the south.

The alum shales comprise one of Sweden's most important natural resources. Whether or not they are exploitable during the next decade, it is important that documentation of their development and variation in chemistry and mineralogy continues, this being fundamental to all future assessments of their economic potential. Likewise, experimentation with new exploitation-techniques requires continued stimulation and reappraisal.

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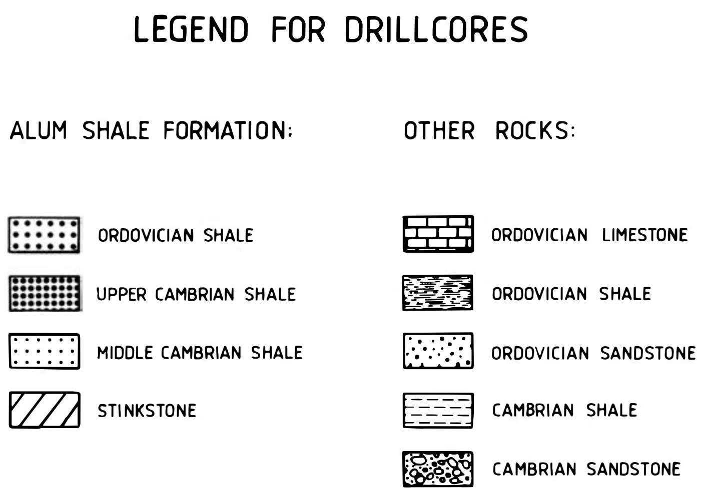
APPENDIX

In order to facilitate comparison of the variable development of the Alum Shale Formation in the different areas of occurrence (Billingen, Kinnekulle, Närke, Östergötland, Skåne, Öland and Jämtland) a single analysed drillcore from each area has been selected to illustrate the lithologies and the contents of organic carbon, uranium and vanadium. Oil yield (Fischer Assays) and calorific value are also available for some areas. No one drillcore is fully representative of an entire area; however, the cores do provide a convenient basis for general comparison. (In a few cases, the contents of the various components specified do not coincide with the average values given in the text). In most areas only a few drillcores have been analysed in sufficient detail to allow the comparison.



For biostratigraphical data given to the left of the lithological column see Fig. 2 in the text.

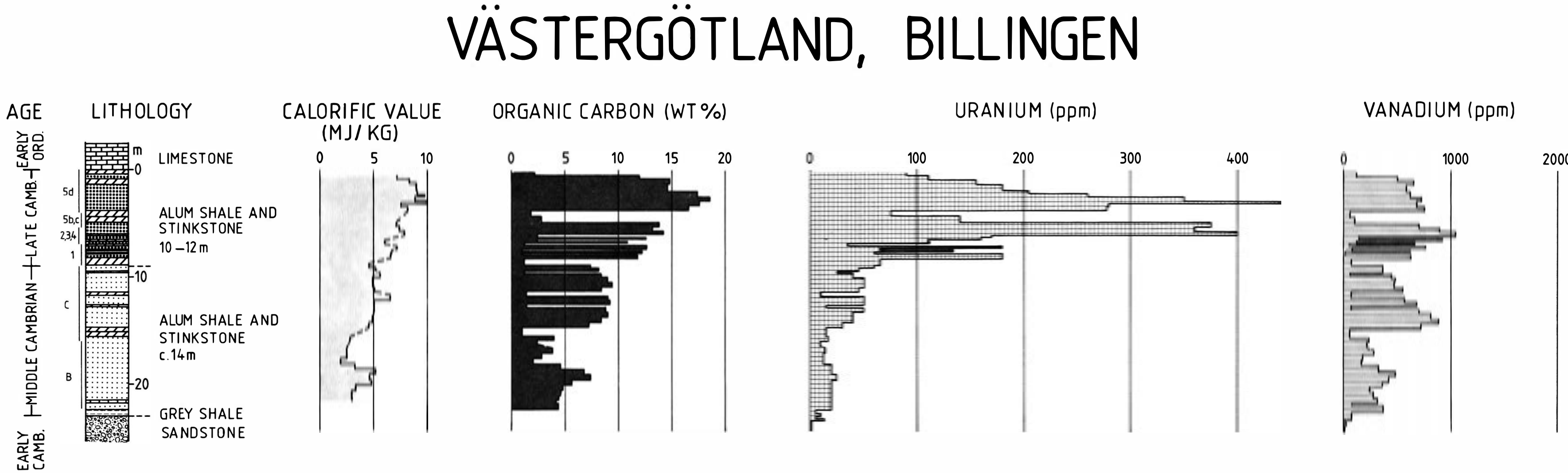


Fig. A1. The alum shales in the Billingen-Falbygden outlier are illustrated by data from drillhole Dbh 65/77 at Ranstad (Andersson 1977, unpublished report). The thicknesses cited are relevant for the outlier in general. Note, however, that the stinkstone in the most uranium-rich section is unusually thick. For biostratigraphical data given to the left of the lithological column see Fig. 2 in the text.

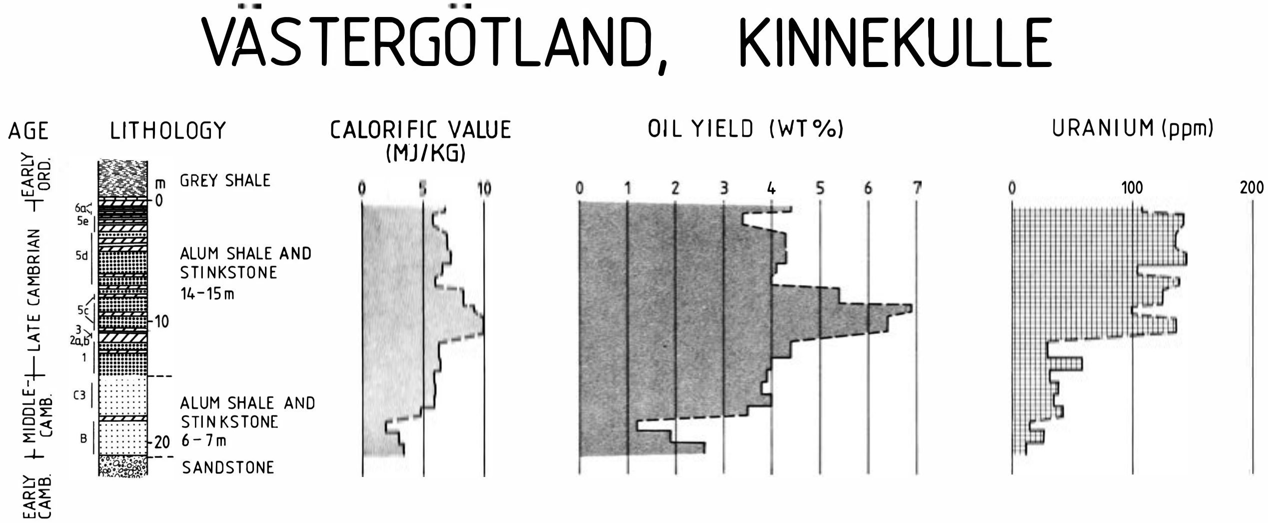


Fig. A2. The alum shales in the Kinnekulle outlier are illustrated by data from drillhole Norra Skagen (Westergård 1943). Analyses of uranium are taken from Dahlman & Eklund 1953 (unpublished report). The thicknesses cited are representative for the entire outlier.

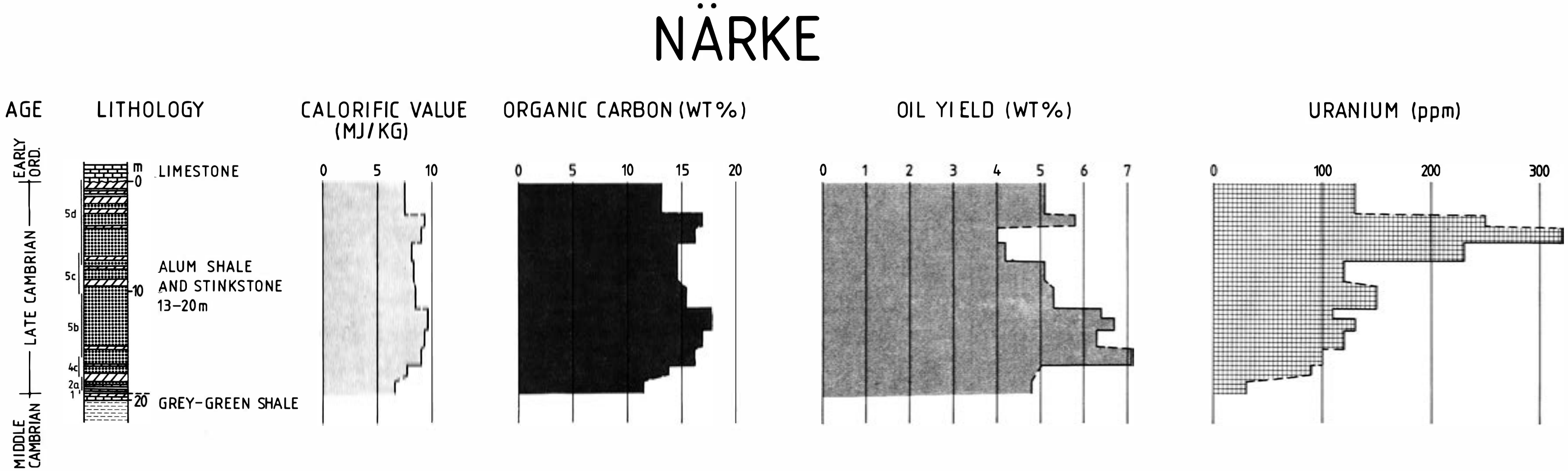


Fig. A3. The alum shales in the Närke outliers are illustrated by data from a Hynneberg drillhole (Eklund in Eklund *et al.* 1961). Eklund reported the organic content as wt % kerogen. To simplify comparison with other areas, the kerogen values have been converted to wt % C_{org} on the basis of kerogen analyses provided in Assarsson & Grundulis (1961). The high uranium peak (>300 ppm) in the *Peltura scarabaeoides* zone is probably due to the presence of a kolm lens. The thicknesses cited are representative for both East and West Närke.

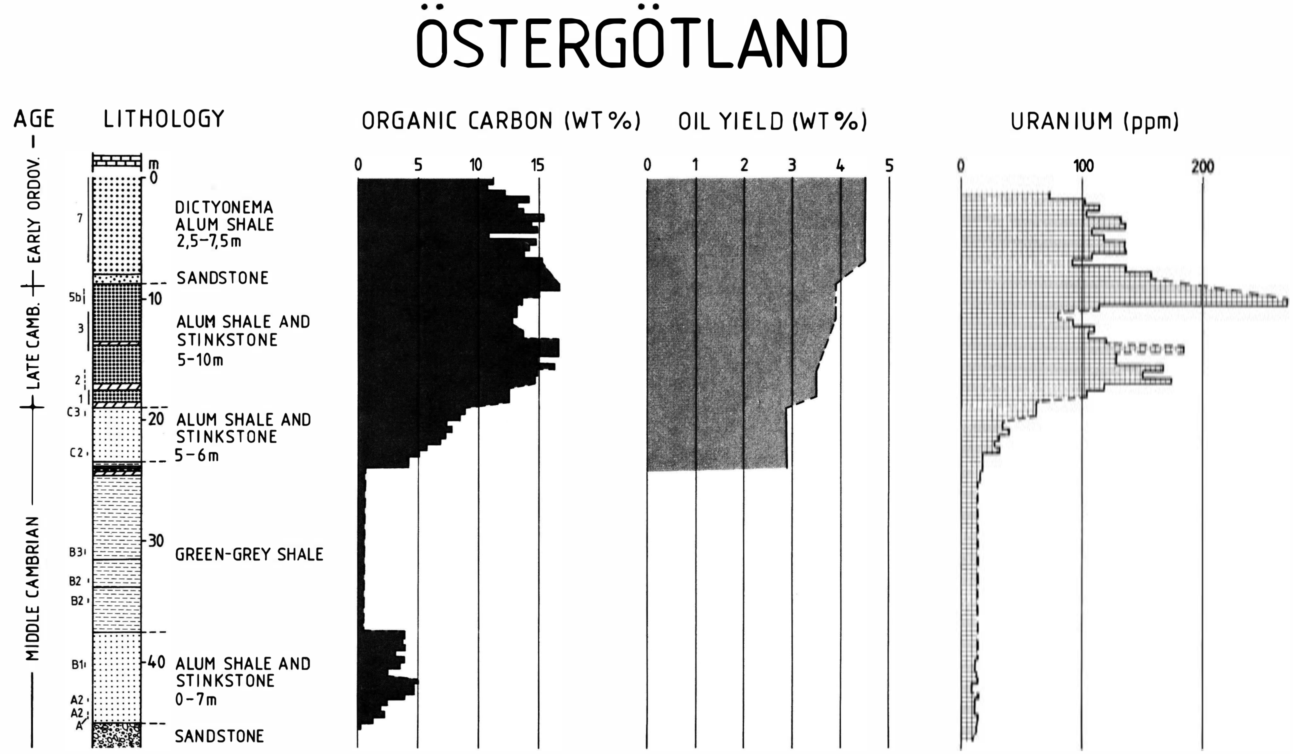


Fig. A4. The alum shales in the Östergötland outlier are illustrated by data from the Nässja drillhole (Wikman *et al.* 1982). Chemical data are taken from Dahlman (1962, unpublished report). The thicknesses cited are relevant for the outlier in general. Note that the alum shale facies in the early Middle Cambrian is restricted to western areas.

SKÅNE

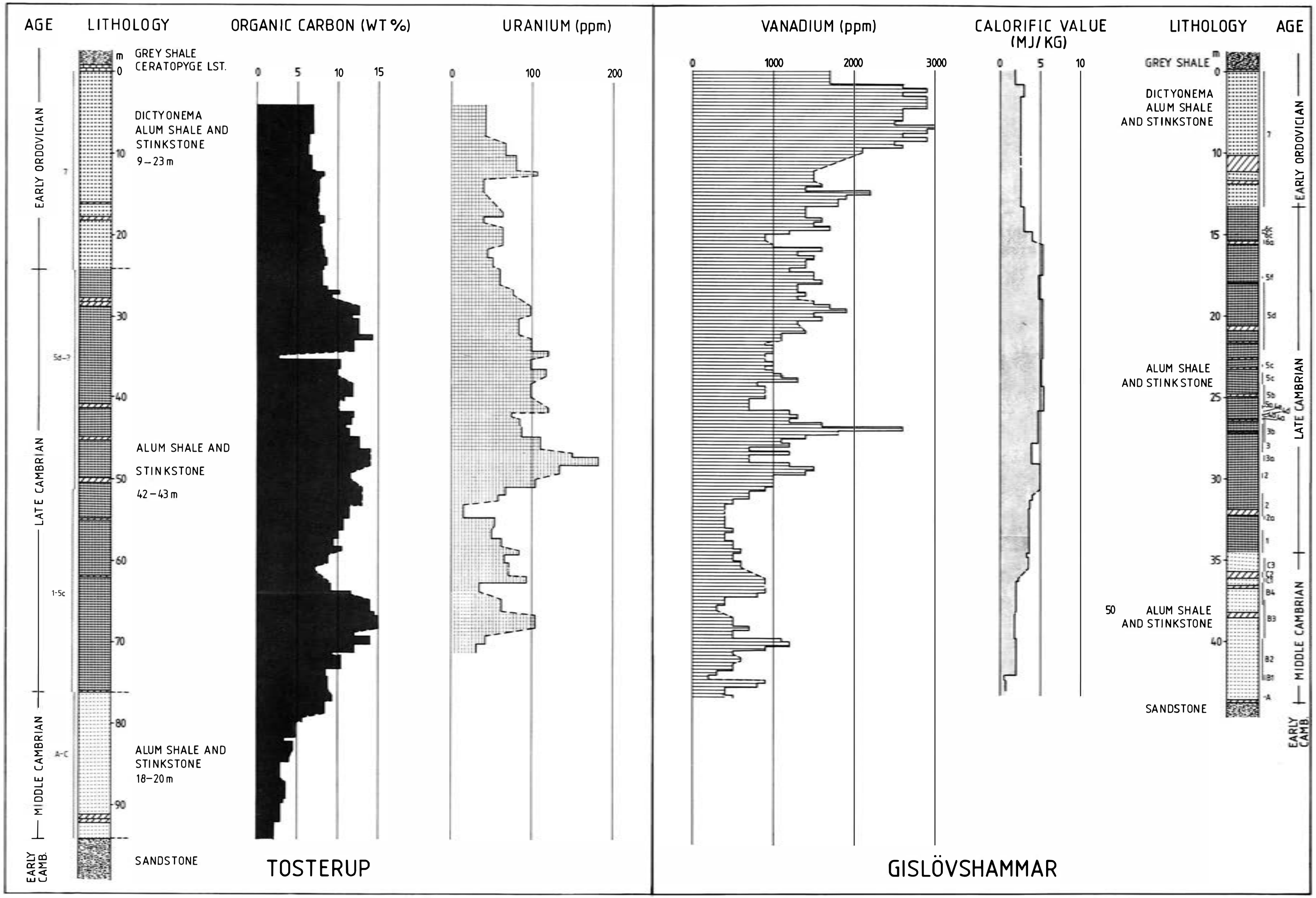


Fig. A5. The alum shales in Skåne are illustrated by data from two drillholes, located at Tosterup (Dahlman 1962, unpublished report) and Gislövshammar (Westergård, 1944a). Analyses of C_{org} were obtained from SGU's archives. The thicknesses cited are representative for southeastern areas. The development of the alum shales inferred to be present beneath the thicker Ordovician and younger strata is unknown.

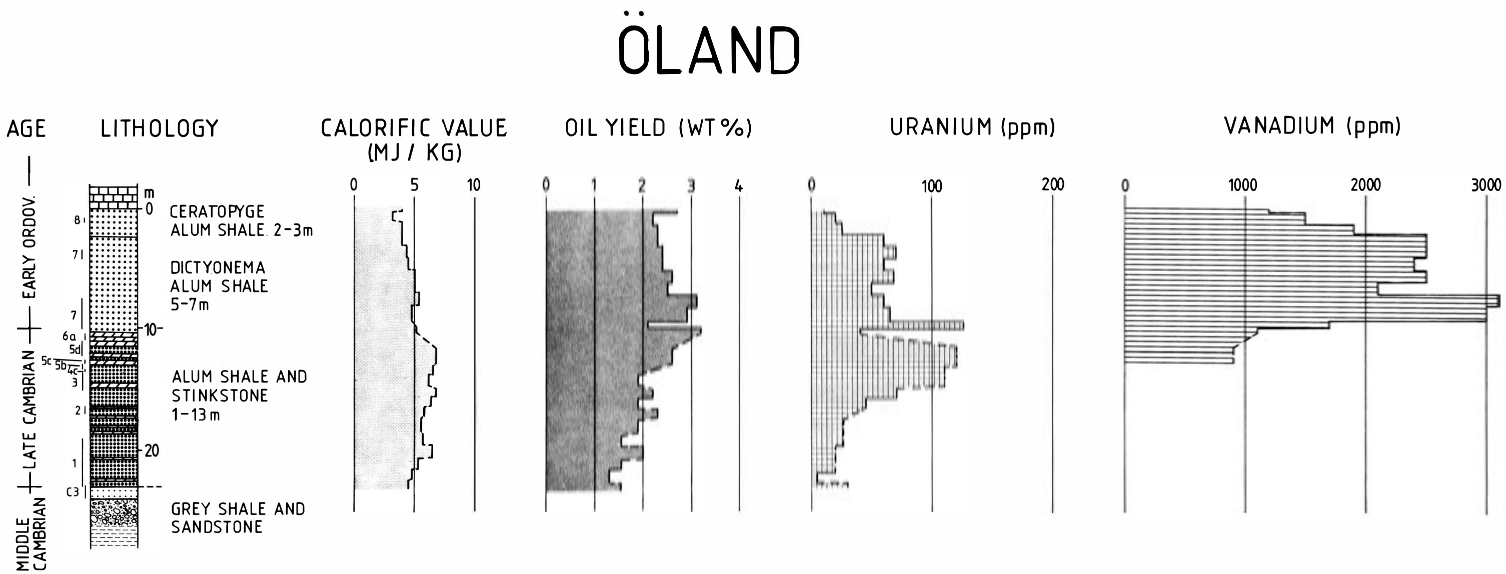


Fig. A6. The alum shales on Öland are illustrated by data from the Ottenby drillhole (Westergård 1944b). Analyses of uranium are taken from Dahlman & Eklund (1953, unpublished report). The thicknesses cited are representative of the southern part of the island, only.

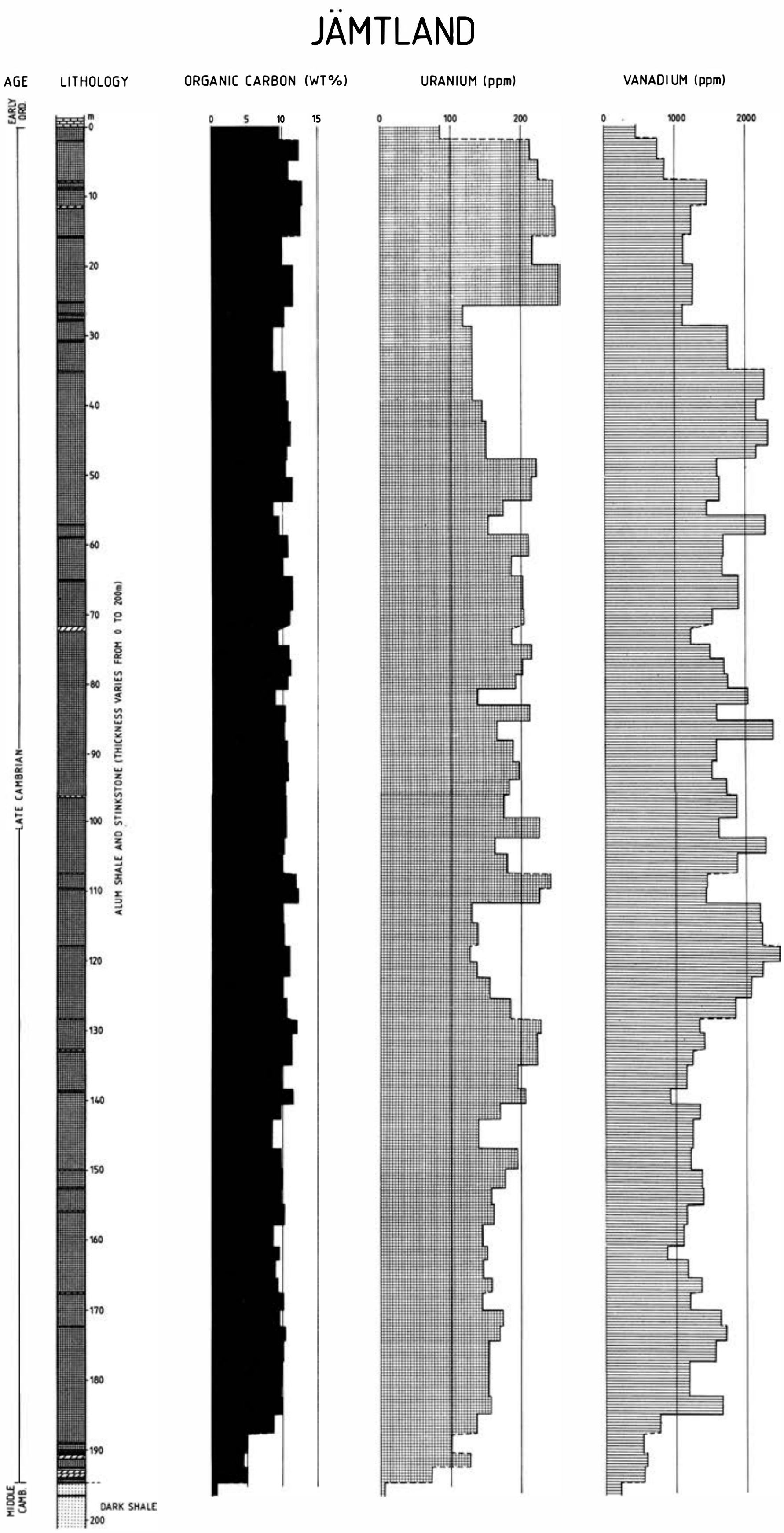


Fig. A7. The alum shales in Jämtland are illustrated by data from the Myrviken 78005 drillhole (Gee *et al.* 1982, unpublished report) located near Myrviken in the Southern Storsjön Area. The hole was drilled near the crest of the Myrviken Antiform (see Fig. 19, section E–F) and contains one of the greatest thicknesses of black shales in Jämtland.

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