

SVERIGES GEOLOGISKA UNDERSÖKNING

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DAVID G. GEE

THE REGIONAL GEOLOGICAL CONTEXT
OF THE TÅSJÖ URANIUM PROJECT,
CALEDONIAN FRONT,
CENTRAL SWEDEN

WITH 2 PLATES



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C. DAVIDSONS BOKTRYCKERI AB, VÄXJÖ

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ABSTRACT

The geology of a part of the Caledonian eastern front in Central Sweden is described, the area extending from the eastern Pre-Cambrian crystalline basement to the mylonites forming the base of the Seve-Köli Nappe Complex in the west. Previous tectonic models for the area are reviewed in relation to mapping by the Swedish Geological Survey in 1969. The front range quartzite nappes of previous authors are shown to be rooted in the central part of the area described here and not derived from over a hundred kilometres further westwards as previously claimed. The Föllinge nappe is thought not to exist, at least not within the map-area. The consequences of these conclusions for the interpretation of the regional tectonic history are discussed.

From the initiation of sedimentation in the area in the late Pre-Cambrian until the deposition of the Middle and Upper Cambrian alum shales and thereafter at least during the Lower and Middle Ordovician (the youngest sediments in the area) it appears that a hinge-zone has been located in the crystalline basement extending approximately NNE-SSW through the area. This hinge permitted downwarping of the basement westwards, accommodating more rapid sedimentation. In the late Pre-Cambrian, arkoses with conglomerates in the east gave way to arkoses and quartzites in the hinge zone and arkoses, quartzites and shales further west. During the Middle and Upper Cambrian the area was stable with black shale deposition. In the Ordovician, a limestone facies in the east passed westwards through calcareous sandstones and shales over the hinge-zone into greywackes.

Within the vicinity of the hinge-zone, lead-dominated sulphides occur in the sandstones below the black alum shales whilst above these within the same zone uranium is concentrated in the calcareous, glauconitic, phosphatic sandstones.

It is thought probable that this hinge-zone extended throughout much of the eastern front of the Caledonides, influencing sedimentation, mineralisation and subsequent orogenic deformation.

I. INTRODUCTION

This paper serves three main purposes. Firstly, it attempts to outline the regional geological setting of the uranium exploration programme in the northern Jämtland, southern Västerbotten Caledonides by reviewing previously published work on the area in relation to recent mapping by Sveriges Geologiska Undersökning*). It thus forms a background to the more detailed investigations of stratigraphy, palaeontology, sedimentation, structure and geochemistry at present in progress. Secondly, in drawing on data from a variety of sources, some unpublished, it is hoped that it will stimulate previous authors and others interested in the project to contribute to the investigations whilst they are in progress. Thirdly, it outlines a tectonic model for this part of the Caledonian front which differs in several respects from previous reconstructions.

The location of the area is shown on the geological map (Plate I). The latter can be compared with Fig. 1, redrawn from the 1:1 000 000 geological map of Sweden (1958) which illustrates the approximate distribution of the four main rock units (i) the Pre-Cambrian crystalline basement, (ii) the sparagmites (arkoses of this paper), (iii) the quartzites and shales and (iv) the Lower Palaeozoic shales, greywackes and limestones. In general, units (iii) and (iv) compose gently rolling country, forested or bog covered and thus poorly exposed with the exception of the larger stream sections. Quartzites generally occupy the higher tops in these areas. Further west Pre-Cambrian rocks, particularly the older sediments, make up a better exposed more hilly terrain still lying below the tree-line.

1. BACKGROUND TO THE SGU INVESTIGATIONS

In February 1969 the uranium division of SGU obtained material from AB Atomenergi (The Atomic Energy Company) related to the latter's work in the area from Flåsjön to Malmomaj during the years 1957 to 1965. Atomenergi geologists, with B Asklund as chief consultant, had carried out regional prospecting and mapping, concentrated on the Tåsjö area but reaching out both further north and south of the area treated here. Their work started with routine airborne gamma-scintillation measurements in 1957. It subsequently included geological mapping, regional geochemistry, block searching, flight radiometric and electro-magnetic measurements and drilling (c. 2340 m). From the viewpoint of the regional geology of this rather poorly exposed area the flight electro-magnetic anomaly maps (reproduced in a simplified form in Plate II and described in Appendix I), were the most valuable information placed at our disposal. Some of these anomaly maps had been interpreted by AB Atom-

*) Swedish Geological Survey, henceforth referred to as SGU.

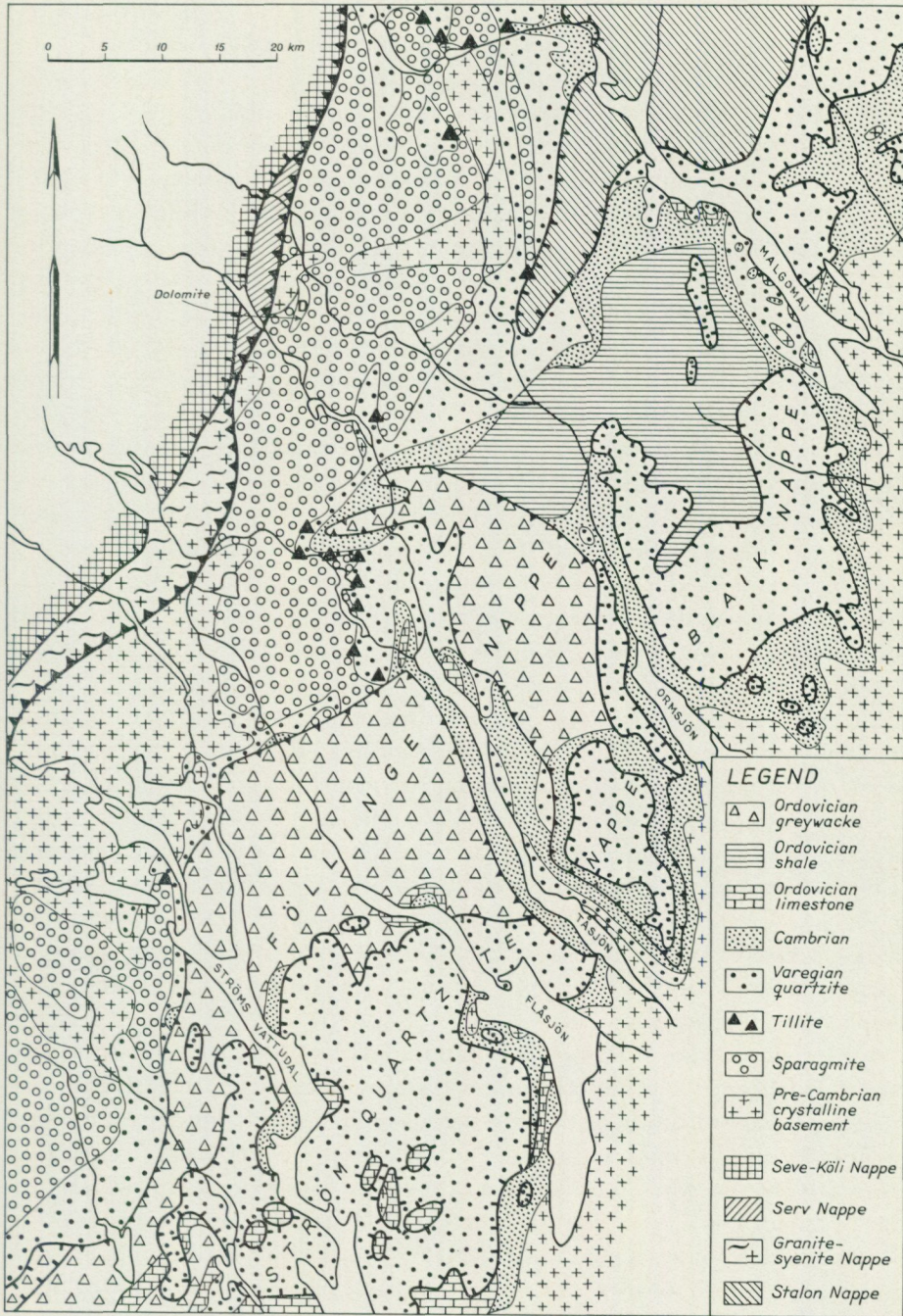


Fig. 1. General geological map of the area from Ströms vattudal to Malgomaj taken (with minor simplification) from the 1:1 000 000 Geological Map of Sweden (1958) described by Magnusson et al. (1960, 1962)

energi geologists in relation to their outcrop mapping but no general geological map of the area of their prospecting was made available to us.

The SGU programme was initiated with the order for vertical air photographs at 1:20 000 and 1:50 000 and accurate topographic maps. On the latter before the 1969 field season all previous available outcrop data were summarised. Our sources included published material (e.g. Asklund and Thorslund, 1935), outcrop maps kindly made available to us by O. Kulling showing the location of his data from mapping in the 1930s, and outcrops recorded by AB Atomenergi. In addition, early in the field season, we obtained outcrop data from Boliden AB largely from areas in which they had no economic interests. These data greatly speeded our first summer's field work which was devoted to regional mapping as a basis for reinterpretation of the flight electro-magnetic anomaly maps.

Our arrival in the Tåsjö area coincided with the final stages of a vast hydro-electric operation, stretching north-westwards from the northern end of Tåsjön. In this context we have obtained c 2230 m of drill-cores which are now contributing towards a reassessment of the regional geology. Asklund commented (1960b p. 45) that "the imposing hydroelectric investigation . . . (provided) . . . excellent opportunities for geological research" and furnished descriptions of the boreholes along with a couple of cursory geological reports over the c 23 000 m of tunnelling.

The first summer's mapping, carried out with the assistance of five university students, achieved accurate location and recording of the earlier reported outcrops. In addition, a substantial amount of new outcrop was found which allowed further reassessment of the earlier reported data and resulted in the production of a preliminary geological map. The latter was directly compared with the flight electro-magnetic anomalies (simplified in Plate II) and gave birth to the geological map, Plate I. In areas west of the main electro-magnetic anomalies, where field data is very sparse, the geological interpretation has been revised locally under the stereoscope using high altitude vertical air photographs (negative scale 1:67 000).

Subsequent to the initial mapping programme of 1969, we have embarked on a detailed analysis of the structure and stratigraphy of the area. At the same time a geochemical study of the uraniferous unit, started with AB Atomenergi by A Andersson, is being continued. The object of this paper is not to anticipate the results of this work; rather it is to provide a background into which they can be fitted. Du Rietz (1960 p. 7), when discussing his own contribution to the Caledonian front structure, commented "As is revealed by the more detailed investigation of the Ormsjö area, a very detailed investigation of all the areas would be necessary to get even a fairly correct picture of the tectonic evolution". It is this detailed investigation on which we are now engaged.

2. PREVIOUS LITERATURE

Due at least in part to the poverty of rock outcrop, the area has been a centre of geological controversy for the last hundred years. Ever since the early fossil hunting tours of Sidenbladh (1874) in southern Västerbotten, when unfossiliferous quartzites and sandstones (now included in the Eocambrian – Brögger's (1900) original sense) were first recorded to overlie the fossiliferous "cambrosilurian", there has been discussion of the general stratigraphy and regional structures. The pioneering work of Törnebohm (1888, 1896) with the application of the theory of nappe tectonics to the Swedish Caledonides, established the relationships broadly as we know them today. Nevertheless overthrusting was not lightly accepted and there were many who subsequently favoured a Palaeozoic (Silurian) age for the unfossiliferous units which overlay the "cambrosilurian" (Wiman 1898, Lidén 1911, Frödin 1922, Quensel 1925 and Backlund 1925). Indeed apart from Högbom (1913), it was not until the early 1930s with the work of Asklund (1933), Asklund and Thorslund (1935) and then Kulling (1941, 1942) and Du Rietz (1943) that the overthrusting of the front range nappes was finally established and the rock units within the nappes related with some certainty to the unfossiliferous units underlying the "cambrosilurian" of the autochthon. Subsequently, discussion has turned to problems of stratigraphic and structural detail involving explanation of facies changes within the rock units, distances of nappe transport, the root-zones for the nappes, etc.

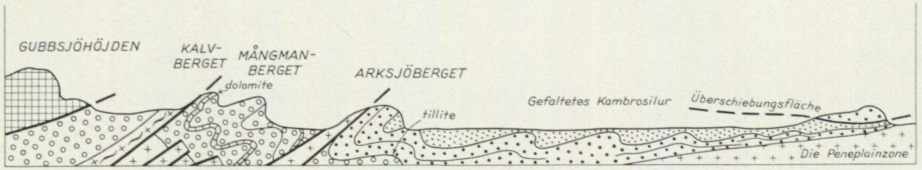
To aid discussion of the more recent contributions to the regional geology, Fig. 2 reproduces four cross-sections through the area of Fig. 1, from Kulling (1955, Fig. 81), Asklund (1935, 1938 and 1960a, Fig. 6 and 7), and Du Rietz (1960, Plate 2). To facilitate comparison I have redrawn the sections at about the same horizontal scale. Stratigraphic nomenclature used in this paper is compared in Table I with that of previous authors.

Considering firstly the stratigraphy, there is general agreement on the age-relationships of the different rock-units. Nevertheless in detail there are remarkable differences in opinion. The lowermost sediments, the sparagmites are dominantly red and grey-green arkoses, feldspathic sandstones and quartzites with intraformational conglomerates, a prominent dolomite appearing in the west. Whereas Asklund regarded the colouring of the sparagmites to be primary and built a stratigraphy involving basal grey quartzites, dolomites and grey-green arkoses overlain by red arkoses, both Kulling and Du Rietz emphasized the notable secondary colour changes that occur with metamorphism and near tectonic discontinuities, doubted the primary colour differences and consequently Asklund's stratigraphy. All three authors and Stålhös (1956) contributed much to the general knowledge of the petrography of these sediments.

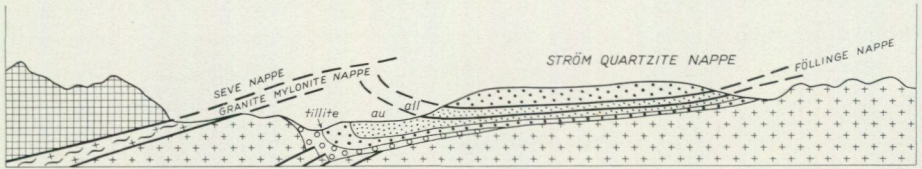
The sparagmites are overlain by a quartzite-shale group (Asklund's "Quartz-

NW

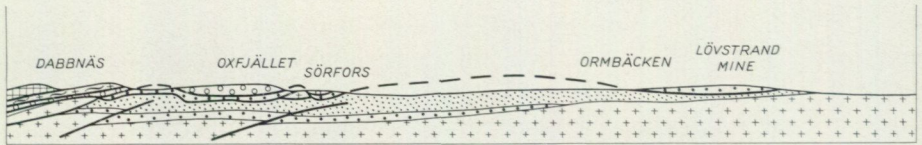
SE



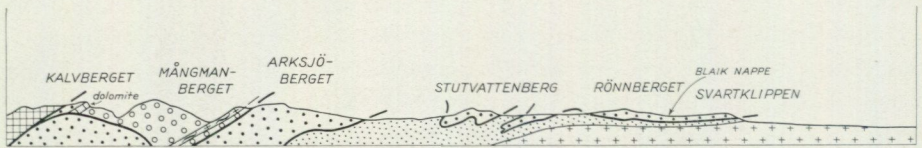
B. Asklund 1935, 1938 and 1960



B. Asklund 1935, 1938 and 1960



Du Rietz 1960



Kulling 1955

0 5 10 15 km

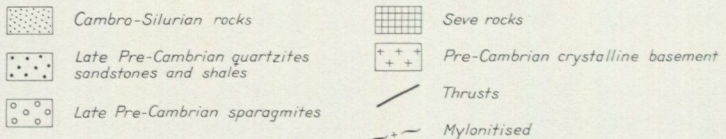


Fig. 2. Some cross-sections through the area of Fig.1 showing earlier interpretations of the structure. Note that Kulling has subsequently (1961 and in press) accepted the Cambro-Silurian sediments to overlie the quartzites of the Blaik nappe.

ite and shale series" or "Varegian formation"). This unit, in places having a tillite formation at the base, partly overlaps and/or oversteps the sparagmites to rest directly on the crystalline basement. On the basis of inferred overlap, Asklund built up a picture of sparagmite basins "aligned in a NW-SE direction perpendicular to the length direction of the Caledonian geosyncline" (1960a p. 138), subsequently transgressed by the quartzites and shales.

TABLE 1
Comparisation of stratigraphic nomenclature

This paper		Kulling		Du Rietz 1960	Asklund	
		1960	<i>in press</i> Lower Thrust Rocks		1960a	
					Autochthon	Allochthon
Shale-Greywacke Group	Grey- wacke- Shale Form.	Ordov. shales lst. & greywacke	Fossiliferous Ordovician & Cambrian	Cambro- Ordovician shales	Shales & limestone	Föllinge- Holmsjö Facies
	Alum Shale Form.	Cambrian alum shales			alum shales	alum shales
Quartzite-Shale Group		Ström Quartzite Series	Vemdal Quartzite Group	Ström Quartzite Series	Varegian Formation or Quartzite- Shale Series (or Form.)	Ström Quartzite
	Tillite Form.	Tillite Formation	Tillite Group	Tillite	Tillite	
Arkose Group		Arkose (sparagmite)	Risbäck Sparagmite Group	Sparagmite Formation	Sparagmite Formations	-

It was in the late 1920s that Kulling located erratic boulders of tillite-like conglomerates in southern Västerbotten. This was shortly before his studies of late Pre-Cambrian tillites in east Greenland (1930) and Spitsbergen (1934). Nevertheless as he recorded in 1942 (p. 110) it was not until 1936 in southern Västerbotten that he first found varved shales in association with the conglomerates and satisfied himself of their glacial origin. Three years previously, Asklund and Thorslund (1935) had located a tillite-like conglomerate in the Sjoutälven section (north-west Tåsjö) and drawn attention to its similarity with the Moelv tillite of the Mjösen area, southern Norway (Holtedahl, 1922). The tillites have been extensively described, particularly by Kulling (1942) and

correlated with other units of late Pre-Cambrian age in the North Atlantic area. It was with this correlation that Kulling (op.cit.) emphasised the use of glacial episodes as a basis for chronostratigraphy within the Eocambrian and introduced the term Varangian glaciation ("Varanger istid" p. 315) as a specific event within the succession of Brögger's Eocambrian sedimentation. Varangian has subsequently been adopted for system nomenclature (Harland, 1964) and is treated as such here.

The red and green shales and white quartzites overlying the tillites have been correlated by all the authors with the type stratigraphy of the latest Pre-Cambrian of the Mjösen area. In the area treated here there are striking differences of opinion about the succession and thickness of this quartzite-shale group lying between the tillites and the overlying black shales of the Middle Cambrian but general agreement that the shale component increases westwards (Du Rietz, 1960). Correlation of the quartzites in the front range nappe with those in the "autochthon" was agreed by all. Du Rietz (1960) stated that the thickness of the group was greater in the overthrust quartzites than it was further west in the "autochthon" of the Sjoutälven section but he quoted no thicknesses. Comparison of section data (Du Rietz, 1960) and Asklund and Thorslund's estimates (1935) suggest the reverse. Both Asklund and Du Rietz, however, show their autochthonous quartzites and shales to thicken westwards (cf. Fig. 2).

The quartzite-shale group contains calcareous, phosphorite-bearing conglomerates near the top. In close association with these are limestone layers and lenses which in Högnäsån have been recorded to contain Middle Cambrian *Paradoxides paradoxissimus* stage fossils (Asklund and Thorslund 1935 a). Asklund (1960a) regarded the quartzites underlying the phosphorite-bearing conglomerates as Pre-Cambrian, implying a hiatus during the Lower Cambrian. A few metres of green-grey siltstone separates these conglomerates from the black alum shales of middle Middle to uppermost Cambrian and Tremadocian age.

Asklund and Thorslund (1935a) demonstrated that the alum shales below the quartzite nappe of Tåsjöberget contained repeated successions. They also recorded marked differences (particularly of thickness) for different stages of the Cambrian and Tremadocian in what they referred to as their "autochthonous" and "allochthonous" units and they interpreted the higher units as being derived from west of the Sjoutälven section (see Fig. 2). In addition they regarded the Ordovician greywackes overlying the black shale sequence to be likewise a separate nappe unit, overridden by the quartzite nappe. Their evidence for the greywacke nappe was largely obtained from south of the area treated here, Asklund and Thorslund (1935b), where proximity of Ordovician limestones and greywackes of the same age was interpreted as due to tectonic discontinuity rather than facies change. Further north, in southern Väster-

botten, Kulling (1942), regarded these nappes within the Cambro-Silurian as possible, but he commented on the lack of supporting evidence in Västerbotten. In 1960, p. 24 he stated with regard to the greywacke nappe; "This nappe-unit, if it is a real tectonic unit, is chiefly a Jämtland-Ångermanland nappe". His doubt over the existence of the Föllinge Nappe was expressed again in 1961 when, on the basis of a reconnaissance of southernmost Lapland, he concluded that most of the sediments west of the Ström Quartzite overlay the latter without important break and should therefore be included within the Ström Quartzite Nappe. This view was restated (Kulling, in Kulling and Strand, in press) where he included the "Föllinge complex" within the "Blaik Nappe Complex", overthrust by the "Olden Nappe", all these being parts of the "Lower thrust rocks".

Fig. 2 illustrates the general agreement that the quartzites of the eastern front overlying the "Cambro-Silurian" had been thrust from the west. Boliden AB's drill-hole data, published by Du Rietz (1943 and 1960), provide very comprehensive evidence of this relationship. All authors agreed that the front range quartzite nappe was derived from somewhere west of the contact with the overthrust Seve-Köli Nappe Complex and had been transported at least 100 km eastwards.

Comparing Kulling's and Du Rietz's sections, it is clear that the former portrays the field data the more correctly in demonstrating (as does Du Rietz's 1943 map) that the so-called allochthonous quartzites in the vicinity of Stuvattenberget dip under the "Cambro-Silurian" and must therefore be regarded as isoclinally folded after thrusting if they are to be treated as allochthonous*). All the sections require overthrusting of the quartzite nappe and then some refolding, the latter in Asklund's opinion (1960a, p. 144) being related to "horst upthrusting" later than the early "roof-tile" nappes.

3. ASPECTS OF THE SGU WORK

Comparison of Plate I and Fig. 1 reveals four principal differences.

(i) The front range quartzite nappes of previous authors have been constructed as klippes. SGU's mapping established overthrusting only in the eastern front. Cambro-Ordovician rocks overlie the quartzites in the west and we have no basis at present to regard the contact between these two rock units as an important regional dislocation. This is in agreement with Kulling's opinion (1961).

(ii) The tectonic boundary between the Föllinge (greywacke) Nappe and the underlying Cambro-Ordovician rocks and quartzites has not been recogni-

*) Doc. O. Kulling has been kind enough to furnish me with proof prints of his book with Professor Strand on the Scandinavian Caledonides (in press). None of the sections accompanying the book cross the area of Plate I but a section from Remdalen to south-east Vojmsjön shows the Cambro-Silurian rocks to overlie the quartzites of the Blaik Nappe Complex more or less conformably.

zed. The greywacke facies does not terminate northwards (south of Långselån) as shown in Fig. 1, but persists through the Gitsån area (22 F, j4) to Målgomaj. The outcrop evidence is abundant (Asklund, 1935) and the construction in Fig. 1 can only be described as somewhat mysterious. This Föllinge Nappe has been shown in various places to cut down through the Cambro-Ordovician succession into the quartzites. We have examined most of these contacts and found local block material derived from the alum shale formation, thus supporting the evidence of the flight electro-magnetic anomalies for continuity of normal stratigraphic relationships, the alum shale formation separating the quartzites from the greywackes.

(iii) In the vicinity of Tåsjo, the quartzite unit was shown (Fig. 1) to underlie the alum shales, the latter being overthrust by the Föllinge Greywacke Nappe and the Ström Quartzite Nappe. Elsewhere the alum shales were shown to rest directly on the Pre-Cambrian basement. This construction does not appear in Asklund and Thorslund (1935a). In that publication they do not refer to the abundant quartzite outcrops (21 F, j 6) on the north-east side of the lake between Brattbäcken and Karbäcken and it is possible that it was the subsequent mapping of these that lead to the 1958 construction. We have found no evidence of this unconformity between the alum shale formation and the underlying unit in this area.

(iv) Likewise we have found no evidence for the unconformity at the base of the Ordovician in the area of Gitsån/Långselån (22 F, j 4).

Our re-interpretation of the regional geology has led to the concept of the Tåsjo hinge-zone. This latter is an inferred fracture belt striking c NNE through central and northern Tåsjo and accounting for westerly downwarping of the crystalline basement to accommodate the thicker western successions. The Tåsjo hinge was the principle phenomenon controlling the tectonic history of the area during the depositional cycle. Subsequently, during the orogenic cycle it controlled the style of deformation by providing the root-zone for the front range nappes.

II. GENERAL STRATIGRAPHY

1. INTRODUCTION

In 1935, Asklund and Thorslund laid the foundation for what they referred to as the autochthonous stratigraphy of the Tåsjo area. They demonstrated in the type area of Sjoutälven (previously called Sjougälven) that arkosic rocks of the sparagmites (200 m +) were overlain by a tillite-like conglomerate followed by a quartzite and shale sequence (240–380 m). These sediments passed upwards through a thin, phosphorite-bearing conglomerate into green siltstones overlain by alum shales and then grey Ordovician shales. The 1958 map (Fig. 1) shows the "autochthonous" stratigraphy to persist both southwards in the western limb of the Fånån syncline and northwards in the western limb of the

Hundsjöbäcken syncline, despite the complications of the Föllinge nappe. The map also shows a remarkable unconformity in the Långselån/Gitsån area (22 F, j 4) with Ordovician shales resting directly on the quartzites.

We have examined the Sjoutälven stratigraphy and found no reason to doubt the essential rock relationships. This stratigraphy and particularly that of the latest Pre-Cambrian, Cambrian*) and Ordovician is recognizable in a NNE-SSW tract from Malmogaj over Gitsån to Sjoutälven and southwards to Fånån. Evidence for Asklund's lower Ordovician Långselån/Gitsån unconformity has not been detected; in all sections examined the alum shale formation separates the Ordovician sediments from the underlying quartzites. Greywackes overlie Ordovician shales in the Fånån and Hundsjöbäcken synclines and where these relationships are exposed both in outcrop and boreholes the most conspicuous phenomenon is the transition, generally rapid, from the shales and silts into the shales and greywackes. As mentioned earlier, Kulling rejected the Föllinge Nappe's extension northwards into Västerbotten. The evidence from the Tåsjö area throws doubt on its existence in the Jämtland type-area.

Description of the stratigraphy is treated below based on a generalized type-section in the area of north-west Tåsjö. The relationship there are summarised in Fig. 3. It has been found convenient to treat the rocks in three lithostratigraphic groups, a lower arkosic and feldspathic quartzite unit with intraformational conglomerates, a middle quartzite and shale unit with subordinate arkoses and an upper shale (including alum shale) and greywacke unit. These three groups require formal lithostratigraphic terminology as do their component formations and members. However, since the detailed study of stratigraphy is at present in progress it would be premature now to attempt definition of type sections. The informal lithological names "Arkose Group", "Quartzite-Shale Group" and "Shale-Greywacke Group" are preferred for this paper.

2. THE ARKOSE GROUP

The Arkose Group*) rests with marked unconformity on the crystalline Pre-Cambrian basement, the latter being composed dominantly of porphyritic granite with some more basic igneous rocks and subordinate gneisses. This

*) With regard to the Cambrian-Ordovician boundary, placed originally by Lapworth (1879) at the top of the Tremadocian (cf. Whittington and Williams, 1964) and in Scandinavia and America at the base, I have followed Scandinavian practice, albeit with some misgiving.

*) In this paper the term Arkose Group has been preferred to the older term Sparagmite (derived by Kjerulf as Sparagmite Formation from Esmark's 1829 introduction of the term - see Holtedahl, p 111 in Holtedahl et al, 1960.) Arkose group is used to emphasize the necessity for definition of local type sections in accordance with internationally accepted stratigraphic nomenclature (cf. Björklykke et al, 1969). The term Sparagmite Group might serve a practical purpose in the general discussion of Eocambrian stratigraphy but there is a marked discrepancy between Swedish and Norwegian usage, in Norway the term referring to Brögger's entire Eocambrian sequence, whilst, in Sweden, sparagmite is restricted to the feldspathic sediments deposited before the Varangian glaciation. This unfortunate ambiguity of usage is misleading and the term is therefore avoided here.

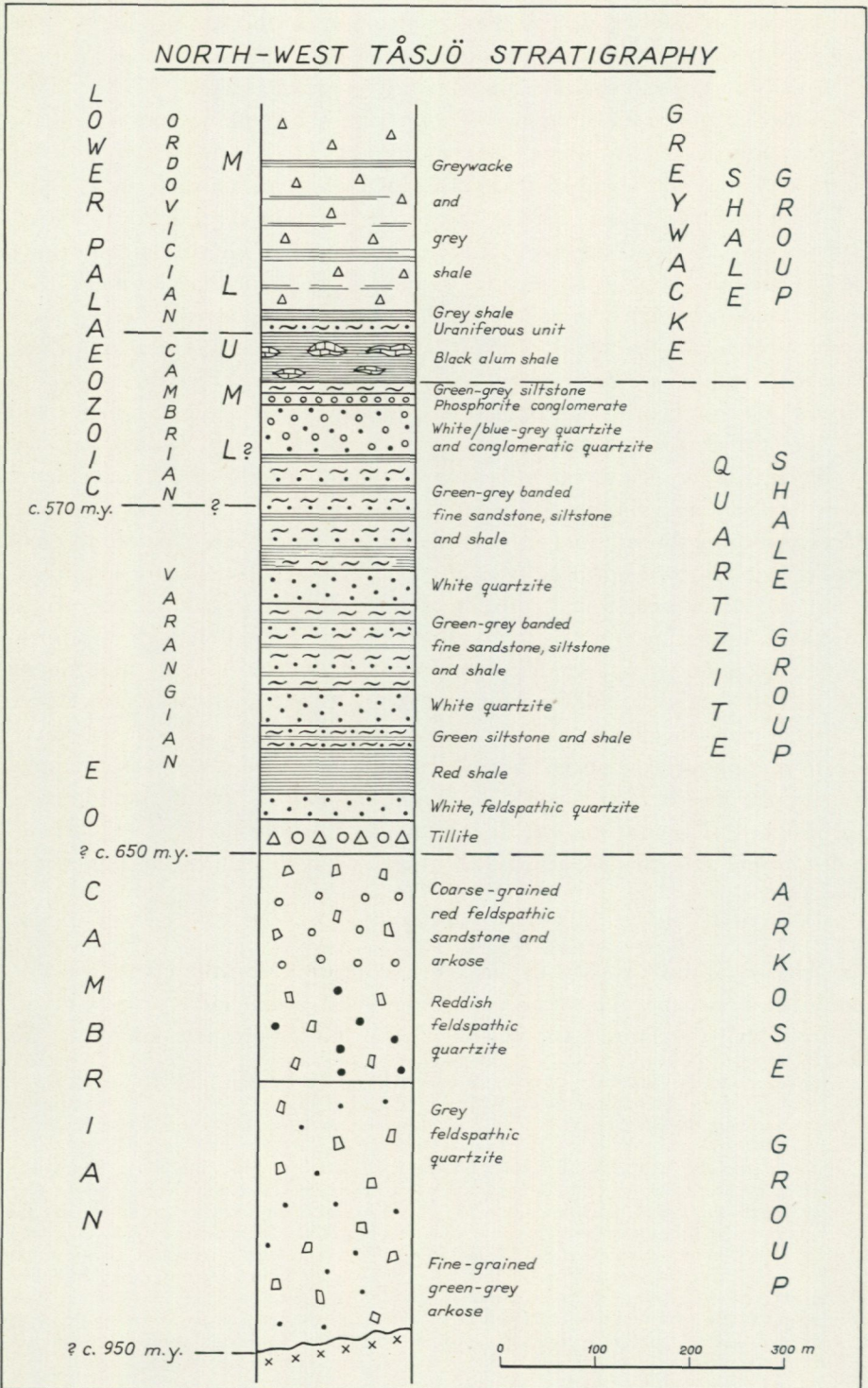


Fig. 3. Summary of the north-west Tåsjö stratigraphy.

unconformity has not yet been remapped and the relationships shown on Plate I are based on the published sources available, principally Du Rietz (1960) and the 1958 geological map of Sweden (described by Magnusson et al, 1960). It is noteworthy that the Arkose group is absent in the south-west part of the map area (Plate I) the overlying group resting directly on the granite basement. Nevertheless Asklund's conclusion that the sparagmite basin was orientated NW-SE remains conjectural. As can be seen from the section, Plate I, the Arkose Group must thin markedly south-eastwards and north-westwards (22 F, c 1), whilst in a northerly direction relevant data is lacking.

Thickness estimates for the group are at present somewhat speculative, but the unit is thought to be in the order of c. 500 m in the thicker parts of the sedimentary trough.

The age of the sediments is likewise somewhat unsure. In that they are overlain by conglomerates interpreted as tillites and correlated with the Varangian glaciation (Kulling, 1942) they are pre-Varangian (i.e. older than c. 650 m.y.) in age. The crystalline basement on which they rest has been referred to as of "Revsund granite" type (late Svecofennian 1785 \pm 40 m.y., Welin et al, in press). The occurrence of so-called sparagmites further south in Norway, thrust south-eastwards over an area of crystalline basement deformed during the Dalslandian orogeny (Magnusson, in Magnusson et al, 1960, p. 55-7.) c. 1100-935 m.y. provides indirect evidence favouring deposition of the Arkose Group during the interval from 935-650 m.y., i.e. in a comparable time interval to that established for the Torridonian sandstones of north-west Scotland (Moorbath et al, 1967, Moorbath 1969). There is an acute need for Rb/Sr age-determination studies on these late Pre-Cambrian sediments similar to those carried out on the Torridonian sediments.

In general, the Arkose Group is remarkable for the paucity of fine-grained sediments. The succession within the group is dominated by two sandstone formations both arkosic, the upper mainly red and the lower grey-green. The passage between these two formations appears to be transitional through feldspathic quartzites. The sandstones are frequently cross-bedded but cleavage folding has made systematic measurements of current directions difficult and way-up is often the only information available. The colour of the sediments, despite local variation due to deformation, is a characteristic feature of the different sandstone units within the group.

The Arkose Group has not been recognised in outcrop east of the western limb of the Fånån syncline. The conglomerates and arkoses below the alum shale formation in the Caledonian front (e.g. in Sångbäcken, south of Tåsjöberget, 21 G, b4) have been included in the overlying group for reasons discussed below (p. 17). How far eastwards the Arkose Group was deposited is open to speculation as indicated on the section accompanying Plate I.

West of Sörsjön (21 F, f 8), the Arkose Group apparently thins out against

the granite basement and the overlying tillite formation overlaps and/or oversteps on to this basement, implying the presence of an unconformity between the two groups. In the north-west part of Plate I (22 F, f 5, 6) a dolomite unit appears, apparently in the upper part of the Arkose Group and this evidence is taken to support the theory of a regional unconformity separating the two major rock units. In outcrop angular discordance has not been recorded.

3. THE QUARTZITE-SHALE GROUP

This unit is most fully developed north-west of Tåsjö (Sjoutälven, Korsselet, Erik-Mattselet). It has an estimated thickness of 4–500 m deposited during the Varangian and the Cambrian (up to and including the lower part of the Middle Cambrian).

A tillite formation, partly composed of unsorted boulder conglomerates and partly of fine-grained banded units with exotic clasts, rests on the uppermost coarse red arkoses of the Arkose Group. For descriptions of the tillites, the reader is referred to Kulling (1942). It is overlain by a white feldspathic quartzite which gives way upwards into red siltstones and shales with subordinate green bands. This likewise is overlain by white quartzite. There follows a sequence of green, banded lithic sandstones and siltstones, sometimes graded, occasionally with load casts and, more often, with small-scale cross-laminated tops. This unit is followed by white orthoquartzite. The green banded sandstones and siltstones are repeated higher in the succession separated by more white quartzites. The uppermost quartzites in this group, often of blue-grey colour, pass upwards into a conglomeratic quartzite with thin green siltstone laminae and occasional black organic "pods". The conglomeratic layers often have a calcareous matrix and resemble the overlying phosphorite-bearing conglomerate. The latter occurs in two thin units associated with subordinate limestones which in Fånån (21 F, f 7) and Högnäsån (21 F, i 8) have yielded fossil fragments, in the latter case related to the Cambrian *Paradoxides paradoxissimus* stage (Asklund and Thorslund, 1935a). North of Malgomaj the phosphorite-bearing conglomerate is of Lower Cambrian age (Kulling, 1955) indicating that the lithofacies is regionally diachronous. Finally, some fifteen metres of a massive green siltstone with thin calcareous layers compose the uppermost member of the group.

South-west of Sjoutälven in the area from Gärdsjön (21 F, d, e 7) to Sörsjön (21 F, f 7, 8), the group retains the general stratigraphy outlined above but lacks the tillite formation at the base, the arkosic conglomerates resting directly on the granitic basement. Westwards from Sjoutälven and Korsselet the basal tillite formation transgresses from the Arkose Group on the basement in the vicinity of Bergvattnet (22 F, e 1), where the recent hydro-electric project has

uncovered extensive new exposures of the unit. North and north-east from this area the Quartzite-Shale Group in general overlies the Arkose Group and tillites have been described from Långmarkberget (22 F, f 1) and Sörfors (22 F, g 3). Thus the Quartzite-Shale Group stratigraphy of north-west Tåsjö is retained regionally in an approximately NE-SW trending tract from north Malgomaj to Gärdsjön.

Towards the east and south-east from the north-west Tåsjö area there is a marked change in facies. Inliers (e.g. Högnäsån, 21 F, i 8) provide some information, but it is the overthrust quartzites of Tåsjöberget and Blaikfjället which give the most notable confirmation of this change of facies eastwards with the marked reduction of the amount of shale and the increased prominence of conglomerates and arkoses. Drill-hole profiles made by Boliden AB in the Lövstrand area (21 G, b 8), lead Du Rietz to describe (1960, p. 16) "a normal section through the Ström quartzite nappe as follows: uppermost a white or pale grey quartzite which has sometimes preserved the texture of a quartzite sandstone. . . In this rock a couple of very thin layers occur of greenish siltstone or quartzitic schist. . . In the lower part the quartzite often passes over into a medium-grained quartzite sandstone which further down passes over into an arkosic quartzite sandstone. . . The latter sometimes has a layer of quartzite conglomerate . . . The arkose may have layers of fragmentary siltstone". "Below the sediments a lenticular mass of schistose granite has often been observed at the bottom of the nappe." Thus along with a marked reduction of the thickness of this eastern succession, we note the probable lack of the basal glacial facies, the red shale formation and the banded green sandstones and siltstones and the increased proportion of clean sandstones and conglomerates.

Conglomeratic, arkosic and sandy units, some twenty metres thick underlie the alum shale formation in the eastern autochthon of the Caledonian front. They are partly exposed in Sågbäcken (21 G, b 4) and known best from the Boliden AB drill-holes referred to above and an AB Atomenergi drill-hole near Djupdal (22 G, f 2) and have been included in the Quartzite-Shale Group for three reasons. Firstly, the latter generally transgresses the Arkose Group on to the crystalline basement; regression of this unit in the Caledonian front is unknown elsewhere. Secondly, despite the immature nature of most of these sediments in the front, the subordinate cleaner sandstones are more reminiscent of the Quartzite-Shale Group than the Arkose Group. And thirdly, the alum shale formation of the Caledonian front, north of Malgomaj (Vojmsjön and to the north) is underlain by a sandstone formation (the Laisberg Series of Kulling, 1942) directly comparable with the Varangian and Lower Cambrian units described here. Thus the conglomeratic facies of the eastern margin of the Malgomaj-Tåsjö area appears to be a southerly facies continuation of the Laisberg sandy facies,

4. THE SHALE-GREYWACKE GROUP

These Lower Palaeozoic rocks, ranging in age from the middle Middle Cambrian to the Middle Ordovician, fall readily into two distinct formations, a lower black alum shale unit and an upper greywacke and grey shale unit.

The Alum Shale Formation

A basal, dark, shale-pebble conglomerate a few centimetres to about a metre thick usually separates the *Paradoxissimus* organic shales and silts from the underlying green siltstone of the Quartzite-Shale Group. Judging from the drill-cores from northern Tåsjö, there follows c. 40–50 m of black shales with stinkstone lenses reaching up, at least in some areas, into the Tremadocian. One or two metres of banded grey limestone may appear at or near the top of the formation.

Marked variations in thickness and character of the different zones of the Cambrian have been claimed by Asklund and Thorslund (1935a), when the unit is traced south-eastwards from the north end of Tåsjö to Tåsjöberget. Their work (see p. 74) suggested that the successions in their autochthonous Sjoutälven profile and the lower part of Tåsjöberget were considerably thinner than in the overthrust shales. Asklund and Thorslund considered this evidence could only be explained by nappe transport of the upper part of the Tåsjöberget alum shales from a root-zone west of the north-west Tåsjö area. Our mapping makes such a construction somewhat complex and a root-zone east of the Seve front impossible to define. The reliability of the thicknesses quoted by Asklund and Thorslund is uncertain – the shales are intensely folded (cf. Asklund 1960a, Fig. 17) and there appears to be no necessity for attributing the facies variations within the formation to anything other than local phenomena within the depositional basin.

Greywacke-Shale Formation

This formation ranges in age from the Lower Arenig (Hunneberg stage^{*)} into the Llandeilian; probably higher. Its thickness is uncertain in that fold repetition has not yet been assessed within the Fånån and Hundsjöbäcken synclines. Nevertheless, preliminary estimates based on the AB Atomenergi drill-holes in the area south-east of Bunksjön (21 F, g 8), suggest thicknesses greater than 200 m and allow the possibility of c. 300 m. This evidence, taken in relation to the data from further south that this greywacke unit ranges into the Upper Ordovician (Asklund and Thorslund, 1935b) makes it probable that the formation originally achieved a thickness of 400–600 m. During the early investigations of the Tåsjö area, Wiman claimed the presence of Monograptids in the

^{*)} Asklund and Thorslund (1935a) considered the basal glauconitic, phosphatic limestone/sandstone to be of Upper Tremadocian age. Tjernvik (1956) demonstrated faunal affinities of this unit with the lowermost part of the Hunneberg stage and Karis (pers.comm.) has recently confirmed this.

Karbäcken area (21 F, j 6) (see Asklund and Thorslund, 1935a, p.92) and therefore maintained that the greywacke sequence extended up into the Silurian. There has been no subsequent confirmation of these finds and we have as yet no complementary evidence to support the presence of rocks younger than Llandeilian (L. Karis, pers. comm.) in the area.

The basal member of the formation in north-west Tåsjö is a calcareous, glauconitic, phosphatic sandstone and siltstone. It is 5–8 m thick and contains several coarse to fine repetitions before passing transitionally into the overlying member, a shale and siltstone. It is within this Lower Arenig, phosphatic sediment that the uranium is concentrated, as has been described by Andersson (in press). This member is treated in detail on p. 27.

The overlying grey shale and siltstone member, some 10–15 m thick, passes upwards transitionally into the greywacke and shale facies. The latter generally exhibits excellent sedimentary structures with graded bedding, typical bottom structures including load-marks, flutes and grooves, and tops with frequent small-scale cross-lamination and convolute bedding. Turbidity current deposition is inferred.

The Greywacke-Shale Formation shows important changes in facies both westwards and eastwards from the area north-west of Tåsjö. Maximum thicknesses of the basal member occur in the area north of Norråker towards Gara-träsksjön (22 F, i 0) and are in the order of 8 m. Eastwards, this is markedly reduced (e. g. c. 2 m in Kvarnån, 21 F, j 8) and it passes in this direction into a limestone facies (Karbäcken 21 F, j 6). Similarly, further north (Onbäcken, 22 F, j 0) the sandy facies is in part replaced by limestone. By Malgomaj (Granliden, 22 G, b 7, and Baktoberget, 22 G, f 2, palaeontological data summarised in Kulling, 1942 p. 52) only limestone accumulated during the deposition of the uraniumiferous sediments in Tåsjö. Westwards from north-west Tåsjö, the thickness of the uraniumiferous sediments diminishes notably and present evidence suggest that the facies is replaced first by grey shales and then probably by grey wackes. The development of the unit south-west of Tåsjö below the greywackes of the Fånån syncline is as yet unknown. Thus the glauconitic, phosphatic facies develops in the transition zone between limestone in the east and shales and greywackes in the west, a relationship summarised in Fig. 6 and 7.

The overlying shale member appears to retain its character over the central part of the map area but is probably replaced westwards by greywacke. Above this, the pre-Caradocian turbidite facies is equivalent to the limestone facies directly south-east of the map-area (Kalkberget, south-west Flåsjön). Thus the general pattern of facies distribution established in the Lower Arenig, with shales and greywackes in the west and limestones in the east, persisted through the Lower and into the Middle Ordovician. The regional facies change from limestone to greywacke with the thicker development of the latter requires a marked sinking of the basement westwards, and implies the existence of

deeper water in the western areas during the Lower and Middle Ordovician. Nevertheless, it is clear from the geological relationships that a truly deep-sea environment, claimed by many authors for similar deposits elsewhere (e.g. Kuenen, 1964), did not exist for the Tåsjö turbidites. Turbidite influx was accommodated by reactivation of the Tåsjö hinge-zone. It is indeed possible that seismic activity associated with this hinge-zone fracturing of the crystalline basement provided the trigger mechanism for the turbidity flow (cf. Heezen, 1959), the rate of movement in this fracture zone controlling the rate of accumulation of the sediments.

III. REGIONAL STRUCTURE

The structure, as illustrated on the map and section Plate I, is dominated by a primary thrust regime (Harland and Bayly, 1958). The front range nappes, with slices of granite basement at their base, give evidence of crustal shortening in the order of at least thirty kilometres, they being rooted in a belt from central Tåsjön to central Malgomaj. West of these lowermost thrust sheets, subordinate imbrication of the basement passes upwards into cleavage folding and minor thrusting of the higher stratigraphic units. In the far west, the metamorphic complex of the Seve-Köli Nappe overthrusts the largely unmetamorphosed sediments described here. The basal thrust of the Seve-Köli Nappe has been traced westwards (Zachrisson, 1969) over the Fjällfjäll/Hehtajaure and Borgafjell Windows, implying a transport distance of at least eighty kilometres, a figure comparable to that estimated by Törnebohm (1888) in a profile westwards from central Jämtland. These transport distances are certainly too small and some authors (Asklund 1938, Kautsky 1953), have suggested figures of over two hundred kilometres to explain the relationships in the windows between the metamorphic complex and the underlying crystalline basement with its veneer of less metamorphosed Eocambrian and possibly Cambrian sediments.

The lowermost front range nappes in the Tåsjö area are apparently made up of at least two thrust-sheets, referred to here as the Tåsjöberget and Blaikfjället Nappes*). Transport of the former was much less in the north than in the south and vice-versa for the latter, implying much differential movement within the mylonite zones beneath the nappes. These two thrust-sheets are themselves imbricated (cf. Du Rietz's profiles, 1960) requiring some oversimplification on the 1:200 000 presentation (Plate I). The Blaikfjället Nappe is shown (section, Plate I) to cut the Tåsjöberget Thrust, this construction being based on Du Rietz's Lövstrand profile (1960, Plate 3). Beneath these overthrust quartzites there is some telescoping and repetition of the alum shales, described

*) This name should not be confused with Kulling's "Blaik Nappe Complex (Blaik skollan)" - a tectonic unit thought to be derived from over 100 km to the west.

first by Asklund and Thorslund (1935a), this formation occupying much of the three to four hundred metre Tåsjöberget hillside.

Subordinate imbrication occurs immediately west of the lower nappes described above, but the structure from central Tåsjön to Malgomaj is dominated by two major synclines the Fånån and Hundsjöbäcken Synclines separated by the Sjutälven Anticline. These folds are asymmetric eastwards and are associated with a well-developed west-dipping axial-surface cleavage. Boudinage of competent units occurs particularly, for example, in the case of the uraniumiferous sandstone overlain and underlain by shales.

The Hundbäcken Syncline passes down into a low angle reverse fault, the Hansselet (22 F, f 1) Thrust. The latter when traced westwards is itself gently folded and the style of this refolding is retained westwards to the vicinity of the mylonites at the base of the Seve-Köli Nappe. Similarly a folded dislocation occurs south of Fånsjön (21 F, e, f 7, 8) referred to as the Sörsjön Thrust. These two thrusts whilst of greater magnitude than the majority of the dislocations in the area between the front range nappes and the Seve-Köli Nappe, are minor phenomena in relation to the Stalon Nappe (Kulling, 1942). The latter, we have only examined in the southern and northern parts of its development in the area of Plate I, and the nappe boundaries have been taken from Kulling (1942) with minor modification, principally with the aid of the flight electro-magnetic anomalies and the knowledge that alum shales occur a few kilometres north of the map area at Stalon.*) The Stalon Nappe is composed dominantly of arkosic sediments, very probably related to the Arkose Group. Some greenstones occur in the northern part of the nappe; their regional distribution has not been reassessed and their location on Plate I follows Kulling (1942). The rocks of the Stalon Nappe have been metamorphosed in greenschist facies (Kulling, 1961): fabrics have been examined showing porphyroblastic epidote deformed by a penetrative schistosity composed of muscovite, biotite and chlorite. Basic rocks are actinolitised and epidotised. This metamorphism is in marked contrast to the sediments beneath the nappe, whilst being reminiscent of parts of the Köli terraines to the west. Kulling (1942) showed the Stalon nappe, north of Stalon, to be folded back westwards over a major antiform and overridden by the Seve-Köli Nappe Complex, implying transport of the Stalon Nappe over a distance of at least forty kilometres.

It is important to note that the front range nappes are derived from a zone which during the sedimentary cycle acted as a basement hinge with marked thickening of the Eocambrian and Ordovician successions westwards. Similarly the Hansselet and Sörsjön Thrusts occur in areas where the Arkose Group shows rather sudden thinning. Apparently, zones of weakness, created in the

*) The first fossils from the Stalon black shales, found by the author in 1970, have been identified by L. Karis as *Lejopyge laevigata* (Dalman), indicating the presence at least of upper Middle Cambrian in the Stalon area.

crystalline basement during the depositional cycle with downwarping of the crust, reactivated during the orogenic cycle providing the root-zones for the nappes below the Seve-Köli Complex.

IV. TECTONIC HISTORY

The crystalline basement underlying the Tåsjö area is thought to be of Svecofennian age (c. 1800 m.y.). After this orogenic and intrusive cycle and subsequent erosion (elsewhere to provide the Jotnian sandstones), this part of the crust apparently remained more or less stable until the deposition of the Arkose Group, the latter occurring at some stage after the Dalslandian orogeny (c. 950 m.y.) and before the Varangian glaciation (c. 650 m.y.).

The Arkose Group and other more or less contemporaneous sediments accumulated in basins marginal to what later in Scandinavia developed as the main Caledonian trough. This deposition must have occurred more or less simultaneously with the accumulation of the thicker late Pre-Cambrian volcano-sedimentary sequences of Spitsbergen (Kulling 1934, Harland 1959, Winsnes 1965) and East Greenland (Katz 1961). In Scotland deposition of the Torridonian, Moian and the lower part of the Dalradian sediments occurred in this interval. In the Tåsjö area this local downwarping of the crust must have been achieved by fracturing of the basement and reflects the earliest Caledonian instability along the western margin of the Baltic shield.

Subsequent deposition, commencing in the Varangian after an interruption implied by regional unconformity between the Arkose and Quartzite-Shale Groups, followed a more obviously Caledonoid pattern. Fig. 4 summarises the regional sedimentary pattern for the Tåsjö area for the Eocambrian and Lower Palaeozoic and includes data from further south in Jämtland (Thorslund, 1960) for the part of the succession younger than that exposed within the area of Plate I. The diagram assumes that the tectonic pattern inferred for the Tåsjö area can be applied further south; thus the major lateral variations in facies are related to basement instability during the depositional cycle and not to subsequent nappe transport. (This does not deny local easterly overthrusting.)

The most prominent feature uniting the Tåsjö sedimentary pattern is the evidence of repeated downwarping westwards of the crystalline basement about a hinge-zone orientated c. NNE-SSW through northern Tåsjö. It reflects the establishment in the late Pre-Cambrian of a fracture system parallel to the incipient Caledonian trough. It is clear from Fig. 4 that the Tåsjö hinge, during Pre-Cambrian sedimentation alone accounted for a downwarping of the basement of the order of 1 000 m. It is particularly interesting that it was the same hinge-zone which, after a period of relative stability in the Middle and Upper Cambrian, reactivated in the early Ordovician, resulting in renewed westerly

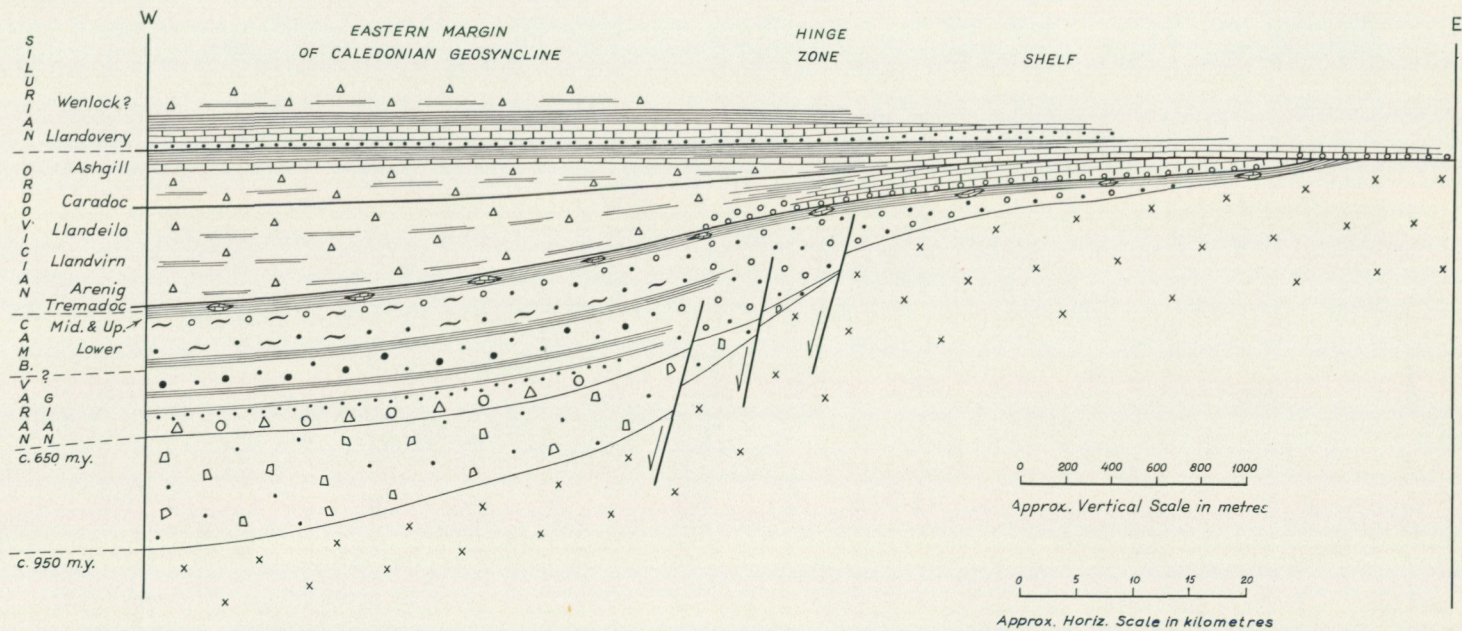


Fig. 4. Generalised presentation of the regional stratigraphical relationships in the Caledonian Front of central Sweden.

subsidence and the deposition of a turbidite facies in close proximity to a limestone shelf environment. Thus throughout much of the Caledonian cycle the Tåsjö hinge defined the western edge of the stable Baltic shelf.

When considering the thickest successions in the Tåsjö area deposited during the late Pre-Cambrian and Lower Palaeozoic and taking them in relation to the evidence of the younger successions further south, it is difficult to accept the traditional view of a miogeosyncline for this part of the Caledonides – neither the amount nor the rate of sedimentation support this concept. Nevertheless it is possible that some fifty to a hundred kilometres west of the Seve front truly miogeosynclinal Caledonian successions did accumulate within the unstable margin of the shield. Tåsjö stratigraphy compares remarkably with the substantially thicker successions described from the Finnmark area, north Norway (Reading, 1965), which can well be referred to as miogeosynclinal in dimension, rate of sedimentation and sediment character.

It is uncertain how long into the Lower Palaeozoic sedimentation continued in the Tåsjö area. The youngest rocks further south in Jämtland are of Upper Llandovery age (Thorslund, 1948) and are overlain by a greywacke succession at least some tens of metres thick. Within the Seve-Köli Nappe Complex, Kulling (1933, 1955, 1969) recorded Ashgillian and Middle and Upper Llandovery fossils in the classical area of Björkvattnet–Virisen, central-west Västerbotten. Correlation westwards of this succession lead Zachrisson (1964 and 1969) to suggest that a substantial volcano-sedimentary pile overlies the Upper Llandovery strata. It would appear probable therefore that orogenic deformation commenced in this part of the Scandinavian Caledonides fairly late in the Silurian. The nearest post-nappe sediments of Old Red Sandstone type occur 250 km south-east of Tåsjö at Röragen where Goldschmidt (1913) collected plant fragments of lower Devonian age (Halle, 1916).

Fig. 5 compares Caledonian Front stratigraphy with that of the metamorphic Köli of the Seve-Köli Nappe Complex. Whereas it is apparent that the successions of the eastern areas were deposited on the unstable marginal zones of the Baltic shield, it is uncertain whether this was likewise the case for the eugeosynclinal development of the Köli. If transport of the Seve-Köli Nappe occurred of the dimension suggested by Asklund (1938) and Kautsky (1953) then the volcano-sedimentary rocks may have accumulated in an oceanic crust environment, west of the Baltic shield.

Orogenic activity, with the formation of the early Caledonian nappes, commenced in northern Scotland and western Ireland in the early Ordovician as is clear from the geological relationships (Dewey, 1961) and the isotopic age-determinations (Pankhurst, 1970). The formation of the nappe structures in the western Caledonides was thus reflected in the east (Scandinavia) by volcanicity within the Köli and reactivation of the Tåsjö hinge-zone, with greywacke accumulation off-shelf from a carbonate environment.

SWEDISH CALEDONIAN STRATIGRAPHY

SEVE-KÖLI NAPPE COMPLEX

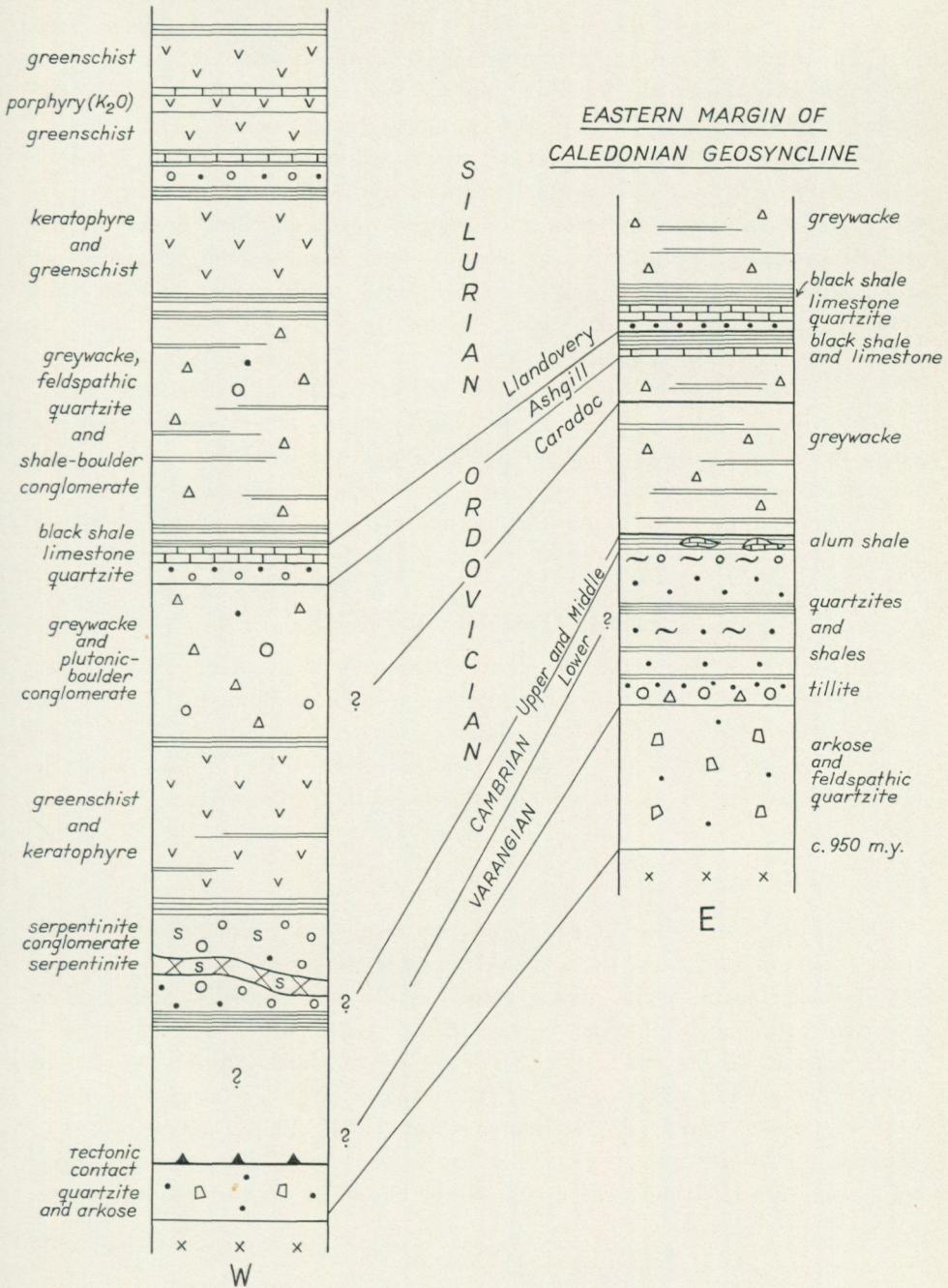


Fig. 5. A comparison of the stratigraphy of the Caledonian Front autochthon and parautochthon with that of the Köli of the Seve-Köli Nappe Complex. (Eastern Margin from Fig.4. and Köli from Kulling 1933, Zachrisson 1969.)

Thus it was not until much later in the Lower Palaeozoic history, some 70–90 m.y. after the early Scottish nappes had formed, that Caledonian orogenic activity culminated along the western margin of the Baltic shield with vast overthrusting of the metamorphic nappes on to areas which during the depositional cycle composed the edge of the stable shield. In the Tåsjö area it seems probable that the overriding of the Seve-Köli Nappe Complex caused the imbrication of the underlying basement and the associated cleavage folding of the sedimentary pile, i. e. the deformation progressed from west to east.

In the wider context of the North Atlantic Caledonides, the tectonic sequence outlined above fits well into a model for the orogenic belt based on plate theory. Concepts of disruption and separation of the Greenland-Baltic shields during the depositional cycle followed by closure of the shields during the orogenic cycle, are more generally acceptable in the light of recent evidence of sea-floor spreading and opening of the Atlantic Ocean. They provide a dynamic model which satisfies the fundamental geological relationships along the eastern front of the Caledonides, relationships dominated by fracturing of the rigid Baltic plate during the sedimentary cycle and overthrusting of the geosynclinal pile on to the plate during the orogenic cycle. It is noteworthy that gravitational models alone do not satisfy the present state of our knowledge of the Scandinavian Caledonian Front in that they do not adequately account for the thrust regime along with the evidence of crustal shortening.

V. ECONOMIC ASPECTS

Within the area of Plate I, a lead sulphide paragenesis was discovered by Boliden AB in 1940 (Grip, 1960) and subsequently explored by diamond drilling and excavation. It is located in the Varangian quartzites overlying the Tåsjöberget thrust. Uranium was not found in the area until 1956–7, the exploration being largely carried out by AB Atomenergi. Published data from their work are not yet available.*)

1. URANIUM

Throughout the Swedish Lower Palaeozoic sequences from Skåne to Tåsjö there occurs in the base of the unit overlying the alum shale formation notable amounts of glauconite and apatite. This basal unit is generally sandy and/or calcareous and may be of upper Tremadocian or Lower Arenig age. The apatite, in the form of phosphatic nodules, may also appear in the uppermost part of the alum shales e. g. in Östergötland (Westergård, 1940) a relationship similar to that recorded from Anglo-Welsh areas (Stubblefield, 1930; Fearnside, 1910). Whereas glauconite may appear higher in the Ordovician successions, the apatite is concentrated almost exclusively to the basal few decimetres.

*) Subsequent to the preparation of this paper, G. Armands has published (GFF, Dec 1970) a short account of the Tåsjö uranium unit.

In the Tåsjö area this phosphatic unit is unusually thick and contains a marked concentration of uranium, the majority of which, as Andersson (in press) has shown, is bound to the apatite. Elsewhere in Sweden, the uranium concentration in this unit appears to be substantially lower, although that in Billingen (Andersson, unpublished report) is comparable with parts of the Tåsjö unit. It is of interest to note that the Anglo-Welsh occurrences mentioned above likewise show a uranium concentration in the phosphatic nodules (Ponsford, 1955).

The Tåsjö uraniferous unit has been described by Asklund and Thorslund (1935 a) and by Andersson (in press). It was not until 1957 that the unit was shown to be uranium-rich, the analysis of radioactive specimens collected by E. and H. Mattson activating AB Atomenergi's exploration of the area. Andersson's work is a direct result of Atomenergi's participation in the exploration. The unit is a calcareous sandstone/siltstone of Lower Arenig age. Apatite and glauconite, the latter in part altered to siderite, are generally prominent but are very variable in quantity from bed to bed within the unit. Apatitic brachiopod shells are common. The basal part of the unit is sharp to the underlying alum shales with stinkstones or thin banded limestone, and may be conglomeratic. The upper part grades into the overlying grey shale member of the Arenig. For a more comprehensive description of the lithologies, the reader is referred to Andersson (in press).

Facies variations in the Lower Arenig are shown schematically in Fig. 6 and have been discussed on p. 19.

Atomenergi's analyses of the unit indicate that the thicker parts, e. g. between Garaträksjön and Norråker contain an average of c. 250 ppm uranium, whilst smaller thicknesses further east in Kvarnån contain c. 500 ppm.

Our present knowledge of the uraniferous unit suggests that the following stratigraphic relationships bear on the genesis of these phosphatic sediments:

- (i) They occur immediately overlying the black alum shale formation.
- (ii) Considering the whole of Sweden the deposition is diachronous, occurring in the upper Tremadocian and/or the lower Arenig.
- (iii) They show greatest thickness and greatest concentration both of phosphorus and uranium in the Tåsjö area, where they occur marginal to a stable shelf environment where limestones were being precipitated. Off the shelf, deeper water conditions existed with accumulation of shales and possibly greywackes.
- (iv) Later in the Ordovician there occur lateral transition zones between limestone in the east and greywacke in the west but these lack the phosphatic transitional facies.

These relationships, summarised in Fig. 7, favour a model for phosphate precipitation suggested by Kazakov (1938, cf. Guldbrandson, 1969), where currents from the deeper parts of the depositional trough well up along the

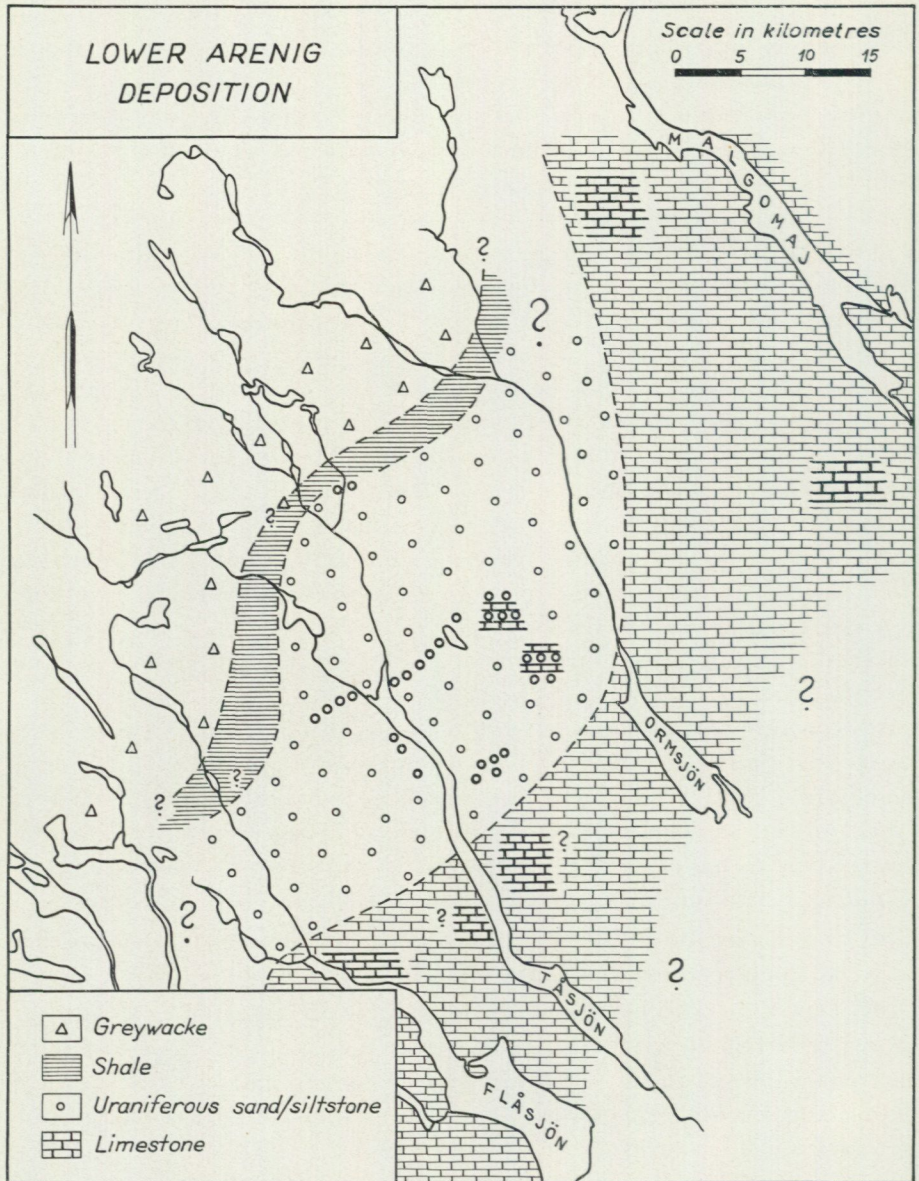


Fig. 6. General distribution of lithofacies during early Ordovician deposition in the area from Flåsjön to Malmgömsjö.

edge of the shelf supplying relatively cold, phosphate-rich water to the warmer, higher pH environment. These circumstances existed later during the Ordovician without the precipitation of apatite implying that the underlying rocks probably influenced subsequent uranium-rich, phosphate deposition during the lowermost Arenig. The source of the uranium in these Lower Arenig sediments is uncertain. It may have been derived from the alum shales (containing up to c 200 ppm uranium), but it is also possible that the uranium source for the latter persisted into the Arenig.

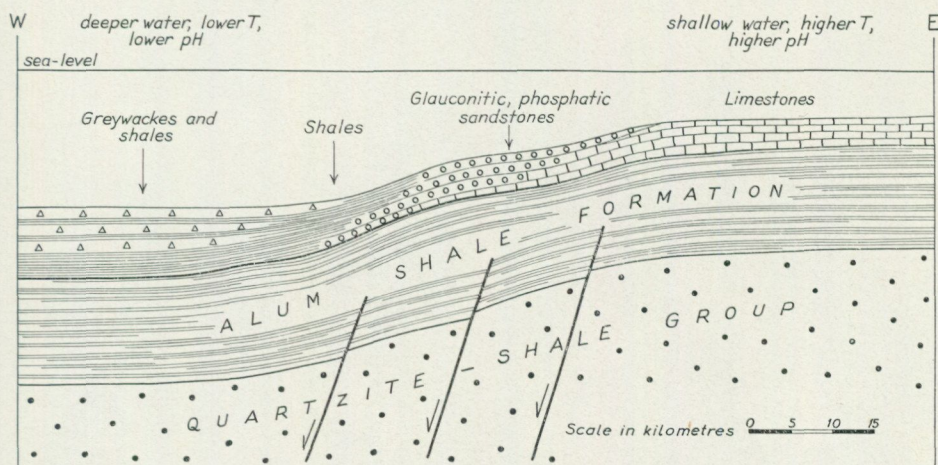


Fig. 7. Diagrammatic presentation of the lithofacies variation during early Ordovician deposition and the inferred relationship to the Tåsjö hinge-zone.

2. LEAD

SGU's exploration programme in the Tåsjö area has not been involved in prospection for lead. The discussion that follows here derives directly from the reinterpretation of the tectonic history of the area as summarised earlier (p. 22). It depends principally on the conclusion that the mineralisation is sited above the vicinity of the hinge-zone in the basement and that this hinge-zone must certainly have been a zone of tension during Eocambrian and Lower Palaeozoic deposition, the westerly downwarping probably being achieved by normal faulting. The Lövstrand/Bellvik mineralisation conforms with the many other lead parageneses located in the eastern border of the Caledonian fold belt (Fig. 8), in its occurrence marginal to the main Caledonian sedimentary pile.

The genesis of the Lövstrand/Bellvik mineralisation cannot be treated in isolation from the other occurrences. "Any theory of genesis must account for the whole mineralisation along the 700 km border belt of the Caledonides." (Moorbath and Vokes, 1963, p. 309). Similar ores occur throughout this zone

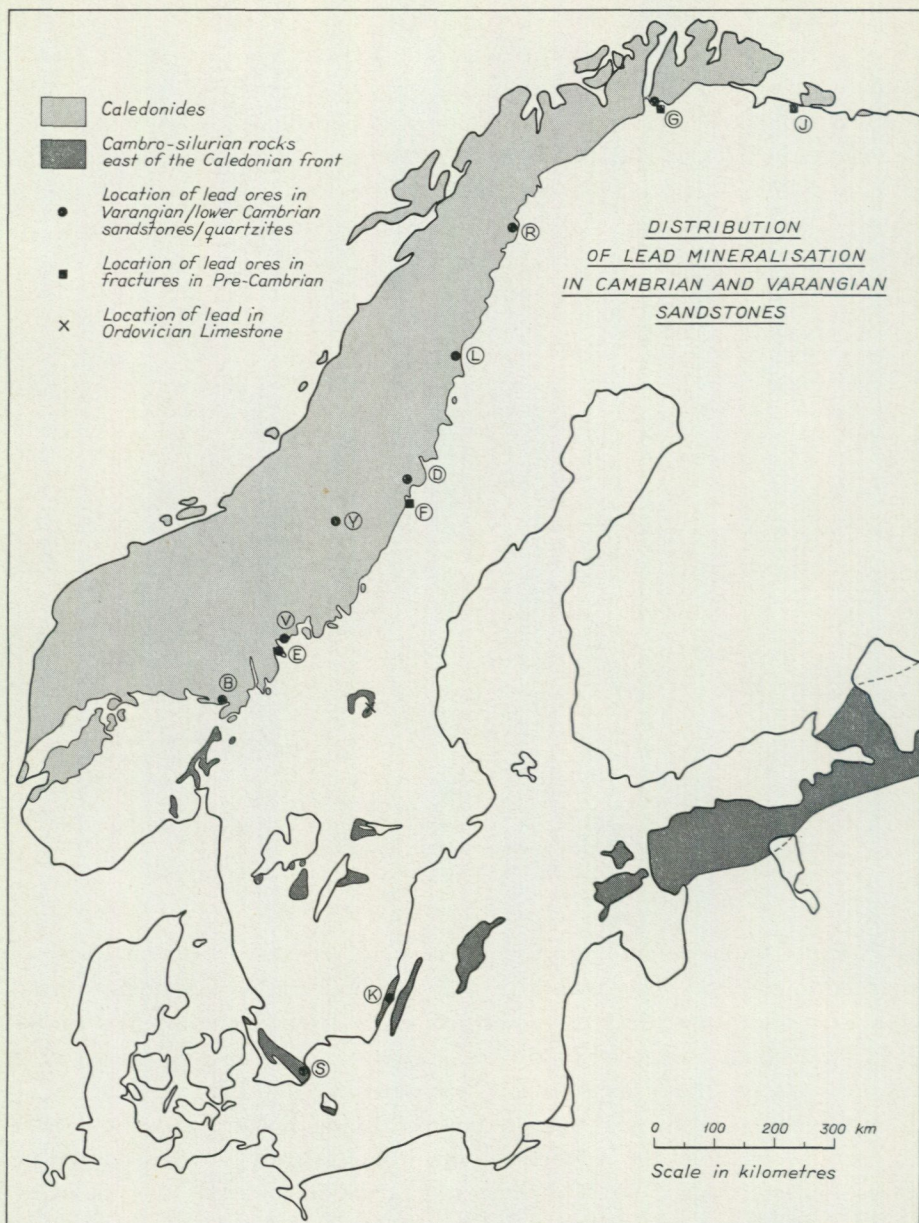


Fig. 8. Distribution of lead sulphide dominated parageneses in the Caledonian Front of Scandinavia. (Also included are the occurrences near Siljan, Simrishamn and Kalmar-sund).

B Bråstadelven D Dorotea E Engerdal F Flåsjön G Gurrogaissa J Jakobs-elv K Kalmar-sund L Laisvall R Rautasjaure S Simrishamn V Vassbo Y Ytteroldsjön X Boda. (Localities taken from Moorbath and Vokes 1963 and Wickman et al 1963).

and show marked mineralogical similarities (galena – sphalerite – pyrite – calcite – fluorspar – barite). In addition the majority contain excess radiogenic lead resulting in anomalous young or negative isotopic ages (Moorbath and Vokes, 1963). According to Grip (1960, p. 158) the mineralising solutions probably “have come from the inner part of the mountain range (Caledonian), from areas undergoing palingenesis at that time”. Moorbath and Vokes (1963, p. 310) commented “The lead isotope analyses appear to substantiate this hypothesis of a distinct source for the solutions.” A principle objection to the Grip theory is that it requires solution migration over a distance of about 200 km; three times this distance if the Simrishamn occurrence (Tegengren, 1924) is included in the same association.

The geological data can be summarised as follows:

(i) The lead parageneses occur as impregnations and fracture fillings within quartzites and sandstones. Although the mineralisation is confined to these sediments it is not stratiform in detail. Patchy and discordant development within the sandstone implies epigenesis, or syngensis with subsequent re-distribution.

(ii) These host rocks are of Varangian and lower Cambrian age and can be recognised as a distinct lithostratigraphic unit from southern Norway, through Sweden to northern Norway. The formation is diachronous, deposited in the eastern margin of a basin existing along the edge of the main Caledonian trough.

(iii) The host rocks are overlain by black organic alum shales, of Middle and Upper Cambrian and lower Tremadocian age.

(iv) The rocks underlying the sandstone formation are generally crystalline Pre-Cambrian basement of varying age and rock-type. In some areas, e.g. Vassbo, unmetamorphosed Pre-Cambrian sediments (Jotnian) separate the crystalline basement from the sandstone formation.

(v) Mineralisation parageneses, similar to those in the sandstone formation, occur in the basement underlying the sandstone in a number of locations along the Caledonian front. Their presence is apparently restricted to fracture fillings.

(vi) The mineralisation in the sandstone formation is related to faulting. Grip (1960 p. 157) commented on the Vassbo ore: “The relation between fissures and ore contours is striking” and noted (p. 155) in the case of the Maiva deposit near Laisvall that “The mineralisation area is lying in the bottom of a fault trough striking about NNE”. The linearity of the Laisvall (Kautsky-malmen) and Vassbo ore-bodies suggests relationship to an underlying fracture system. Grip regarded this relationship to fracture systems as indicative of mineralisation during Caledonian overthrusting, and commented (p. 158) “Any reason to look for the origin of the mineralising solutions in the Pre-Cambrian basement hardly exists”.

(vii) In that the mineralised sediments range in age into the lower Cambrian and the mineralisation is displaced by Caledonian thrusting, the formation of the ore must have been post-lower Cambrian and pre-Devonian in age.

These seven points, taken in relation to the Tåsjö evidence of hinge-zone location for the mineralisation, favour a direct derivation of the mineralising solutions through the underlying basement, a hypothesis somewhat simpler than one involving solution migration laterally through hundreds of kilometres of rock. Regional stratigraphic evidence from the Caledonian front supports the existence of this hinge-zone throughout the length of the eastern edge of the Caledonian trough permitting a similar mode of occurrence for all the lead mineralisations.*) As noted earlier, similarities in paragenesis, require a common source and probably a similar time for mineralisation. In view of the unambiguous relationship spatially to the Caledonides it is of interest to speculate on both when the mineralisation occurred and from whence it was derived.

The mineralisation of the basement underlying the sandstones may have occurred either by transport of the mineralising solutions upwards through the crust or downwards from an already impregnated overlying sandstone. In that the lead mineralisation is related to the Tåsjö hinge-zone, the former is more probable. The underlying basement is notably inhomogeneous both in rock-type (igneous, metamorphic and sedimentary) and age (Svecofennian to Dalslandian). If therefore the mineralisation is to be derived from depth it must come from the deeper levels of the crust or even the upper mantle.

The time of mineralisation is perhaps even more controversial. In that the sulphides are strata-bound and the alum shale formation presents an excellent impermeable cap-rock, it is probable that the mineralisation occurred after the deposition of these Middle and Upper Cambrian and Lower Tremadocian rocks. This theory finds support in Laisvall where the ore-distribution is partly controlled by the presence of thin shale units within the sandstone formation. It is also of interest to note that in the one area where a substantial alum shale cap-rock is absent (Boda, Fig. 8) lead mineralisation occurs in overlying Lower Ordovician limestones. It is clear also that if these excess radiogenic leads in the Boda area are definitely related to the Varangian/Lower Cambrian sandstone occurrences, then it is probable that the latter also are of middle Ordovician or younger age. Considering the mineralisation in relation to movement within the Tåsjö hinge-zone it appears more likely that it occurred when the hinge was active than when it was passive. This would support a post-Cambrian age.

These indirect lines of evidence suggest that the lead mineralisation was

*) On Fig. 8 two lead occurrences with the same stratigraphic relationships as those in the Caledonian front have been indicated, Simrishamn and Kalmarsund. In the case of both these mineralisations there exist spacial relationships to hinge-zones marginal to the Skåne and Baltic troughs, respectively.

related to the Caledonian cycle in that it occurred at a time during or after the early Caledonian nappes formed in northern Scotland and western Ireland and volcanicity was widespread in northern England, Wales and western Scandinavia. Indeed it is not impossible that the chalcopyrite – sphalerite – pyrite – pyrrhotite – galena mineralisations related to this volcanicity near the centre of the Caledonian trough (in an oceanic crust environment?) were at least partly synchronous with the Caledonian Front lead mineralisations. This hypothesis thus requires deep crust (or upper mantle) derivation of the mineralisation related to hinge-zone fracturing occurring along the western margin of the Baltic plate, during Ordovician and/or possibly Silurian deposition.

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At the start of the 1969 field season we were introduced to the geology of central and northern Jämtland by Doc. A. Strömberg and to the Tåsjö area by AB Atomenergi's geologist Dr. G. Armands. We benefited much from this excursion, with the demonstration of type sections and the discussion of different aspects of Caledonian Front geology and our subsequent fieldwork was notably accelerated by this introduction. Subsequent treatment of the data and reassessment of the AB Atomenergi material has been greatly facilitated by G. Åkerblom.

Most of the outcrop mapping was carried out by five students R. Kumpulainen, B. and L. Stenpil, T. Thelander and J. Vesel, employed by SGU as extra-geologists. Two of them, Kumpulainen and Thelander, continue their work for post-graduate degrees.

The Boliden Company has been most cooperative in allowing publication of their flight electro-magnetic anomaly maps and for advice in this context Dr. P. S. Parasnis, is particularly acknowledged.

Dr. E. R. Gee, Doc. O. Kulling and Dr. E. Zachrisson have read the manuscript and their comments have notably improved the published script. Mrs. Stina Järnefors has skillfully redrawn the maps and diagrams. Dr. B. Flemström has kindly revised the spelling of the place-names on Plates I and II. These and others who have participated indirectly in the Tåsjö project are thanked for their contributions towards unravelling the problems of Caledonian Front geology.

No acknowledgements would be complete without mention of the help we have received in the Tåsjö area, particularly in Norråker, where Håkan and Dagnie Lindh have done much to promote an efficient field season.

APPENDIX

The Flight Electro-magnetic Anomaly Map, Plate II

A simplified map of the flight electro-magnetic anomalies is reproduced at 1:200 000 in Plate II. These measurements were made during the summers of 1961–5 by the Boliden Company. Measurement data are included in the legend to Plate II. The results from 1961–4 were originally compiled at 1:20 000, (from 1965 at 1:50 000), and the subsequent reduction to 1:200 000 has resulted in minor simplification of the anomaly patterns.

The method is designed to detect conductive rock units occurring near the surface. In the Tåsjö area these include principally the alum shale formation. Depth of detection varies with the thickness and orientation of the strata and, whilst in general it probably does not exceed 50 m, flat-lying alum shale at greater depths may be detected. We have checked the anomaly maps during the outcrop mapping and found that there is in general good correlation between the presence of alum shale and the maxima of the anomalies, at least those measured during 1961–4. Nevertheless the outcrop mapping suggested errors of several tens of metres up to c 200 m for some of the anomalies and subsequent ground electro-magnetic slingram measurements have confirmed these errors. We have therefore chosen to carry out ground slingram measurements in areas where drilling is anticipated.

In those areas where the flight measurements were made with line separation of 500–1000 m (during 1965) the method failed to detect alum shales in the bedrock in several localities, particularly along the eastern margin below the quartzite nappes. Hence the more notable divergences between the geological map (Plate I) and the anomaly map (Plate II).

Plate II illustrates well the immeasurable value of this type of flight geophysical method when employed in an area of relatively gentle relief where superficial deposits blanket the bedrock and good river sections may be separated from each other by extensive areas of forest and bog. It is a technique that has already been applied extensively further north in the Caledonian Front and should be regarded as an essential base for all detailed mapping to the south.

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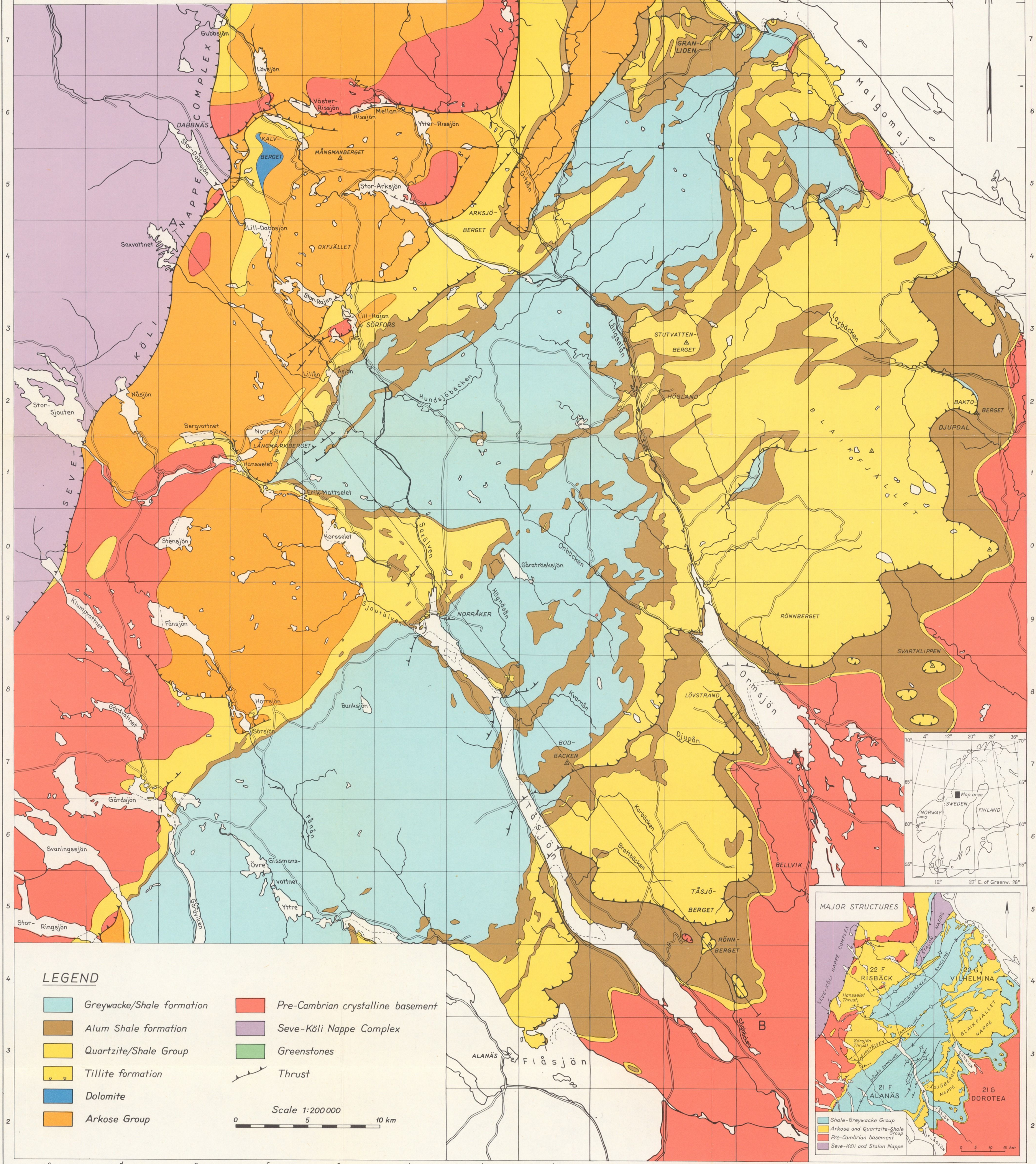
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GEOLOGICAL MAP OF THE CALEDONIAN FRONT FLÅSJÖN TO MALGOMAJ

NORTHERN JÄMTLAND, NORTH-WEST VÄSTERNORRLAND AND SOUTHERN VÄSTERBOTTEN
D.G.GEE 1970

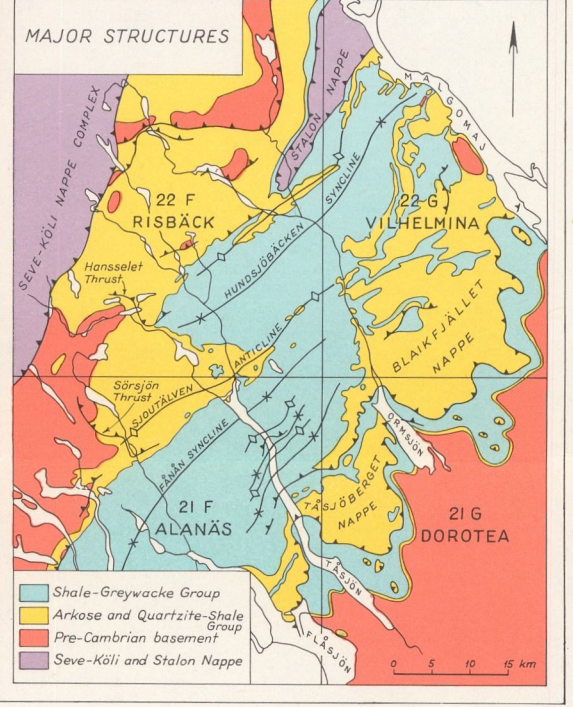
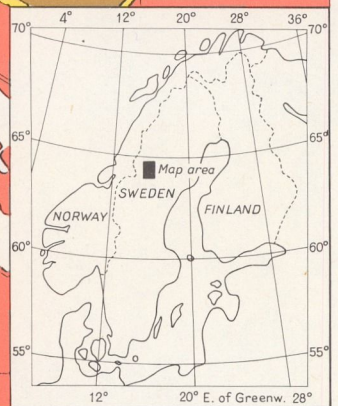
THE REGIONAL GEOLOGICAL CONTEXT OF THE TÅSJÖ URANIUM PROJECT, CALEDONIAN FRONT, CENTRAL SWEDEN.
D.G.GEE



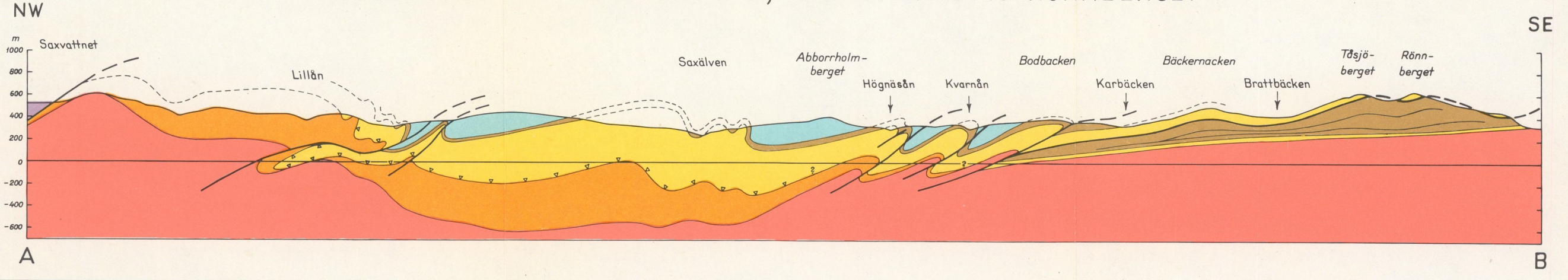
LEGEND

- Greywacke/Shale formation
- Alum Shale formation
- Quartzite/Shale Group
- Tillite formation
- Dolomite
- Arkose Group
- Pre-Cambrian crystalline basement
- Seve-Köli Nappe Complex
- Greenstones
- Thrust

Scale 1:200 000
0 5 10 km



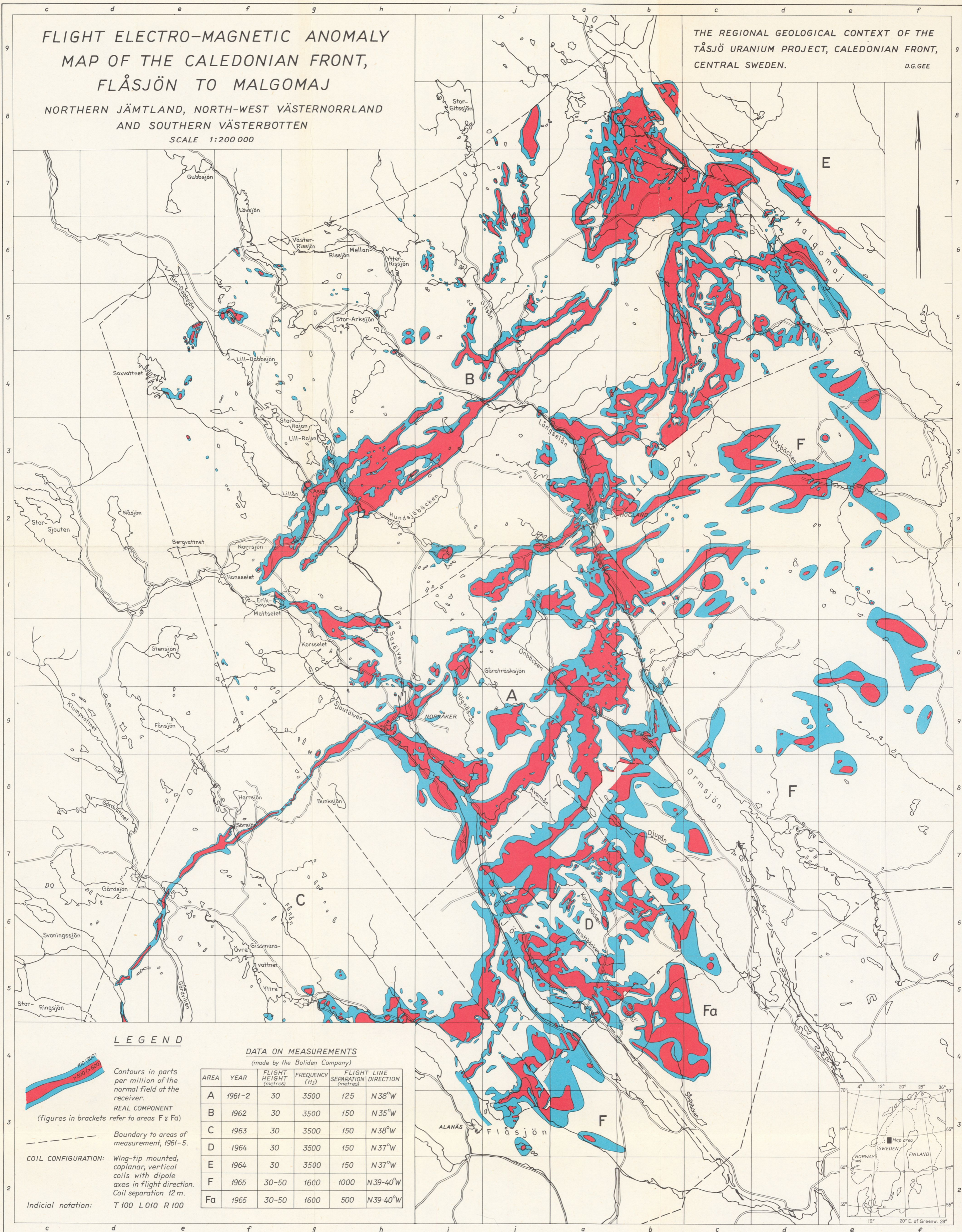
DIAGRAMMATIC SECTION A-B, SAXVATTNET TO RÖNNBERGET



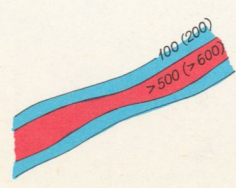
FLIGHT ELECTRO-MAGNETIC ANOMALY MAP OF THE CALEDONIAN FRONT, FLÅSJÖN TO MALGOMAJ

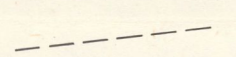
NORTHERN JÄMTLAND, NORTH-WEST VÄSTERNORRLAND
AND SOUTHERN VÄSTERBOTTEN
SCALE 1:200 000

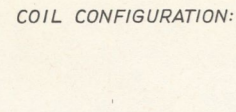
THE REGIONAL GEOLOGICAL CONTEXT OF THE
TÅSJÖ URANIUM PROJECT, CALEDONIAN FRONT,
CENTRAL SWEDEN.
D.G.GEE



LEGEND

 Contours in parts per million of the normal field at the receiver.
REAL COMPONENT
(figures in brackets refer to areas F x Fa)

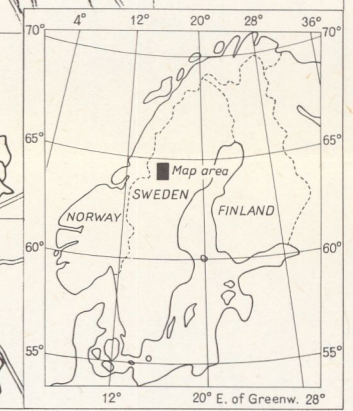
 Boundary to areas of measurement, 1961-5.

COIL CONFIGURATION:  Wing-tip mounted, coplanar, vertical coils with dipole axes in flight direction. Coil separation 12 m.

Indicial notation: T 100 L 010 R 100

DATA ON MEASUREMENTS
(made by the Boliden Company)

AREA	YEAR	FLIGHT HEIGHT (metres)	FREQUENCY (Hz)	FLIGHT LINE SEPARATION (metres)	DIRECTION
A	1961-2	30	3500	125	N 38°W
B	1962	30	3500	150	N 35°W
C	1963	30	3500	150	N 38°W
D	1964	30	3500	150	N 37°W
E	1964	30	3500	150	N 37°W
F	1965	30-50	1600	1000	N 39-40°W
Fa	1965	30-50	1600	500	N 39-40°W



PRISKLASS E

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