5. The Jotnian Mälar Sandstone of the Stockholm Region, Sweden

By

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ABSTRACT.—The Mälar sandstone is a fine- to medium-grained subarkose intercalated with beds of fine-grained and coarse arkose and gravelly layers. The field geology and some of the petrographical features of the sandstone exposed on Ekerö, Pingst, and Midsommar islands are described.

Introduction

The present paper is an account of some features of the Jotnian Ekerö (Mälar) sandstone, which was remapped during an investigation of the area in the summer of 1960. This project was originally intended to supply data for a comparison between Sub-Jotnian dolerite boulders in the sandstone conglomerates and the probably Jotnian dolerites described by one of the authors (R.G., 1961) from the Eskilstuna region, about 40 miles further WSW.

The areal distribution of the sandstone is given by the map (Fig. 1) and is confined to the islands Pingst and Midsommar, and the Rasta area on Ekerö Island. Additional smaller occurrences are mentioned by TÖRNEBOHM (1862, p. 16–17) from Adelsö and the SE part of Kurö Island. More distant localities include Vargholmen and Granholmen islands N of Eskilstuna, the Lake Båven area, and a problematic occurrence in Gripsholm Bay.

The Ekerön–Björkfjärden part of the Mälar sandstone has previously been described by A. E. TÖRNEBOHM in his comments on the Södertälje geological quadrangle (TÖRNEBOHM 1862) and by B. ASKLUND (1924), who made the area the subject of a special investigation. Other papers concerning the Ekerö sandstone area include works by P. GEIJER (1922, dealing, *inter alia*, with the petrography of the porphyry boulders found in the conglomerates), O. TAMM (1915, an investigation on sandstone erratics S of Lake Mälaren) and N. SUNDIUS (1948, comments on the geological map of the Stockholm region).

Setting and tectonics

The Mälar sandstone of the area rests on somewhat weathered Archaean (Svecofennian) gneiss and gneiss-granite displaying WNW directions of strike. These rocks are often veined and invaded by the late-Svecofennian Stockholm granite plus pegmatite and aplite dikes genetically related to the granite. In late

Svecofennian times there was also an intense migmatization and granitization, locally changing parts of the gneiss-granite into reddish pegmatite-rich migmatite.

As mentioned by earlier writers, the weathered parts of the Archaean rocks sometimes display a red colouring. Although the present investigation does not include systematic work on the weathering of the basement complex, a consideration of the tectonics and topography easily shows that the distribution of the areas previously considered to be pre-sandstone weathered implies a Sub-Jotnian chemical weathering of several scores of metres, which is in accordance neither with the actually observed contact relations nor with the lithology of the Mälar sandstone. Very tentatively it may be suggested that Pre-Cambrian or later weathering might be of importance in this area, which falls within the belt of Cambrian sandstone dikes (cf. MARTINSSON 1958) and in the neighbourhood of the Cambro-Silurian deposits of the Baltic. On Ekerö there are traces of a post-sandstone abrasion surface later than the tilting of the sandstone-bearing block. Apart from a weathered crust some decimetres or at most a few metres thick, the grey gneiss-granites (on Pingst) and the grey gneiss remnants in the red granite (on Ekerö) usually remain grey, even immediately below the actually observed contact toward the sandstone.

The basement/sandstone contact is exposed both on Pingst Island and in the NE part of the sandstone area on Ekerö. The latter outcrops prove that the sandstone is considerably more extensive than assumed by ASKLUND (1924, map), and do thus confirm SUNDIUS' suggestion (1948, p. 64) on the subject. Till-covered sandstone ridges can be traced morphologically from Rasta to the area W of Slinkbacka, where they disappear at one of the faults running parallel to the marked Yttersta–Närsta fault line.

The sandstone actually exposed on Ekerö is about 300 m thick, but the topographical features in the area W and NW of the outcropping strata suggest the presence of additional sediments wholly covered by Quaternary deposits. In all occurrences the sandstone has been faulted and tilted by Late-Jotnian or Post-Jotnian movements, so that the layers now display the following mean directions of strike and dip (cf. map, Fig. 2): Ekerö N 8°E, 42°WNW; Pingst N 15°W, 35°WSW; Midsommar N 75°W, 40° NNE. On Ekerö small fault lines traverse the sandstone parallel to its strike, dipping about 45°E and also vertically, then striking about N 75–90°W. None of the evident faults show more than a few inches' throw, and on the whole, as is proved by stratigraphical persistence, fail to alter substantially the original thickness of the sandstone. The faults striking NNE are sometimes lined by a thin phyllosilicate or iron oxide tarnish, whereas the vertical dislocations striking W are often tension cracks and occasionally carry prominent calcite or quartz veins. On Midsommar and especially Pingst traces of tectonic action are considerably more prominent. On Midsommar there are zones of intense faulting and brecciation as well as signs of some weak low-amplitude folding, the fold axes now dipping 45–60°N.

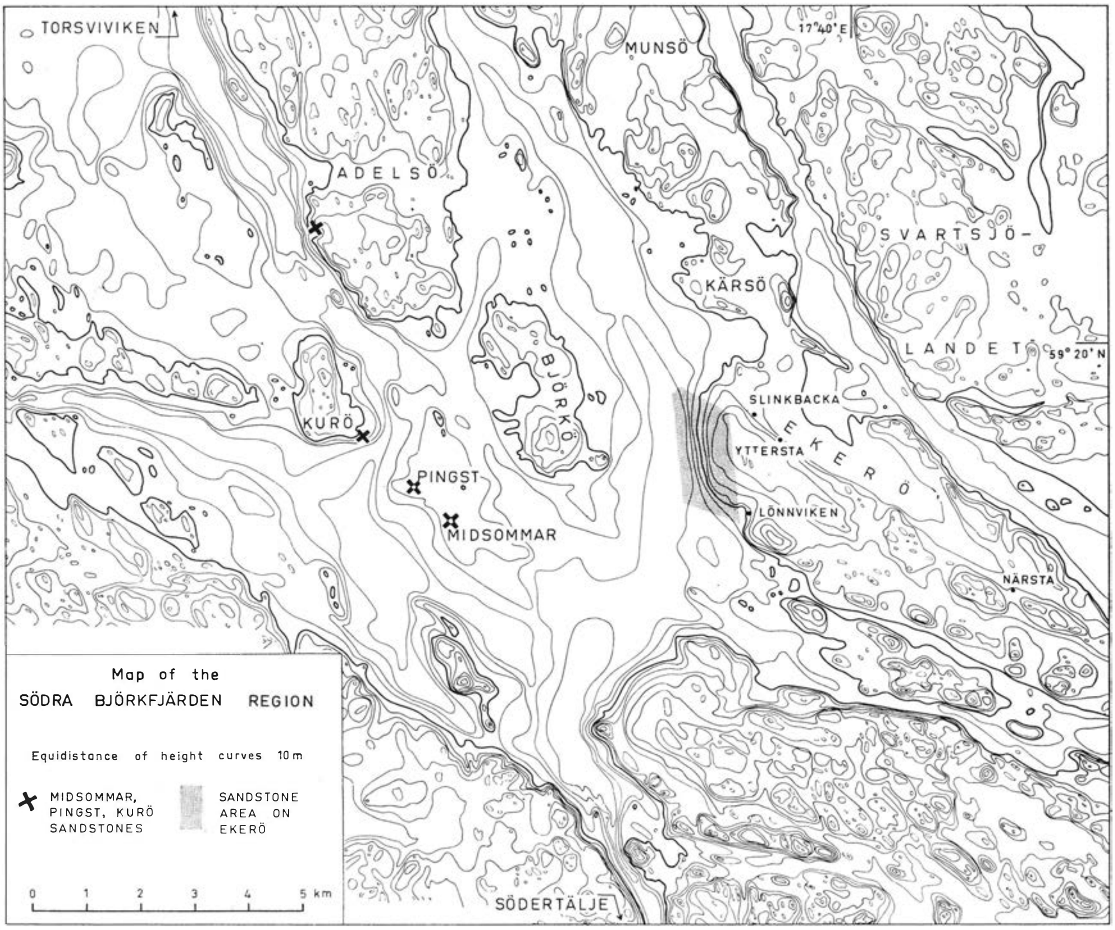


Fig. 1. General map of the Mälar sandstone area. Isobaths are interpolated from the data of sea chart no. 111, isohypses are in the E part of the map drawn acc. to the topographical map of Sweden, in the W part according to unpublished data courtesy Rikets Allmänna Kartverk.

The sharpstone-conglomerate on Pingst is fractured and dislocated by several faults belonging to the large Södertälje–Adelsö–Torsviviken fault zone (cf. maps, Figs. 1 and 2). Movements along this and subparallel fault lines, as well as other zones of dislocation striking predominantly WNW are responsible for the fracturing of the sandstone into several block areas and the tilting of these blocks, while the vectorially composite Mälarmården fault delimiting the Lake Mälaren basin in the south is evidently responsible for the downthrow of the sandstone area as a whole. A consideration of the bottom topography of Lake Mälaren and the tectonics of the exposed sandstone areas make a regionally important folding of the sandstone improbable, and suggest that the Jotnian sediments do not form a continuous cover on the bottom of S. Björkfjärden.

Petrographical features

GROSS LITHOLOGY.—The Mälar sandstone exposed on the islands investigated is a purple to yellowish-red, medium- to fine-grained, quartz-cemented subarkose (PETTIJOHN 1957) intercalated with layers of coarser arkose and pebbly gravel beds. In the Rasta area of Ekerö Island the sandstone sequence is initiated by a maroon, thoroughly silicified, ferruginous claystone resting on and filling cracks in a somewhat weathered, considerably tectonized, red, late-Svionian, migmatitic, pegmatite-veined granite with remnants of granitized grey gneiss. In the claystone there are veins and small patches of blue cryptocrystalline quartz partly showing relict banding, and angular fragments of wholly unweathered microcline-perthite, similar to the corresponding mineral of the granite. The claystone carries several horizons of small granite pebbles and gradually passes into siltstone and eventually fine-grained sandstone. About 5 ft above the base of the sandstone sequence these beds are succeeded by a coarse sharpstone conglomerate of an estimated thickness of more than 40 m. Strictly local red granite and minor amounts of pegmatite and reddish-grey gneiss-granite predominate (97 %), the poorly sorted boulder material containing blocks 50 cm and more across. In the upper parts of this basal conglomerate the boulders become increasingly better rounded and bedded and are interrupted by layers of arkosic sandstone (Fig. 3). The succeeding strata, which occupy the riparian outcrops of Ekerö show purple, as a rule cross-bedded (0.3–0.8 m thick sedimentation units) subarkoses with numerous gravelly layers of, in the bottom beds, arkosic and upwards increasingly subarkosic character. Laterally the pebbly zones cannot be followed for any considerable distance. Here there is some small-scale festoon cross-bedding of the finer sands, the gravelly layers partly forming channel-fillings eroding into the underlying sandstone. Generally the pebbles of the gravelly beds float within a matrix of medium sand and are not in contact with each other. There are also several coarse conglomerate layers, the uppermost well-defined beds of rounded and sub-rounded boulders being found in outcrop 5 and the corresponding stratigraphical levels, which are about 100 m above the base of the Mälar sandstone. Two horizons of fine, reddish-yellow, thin-bedded, platy, ripple-marked arkose interrupt the gravelly subarkoses in outcrops 3–15 and 25–26 (Fig. 2). These beds are particularly abundant in mud-cracks and thin clayey layers not more than a few millimetres thick. The change in lithology is abrupt at the uncovered upper boundary of the lower arkose bed. In the quarry (outcrop 14) and in the neighbouring parts of outcrop 15 a layer of considerably recrystallized quartzite, about 4 m thick, is sandwiched between beds of pebbly, quartz-cemented, subarkose sandstone.

The outcrops on Pingst Island are wholly made up of poorly sorted sharpstone conglomerates (Fig. 4) with infrequent layers of fine- to medium-grained, pebbly,

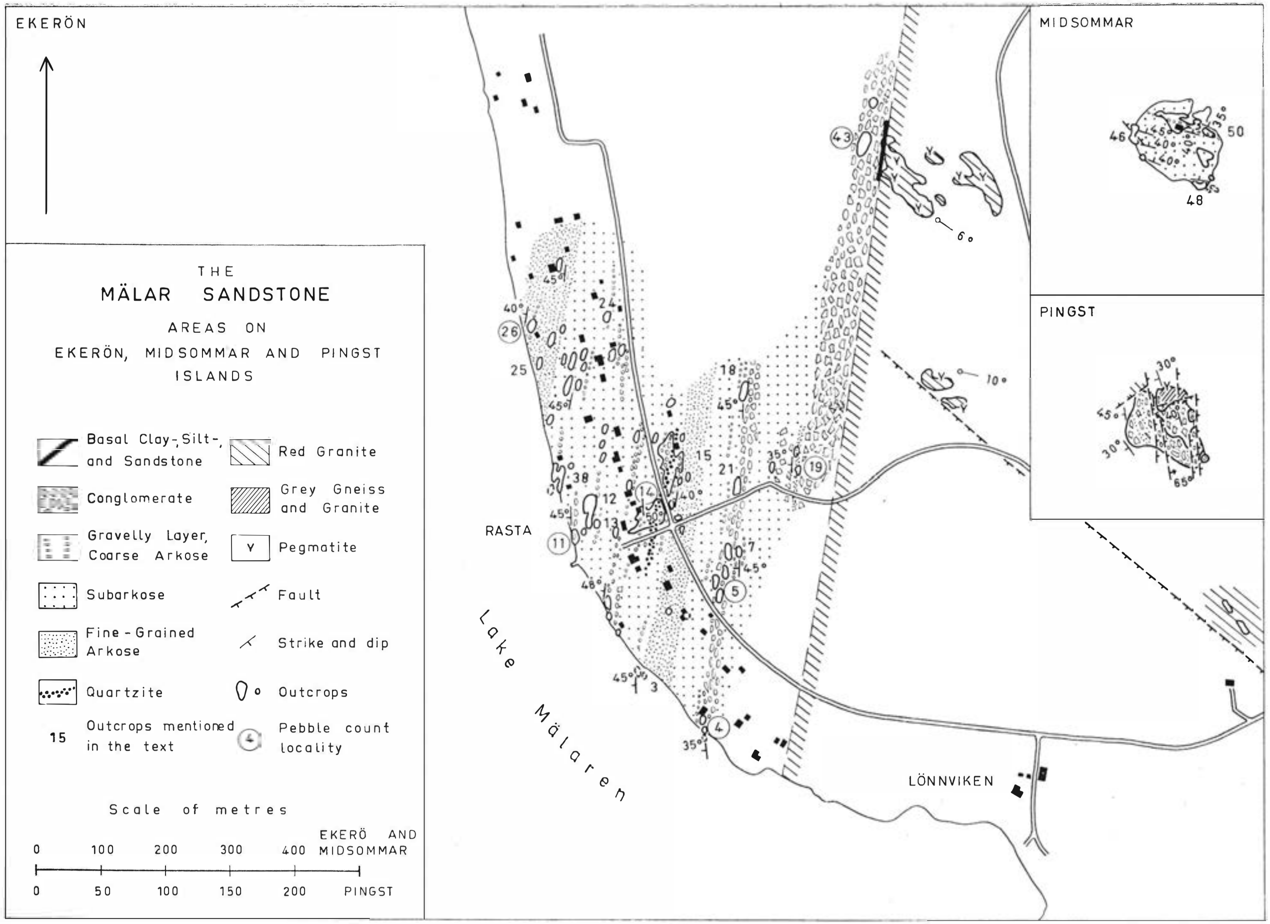


Fig. 2. Lithological map of the Mälar sandstone.

Fig. 3.

Fig. 4.

Fig. 3. Upper bedded layers of the basal conglomerate. Boulder, SW of Slinkbacka, Ekerö.
Fig. 4. Basal sharpstone conglomerate, Pingst Island.

quartz-cemented arkose (Fig. 5), varying considerably in dip and attitude. The actual contact toward the Svecofennian basement runs N 10°W and is exposed for a few metres near the northern shore of the island. The contact is distinct: polymict boulders embedded in poorly sorted angular arkose rest on considerably sheared and quartz-healed grey gneiss-granite with a few red pegmatite veins. Most of the basement/sandstone contacts (of $\pm$ EW attitude) are tectonical and marked by zones of quartz-healed, greyish-white, pseudoquartzite mylonite. On the northwesternmost tip of the island red weathered granite is in contact with the conglomerate, the contact (N 55°E, dip 30° toward NW) here also being a tectonic one. The boulder material of the sharpstone conglomerate consists of red granite and pegmatite(-quartz) plus grey gneiss-granite $>$ buff or greyish-white quartzite $\gg$ grey (garnet-)gneiss $>$ metabasite $>$ dolerite and porphyries. It thus mirrors the more diversified character of the bedrock in this part of the sandstone area and is in spite of its polymict character, considered to be of local provenance. The inter-boulder sand-gravel material is characteristically grey, the iron mineral on Pingst Island mostly being pyrite, as contrasted with the hematite (and limonite) of the other localities. Quartz, limonite, and calcite fill the post-cementation fractures.

As shown by the previous investigators Midsommar Island is built up of fine-grained, yellowish-red, subarkose sandstone (Fig. 6) with pebbly beds and coarse subarkose in the northernmost outcrops. Ripple marks (ripple index 1:7 to 1:12) are common, cross-bedding is comparatively scarce or absent

Fig. 5. Arkose bed in the sharpstone conglomerate of Pingst Island.

except for the (lowermost) outcrops on and just off the S and SE shores of the island, where asymmetrical ripple marks are also found in great abundance.

Sandstone fills a number of fissures in the precipitous cliffs of the south-eastern Kurö headland. The rock is, at first sight, difficult to distinguish from tectonical quartz-chlorite veins and friction debris filling cracks in the heavily tectonized basement Archaean. The sandstone layer mentioned by TÖRNEBOHM (1862, p. 17) rests on a ledge about 2 m above the waterline and is a crevasse filling less than 2 cm thick, from which the granite roof has been partly removed. The Kurö sandstone is greyish-green and consists of angular to subangular quartz and feldspar with a few larger rounded sandstone and quartz grains. Layered chloritic matrix is abundant (about 25 %) and often embays and corrodes the detritus grains, some of which are derived from the walls of the fissure. Secondary quartz outgrowths are common. There is evidence of post-depositional tectonic movement along the sandstone-filled cracks.

MINERAL COMPOSITION.—Detrital quartz is the main constituent of the Ekerö sandstone, averaging 65 % of the common subarkose. The mineral comprises single or composite crystal units with straight to strongly undulatory extinction, a feature which a survey of granite slides from the Stockholm region shows to have no significance as regards provenance. Single crystal quartz is predominant; the other types are multicrystal granite quartz, characteristically patchy vein quartz, a lesser amount of considerably deformed,

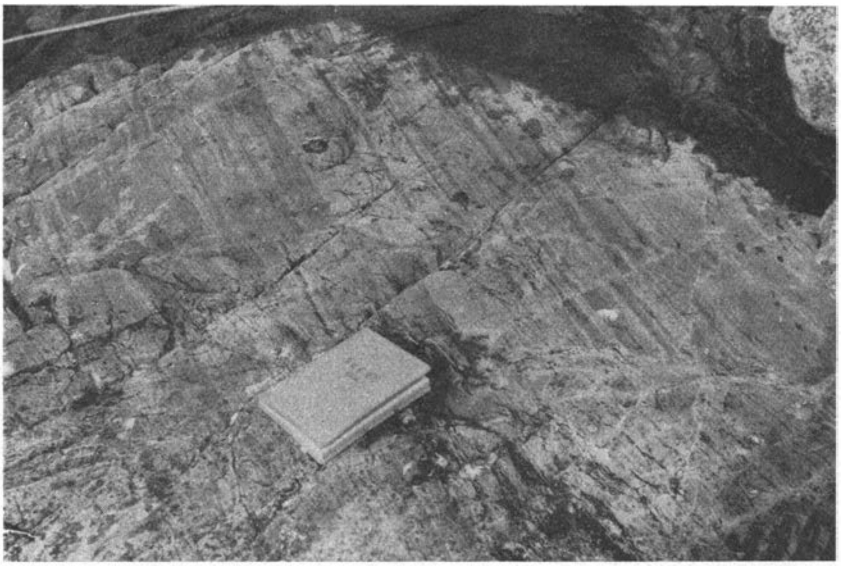


Fig. 6. Subarkose. Midsommar Island, outcrop 46.

probably Svecofennian, quartzite, and occasionally a minor number of chert grains. Part of the quartz is inherited from older sedimentary formations, since there are truncated cement rims and overgrowths. Böhm striation and lamellar deformation lineation are exceedingly common.

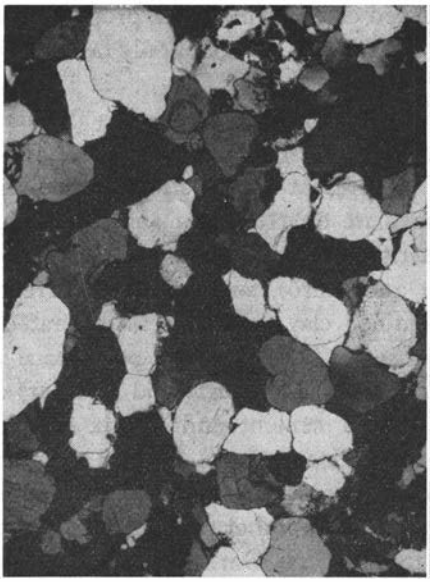
Feldspars include unaltered microcline or microcline-perthite, fresh to sericitized sodic plagioclase and turbid andesine. There are also some grains of untwinned potash feldspar, some of which were identified as orthoclase. Evidence of subaerial weathering is usually slight, though some of the plagioclase may be altered to a fine-scaly, iron-impregnated, clay mass. Many of the feldspar grains, especially the altered ones, are post-depositionally crushed, the débris having been moved into the interstices between the quartz grains. Detrital phyllosilicates average 0.3 % and consist of thin flakes of muscovite and chlorite. Biotite is almost wholly absent, except as strongly chloritized remains in gravel-size granite grains. Heavy minerals include epidote, sphene, zircon, garnet, ores, apatite, tourmaline, and amphibole. Epidote is easily the most common heavy mineral of the gravelly sandstones, its content diminishing rapidly in passing toward finer grades. Sphene, zircon, apatite, garnet, hematite, and magnetite are almost ubiquitous, while amphibole, and tourmaline number a few stray grains only. Detrital ores, zircon, and sphene are sometimes distinctly placered, which is especially true of the fine-grained sandstones (Fig. 11).

Sand- and gravel-size rock fragments include feldspar-quartz-gneiss and granite débris, deformed quartzite and a number of Post-Svecofennian rocks including dolerite, porphyries, granophyric quartz-feldspar intergrowths, reddish-brown or deep blue-green chert, sericite-matrixed sandstone, mature orthoquartzite, shale, clay galls, and deformed clay laminae. The prophyries and dolerites are often of a rather supracrustal habit and are commonly heavily iron-impregnated.

The petrology of the Sub-Jotnian porphyries and dolerites has previously been discussed by a number of authors including P. GEIJER (1922) and B. ASKLUND (1924), and is not a subject of the present investigation. A trachyhyaline, heavily hematite-drenched, intermediate quartziferous volcanite rich in quartz-chlorite amygdules, however, merits special mention.

Matrix minerals are chlorite (Pingst and Kurö), sericite (all occurrences, particularly Midsommar) and an unidentified clay substance incorporated in and masked by the hematite cement (Ekerö). Elimination of pore space was accomplished by cementation, pressure solution (of quartz and feldspar) and deformation (mainly feldspar). The sum of cement and matrix (Table 1, column 18), related to the packing density of KAHN (1955), may be considered a rough measure of post-depositional deformation. The amount of cement plus matrix tends to be reversely proportional to the number of contacts per grain, which is always larger than the 0.85 found by A. GAITHER (1953) in undeformed sandstones. No correlation could be found between grain-size, total quartz content or stratigraphical position as against the amount of cement plus matrix elimination. Neither is there any apparent relation between pressure solution and the amount of clay matrix now present (HEALD 1955, FOLK 1960, p. 60). However, coarse beds tend to be relatively poor in quartz cement and rich in hematite, which may depend either on the original presence of a prominent clay mode, or the early deposition of abundant iron oxides. Identifiable matrix and cement are lowest in the quartzite layer (outcrops 14–15), which abounds in intricately crenulated quartz-grain boundaries (Fig. 9). Pressure solution phenomena are found at the contacts between quartz grains in most of the Mälar sandstone, and may develop into rudimentary microstylolitic seams orientated roughly parallel to the original bedding surfaces. The quartz cement is of at least two generations, occasionally showing minute quartz crystals grown from the surface of quartz detritus and enclosed in compact cement. Hematite is the second most abundant cement mineral and is responsible for the red and purplish general colour of the sandstones. Reduction has occurred along dislocation zones, cracks and around minute detrital inclusions of shale, and gives the rock a yellow hue. Recent weathering produces a yellowish-grey rind of about 1 cm thickness with accumulations of iron oxide in the zone separating this layer from the unaltered sandstone.

Calcite is virtually absent in all the thin-sections examined, except the coarse gravelly arkose bed found just below the conglomerate zone of outcrop 5. Some of the calcite is apparently detrital, but the calcite grains are easily deformed and surrounded by large secondary outgrowths replacing the hematite matrix. In these slides calcite is also seen to replace some heavily sericitized and saussuritized plagioclase grains and corrodes the margins of detrital quartz,



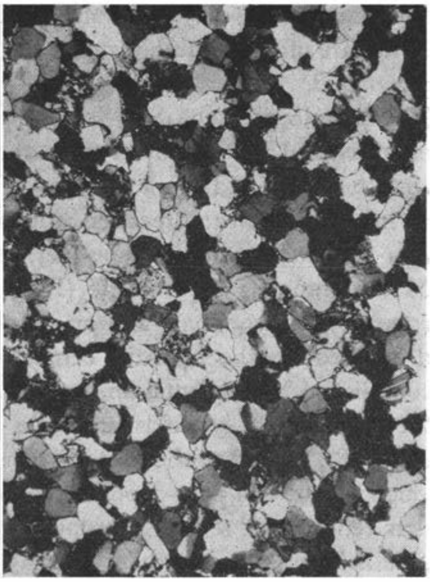


Fig. 7. Fig. 8.

Fig. 7. Ekerö subarkose. Outcrop 13. + nic., 25 ×.

Fig. 8. Fine-grained subarkose. Outcrop 19, Ekerö. + nic., 25 ×.

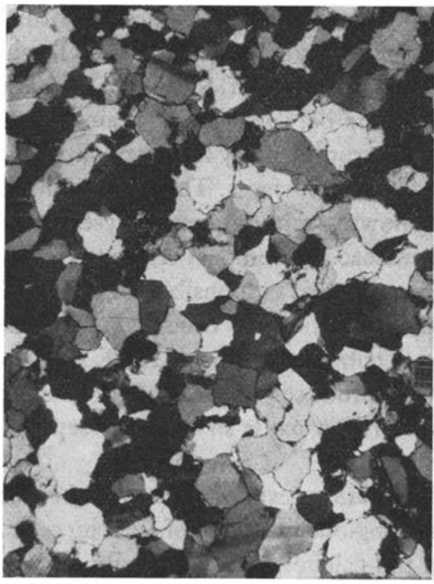


Fig. 9. Fig. 10.

Fig. 9. Quartzite. Outcrop 14, Ekerö. + nic., 25 ×.

Fig. 10. Fine-grained arkose, lower arkose bed, outcrop 3, Ekerö. + nic., 25 ×.

Table 1. Mineral composition of the Mälar sandstones (vol. %).

Outcrop and specimen No.	Rock	Granular quartz	Cement quartz	Total quartz	Potash feldspar	Plagioclase [a]	Total detrital feldspar	Supracrustal and hypabyssal rocks	Detrital ores	Ore cement	Other cement, mainly authigenic feldspar	Sericite matrix	Muscovite	Chlorite	Calcite	Heavy minerals minus ores	Total cement and matrix
	EKERÖ:																
38	Subarkose	66.9	10.2	77.1	9.6	4.2	13.8	3.6	0.6	3.6		0.9		—	0.2	0.2	14.7
13	Subarkose	64.3	12.9	77.2	10.2	3.1	13.3	2.8	0.2	5.3		0.7	0.1	0.3	—	0.2	18.4
12	Subarkose	71.4	8.6	80.0	8.9	2.9	11.8	2.9	0.3	3.0	0.7	1.0	0.1	+	—	0.2	13.3
19	Fine-grained subarkose	61.4	12.3	73.7	8.5	5.2	13.7	3.3	0.6	8.6		—	+	—	—	0.1	20.9
14	Quartzite			88.6	6.4	2.5	8.9	1.0	0.4	1.5	—	--	0.2	—	—	0.4	~5
15	Fine-grained arkose			71.9	15.6	8.8	24.4	1.1		2.7		—	0.1	0.3	—	0.3	
3	Fine-grained arkose	60.2	3.4	63.6	18.8	10.0	28.8	1.0	0.5	1.2	—	3.4	+	0.2	0.3	0.8	8.1
25	Fine-grained arkose	61.2	8.7	69.9	12.8	6.1	18.9	2.0	1.8	5.8		0.8		0.2	—	0.7	15.4
7	Gravelly arkose	45.1	1.1	46.2	11.7	13.7	25.4	3.8	0.4	12.6	1.3	0.4	0.2	0.2	7.8	1.6	15.4
21	Coarse arkose	55.5	1.5	57.0	12.8	12.8	25.6	3.3	0.2	9.1		2.4	—	0.4	1.5	0.3	13.0
18	Coarse arkose			63.7	14.7	13.1	27.8	1.9	0.1	0.5	1.5	3.1	+	0.7	0.2	0.4	~10
24	Gravelly lithic sandstone	60.4	2.2	62.6	6.8	4.4	11.2	20.7	0.5	1.6	2.0	0.3	+	0.9	—	0.2	6.9
	MIDSOMMAR:																
46	Subarkose	73.7	2.7	76.4	10.2	2.5	12.7	1.5	0.1	1.2	2.0	5.8	0.1	0.2	—	0.1	11.7
48	Subarkose	71.2	8.3	79.5	13.8	1.6	15.4	1.5	0.2	0.1	0.8	2.1	0.1	+	—	0.3	11.3
50	Coarse-grained sandstone	75.0	2.0	77.0	8.1	2.0	10.1	4.6	0.4	0.6	—	7.2	+	0.1	—	+	9.8
	PINGST:																
51	Arkose bed in sharpstone conglomerate			55.9	15.0	11.9	26.9	3.5	0.4	0.2	1.1	4.8		5.5[b]	—	1.6[c]	

[a] Partly altered into sericite, zoisite, zeolites and clay minerals. [b] Mainly matrix.
[c] Including 0.9 % pyrite cement.

often attacking these crystals along the hematite-covered or vacuole-studded rims between the detrital grains and the secondary outgrowths. Authigenic, untwinned, clear or hematite-dusted potash feldspar is rather common, as are secondary rims around detrital feldspar grains. The distinction between authigenic feldspar and detritus is, however, somewhat equivocal, since there is often some recrystallization and healing of the post-depositionally crushed detrital feldspar grains. Some of the Ekerö subarkoses contain a zeolitic cement mineral that has a refraction index of 1.50 – 1.51, $n_Z - n_X$ 0.011, $c \wedge Z$ about 25°, two directions of perfect cleavage ($\| c$) with an intercleavage angle of $89 \pm 2°$ bisected by one of the optical planes. The optical axis angle is moderate, but could not be measured exactly because of the small size, inhomogeneous extinction and hematite flecks of the mineral. We were not successful in sepa-

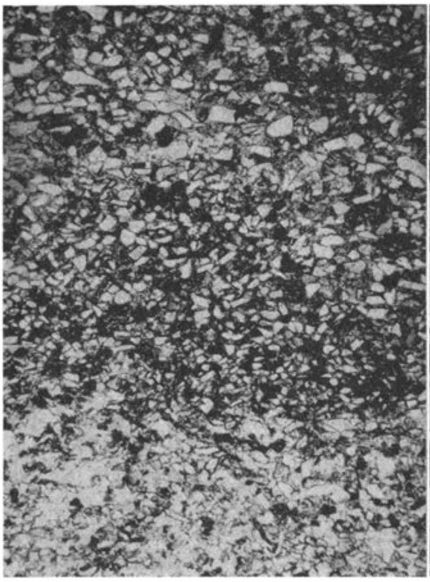
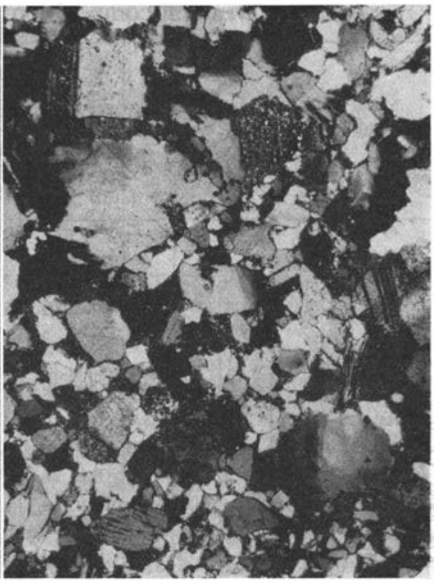



Fig. 11. Fig. 12.

Fig. 11. Basal siltstone, outcrop 43, Ekerö. The tendency for heavy minerals placering is noticeable, cement is quartz and hematite. || nic., 25 ×.

Fig. 12. Matrix arkose of the Pingst Island conglomerate. Roundness and sorting are poor, feldspar is very prominent. + nic., 25 ×.

rating the zeolite for X-ray identification, but the optical properties seem to fit laumontite best. Small scaly crystals of the same mineral are also found to replace plagioclase.

Törnebohm (1862) mentions the occurrence of vein laumontite in the Ekerön sandstone. The mineral is here in analogy with the laumontite of the widespread fissure occurrences in the Central Swedish Archaean (Wiman 1930, p. 89–96) of a hydrotermal origin. According to Deffeyes (1959) laumontite has never been reported from a sedimentary rock that has not been subjected to high temperatures. It is either hydrothermal or belongs to the zeolite metamorphic facies (Fyfe, Turner, Verhogen 1958).

Table 1 gives the mineral proportions of the Ekerö sandstones obtained by 1000-point counts of thin-sections. In this table granite débris has been included with the constituent minerals, a classification partly due to the difficulty of defining a boundary, but which also serves to bring out the arkose tendency of the granite-pebble carrying coarse sandstones. The only rocks in Table 1 with large amounts of composite quartz-feldspar grains are 7, 18, and 21, where the volume percentage of these grains is between 10 and 20. The (Sub-Jotnian) rock fragments of column 9 include porphyries, dolerites, claystone, chert. and sandstone, while the deformed, probably Svecofennian, quartzite was grouped with quartz.

Table 2. Composition of the pebble material in conglomerates and gravel beds of the Mälar sandstone.

Outcrop No.	Number per cent								
	Granite and gneiss	Garnet gneiss	Pegmatite and feldspar	Quartz	Porphyry etc.	Basic igneous roocks	Sandstone and chert	Claystone and schist	Sum of porphyries and sand-stone
EKERÖ									
19	52	–	25	24	–	2	4	2	4
4	72	–	14	6	4	2	2	–	6
5	74	–	19	5	2	+	+	–	2
14	10	1	18	32	14	1	15	9	29
11	26	1	8	22	16	4	5	18	21
26	29	–	4	22	29	1	5	10	34
MIDSOMMAR									
50	17	+	21	40	9	+	12	1	21

Outcrop numbers refer to Fig. 2, counted grain-size fractions are 5–15 cm for localities 4 and 5, 0,7–3 cm for the other localities. The number of pebbles counted is 54 at loc. 4, 100–120 at the other localities.

Pebble counts have been made on several conglomerate and gravel beds, the results summarized in Table 2 demonstrating a pronounced tendency for the granite material of the upper beds to be overwhelmed by Sub-Jotnian supracrustals and hypabyssals represented by the sum values of column 10. A similar tendency is also found in the thin-sections, where gravel- and sand-size grains are on average 16 % granite as against 3.5 % other rock fragments in the lower gravelly beds (outcrop 18 etc.), as contrasted with 20.7 % others and about 4 % granite in the upper coarse arkose of outcrop 24. Since the percentages of rock-fragments and the grain size of the gravel are about the same at both localities and the frequency of gravel beds decreases upwards, this indicates a levelling or burying of the local granite-gravel supplying sources.

The conglomerate matrix of the basal conglomerates on Pingst and Ekerö islands is a poorly sorted and rounded gravelly arkose (Fig. 12). In the upper conglomerate horizons of Ekerö (outcrops 4, 5, 7, 18, 21) the matrix is a subarkose of the common type. Here the rounding of the gravel and stones is relatively good and the boulders are in touch with each other.

SIZE DISTRIBUTION.—The apparent long-axis diameters have been measured on 200 grains per thin-section (400 in thin-section 7), and the statistics derived from the first two moments corrected for the sectioning effect by Krumbein's approximative formula (KRUMBEIN 1935) have been calculated (Table 3). Figs. 13 and 14 give the uncorrected cumulative diagrams, for which the median values and coefficients of sorting ($\sqrt{Q_3/Q_1}$) will be found in Table 3. These data fail

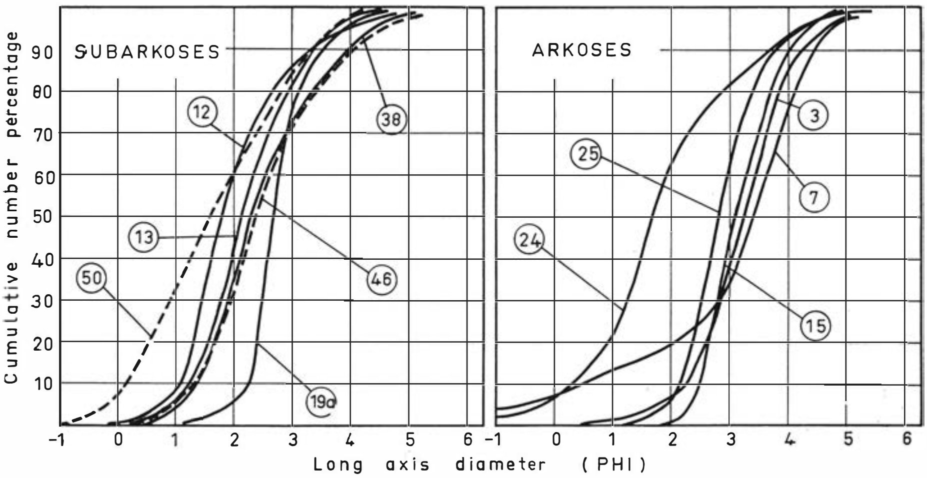


Fig. 13. Grain-size distribution in Mälar sandstone subarkoses and arkoses. Specimen numbers are those found in Table 1.

to give the actual size, but since they are used for the purpose of comparison, no corrections were introduced. The sorting in the different well-defined rock groups (subarkoses and fine-grained arkoses) is thus rather uniform, and usually fairly good. The size inhomogeneity apparent in the field is, however, rather a matter of inter-bed variation between the gravelly layers and the regular subarkoses than a case of poor sorting within the individual subarkose

Table 3. Grain-size coefficients of the Mälar sandstones (number frequency data).

Outcrop and specimen No.	Rock	M_a (mm)	σ_a	M_d (mm)	So	Orientation of thin-section relative to bedding
12	Subarkose	0.36	0.18	0.29	1.45	Perpendicular
13	Subarkose	0.33	0.17	0.24	1.42	Perpendicular
38	Subarkose	0.28	0.15	0.22	1.56	Random
46	Subarkose	0.29	0.18	0.21	1.57	Perpendicular
19	Fine-grained subarkose	0.20	0.05	0.16	1.20	Perpendicular
50	Coarse subarkose	0.55	0.39	0.33	1.86	Random
3	Fine-grained arkose	0.15	0.09	0.10	1.40	Random
15	Fine-grained arkose	0.16	0.05	0.12	1.35	Perpendicular
25	Fine-grained arkose	0.19	0.06	0.14	1.32	Parallel
21	Coarse arkose	0.68	0.57	0.41	2.60	Perpendicular
7	Gravelly arkose	0.38	0.73	0.09	1.70	Perpendicular
24	Coarse lithic sandstone	0.54	0.64	0.32	1.65	Random

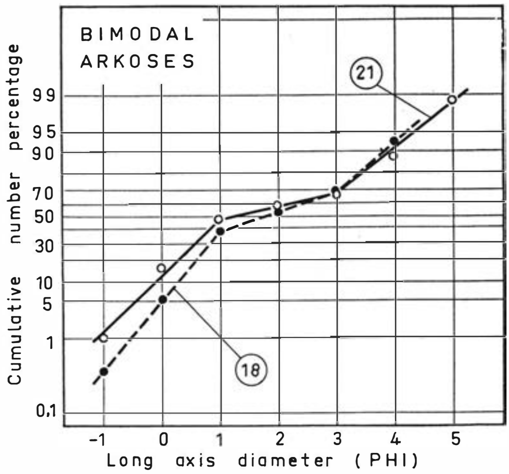


Fig. 14. Grain-size distribution in bimodal Mälar sandstone arkoses.

beds. Some of the coarse arkoses show a clearly bimodal size distribution, the break occurring between uncorrected $\theta = 1$ and 3 (0.5–0.12 mm) (cf. Figs. 14 and 15). In comparison with the Jotnian Satakunta sandstones of Finland, for which rocks grain size data have been published by A. SIMONEN and O. KOUVO (1955), the bulk of the Mälar sandstones shows a higher degree of maturity, which applies both to sorting and mineral composition.

ROUNDNESS.—The roundness of 200 grains per thin-section was measured visually by comparison with POWERS' (1953) charts. The measurements show a general maximum in the rounded-subrounded (R.I. = 0.45–0.55) classes. There is a pronounced correlation of grain size and roundness in most of the slides investigated. In some of the coarse bimodal-grain-size arkoses the distribution of roundness shows a maximum for the coarse quartz mode in the rounded and for the matrix quartz detritus in the subangular-subrounded classes. Reverse roundness relations are, however, found in some of the angular-pebble beds on Ekerö, which indicates an addition of coarse local fractions to the better rounded fine and medium material. Mineral versus roundness correlation was found to be perceptible in the two slides from Ekerö investigated for this feature. The quartz plus chert plus quartzite detritus has a maximum (51 %) in the rounded class, while the sum of other rock fragments and feldspar shows a rather even spread of 86 % of the measured grains over the subangular, subrounded, and rounded classes. This feature is partly due to the ease of feldspar fracturing along cleavage planes, but may also indicate different average transportation distances for these two mineral groups.

The fine-grained arkoses are on the average somewhat less rounded, but have better concentrated roundness maxima than the common Ekerö subarkose. No correlation between roundness and stratigraphical level was found in the latter type of sandstone.

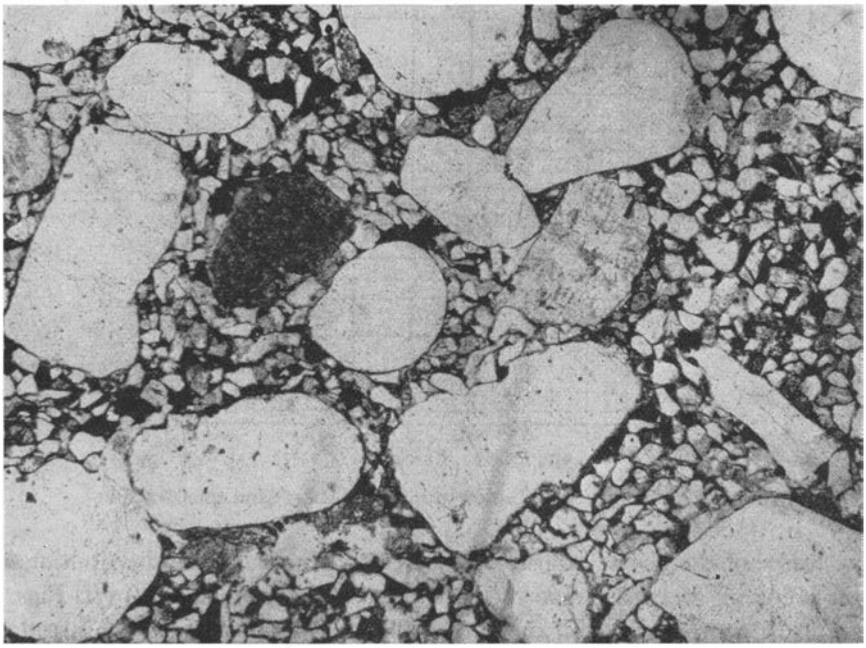


Fig. 15. Ekerö arkose showing polymodal grain-size and roundness distribution. Cement is hematite, the dark large grain is a fine-grained dolerite. Outcrop 18. || nic., 25 ×.

Provenance and manner of deposition

In his paper of 1922 P. GEIJER remarked upon the absence in the Ekerö sandstone of garnet-gneiss rocks from the territory bounding Lake Mälaren in the south. ASKLUND (1924) concluded that a source area of porphyries, akin to those found in the sandstone conglomerates, is on the lake bottom to the NW of the Rasta area on Ekerö. Though cross-bedding is common in the Ekerö subarkose, the moss cover and small size of the outcrops prevented us from measuring more than seven beds, four dipping toward W–SW, two toward S–SW, and one falling within the N–NE sector. Imbricate structures indicate a general direction of transportation toward SW. The measurement on the bedding planes of 114 long-axis projections of the intact-framework conglomerate of outcrop 5 gave the distribution shown in Fig. 16, whereas thin-section measurements of sand grains were not conclusive. These data, though admittedly scarce, confirm in a general fashion the transportation vectors assumed by the above investigators. Several of the mineralogical and textural features mentioned in the preceding text, indicate a polysource origin of the sandstones and the admixture of local immature material to sands showing marks of a considerable abrasion history. The disrupted framework, thickness, and poor sorting of the basal sharpstone conglomerates point toward a talus

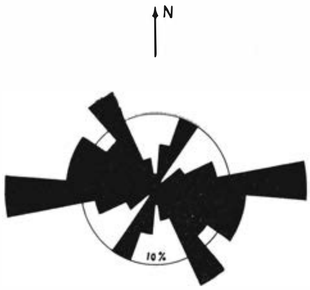


Fig. 16. Long axis orientation of the cobbles in the upper Ekerö conglomerate (outcrops 5–7).

origin of these beds (cf. ASKLUND, 1924, p. 310). The high percentage and slight weathering of feldspar and rock fragments, the abundance of gravelly beds and cross-bedding, and the overall trend toward finer types of low and uniform bedding thickness indicate, besides the earlier stressed arid climatic conditions (ASKLUND 1924, p. 310–313), a considerable morphological relief and deposition by running water in a successively filling basin with episodes of subaqueous sedimentation. The relatively good sorting and mineral immaturity of the fine-grained arkoses may be due to the deposition in littoral zones of winnowed, size-resorted outwash. This idea is lent further support by the frequency of ripple-marks and mud-cracks in these particular beds. Dreikanters reported by ASKLUND prove that aeolian action was of some importance. However, considering the absence of higher Jotnian vegetation this may be expected to be the case under a variegated range of climatic conditions and can, *per se*, except demonstrating a supraaquatic environment, hardly be taken to indicate the main agent of transportation.

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References

BGIU = Bulletion of the Geological Institution(s), Up(p)sala.
GFF = Geologiska Föreningens i Stockholm Förhandlingar.
SGU = Sveriges Geologiska Undersökning.

ASKLUND, B., 1924: Mälarporfyrernas läge och sandstensområdet på Ekerön. *GFF*, *46*, 301–315.

DEFFEYES, K. S., 1959: Zeolites in sedimentary rocks. *J. Sed. Petrology*, *29*, 602–609.

FOLK, R. L., 1960: Petrography and origin of the Tuscarora, Rose Hill and Keefer formations, Lower and Middle Silurian of eastern West Virginia. *J. Sed. Petrology*, *30*, 1–58.

FYFE, W. S., TURNER, F. J., VERHOGEN, J., 1958: Metamorphic reactions and metamorphic facies. *Geol. Soc. Amer.*, Memoir 73.

GAITHER, A., 1953: A study of porosity and grain relationships in experimental sands. *J. Sed. Perology*, *23*, 180–195.
GEIJER, P., 1922: Problems suggested by the igneous rocks of Jotnian and sub-Jotnian age. *GFF*, *44*, 411–443.
GORBATSCHEV, R., 1961: Dolerites of the Eskilstuna region, Eastern Central Sweden. *SGU*, Ser. C, No. 580.
HEALD, M. T., 1955: Stylolites in sandstones. *J. Geol.*, *63*, 101–114.
KAHN, J. S., 1956: Analysis and distribution of the properties of packing in sand-size sediments, pt. I. *J. Geol.*, *64*, 385–395.
KRUMBEIN, W. C., 1935: Thin-section mechanical analysis of indurated sediments. *J. Geol.*, *43*.
MARTINSSON, A., 1958: The submarine morphology of the Baltic Cambro-Silurian area. *BGIU*, *38* (1960), 11–35.
PETTIJOHN, F. J., 1957: Sedimentary rocks. 2nd ed., Harper & Bros., New York.
POWERS, M. C., 1953: A new roundness scale for sedimentary particles. *J. Sed. Petrology*, *23*, 117–119.
SIMONEN, A. and KOUVO, O., 1955: Sandstones in Finland. *Bull. Comm. Géol. de Finlande*, No. 168, 57–87.
SUNDIUS, N., 1948: Beskrivning till berggrundskarta över Stockholmstrakten. *SGU*, Ser. Ba, No. 13.
TAMM, O., 1915: Några iakttagelser angående Mälarsandstenen. *GFF*, *37*, 265–275.
TÖRNEBOHM, A. E., 1862: Några ord till upplysning om bladet "Södertelge". *SGU*, Ser. Aa, No. 4.
WIMAN, E., 1930: Studies of some Archaean rocks in the neighbourhood of Upsala, Sweden, and of their geological position. *BGIU*, *23* (1932), 1-170.