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Cover: A view from the southeastern part of Utö showing a typical locality in the investigated area.
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ABSTRACT

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Erratics of sedimentary rocks of Middle Proterozoic to Early Palaeozoic age occur in the Stockholm Archipelago east of the Central Swedish mainland. The erratics were evidently accumulated during the latest deglaciation in Late Weichselian times. They are tentatively referred to three sedimentary units. Unit 1 (Lower to Middle Riphean) and unit 2 (Upper Riphean and Vendian) comprise the informally introduced Söderarm formation. Unit 3 includes Lower Cambrian sandstone and siltstone of the File Haidar Formation, as well as Ordovician limestones of the Oeland, Viru, and Harju Series. Erratics of unit 1 are abundant and consist of fine to medium grained reddish sandstones. They are inferred to represent small outliers throughout the Stockholm Archipelago as well as in the Åand Sea. Erratics of unit 2 are also abundant and consist mainly of feldspar rich sandstones. This unit is suggested to reflect a regional tectonic event that occurred about 900–1,000 Ma. Shale erratics, probably Late Riphean to Vendian in age, are assigned to unit 2 and are sparsely distributed in the Stockholm Archipelago and on the Åland Islands. The shale occurs in basins in the Åland Sea and in the Bothnian Sea. Erratics of Lower Cambrian siltstone and sandstone from unit 3, presumably belonging to the *Holmia inusitata* and *Holmia kjerulfi* group Zones, are sparsely distributed in the investigated area. *In situ* occurrences could be expected in certain sheltered positions in the Stockholm Archipelago and in the Åland Sea. Erratics of Ordovician limestone are abundant in the northern part of the Stockholm Archipelago and sparsely distributed in the southern part. Based on the recorded erratics a rock sequence may be inferred to comprise the Ordovician *"Obolus"* conglomerate, Latorp, Lanna, and Holen Limestones of the Oelandian; Segerstad Limestone of the Viruan; and Baltic limestone of the Rakvere, Nabala, and Pirgu Stages of the Harjuan. Dolomitic Baltic limestone probably occupies areas in the Åland Sea and Bothnian Sea. Glacial striae show a direction of ice movement from the northwest in the southern part of the Stockholm Archipelago, and on the Uppland mainland. In the northern part of the Stockholm Archipelago the youngest striation is from the north.

Key words: Erratics, basin development, Weichselian deglaciation, Riphean, Vendian, Cambrian, Ordovician, Stockholm Archipelago, Åland Sea.

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Introduction

The Meso- and Neoproterozoic to Lower Palaeozoic sedimentary sequence in the Stockholm Archipelago and the Åland Sea occupies an intermediate location between the two main basins of the Baltic Proper and the Bothnian Sea (Figs. 1 and 2). However, data from this area are scanty because most of the sedimentary sequence present is in offshore positions. Neither major outcrops nor drillings have supplied any information for the reconstruction of the sedimentary sequence. The only data so far is from onshore occurrences of erratics and fissure fillings of sandstone. Seismic investigations have provided indirect information on the offshore sequences in the Åland Sea and in the archipelago areas.

One of the aims of this investigation is to reconstruct the sedimentary rock sequences based on the erratics. The investigation is hampered because it is likely that abrasion by Pleistocene land ice has selectively eliminated soft lithologies among the erratics. Furthermore, the sedimentary sequence most likely was subject to extensive erosion before the Pleistocene.

The lack of fossils, especially in the Meso- and Neoproterozoic parts, hampers the dating of the sequence. This circumstance makes it necessary to rely on evidence such as lithological composition, which must be regarded as unreliable, and comparison with coeval sedimentary sequences. Such procedure might be justified by the fact that sedimen-

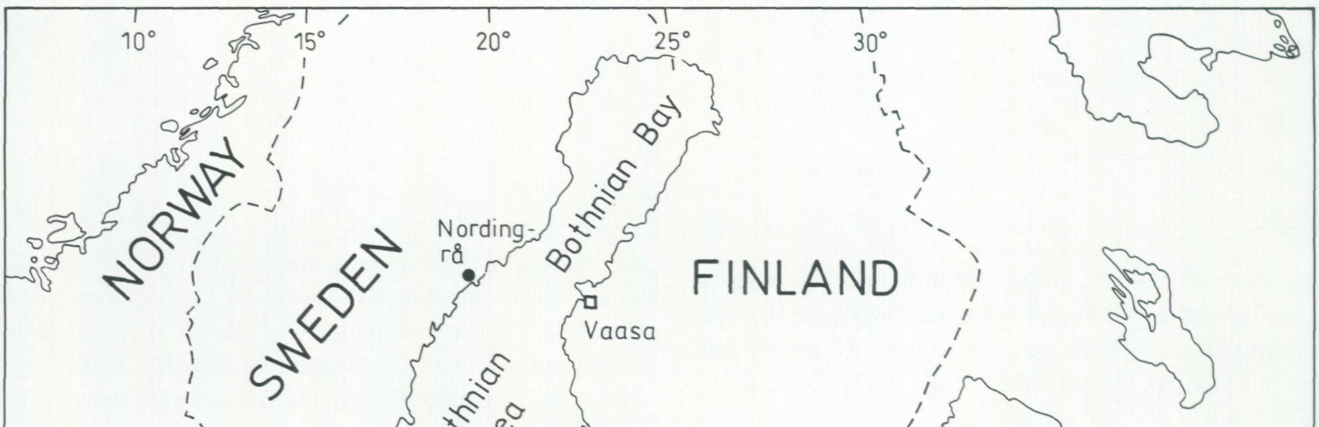

Fig. 1. Regional location of east central Sweden, Åland Islands, and the Baltic Proper. Black dots denote areas of geological importance mentioned in the text.

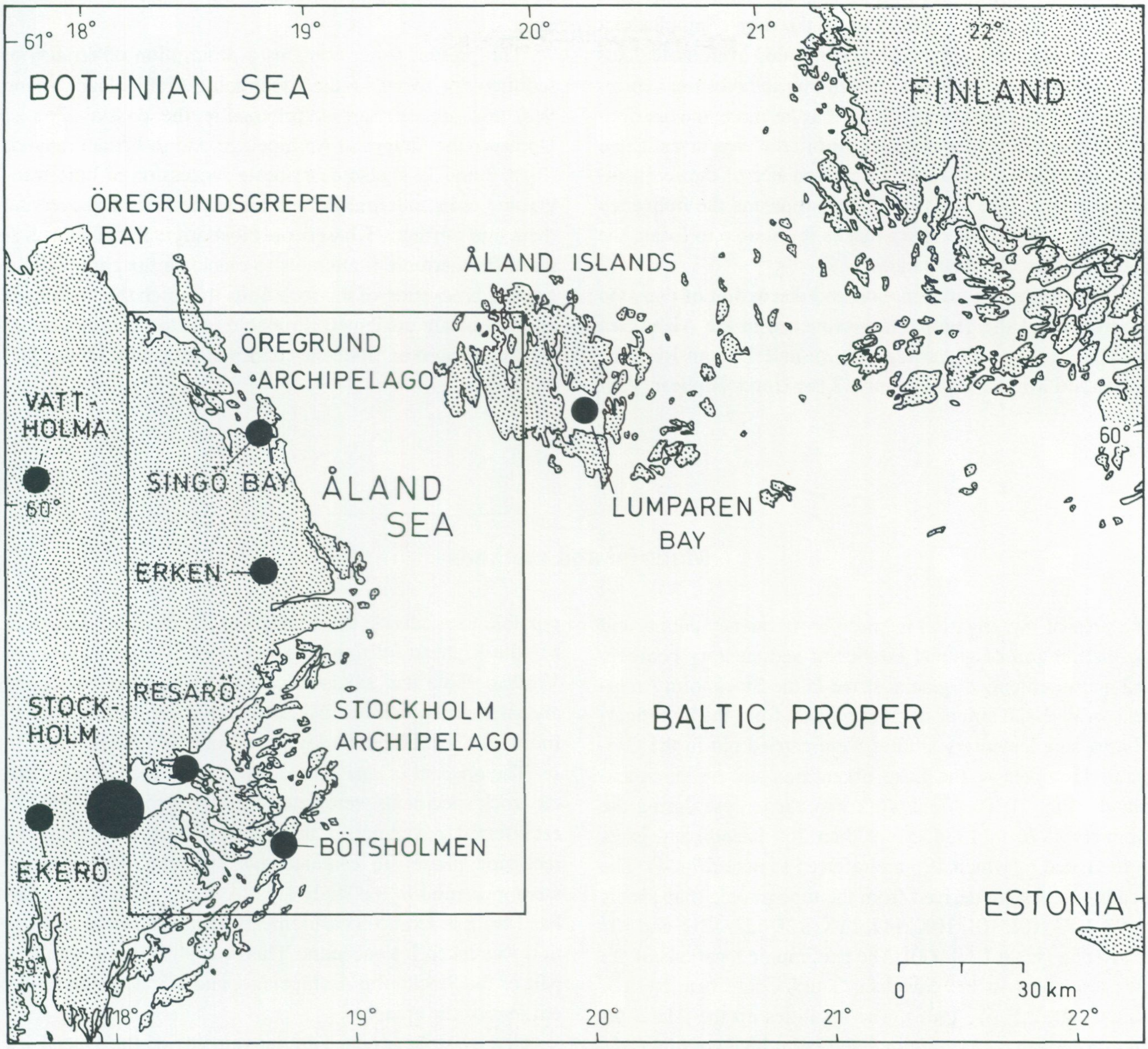

Fig. 2. Geographical extent of the investigated area in the Stockholm Archipelago (orthogonal frame).

tary sequences, inferred to be contemporaneous, are available near the area investigated. When fossils are present, the dating is more reliable.

The question of the provenance of the erratics, which is another main theme of this investigation, depends for its answer on the assumption that the distribution of the erratics really indicates the location of *in situ* occurrences. In the area investigated two patterns of preservation of erratics are obvious; long transported erratics which are rounded and of smaller size, and short transported erratics with angular shape and relatively great volume. Erratics of the latter kind are indicative of nearby *in situ* occurrences. Both kinds of erratics have been noticed to co-occur in parts of the area investigated.

The movements of the glacial ice sheet are indicated principally by striae, as well as by the sculpturing of bedrock surfaces. These movements determined the transport direction of the erratics. In the area investigated several movements have been indicated. The erratics which are confined to nearby *in situ* occurrences are inferred to have been influenced by the youngest movements in the area.

When reconstructing sedimentary successions that cannot be directly observed but are represented by dislocated erratics, one has to make use of evidence that may be highly circumstantial. For instance, the relative ages of certain lithologies can be inferred from the presence of older clasts in a younger lithology. By the consequent use of this method it is possible to distinguish at least two parts of the Proterozoic, i.e. the Lower and Middle Riphean on the one hand and the Upper Riphean/Vendian on the other. Samples that resemble one another in aspect are intruded by dolerite dikes occurring in the Åland Sea, making an indirect time correlation possible (Söderberg 1993). Furthermore, the distribution of the sedimentary erratics within the area investigated provides information about the provenance of the sedimentary sequence. The study of glacial striae and the frequency of different kinds of erratics makes it possible to locate the sites of the *in situ* occurrences.

To facilitate the presentation and discussion of data, the subdivision of the sedimentary sequence in the Åland Sea used here follows Söderberg (1993); unit 1 comprising the Lower and Middle Riphean, unit 2 the Upper Riphean/Vendian, and unit 3 the Lower Cambrian and the entire Ordovician.

The present paper contains a description of erratics of sedimentary rocks in the Stockholm Archipelago, Åland Sea, and adjacent areas, principally the coastal area of Uppland, the Öregrund Archipelago and the Åland Islands (Figs. 2 and 3). It also describes a succession of lithostratigraphic units, inferred in the manner described above, and their age attribution based on biostratigraphy where possible. Furthermore it attempts to elucidate the chronostratigraphic bracketing of the rock units to which the investigated erratics are attributed. Probable *in situ* occurrences are proposed based on frequency data and measurements of glacial striae.

Material and methods

The present investigation is based on frequency counts and the distribution of glacial erratics of sedimentary bedrock, and measurements of glacial striae in the Stockholm Archipelago. With the aim of comparing data from the investigated area supplementary studies were carried out in the Öregrund Archipelago, the Lake Erken area and on the Åland Islands (Fig. 3). The field work was carried out during the summers 1976 to 1984. More than 200 islands and islets were visited of which 196 are referred to here (Fig. 4). The locality names are derived from the topographic map sheets 9I, 9J, 10G, 10I, 10J, 10K, 11J, 11K, 12I, 12J, 13H, and 13J of Sweden (scale 1:50 000). The geographic locations of the sites are given in the Swedish Gauss Coordinate System (Rikets nät, 2.5° W, 1938). The localities on the Åland Islands are given by longitudinal and latitudinal coordinates.

On the islands and islets visited, frequency counts were made on those beaches consisting of wave-washed moraine. On the beaches visited two or three spots were randomly chosen. At each spot all neighboring clasts were counted until the number of 100 specimens was reached. This was done in order to obtain a more objective determination of the distribution of the erratics. A mean, calculated from 2 or 3 spots counted, represents the average frequency at each site. More than 40,000 rock specimens were included in the frequency counts. The size of the rock specimens counted ranges between cobbles and boulders, following the terminology of Wentworth (1922).

At the beginning of the investigation a rough field classification of the rock specimens was made into crystalline rocks, pre-Ordovician sandstones and Ordovician limestones. However, during the progress of the study it became possible to subdivide the material in the field into Lower to Middle Riphean (="Jotnian") sandstone, Upper Riphean to Vendian shale and sandstone, Lower Cambrian sandstone and siltstone, Lower and Middle Ordovician "Orthoceratite" limestone, and Upper Ordovician Baltic limestone (Fig. 5).

The original *in situ* locations of the erratics of sedimentary rock specimens were determined with the aid of the latest inferred movements of the glacial ice-cap, i. e. during the recession phase. To evaluate this direction, glacial striae were measured in the study area. A mean value was calculated from at least 5 measurements. Magnetic field declination was taken into account. This was 2° E in the northern part of the Stockholm Archipelago, and 1.5° E in the southern part of the area.

Glacial striae, created by movements of the glacial ice cap before or during early phases of the recession, were noticed but not dealt with. This procedure was motivated by the interpretation that these movements had minor influences on the composition of the population of sedimentary bedrock erratics now present in the investigated area. Two older movements of the ice cap are indicated by the striae measurements.

Examination of the sedimentary erratics was performed in the field by the naked eye and in the laboratory with the aid of a magnifier. The examination consisted of determinations of lithology, colour, grain size, roundness, mineralogical content and sedimentological structures. In addition, the size of the erratics was also determined in order to improve the definition of erratic fans by including their size gradients. The colour was determined from a rock colour chart (Goddard et al., 1963). Grain size and roundness were deter-

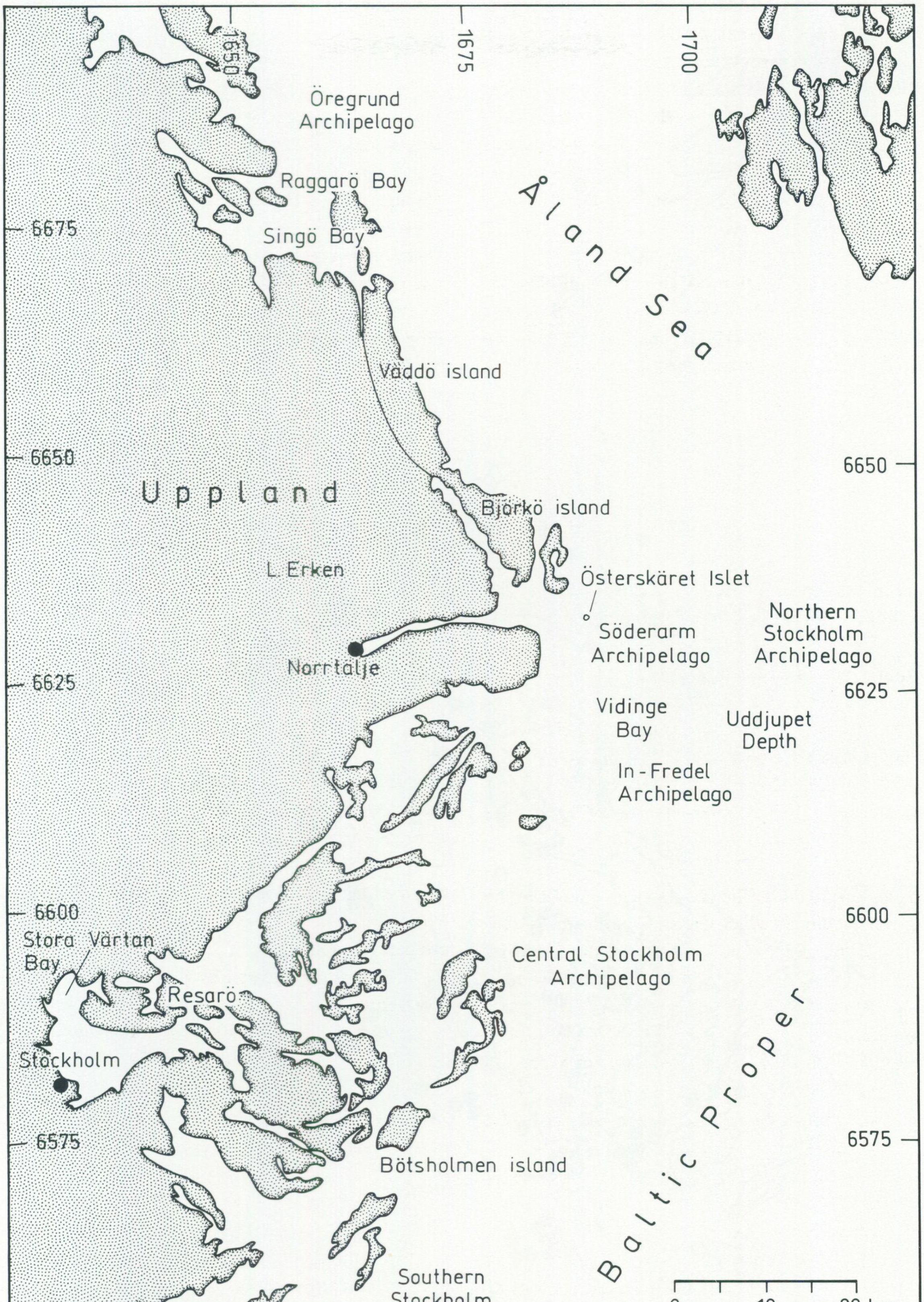

Fig. 3. Location of names mentioned in the text.

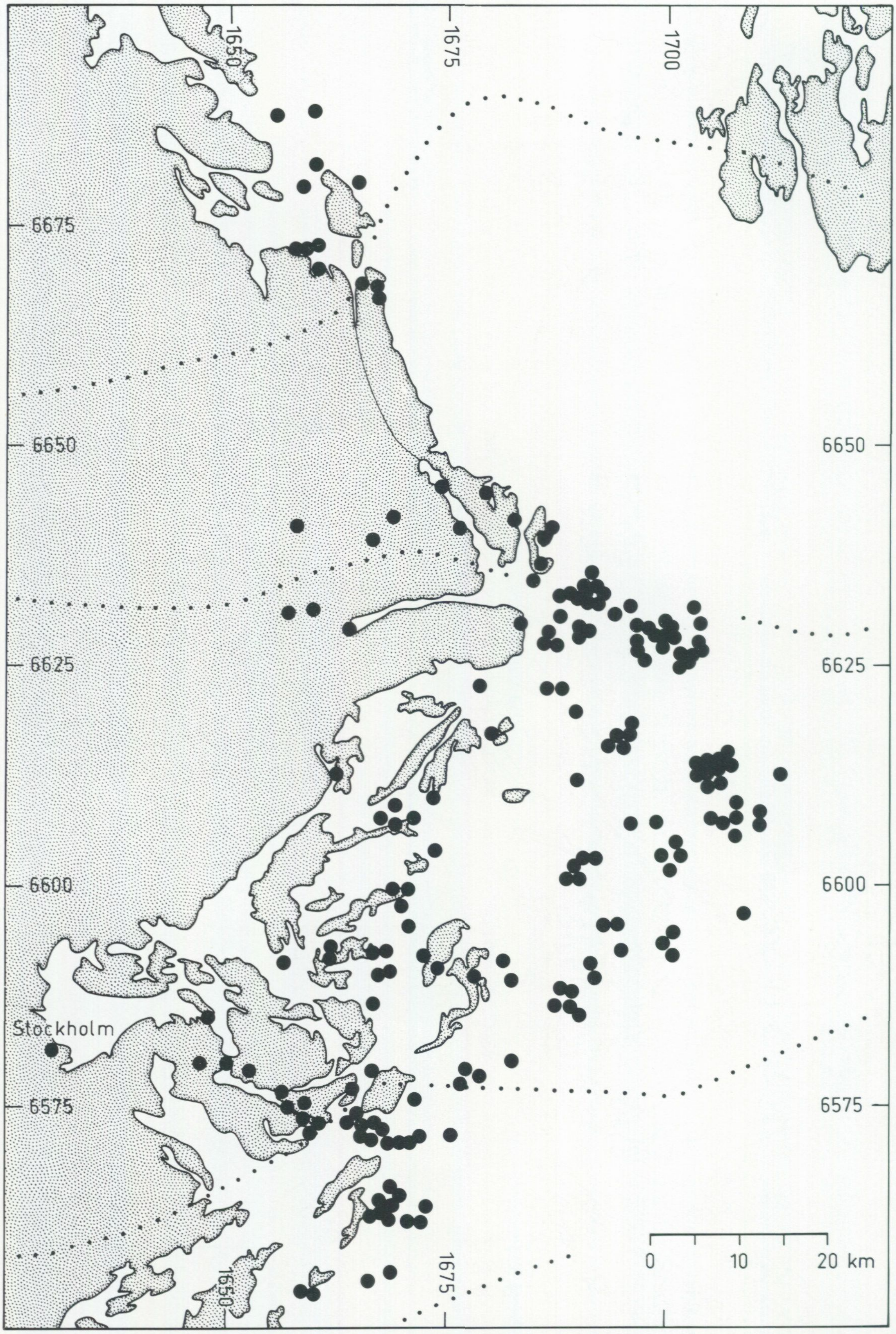

Fig. 4. Geographic positions of investigated localities within the study area. The coordinates are presented in the Swedish Gauss System, "Rikets Nät", 2.5° W, 1938. Some inland ice recession equicesses are plotted with dotted lines, following Strömberg (1971).

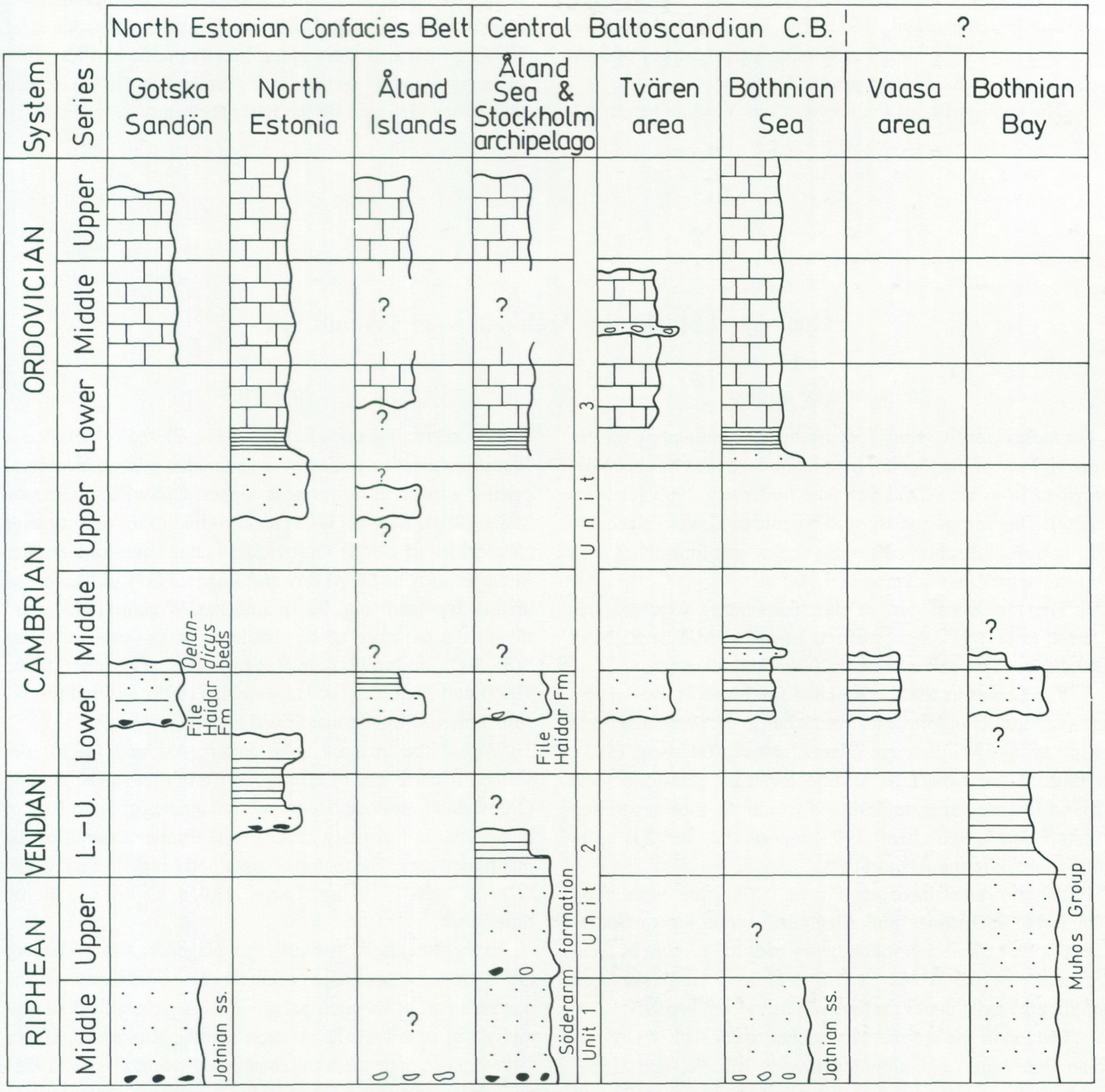

Fig. 5. Tentative stratigraphic scheme of the sedimentary sequence of the Stockholm Archipelago and Åland Sea. Modified after Lundqvist 1979, Chumakov & Semikhatov 1981, Bergström (1981), Ahlberg et al. (1986), Hagenfeldt, 1989c), Jaanusson (1982), Männil (1989), and Söderberg (1993).

mined from a reference card made by Geological Speciality Co. P. O. Box 36088 Houston, Texas. This card is based on the reference scale of Wentworth (1922). Calcium carbonate contents were determined by the weight loss caused by disintegration of calcium carbonate by hydrochloric acid. Shales and dolomitic limestones were identified by examination of thin sections.

X-ray diffraction was also used to determine the presence of dolomite in the erratic specimens of the Baltic limestone. The samples were crushed and stored in a sample holder. Subsequently they were scanned with CuK_{α} from 28° to 38° with a speed of 1° per minute.

The macrofossils collected for this study and mentioned in the text are housed at the collections of the Department of Palaeozoology, Swedish Museum of Natural History, Stockholm.

Data from the present investigation, comprising frequency counts of sedimentary erratics, striae measurements, and the location of dolomitic limestone boulders, are presented separately (Hagenfeldt 1995). The list of data can be requested from "The library of the Geological Survey of Sweden, Box 670, S-751 28 Uppsala, Sweden".

The subdivision of the Riphean and Vendian herein follows Chumakov & Semikhatov (1981). The "Jotnian" in Sweden is c. <1,500–1,200 Ma in age (Lindström et al. 1991), which is slightly older than the value of 1400–1000 Ma suggested by Chumakov & Semikhatov (1981). Hence, unit 1 may also include the Early Riphean.

Geology of Stockholm Archipelago and Åland Sea

Sedimentary rocks

The most extensive single occurrence of sedimentary rock in the vicinity of the Stockholm Archipelago area has been described from the Åland Sea (see Söderberg 1993 for a review). This Meso- and Neoproterozoic to Lower Palaeozoic basin has sandstones, siltstones, shales, and limestones with a total aggregate thickness of 1,700 m.

The lowermost part of the sedimentary sequence, referred to unit 1, consists of red Lower to Middle Riphean sandstone. The unit is up to 1,200 m in thickness.

The Lower to Middle Riphean sandstone is overlain by sandstones, conglomerates and shales of presumed Late Riphean and Vendian age (Hagenfeldt & Söderberg 1985). Clasts of the Lower to Middle Riphean sandstone were found in conglomerate assigned to unit 2, thus separating units 1 and 3. Söderberg (1993) reports that unit 2 is up to 400 m thick in the Åland Sea.

The Lower Palaeozoic, i.e. unit 3, is represented by Cambrian sandstones and siltstones. According to Söderberg (1993) Cambrian sedimentary beds are present as local remnants in the Åland Sea. In addition, Cambrian beds might also exist under outliers of Ordovician bedrock.

The top of the sedimentary sequence consists of Ordovician limestones spanning the Lower, Middle, and Upper Ordovician, subdivided into "Orthoceratite" limestone and Baltic limestone. The Ordovician outcrops are more extensive in the southern Åland Sea, as compared with Cambrian strata. The Cambrian and the Ordovician together are up to 350 m thick, which is a relatively great thickness compared with other areas on the Baltic Shield.

Onshore occurrences of fissure fillings of inferred Lower Cambrian sandstone have been reported from the Bötsholmen Island in the Stockholm Archipelago area (Fig. 2; Holmquist 1920). Recently, a new discovery of a presumably Lower Cambrian fissure filling was made on the Resarö island, in the vicinity of Stockholm (Fig. 2; Hagenfeldt & Söderberg 1994).

Erratics

In the Öregrundsgrepen Bay area (Fig. 2) the occurrence of limestone erratics indicates a sedimentary sequence comprising Lower to lowermost Upper Ordovician (Persson 1985, 1986). Wiman (1903) and Frödin (1956) report raised frequencies of Lower Ordovician Lanna limestone erratics in the vicinity of Singö Bay and Raggarö Bay in the coastal area of Uppland (Fig. 3). In addition, Wiman (1903) mentioned the presence of big boulders of Lower Ordovician "*Obolus*" sandstone near Raggarö Bay. Persson (1988a, 1990) and Söderberg & Hagenfeldt (1995) verified the results obtained by the mentioned authors.

Within the area of Lake Erken, Asklund (1930) described occurrences of erratics of Cambrian sandstone and Ordovician limestone. He found frequencies of up to 20% of Palaeozoic sedimentary rocks in the erratic material of the mentioned area. The material contained Lingulid Sandstone, "*Obolus*" shale, Latorp, Lanna, Holen, Dalby and Baltic limestones.

In the Stockholm Archipelago, Hagenfeldt & Söderberg (1985) reported extensive occurrences of erratics from the northern part of the archipelago area. A generalized stratigraphy was based on the erratics; Middle Riphean to Upper Ordovician. Apart from the mentioned work, Frödin (1956) remarked on the presence of Baltic limestone in the northern part of the archipelago. Frödin (1956) thought that the erratics had been transported over long distances, perhaps from the Bothnian Sea area.

The presence of dolomitic limestone erratics along the coastal area of Uppland, as well as in adjacent areas, has been known but never fully investigated. The currently reported distribution of dolomitic limestone comprises the archipelago area between the Åland Islands and the Finnish mainland (Uutela 1989), and the coastal area of Uppland (Söderberg 1993).

Glacial striae

During the Late Weichselian deglaciation in the Stockholm Archipelago and areas northward (see Persson 1982a, 1982b, 1985, 1986, 1988a, 1988b, 1990 for reviews) the ice movement was from northwest to southeast in the southern Stockholm Archipelago (Fig. 3). In the central and northern parts of the archipelago the ice movement was from north to south, which indicates a clockwise turning of the ice front. Along the coastal area of Uppland the ice movement was affected by a calving bay located in Åland Sea (Frödin 1956, Strömberg 1971). This circumstance resulted in a northwest to southeast movement of the ice. Söderberg (1982) described the distribution of terminal moraines at the bottom of Åland Sea. From these data Söderberg (1982) estimated the movement of the ice during the local recession to be roughly from north-northwest to south-southeast in the submarine area of the Åland Sea.

Descriptive part

The assignment of the lithologies of the investigated erratics to stratigraphic units of the *in situ* bedrock is made with highly variable degrees of certainty. Lithologies attributed to unit 1 show similarities with Lower to Middle Riphean sandstone and are hence assigned to this formation. Unit 3 is Lower Palaeozoic (Cambrian and Ordovician). Unit 2, which herein occupies an intermediate position in the sedimentary succession between units 1 and 3, is correlated with the least certainty. Because of indications described below unit 2 is tentatively correlated with Upper Riphean/Vendian strata. In order to simplify the presentation of data the units are presented in the following text in the order of their inferred stratigraphic succession.

Lithological and sedimentological observations

The primary examination of the material resulted in a subdivision of the sedimentary bedrock into three main categories. These are: sandstones and siltstones with associated conglomerate horizons, shales with intercalating laminations of sandstone and finally calcarenitic and calcilutitic limestones.

Söderarm formation

The Söderarm formation, here described as an informal unit, comprises two parts, i.e. unit 1 consisting of reddish sandstone and unit 2 consisting of greyish and reddish sandstones and conglomerates (Fig. 5). In the latter unit a black shale is supposed to be interfingering. The lower boundary of the Söderarm formation consists of crystalline basement belonging to the Svecofennian Subprovince (Gaál & Gorbatschev 1987). The Upper boundary is provided by unit 3, which is represented by fossiliferous sandstone and limestone. The designation of the Söderarm formation refers to the Söderarm Archipelago (Fig. 3), where the most complete sequence of erratics was found. The *in situ* position of the Söderarm formation is supposed to be in the Åland Sea, partly also as small remnants in the Stockholm Archipelago area. No formal description is as yet possible due to absence of onshore outcrops and drill-cores.

Sandstones, attributed to the Söderarm formation, were devoid of acid-resistant microfossil, as well as other remnants of organic life.

Unit 1: Lower to Middle Riphean

Several types of sandstone are supposed to make up unit 1 (Table 1). The colour of the sandstones ranges from dark reddish brown (10R 3/4) to very light grey (N8). The grain size varies from very fine sand with subangular grains, to medium – very coarse sand with subrounded to rounded grains. Occasionally, the latter type shows graded bedding. The mineral content consists mainly of quartz particles, partly coated with a film of iron hydroxide. In the very fine-grained sandstones small flakes of mica and occasional feldspar grains occur together with quartz. Also ripple marks were observed.

Unit 2: Upper Riphean/Vendian

The sandstones of this unit are distinguished by the presence of eroded sandstone pebbles derived from unit 1. Shale clasts have an uncertain stratigraphic position, but are believed to represent sedimentation during the time range of unit 2. Several types of sandstone are differentiated in unit 2.

The first lithology distinguished consists of greyish brown (5YR 3/2) to greyish red (5R 4/2) sandstone with subrounded grains which range in size from medium sand to pebbles (Table 1). Quartz and feldspar form the main minerals. Pebbles of the above mentioned very fine sandstone from unit 1 and granite are the main detrital components. The sandstone is slightly calcareous and displays primary structures such as cross bedding and graded bedding.

The second lithology is moderate orange pink (10R 7/4) to pale red (10R 6/2) sandstone. The grain size varies from very fine sand to pebbles. The grains are subangular to subrounded. Pebbles are quartz and feldspar. In certain horizons mica flakes are abundant. Greenish grey (5G 6/1) and dark reddish brown (10R 4/6) clays occur, the former mostly in thin layers. Detrital components consist of mica schist, obviously derived from the surrounding crystalline basement, and reddish sandstone from unit 1. Calcite crystals are visible on fresh surfaces of rock specimens. The calcium carbonate content reaches 15%. Graded bedding and cross bedding are the observed sedimentary structures.

Table 1. Comparison between sandstones derived from the Söderarm formation and File Haidar Formation. A = grain size; B = roundness; C = colour, D = mineral content; E = detrital content; F = sedimentary structures. Brackets indicate sparse occurrence. Dashes indicate non presence.

A	B	C	D	E	F
Unit 1 ("Lower to Middle Riphean")					
1. very fine sand	subangular	reddish brown	quartz (feldspar) mica	-	-
2. medium to very coarse sand	subrounded to rounded	light grey	quartz	-	cross b. ripples
Unit 2 ("Upper Riphean/Vendian")					
1. medium sand to pebbles	subrounded	greyish red	quartz feldspar	unit 1 granite	graded b. cross b.
2. very fine sand to pebbles	subangular to subrounded	orange pink to pale red	quartz feldspar mica	mica schists unit 1 clay clasts	graded b. cross b.
3. Coarse sand to pebbles	subangular to subrounded	yellowish to olive grey	quartz feldspar clay clasts	unit 1	-
Unit 3 ("Lower Cambrian")					
1. coarse sand	subrounded	greenish grey	quartz (feldspar) pyrite	greyish shale of unit 2 ? clay clasts	graded b. cross b.
2. very fine sand	subrounded	light grey	quartz	-	-

The third lithology consists of pale yellowish brown (10Y 6/2) to light olive grey (5Y 6/1) sandstone. The dominant grain size varies from coarse sand to pebbles. The grains are subangular to subrounded. Quartz and feldspar are the main mineral components and occasionally reach pebble size. The matrix is argillaceous. Greenish grey (5G 6/1) clay clasts are present. Pebbles of a greyish red (10R 4/2) to pale reddish brown (10R 5/4) sandstone with grain sizes ranging from medium to coarse grained sand occur as detrital components. Conglomerate horizons are present. No calcium carbonate content was detected by the hydrochloric acid test.

The fourth type of sedimentary bedrock from unit 2 is composed of shale with intercalated laminae of sandstone. The colour of the shale is medium grey (N5) to greyish black (N2). The shale is thinly laminated. The intercalated sandstone laminae are 2–10 mm thick. The sandstone consists of coarse to very coarse rounded grains of quartz and feldspar. Some shale surfaces have abundant mica flakes. Sedimentary structures are cross bedding and mud cracks filled by sandstone. The mud-cracks are ptygmatically folded. A dark coloured organic residue was discovered in an attempt to extract acid-resistant microfossils from the shale. However, though such fossils are present, their state of preservation did not permit any accurate identification.

File Haidar Formation

Lithologies, here assigned to the Lower Cambrian, have a close affinity to the File Haidar Formation (Fig. 5) on Gotland, Gotska Sandön, Öland, and south central Sweden (Fig. 1; see Moczydlowska 1991 and Hagenfeldt 1994 for reviews). Hence, equivalent erratics in the present material have been assigned to that formation.

Unit 3: Lower Cambrian

The main lithology of unit 3 consists of very fine sandstone with interfingering layers of a very coarse sandstone (Table 1). The colour varies from greenish grey (5G 6/1), through medium grey (N5), light grey (N7), and dark grey (N3) to brownish grey (5YR 6/1). The grains of the coarse sandstone are subrounded. The bulk of the sandstone consists of quartz grains. Pebbles of medium grey (N5) shale may have been eroded from unit 2 of the Söderarm formation. In many cases, however, the pebbles may alternatively represent rip-up mud clasts from penecontemporaneous argillaceous deposits. Only a few feldspar grains are present. Pyrite crystals and "greenish grey" (5G 6/1) clay clasts occur. Mica flakes are abundant in certain horizons within the very fine grained sandstone. Sedimentary structures such as graded bedding and cross bedding occur. The amount of calcium carbonate is low, compared with unit 2 of the Söderarm formation. Trace fossils such as *Monocraterion, Skolithos*, and *Serpulites* were observed in the very fine grained sandstone. Two erratics attributed to unit 3 were searched for acid-resistant microfossils, but were found to be devoid of such fossils.

Ordovician strata

Ordovician limestone and conglomerate supposedly form the uppermost part of the sedimentary bedrock sequence in the investigated area (Fig. 5 and 6). The erratics comprise the "*Obolus*" conglomerate, Latorp Limestone, Lanna Limestone, and Holen Limestone of Oelandian age. The Viruan comprises the Segerstad Limestone, but could also be represented by other units, not detected in the present material. The Harjuan is represented by the Baltic limestone, which is the uppermost stratigraphic unit observed.

Unit 3: Lower Ordovician (Oelandian)

Erratics of the so-called "*Obolus*" conglomerate are black (N1) in colour and actually consist of dark shale with numerous shells of *Ungula* sp. (Lars Holmer personal communication 1989; see also Puura & Holmer 1993). The shale contains pyrite laminae.

The Latorp Limestone erratics are greyish red (10R 4/2). Brilliant green (5G 6/6) glauconite occurs together with black (N1) phosphorite at the bottom of the strata. Along discontinuity surfaces dusky yellow (5Y 6/4) goethite occurs. The limestone is medium bedded between discontinuity surfaces. Shell fragments and pygidia of *Megistaspis* (*Varvaspis*) sp. were observed.

The erratics derived from the Lanna Limestone are moderate brown (5YR 4/4) in colour, and yielded a fossil content of orthocone nautiloids and trace fossils such as *Trypanites*.

The Holen Limestone erratics show a greyish red (10R 4/2) colour, and contain pygidia of probably *Megistaspis* (*Varvaspis*) *gigas*.

Unit 3: Middle Ordovician (Viruan)

Erratics from the Segerstad Limestone are light grey (N7) in colour and contain *Angelinoceras latum*.

Lithologies of a dark greyish (N3) limestone of a nodular appearance are tentatively referred to the Middle Ordovician. The lithologies resemble the Dalby limestone, but as no fossils were found, this assumption must be considered as tentative. These types of lithology are included in the Middle Ordovician part of the frequency counts.

Unit 3: Upper Ordovician (Harjuan)

Erratics of calcilutitic Baltic limestone are pale yellowish brown (10YR 6/2) in colour. The limestone contains appreciable amounts of chert. Cavities and fissures in the Baltic limestone are filled with calcite crystals. The limestone erratics are partly transected by veins filled by calcite. Fossil components in the Baltic limestone are crinoid segments, pygidia of trilobites, gastropods, bryozoans, molluscs, calcareous algae (*Vermiporella* sp.), brachiopods (*Vellamo* sp., *Sowerbyella* sp., and corals (*Cyclocrinites* sp.).

In some erratics of the Baltic limestone greyish pink (5R 8/2) dolomite was noticed. The dolomite occurs as clasts with sharply defined margins. A sharp contact was visible to the naked eye between the dolomite clasts and the calcilutite limestone. Occasionally, growth of dolomite was observed on macrofossils.

Microscope examination of thin sections revealed the presence of dolomite rhombs scattered in a calcilutite matrix. The rhombs gradually increase in number towards the dolomite clasts, until the rock reaches the composition of dolostone.

X-ray diffraction analysis further confirms the presence of dolomite. The measurements gave peaks at 34.32° (calcite) and at 36.11° (dolomite).

FREQUENCY COUNTS OF ERRATICS

The frequencies presented here were calculated from the total amount of erratics, including both crystalline and sedimentary erratics. Erratics attributed to crystalline rocks in the investigated area were not further differentiated in the present study. However, apart from Svecofennian rocks, dolerites and rapakivi granite occurred amongst the erratics. In

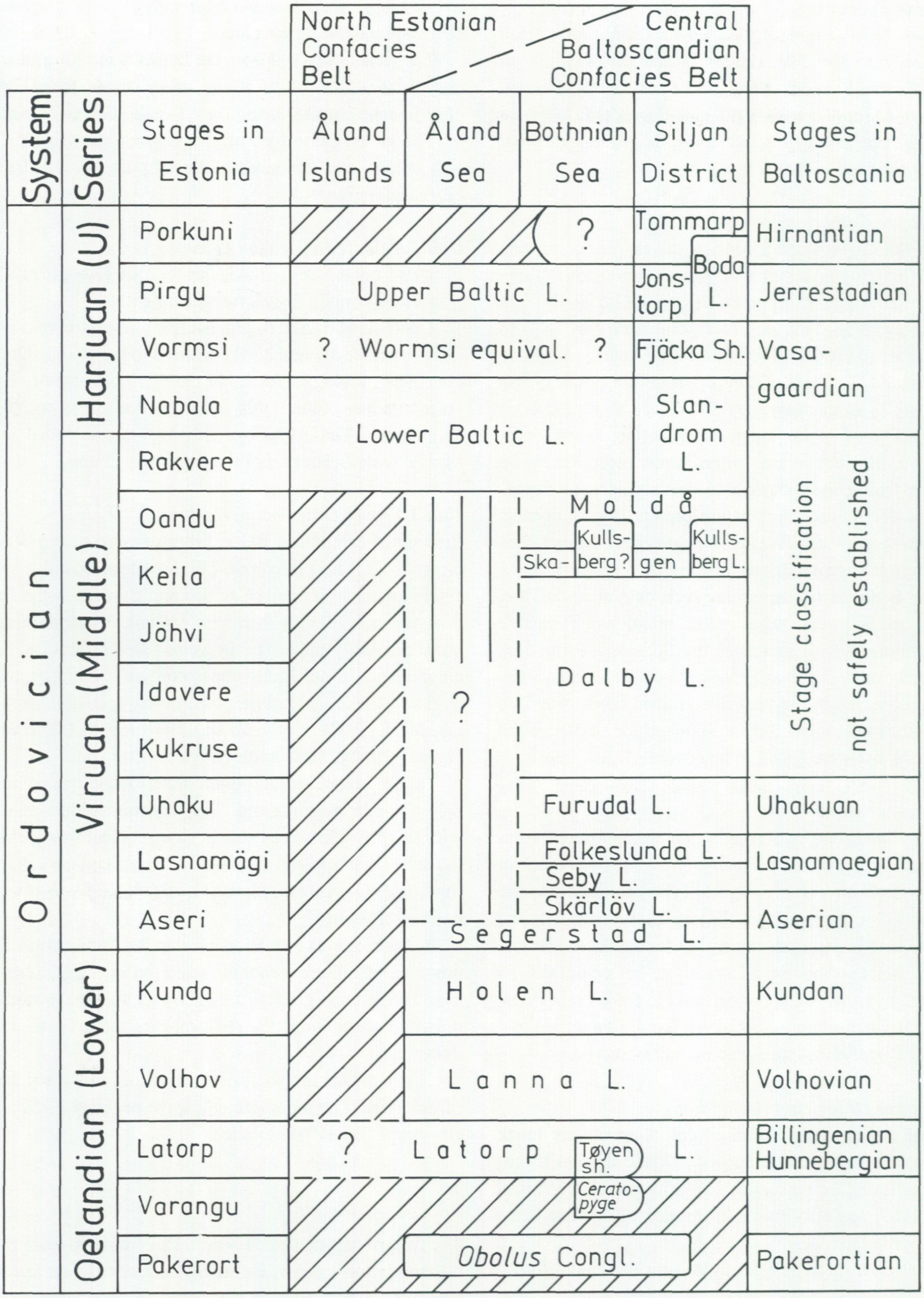

Fig. 6. Correlation scheme of the Ordovician of the Central Baltoscandian Confacies Belt and North Estonian Confacies Belt in the North Baltic area and south central Sweden. Modified after Jaanusson (1982), Hagenfeldt & Söderberg (1985), and Männil (1989).

addition to the frequencies the size of the erratics was also determined by the greatest diameter.

Unit 1: Lower to Middle Riphean

The erratics of unit 1 have a frequency span between 0 and 24% (Fig. 7). The southern and central parts of the Stockholm Archipelago yielded 0 and 5% respectively. Greater frequencies occurred to the east and north.

Erratics from unit 1 were not found in the Lake Erken area and in the Öregrund Archipelago.

On the Åland Islands two investigated localities, i.e. Karrböle and Gunnarsdal, yielded 18 and 38 % erratics from unit 1, respectively. Boulders assigned to unit 1 were concentrated in the Söderarm Archipelago, just south of the Åland Sea basin, and on the Åland Islands. However, scattered occurrences of boulders, up to one metre in diameter, were noted all over the Stockholm Archipelago.

Unit 2: Upper Riphean/Vendian

The majority of the sandstone erratics originate from unit 2. These erratics are scattered in the southern and central part of the Stockholm Archipelago, ranging from 0 to 2% in frequency (Fig. 8). In the eastern and northern part of the archipelago area the frequencies generally reach much greater local values. In the western part of the Söderarm Archipelago frequencies as great as 67% were found. It is noteworthy that erratics of unit 2 are absent in the Lake Erken area, the Öregrund Archipelago, and on the Åland Islands. The recorded finds of boulders from unit 2 are concentrated to the Söderarm Archipelago, maybe because the bulk of the exposed sedimentary bedrock immediately to the north of this area consists of this unit.

Finds of shale erratics, presumably derived from unit 2, are concentrated to the Söderarm Archipelago (0–8%). Only a few scattered occurrences are noted to the south with frequencies below 1% (Fig. 9). Furthermore, large boulders with a diameter of about half a metre were observed only in the Söderarm Archipelago. Shale erratics are absent in the southern part of the Stockholm Archipelago, the Lake Erken area, and the Öregrund Archipelago. An isolated find was made in the northern part of the Åland Islands.

Unit 3: Lower Cambrian

Erratics from unit 3 are scattered all over the Stockholm Archipelago, the Lake Erken area, the Öregrund Archipelago, and on the Åland Islands, ranging from 0 to 5% (Fig. 10). Occasionally, the erratics reach the size of small boulders less than half a metre in diameter, which are glacially striated. Contrary to units 1 and 2, the Lower Cambrian of unit 3 shows an even distribution of frequencies and is not particularly concentrated in any part of the investigated area.

Unit 3: Lower Ordovician (Oelandian)

The frequency of the Ordovician limestone in the Stockholm Archipelago ranges from 0% to 20%. Erratics of reddish "Orthoceratite" limestone, comprising the Latorp, Lanna, and Holen Limestone, have frequencies from 0 to 4 % in scattered occurrences in the Stockholm Archipelago (Fig. 11). However, greater frequencies, i.e. from 6 to 15%, occur locally in the northern part of the area connected with the presence of boulders of about one metre in diameter. The boulders are striated and angular in shape.

Supplementary studies south of Lake Erken yielded 16% for erratics of reddish "Orthoceratite" limestone. The erratics were represented by striated and angular boulders.

In the Öregrund Archipelago, and southeast of Singö Bay, relatively great frequencies were obtained for the reddish "Orthoceratite" limestone erratics (9–15%). Striated boulders occur even here.

Unit 3: Middle Ordovician (Viruan)

Of the Middle Ordovician, only the Segerstad Limestone could so far be identified by the methods employed. However, a dark greyish limestone with a nodular appearance, similar to the Dalby limestone, was classified as Middle Ordovician, though not biostratigraphically determined. In the Stockholm Archipelago only scattered occurrences are noted, ranging between 0 and 5%, which is considerably less than frequencies obtained for the reddish "Orthoceratite" limestone (Fig. 12). In addition, erratics of the Middle Ordovician limestones are smaller in size.

South of Lake Erken frequencies up to 19% were noted for the Middle Ordovician limestone. At this site striated boulders up to one metre in diameter were found.

In the Öregrund Archipelago greater frequencies were found southeast of Singö Bay (0–3%), and the size increased to small boulders. In the northern part of the Öregrund Archipelago only small pebbles were found.

No erratics of Middle Ordovician limestone were present at the investigated localities on the Åland Islands.

Unit 3: Upper Ordovician (Harjuan)

The uppermost part of the sedimentary sequence represented by erratics in the study area was characterized as Upper Ordovician Baltic limestone. The distribution pattern showed scattered occurrences from 0 to 2 % in the southern part of the Stockholm Archipelago (Fig. 13). In the central and northern part of the archipelago an increase in frequency is noticed, locally reaching 12%. In the present material boulders were found up to half a metre in diameter. The boulders are striated. In the Lake Erken area, Öregrund Archipelago and on the Åland Islands scattered occurrences yielded up to 3%.

Increased frequencies of dolomitic Baltic limestone erratics were found in the Söderarm Archipelago (Fig. 14).

A search north of the Lake Erken area, as well as north of Stockholm, yielded rock specimens of dolomitic Baltic limestone. In the collections of the Geological Survey of Sweden, Uppsala, there are specimens of dolomitic Baltic limestone found in the northern Uppland.

On the Åland Islands dolomitic Baltic limestone erratics were found in the present investigation at Gunnarsdal, Geta, Brantsböle, and Finnström to the north of Lumparen Bay. Scattered occurrences of dolomitic Baltic limestone erratics were present at the bottom of the Åland Sea, north of the Stockholm Archipelago area (Söderberg & Hagenfeldt 1994).

Glacial striae measurements

In the southern and western part of the Stockholm Archipelago the glacial striae indicated that the movement of the ice sheet was N15°–25°W (Fig. 15). In the central part of the archipelago, a north to south motion of the ice sheet was indicated. In addition to the mentioned direction of inland ice movement during the recession, earlier phases were noted between N10°W and N5°E. These striae are preserved in sheltered positions.

In the Söderarm Archipelago a direction of movement of the ice mass from the north is noted. However, in the Björkö area (Fig. 3), to the northwest of the Söderarm Archipelago, an ice movement during the deglaciation was indicated ranging between N10°–15°E.

At the northern part of Lake Erken one observation outside the area containing limestone erratics gave N30°W as direction of the ice movement.

In the Öregrund Archipelago a direction of the ice movement is noted from NW towards SE, ranging between N20°–60°W.

In addition, traces of earlier glacial movements in the Stockholm Archipelago were found as scattered occurrences in sheltered positions. From these observations a variation was noted between N20°–60°W, as well as other directions ranging from N5°–30°E.

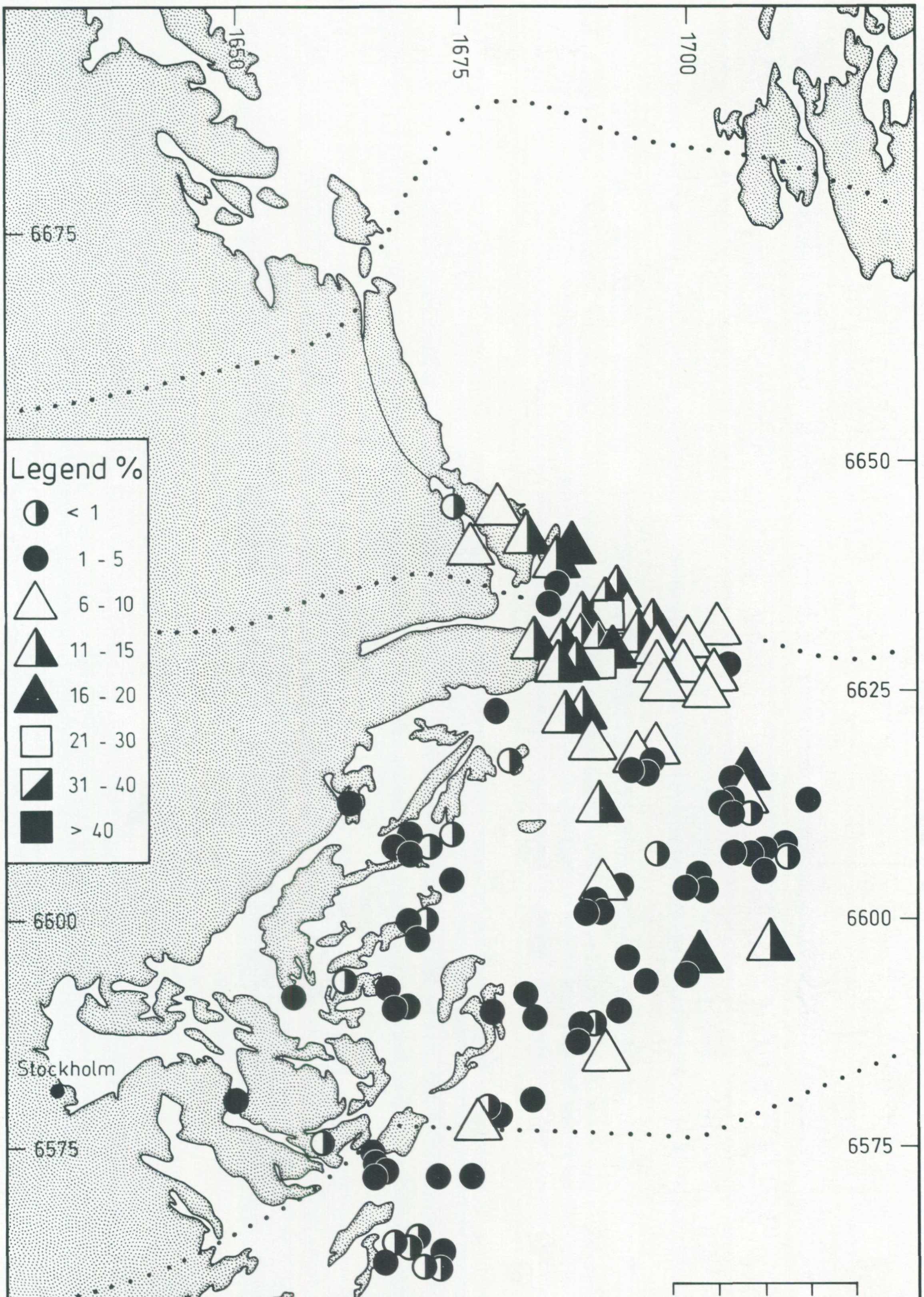

Fig. 7. Frequency counts of sandstone erratics from unit 1 of the Söderarm formation (Lower to Middle Riphean). Dotted lines: see Fig. 4.

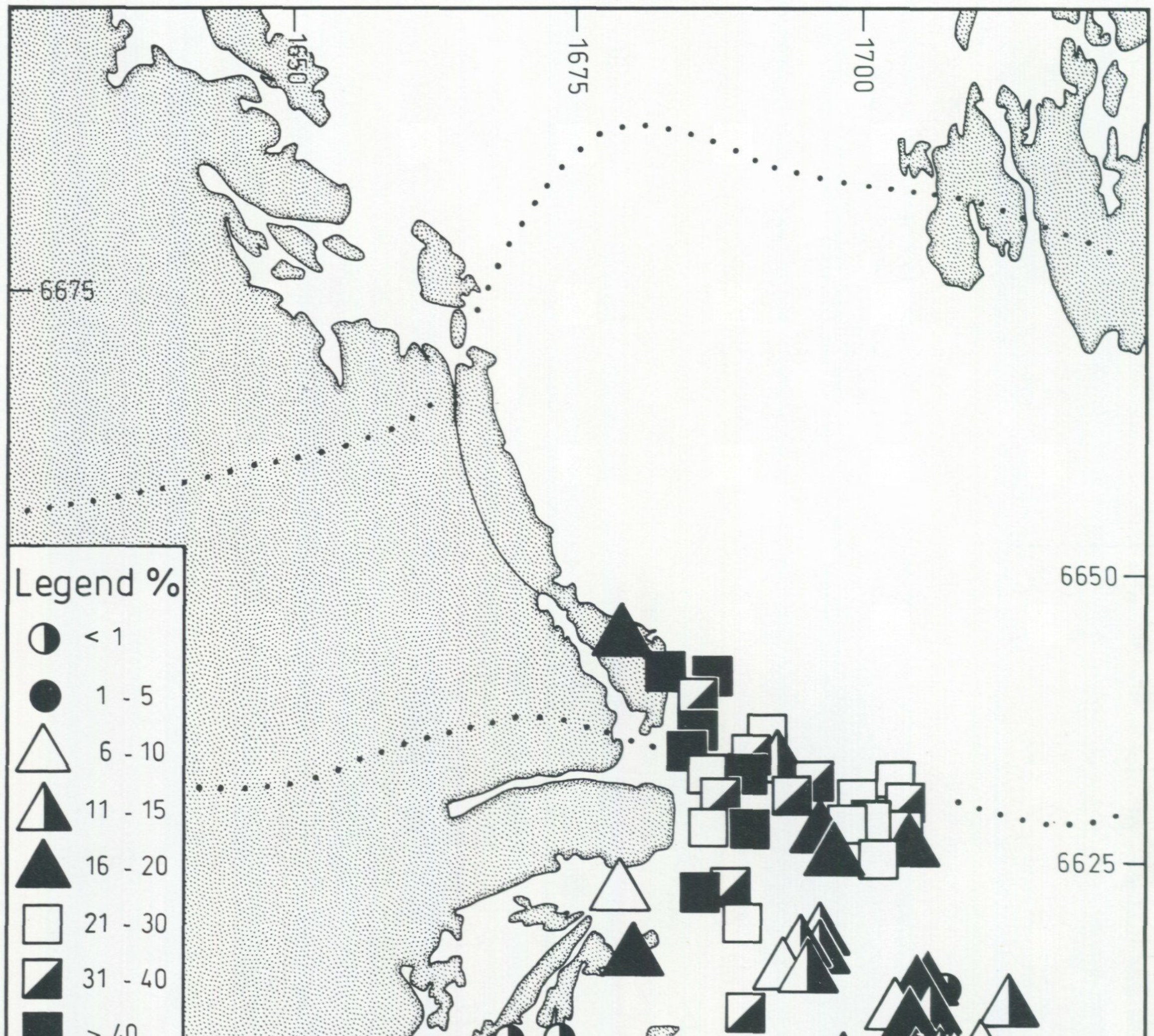

Fig. 8. Frequency counts of sandstone erratics from unit 2 of the Söderarm formation (Upper Riphean–Vendian). Dotted lines: see Fig. 4.

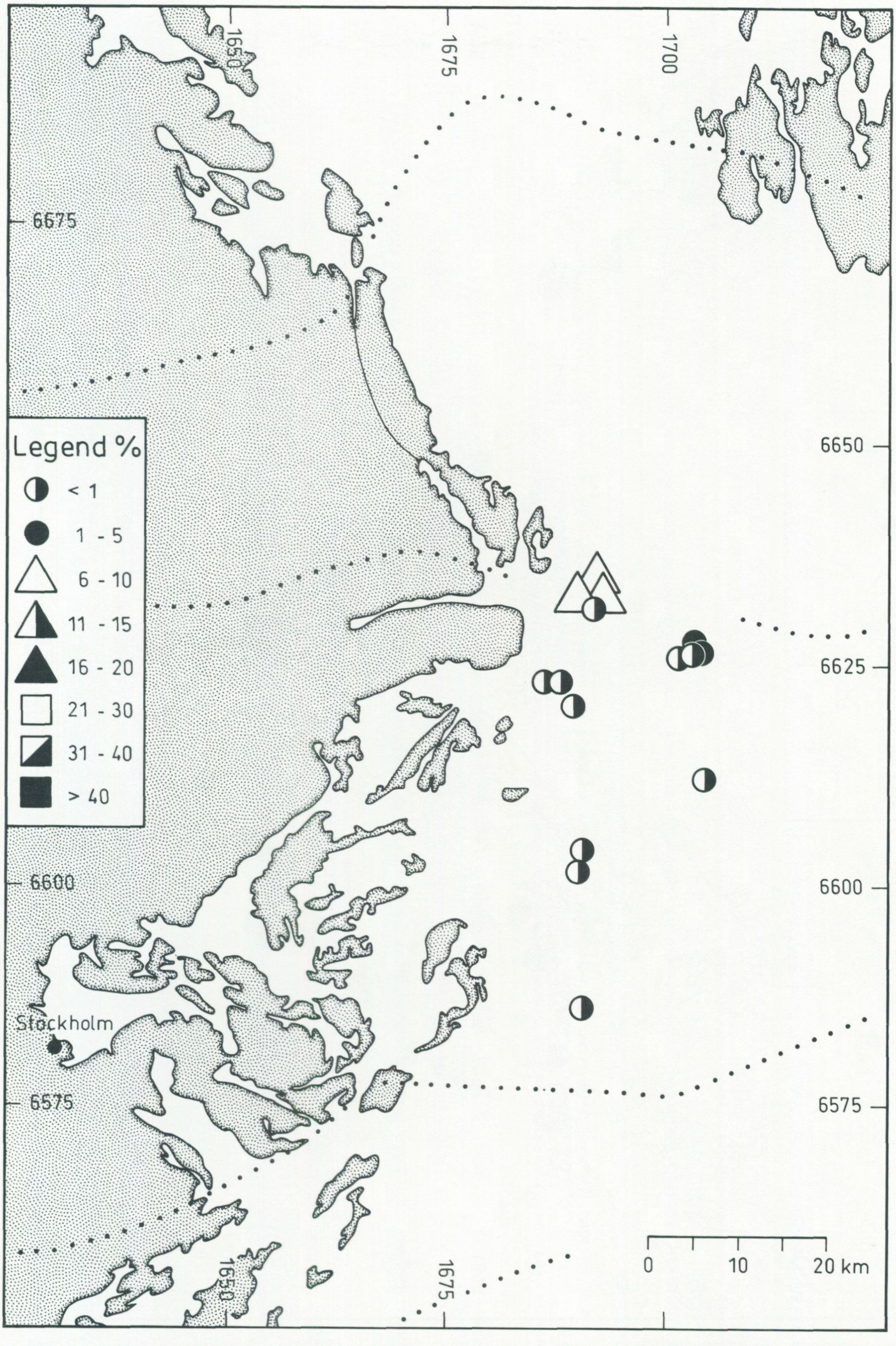

Fig. 9. Frequency counts of shale erratics from unit 2 of the Söderarm formation (Upper Riphean–Vendian). Dotted lines: see Fig. 4.

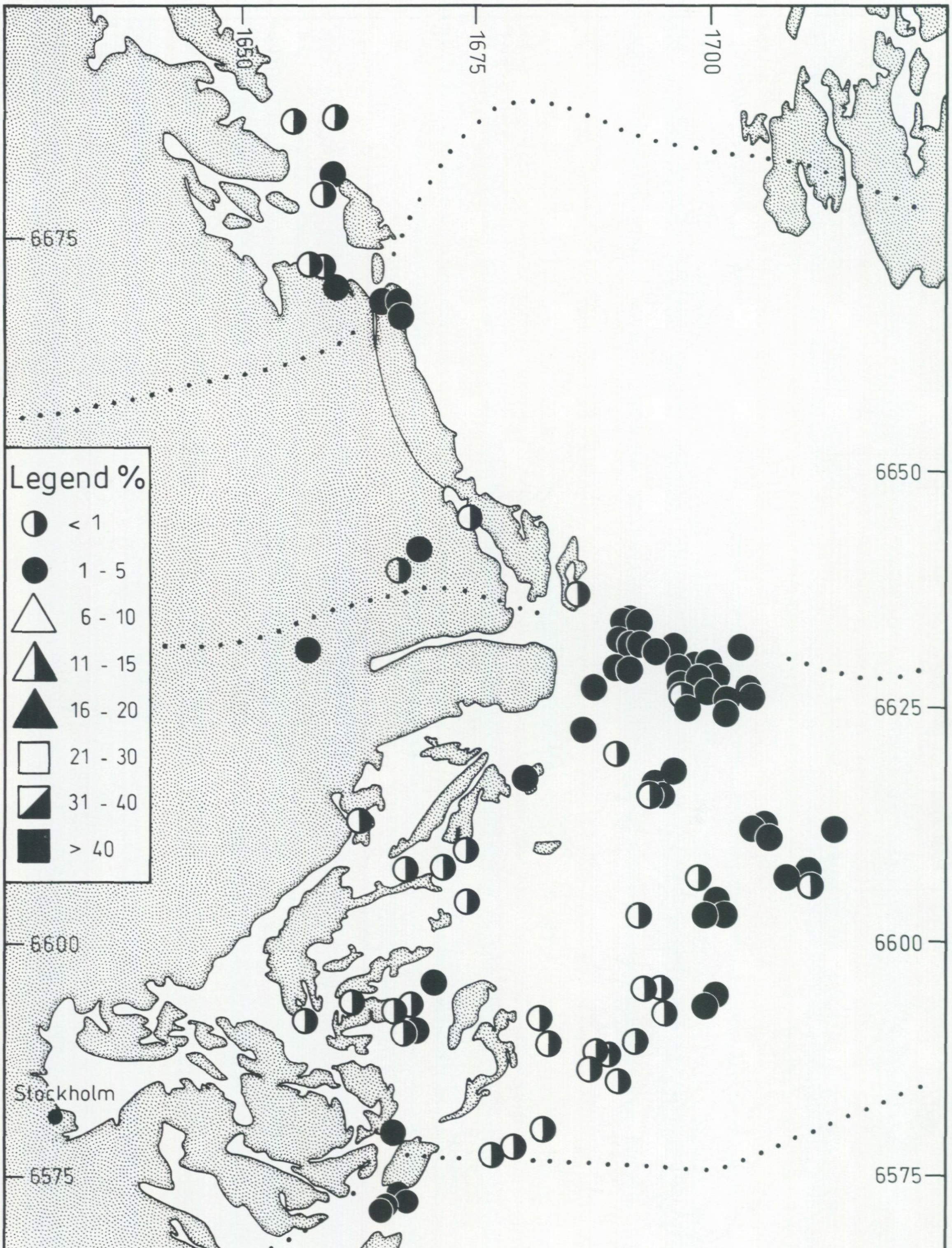

Fig. 10. Frequency counts of sandstone erratics from unit 3, equivalent to the File Haidar Formation (Lower Cambrian). Dotted lines: see Fig. 4.

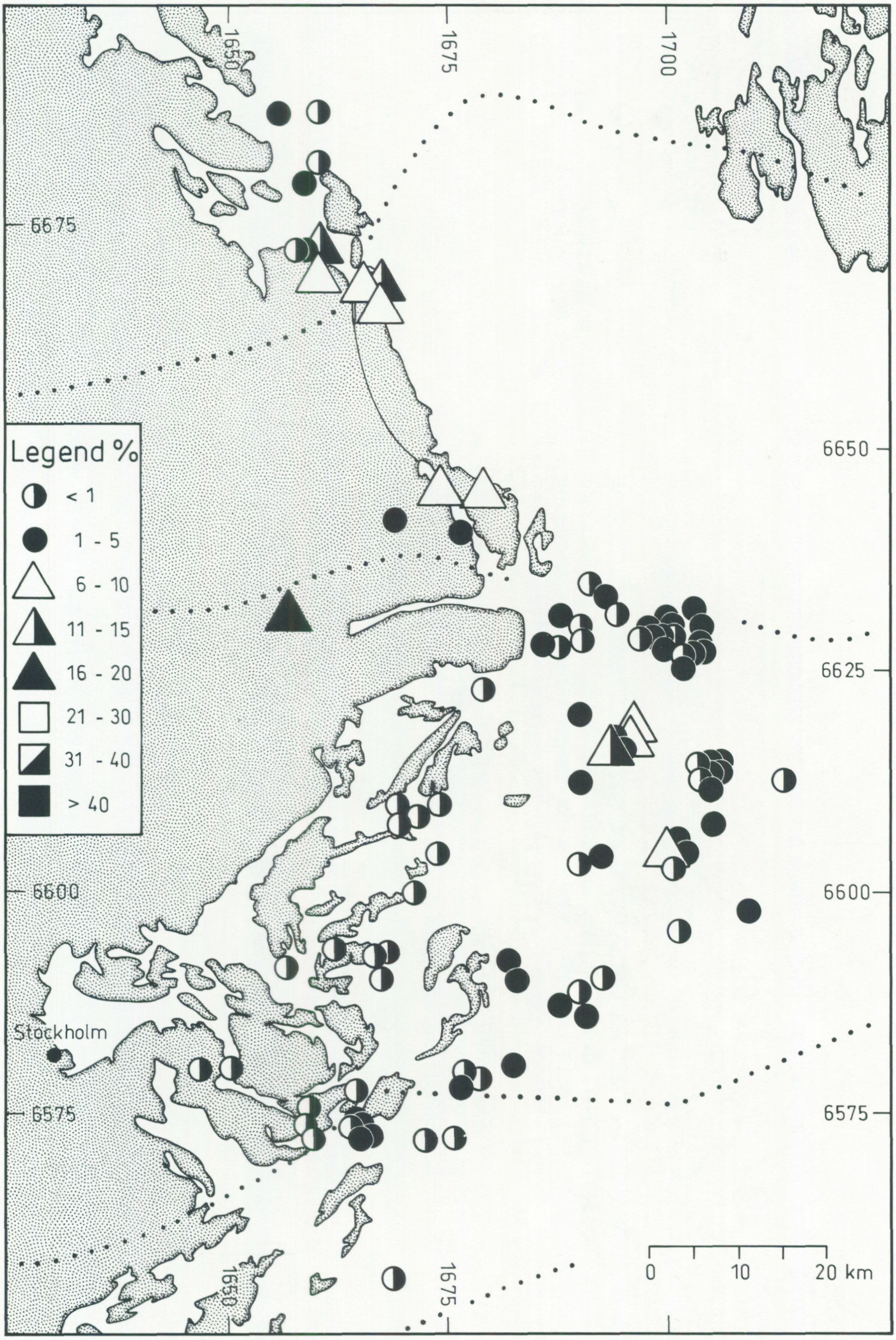

Fig. 11. Frequency counts of "Orthoceratite" limestone erratics from unit 3 (Lower Ordovician). Dotted lines: see Fig. 4.

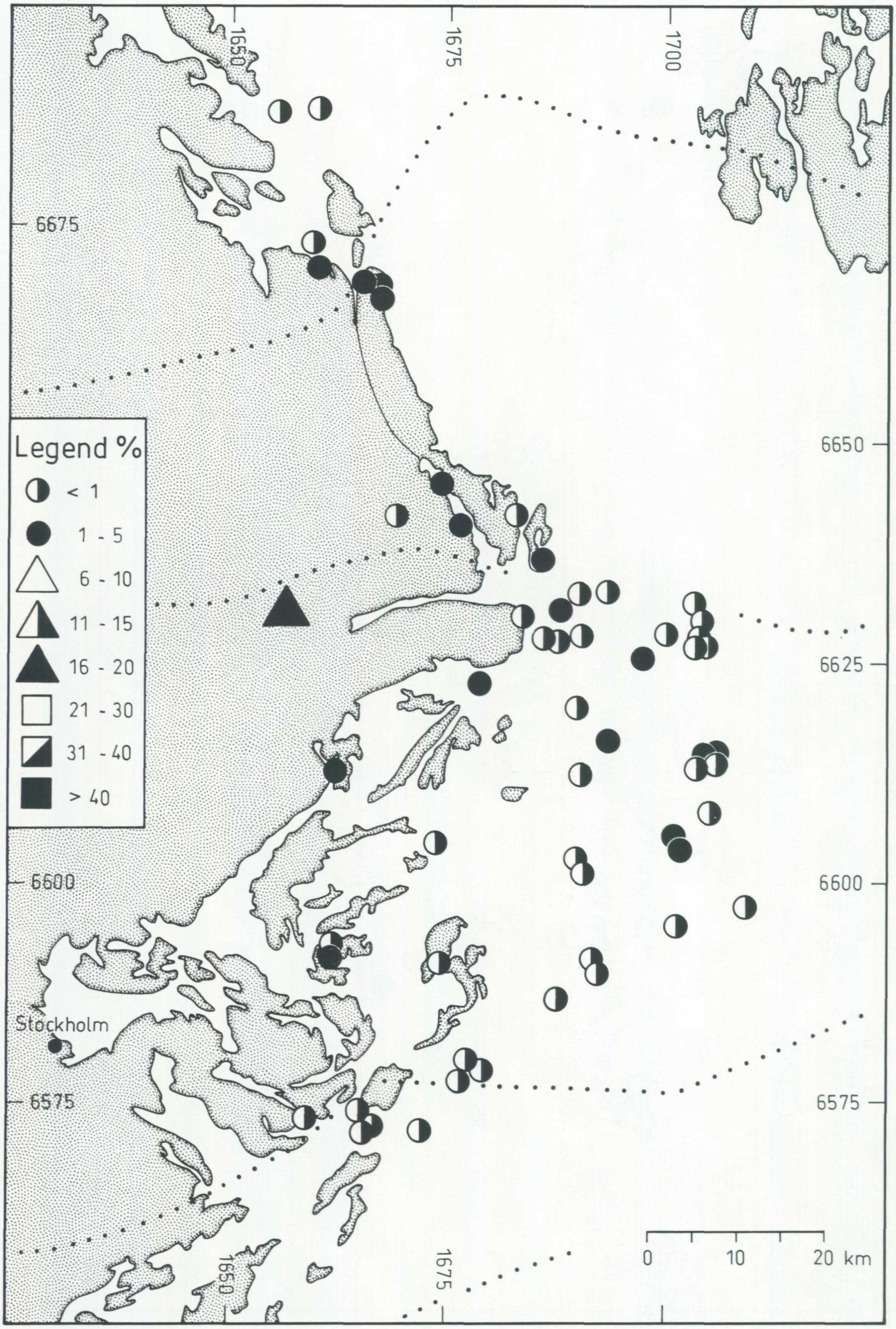

Fig. 12. Frequency counts of limestone erratics from unit 3 (Middle Ordovician). Dotted lines: see Fig. 4.

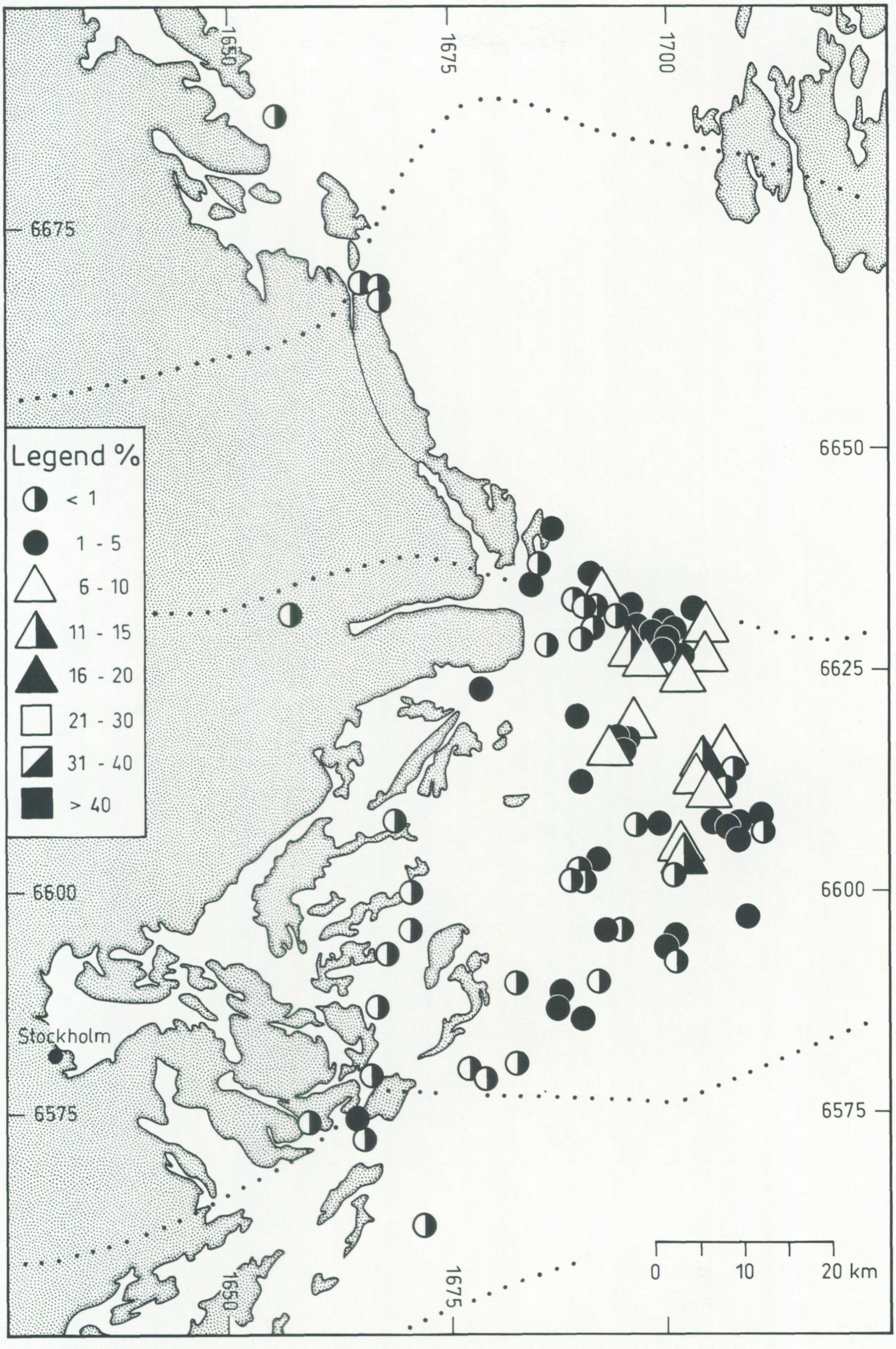

Fig. 13. Frequency counts of Baltic limestone erratics from unit 3 (Upper Ordovician). Dotted lines: see Fig. 4.

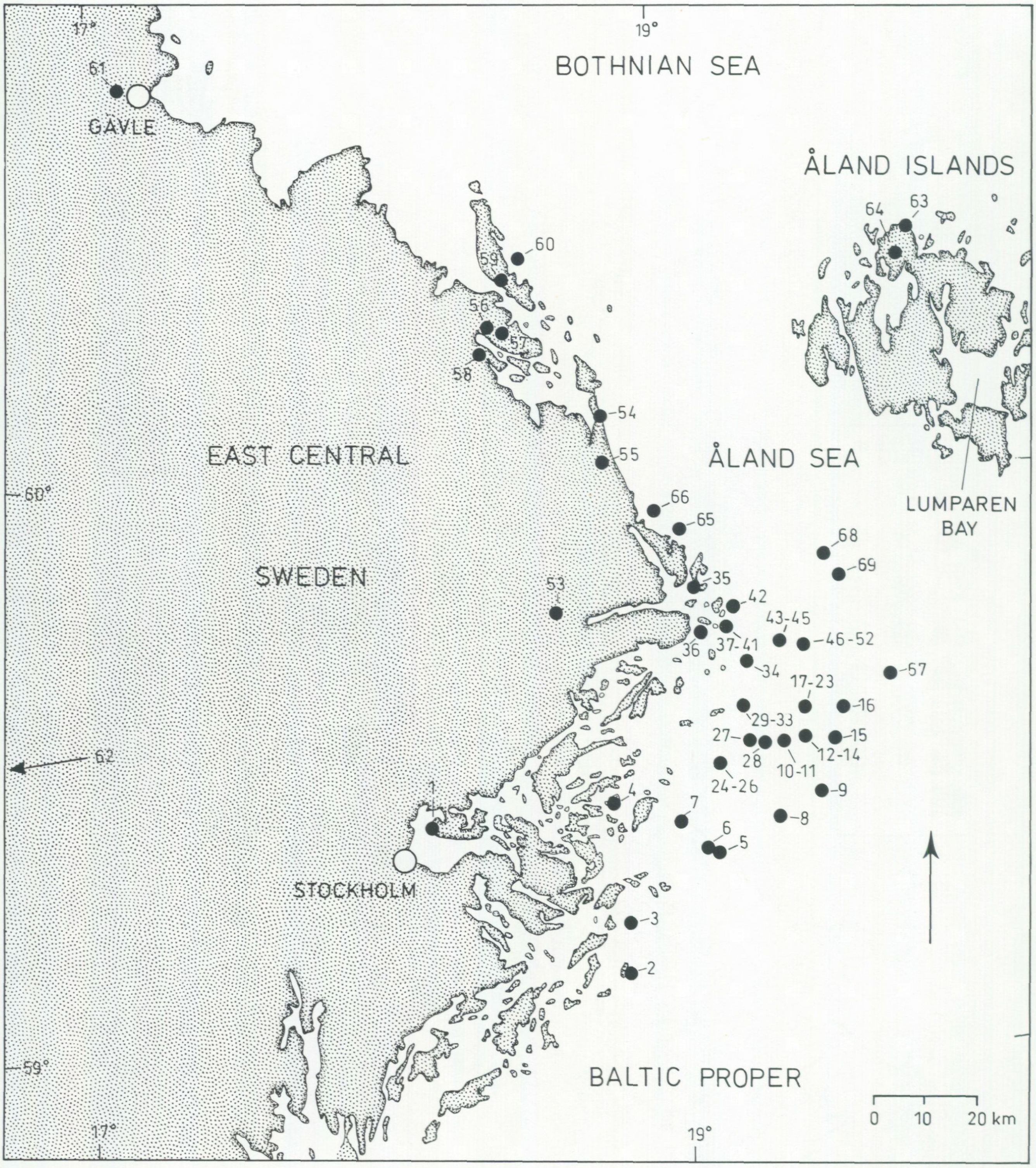

Fig. 14. Geographic location of sites where erratics of dolomitic Baltic limestone have been found in the investigated area. See Hagenfeldt (1995) for the names of the sites.

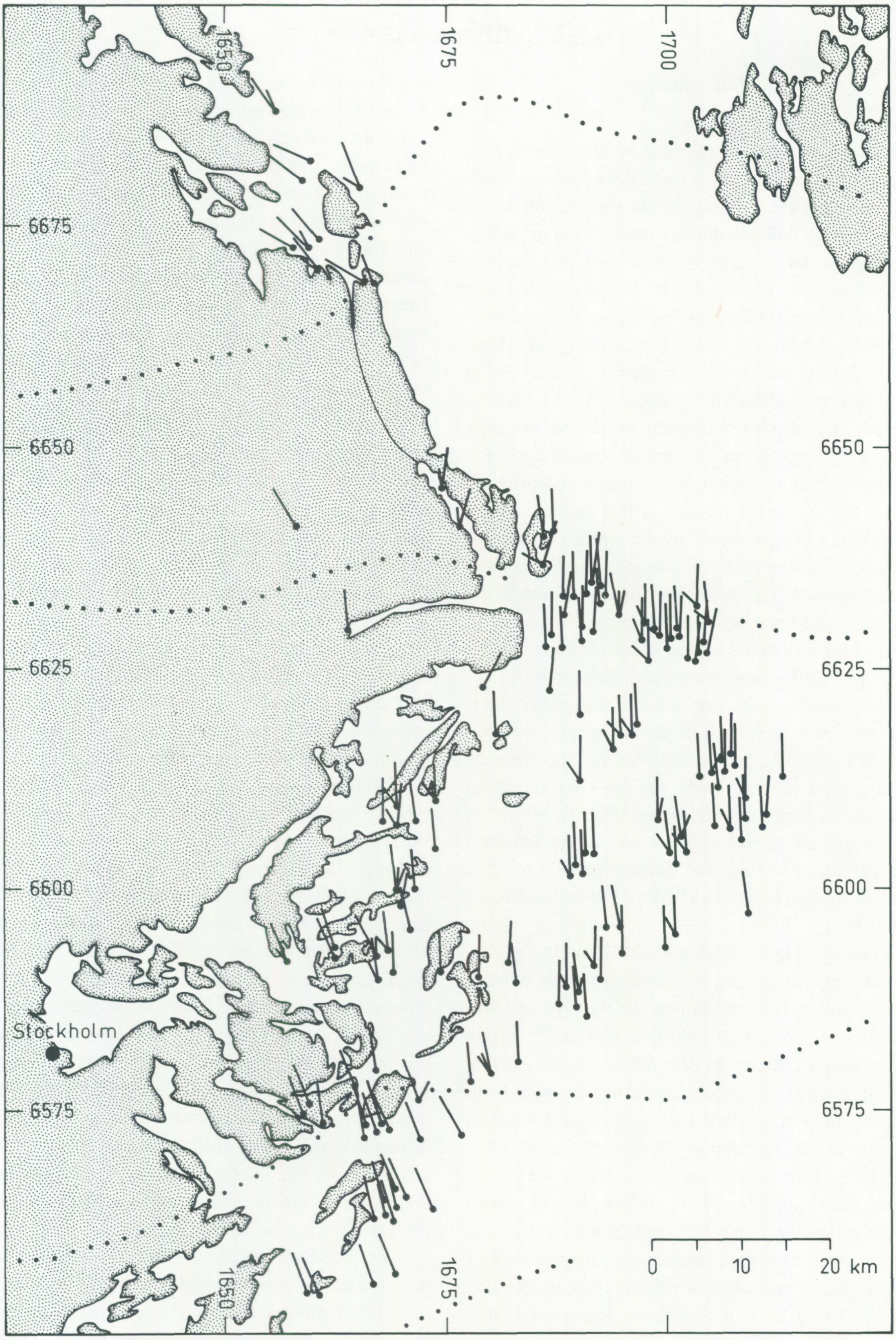

Fig. 15. Observations of glacial striae. The latest direction of the inland ice movement is shown by the longest lines, while older, not further subdivided directions are marked by shorter lines.

Discussion

Age and distribution

Unit 1: Lower to Middle Riphean

Erratics from this part of the sedimentary sequence display lithologies similar to the Lower to Middle Riphean sandstone in surrounding areas (Table 2). The reddish colour, the degree of roundness (subangular to rounded), the grain size (very fine to very coarse-grained sandstone), and the very good consolidation are comparable with similar sandstones in the Dalarna, Ekerö, Gävle, Nordingrå, and Satakunta areas (Figs. 1 and 2; Juhlin et al. 1991; Flodén et al. 1993; Gorbatschev 1967; Bergman 1980; Kohonen et al. 1993), as well as the basal part of the Muhos Group (Fig. 5). However, the content of feldspar is less in the lithologies of unit 1 in the Åland Sea, as compared with the average composition of the Lower to Middle Riphean sandstone occurrences mentioned above. There is a possibility that only the uppermost part of unit 1 is represented by the erratics, whereas a more feldspar rich lower part is not exposed, and hence did not yield any erratics. This lower part is represented in the Gävle, Mälaren, and Satakunta sandstones.

In the Gotland area of the central Baltic the upper part of the Lower to Middle Riphean is not comparable to unit 1 because of the generally more fine grained appearance. Gorbatschev (1962) also emphasized the difference between true Lower to Middle Riphean lithologies and the presence of more fine grained sandstones on the East European Platform as in the Gotska Sandön area (Fig. 1). However, dredgings in the submarine cliff present in the Landsort Deep not far from Gotland and Gotska Sandön yielded coarse grained reddish Lower to Middle Riphean sandstones (Flodén 1980).

In Lake Ladoga (Fig. 1) reddish sandstones occur in a sequence containing two phases of Middle Riphean dolerite intrusion (Amantov 1992; Koistinen 1994). The reddish sandstone has a composition similar to that of unit 1. In this part of the sequence other types of sandstone occur as well. A white fine grained sandstone, occurring together with intervening layers of black shale in drill-cores, was dated as deposited prior to the intrusion of the latest dolerites in the Ladoga basin. Similar lithologies have been found in the present erratic material, referred to unit 2 because of resemblance to the relatively young Visingsö Group, which also contains dark shale and white sandstone. The presence of similar lithologies in two units of different age casts some doubt on the dating of unit 2 erratics attempted in the present paper, a circumstance to which reference will be made below.

Unit 1 of the Söderarm formation is present as erratics all over the investigated area, as well as in the supplementary investigations in the Lake Erken area, the Öregrund Archipelago, and on the Åland Islands. The relatively great frequencies of erratics of unit 1 in the northern part of the Stockholm Archipelago indicate the presence of the mentioned unit in the Åland Sea area, corroborating marine seismic investigations (Söderberg 1993). In the Stockholm Archipelago, small *in situ* occurrences of unit 1 of the Söderarm formation might be indicated by locally increased frequencies, in combination with the presence of striated boulder erratics. The discovery of a small outcrop of unit 1 of the Söderarm formation, on the Österskäret islet outside the Åland Sea basin (Figs. 3 and 16) is in accordance with this suggestion (Hagenfeldt & Söderberg 1994).

Unit 2: Upper Riphean/Vendian

One of the main criteria for the attribution of erratics to unit 2 is the content of clasts derived from unit 1 in such lithologies. Gorbatschev (1967) mentioned the analogous case that in the Gävle sandstone no cannibalistic trends were noted in the Lower to Middle Riphean sandstone itself, though other sandstones preceding the Lower to Middle Riphean were incorporated as detrital in the sandstone sequence. If this analogy holds, the presence of detrital parts of unit 1 can be used as a criterion for the separation of units 1 and 2. Furthermore, the predominantly red colour of sediments, referred to unit 1, is not present in erratics attributed to unit 2.

Sandstones known to be of Lower to Middle Riphean type are well consolidated, which is not the case with lithologies assigned to unit 2. This distinction must be considered as local. Gorbatschev (1967) advanced the concept that there might have been an overburden of rocks of at least up to 600 m thickness above the top of the present Lower to Middle Riphean sandstone. This was indicated by compactional features in the topmost part of the Gävle sandstone. No such structures were found in the present erratics from the Stockholm Archipelago, which are poorly consolidated.

Clasts of Svecofennian origin have been described from several parts of the Lower to Middle Riphean Gävle Sandstone. This circumstance does not imply that the erratics assigned to unit 2, where such clasts also occur, must be of the same age as the Gävle sandstone, because situations in which the Svecofennian bedrock was eroded may have existed on different occasions.

Compared with the Visingsö Group, dated as deposited during a time range comprising the Late Riphean and Vendian, lithologies attributed to unit 2 are in part similar. The poor consolidation and high content of feldspar, combined with the presence of conglomerate horizons (Vidal & Bylund 1981) are similarities between the middle unit of the Visingsö Group and unit 2 of the Söderarm formation.

Table 2. Outcrops of sedimentary bedrock spanning the Upper Proterozoic and Lower Palaeozoic. Abbreviations are as follows - L.-M.R. = Lower to Middle Riphean; U.R. = Upper Riphean; V. = Vendian; C. = Cambrian; O. = Ordovician, S. = Silurian. A question mark indicates uncertain dating. References as follows: 1. Wannäs (1989); 2. Axberg (1980) 3. Söderberg (1993); 4. Amantov 1992; 5. Grigelis (1991); 6. Winterhalter (1982); 7. Ormö (1994); 8. Flodén et al. (1993); 9. Flodén (1980); 10. Vidal (1974, 1976), Axberg & Wadstein (1980); 11. Tynni & Uutela (1984); 12. Bergman (1980); 13. Juhlin et al. 1991; 14. Gorbatschev (1967); 15. Kohonen et al. (1993); 16. Gorbatschev & Kint (1961).

Locality	System/Series					
Offshore						
1. Bothnian Bay	L.-M.R.?	U.R.	V.	C.	-	-
2. Bothnian Sea	L.-M.R.	U.R.?	V.?	C.	O.	-
3. Åland Sea	L.-M.R.	U.R.	V.	C.	O.	-
4. Gulf of Finland	-	-	V.	C.	-	-
5. Lake Ladoga	M.R.	U.R.	V.	C.	-	-
6. Lumparen Bay	-	-	-	C.?	O.	-
7. Tvären Bay	-	-	-	C.?	O.	-
8. Lake Mälaren*	M.R.	-	-	-	-	-
9. Gotland area	L.-M.R.	-	-	C.	O.	S.
10. Lake Vättern	-	U.R.	V.	C.	O.	-
Onshore						
11. Hailuto Island and Muhos area	L.-M.R?	U.R.	V.	-	-	-
12. Nordingrå area	L.-M.R.	-	-	-	-	-
13. Dalarna area	L.-M.R.	-	-	-	-	-
14. Gävle area	L.-M.R.	-	-	-	-	-
15. Satakunta area	L.-M.R.	-	-	-	-	-
16. Ekerö, Pingst, and Midsommar Islands*	M.R.	-	-	-	-	-

* Dating of the basal part of the Mälar sandstone by the K-Ar method indicated that an age of the Mälar sandstone is 1203-1216 Ma (Flodén et al. 1993). Hence, the sequence is not older than Middle Riphean.

Following the concept that the Lower to Middle Riphean sedimentary rock sequence was eroded as a consequence of tectonic events, a possible association is with the Sveconorwegian orogenic cycle around 1080–1000 Ma (Lindström et al. 1991). Similar conditions are indicated on the East European Platform, where nonconformities exist between the Middle and Upper Riphean Groups in aulacogen basins (Chumakov & Semikhatov 1981).

The black shale erratics, probably belonging to unit 2 of the Söderarm formation, might be time equivalent with similar shales from the upper unit of the Visingö Group. Vidal (1976) dated the shales by examination of acid-resistant microfossils (acritarchs) as deposited during Early Vendian time (= late Riphean Kudashian, R_4, Vidal & Siedlecka 1983, p. 69). Despite the coalified nature of the microfossils from the shales attributed to unit 2 of the Söderarm formation, it is suggested that unit 2 is equivalent to the Visingsö Group. A Late Riphean to Vendian age is therefore proposed for the unit.

Dark grey, red and greenish mudstone occurs as interbeds in the predominantly sandy sequence of the Satakunta basin (Kohonen et al. 1993). The mudstone interbeds are most frequent in the upper parts of the sequence. The dating of dolerites intruding in the sedimentary sequence in Satakunta basin indicated a Lower to Middle Riphean age for the sedimentary bedrock. Similar conditions are noticed in the Lake Ladoga basin, where black shales are interfingering in the Middle Riphean sandstone (Amantov et al. 1995). However, there are no reports of organic material in support of the possibility that marine conditions prevailed during Early to Middle Riphean time in the Satakunta and Lake Ladoga basins, contrary to indications in the Åland Sea by the presence of presumed acritarch microfossils. If the discussed difference in facies conditions holds a correlation between the black shale present in the Visingsö Group and the Åland Sea is favoured.

Unit 2 of the Söderarm formation has a distribution pattern which indicates an *in situ* occurrence restricted to the Åland Sea and the western part of the Söderarm Archipelago (Fig. 16 and Table 3). In addition, Veltheim (1962) described sandstone erratics from the northern Åland Sea, which are comparable with sandstones of unit 2 of the Söderarm formation (cf. Söderberg 1993). These finds indicate that unit 2 might be locally exposed in the northern part of the Åland Sea. Data from supplementary studies in the Lake Erken area, the Öregrund Archipelago, and the Åland Islands showed the absence of erratics deriving from unit 2. This circumstance suggests the absence of equivalents of unit 2 in the Bothnian Sea. Another possibility is that the equivalent of unit 2 may be covered by younger bedrock and is thus not represented in the erratic material.

Based on data derived from erratics dark shales are thought to have been deposited in the Åland Sea basin. Supposed equivalents to this shale are present in the Vättern basin, and may indicate that the shale in the Åland Sea area formed a northeasterly continuation of the Visingö Group (Amantov et al. 1995). In the Bothnian Bay silty shales of the Muhos Group (Wannäs 1989), of an inferred Late Riphean to Early Vendian age (Tynni & Uutela 1984), may be the northernmost extension of a marine transgression, extending from the Mjösa District in Norway to the Bothnian Bay (Fig. 1).

Unit 3: Cambrian

Erratics, containing trace fossils indicating an Early Cambrian age, were assigned to the Lower Cambrian File Haidar Formation. *In situ* finds of *Monocraterion* have been made in the lower part of the Lingulid sandstone member of the Lower Cambrian File Haidar Formation in the Kinnekulle area (Fig. 1; Jensen 1995). In these parts of the Lower Cambrian in south central Sweden finds of macrofossils and microfossils indicate a *Holmia inusitata – Holmia kjerulfi* age (Moczydlowska 1991). In addition, results based on studies of acritarchs from the islands of Gotland, Gotska Sandön, and the Bothnian Sea area also indicate that the Lower Cambrian in the Åland Sea should be assigned to the *Holmia inusitata – Holmia kjerulfi* age and probably the *Proampyx linnarssoni* Zone (Hagenfeldt 1989a). The finds of the above mentioned trace fossils suggest that the range of the Lower Cambrian in the Åland Sea is within a similar time span.

Erratics, which have been derived from the Lower Cambrian of unit 3, are present all over the Stockholm Archipelago, the Lake Erken area, the Öregrund Archipelago, and on the Åland Islands. The occurrence of big boulders of the Lower Cambrian in the Söderarm Archipelago, as well as along the coast of Väddö Island (Fig. 3) in the northern part of the study area, though moderate in frequency, indicates the presence of unit 3 in the Åland Sea.

Middle Cambrian *Oelandicus* beds (Fig. 5) are thought to be missing in east central Sweden and the Åland Sea, though present in the Bothnian Sea, western Finland, and on the islands of Öland, Gotland and Gotska Sandön (Ahlberg 1989, Hagenfeldt 1989b), as well as possibly on the Åland Islands (Uutela personal communication 1989). The presence of the upper parts of the Middle Cambrian, i.e. the *Paradoxides paradoxissimus* and *P. forchhammeri* Stages, is neither verified in the Åland Sea, nor in the Bothnian Sea, nor in the Gotland and Gotska Sandön areas. On the basis of previously presented data one cannot exclude the possibility that shales of the *Eccaparadoxides oelandicus* Stage crop out in the Åland Sea. The softness of the shale might have caused the absence of erratics of this part of the sequence.

In the erratic material of the present investigation there are no Upper Cambrian rocks, though such rocks are preserved as sandstone fissure fillings on the Åland Islands (Holmer & Popov 1990). There is no evidence of the occurrence of erratics derived from the Alum Shale Formation, in spite of the occurrence of this formation in the Baltic Proper and south central Sweden (Thickpenny 1987).

Unit 3: Ordovician

The dating of the Ordovician limestone erratics indicates a time range including Oelandian to Harjuan. Finds of erratics of "*Obolus*" conglomerate in the present investigation on the island of Väddö suggest that this unit is represented in the sedimentary sequence in the Åland Sea. If this statement holds true an extension of Tremadocian beds may have existed from the north Estonian escarpment area, through the Åland Sea and Bothnian Sea areas to the Siljan District (Fig. 1; Holmer & Popov 1992). On Gotska Sandön, Gotland, and the Åland Islands, Tremadocian beds are supposed to be missing (Grahn 1982; Tynni 1982). However, recent finds of thin beds of "*Dictyonema*" bearing Alum shale from the central part of Gotland (Andersson et al. 1985, p. 26) correlate with coeval sequences in the Åland Sea.

Furthermore, the presence of "Orthoceratite" limestone, including the Latorp, Lanna and Holen Limestones, is indi-

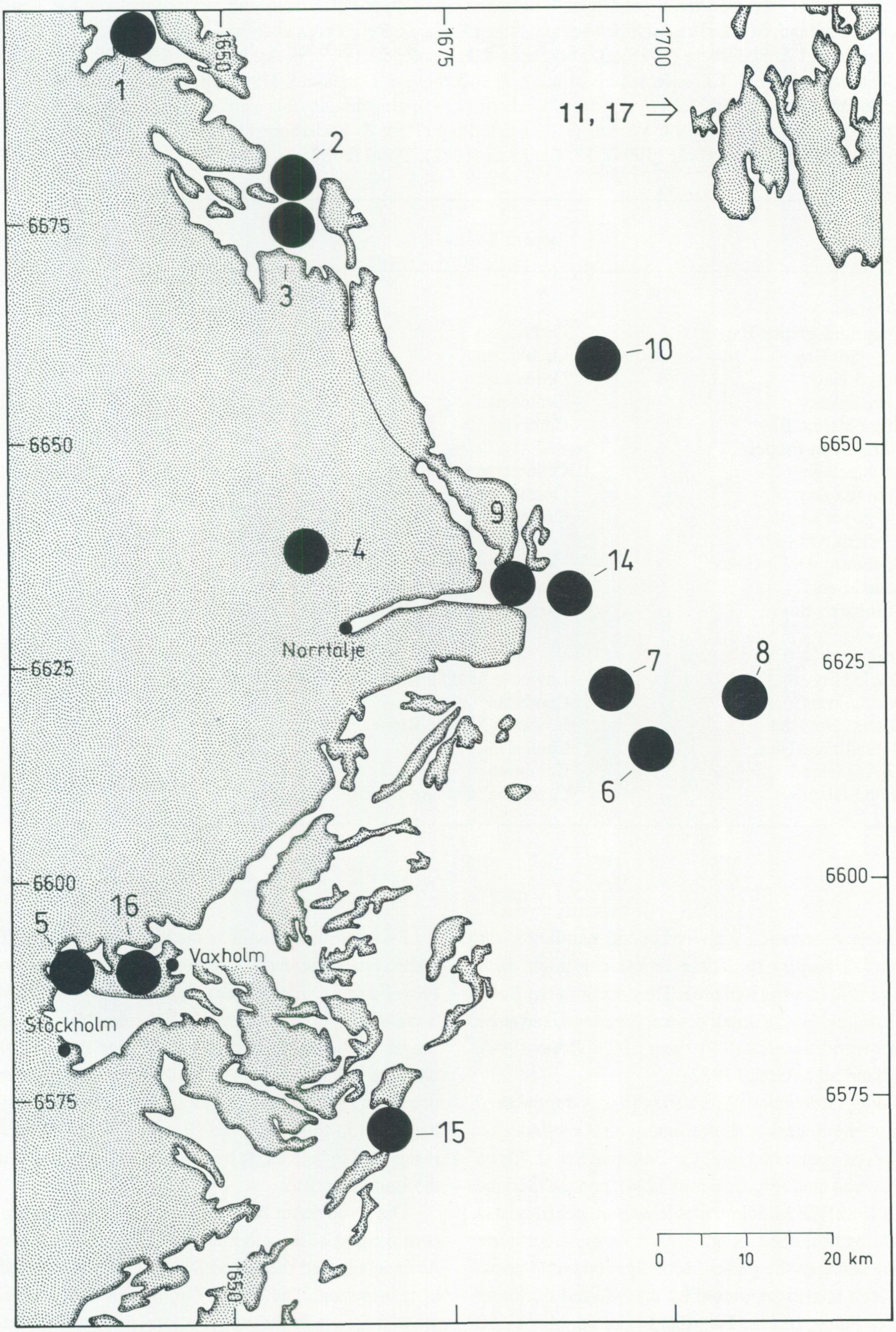

Fig. 16. *In situ* occurrences of presumed sedimentary rocks in eastern Sweden. Redrawn from Söderberg (1993); Hagenfeldt & Söderberg (1994); Söderberg & Hagenfeldt (1995) and the present paper. The sites are presented in Table 3.

Table 3. Suggested *in situ* occurrences of Upper Proterozoic and Lower Palaeozoic sedimentary rocks in the coastal area of Uppland, Stockholm Archipelago, and Åland Sea area. References as follows: 1. Persson (1985, 1986); 2. Hagenfeldt & Söderberg (1985); 3. Söderberg & Hagenfendt (1995); 4. Asklund (1930); 5. Hagenfeldt & Söderberg (1994); 6. Hagenfeldt (this article); 7. Söderberg & Hagenfeldt (1995); 8. Hagenfeldt (this article); 9. Söderberg & Hagenfeldt (1995); 10. Söderberg (1993); Hagenfeldt (this article); 11. Winterhalter (1982); 12. Gorbatschev (1967); 13. Wiman (1918); 14. Hagenfeldt & Söderberg (1994)); 15. Holmquist (1920); 16. Hagenfeldt & Söderberg (1994); 17. Bergman (1982), Tynni (1982).

Locality	System/Series
Offshore	
1. Öregrundsgrepen Bay	Ordovician
2. Raggarö Bay	Ordovician
3. Singö Bay	Ordovician
4. Lake Erken	Ordovician
5. Stora Värtan Bay	Cambrian
6. North of In-Fredel Archipelago	Ordovician
7. Vidinge Bay	Ordovician
8. Uddjupet Depth	Ordovician
9. Western part of Söderarm Archipelago	Upper Riphean/Vendian
10. Åland Sea	Lower to Middle Riphean to Ordovician
11. Lumparen Bay	Cambrian? and Ordovician
Onshore	
12. Gävle City	Lower to Middle Riphean and Cambrian
13. Wattholma Quarry	Cambrian
14. Österskäret Islet	Lower to Middle Riphean
15. Bötsholmen Islet	Cambrian
16. Resarö Island	Cambrian
17. Åland Islands	Cambrian and Ordovician

cated by finds of erratics with orthocone nautiloids and *Megistaspis* (*Varvaspis*) sp. These limestones might have covered the entire investigated area. They occur in the Bothnian Sea (Löfgren 1985), south central Sweden (Jaanusson 1982), east central Sweden (Söderberg 1993; Ormö 1994), and the Gotland area (Grahn 1982).

The Middle Ordovician Viru Series is only represented by erratics of the Segerstad Limestone with *Angelinoceras latum*. However, comparing with the Bothnian Sea (Löfgren 1985), the Tvären area (Fig. 1; Ormö 1994), and the Gotland area (Grahn 1982) the Middle Ordovician part, possibly also including Dalby limestone, is believed to be more complete in the Åland Sea than the present investigation could document. This idea is also supported by the inferred thickness of the Lower Palaeozoic in the Åland Sea, i.e. about 350 metres (Söderberg 1993), because the Cambrian, Oelandian and Harjuan together are not expected to reach this thickness.

Finds of macrofossils in the Upper Ordovician (Harjuan) Baltic limestone erratics, represented by *Vellamo* sp., *Sowerbyella* sp., *Cyclocrinites* sp., and *Vermiporella* sp. make a correlation possible with the Rakvere, Nabala, and Pirgu Stages of the North Estonian Confacies Belt. A correlation with the Lumparen Limestone is suggested, in spite of the uncertain range of the conodont *Amorphognathus superbus* identified in this limestone (Bergström 1977). This species is reported to be present by Merrill (1980) in drill cores from the Lumparen Bay.

The Ordovician limestone of unit 3, making up the uppermost part of the sedimentary sequence in the Stockholm Archipelago and the Åland Sea, shows a diversified pattern of distribution. The Upper Ordovician Baltic limestone is more frequent in the northeastern part of the investigated area than the Lower and Middle Ordovician "Orthoceratite" limestone. However, the frequency of the limestone lithologies is reversed in the western part. Locally greater frequen-

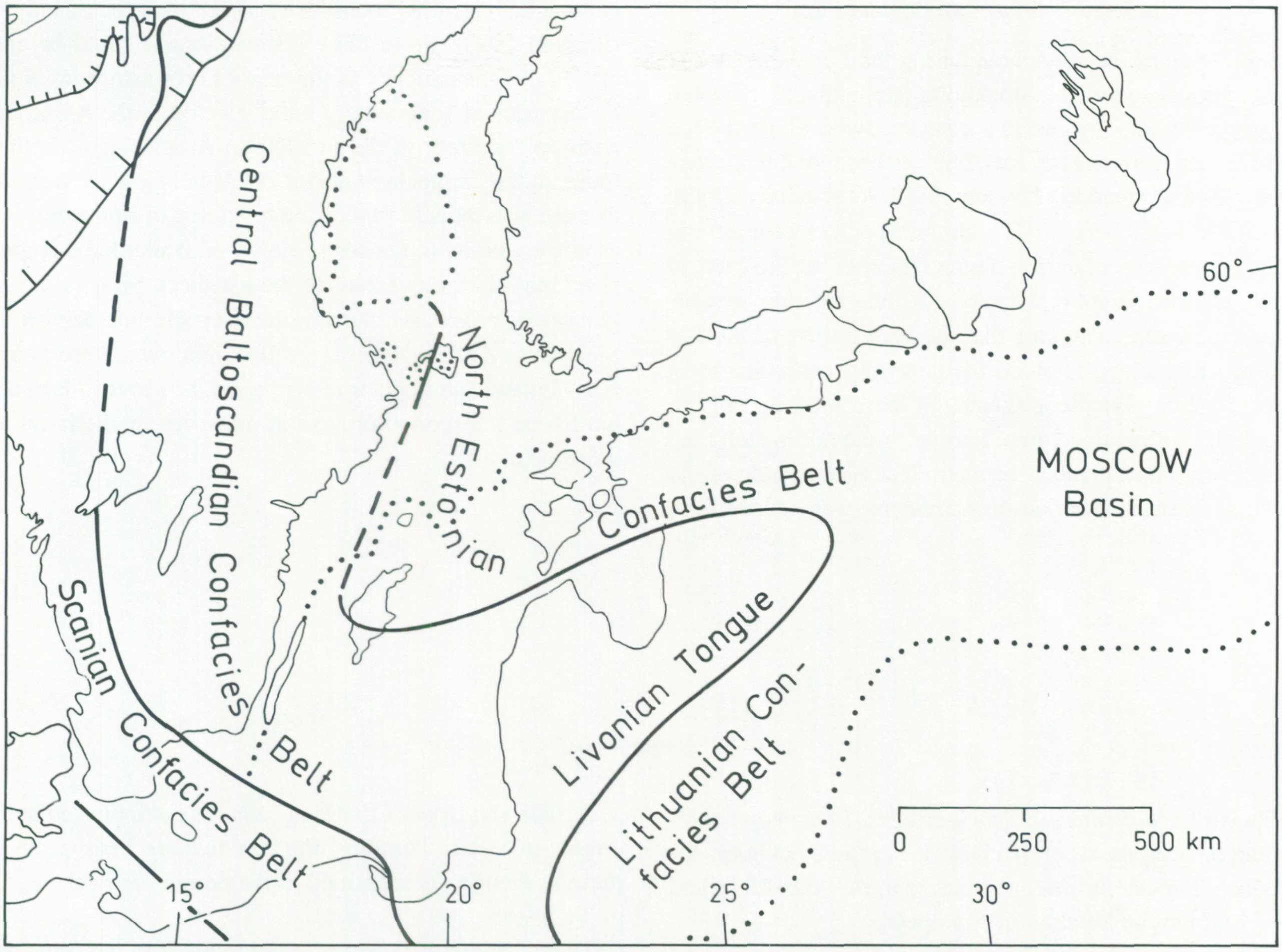

Fig. 17. Distribution of confacies belts during the Ordovician. Mainly after Jaanusson (1982). The Åland Sea and the Stockholm Archipelago are suggested to belong to the Central Baltoscandian Confacies Belt, while the Åland Islands are brought to the North Estonian Confacies Belt.

cies are noted in the area south of the Vidinge Bay (Söderberg & Hagenfeldt 1995; Figs. 3, 11 and 13). Here, the "Orthoceratite" limestone and the Baltic limestone are supposed to be present *in situ*, suggested by the composition of the erratic population. In addition, great frequencies of Baltic limestone erratics are noticed south of the Uddjupet Depth, also suggesting a local *in situ* occurrence in that area. In addition, great frequencies of Baltic limestone in the In-Fredel Archipelago also suggest a local *in situ* occurrence in the vicinity to the north of that archipelago. Otherwise, the general frequency pattern indicates an *in situ* occurrence of the Baltic limestone in the Åland Sea, especially in the eastern part; see also Söderberg (1982, 1993).

Frequent erratics of dolomitic Baltic limestone were found in the Stockholm Archipelago. These finds indicate *in situ* occurrence of such limestone in protected positions within the archipelago, as well as in the Åland Sea basin. Subsea investigations in the Åland Sea corroborate this discovery (Söderberg & Hagenfeldt 1994). In addition, dolomitic Baltic limestone erratics, found in the northern part of the Åland Islands, probably originate from the Bothnian Sea and are correlated with the Saunja beds in northern Estonia. The occurrences in the Åland Sea and the Bothnian Sea could possibly be regarded as a westerly extension of dolomitic limestone facies present as far east as the St. Petersburg area and corresponding to the Nabala (FIa) Stage.

Following Jaanusson (1976), the Stockholm Archipelago and Åland Sea areas are inferred to belong to the Central Baltoscandian Swedish Confacies Belt, which is indicated by reddish limestone erratics present in the investigated area. Furthermore, the investigated area constitutes the easternmost occurrence of this belt, as strata of the North Estonian Confacies Belt are present in the Lumparen Bay (Fig. 17).

The Late Weichselian deglaciation

The direction of ice movement during the Late Weichselian deglaciation stage of the Stockholm Archipelago, indicated by glacial striae, changed in a constant sense along the ice front. Going from west to east, one can observe a clockwise turning of the direction (Persson 1990). As stated by Frödin (1956) and Strömberg (1971), the further clockwise turning of the ice movement during the recession of the ice front in the Väddö area might represent an accommodation to topographic obstacles. It seems that the eastern part of the Söderarm Archipelago retained the generally north–south direction, which also predominates in the central part of the Stockholm Archipelago area. Further to the north, along the coastal area of Uppland, a counter clockwise turning of the ice front, shown by striae measurement, was caused by a calving bay, forming a concave lobe all over the Åland Sea (Persson 1990). From these observations it could be concluded that the majority of the erratics originate from *in situ* occurrences of sedimentary rocks located in the Åland Sea basin to the north of the Stockholm Archipelago. Furthermore, in the archipelago area itself, locally greater frequencies are also thought to indicate restricted *in situ* occurrences in the vicinity to the north. However, it should be emphasized that older movement of the ice sheet, prior to the deglaciation, might have accumulated erratic boulders in the Stockholm Archipelago. Large boulders, which are poorly consolidated and angular in shape are, however, inferred to have been transported only short distances by the latest ice movement.

Results

1) Finds of sedimentary bedrock erratics, frequency counting and measurements of glacial striae in the Stockholm Archipelago indicate *in situ* occurrences in the Åland Sea, and locally within the Stockholm Archipelago.

2) The sedimentary bedrock sequence is subdivided into 3 units, of which the lower two are referred to the informal Söderarm formation. The units are interpreted as belonging to a total time range from the Early to Middle Riphean to the Late Ordovician as follows: unit 1 of the Söderarm formation: Early to Middle Riphean, unit 2 of the Söderarm formation: Late Riphean to Vendian, unit 3: Lower Cambrian sandstone and siltstone of the File Haidar Formation and Lower to Upper Ordovician limestones. Major tectonic events are indicated during the deposition of unit 2 of the Söderarm formation.

3) Supplementary investigations in adjacent areas (Lake Erken, Öregrund Archipelago, and Åland Islands) indicate the absence of erratic boulders of unit 2. If this is correct, unit 2 of the Söderarm formation might occur *in situ* only in the Åland Sea and the northern part of the Stockholm Archipelago.

4) Deposition of Lower Cambrian strata was initiated during the time of the *Holmia inusitata* and *Holmia kjerulfi* group Zones.

5) Middle and Upper Cambrian beds are not indicated in the erratic material. Possibly, the *Oelandicus* beds may be present, though not identified in the erratic material.

6) Tremadocian strata are indicated by finds of the "*Obolus*" conglomerate in the Åland Sea area.

7) "Orthoceratite" limestone is indicated to occur *in situ* in the Åland Sea and in the northern part of the Stockholm Archipelago. The bedrock sequence is suggested to consist of the Latorp, Lanna and Holen Limestone.

8) The occurrence of Segerstad Limestone is demonstrated by finds of *Angelinoceras latum*. Indications of a more complete Middle Ordovician sequence, possibly also including the Dalby limestone, would have to be searched for by a more intensive and further differentiated study of the erratics, including further micropalaeontological investigations.

9) Harjuan, dolomitic Baltic limestone (Upper Caradocian to Ashgillian), with *Vermiporella* sp., *Cyclocrinites* sp., *Vellamo* sp. is indicated to occur *in situ* in the Åland Sea, in the northern part of the Stockholm Archipelago and in the Bothnian Sea.

10) The Åland Sea and Stockholm Archipelago areas are indicated to have belonged to the Central Baltoscandian Confacies Belt during Ordovician time. The Åland Islands are attributed to the North Estonian Confacies Belt.

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