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Bedrock stability in southeastern Sweden. Evidence from fracturing in the ordovician limestones of northern Öland

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BEDROCK STABILITY IN SOUTHEASTERN SWEDEN - EVIDENCE FROM FRACTURING IN THE ORDOVICIAN LIMESTONES OF NORTHERN ÖLAND

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ABSTRACT

The stability of the bedrock in SE Sweden with regard to radioactive waste disposal has recently been the subject of some controversy. In order to better assess the age and significance of fracturing in the Precambrian basement at the site of the Äspö Hard Rock Laboratory (HRL), near Oskarshamn, a detailed analysis of fracturing in the lower Ordovician limestones exposed along the west coast of the neighbouring island of Öland has been carried out. The limestones form continuously exposed shore platforms, in segments up to 30 m broad and several kilometres long. These, and the numerous quarries, provide ideal objects for quantitative analysis (ground and air photo mapping, scanline logging), and unique opportunities for investigating the amount of movement on the fractures, because of well-developed bedding and abundant rod-shaped fossils on the bedding surfaces.

The fracture patterns are dominated by two sets of subvertical fractures, a NW trending closely spaced and strongly orientated set (set A) and a NNE-ENE trending widely spaced and variably orientated set (set B). Only about 10% of the fractures in both sets show lateral fossil displacement, with maximum movement of 5 cm, and only 3% of the fractures show vertical displacement of bedding (maximum 8 cm).

All in all, the lower Ordovician limestones along the exposed shoreline have suffered remarkably little deformation since deposition, i.e. over the last 500 million years. Appreciable bedrock instability, if it occurred, must have been concentrated offshore, or in the unexposed segments of the coastline, where some weak indications of slight movement (changes of a few metres in stratigraphic level) have been observed. Among other recommendations for further work, geophysical investigations to test these indications are suggested.

ACKNOWLEDGEMENTS

We would like to thank Patrick Nilsson and Agneta Månsson for excellent assistance in the field, including the "breathtaking" photography which made the air photo mapping possible. We are grateful to Chris Talbot for a very thorough review. The Geological Survey of Sweden is thanked for permission to publish Figure 2-3.

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SUMMARY

A detailed study of fracturing in the Ordovician (Arenig) limestones exposed along the west coast of the island of Öland (SE Sweden) has been carried out. Because the age of deformation is clear (post-Ordovician), this evidence may help to assess the age and significance of fracturing in the underlying Precambrian basement on the adjacent mainland, where the Äspö Hard Rock Laboratory (HRL) of the SKB is being built. The study concentrated on northern Öland (directly opposite Simpevarp), where the limestones are exposed on wide wave-cut pavements, on rocky shores and in numerous quarries, giving five continuously exposed sections, each several kilometres in length. Particularly the wave-cut pavements are ideal objects for quantitative fracture analysis (ground and air photo mapping, scanline logging); thanks to the occurrence of well developed bedding and the abundance of rod-shaped fossils on the subhorizontal bedding surfaces, they provide unique opportunities for investigating the amount of movement which has taken place on each individual fracture.

Results showed that the northern tip of the island (north of Byxelkrok) has a simple but somewhat different pattern to the rest of the coastline to the south, possibly indicating a NW-SE trending disturbance running through the exposure gap at Byxelkrok Bay (a reactivated SE continuation of the Västervik fault zone?). South of Byxelkrok, however, over a distance of 30 km, the fracture pattern shows rather constant characteristics, dominated by a NW trending, closely spaced fracture set (set A), showing strong preferred orientation and widespread mineralization (calcite coating), and a more widely spaced and variable NNE-ENE trending set or group of subsets (set B), showing bimodal or multimodal distributions and less mineralization. About 10% of the fractures in both sets show lateral displacement of fossils (maximum 5 cm), with a tendency for dextral movement on set A and sinistral on set B. However, 90% of the fractures show no lateral displacement whatsoever. The proportion of fractures showing vertical displacement of bedding (to a maximum of 8 cm) is even less, only 3%. None of the continuously exposed shore sections showed signs of faulting, except some quarries, where large subhorizontally slickensided surfaces are sporadically exposed. However, even slickensided surfaces signified only small movements (a few cm) and were not concentrated in zones or confined exclusively to the quarries or to particular fracture sets. All in all, the Ordovician limestones along the exposed shorelines and in the quarries have suffered remarkably little deformation in the last 500 million years.

Appreciable bedrock instability during this time period, if it occurred, must have been concentrated offshore, or in the unexposed segments of the coastline (exposure gaps), where weak indications of slight movement (e.g. changes of a few metres in stratigraphic level over distances of kilometres) have been observed. The history of the slight post-Ordovician deformation in the exposure shore sections have been analyzed in terms of infinitesimal strain increments (leading to an interpretation of stress history).

To understand the significance of these results for assessing the stability of the Precambrian crystalline bedrock of the adjacent mainland (e.g. at Äspö) it is recommended (a) that similar studies are extended to southern Öland, (b) that complementary studies are made of the outcrops with Cambrian sandstone dykes on the islands offshore from Simpevarp (between Äspö and Öland), and (c) that geophysical studies, particularly detailed high-resolution reflection seismic profiling, be carried out on Öland and between Öland and the mainland to see if it is possible to recognize faults in the Cambro-Ordovician strata and Quaternary sediments. The fracture systems on the mainland should then be reassessed in the light of a well-founded and demonstrable offshore Phanerozoic history.

1 INTRODUCTION

The idea behind the present project was conceived during the early years of the Swedish radwaste debate about bedrock stability and born one clear day in February 1989 standing on the cleaned outcrops of Äspö island, the site of the Hard Rock Laboratory (HRL). Inconclusive discussions about the age and significance of the numerous fractures and fracture zones exposed in the Oskarshamn area were in progress; the long-term stability of the old crystalline bedrock was the bone of contention. Eastwards, behind the blocks and chimneys of the Oskarshamn nuclear power stations, the long low outline of the island of Öland could be clearly seen, less than 25 km away (Figure 1-1). The obvious question arose: what does the (certainly Phanerozoic) fracture pattern in the Ordovician limestones, exposed and quarried along the Öland coastline, look like? The answer was: we do not know. This was the starting point for the study reported here. The project proposal was submitted after a first reconnaissance of northern Öland in October 1989, and the work was carried out during and following three field campaigns, in May, June-July and October 1990.

1.1 BACKGROUND

Stable bedrock is important for the siting of a high-level nuclear waste repository, both from the point of view of the long-term integrity of the repository contents and installations, and the long-term modelling of the hydrogeological regime. It is generally accepted that the bedrock within which such a repository will be built should have been stable in the past for time periods much longer than those for which it must be secure in the future (100 000 to 1 million years). From this point of view, southeastern Sweden has been regarded as the most tectonically stable part of the country. The aim of the present project was to contribute to the analysis and quantification of this bedrock stability through a detailed study of the brittle deformation in the cover rocks nearest to the Precambrian basement at the site of the underground rock laboratory (HRL) now under construction (Stanfors 1989).

The question of bedrock stability is at present the centre of some controversy. Some workers maintain that SE Sweden has been an area of great stability for the last 1000 million years. Despite episodes of mountain building in the surroundings comparable to the present-day Himalaya (Caledonian orogeny), despite nearby crustal rifting and extensive volcanism during the Permian (Oslo graben) and despite adjacent Mesozoic to Tertiary faulting ultimately related to the opening of the North Atlantic (reactivation of the Tornquist line), this part of the country is thought to have remained largely undeformed and close to sea-level, unaffected by more than very small vertical movements. By contrast, other workers suggest that the entire bedrock in Sweden is being deformed by on-going compression, that major faulting (and M = 7-8 earthquakes on the Richter scale) occurred about 10 000 years ago to the north and probably also in the southeast, and that many of the fractures mapped in the crystalline basement in SE Sweden formed, or at least moved, towards the end of the last glaciation and may well be moving today.

Criteria to test these opposing points of view are extremely difficult to find. Direct dating of fractures in the bedrock (e.g. radiometrically) is difficult and uncertain. A datum of specific age on which unambiguous observations can be made which constrain the age of development of the fracture systems, is usually lacking in the Precambrian basement. In this situation, it seemed that the spectrum of uncertainty could be considerably reduced by carrying out a definitive study of the brittle deformation in the overlying Cambro-Ordovician sedimentary sequences. Because of the stratigraphic control, this could contribute to the isolation of post-Ordovician effects from earlier structures and could yield quantitative estimates of the amount of deformation of this part of the Swedish bedrock over the last few 100 million years. The Paleozoic rocks on the northern part of the island Öland, immediately offshore from the planned HRL site (Figure 1-1), provided the obvious starting point for such a study.

The shore outcrops of Ordovician limestone in northern Öland did indeed turn out to provide important new insights into the question of bedrock stability. This is due to a unique combination of circumstances. Firstly, long sections consist of a 10-30 m wide horizontal rock pavement, with continuous exposures of single stratigraphic horizons up to 2000 m long. The location of these sections and the individual measurement localities are shown on Figure 1-2. Secondly, the bedding planes exposed are often covered with fossils, particularly orthocerids and large trilobites, and these are often intersected by fractures, thus enabling direct measurement of the amount of lateral displacement. This type of quantitative displacement data is usually not available and we know of no other study in the literature in which such data are reported. Much of our work, therefore, centred on developing a methodology which would quickly and efficiently provide a reproducible data base, so that

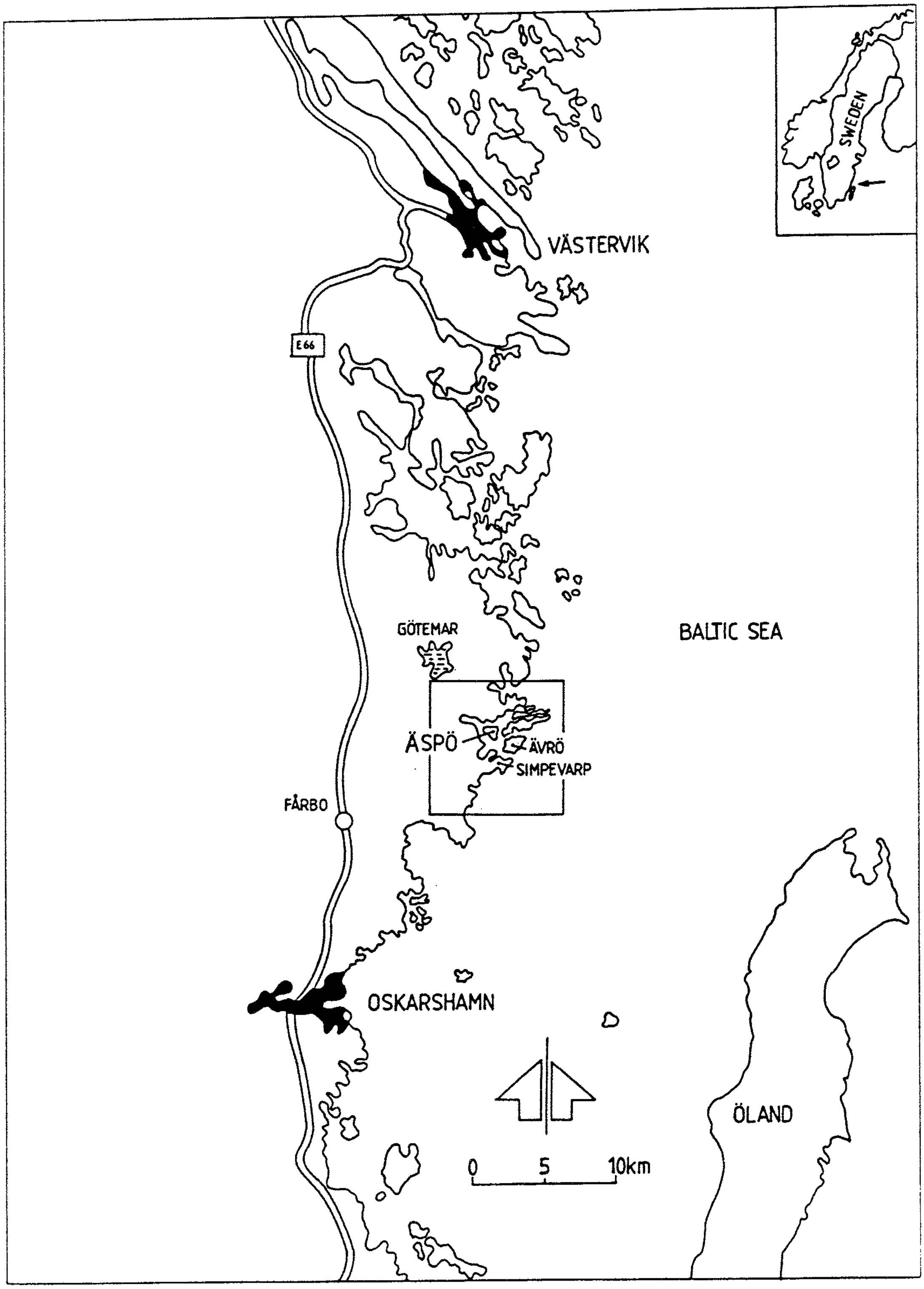


Figure 1-1 Location of northern Öland in relation to the HRL site at Äspö.

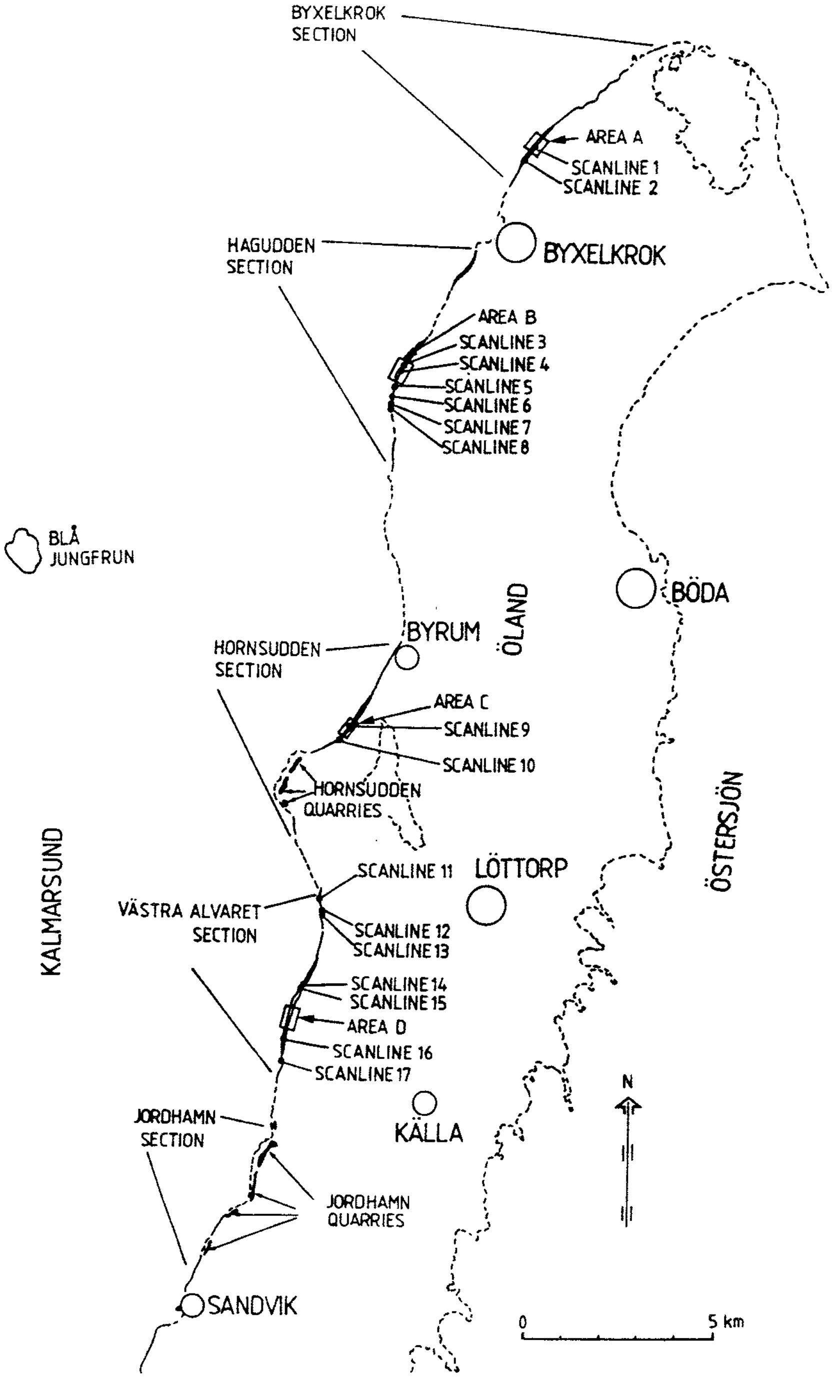


Figure 1-2 *Location of outcrops along the northwestern coastline of Öland, with the measurement stations for fracture analysis in the present study. Line ornament gives the type of coastline: double line - rock platform; single line terraced shore or small cliff; broken line - no bedrock exposures. Quarries in black.*

well-founded interpretations with respect to bedrock stability could be based on this unique source of information.

1.2 REPORT STRUCTURE

After a brief overview of the geological framework of northern Öland (Chapter 2), we introduce the various parameters pertaining to the description of individual fractures, with particular emphasis on the size of the fractures being measured and the displacement determinations, but including also more qualitative characteristics (Chapter 3). The definition of the fracture patterns then follows (Chapter 4) - first, with a discussion of the methods used for collecting the data (4.1), and afterwards, with a description of the relationships along the continuously exposed shore sections studied (4.2). Chapter 4 concentrates on the definition of the various fracture sets with respect to preferred orientation. The orientation analysis itself, however, does not contribute directly to the question of bedrock stability, although it may eventually help to distinguish pre-Cambrian from post-Cambrian fracture sets in the basement. Chapter 5, therefore, considers bedrock stability from two points of view, both based on semi-quantitative data: the variations in fracture density (5.1), and the results of an analysis of the displacement data and other kinematic indicators (5.2). From the latter we show that no movement has occurred on a large majority of the fractures observed, and that those showing movement rarely have displacements of greater than a few centimeters. The present data allow a provisional dynamic history of post-Ordovician fracturing to be set up (5.3). In Chapter 6, it is pointed out that it is imperative to establish the regional significance of the northern Öland results and some recommendations for further studies are made.

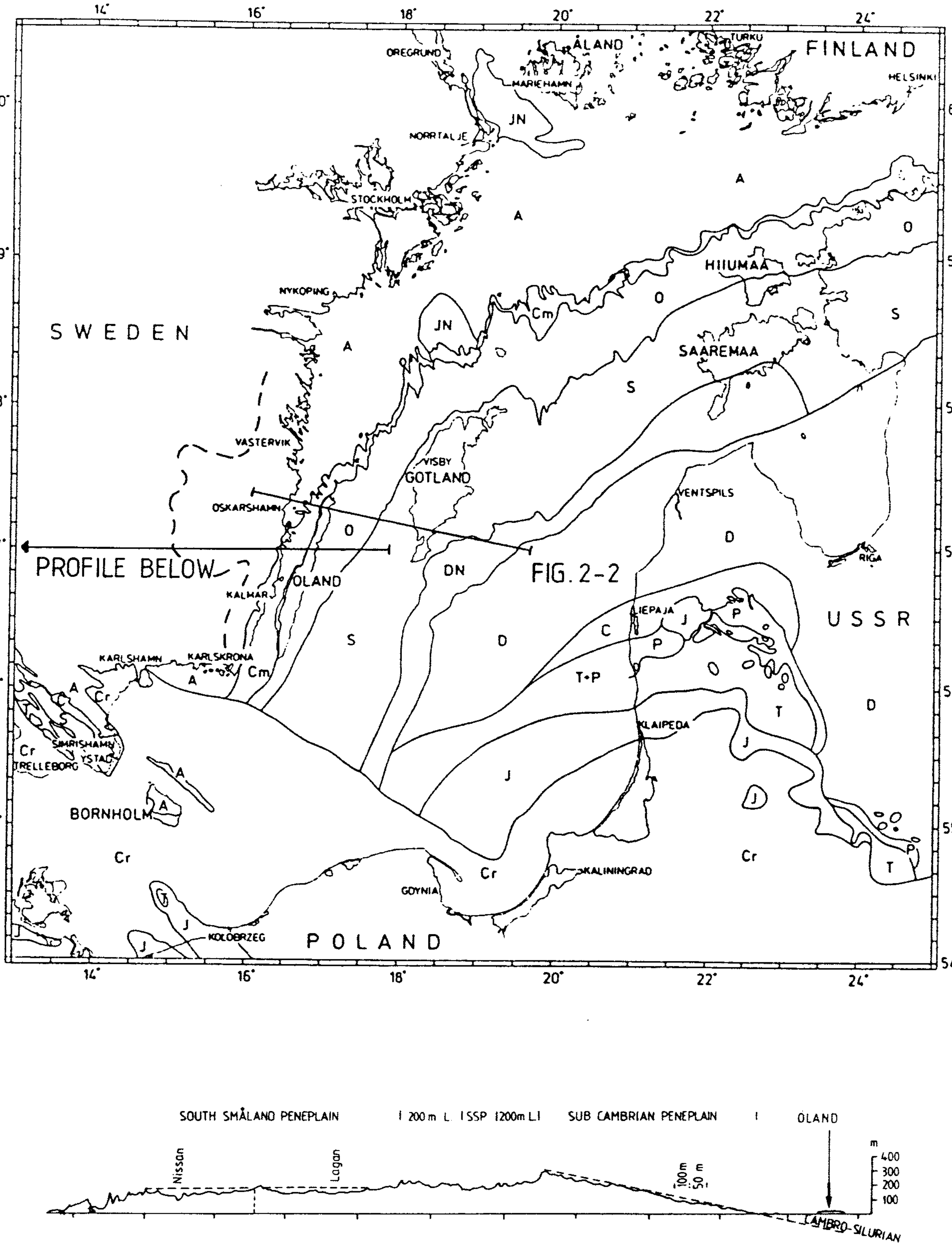


Figure 2-1 *Distribution of Palaeozoic and Mesozoic formations on the floor of the Baltic Sea, showing the position of Öland (from Martinsson 1979). Below, E-W profile from Öland westwards, showing the base of the Cambrian unconformity and its extension inland as the pre-Cambrian peneplain (from Lidmar-Bergström 1988).*

2 GEOLOGICAL OVERVIEW

The stable part of SE Sweden is bounded to the west by the Protogine zone and to the south by the Tornquist line, along and across which there occur a variety of faulted Paleozoic and Mesozoic strata (Figure 2-1). The stable block extends northwards to the NW-trending Västervik zone, an ancient fault zone of crustal dimensions (see Henkel et al. 1990). On this block, practically undisturbed lower Paleozoic rocks occur offshore (submarine, and on the islands of Öland and Gotland) and along part of the mainland coast from just south of Oskarshamn down to Karlskrona. Along the same stretch, the sub-Cambrian peneplain extends inland for several tens of kilometres, as an almost planar surface closely corresponding to the "Gipfelflur" (Lidmar-Bergström 1988, see Figure 2-1). The best exposures of the lower parts of the Paleozoic sequence occur on Öland, where uppermost Cambrian and lower Ordovician formations are seen along the west coast, dipping very gently E or SE (Figure 2-2). The Lower Ordovician is also exposed, patchily, in the interior of the island, as ice-scoured and sparsely vegetated rock pavements ("alvar"). On the mainland, poor coastal exposures and isolated minor outliers of basal Cambrian conglomerates and sandstones, usually occurring as fissure fillings, mark the sub-Cambrian peneplain, from which occasional monadnocks rise through the cover sequences (e.g. Blå Jungfrun, between northern Öland and Oskarshamn, see Figure 2-2).

2.1 LITHOSTRATIGRAPHY

The general geology of northern Öland, and its relation to the adjacent mainland, is shown in Figure 2-3 (Lundegårdh et al. 1985). The area is well known from numerous paleontological, sedimentological and stratigraphic studies on the well exposed Lower Ordovician limestone sequence along the coast (e.g. Lindström 1963, Jaanusson & Mutvei 1982, Grahn 1986, Nordlund 1989a, b, c) and on material from the Bödahamn borehole cores (Bohlin & Jaanusson 1955, Lundegårdh et al. 1985). For the purposes of this study, however, much of this literature was found to be too specialized and localized, and not accompanied by sufficiently accurate maps. Fortunately, the sequence shows a fairly clear subdivision into four litho-stratigraphic units which can be readily identified in the field. The first stage of the field work was therefore a general mapping of the whole coastline (scale 1:12 500), using the

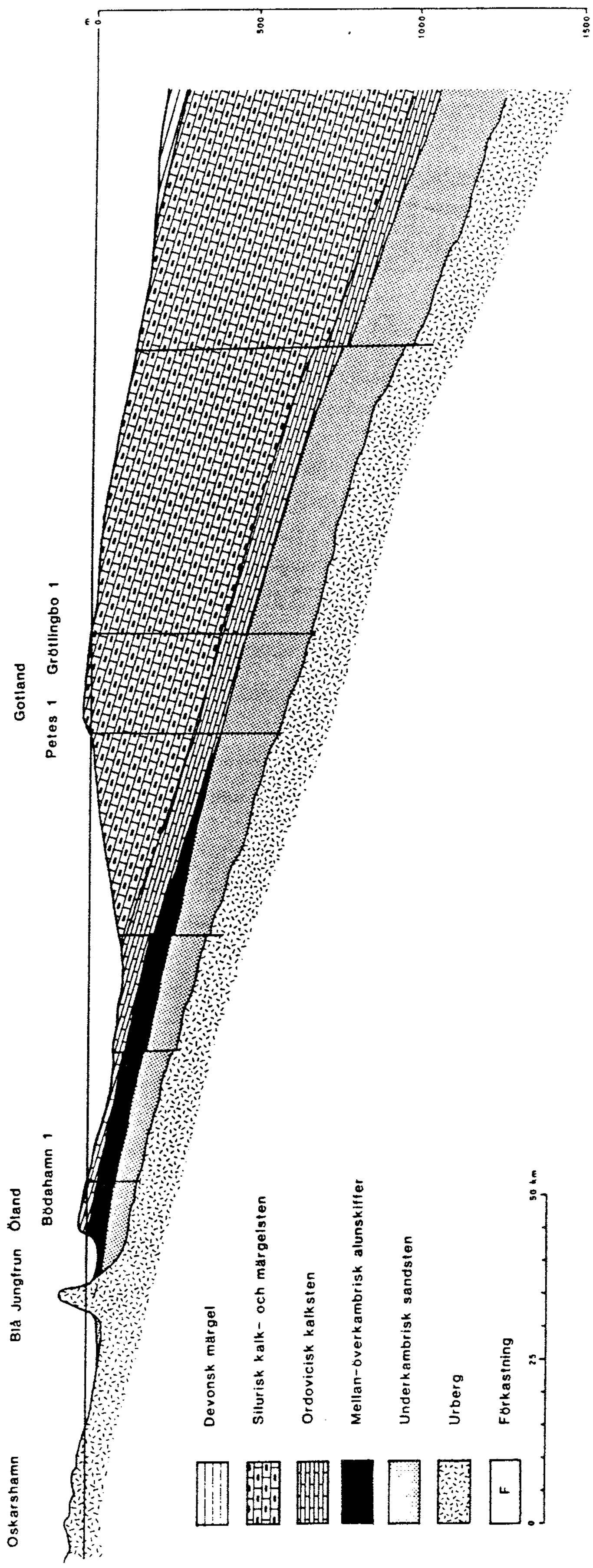


Figure 2-2 *Interpreted E-W geoseismic profile through northern Öland (Oskarshamn to Gotland, see Figure 2-1), showing the regional attitude of the main formations (from Kornfält & Larsson 1987).*

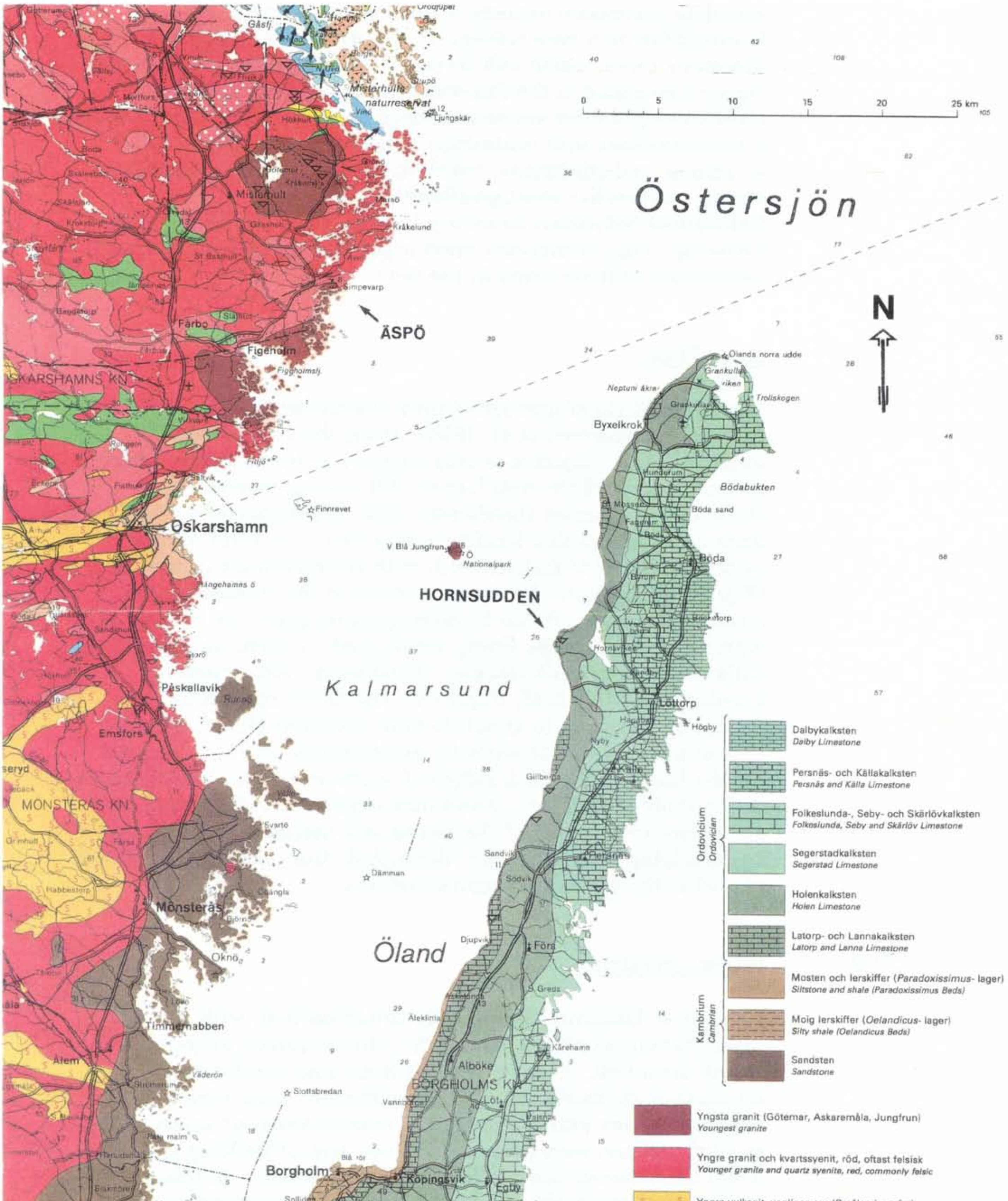


Figure 2-3 *Geological map of northern Öland and the adjacent mainland (from Lundegårdh et al. 1985).*

complete succession exposed along the shore north of Hornsudden as a type section. Three lithologically distinct limestone units, which will be called simply Lower, Middle, and Upper Limestone in the following, can be distinguished, and their characteristics are summarized on Figure 2-4. They overlie a heterogeneous unit containing dark shale, concretionary sandstone and stinkstone, which is assigned to the Alum Shale. This formation lies stratigraphically astride the Cambrium/Ordovician boundary (Andersson et al. 1985). The following notes summarize some aspects of the appearance and recognition of these units in the field.

2.1.1 Alum Shale

The Alum Shale of northern Öland is everywhere very thin (less than 2 m, Andersson et al. 1985). Along the coastal section studied in this project it is only exposed at Hornsudden, where it forms the base of the well known cliff outcrop north of Hornsudden quarries (Lindström 1963, Stephansson 1971). The dark mudstone at this locality is less than 1 m thick and is underlain by a "stinkstone" unit with characteristic concretions (Figure 2-4). Also at the extreme south of the studied section (south of Sandvik), it can be distinguished again, just below the water line, and it rises slowly southwards to form the base of the cliffs south of Grönvik (locality "Bruddesta", illustrated in Lundegårdh et al. 1985, Figure 5). The thickness of this formation increases to about 20 m in southern Öland. Diapiric flow of the unit was thought by Stephansson (1971) to account for the linear hump-back ridges of southern Öland. The thinness of the shale in northern Öland may explain the absence of such structures in this part of the island and makes it unlikely that the overlying limestones are "decoupled" from the basement with regard to the observed fracture systems.

2.1.2 Lower Limestone

The Lower Limestone is typically thinly bedded, with thin shaly intercalations in places, and with a characteristic grey-greenish colour. As a unit, it is very thin (1-3 m), and rarely forms continuous exposures. Quantitative fracture data were not collected in this unit, although the coastal outcrops south of the studied sections were searched for any sign of faulting since the Alum Shale/Lower Limestone contact is the most prominent marker horizon on the island. The transition upwards to the Middle Limestone is gradational, being marked by an increasing thickness of the individual beds and a colour change from greenish to reddish. Striking dark-red blotchy horizons occur at a certain level in this transition - the "bloody layer" of Bohlin

(1949) and Nordlund (1989c). This layer is considered by the latter author to be synchronous over the area, marking the base of the "Asaphus Limestone".

2.1.3 Middle Limestone

The Middle Limestone becomes massive or poorly bedded above this transition and the lower and middle parts of the unit tend to be reddish in colour. Along the coast, the middle parts form low, joint-facetted cliffs or steep, terraced shore outcrops (see Figure 4-2) which are not usually amenable to scanline logging and are never suitable for areal mapping. However, many of the bedding planes, when exposed, are covered with large orthocerids and trilobites. Towards the upper part of the unit (see Figure 2-4), the colour changes back to grey and the limestone becomes very well bedded. It is this "upper Middle

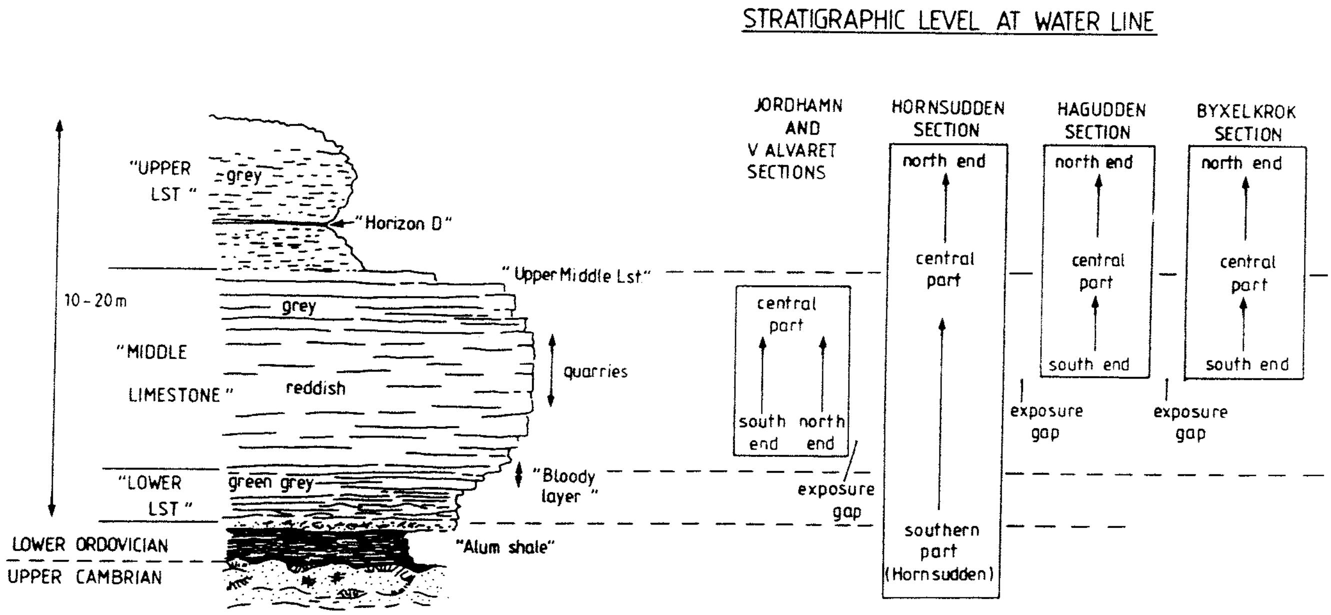


Figure 2-4 *Generalized lithostratigraphic column for northern Öland, based on the continuous shore section north of Hornsudden (see Figure 2-2). To the right of the column, the stratigraphic range of the main shore sections is given, together with the younging direction at water line, parallel to the shore (arrows). The change in stratigraphic level at water line across the exposure gaps between the shore sections is seen by comparing the north end of one section with the south end of the next section to the right.*

Limestone" which provides the broad, wave-washed shore platforms on which most of our quantitative data was collected and which provided ideal objects for areal mapping of the fracture patterns (Figure 2-5a, see also Figure 4-3).

2.1.4 Upper Limestone

The Upper Limestone can be clearly distinguished from the underlying units along the shore because of its characteristically different weathering/erosion behaviour (Figure 2-5b). It forms rounded, knobbly outcrops, often with strange erosional shapes (for instance, the geological monument "Byrums Raukar", north of Hornsudden). The base of the unit is surprisingly sharp and easily identified, so this contact also forms an important marker for along-shore correlations. In the northern areas, it seems to correspond to the base of Zone 4 (Microzarcodina flabellum) of Nordlund (1989c), but further south (Hornsudden, Jordhamn) it is much higher in the biostratigraphic sequence. The Upper Limestone is often cut through by a prominent, bedding-parallel, planar discontinuity, which the waves have used to undercut the cliffs (surface "D" of Nordlund 1989c). An obvious feature of the Upper Limestone is the lower fracture density in relation to the immediately underlying limestones. With regard to fracture density, therefore, the question of lithological control is clearly important (see discussion, Chapter 5.1).

2.2 POST-DEPOSITIONAL HISTORY

Stable, shallow marine conditions continued into Devonian times, after the deposition of the above units. However, the overburden was probably never more than several hundred metres (maximum 2 km). The Alum Shales of Öland are immature and still yield oil on distillation (Andersen et al. 1985) and maximum temperatures have been estimated at 90°C (cf. Bergström 1980, Zeck et al. 1988). This thin Lower Paleozoic and younger cover has been largely removed from the exposed parts of the Baltic Shield, but is preserved under the Baltic Sea. Time control on later events is therefore very poor.

The main periods of tilting (to give the present slight eastward dip, see Figure 2-2), uplift and unroofing (to attain the present exposure level), and flexuring and fracturing (to produce the structures described in this report) certainly post-date the main depositional episode, but are otherwise indefinite in sequence and position within the 450 Ma time frame. The main datable event is the Pleistocene glaciation, which is evidenced by widespread moraine and glaciofluvial deposits, indications of ice-scouring (poorly developed in northern Öland) and prominent

a

b

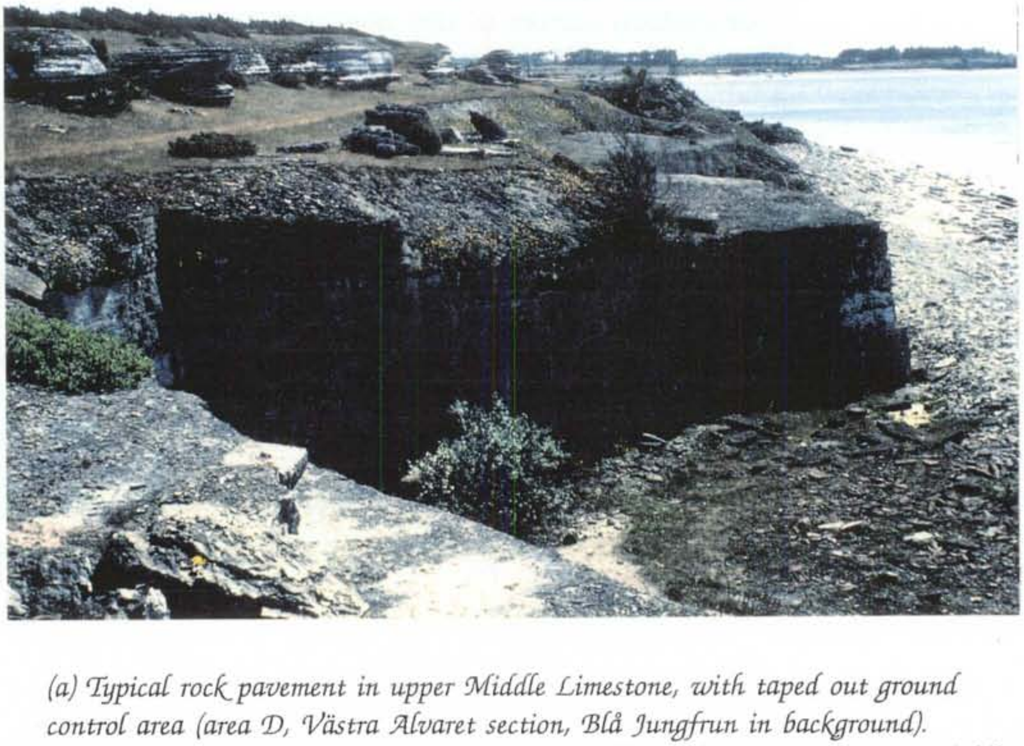


Figure 2-5 *(a) Typical rock pavement in upper Middle Limestone, with taped out ground control area (area D, Västra Alvaret section, Blå Jungfrun in background).*
(b) Disused quarry north of Jordhamn. Rock walls are fracture surfaces in Middle Limestone (with patchy calcite coating at right-hand edge). Above the quarry, a raised beach backed by low cliffs of Upper Limestone showing typical erosional forms.

ancient shorelines (cf. Königsson 1968). One of these is a well-marked raised beach backed by undercut clifflets of Upper Limestone in the Jordhamn area, about 15 m above present sea-level (Figure 2-5b). Present surface uplift rates are about 1 mm/yr, but during ice retreat, rates of up to 10 mm/yr have been estimated (Ekman 1988).

The most important aspect of the post-depositional history for the present study is the fragmentary evidence of slight tectonic disturbance of the limestones on a regional scale. Already in the literature, comments are found on level changes in different markers and indications of local disturbance of bedding. The main zone of disturbance lies immediately south of Borgholm: the Gestadås structure, described by Stephansson (1971, p. 70) and not judged to be a diapiric effect (see also Lundegårdh et al. 1985). Within the N-trending Gestadås zone, a fault with 10 m downthrow to the east is noted, but otherwise, no faults have been reported or observed in northern Öland. However, the Gestadås structure lies on the south side of an obvious culmination located at Köpingsvik (Figure 2-3), marked by the sharp northward swing of the (Middle Limestone) klint and then the slow northward descent of the Alum Shale to sea-level (at the "Bruddesta" locality mentioned above). Tracing the above lithostratigraphy along the coast showed that another slight culmination occurs in the northern part of the island, at Hornsudden. Further north, in the exposure gaps north of Byrum and north of Byxelkrok (Byrum Sandvik and Byxelkrok Bay, respectively), a noticeable change in stratigraphic level at water line takes place (Figure 2-4). In these areas faulting and disturbance, similar to the Gestadås zone at Borgholm, cannot be ruled out. This question will be returned to in Chapter 4.3. Here, it is important to note that for none of these culminations or possible faulted zones does the evidence allow a discussion of the trend of the structures. If they cross the island and have measurable displacements, they may be mappable with offshore and/or onshore geophysics, but at present their orientation and significance is unknown. The linearity of the coastline, the slightness of the bedding disturbance and the poorness of the outcrop clearly leave the question open, until other evidence is forthcoming.

3 FRACTURE CHARACTERISTICS

The definition of fracture used here follows the recent SKB recommendation and AGI usage: "A general term for any break in a rock, whether or not it causes displacement, due to mechanical failure by stress. Fractures include cracks, joints and faults." (Bäckblom 1989). A "break" is taken to be any planar discontinuity with zero cohesion, or with clear signs of mechanical weakness, at the present time, i.e. excluding fractures which are now completely healed by later mineralization (veins) or other features which indicate that the deformation took place without loss of cohesion (e.g. ductile shear zones). We also confine our use of "fracture" to tectonic fractures, i.e. ones which seem to have been produced by brittle failure under differential stress due to crustal movements. This excludes breaks which are thought to be of artificial origin (e.g. formed during quarrying) or due to very localized non-crustal stresses (e.g. due to the battering of the coastal rock pavements during storms). In the case of Öland, these restrictions are unimportant: artificial and localized fracturing are easily distinguished and completely healed features are uncommon. What are very common, however, are mineralized fractures, which show sporadically coated surfaces, fractured mineral linings and irregular wall-rock alteration, but which are still planes of mechanical weakness, used by the quarrymen and picked out by coastal erosion and weathering.

The purpose of this chapter is to comment on specific characteristics of the fractures in Öland, features which were noted or measured for each individual fracture in addition to its orientation. These include the size of the fractures, the amount and type of displacement, the character of fracture surface and wall rock features, and observations on fracture terminations. This has been exclusively a field study up to now. Some of the statements here are therefore of a preliminary nature (mineralogy of coatings, deformation mechanism, etc.), as yet lacking microscopic confirmation.

3.1 SIZE (LENGTH)

The question of fracture size is one of the most difficult to deal with systematically, although it is obvious to even the most casual observer that fractures vary in size and hence importance. Theoretically, when the fracture system does not show systematic displacement variations (the present case, see

Chapter 5.2), the only way of defining size is in terms of length, i.e. lateral extension in space. If exposure were extensive enough, it would be found that all fractures have a finite lateral extent and hence a finite trace length on a reference plane, such as bedding. In that case, the length (size) of each joint could theoretically be measured. However, outcrop size is practically never large enough, and is certainly not the case on Öland. Numerous attempts have been made to solve the size problem in limited windows using complicated statistical treatments of inadequate data sets from, for instance, small outcrops, tunnel walls, drill cores, etc. (e.g. Cruden 1977, Priest & Hudson 1981, Baecher 1983, La Pointe & Hudson 1985, Rouleau & Gale 1985, Caprariis 1988). We judged these to be too cumbersome and time-consuming for the present study and decided to introduce size only in the sense of a lower cut-off (e.g. Rouleau & Gale 1985). This means that only fractures above a certain length are measured and included in the statistics. For the purpose of this survey, a lower cut-off size of 2 m was chosen: fractures with a trace length on the bedding surface of less than 2 m, as well as strongly irregular fractures without a straight segment at least 2 m long, were not taken into account. This "2 m rule", although rather arbitrary, was also useful in that it guaranteed that only tectonic fractures would find their way into the statistics. Experience showed that quarrying, and along the coast, storm battering, mainly resulted in fractures falling below the cut-off. Above the cut-off, fractures were only roughly classified according to size (see Figure 4-1) but this was not used in the statistical treatment. However, the trace length of fracture exposed with a given trend was systematically measured in the case of areal mapping in order to give meaningful orientation statistics (see Chapter 4.1.2) and estimates of fracture density (see Chapter 5.1).

3.2 DISPLACEMENT

The definition of fracture does not specify whether displacement has occurred on the plane of discontinuity or not. In this study, displacement was a quantity which had to be determined as far as possible in each individual case. Öland is perhaps a unique locality in this respect: because of the well differentiated bedding and the abundant, mainly rod-shaped fossils (orthocerids), movement in any direction can often be directly observed and measured. The observational data on each fracture thus contains specific information on three types of displacement, using an arbitrary lower-cut off 1 cm as the limit of resolution in the field. "No displacement" thus really means "none distinctly observable under the present outcrop conditions", i.e. on our experience, a displacement less than about 0.5 cm. The three displacement types, with some comments, are as follows:

1) Aperture
On the above definition, closed fractures showed no displacement perpendicular to the fracture walls, whilst open fractures or fissures showed a certain aperture, which was measured in each case (if it exceeded 0.5 cm, see above). Most of the fractures which are visible on the air photos fall into the category of open fractures, but apertures never exceeded 10 cm. In the scanline data (Appendix A), 10% of the fractures were classified as open.

2) Vertical displacement of bedding
All fractures observed could be characterized with respect to bedding displacement. Only very few would have to be designated small faults (3%), with throws of a few cm (maximum 8 cm), and those were all normal in the sense that the hanging-wall was downthrown (Figure 3-1a). No faults with displacements of more than a few cm were observed anywhere along the exposed coastline. This applies not only to the scanline and areal mapping locations, for which quantitative data was collected, but also to all outcrops between, where specific searches for fractures with displacement were carried out. However, the possibilility of faulting in sections of coastline lacking exposure must be kept in mind (cf. Chapter 4.3).

3) Horizontal displacement of fossils
Particular attention was paid to the intersection of fractures with fossils on the bedding planes, with a view to determining the amount of lateral movement (Figure 3-1b). Unfortunately, not all fractures could be characterized in this way, although each was searched along its entire exposed length (i.e. not just at the scanline intersection, see Chapter 4.1.1). 21 % of the fractures in the scanline data (Appendix A) intersect fossils, and 9% of these showed displacement (sinistral or dextral) of 0.5 cm or more (maximum 5 cm). Observations along the exposed shore sections between the scanline and areal mapping locations indicate that this data is quite typical. Hence, as a general rule, fractures showing lateral displacement make up less than 10% of the total population.

a

b

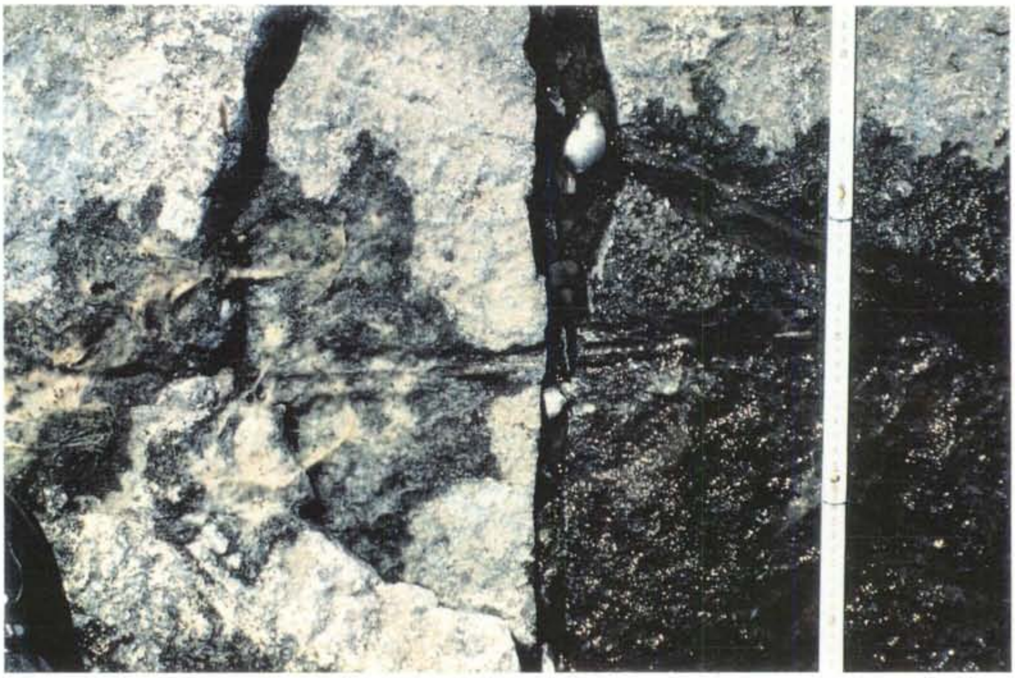


Figure 3-1 (a) *Vertical displacement of bedding on one of a group of small fractures, and irregular alteration border (bleaching of reddish Middle Limestone), Hornsudden section.*

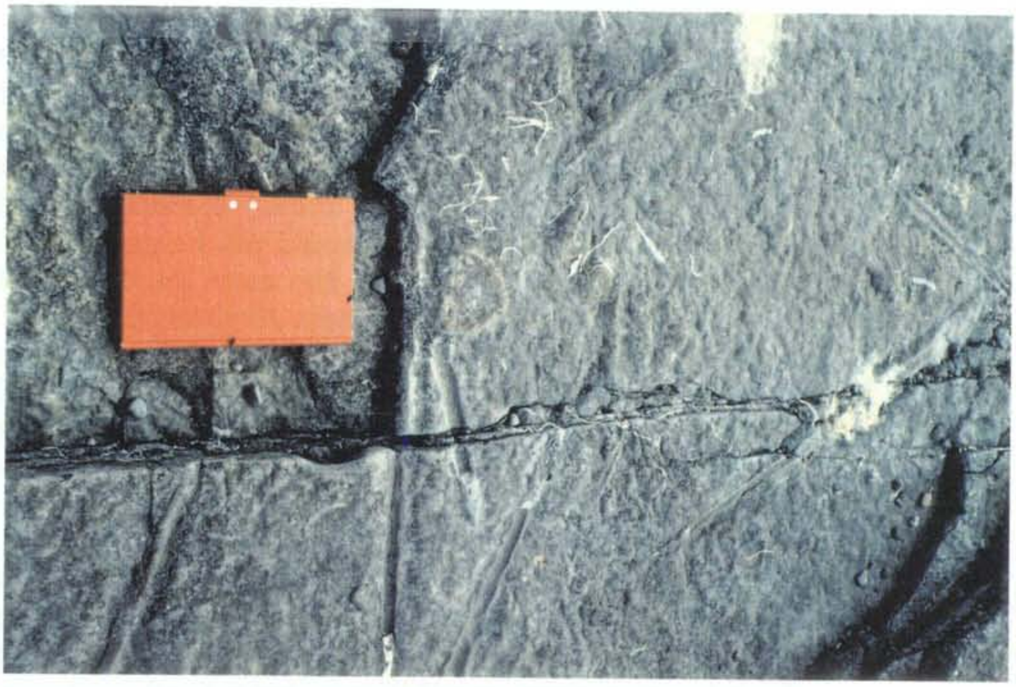
(b) *Laterally displaced fossil, about 1 cm, Västra Alvaret section (see Appendix B, area D, ground control map).*

3.3 PHYSICAL FEATURES

As noted above, mineralized fractures are common along certain stretches of the coastal outcrops. In most cases, the fractures are not healed, however, and the mineralization occurs as coatings on the opposite fracture surfaces. Macroscopic observation suggests that the coatings are mainly of calcite, but the possibility of other minerals should not be excluded at this stage. Along the measured scanlines, the most mineralized localities (e.g. scanlines 4 and 10, Appendix A) showed 50-60% of the fractures with calcite coating. In some of the quarries, many of the quarry faces are similarly coated, and illustrate the discontinuous nature of the coatings when they are seen on large enough surfaces. Both in the quarries and along the shores, fracture mineralization is often seen to be associated with wall-rock alteration (Figure 3-2a). This is particularly noticeable in the reddish pats of the Middle Limestone, where fractures may be marked by irregular greenish alteration borders varying in width from a few mm to tens of cm. Interestingly, however, there is not a strict correlation: mineralized fractures without alteration borders are common, and alteration borders along apparently unmineralized fractures also occur. Also, the relation between the presence or absence of mineralization and alteration, and particular fracture sets is not very consistent (for more discussion, see Chapter 4).

A particular search was made for surfaces markings of genetic significance, such as plumes and pressure solution phenomena (stylolites), as well as other features possibly associated with movement on the fracture planes, such as slickensides (mechanical striations, shear fibre veins, etc.) and en echelon veinlet systems (c.f. Hancock 1985, Engelder 1987, Hancock & Barker 1987, Ramsay & Huber 1987). Along the shore outcrops, none of these features were common on the fractures (although stylolites were common on bedding surfaces), and they were seldom encountered along the chosen scanlines (Appendix A). However, this lack is certainly partly due to the lack of outcrop depth and to the effect of wave erosion. The fracture surfaces in many of the quarries show excellent examples of all those features, albeit still in a minority with respect to the number of unmineralized and coated fracture surfaces without obvious markings. Important for the present study was the search for slickensided surfaces indicating lateral movement. Where these were common (for instance, in the Jordhamn quarries, Chapter 4.2.5), they were mainly of "pressure solution" type, i.e. combinations of calcite shear fibres and oblique stylolites or "slickolites" (Ramsay & Huber 1987), sometimes exposed on large surfaces, many tens of m long and several m high (Figure 3-2b). The impressiveness of these subhorizontally striated

a



b

Figure 3-2 *(a) Calcite coating or calcite fill of fracture showing no fossil displacement and no alteration border, Hagudden section.*
(b) Subhorizontal slickensides (calcite fibres, slickolites i.e. pressure solution and redeposition phenomena) on a large fracture surface in Hornsudden quarry.

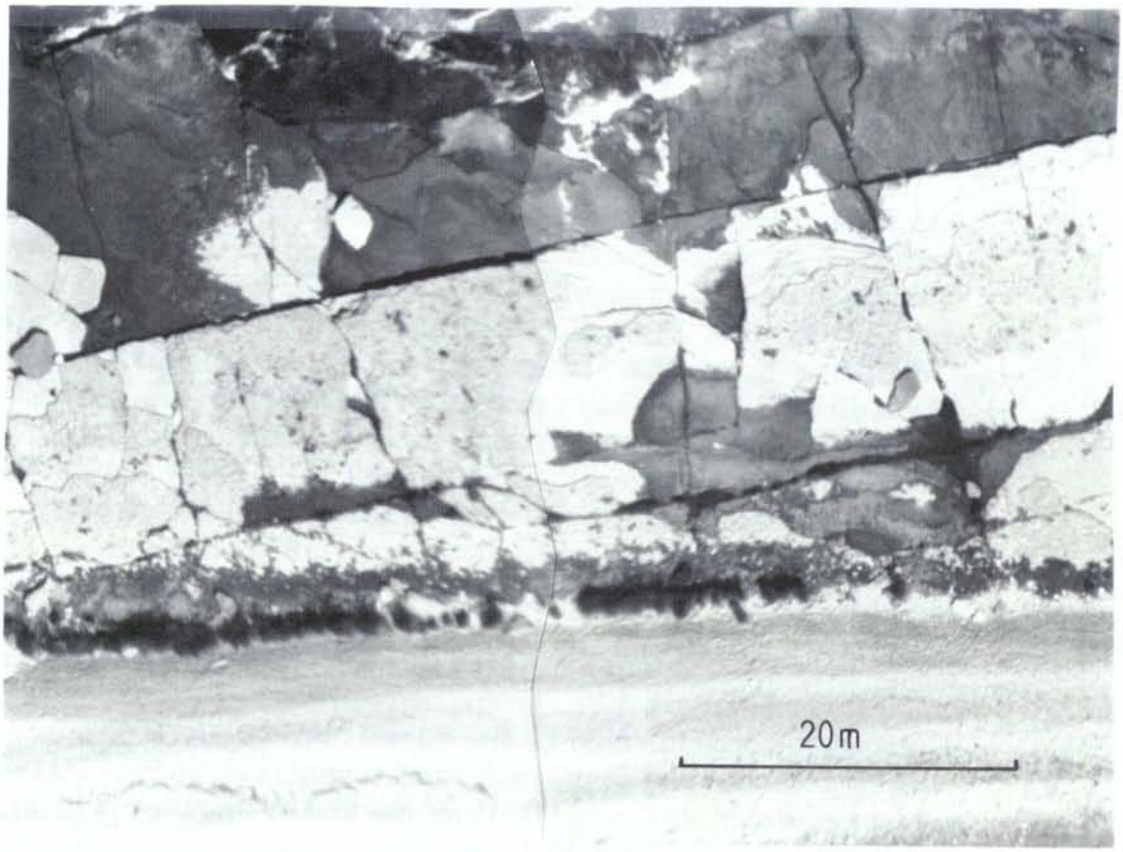
surfaces, however, was found to be sometimes misleading: in examples where such fractures were found to intersect fossils, the lateral movement implied was still only of the order of cm (see Chapter 4.2.5 and Chapter 5.2.2).

3.4 TERMINATIONS

A further feature of potential genetic significance is the nature of the fracture terminations. Visual inspection of the fracture maps shows that many fractures terminate by abutment against other fractures (T junctions), without any systematic truncation of one set by another. Many, however, can be followed in at least one direction until they are seen to die out in (at the scale of observation) undeformed rock. These true terminations in northern Öland were generally simple, without the development of splays of any type, and never with "horsetails" and other minor structural features indicating significant lateral displacement.

The only termination features which are widely developed are "sidesteps" (Figure 3-3). Frequently, the dying out of one fracture is accompanied be the appearance of a similarly orientated fracture to one side, and it seems clear that this is to be interpreted as a relay feature: the strain involved is being relayed from one fracture to the other, across a narrow bridge. The bridge itself may appear undeformed, but often it is cut by many small fractures at right angles. The bridges are therefore often picked out by the wave action, forming typical oblong holes in the rock platforms (Figure 3-3B). Data was collected on the distribution of sinistral and dextral "sidesteps" in case this should show systematic variations with genetic implications (Chapter 5.2.3).

a



b

Figure 3-3 (a) *Example of large scale dextral "sidestep", rock pavement of area A, Byxelkrok section.*
(b) *Example of small scale dextral "sidestep", Hagudden section.*

4 FRACTURE PATTERN ANALYSIS

In this chapter, emphasis is on the preferred orientation characteristics of the observed fracture systems. These can be roughly revealed by unsystematic mapping and observation, whereby the field worker moves along the outcrops collecting measurements until he feels he has enough data for meaningful generalizations. This quickly uncovers general tendencies, but it does not give reproducible or statistically definitive results. On the other hand, detailed mapping and measurement of every fracture is very time consuming, and often unsatisfactory because of difficult outcrop conditions (lack of exposure, inaccessibility, etc.). The logistics and aims of the present study forced us to find a practical middle way, i.e. to develop simplified methods in order to generate reproducible data sets, tailored to the problem at hand. These methods are outlined in the next section, before summarizing the results from the five continuous coast sections studied.

4.1 METHODS

The main simplification used in the present study was to confine the systematic data to 2D, i.e. to analyse the fracture patterns in terms of fracture traces in horizontal projection. This is appropriate here from two points of view. Firstly, the Öland outcrop surfaces are already strongly two-dimensional and subhorizontal (bedding planes exposed on coastal rock platforms, large quarry floors, huge areas of "alvar"). This in itself would not have been critical, since enough relief exists everywhere to allow the vertical dimension to be taken into account (as is in fact done in the case of some parameters, e.g. vertical displacement, fracture surface markings, etc.). Secondly, however, precisely such observations showed that practically all the fracture planes were steeply dipping, usually subvertical. The assumption in the present work is thus that the 3D fracture network can be adequately defined by systematically studying the fracture trace pattern on subhorizontal outcrop surfaces. Only the strikes of the fractures need to be measured, thus cutting work time in the field by half and making pattern analysis on air photos and maps appropriate for comparative purposes. This assumption also simplifies data processing and statistical analysis (e.g. stereographic projection becomes unnecessary), with a minimal loss of definitiveness.

Because of varying outcrop conditions, three different methodologies were employed. The data sets derived from these are affected by different types of uncertainty, as outlined below, and these must be born in mind when comparing the results.

4.1.1 Scanline logging

The main technique for quickly and systematically collecting fracture data which can be processed semi-quantitatively is known as scanline logging (La Pointe & Hudson 1985). In this technique, a tape is used as a linear distance scale and every fracture intersected by the tape is measured and described. The types of measurement and the features described are determined by the aims of the survey. For the present study, an appropriate field data sheet was set up, as shown on Figure 4-1. Summaries of all the scanline logs are given in Appendix A. In all, we collected data along 17 100 m long scanlines distributed along the whole shoreline (for locations, see Figure 1-2), particularly along sections where areal mapping was not possible or was inappropriate because of the narrowness and steepness of the outcrops (Figure 4-2). It should be noted that scanlines do not need to be straight along their whole length - many of our logs consist of a series of straight segments of varying orientation and the data is treated according to the trend of each segment.

In populations of fractures of similar size, the main problem with scanline data is the distortion introduced by the fact that fractures in sets which run at a low angle (subparallel) to the scanline are under-represented, as opposed to fractures in sets at a high angle (cf. Terzaghi 1965). The probability of fracture traces being intersected decreases according to the sine of the angle between fracture trace and scanline (La Pointe & Hudson 1985). We use this relationship as a basis for "weighting" the individual fracture trends when plotting the trend histograms: a fracture trace perpendicular to the scanline is given the weight number 2, and all others are given a weight number according to the function 2/sin& (where & is the angle between trace and scanline, at the point of intersection). The weight numbers are then rounded to integers such that 2 corresponds to the range 2 to 2.5, 3 corresponds to the range 2.5 to 3.5, etc. A more precise treatment is not justified in the light of a whole range of uncertainties, including measurement imprecision, plotting limits, statistical uncertainties due to size variations, irregular spacing, etc. Taking these into consideration would require an enormous surveying and computing effort which can hardly be justified at the present stage. The weighted histogram rose diagrams derived from the scanline data (see Appendix A) are thus to be viewed as first approximations, in which the most serious distortion has been roughly corrected. The relative heights of the histogram columns approximately reflect the

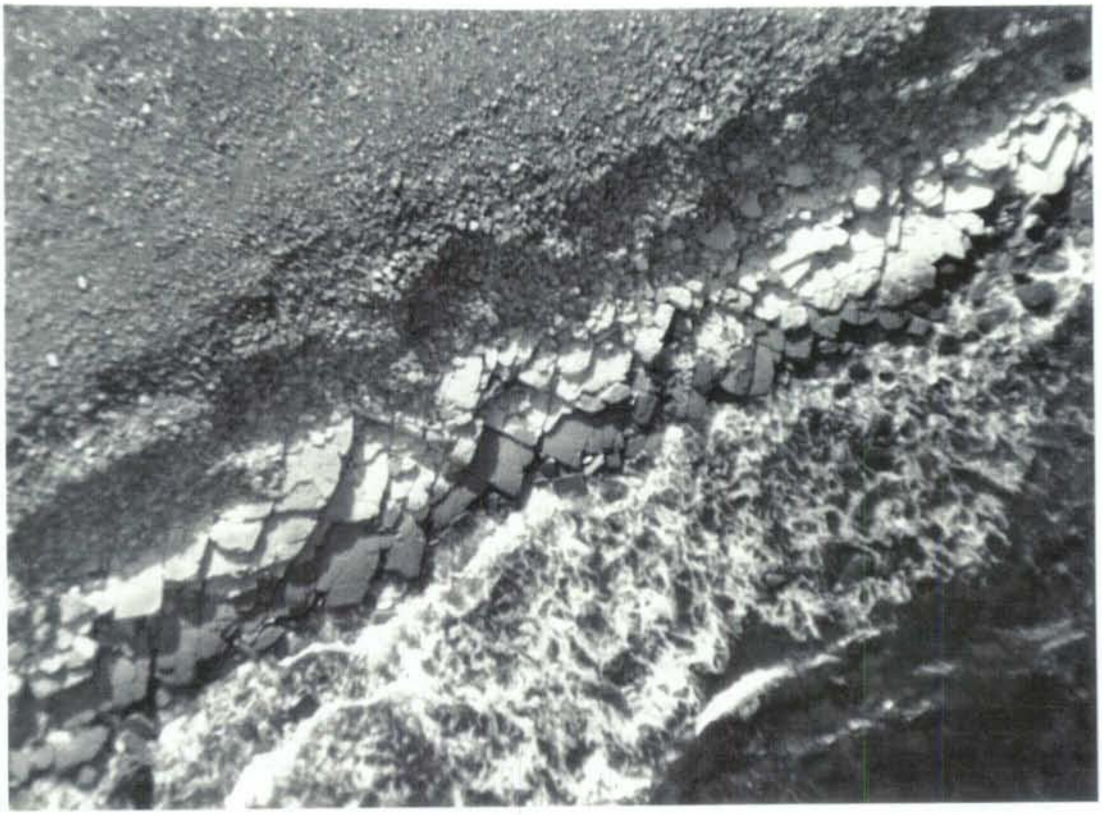
SAMPLE FIELD WORK SHEET

STATION

DIST-ANCE (metres)	TREND (magnetic)	WEIGHT ("nominal length") ↓ to be filled out later	SIZE L = large M = med.	SHAPE S = straight I = irreg.	DISPLACEMENT bedding (cm., downthrow) ? = no bedding observed	DISPLACEMENT fossil (cm., sense) ? = no fossil	aperture (cm.)	REMARKS – mineralization? – wall rock alteration? – slickensides? – relay structures? (sidesteps) * scanline trend !!
(1) 0.10	323	2	M	S	0	0	0	* scanline 022
(2) 0.80	65	3	M	S	0	0	0	dies out at sidestep sin. cuts thru' calcite of set A
(3) 0.80	329	2	M	S	0	0	0	member of set of // joints with many terminations and sidesteps
(4) 2.70	326	2	L	S	0	in whole zone 0, 0, 0,	0	whole zone of sub-parallel joints with some large ones (measured) and many small (5-10 intersect scanline)
(5) 3.30	323	2	L	S	0		5cm	with 2-5cm thick calcite fill, discontin. along joints, no slickensides
(6) 4.70	327	2	L	S	0		0	
(7) 6.20 zone visible on air photo	324	2	L	S	0 (in places suggestion of few mm to 1cm downthrow to SW)		2-3cm	
(8) 6.60	52	4	M	S	?0	?	0	anastomosing zone ca 10cm wide with 3
(9) 9.00	320	2	M	I	0	0	0	sidestep sin. – part of splayed end of large joint in similar direction (calc. filled, ~1cm downthrow to SW)
(10) 10.90	67	2	M	I	0	½cm sin.	0	
(11) 11.40	328	3	M	S	0	½cm sin.	0	calcite fill max. ½cm thick

Figure 4-1 *Sample work sheet for scanline logging, as used in the present project (beginning of scanline 9, see Appendix A).*

a



b

Figure 4-2 *(a) Air view of a narrow terraced shore in reddish Middle Limestone, location of scanline 17, Västra Alvaret section.*
(b) Ground view of the same shoreline (Blå Jungfrun in background).

"importance" of fracturing in the given trend range, making the scanline data comparable with the results of map analysis (cf. also Chapter 5.1).

4.1.2 Areal mapping

Areal maps of the broadest rock pavements along the coast of northern Öland were prepared on the basis of air photos, with detailed mapping of small areas in the field providing ground control. The maps of the four areas studied (Appendix B, areas A-D; for location, see Figure 1-2) are based on serial photos taken with a hand-held camera from a small airplane, which was hired specially to fly along the shore at low level (150-200 m altitude). In spite of the unsophisticated method, the results were surprisingly good: the overlapping frames could be fit together in long strips and showed minimal distortion, and north arrows and other markers painted on the rocks could be identified with no difficulty (Figure 4-3). Since the fracture spacing of the main fracture sets is generally less than the width of the rock pavements, a distortion of the type inherent in the scanline data is not important. Hence, the orientation statistics can be presented directly in terms of the length of fracture trace within a given angular interval (10°, in this study). This is done by digitizing the fracture maps and using a standard PC programme (cf. also Nisca 1987). The height of the columns on the histogram rose diagrams from the air photo maps (Appendix B) thus give a reliable image of the importance of visible fracturing (total length of fracture trace within the given trend interval).

Ground control of the pavements covered by the air photo maps had to be achieved by surveying small areas with tape and compass (Figure 4-4), since the logistics of the field campaign did not allow us to use the air photos directly in the field. The ground control maps (insets in Appendix B), although time-consuming to make and often unrepresentative, constitute an important link with the scanline data, since the fractures were described individually in the same way (displacement, surface markings, mineralization, etc.). The air photos alone only provide undifferentiated orientation and fracture density data, and only for photographically resolved fracture traces. In the ground studies, the length/orientation data was collected directly by measuring the trend of each 2 m long segment of every fracture trace (i.e. not by digitising the maps, which are sketches rather than precise surveys).

a

b

4.1.3 Quarry data

The quarries presented a special problem which could not be solved by scanline logging or areal mapping (too few fractures, too irregular outcrops, numerous inaccessible parts, active quarrying, etc.). However, it became clear that they could provide important information which was hard to obtain along the shores. This applies particularly to fracture surface features (slickensides, mineral coatings, plumes, etc.) which were often spectacularly exposed along large, freshly exposed walls. In many places, the quarrying has largely been directed by the fracture system. In the quarries, however, the orientation data is unsystematic, representing simply those surfaces which happened to be accessible for measurement. To emphasize this, the data is not plotted as histogram rose diagrams, but as simple histograms in which each measurement unit is marked with significant observational data (see Appendix C, sheets 4 and 6).

4.2 RESULTS

4.2.1 Byxelkrok section

The Byxelkrok section of the northern Öland coastline is continuously exposed over a distance of about 4 km, with some additional outcrops at the extreme north of the island (Figure 1-2). The southwest end of the continuous segment starts near the first parking area to the west of the road, driving north from Byxelkrok village on highway 136. From these small cliffs (in reddish Middle Limestone) northeastwards, a broad wave-washed rock platform develops (upper Middle Limestone) which sinks slowly below sea level along the edge of the well-known nature reserve "Neptuni åkrar". Towards the northeast end of the continuous segment, at the level of parking area 4 to the west of the road, a solitary tree marks the beginning of another line of low cliffs against the now submerged rock platform. These belong to the Upper Limestone in our terminology, and the sedimentology and stratigraphy of the rocks at this locality have been described in detail by Nordlund (1989a, Figs. 1 and 2, locality "Hälludden"). According to this work, the prominent discontinuity surface at mid-height in the cliff (horizon D, see also Figure 2-4) lies just above the Arenig-Llanvirn boundary. This locality has also been described by Bohlin (1949) and is included in the excursion guide of Jaanusson & Mutvei (1982).

Figure 4-3 *(a) Air view of the corner of ground control area, area B (see Appendix B), showing one of the corner markings.*
(b) Ground view of the same rock pavement, further north (looking along the set A fracture set towards Simpevarp - reactors visible left background).

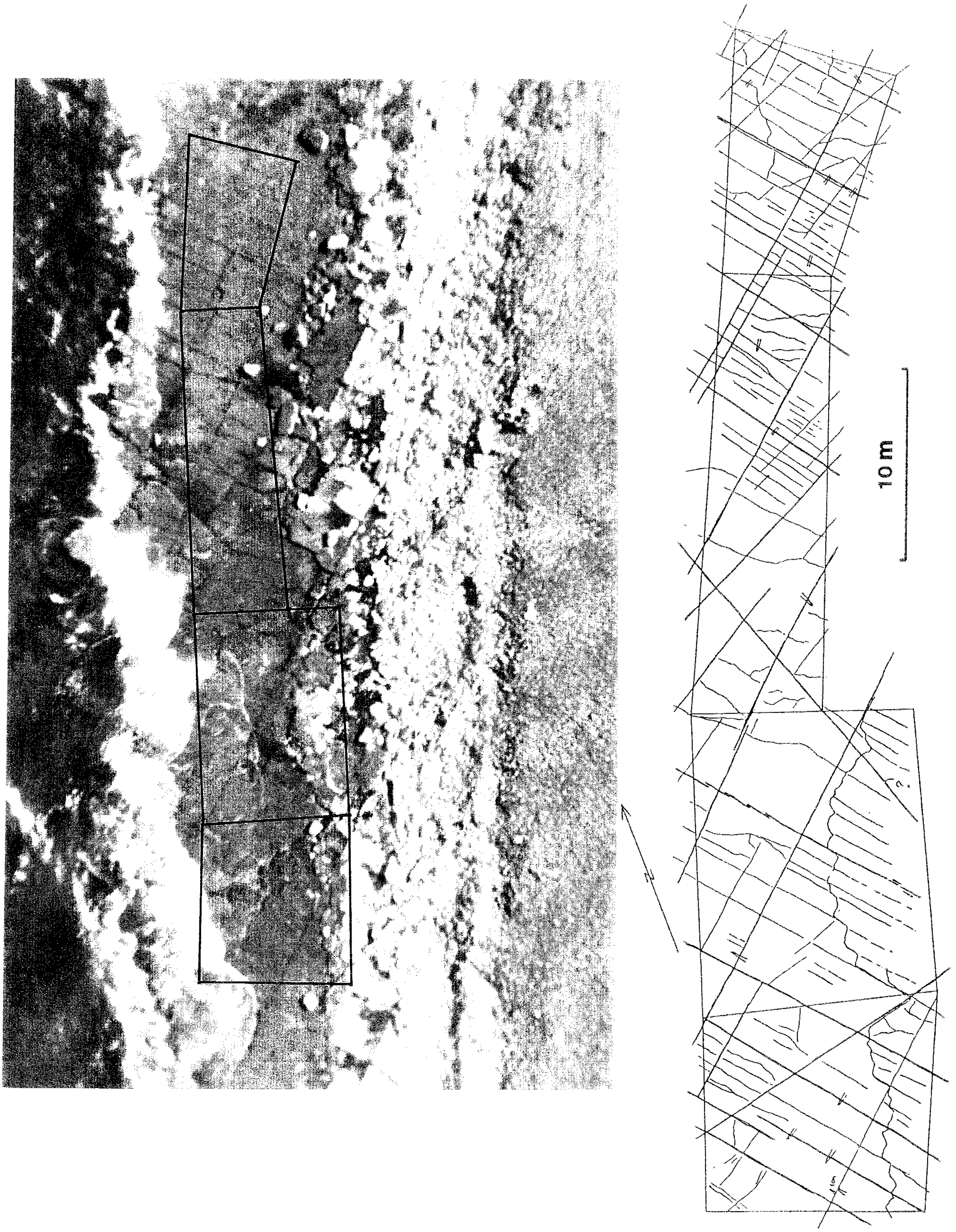
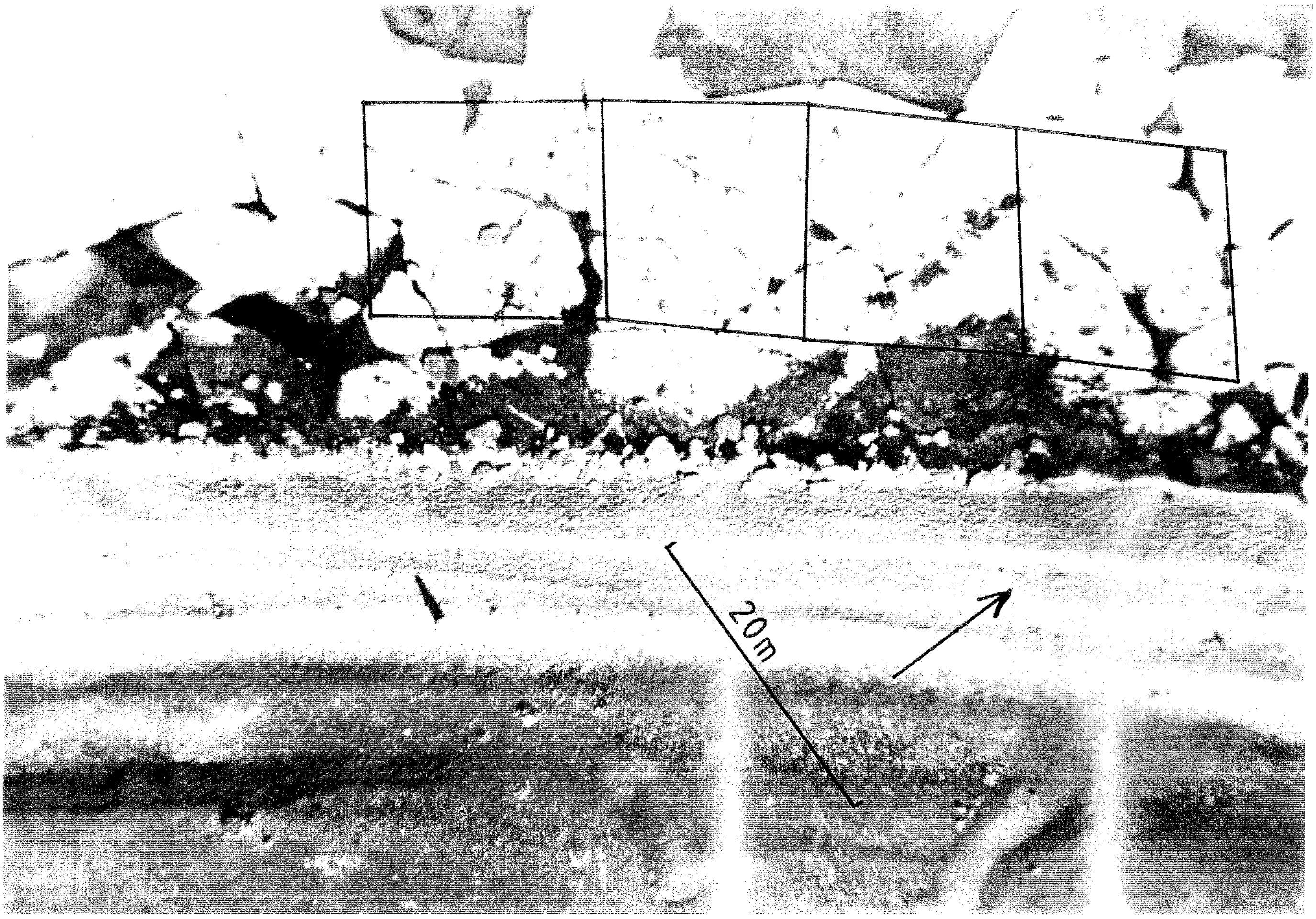
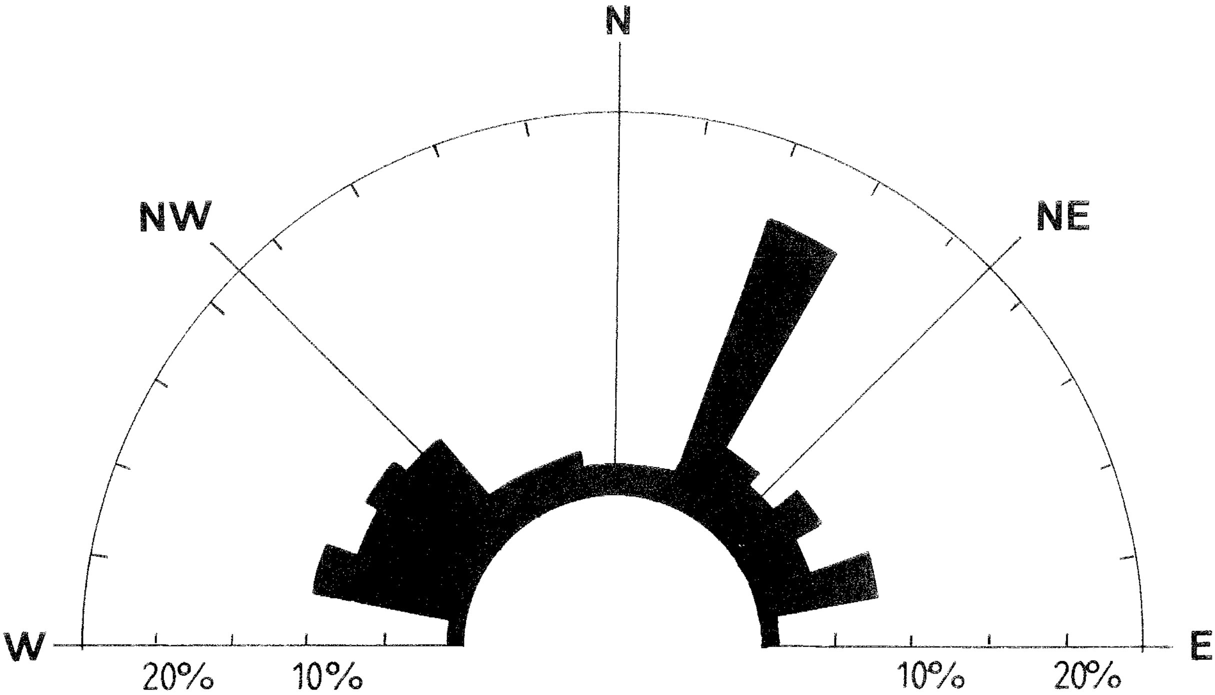


Figure 4-4 Air photo and detailed ground control map of the same segment of area D, Västra Alvaret section (cf. Appendix B). At the time of the flight, water levels were relatively high and much of the ground control area was awash.



GROUND CONTROL AREA A



BYXELKROK SECTION (AIR PHOTO DATA)

For the present project, the important observation is that the Byxelkrok section youngs continuously northeastwards from its southwest end towards "Hälludden" (see Figure 2-4), with only extremely slight dip variations. There are no signs of tectonic disturbance, except for a system of prominent fractures showing practically no displacement.

Relations in the Byxelkrok section are represented by scanlines 1 and 2 (Appendix A) and area A (Appendix B). The air photo map of area A shows the fracture pattern of the best exposed (least submerged) part of the upper Middle Limestone rock pavement and the location of the ground control map (Figure 4-5a, on the shore at the level of the second parking area, by "Forgalla skepp"). Scanline 1 ends just south of the latter, and scanline 2 is located about 500 m south of scanline 1 (Figure 1-2), at the level of the "Höga flisa" rune stone.

Characteristic for the Byxelkrok section is an open trellis-work of rather irregular fractures, with occasional extremely long and straight traces, particularly in a NNE direction. In the histogram rose diagrams, this shows itself in the wide, variable occupation of practically all the trend intervals, although irregular peaks are defined in the NW and NE quadrants, with a sharp high peak (the large straight fractures mentioned above) at 025°. The ground control mapping was carried out in an area of irregular interlacing fractures which is rather atypical. However, comparison of the air photo and ground control maps (Appendix B, area A) underlines a feature which is different to the other shore sections: all the fractures mapped on the ground can be identified on the air photos, i.e. the air photo map gives a true picture of the fracture density in this area (Appendix B, area A). This was confirmed also for scanline 1. The wide joint spacing in the Byxelkrok section is in fact too large to obtain representative results with 100 m long scanlines, as comparison of scanlines 1 and 2 with each other and with scanlines in other sections well illustrates (Appendix A). For these reasons, the digitized air photo fracture map provides the best basis for meaningful orientation statistics (Figure 4-5b).

Along the Byxelkrok section, mineralization and alteration borders are only observed very sporadically, without clear relation to fracture orientation, and no unambiguous evidence

Figure 4-5 *Byxelkrok section (see p. 31): air photo of ground control area (area A, Appendix B) and summary of digitized fracture trend data from air photo map. NB. Byxelkrok section differs from the other areas in that (1) all fractures are visible as traces on the air photo maps and (2) the fracture spacing is too wide and heterogeneous for the scanlines and ground control map to be representative. Here, therefore, the digitized air photo map gives a better idea of the orientation statistics than the ground data.*

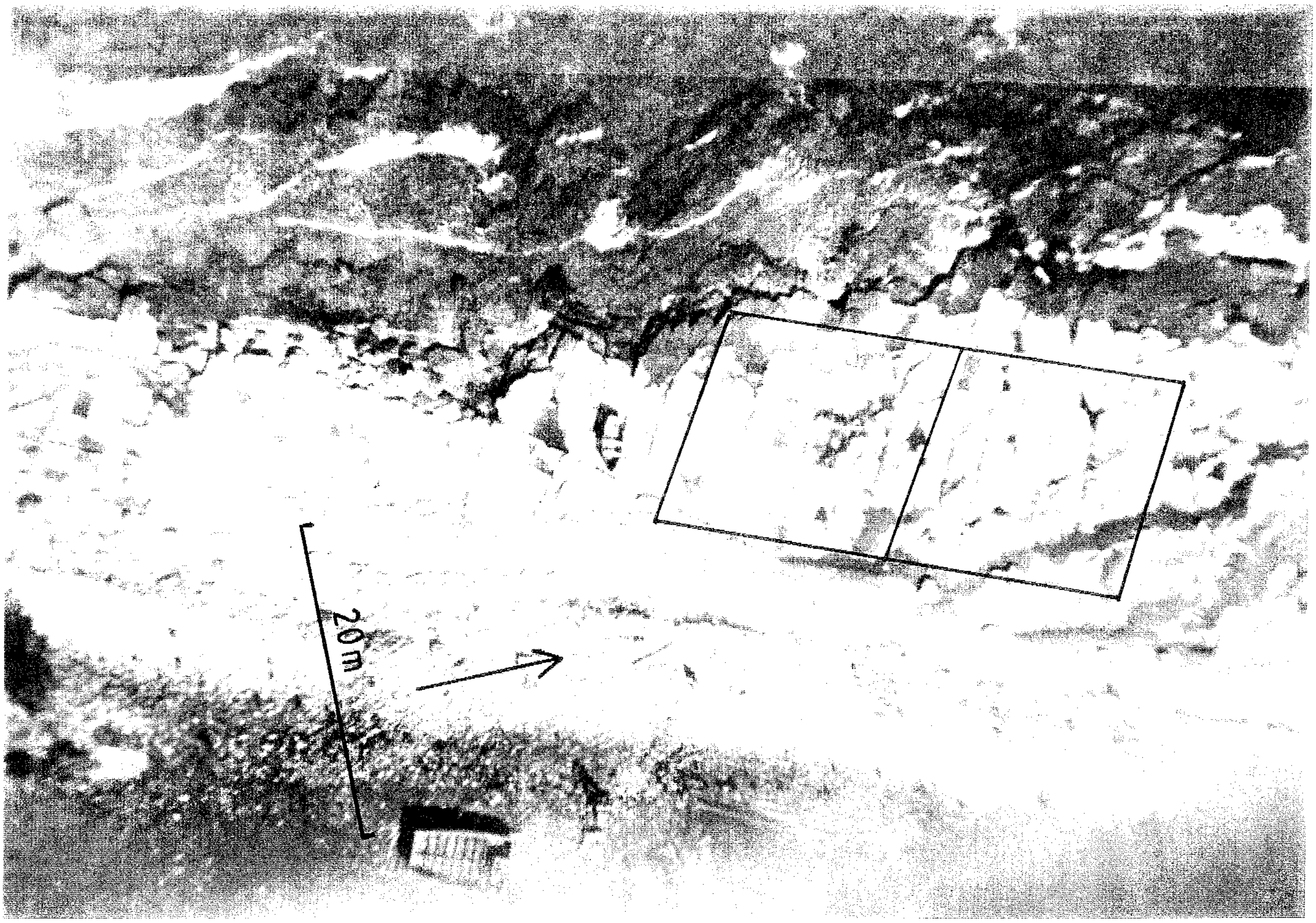
for different ages of fracture formation was found.

4.2.2 Hagudden section

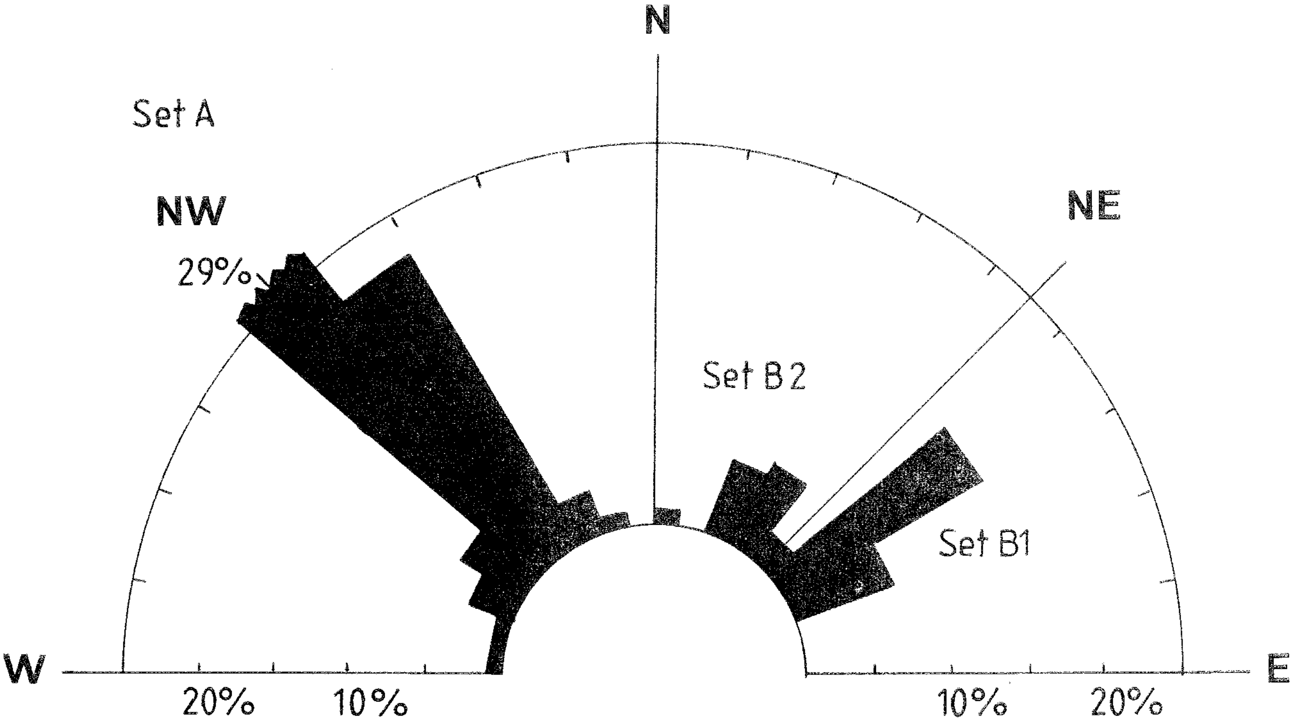
The Hagudden section is continuously exposed over a distance of about 3 km, with a stretch of less continuous outcrop to the south (as far as Rörstensudden) and another stretch of pavementin the bay by Enerum making a total length of 6 km (Figure 1-2). Stratigraphic relationships are very similar to Byxelkrok: in the south (Hagudden point), reddish Middle Limestone forminglow cliffs and narrow shore terraces; in the central area (Bådstenarna), a broad rock pavement in upper Middle Limestone; in the north, low cliffs (Sandviken) and eventually a broad platform (Enerum) in Upper Limestone. As at Byxelkrok, the Upper Limestone outcrops have been the subject of detailed paleontological and sedimentological study (Nordlund 1989c, see also Bohlin 1949, Jaanusson & Mutvei 1982). For the present study, the important observation is that the Hagudden section also continuously youngs northwards (as in the Byxelkrok section, see Figure 2-4), with extremely low but constant dips and no large-scale tectonic disturbance. The fact that the stratigraphy is repeated along these two sections and makes a rapid "jump" across the unexposed bay of Byxelkrok (a distance of 2 km) may indicate the presence of some sort of tectonic disturbance through this exposure gap (see Chapter 4.3).

The air photo map of the broadest part of the upper Middle Limestone platform (Appendix B, area B) shows the photographically resolvable fracture pattern in this area, and is accompanied by a ground control map of a small part of the same area, located at the level of the isolated hut and small boat slipway on the shore (Figure 4-6a). Scanlines 3 and 4 were laid out immediately north of the ground control map location, whereas scanlines 5 to 8 were spaced out along the outcrops to the south (Figure 1-2). In contrast to the Byxelkrok section, ground control showed that many of the fractures which exist are not distinguishable on the air photos (i.e. the air photo maps cannot be used for fracture density estimates), and that some "fractures" on the air photos are spurious markings (morphological breaks of no tectonic significance). In this case, therefore, it is a compilation of the scanline data which gives the best summary of the orientation statistics (Figure 4-6b).

The Hagudden section shows a major fracture set in the NW quadrant with very strong preferred orientation (very high and narrow peaks on the weighted histogram rose diagrams). We will refer to this as set A, and in the Hagudden section, it lies at about 320°. Set A fractures are characteristically mineralized, with the fracture surfaces coated with calcite, usually granular



GROUND CONTROL AREA B



HAGUDDEN SECTION (ALL SCANLINE DATA)

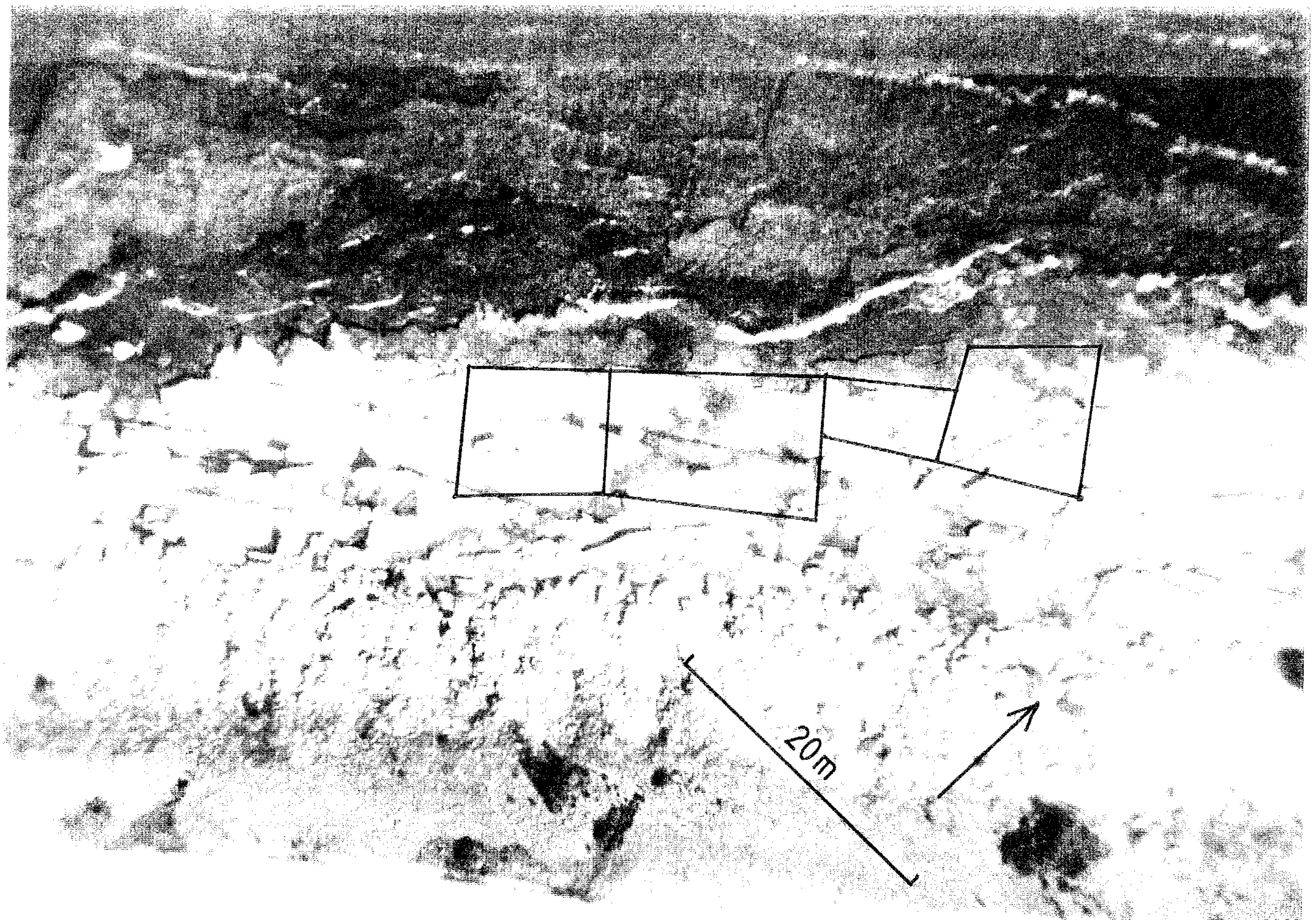
and lacking slickensides, and often showing sidesteps of both sinistral and dextral sense. In contrast, the NE quadrant shows two sets, the main one with a prominent peak at about 55° and a minor one with a low peak at 30°. These sets, B_1 and B_2 respectively, are only sporadically calcite coated, but often show alteration borders (greenish in the reddish limestones) up to 15 cm broad. Only sets A and B1 can be clearly identified on the air photo map (Appendix B, area B).

4.2.3 Hornsudden section

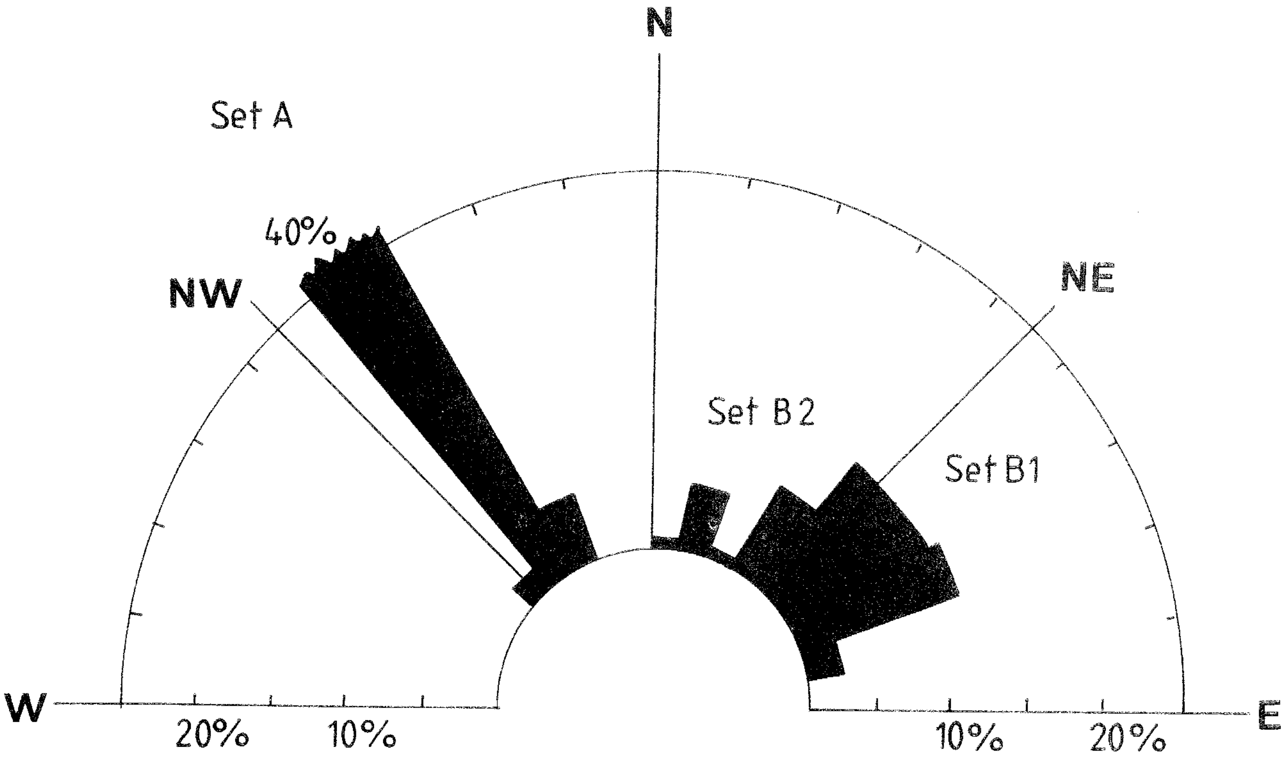
The Hornsudden section in northern Öland is a 6 km long stretch of combined coastline and quarry outcrops. It starts on the south side of Hornsudden itself, a prominent headland immediately opposite the basement monadnock island of Blå Jungfrun, at the locality Torsudde, and ends in the north at "Byrums raukar", a geological monument consisting of strangely shaped sea stacks in Upper Limestone. From the northern side of Hornsudden northwards, a continuous shore section shows the complete stratigraphic succession, from Alum Shale to Upper Limestone, as described in Chapter 2.1 (see Figure 2-4). This is another section of coast which youngs continuously northwards, to be followed by a stretch of unexposed shoreline (Byrums sandfält), across which a marked change in stratigraphic level takes place (from Upper Limestone at Byrum to Middle Limestone at the south end of the Hagudden section, as across the exposure gap between Hagudden and Byxelkrok).

An air photo map of part of the upper Middle Limestone rock pavement between Hornsudden and Byrum has been constructed and analysed, as in the previous sections (Appendix B, area C). Ground control is provided by the detail mapping of a small area at the south end of the platform (Figure 4-7a), located at the road junction for the hamlet Ålkistan. Ground control is also provided by scanline 9, which crosses the rock platform immediately north of the detail map, complimented by scanline 10, just to the south of the air photo map. Comparison with the air photos again shows that many of the fractures encountered on the ground were not resolved photographically, particularly the NE trending set (see area C, Appendix B), so the discussion of the orientation statistics below is based on a compilation of the scanline and detail map data (Figure 4-7b). Measurements and observations in the Hornsudden quarries provided important additional information but are not included in the statistics because of their unsystematic nature (Appendix C, sheet 4).

Figure 4-6 *Hagudden section: air photo of ground control area (area B, Appendix B) and summary of fracture orientation statistics from scanline data.*



GROUND CONTROL AREA C



HORNSUDDEN SECTION (ALL SCANLINE AND GROUND CONTROL DATA)

The orientation statistics from Hornsudden shows similar relations to Hagudden in the NW quadrant: a strong preferred orientation of joints with narrow spacing (1-5 m) giving a narrow peak at 325°. These belong to set A as defined in the Hagudden section, showing also the same characteristics: typically calcite-coated fracture surfaces (granular, rarely slickensided), sporadic alteration borders, and common sinistral and dextral sidesteps. The NE quadrant, however, shows different preferred orientations to Hagudden, with a very broad low peak between 40° and 70°, and a clear but minor peak at 15°. We refer to these again as B1 and B2 respectively, without implying a strict correlation. The B set fractures show sporadic mineralization and alteration borders, and are generally longer, more widely spaced (5-20 m) and more open fractures, and most of them are visible of the air photos.

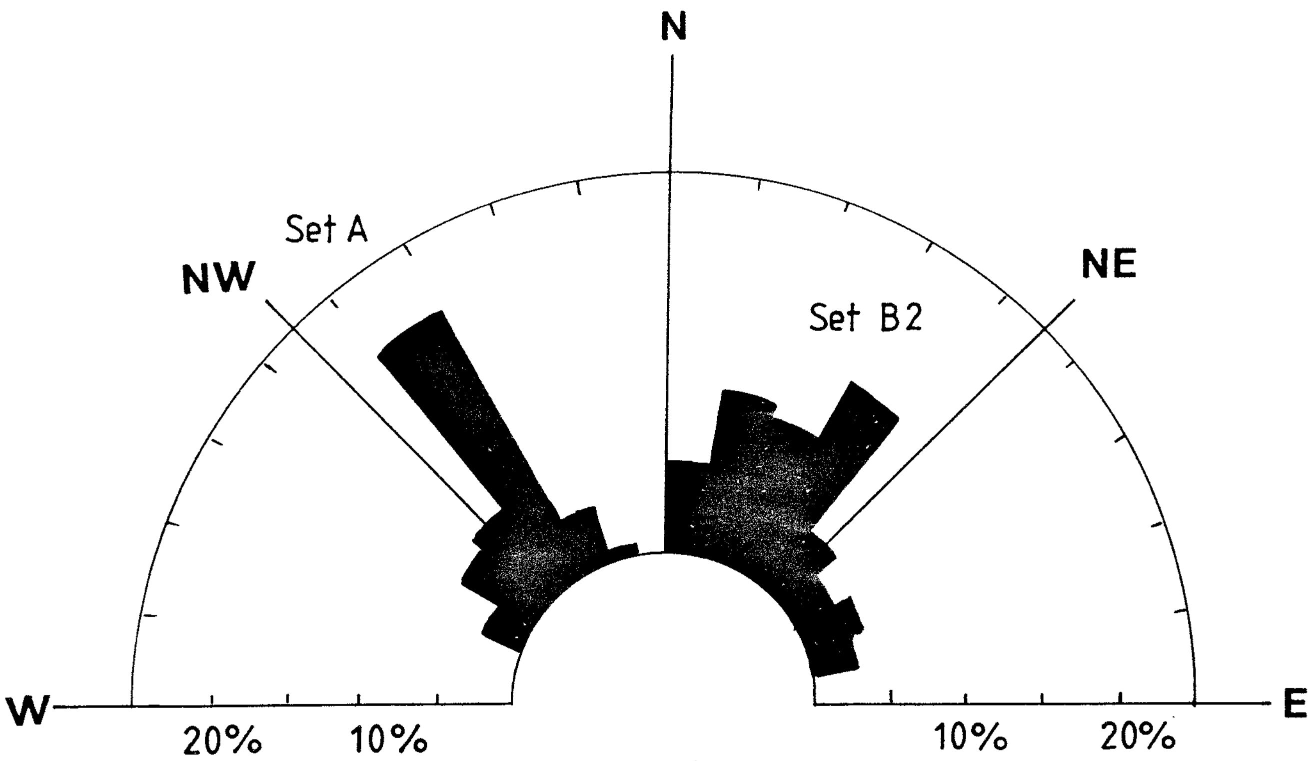
The data from the Hornsudden quarries support and complement the shoreline results (Appendix C, sheet 4). The three sets can be identified as above (although the unsystematic nature of the measurements means that the relative column heights are different). The B1 fractures are particularly prominent, often as huge surfaces several metres high and several tens of metres long, and are practically always covered with a thin layer of granular calcite, with only very occasionally subhorizontal slickensides of fibrous calcite and "slickolites". In contrast, A and B2 set fractures are under-represented as quarry faces. When observed, the former are generally calcite covered but unslickensided, whereas the latter practically always show subhorizontal slickensides (Appendix C, sheet 4; for further discussion, see Chapter 5.2.2). These relations are obscured along the shore because of the lack of exposure depth and the wave-washed nature of the outcrops.

Several observations of set B fractures cutting through the calcite coating/calcite fill on set A fractures suggest that set A is older. However, mineralization and wall rock alteration seems to affect all fractures sporadically, so a clear time relationship is elusive.

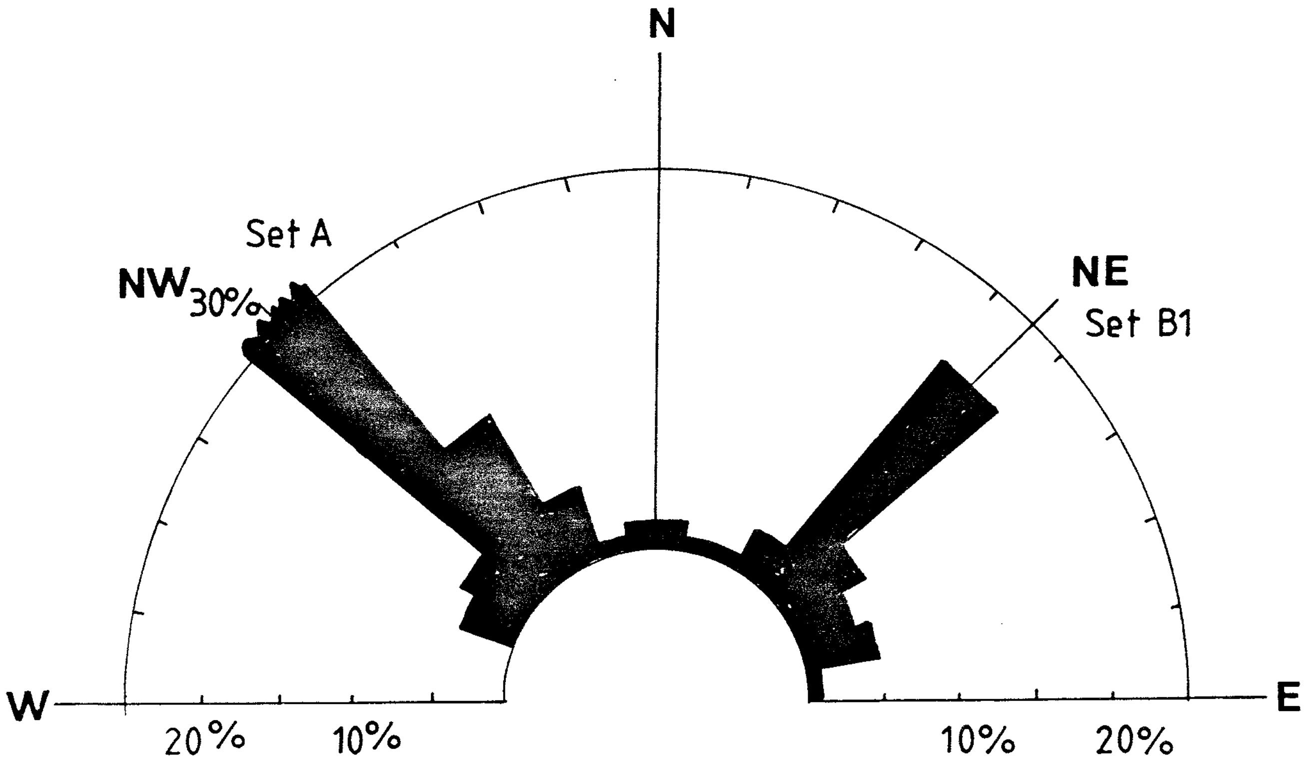
4.2.4 Västra Alvaret section

The Västra Alvaret coast section starts at a small bay with a group of fishing huts, north of Grytehamn quarry, and ends at the road junction to Lottorp, near the small harbour and uninhabited fishing hamlet "Alvedsjö bodar", a distance of about 5 km. Exposure is continuous except for a break between

Figure 4-7 *Hornsudden section: air photo of ground control area (area C, Appendix B) and summary of fracture orientation statistics from scanline and ground control data.*



a) VÄSTRA ALVARET SECTION - NORTH
(ALL SCANLINE DATA)



b VÄSTRA ALVARET SECTION - SOUTH
(ALL SCANLINE DATA)

Eskilslund and Kristinelund, subdividing it into a northern and a southern segment. This break corresponds to a slight depression. The northern segment, in Middle Limestone, youngs southwards, corresponding to the south side of the Hornsudden culmination (Figure 1-2). The southern segment is practically horizontal, and because the upper Middle Limestone is here at sea level, is composed of a long rock pavement which is very often awash. Towards the south, however, it rises slightly (the area of air photo map D, Appendix B), and eventually gives way to a narrow terrace shore in reddish Middle Limestone. The general structure of the Västra Alvaret section is thus a wide shallow depression (see Figure 2-4).The air photo map of part of the southern Västra Alvaret section (Appendix B, area D) gives a good impression of the fracture pattern in the southern segment, although comparison with the ground control map (see also Figure 4-4) shows also here that many of the NW trending fractures are not imaged on the air photos. The ground control area itself lies midway between the two isolated huts which are the only landmarks along the shore. Scanlines 14 and 15 lie at the level of the northern (red wooden) hut, whilst scanline 16 is by the southern (stone) hut and scanline 17 by the group of huts at the south end of the section. The compiled data from these four scanlines and the ground control map area give the best overview of the orientation statistics in this area (Figure 4-8b). The northern segment is represented here by the three scanlines 11, 12 and 13 (Figure 1-2), which are compiled on Figure 4-8a.

Both the southern and the northern segments show the well defined peak in the NW quadrant at around 320° (Figure 4-8), corresponding to fracture set A in the Hagudden and Hornsudden sections (Figures 4-6 and 4-7). The characteristic spacing and sidestepping of this set remain, but the mineralization (calcite coating) is noticeably absent. In the NE quadrant, the two compilations show rather different distributions, both broad and variable, but with an emphasis on NNE trends, i.e. subset B2 in comparison with Hagudden and Hornsudden, in the north (Figure 4-8a) and ENE trends, i.e. subset B1, in the south (Figure 4-8b).

4.2.5 Jordhamn section

The Jordhamn section consists of a line of quarries, starting at the bay of Grytehamn in the north and ending at Sandvik, the centre of the rock dressing industry, in the south (Figure 1-2).

Figure 4-8 *Västra Alvaret section (for air view of ground control area see Figure 4-4, cf. area D, Appendix B). (a) Summary of fracture orientation statistics from the northern segment, scanlines 11-13. (b) Summary of fracture orientation statistics from the southern segment, scanlines 14-17 and ground control area D.*

There are practically no shore exposures in this area. The quarries are cut in a particularly thick layer of massive and practically unfractured limestone making up the central part of the Middle Limestone, although the quarry walls sometimes extend up into the Upper Limestone. In places, the transition from Middle to Upper Limestone is well defined and marked by remnants of a raised beach, behind which the typical erosional forms of the Upper Limestone along the present coast (e.g. Byrums Raukar) are well preserved (Figure 2-5). Bedding is practically horizontal in this area. The presently active quarry at Grytehamn is the locality called "Gillberga" by Nordlund (1989c). An inactive quarry south of this is presumably the locality mentioned in Talbot (1990), although his designation of this area as a "fault zone superbly exposed" presumably reflects a comparison with the generally poor 2D exposures on the mainland at Äspö.

Sheet 6 in Appendix 3 presents a summary of data from the quarries in the Jordhamn section as a simple histogram (unsystematic survey). Comparison with the scanline data from the other sections and with the quarry data from Hornsudden shows obvious similarities. In the NW quadrant, set A fractures show a good preferred orientation, as usual, and observation of the fractures show also here the dominance of unslickensided surfaces, sporadically covered with thin coatings of granular calcite. Also the broad B1 set is easily identified and shows only occasional slickensiding, whereas the almost N-S trending set B2 show dominantly slickensided surfaces, typically with fibrous calcite and pressure solution effects (slickolites). The size of some of these surfaces is impressive, but does not necessarily imply much displacement (see Chapter 5.2.2).

The occurrence of different sets of striations and the mixture of slickensided and unslickensided surfaces suggest that the lateral displacements took place after fracture formation, by reactivation of already formed and partly mineralized fractures.

4.3 CONCLUSIONS

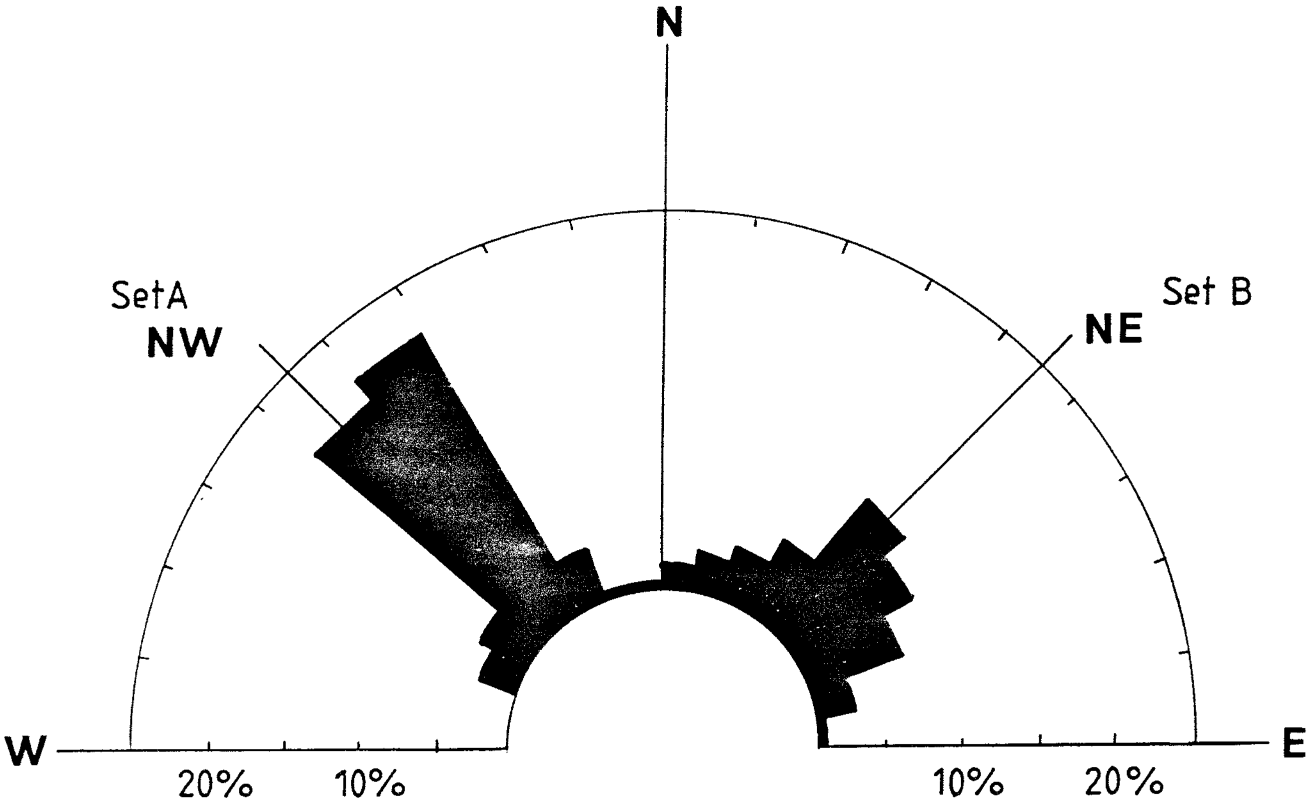
The data presented and summarized above is mainly concerned with the analysis of the fracture pattern in terms of orientation statistics. The data is derived from the same stratigraphic horizon along the whole shore, the upper part of the Middle Limestone. The age of the limestone is Lower Ordovician (Arenig), i.e. ca. 480 Ma, providing a definitive lower limit for the age of the fractures. The results of the orientation analysis can be outlined as follows:

(1) Of the five more or less continuously exposed shore sections (or lines of quarries), the four southern ones show a consistent general pattern which can be described in terms of two main fracture sets with different characteristics. Set A, in the NW quadrant, shows a high degree of preferred orientation (high narrow peaks in the orientation statistics) with trends varying between 310 and 330 degrees (Figure 4-9a) and a spacing of the order of 1-5 m. In many areas, the fractures are calcite coated or calcite filled, and closed, and for that reason they are only partly distinguishable on the air photo maps. Set B, in contrast, shows a low degree of preferred orientation (low peaks in the orientation statistics) and often occurs in subsets (labelled B1 and B2) which vary in orientation and importance from place to place (generally between NNE and ENE). These fractures tend to be more open and more widely spaced (of theorder of 5-20 m), and are practically always visible on the air photos. Concomitant with these peaks, some very constant vacancies in the orientation statistics occur: fractures in the trend ranges 80-110° (260-290°) and 340-360° are practically absent along the whole coastline south of Byxelkrok, a distance of 30 km.

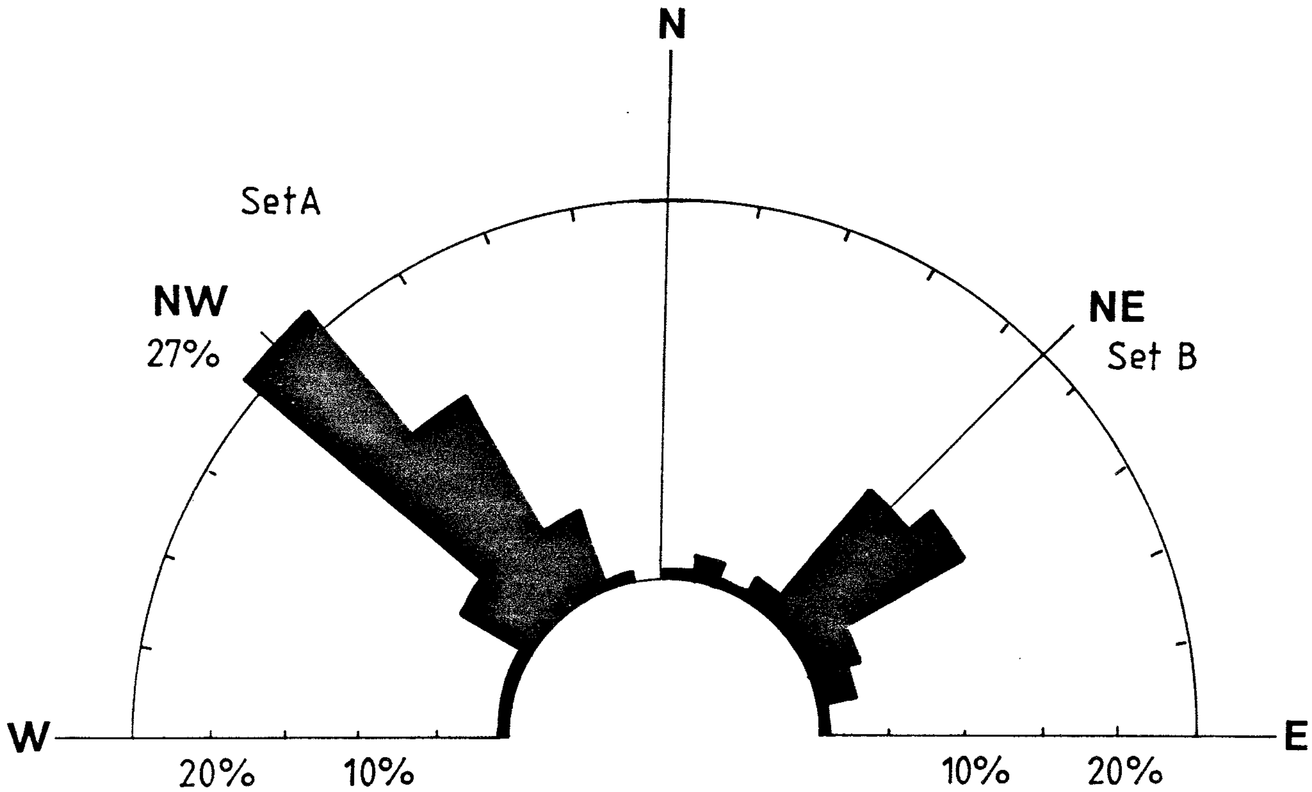
(2) The Byxelkrok section, i.e. the shoreline north of Byxelkrok Bay, does not fit into the above scheme very well, as is obvious from the air photo map (Appendix B, area A). Set A is absent, or is represented by a broad low peak (Figure 4-5b), whereas the dominant direction, in the form of long straight fractures is a prominent high peak in the NE segment, together with many other minor ones. Also, the fracture density in the section is anomalously low (similar to the least fractured quarry outcrops, see Table 5-1), and the ground control maps and scanlines are unrepresentative (hence the use of the air photo map for the orientation statistics in this area).

(3) Byxelkrok Bay thus subdivides the shoreline of northern Öland into two sections with different fracture patterns. As mentioned in Chapter 4.2.2, the bay also marks a small, but sharp change in the stratigraphic level exposed at the water line (middle Upper Limestone in the south, middle Middle Limestone in the northe, see Figure 2-4). These two features together suggest that the bay marks the position of a tectonic disturbance. Since it lies on the SE continuation of a prominent NW trending fault zone in the basement (southwestern margin of the Västervik zone, against the Småland gneiss/granite complex), it may be reflecting this change in basement structure and its later, slight, reactivation.

(4) Although all the fractures are certainly younger than Early Ordovician in age, there are few ambiguous indications of relative timing amongst the different sets. At some localities,



a) NORTH ÖLAND - AREAS B, C, D
(ALL SCANLINE AND GROUND CONTROL DATA)



b NORTH ÖLAND - AREAS B, C, D
(AIR PHOTO DATA)

however, set B fractures were seen to cut through the calcite coating/calcite fill of set A fractures, indicating a possible time sequence in fracture generation (set A early, set B late). Neither the statistics nor the fracture characteristics suggest the presence of conjugate shear joints as sets of regional significance: we interpret the fractures in the limestones of northern Öland as originating as extension joints. Some of these were then reactivated by shear movement at a later stage. This point will be discussed further in the following chapter.

Figure 4-9 *(a) Northern Öland: summary of fracture orientation statistics from all scanlines and ground control areas in Hagudden, Hornsudden and Västra Alvaret sections.*
(b) Northern Öland: summary of fracture orientation statistics from air photo maps B, C and D, in Hagudden, Hornsudden and Västra Alvaret sections respectively.

5 BEDROCK STABILITY

The fracture pattern analysis itself does not contribute directly to the question of bedrock stability, although it may provide some control on the timing of fracture formation in the underlying basement (e.g. by helping to distinguish between pre-Cambrian and post-Cambrian fracture sets). The aim of the Öland work, however, was to use the unique geological circumstances to put quantitative controls on the amount of post-Cambrian deformation, especially with respect to discontinuities which could have taken up geologically recent (e.g. Quaternary) movement. The fractures and fracture systems described above are all potential movement planes or zones of that type, either when they formed or as planes of weakness in subsequent stress fields. From the stability point of view, therefore, two types of additional information are important: fracture density variations ("intensity" of fracturing), and displacement relationships and other kinematic indicators (amount of post-Ordovician movement and movement history).

5.1 FRACTURE DENSITY

Fracture density is a parameter describing the intensity of fracturing in 2D, defined as the length of fracture trace per unit area on the surface in question. For the air photo maps and the ground control areas, this definition can be used in its strict form with the present data (Table 5-1). However, as noted above, only the air photo map of area A (Byxelkrok section) is judged to encompass all the existing joints at and above the 2m cut-off level. The air photo maps of the other areas (B, C, D) give too low figures because many of the fractures are not identifiable on the photographs. For this reason, the scanline data has been used to obtain fracture density figures in those areas. The weight number assigned to each fracture to correct for the main distortion in the orientation statistics (Chapter 4.1.1) is in fact what can be termed a "nominal length" - it is approximately the length a fracture of that orientation would have within a window represented by a 2 m broad strip along the scanline (the scanlines are drawn as 2m broad strips in Appendix 1). Hence, adding up the weight numbers for a particular fracture set or for the whole population gives a total "nominal length" which can be converted to a fracture density by dividing by the "scanline area" (200 m^2). The fracture densities calculated in this way for sets A and B and for the total population, for each scanline, are also given in Table 5-1. Finally, the direct measurement of the area

Table 5-1 *Fracture density measurements, 'Middle Limestone' (lower Ordovician), northern Öland. Units: length of fracture trace in metres per 100 m^2 of bedding surface. For scanline data the unit used is 'nominal length' (see text).*

	set A	set B	all fractures
Byxelkrok			
air photo map analysis (13 000 m^2)			19
Jordhamn			
quarry, direct measure, Grytehamn (500 m^2)			19
quarry, direct measure, Bäckekärret (1500 m^2)			9
Hagudden			
scanline 3	38	20	63
scanline 4	36	2	48
scanline 5	36	29	73
scanline 6	34	35	80
scanline 7	25	28	59
scanline 8	38	14	63
– average scanlines 3-8	35	18	64
ground control map B (443 m^2)	50	1	60
Hornsudden			
scanline 9	34	26	63
scanline 10	20	38	71
– average scanlines 9-10	27	32	67
ground control map C (459 m^2)	37	26	84
Västra Alvaret			
scanline 11	31	35	(121)
scanline 12	27	17	75
scanline 13	13	21	64
scanline 14	25	16	50
scanline 15	27	50	91
scanline 16	32	37	86
scanline 17	42	29	93
– average scanlines 11-17	28	29	77 (excl.11)
ground control map D (515 m^2)	49	27	86

of some quarry floors, together with the length of fracture trace exposed (measured by tape), provided a third source of fracture density data. These figures (Table 5-1) serve as a good basis for comparison, giving the minimum fracture density on Öland, since the quarries are sited in the "best" positions, meaning not only thickly bedded or massive rock units, but also a low degree of fracturing (Figure 5-1).

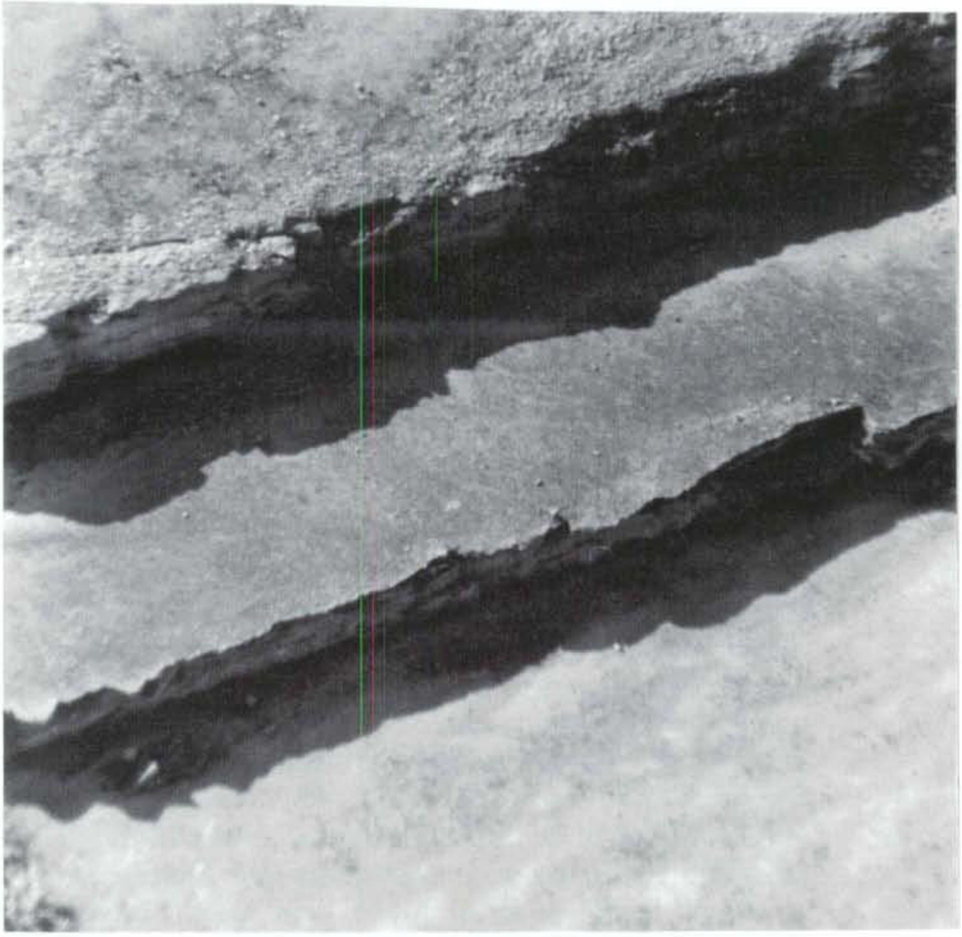
The fracture density in the two measured quarries of 9 and 19 (units: metres of fracture trace per 100 m^2 of bedding surface) corresponds approximately to that deduced from the Byxelkrok air photo map (19 m/100 m^2), which, as noted above, was already judged qualitatively in the field to show a lower degree of fracturing than the other shore sections. The latter show a fairly constant average density as deduced from the scanline and ground control map data, with total densities varying between 60 and 86 m/100 m^2, i.e. 3 to 10 times the quarry and Byxelkrok figures. Interesting is also the relative importance of the set A and set B fractures, i.e. approximately equal at the 20 to 40 m/100m^2 level. The strong preferred orientation (single high peak) of set A is compensated by the broad spread of orientations within the B set (two or more low peaks) as far as fracture density is concerned.

The significance of the above fracture density data should not be overestimated. The amount of data is far too low for concrete results and the manipulation of the scanline data used can hardly be called definitive. Also, vertical sections show that fracture density is controlled to some extent by lithology and bedding thickness, as has been noted in the literature on jointing in sedimentary sequences (e.g. Brosch 1983, Narr & Lerche 1984, Aguilera 1988, Bahat 1988, Huang & Angelier 1989). Although care was taken along the shore sections to locate measurement stations at the same stratigraphic level (upper Middle Limestone), lithological differences certainly occur. Also, the quarry data is derived from the middle part of the Middle Limestone, and therefore not strictly comparable. The interpretation of these data with respect to bedrock stability is thus fraught with difficulties, and will only become meaningful after more systematic studies, not only of the different lithologies of the cover sequences but of the crystalline basement of the mainland, as well.

5.2 KINEMATIC INDICATORS

As noted previously, the limestone pavements of northern Öland are in many respects unique in that the probability of finding positive information on whether or not movement has taken place on each individual fracture is unusually high, and there is

a



b

Figure 5-1 *Jordhamn section, least fractured quarry sections, used for determination of minimum fracture density.*
(a) Air photo of bedding surface in Grytehamn quarry.
(b) Ground photo of bedding surface in Bäckekärret quarry.

even a good chance of measuring the actual amount of movement in many cases (Chapter 3.2). During the ground control mapping and scanline logging, every fracture was studied with this in mind, since this is a critical contribution to the discussion on the stability of the bedrock during fracture formation and reactivation. In the following, we first discuss the quantitative indicators - bedding and fossil displacement - which give an actual measure of movement, and then the more qualitative kinematic indicators - slickensides, etc - which only show whether or not movement has taken place, and in which direction.

5.2.1 Fossil and bedding displacement

Only 9% of all the observed fossil/fracture intersections showed any lateral displacement, and this is thought to be representative of the total fracture population (Chapter 3.2). Strike-slip varied up to a maximum of 5 cm, with both dextral and sinistral senses. Looking at the statistics of displacement and orientation (Appendix C, sheets 1-6) shows that there is a tendency for displacement to be observed more often on set B fractures than set A (ratio 2:1). Also, there is a tendency for displacement to be dextral on set A and sinistral on set B, although this is by no means exclusive. The main conclusion to be drawn from the fossil data is that most fractures in all sets show no lateral displacement whatsoever, i.e. with regard to lateral (strike-slip) movement in any direction the exposed platforms have been quite remarkably stable for the last 500 Ma. This generalization applies to block sizes several kilometres in length, albeit only 10 s of metres wide.

With regard to vertical displacement of bedding, even less movement is indicated within the same elongate blocks. Only 3% of the fractures showed any dip-slip (and this could be determined for every fracture observed), with throws up to a maximum of 8 cm. All observed cases of vertical displacement could be classified as small normal faults, although the true slip direction could rarely be determined. Examples of vertical displacement of bedding were not confined to a particular fracture set (see Appendix C), and within one set downthrows were observed in both directions. Also in the vertical direction, therefore, the shore pavements and quarries suggest exceptional stability over very long periods of time.

5.2.2 Slickensides

In addition to the above, several other movement indicators were noted, of which slickensides were the most common (see Chapter

3.3). In the quarries of Hornsudden and Jordhamn, where slickensided surfaces are often spectacularly exposed, an attempt was made to determine their systematics (Appendix C, sheets 4 and 6). This showed again that only a small percentage of the exposed surfaces were striated. Most of the observed slickensides were subhorizontal, although some surfaces showed variable oblique directions. There is a greater tendency for fractures with strikes in the NE quadrant (B sets) to be slickensided than NW trending fractures (set A). The sense of shear, when it could be unambiguously determined, was variable. A search was naturally made for examples of slickensided fractures intersecting fossils or offsetting veins, with only limited success. The few examples found showed displacements varying from less than 1 cm to a maximum of 4 cm, and this agrees with the observation that the calcite fibres are of the order of centimetres in length (cf. Ramsay & Huber 1983). All in all, the slickenside and fossil displacement data fit together very well, although the rarity of occurrence makes it difficult to make statistically well-founded interpretations.

At this point it is appropriate to comment once again on the observation by Talbot (1990, p. 14), that the Jordhamn quarries lie in a "superbly exposed fault zone". The description of the physical features of the faults and slickensides in this work is accurate, and fits well with our data. Some of the huge surfaces (60 m long, 4-6 m wide, Talbot 1990) covered with calcite fibres and pressure solution striations are certainly impressive. Our work indicates, however, that care must be taken not to overemphasize their importance. Taken within the context of the whole shoreline, they are not unusual in themselves - every fracture showing a fossil displacement of a few cm would look the same if it were quarried out. Neither do the slickensided surfaces seem to be concentrated in zones or confined to a particular joint set. This is a good example of how the fossil data are critical for determining the amount of displacement, and how the Öland data can make a significant contribution to the discussion of bedrock stability.

5.2.3 Sidesteps

The common occurrence of "sidesteps" (Chapter 3-4, Figure 3.3) was noticed at an early stage and studied systematically because of the suspicion that some fractures could be arranged in en echelon-like zones which might be an indication of development in a shear regime. However, the same type of unsystematic distribution was observed as for the other indicators: all fracture sets showed the same feature (although there was a greater tendency for association with set A, see Appendix C, sheet 7), and the proportion of sinistral and dextral sidesteps was practically 50/50 within each set. On the basis of this and many qualitative observations, we now conclude that they represent relay structures, as described, for instance, in Olson & Pollard (1989), related to the mechanism of extensional crack propagation and the type of the paleostress environment. They confirm, in fact, the impression that all fractures on Öland were generated as extensional fractures (joints in the genetic sense, cf. Engelder 1987, Pollard & Aydin 1988), not as shear fractures (i.e. not in conjugate systems). The observed shear displacements probably took place during slight reactivation of the already formed extension fractures in a subsequent and different stress field (see below).

5.3 STRAIN/STRESS HISTORY

Based on the above discussion and the fracture pattern analysis (Chapter 4) it is possible to draw some tentative conclusions on the history of fracture formation and reactivation in the Öland limestones, and their significance in terms of strain and stress history. The basic premises are as follows:

1) The constancy of the fracture and displacement pattern along the shoreline between Byxelkrok and Sandvik (a distance of about 30 km, see Figure 1-2) indicates failure in a broadly regional stress field rather than in a series of varying local stress fields.

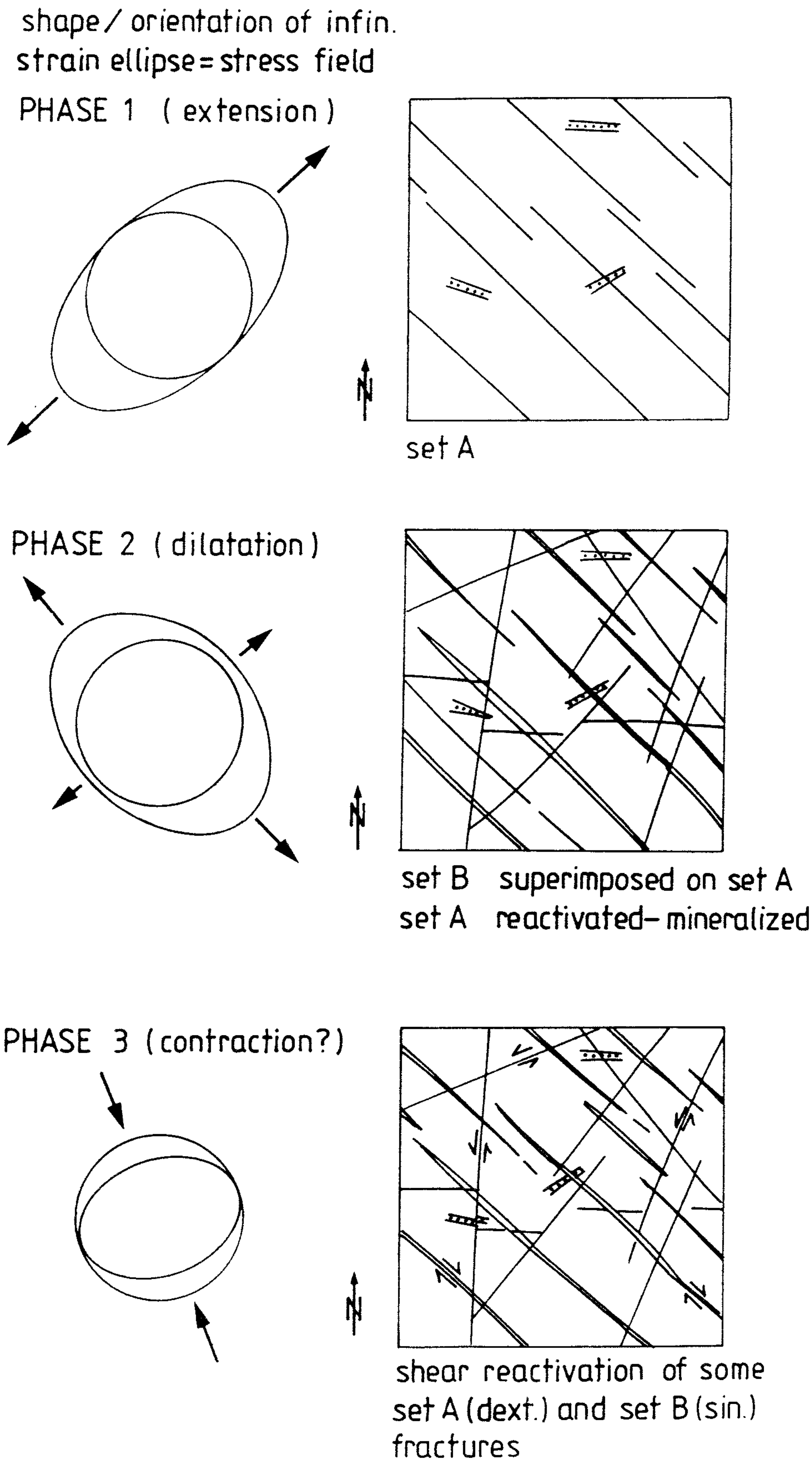
2) All the fractures formed as extensional phenomena (true joints). These may or may not have been reactivated at a later stage by shear movement. Systems of original shear fractures (e.g. in conjugate sets) have not been recognized.

3) Fractures of set A seem to have been formed and mineralized before the development of at least some of the set B fractures.

4) The strain induced, at least within the exposed elongate blocks, has been extremely small, with calcite fills and apertures measured in centimetres on the few veins and open joints, and maximum lateral or vertical displacement measured in centimetres on only a small proportion of the fractures along

Figure 5-2 *Interpretation of the history of fracturing and fracture reactivation in the limestones of northern Öland in terms of the deduced infinitesimal strain ellipse of the different strain increments (phases 1-3). Note that the ellipses drawn here only serve to visualize the ellipse type for comparison with the Ramsay strain field diagram (Figure 5-3) - the actual ellipse in each case, being infinitesimal, would be indistinguishable from the original circle. The principal axes of stress are, by definition, parallel to the principal axes of infinitesimal strain at each stage in the deformation.*

INTERPRETATION OF FRACTURING HISTORY OF ORDOVICIAN LIMSTONES IN NORTHERN ÖLAND. (CF. Fig. 5-3)



kilometres of continuously exposed rock. A large proportion of fractures show no displacement in any direction. Hence, it is appropriate to discuss fracture development in terms of infinitesimal strain, allowing direct dynamic interpretation (stress field).

These basic premises lead to the following sequence of fracture system development in northern Öland (south of Byxelkrok), as summarized in Figure 5-2.

Phase 1 Development of set A fractures.

The strong preferred orientation of the extension fractures suggests an initial strain increment with the infinitesimal strain ellipse showing a single extension axis orientated NE-SW. This corresponds to extensional strain on the boundary between fields 1 and 2 on the Ramsay plot of 2D strain ellipses (Ramsay 1967, see Figure 5-3).

Phase 2 Development of set B fractures, possibly with continued development of set A.

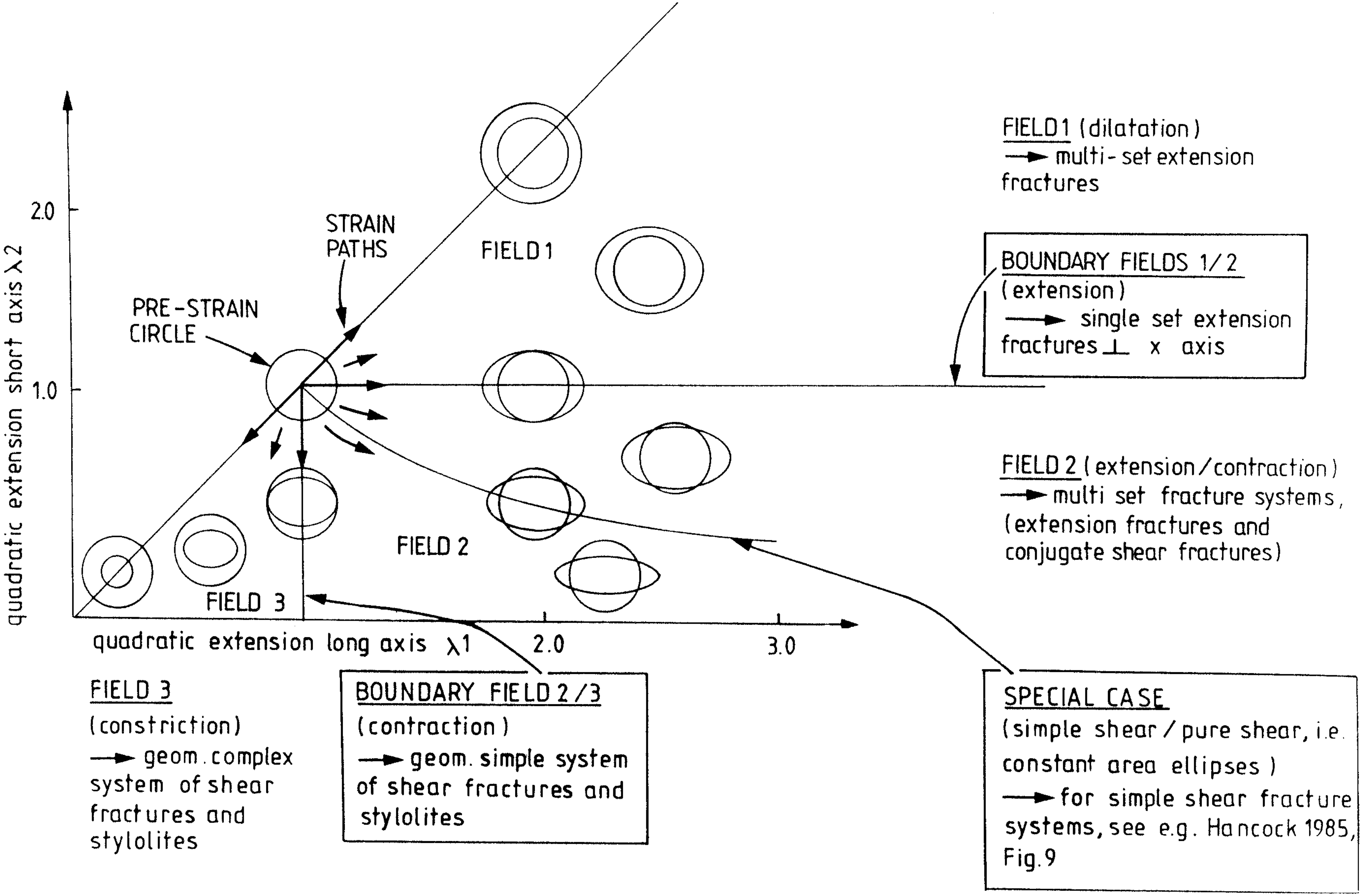
The wide spectrum of set B extension fractures and the partly ambiguous timing and mineralization relations suggest that the next increment of infinitesimal strain can be represented by an ellipse of dilatational type (strain field 1, Figure 5-3), with major extension NW-SE and continued minor extension NE-SW (Figure 5-2). The opening of already formed A fractures in this field may have facilitated the movement of fluids, causing the preferential mineralization of this set.

Phase 3 Sporadic shear reactivation of both A and B sets

The sporadic occurrence of shearing and the preference (but not exclusive occurrence) of dextral movement on A fractures and sinistral movement on B fractures suggests a final increment of strain with an infinitesimal strain ellipse of contractional or constrictional type (boundary of strain fields 2 and 3, or field 3, Figure 5-3), with the main contractional axis roughly N-S.

Because there is a direct relationship between the principal axes of infinitesimal strain and the principal axes of stress, the stress

Figure 5-3 *The Ramsay plot and classification of all possible 2D strain fields, and a proposed interpretation of their geological significance in relation to regional brittle deformation (after Ramsay 1967, cf. Davis 1984).*



quadratic extension short axis λ2
2.0
1.0
STRAIN PATHS
PRE-STRAIN CIRCLE
FIELD 1
FIELD 2
FIELD 3
quadratic extension long axis λ1
2.0
3.0
FIELD 1 (dilatation)
→ multi-set extension fractures
BOUNDARY FIELDS 1/2
(extension)
→ single set extension fractures ⊥ x axis
FIELD 2 (extension/contraction)
→ multi set fracture systems, (extension fractures and conjugate shear fractures)
FIELD 3
(constriction)
→ geom. complex system of shear fractures and stylolites
BOUNDARY FIELD 2/3
(contraction)
→ geom. simple system of shear fractures and stylolites
SPECIAL CASE
(simple shear / pure shear, i.e. constant area ellipses)
→ for simple shear fracture systems, see e.g. Hancock 1985, Fig. 9

field during phases 1 and 2 can be deduced as essentially tensional (no compressional component in the horizontal plane). There is good evidence that it was also tensional earlier, i.e. during the development of the Cambrian clastic dykes. It is interesting to note that the only proven post-Cambrian fractures on the adjacent mainland (Simpevarp and surroundings), those which cut through the Cambrian clastic dykes (Nordenskjöld 1944), show a preferred orientation identical with the set A fractures on Öland (Figure 5-4).

The main change in stress regime took place between phases 2 and 3. During phase 3, the Öland limestones appear to have suffered horizontal compressional stress, with a maximum in a N-S direction. The existence of a corresponding tensional axis at right angles (infinitesimal strain in field 2, Figure 5-3) seems unlikely considering the sporadic nature of the shear reactivation: tension would be expected to have released movement on all appropriately orientated planes of weakness, which would have included most of the fractures in both set A and set B.

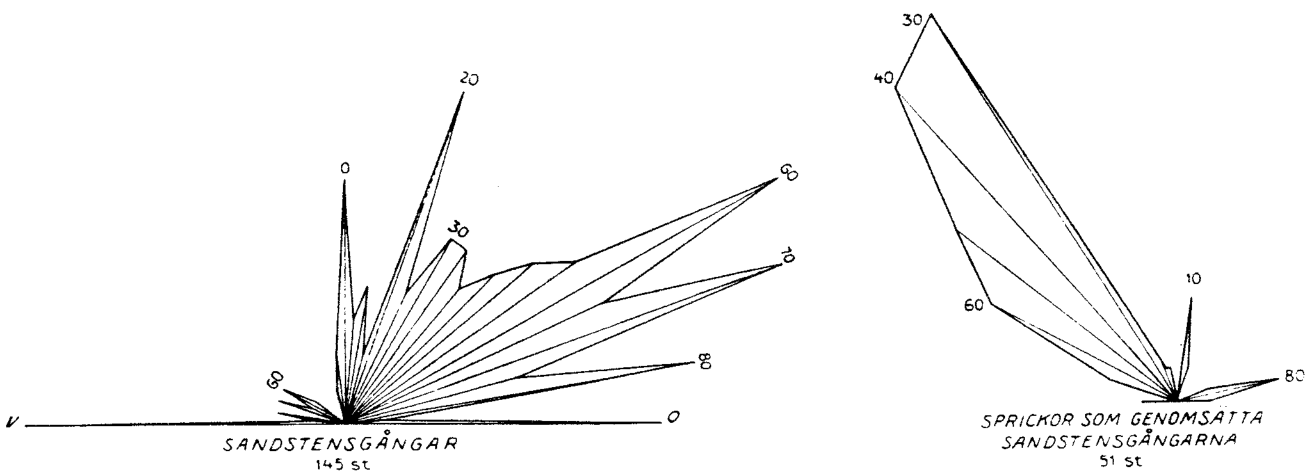


Figure 5-4 *Histogram rose diagrams for Cambrian sandstone dykes in the Precambrian basement of the Simpevarp area (A) and for fractures post-dating dyke formation (B), from Nordenskjöld 1944.*

5.4 CONCLUSIONS

The main conclusion of this discussion is that the exposed shore sections of northern Öland only show signs of absolutely minimal bedrock instability over the last 500 Ma. The data also allow a basic structural history to be deduced which is partly correlatable with features in the Simpevarp area. However, it should be noted that the data relates to continuously exposed rock blocks of finite extent (strips a few tens of metres wide and a few kilometres long). These are separated and surrounded by unexposed areas, under water or covered with regolith and vegetation, from which there are at the moment practically no hard facts of relevance to the stability problem. Some indications of the possibility of post-Ordovician effects in these areas have been noted in Chapter 2.2 and 4.3, and these lead to the recommendation for geophysical studies in Chapter 6.

6 RECOMMENDATIONS

The apparent regularity of the surface of the pre-Cambrian peneplain across southeastern Sweden (Lidmar-Bergström 1988), suggests that the whole of this part of the country has suffered remarkably little deformation during the last 500 million years. As indicated above, this conclusion needs to be tested as rigorously as possible. The local evidence of a simple Phanerozoic fracture pattern and notable lack of disturbance from the shore platforms and quarries of northern Öland may not be representative of the general area covered by Paleozoic strata in this part of the Baltic. Even if it is, the area may be separated from the mainland by a zone of disturbance (for instance, along Kalmarsund) or intersected by fault zones (for instance through the exposure gaps), allowing for a more complex Phanerozoic deformation history of the basement than is apparent. Fracture systems on the mainland seem to be much more complex, although some obvious similarities exist, e.g. between the orientation of the main maximum of "young scarps and fractures" (Mörner 1989) and the total fracture rosette (Ericsson 1988), and fracture set A on Öland. However, much of the reported data from the mainland and many of the interpretations are at variance with the data and interpretations presented above (e.g. Nisca 1987, Tirén et al. 1987, Tirén & Beckholmen 1988a, b, Talbot & Riad 1988, Talbot et al. 1988, Talbot & Munier 1989, Munier 1989, Talbot 1990, Mörner 1989). Before pursuing such comparisons and correlations in more detail, therefore, it is imperative to establish the regional significance of the northern Öland data set. In order to accomplish this, we recommend the following studies:

a) Extension of the fracture analysis in the Ordovician limestones to other parts of Öland. Since the Middle Limestone is not exposed at water level south of Sandvik, such analysis will not be as systematic as that allowed by the shore platforms to the north, but will allow the representativeness of the northern Öland data set to be tested, using a combination of quarry data, ground observation in the large areas of "alvar" and aerial photograph analysis.

b) Detailed study of the sandstone dyke swarms and fracture systems in the basement on the islands surrounding and offshore from Simpevarp and on the mainland, at the localities reported by Nordenskjöld (1944). This would enable proven post-Cambrian fractures (i.e. fractures cutting through the sandstone dykes) to be isolated in a basement area close to Äspö and to be analyzed with respect to orientation and displacement in comparison to the northern Öland data. A complimentary study of the island of Blå Jungfrun, a monadnock of Precambrian granite within the area of Palaeozoic cover between Simpevarp and Öland, should be included in this research.

c) Marine geophysical surveys, particularly high-resolution shallow reflection seismic profiling in a network across the seaway between Öland and the mainland, should be carried out to see if it is possible to recognized faults in the Cambro-Ordovician strata and the Quaternary sediments. Vertical displacements of more than a few metres should be detectable with presently available equipment. Shallow seismic reflection profiling, geoelectrical and radar surveys onshore on Öland might also contribute to deciding whether the outcrop gaps along the coast, which in some cases mark changes in stratigraphic level with respect to the water line, represent zones of disturbance and, if so, to assessing their trends and displacements.

Having established this regional context, it should be possible to go back into the data base from the mainland and draw more confident conclusions about the timing and significance of fractures developed in the Äspö area. This in turn will allow interpretation of the stress regimes that have operated during the last 500 million years.

The localization of a final repository for high-level radioactive waste in bedrock at depths of several hundred metres will require a choice of an undisputably stable environment. It may prove preferable to choose a location in the crystalline basement beneath a cover of undisturbed Palaeozoic strata in order to demonstrate the required stability. In a recent study (Ahlbom et al. 1990), it has been shown that there may be hydrological advantages in placing the repository beneath Cambrian sandstones. From all points of view, a continuing focus on relations in the Palaeozoic cover of the Precambrian of southeastern Sweden seems eminently justifiable.

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LIST OF APPENDICES

APPENDIX A

Scanline logs 1-17 - summary of data

APPENDIX A

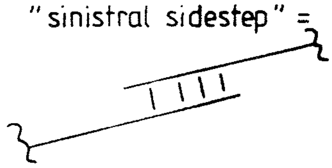
LEGEND TO SCANLINE LOGS

irregular joint, general trend over distance of 2 m

straight joint for distance greater than 2 m

"dextral sidestep" =

"sinistral sidestep" =



displacement of bedding (vertical)

no displacement

bedding displaced 2 cm, downthrow on side indicated

R = reverse fault, otherwise normal

displacement of fossils (horizontal)

fossil not intersected at any point within outcrop

intersection of joint with fossil specifically observed, no displacement

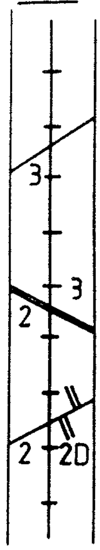
fossil displaced 2 cm with sense shown (D-dextral, S-sinistral)

aperture

"closed" joints, aperture of the order of maximum few m.m.

"open" joints, aperture 2cm

LOG



left column	right column
figure gives weighting number.	figure gives displacement in cm.

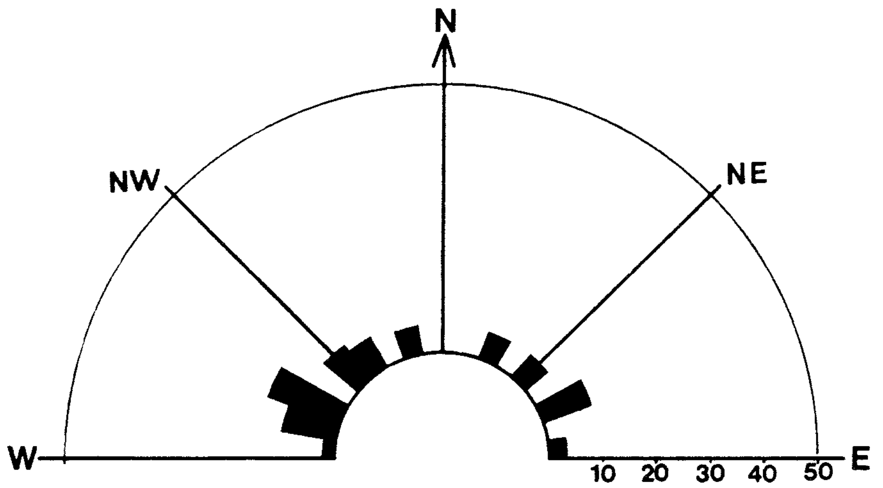
mineralization / structure

cc discontinuous carbonate coating on joint surface

a.b.10 discontinuous alteration border to joint trace, 10 cm wide

ss slickenside striations / aligned fibres observed

WEIGHTED HISTOGRAM ROSE

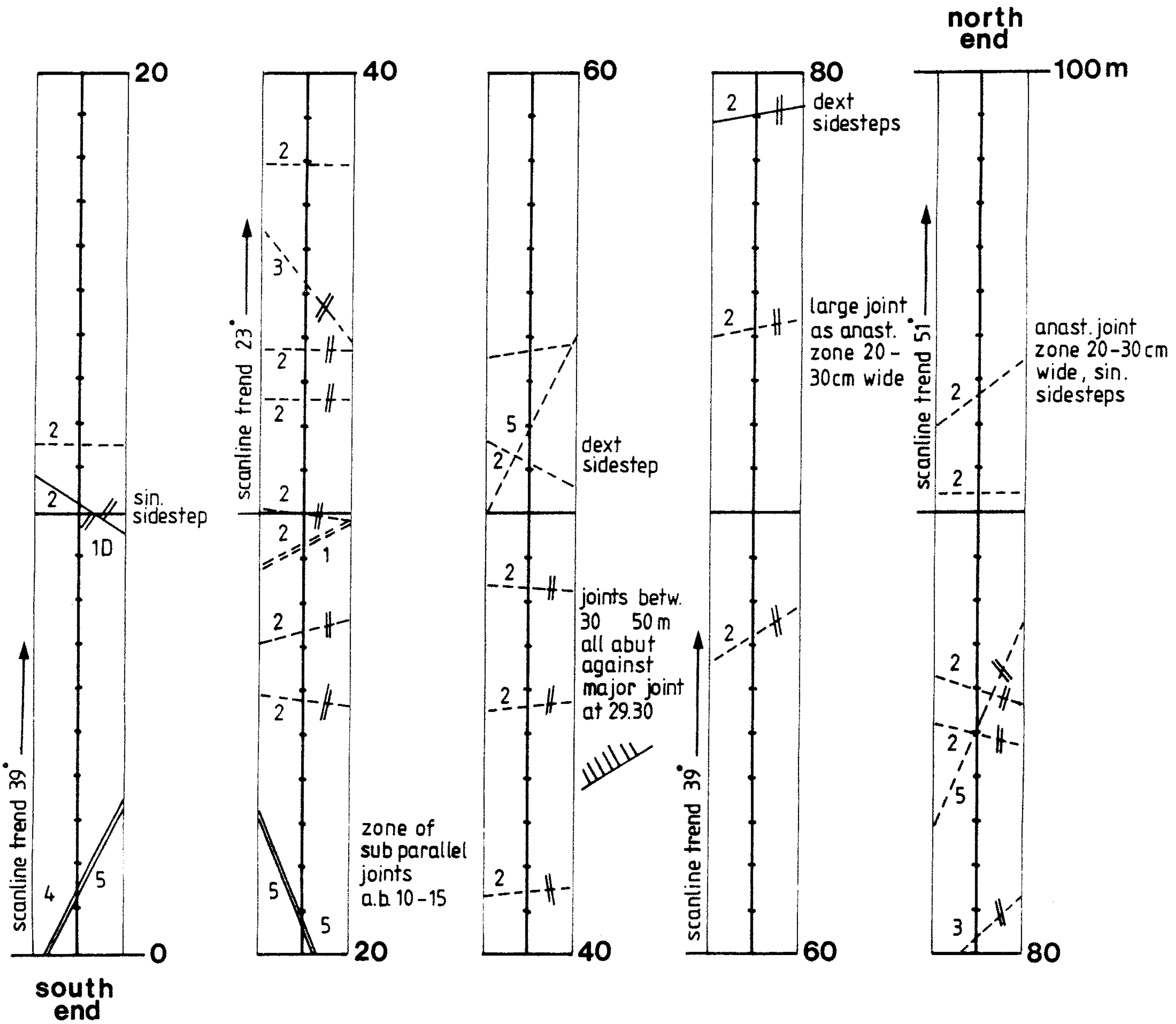


SCANLINE NO. 1

LOCATION

Northern Öland
shore platform north of
Byxelkrok (Neptuni Åkrar)
- scanline ends about
50 m south of area A
- upper middle limestone

DATA SUMMARY



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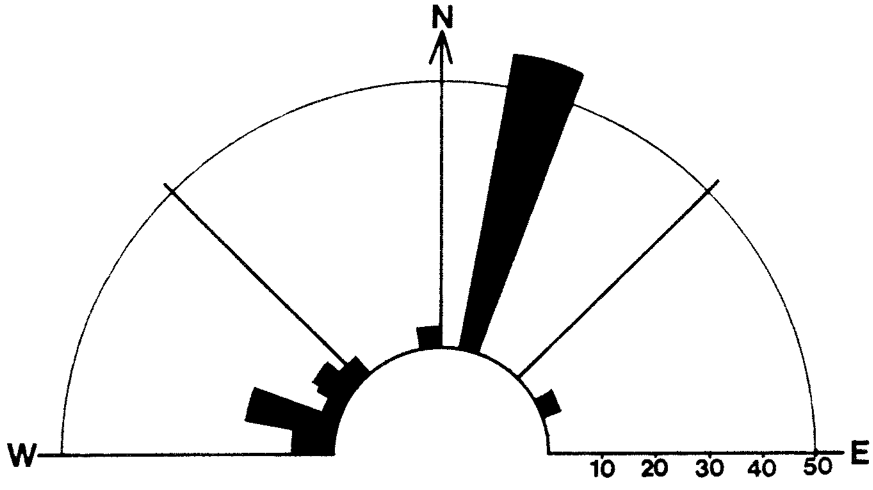
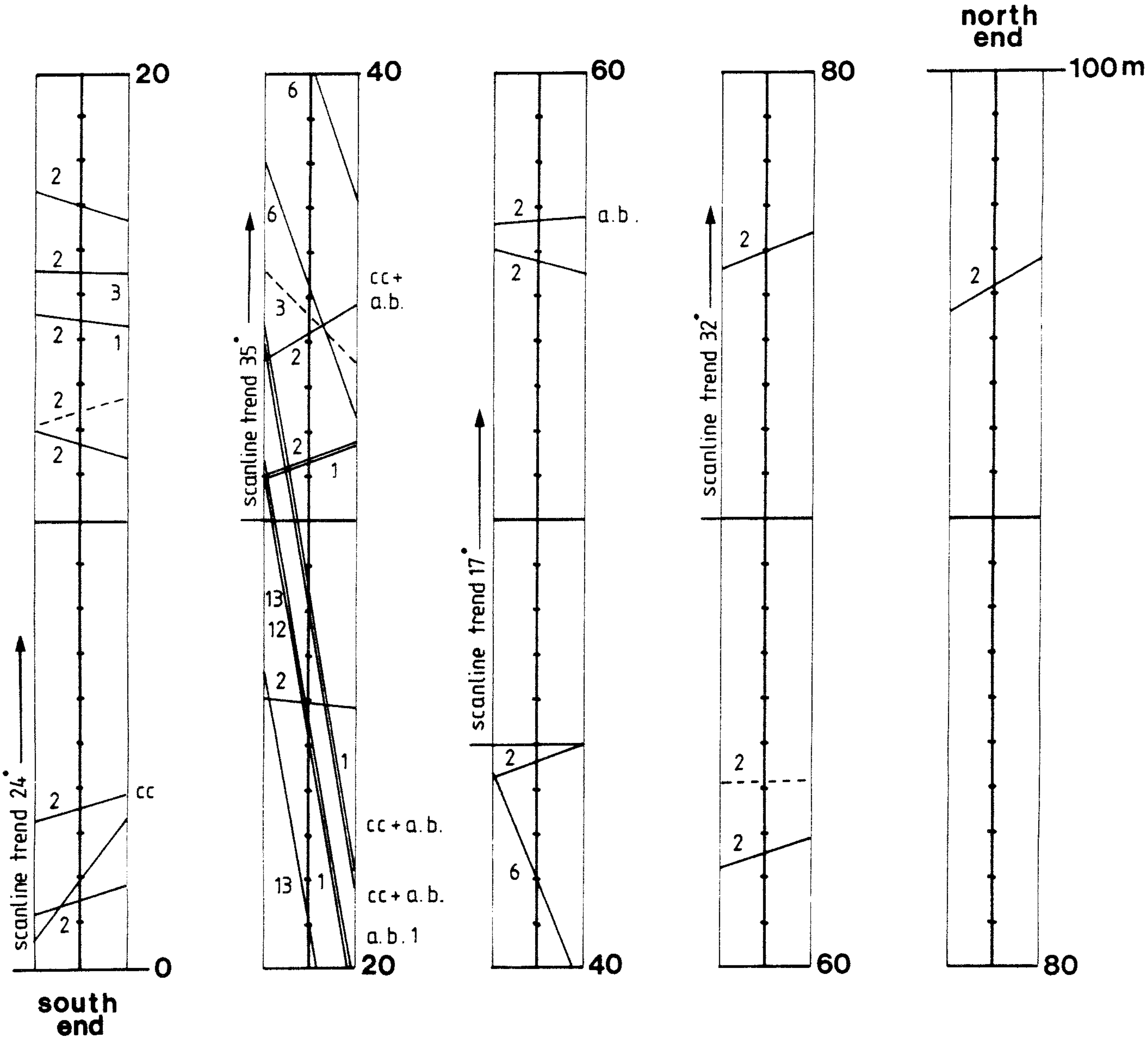


SCANLINE NO. 2

LOCATION

Northern Öland
terraced shore north of
Byxelkrok (Höga Flisa)
- about 400 m south of scanline 1
- middle limestone

DATA SUMMARY



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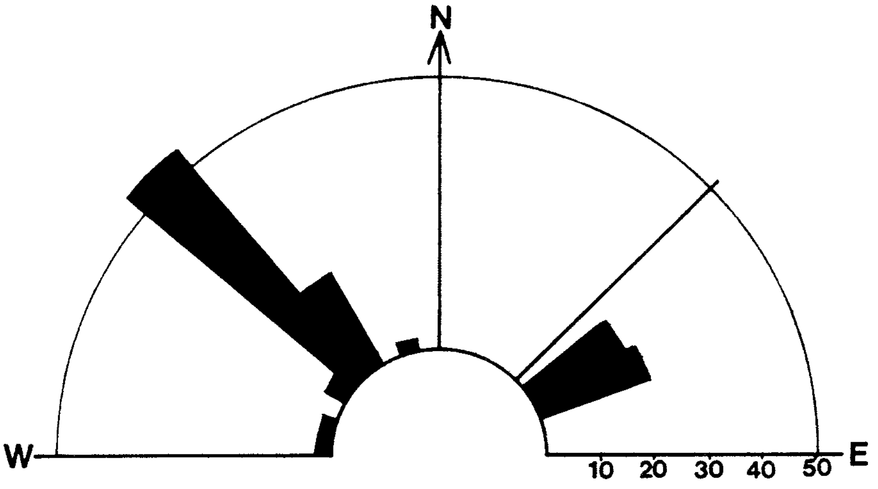


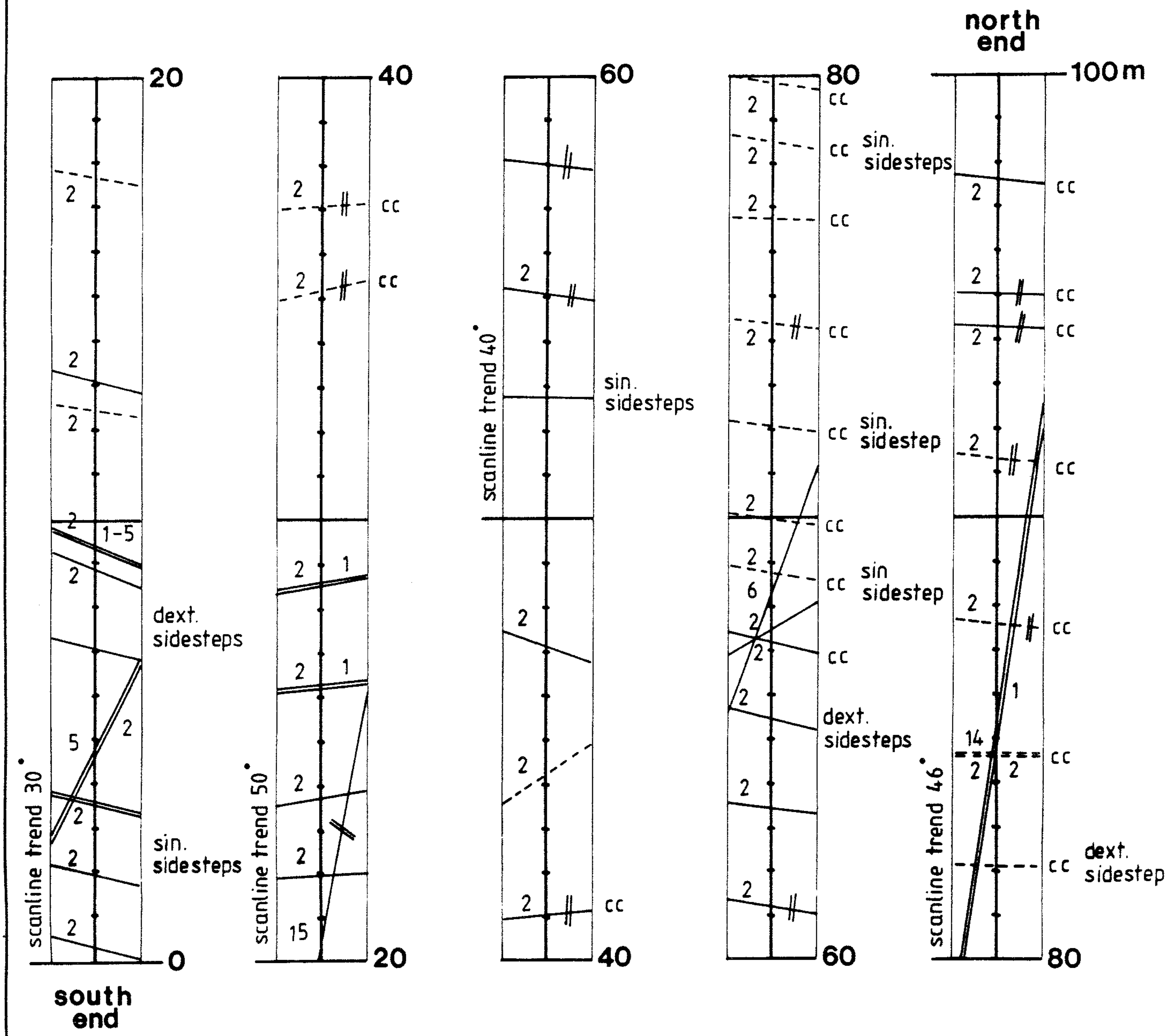
SCANLINE NO. 3

LOCATION

Northern Öland
shore platform north of
Hagudden. (Bådstenarna)

- start about 100 m north of area B, continuation of scanline 4
- top middle limstone

DATA SUMMARY



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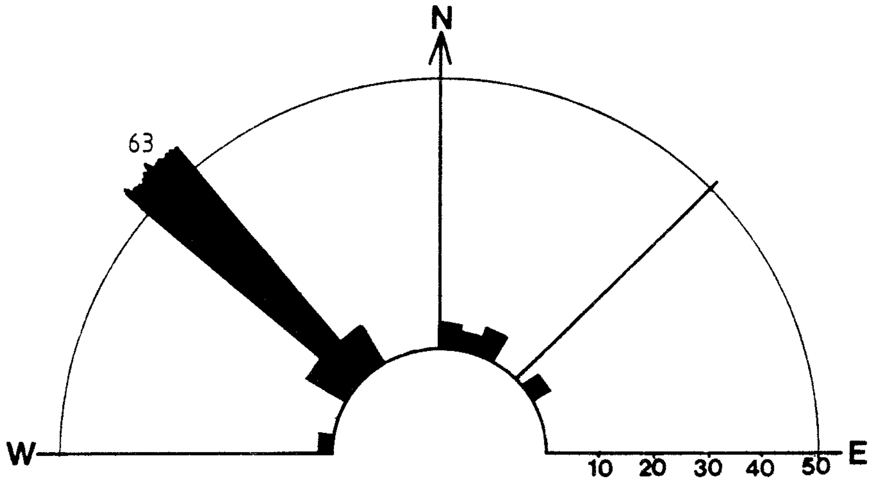
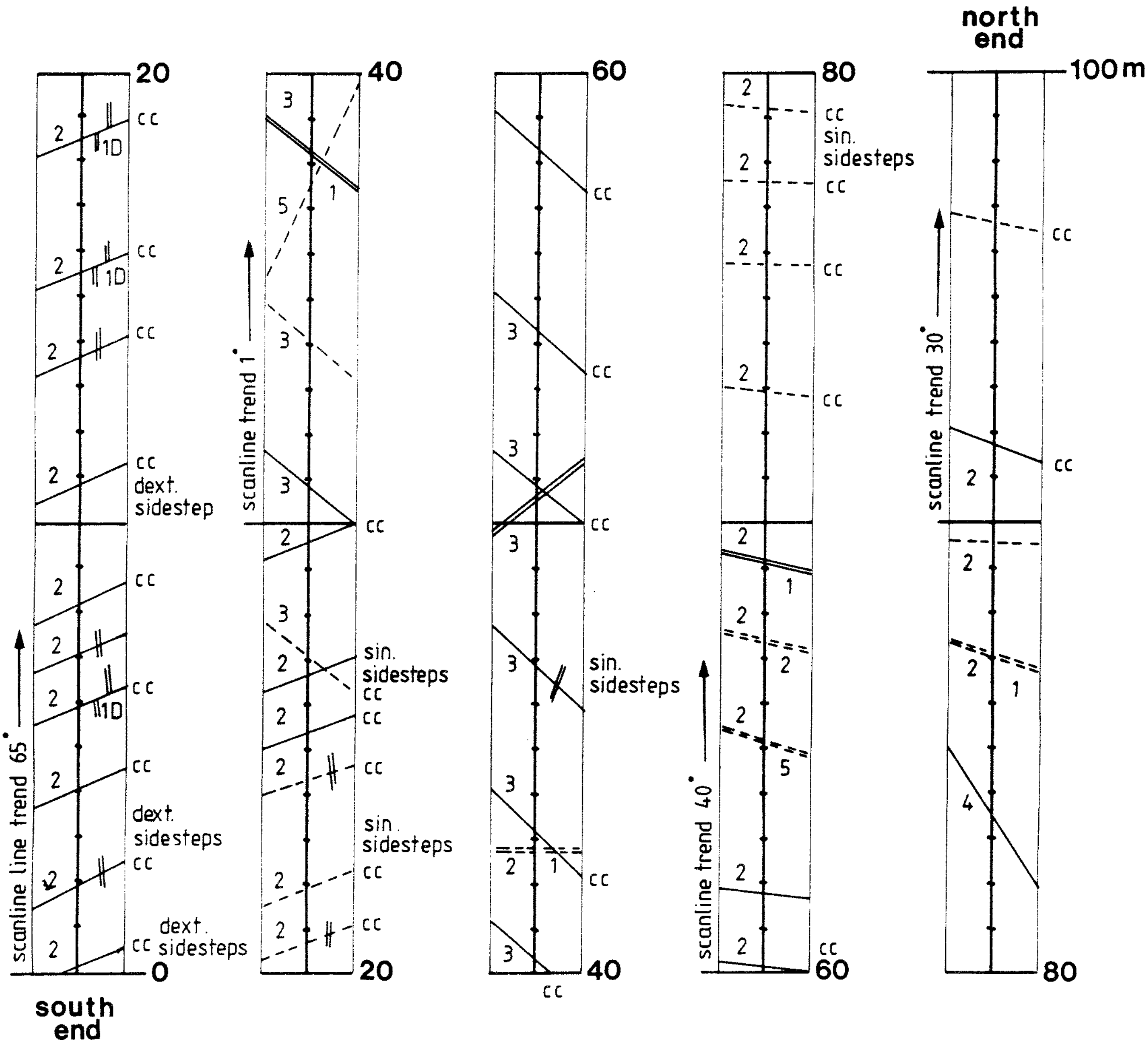


SCANLINE NO. 4

LOCATION

Northern Öland
shore platform north of
Hagudden (Bådstenarna)
- start at north end of area B
- top middle limestone

DATA SUMMARY



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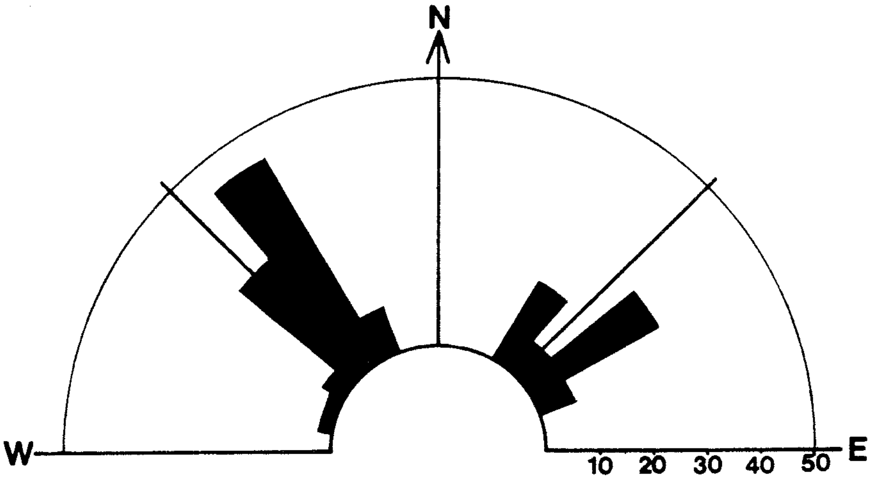
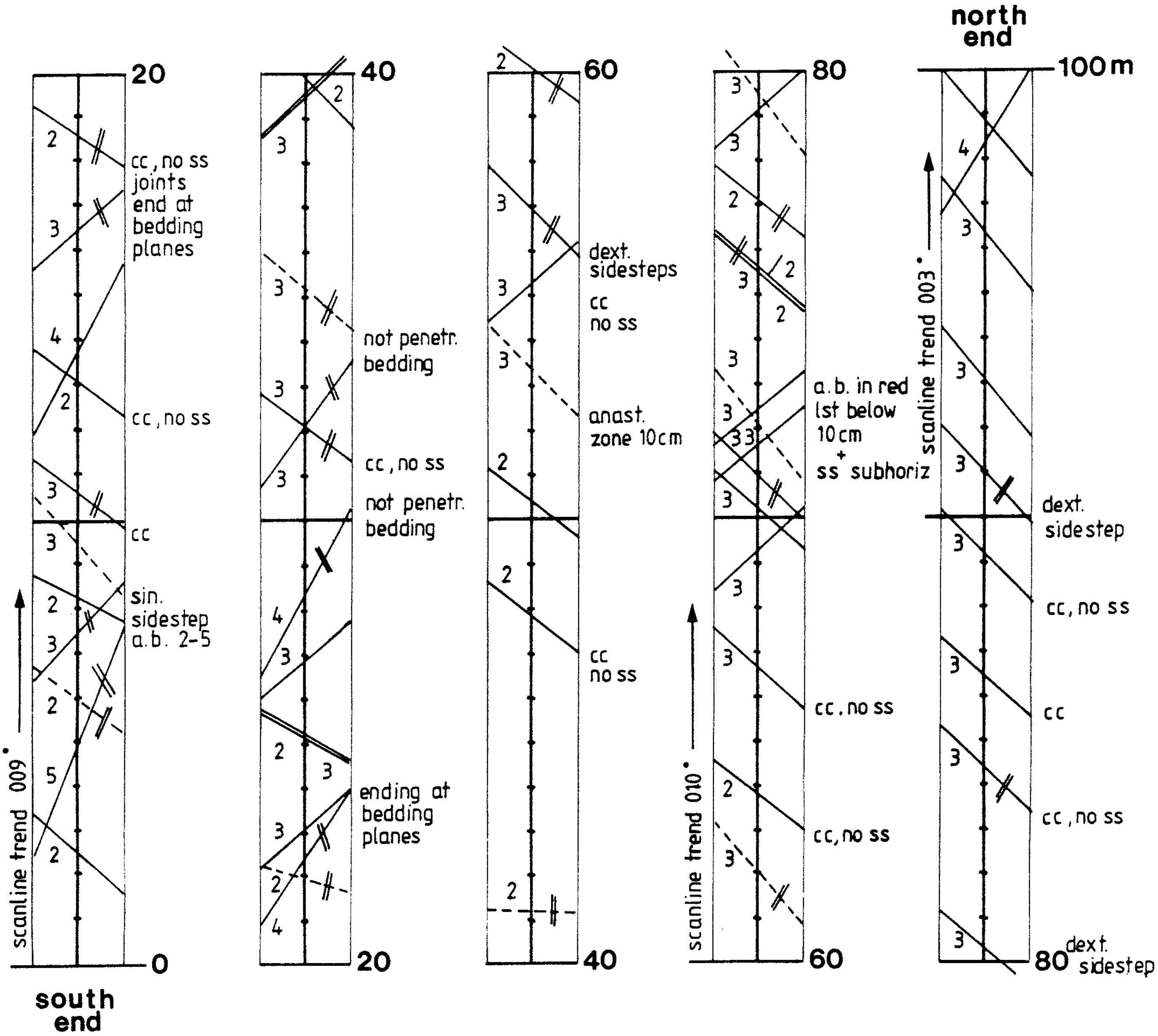


SCANLINE NO. 5

LOCATION

Northern Öland
terraced shore north of
Hagudden (Bådstenarna)
- ends 200 m south of area B
- upper middle limstone

DATA SUMMARY



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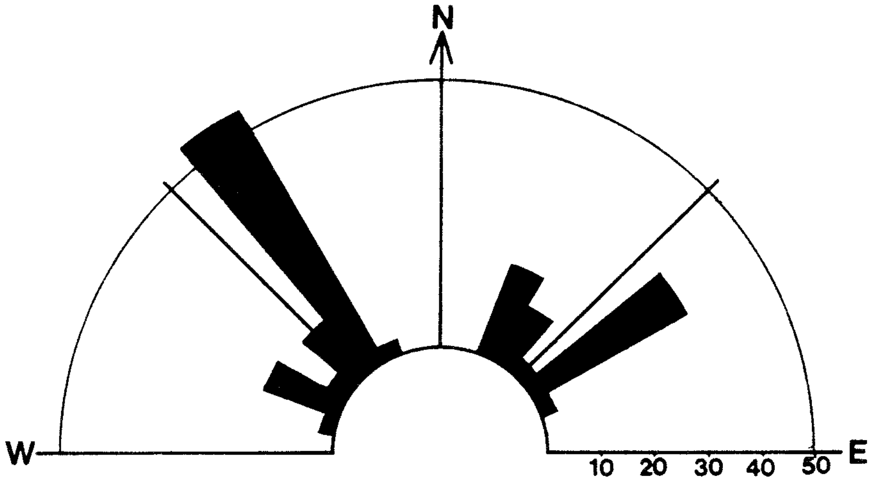
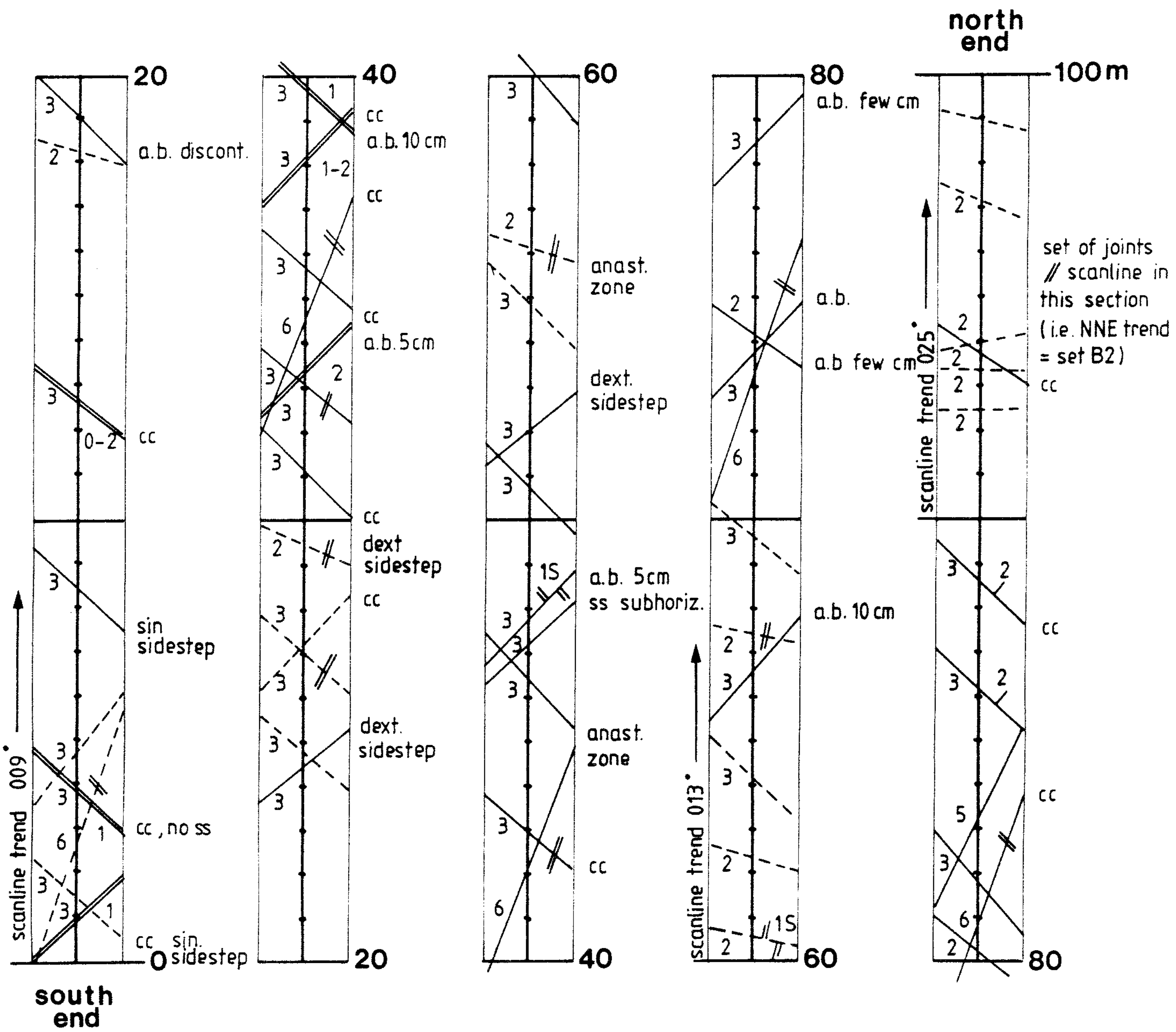


SCANLINE NO. 6

LOCATION

Northern Öland
terraced shore north of
Hagudden
- start 100 m north of end of scanline 7, ca. 600 m south of area B
- upper middle limestone

DATA SUMMARY



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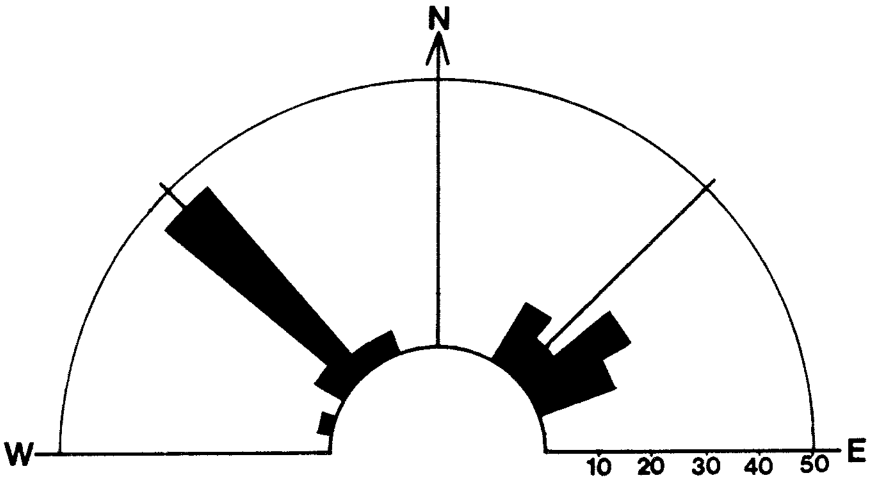


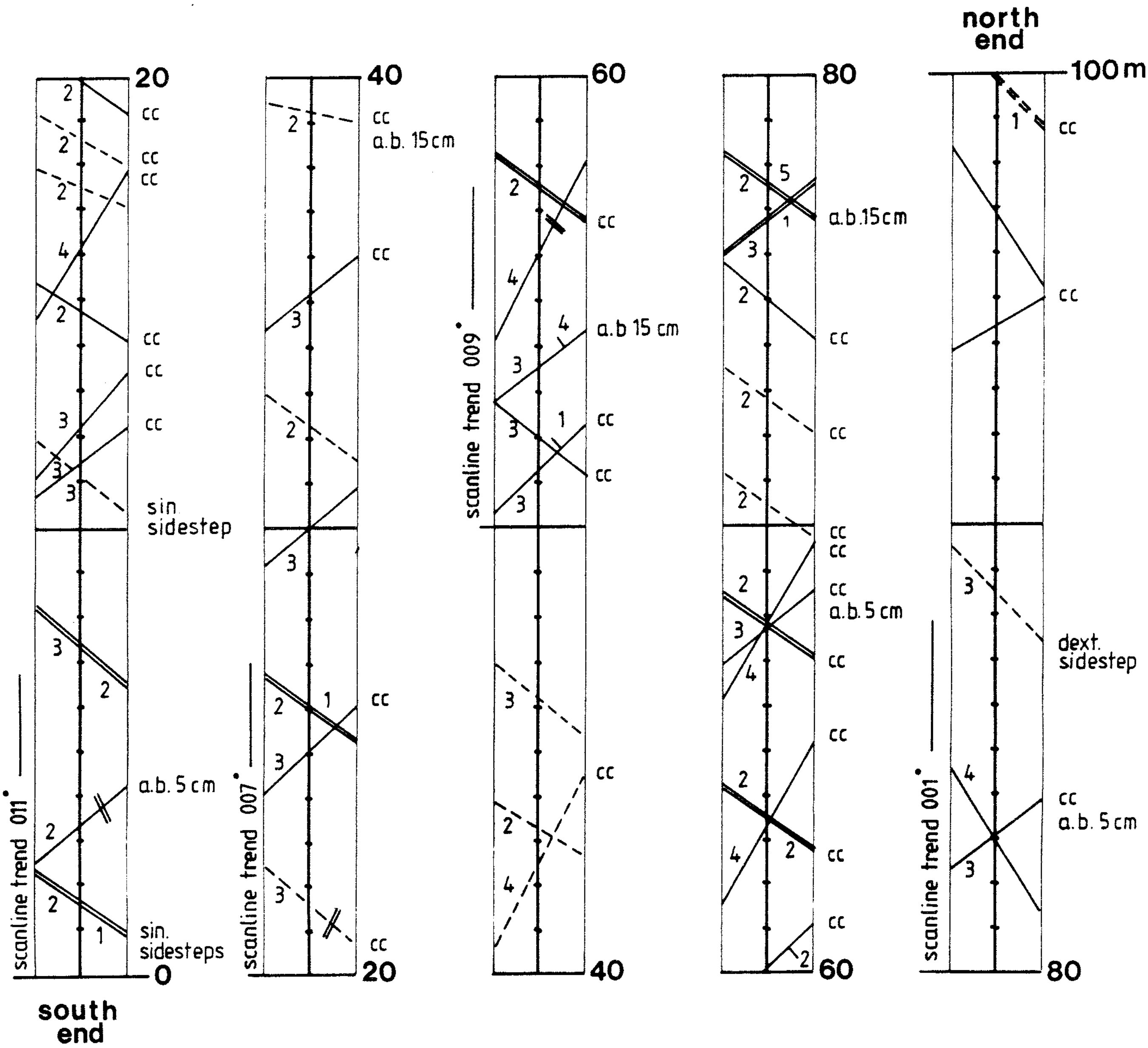
SCANLINE NO. 7

LOCATION

Northern Öland
terraced shore north of
Hagudden

- northward continuation of scanline 8, ends 100 m south of start of scanline 6
- upper middle limestone

DATA SUMMARY



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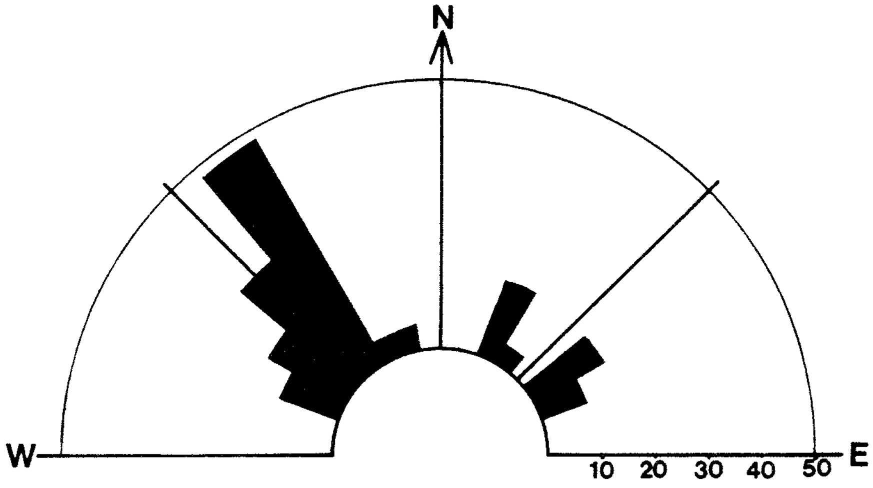
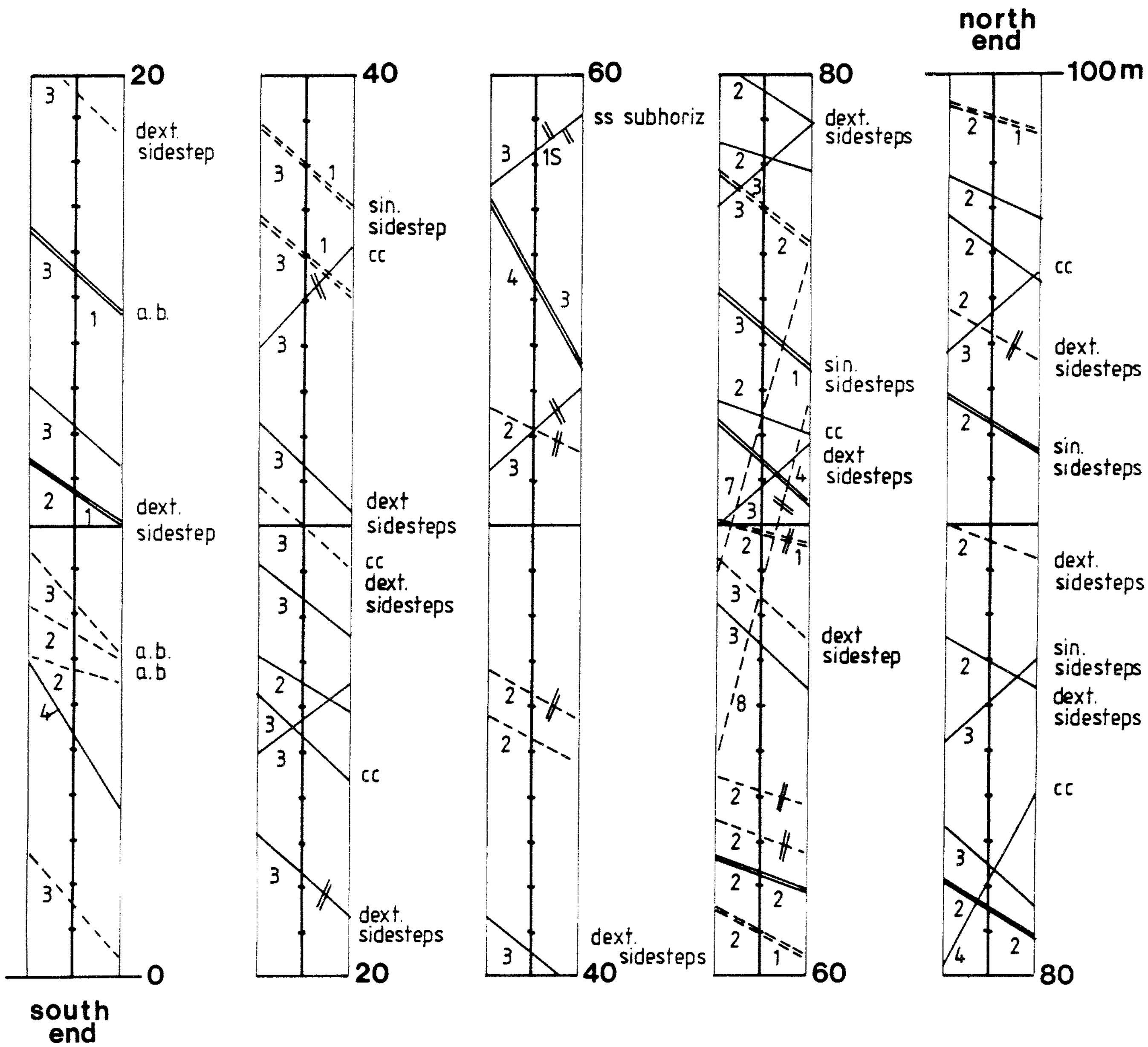


SCANLINE NO. 8

LOCATION

Northern Öland
terraced shore north of
Hagudden
- start at navigation marker, southern continuation of scanline 7
- upper middle limestone

DATA SUMMARY



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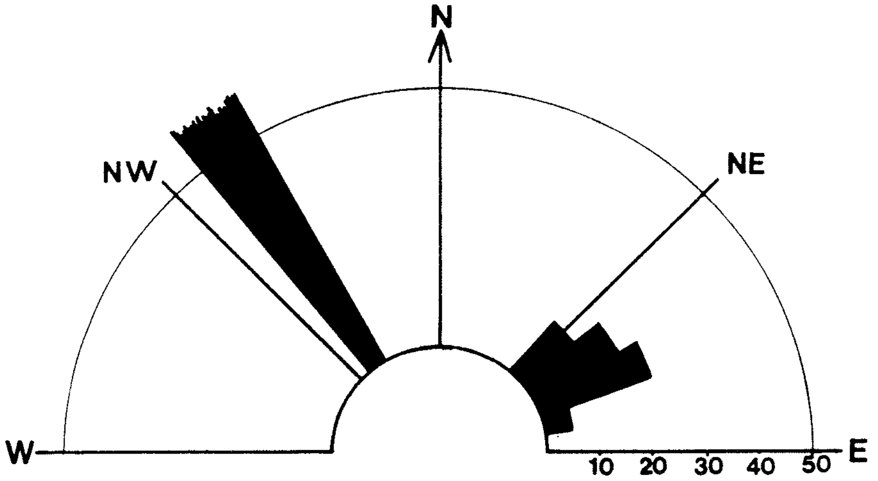


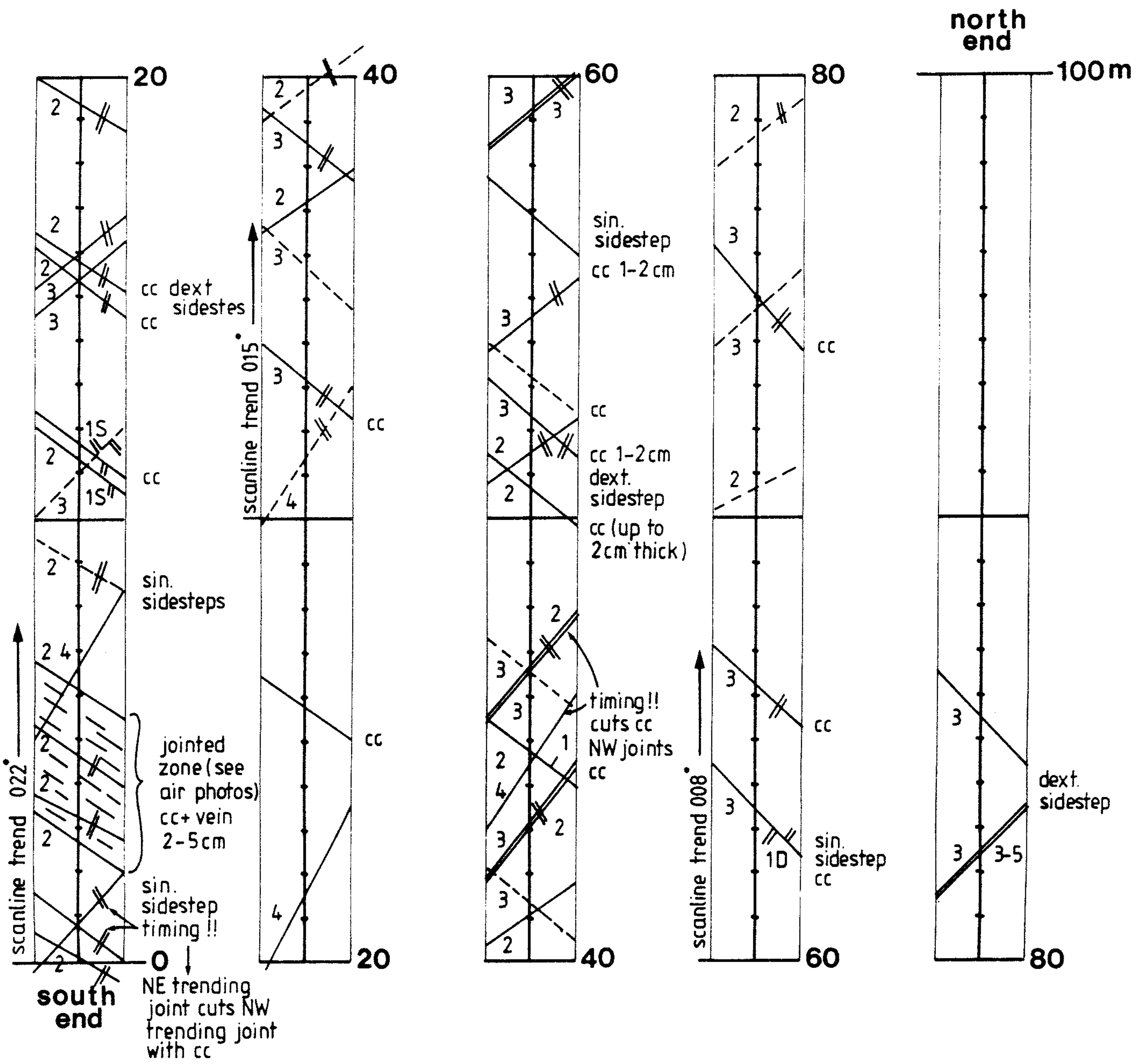
SCANLINE NO. 9

LOCATION

Northern Öland
shore platform north of
Hornsudden (Ålkistan)

- starts immediately north of area C
- top middle limestone

DATA SUMMARY



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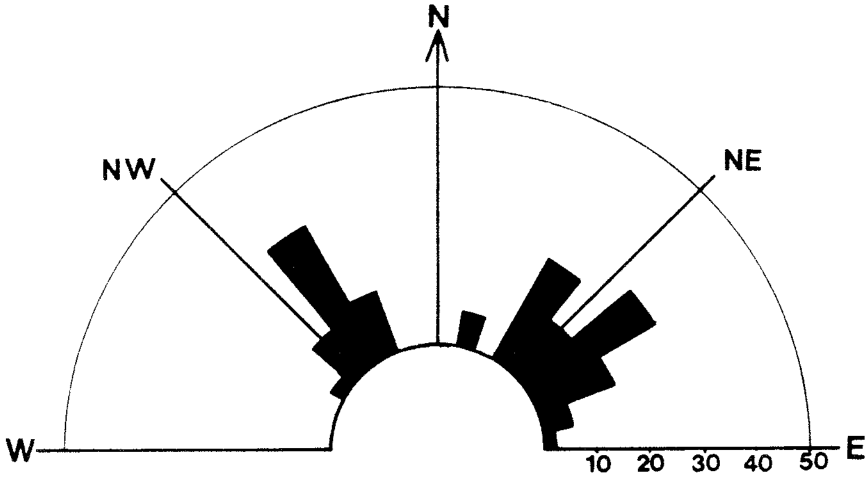
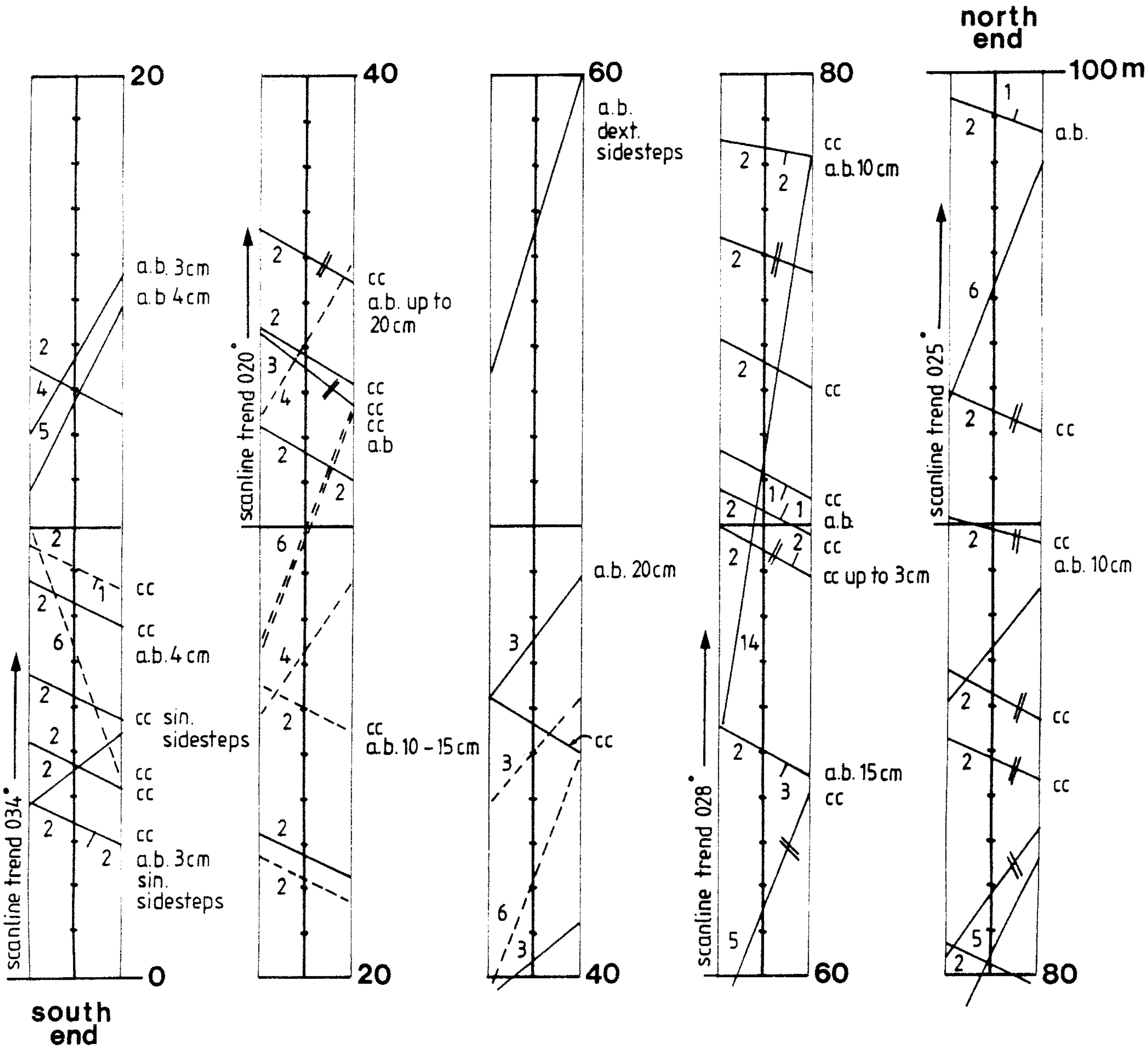


SCANLINE NO. 10

LOCATION

Northern Öland
terraced shore north of
Hornsudden (Ålkistan)
- ends about 100 m
  south of area C
- middle limestone

DATA SUMMARY



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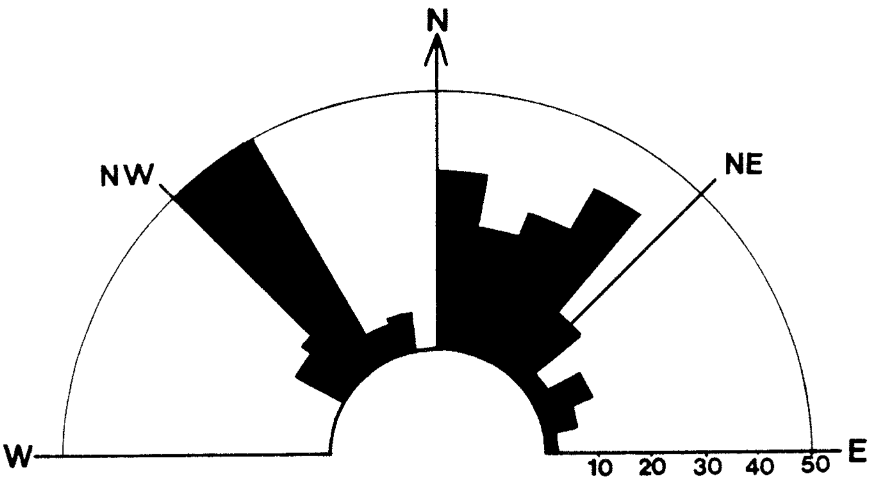
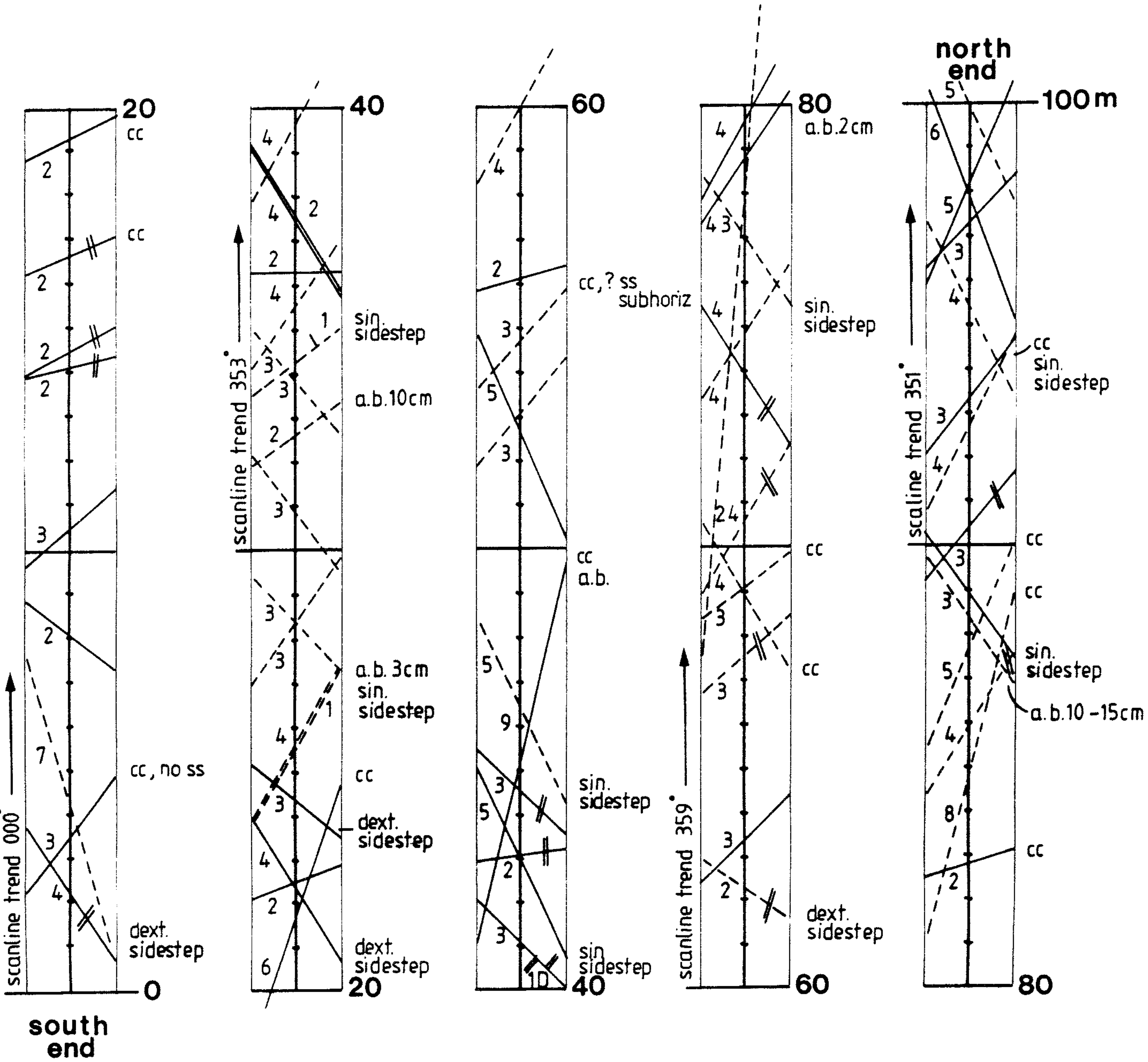


SCANLINE NO. 11

LOCATION

Northern Öland
terraced shore at north end of Västra Alvaret section (Kristinelund)
- starts about 200 m north of scanline 12, at road junction
- upper middle limestone

DATA SUMMARY



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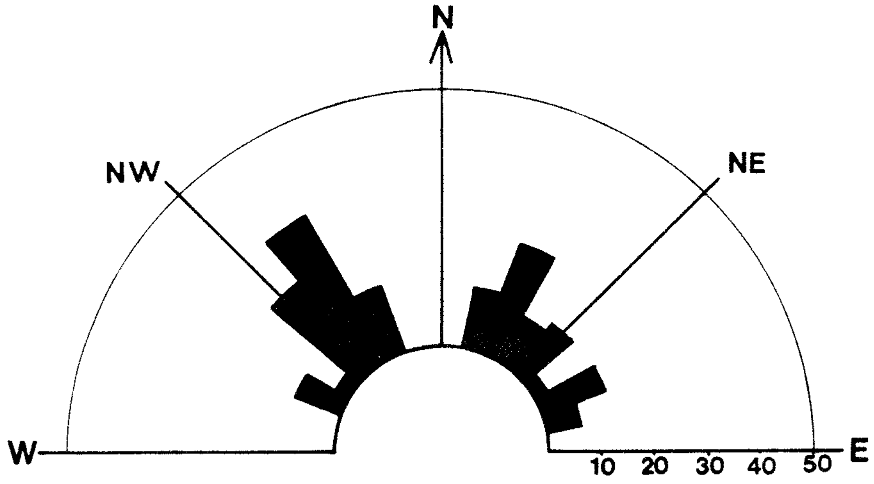
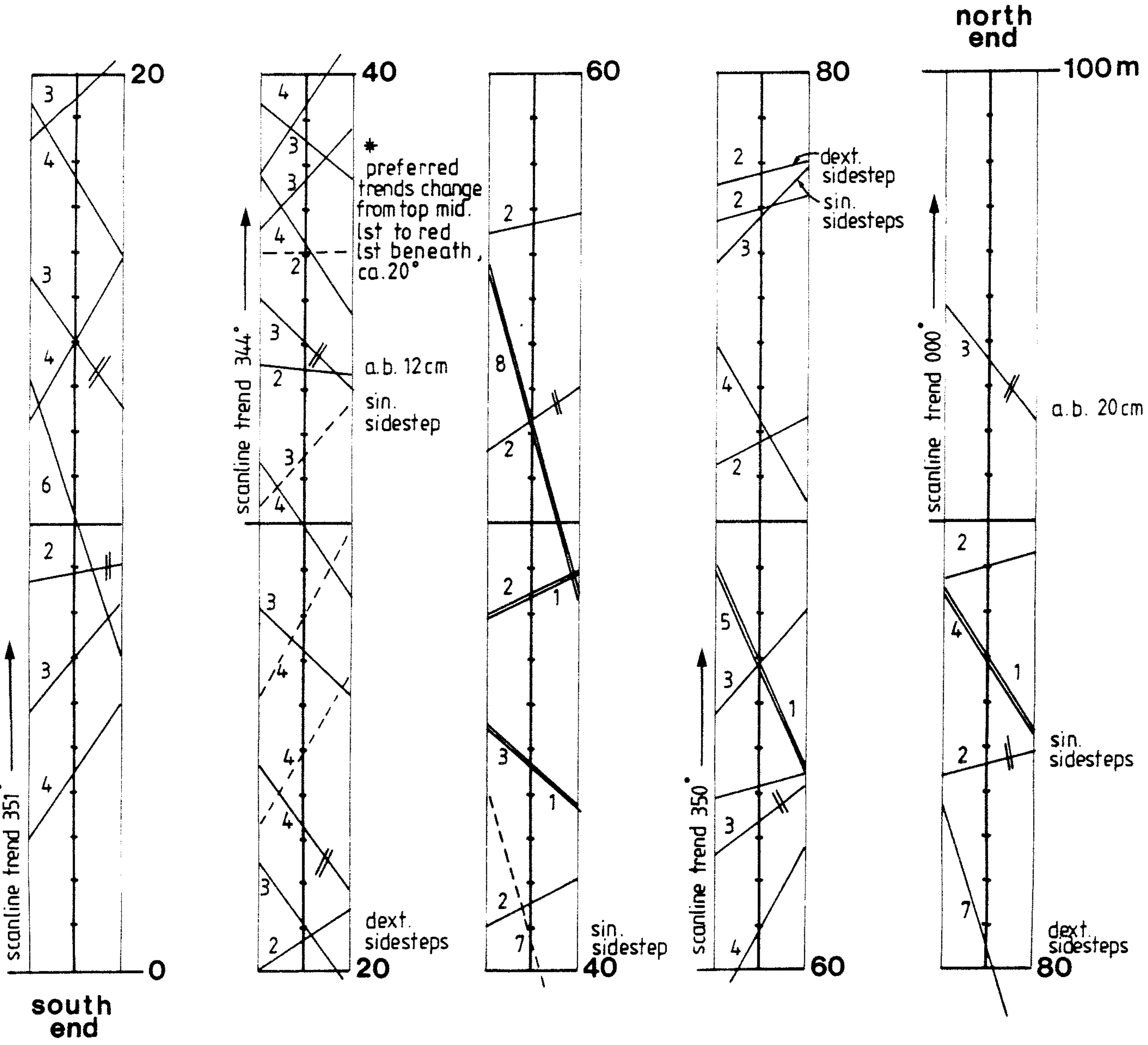


SCANLINE NO.12

LOCATION

Northern Öland
shore platform at north end of Västra Alvaret section (Kristnelund)
- ends 200 m south of scanline 11
- top middle limestone

DATA SUMMARY



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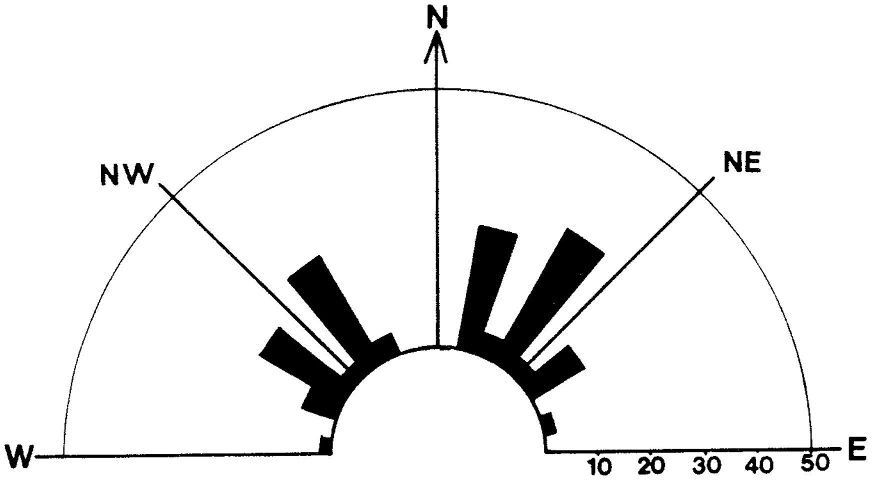
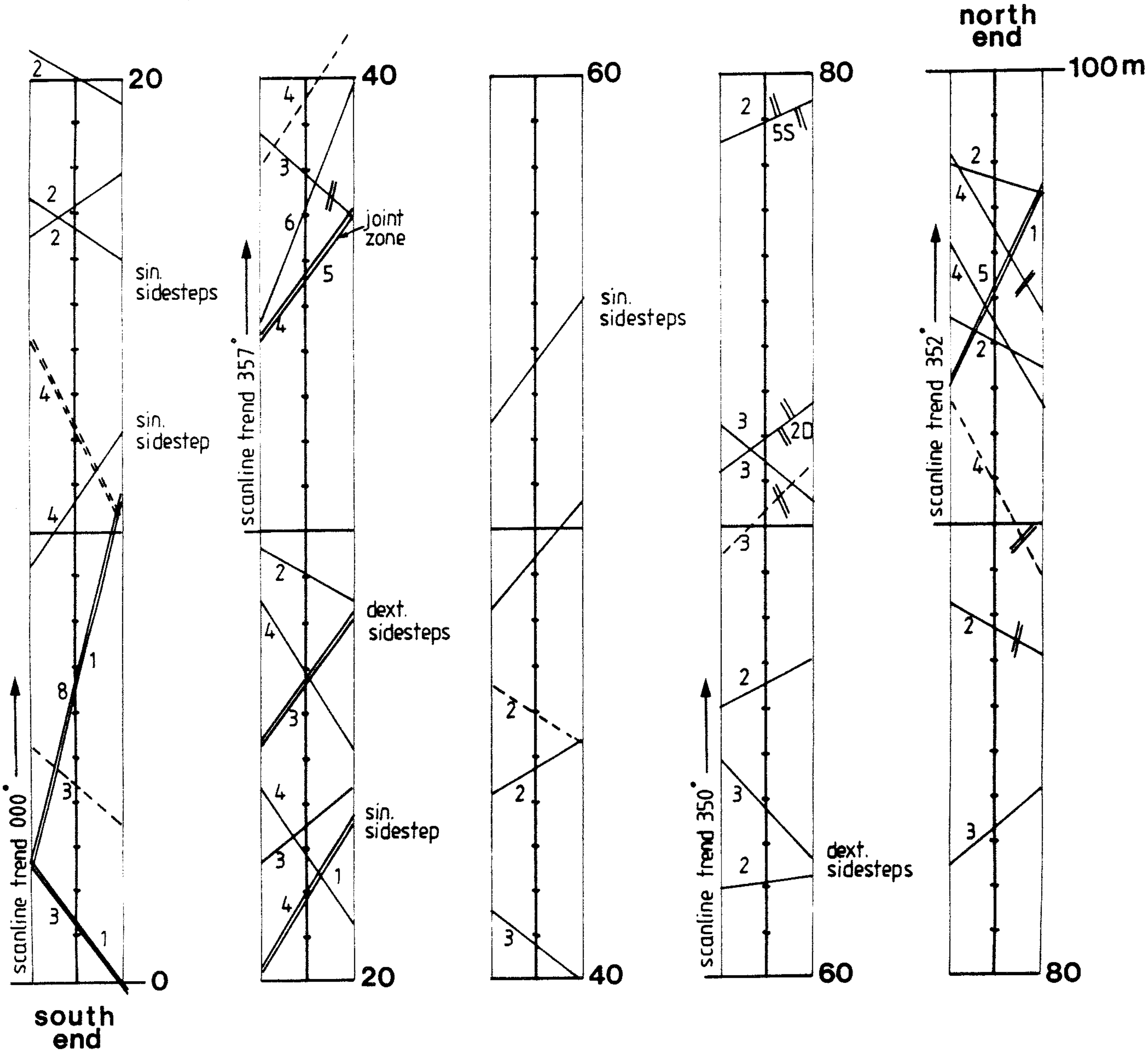


SCANLINE NO. 13

LOCATION

Northern Öland
shore platform at north end of Västra Alvaret section (Kristinelund)
- southward continuation of scanline 12
- top middle limestone

DATA SUMMARY



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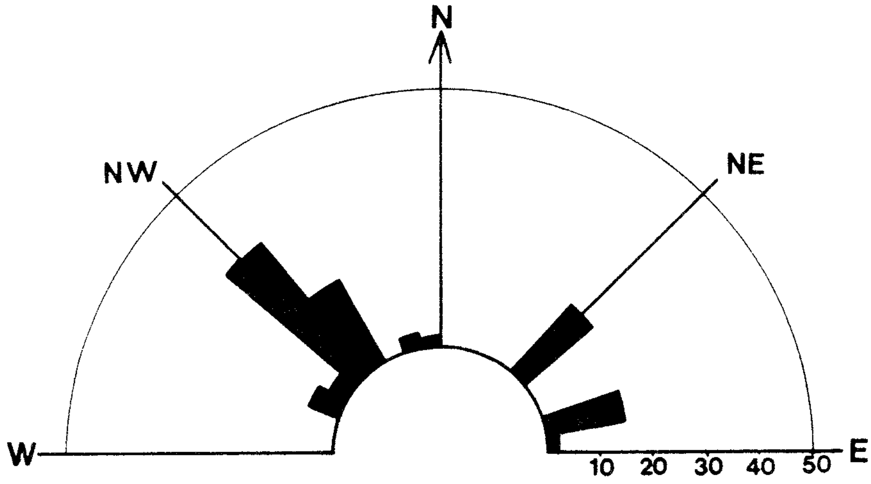


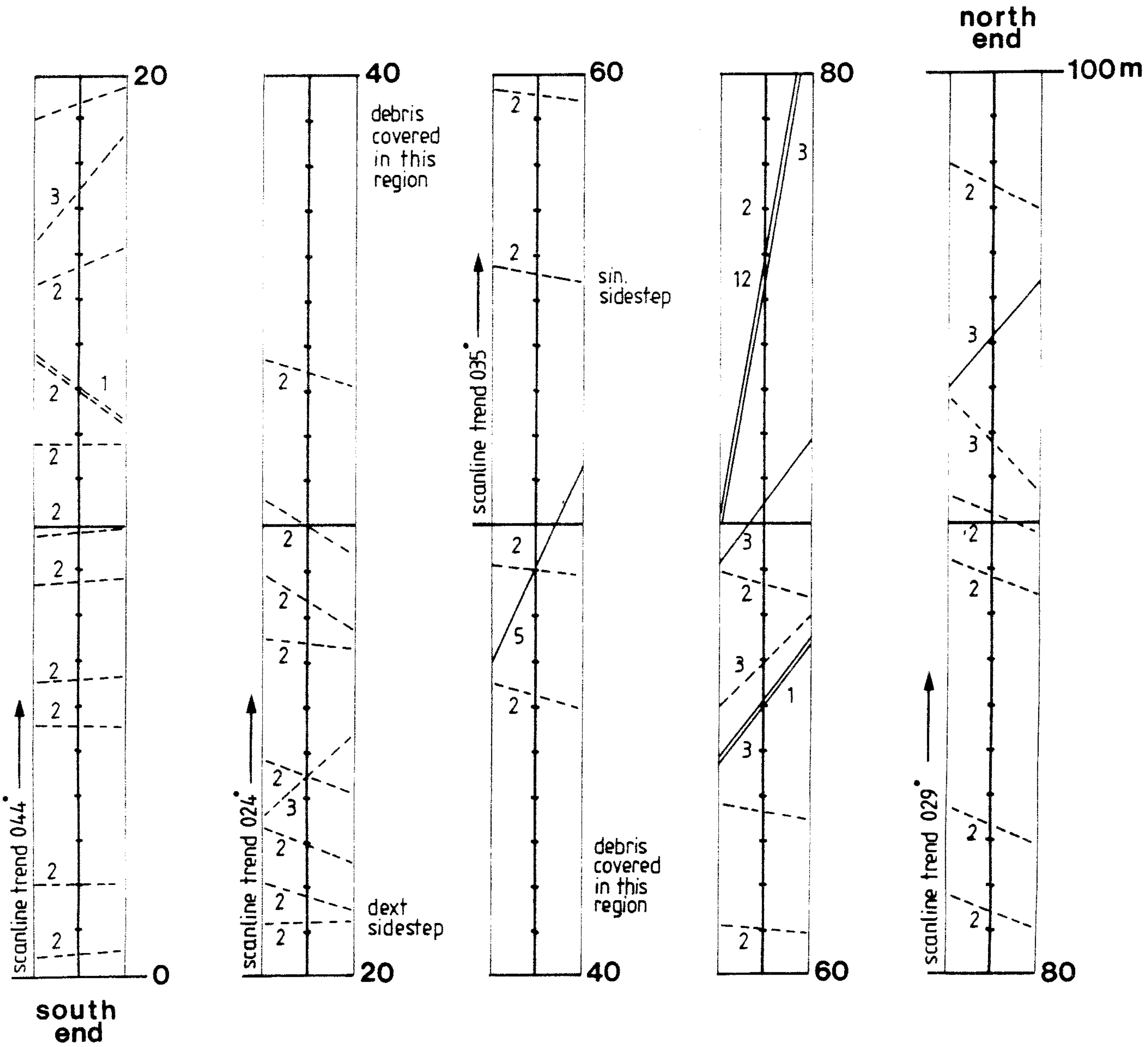
SCANLINE NO. 14

LOCATION

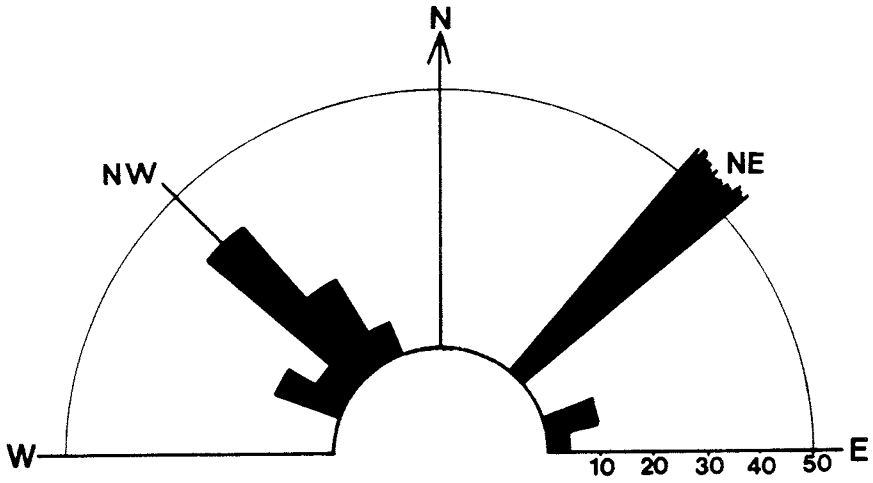
Northern Öland
shore platform in
central part of Västra Alvaret
section (Eskilslund)

- ends about 400 m south of area D, northward continuation of scanline 15
- top middle limestone

DATA SUMMARY



WEIGHTED HISTOGRAM ROSE

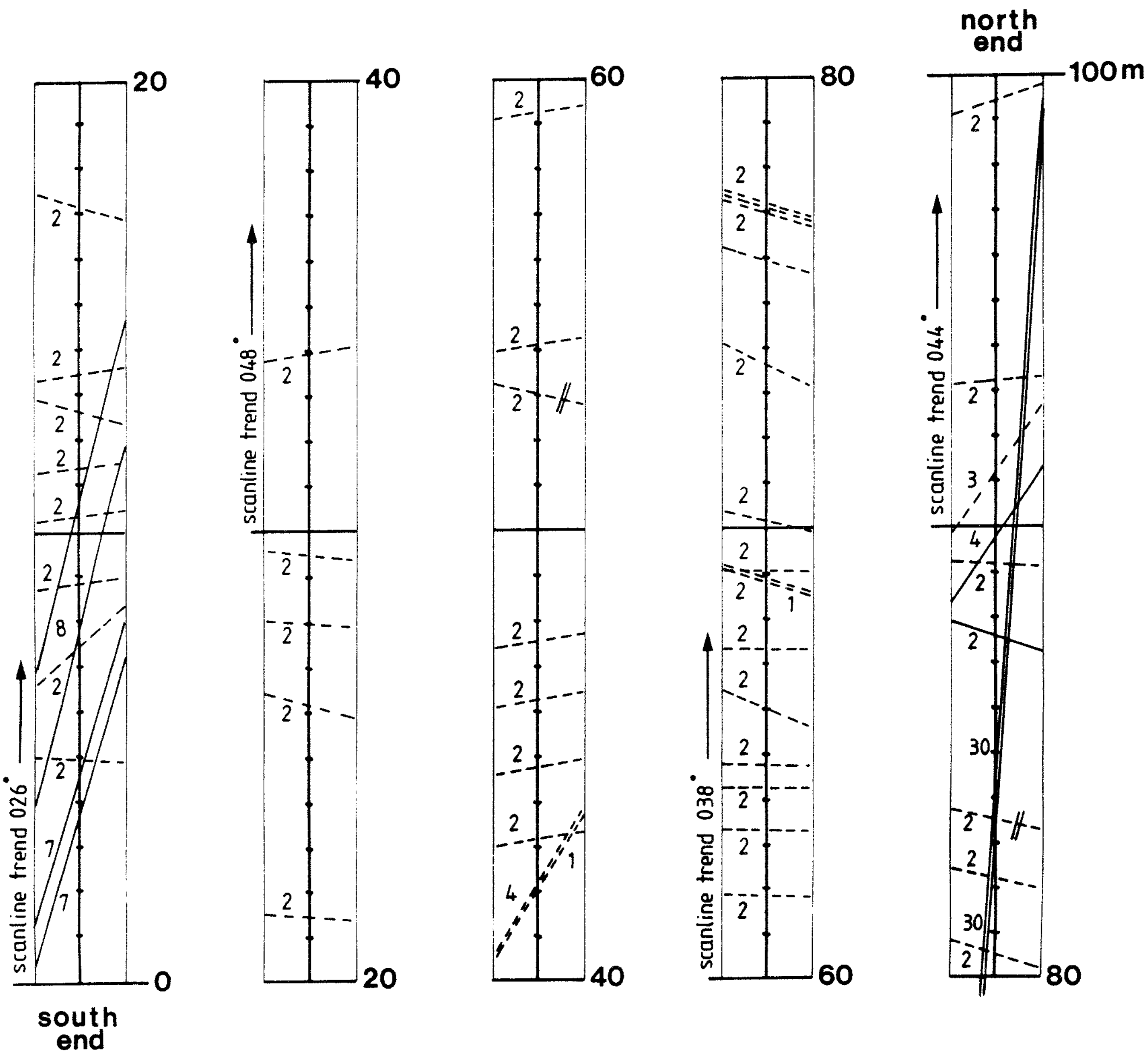


SCANLINE NO. 15

LOCATION

Northern Öland
shore platform in central part of Västra Alvaret section (Eskilslund)
- southward continuation of scanline 14, starts at isolated red hut
- top middle limestone

DATA SUMMARY



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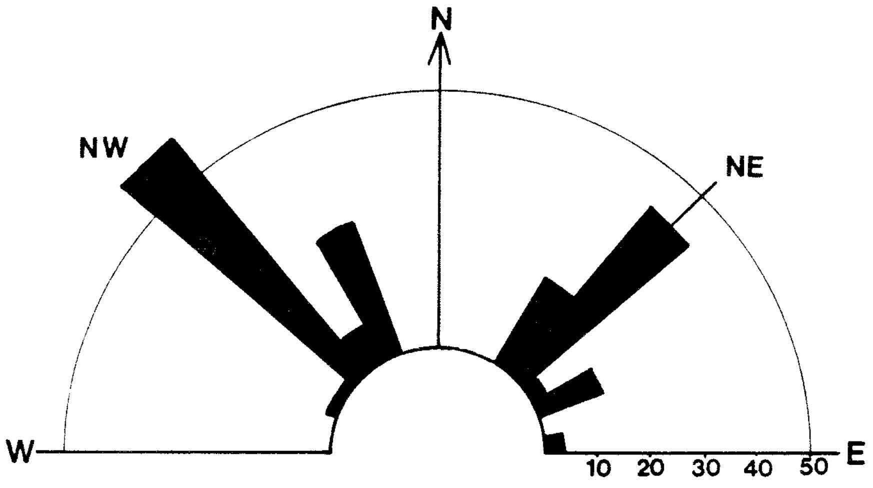
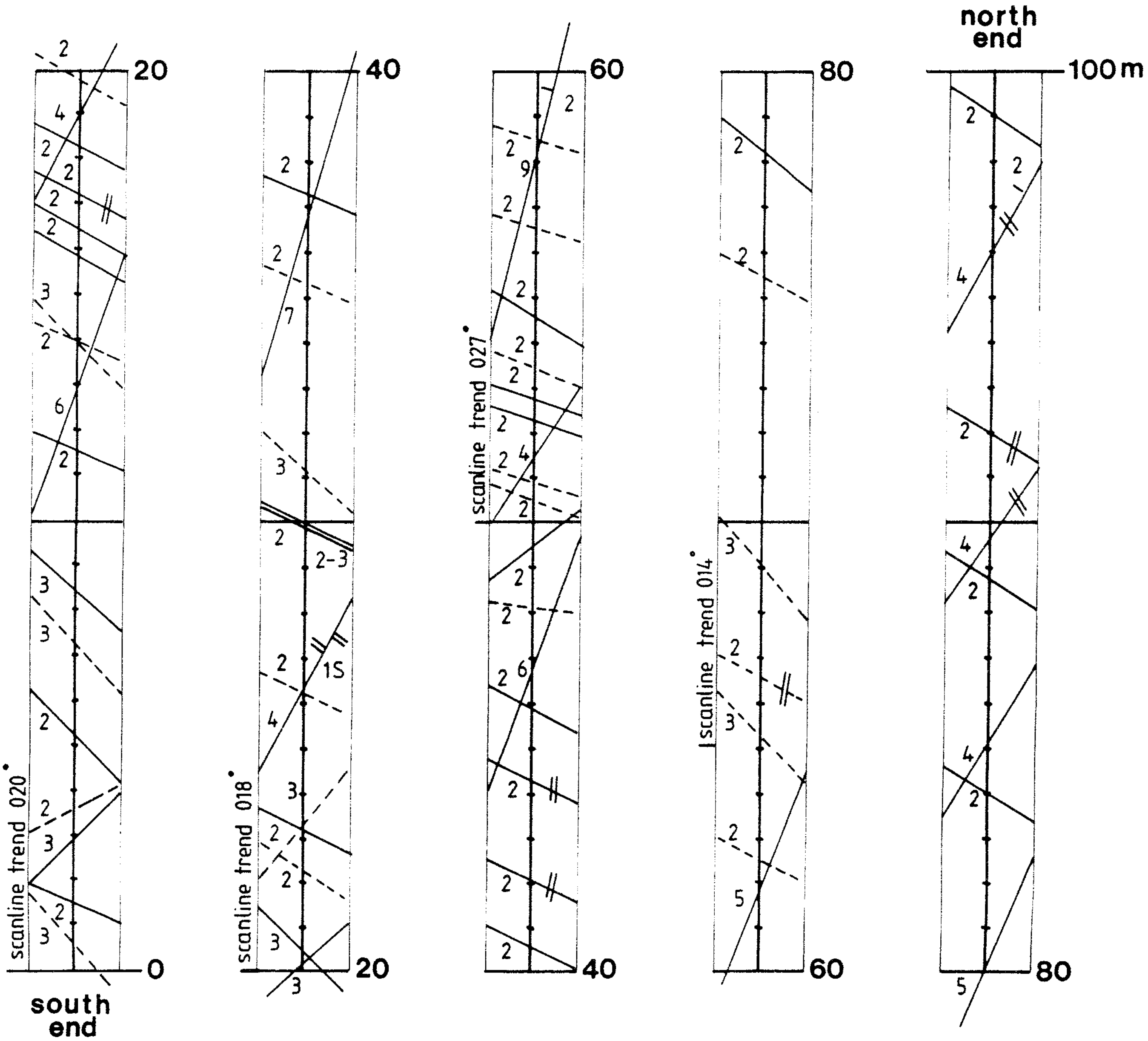


SCANLINE NO.16

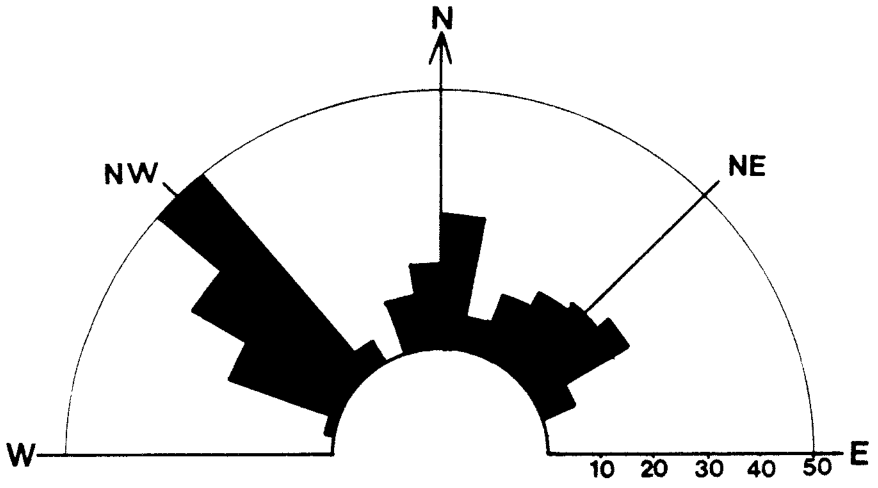
LOCATION

Northern Öland
shore platform in southern part of Västra Alvaret section (Hagelstad)
- ends about 350 m south of area E, near isolated stone hut
- top middle limestone

DATA SUMMARY



WEIGHTED HISTOGRAM ROSE

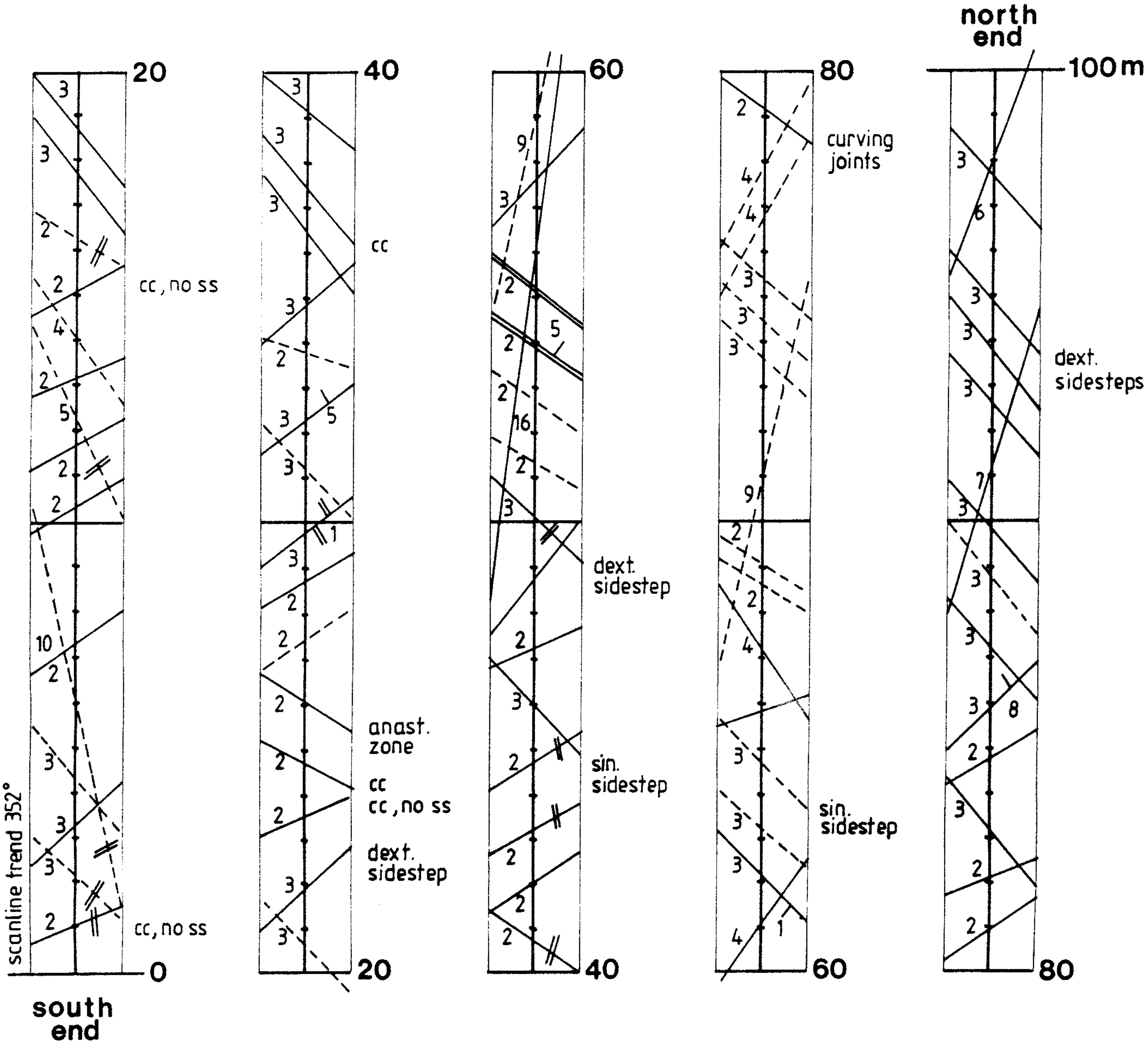


SCANLINE NO. 17

LOCATION

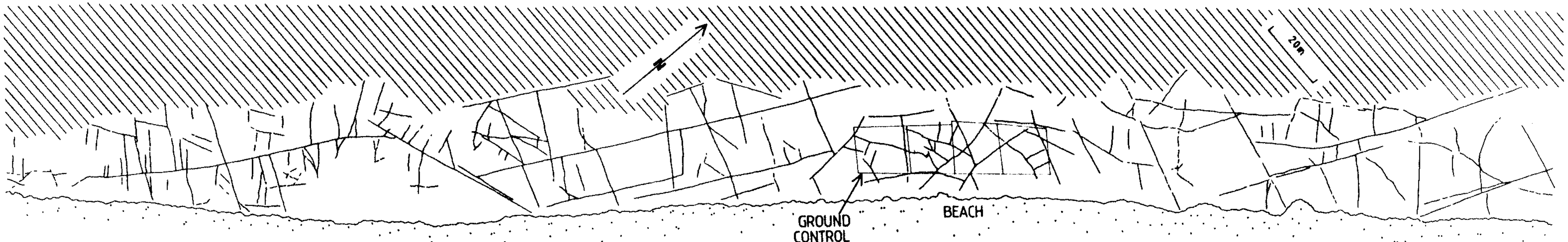
Northern Öland
southern end of
Västra Alvaret section,
terraced shore
- starts by group of huts, ends about 500 m south of scanline 16
- upper middle limstone

DATA SUMMARY

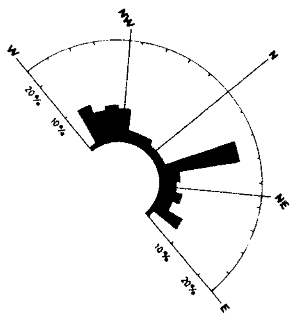


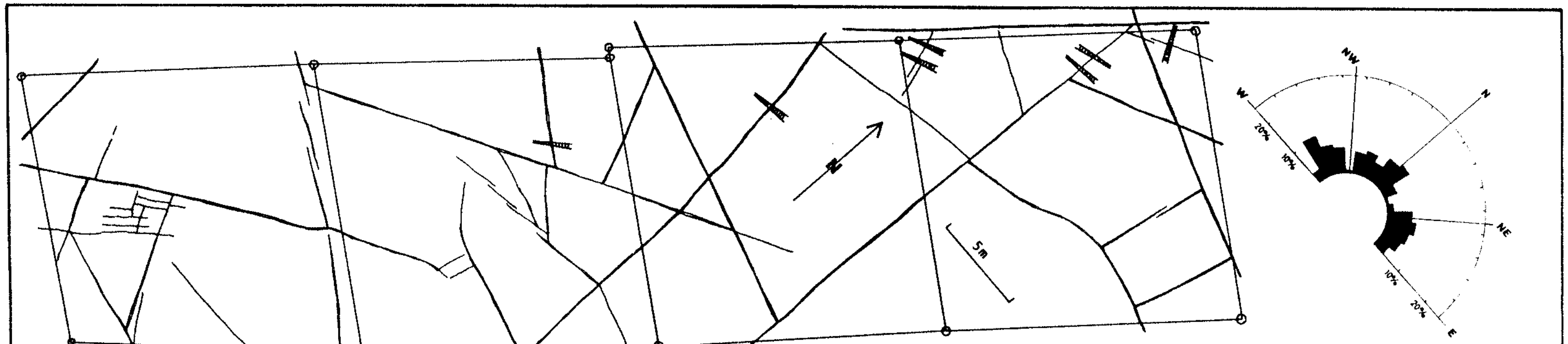
APPENDIX B

Air photo and ground control maps

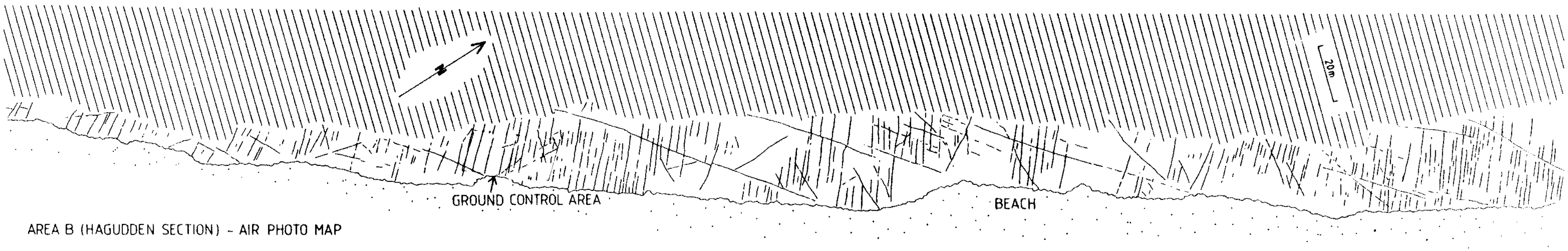


AREA A (BYXELKROK SECTION) - AIR PHOTO MAP

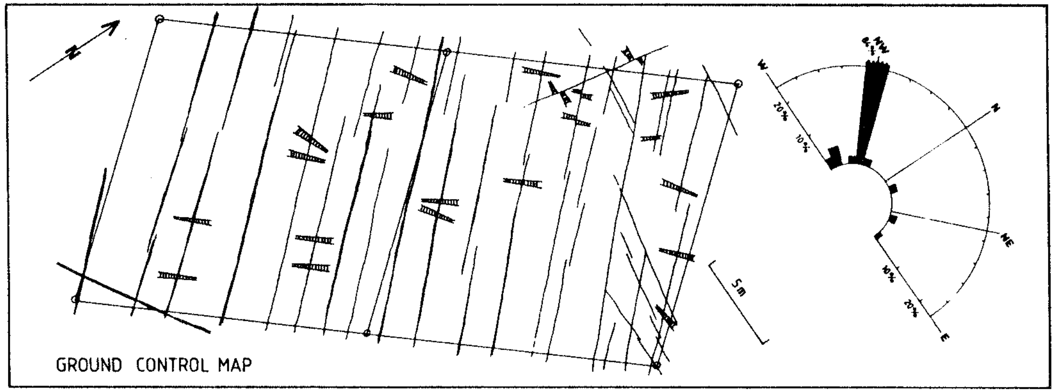




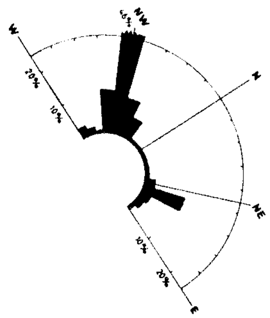
GROUND CONTROL MAP

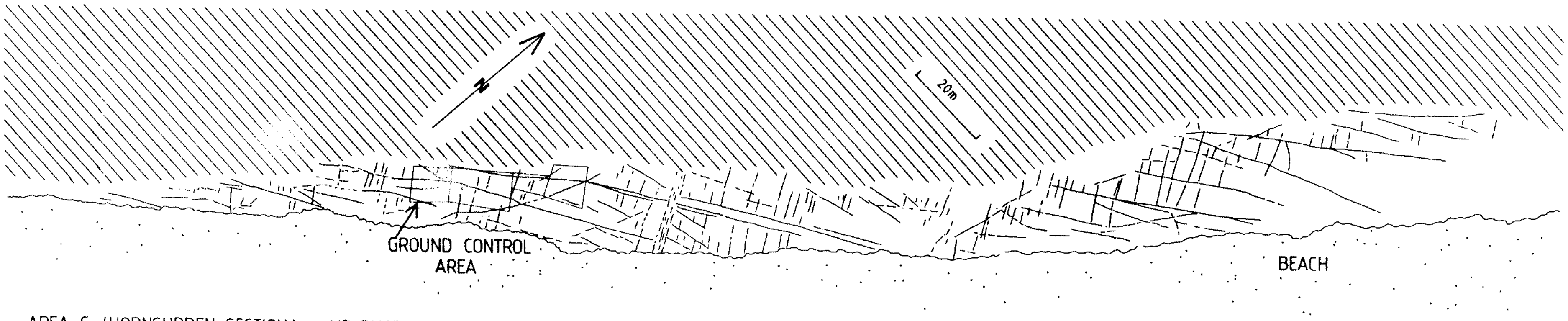


AREA B (HAGUDDEN SECTION) - AIR PHOTO MAP

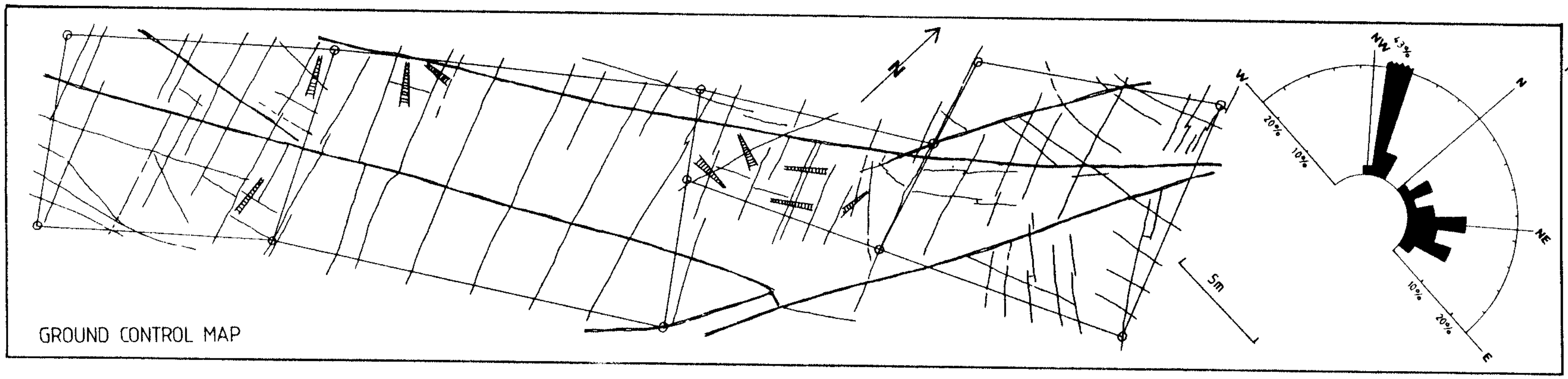


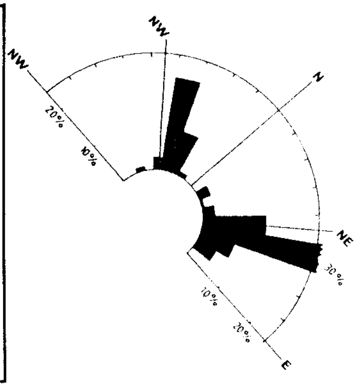
GROUND CONTROL MAP

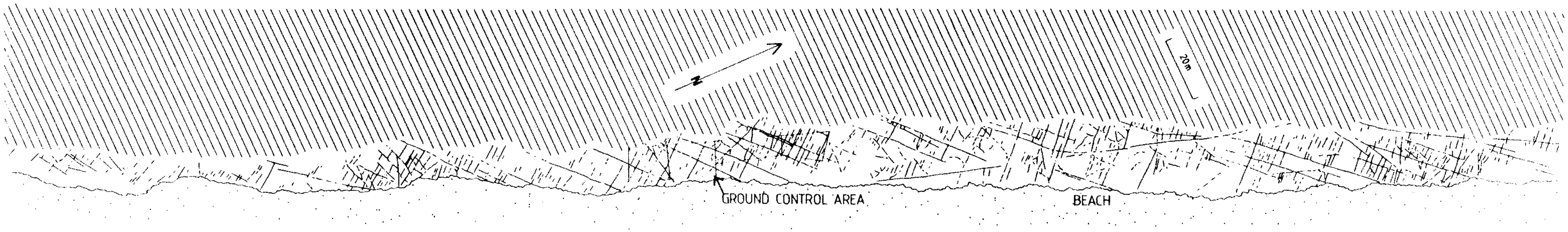




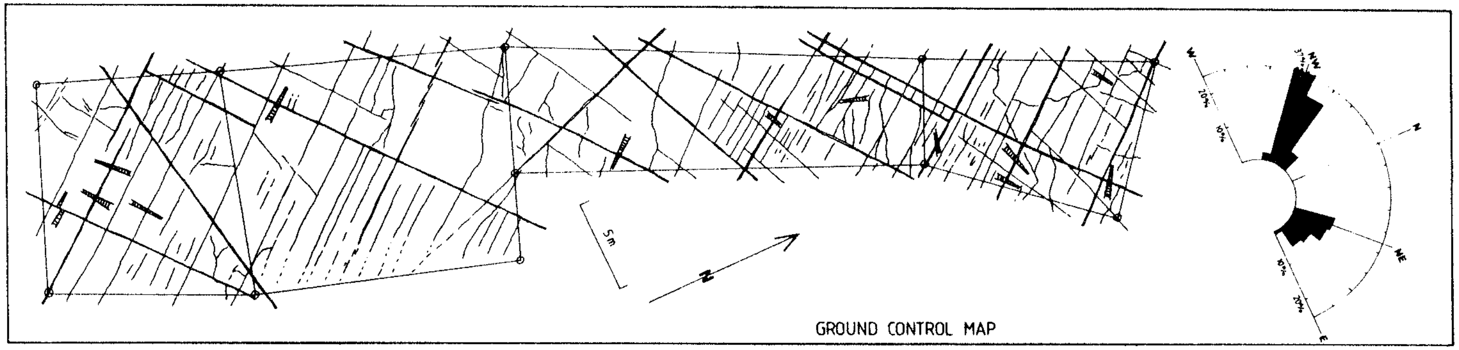
AREA C (HORNSUDDEN SECTION) - AIR PHOTO MAP



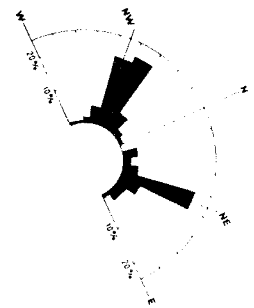




AREA D (VASTRA ALVARET SECTION) - AIR PHOTO MAP



GROUND CONTROL MAP



APPENDIX C

Summary of displacement data

BYXELKROK SECTION

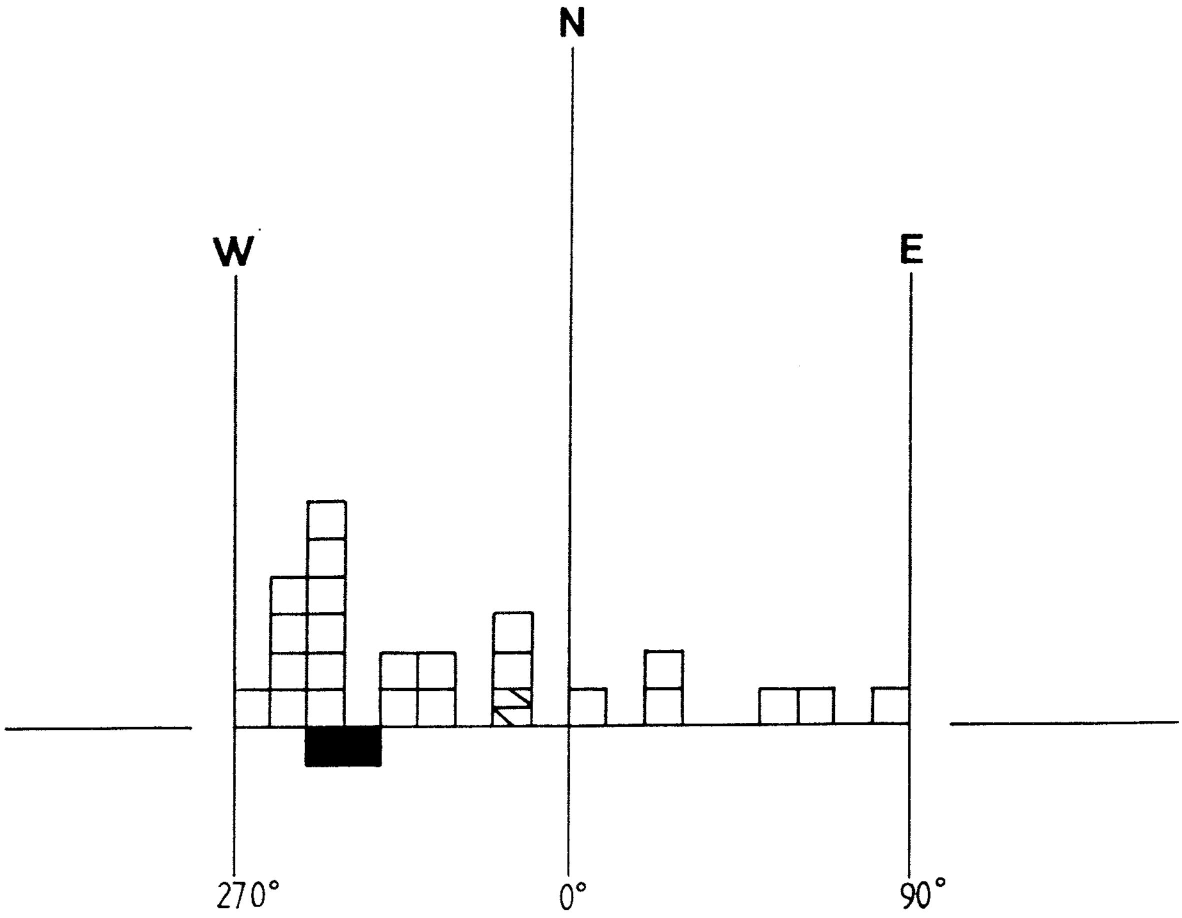
Displacement data
scanlines 1, 2
+ ground control area A

Appendix C
Sheet 1

□ no fossil displacement (observed)

fossil displacement, dextral } max. displacement 1cm
fossil displacement, sinistral

■ bedding displacement (small normal fault) } max. displacement 3cm



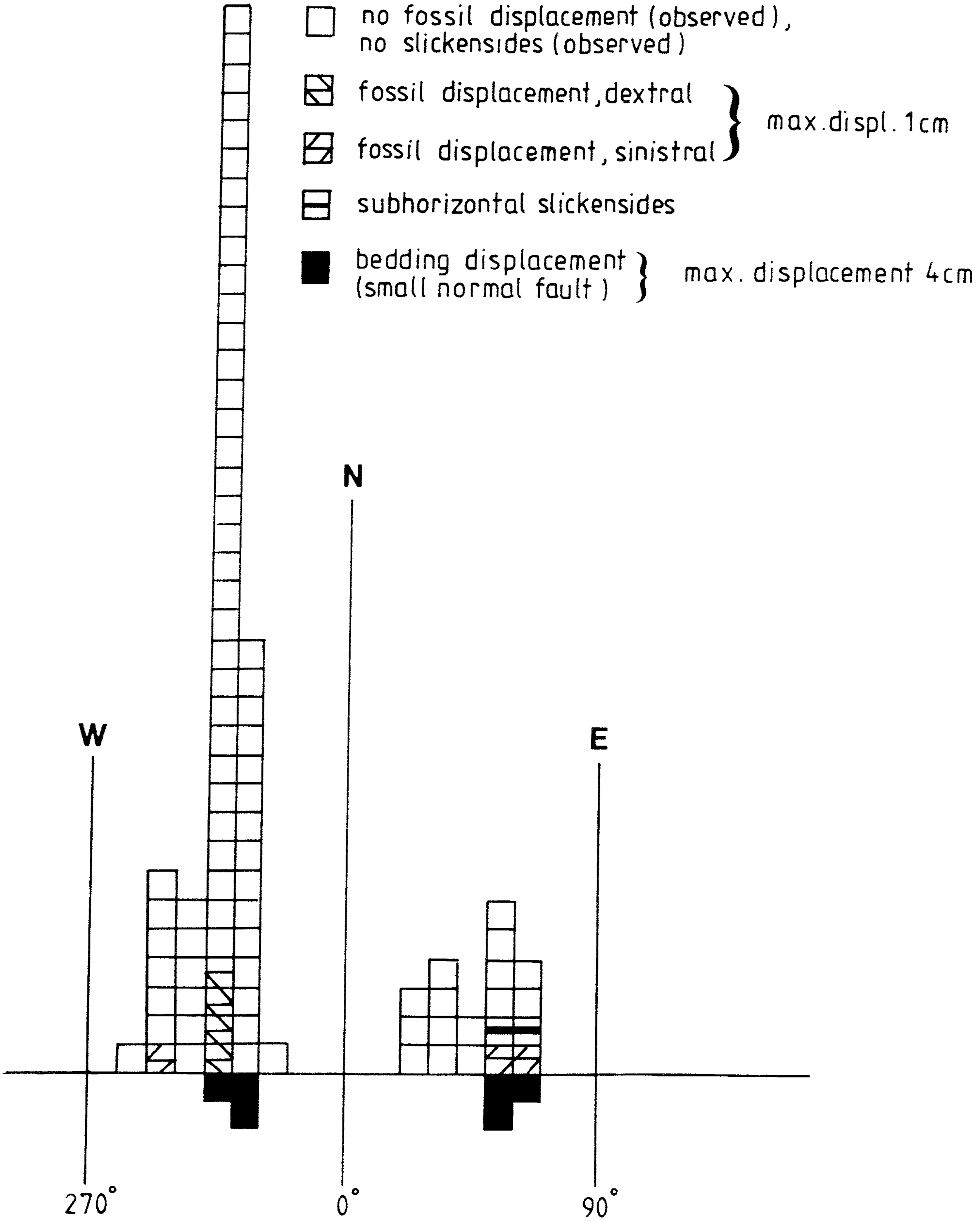
HAGUDDEN SECTION

Displacement data

scanlines 3-8

+ ground control area B

Appendix C
Sheet 2



HORNSUDDEN SECTION

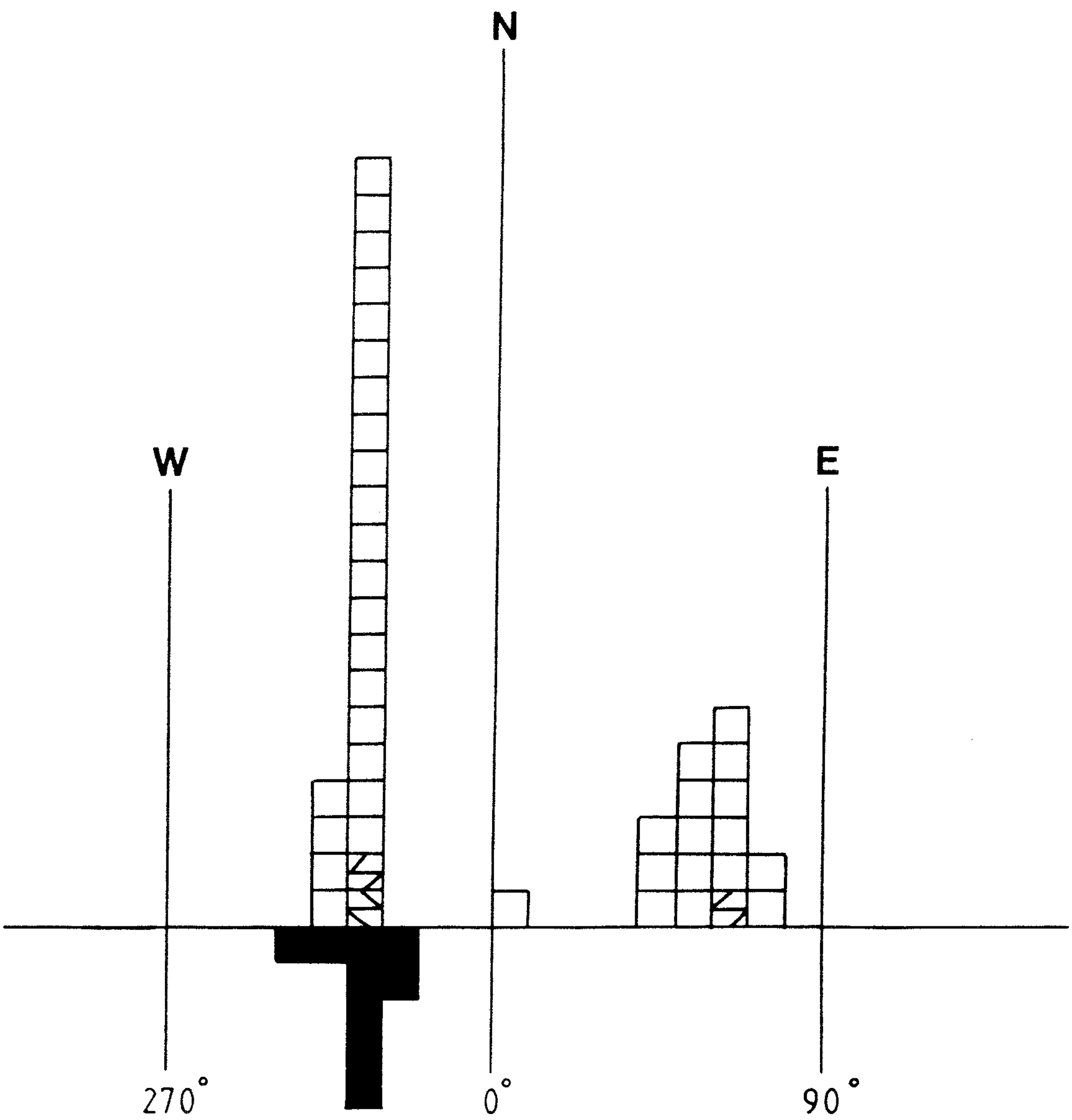
Displacement data
scanlines 9,10
+ ground control area C

Appendix C
Sheet 3

☐ no fossil displacement (observed)

fossil displacement, dextral
fossil displacement, sinistral
} max. displacement 1cm

■ bedding displacement (small noral fault) } max. displacement 3cm

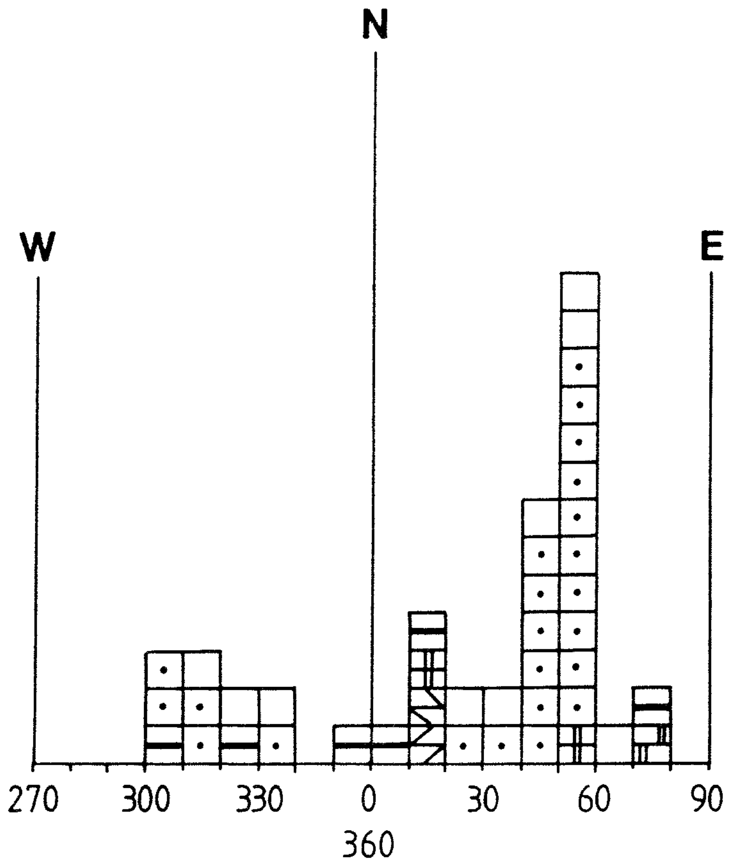


HORNSUDDEN SECTION

Quarry data

Appendix C
Sheet 4

- no surface markings or coating (no slickensides)
- surface with calcite coating, no slickensides (granular calcite)
- surface with slickensides (calcite fibres, slickolites), subhorizontal
  - -"- dextral
  - -"- sinistral
- slickensided fracture intersects fossil, displacement < 1 cm
- -"- displacement 1-4 cm



VÄSTRA ALVARET SECTION

Displacement data

scanlines 11 - 17

+ ground control area D

Appendix C

Sheet 5

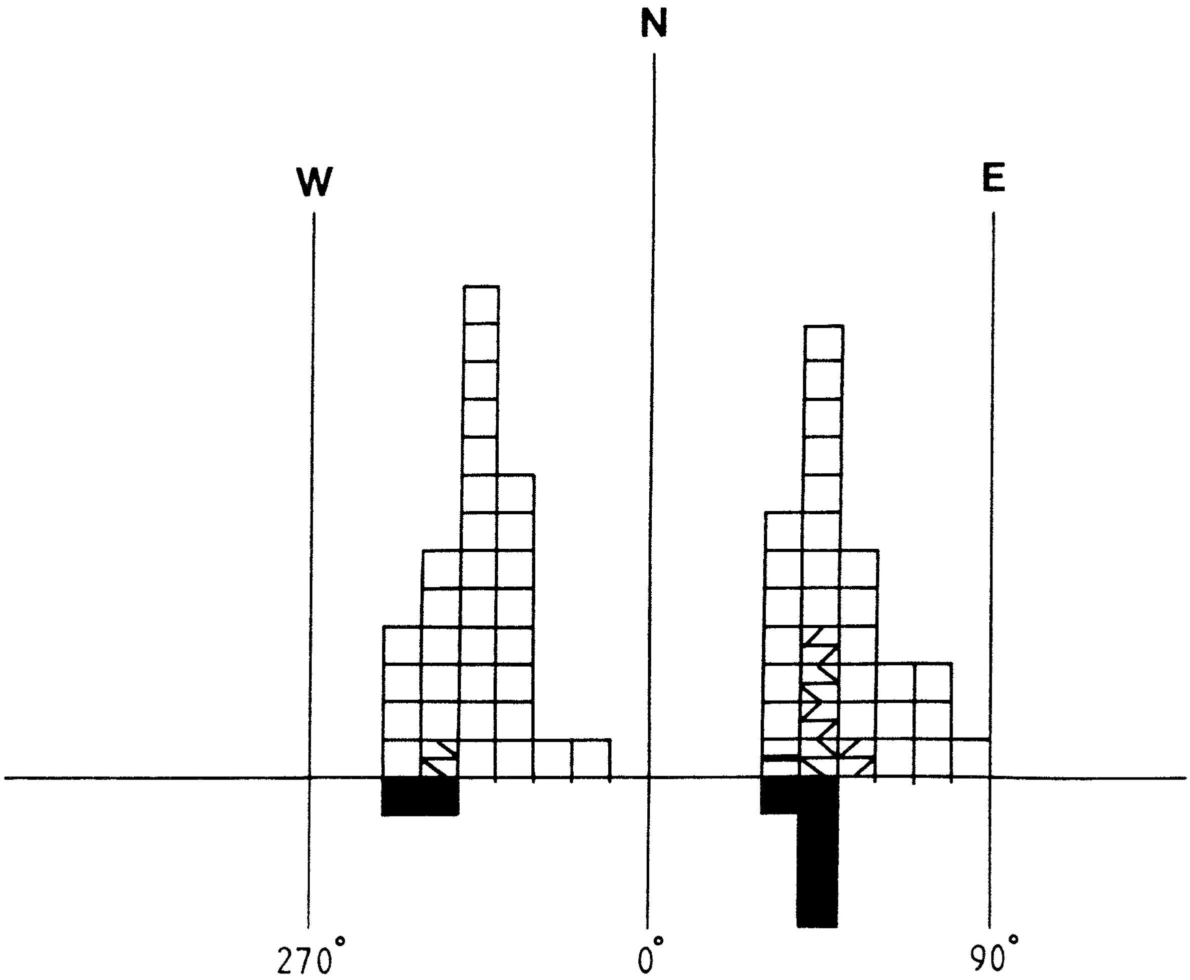
□ no fossil displacement (observed), no slickensides (observed)

fossil displacement, dextral } max. displacement 5cm

fossil displacement, sinistral } max. displacement 5cm

subhorizontal slickensides

■ bedding displacement (small normal fault) } max. displacement 8cm



JORDHAMN SECTION

Quarry data

□ no surface markings or coating (no slickensides)

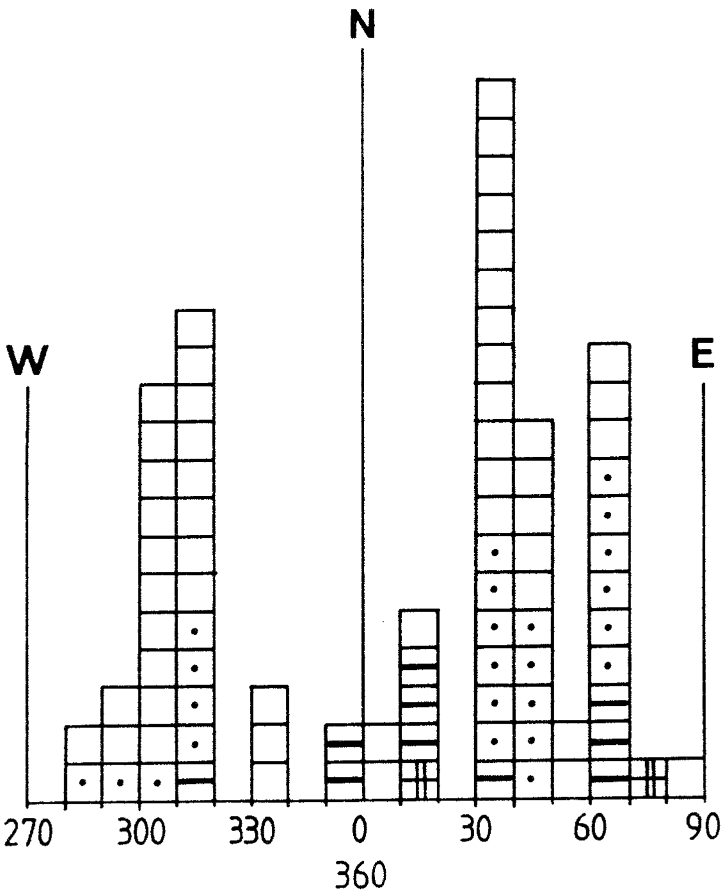
⊡ surface with calcite coating, no slickensides (granular calcite)

⊟ surface with slickensides (calcite fibres, slickolites), subhorizontal

- " - dextral

- " - sinistral

⊞ slickensided fracture intersects fossil, displacement < 1cm



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TR 79-28
The KBS Annual Report 1979
KBS Technical Reports 79-01 – 79-27
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Including Summaries of Technical Reports Issued during 1991
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TR 92-01
GEOTAB. Overview
Ebbe Eriksson[1], Bertil Johansson[2], Margareta Gerlach[3], Stefan Magnusson[2], Ann-Chatrin Nilsson[4], Stefan Sehlstedt[3], Tomas Stark[1]
[1]SGAB, [2]ERGODATA AB, [3]MRM Konsult AB
[4]KTH
January 1992

TR 92-02
Sternö study site. Scope of activities and main results
Kaj Ahlbom[1], Jan-Erik Andersson[2], Rune Nordqvist[2], Christer Ljunggren[3], Sven Tirén[2], Clifford Voss[4]
[1]Conterra AB, [2]Geosigma AB, [3]Renco AB, [4]U.S. Geological Survey
January 1992

TR 92-03
Numerical groundwater flow calculations at the Finnsjön study site – extended regional area
Björn Lindbom, Anders Boghammar
Kemakta Consultants Co, Stockholm
March 1992

TR 92-04
Low temperature creep of copper intended for nuclear waste containers
P J Henderson, J-O Österberg, B Ivarsson
Swedish Institute for Metals Research, Stockholm
March 1992

TR 92-05
Boyancy flow in fractured rock with a salt gradient in the groundwater – An initital study
Johan Claesson
Department of Building Physics, Lund University, Sweden
February 1992

TR 92-06
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Roland Pusch, Harald Hökmark
Clay Technology AB and Lund University of Technology
December 1991

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Discrete fracture modelling of the Finnsjön rock mass: Phase 2
J E Geier, C-L Axelsson, L Hässler, A Benabderrahmane
Golden Geosystem AB, Uppsala, Sweden
April 1992

TR 92-08
Statistical inference and comparison of stochastic models for the hydraulic conductivity at the Finnsjön site
Sven Norman
Starprog AB
April 1992

TR 92-09
Description of the transport mechanisms and pathways in the far field of a KBS-3 type repository
Mark Elert[1], Ivars Neretnieks[2], Nils Kjellbert[3], Anders Ström[3]
[1]Kemakta Konsult AB
[2]Royal Institute of Technology
[3]Swedish Nuclear Fuel and Waste Management Co
April 1992

TR 92-10
Description of groundwater chemical data in the SKB database GEOTAB prior to 1990
Sif Laurent[1], Stefan Magnusson[2], Ann-Chatrin Nilsson[3]
[1]IVL, Stockholm
[2]Ergodata AB, Göteborg
[3]Dept. of Inorg. Chemistry, KTH, Stockholm
April 1992

TR 92-11
Numerical groundwter flow calculations at the Finnsjön study site – the influence of the regional gradient
Björn Lindbom, Anders Boghammar
Kemakta Consultants Co., Stockholm, Sweden
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TR 92-12
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Sven Norman
Abraxas Konsult
May 1992

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Jordi Bruno[1], Patrik Sellin[2]
[1]MBT, Barcelona Spain
[2]SKB, Stockholm, Sweden
June 1992

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Numerical calculations on heterogeneity of groundwater flow
Sven Follin
Department of Land and Water Resources, Royal Institute of Technology
June 1992

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Kamlunge study site.
Scope of activities and main results
Kaj Ahlbom[1], Jan-Erik Andersson[2], Peter Andersson[2], Thomas Ittner[2], Christer Ljunggren[3], Sven Tirén[2]
[1]Conterra AB
[2]Geosigma AB
[3]Renco AB
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Vesa Henttonen, Miko Suikki
JP-Engineering Oy, Raisio, Finland
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The implication of fractal dimension in hydrogeology and rock mechanics Version 1.1
W Dershowitz[1], K Redus[1], P Wallmann[1], P LaPointe[1], C-L Axelsson[2]
[1]Golder Associates Inc., Seattle, Washington, USA
[2]Golder Associates Geosystem AB, Uppsala, Sweden
February 1992

TR 92-18
Stochastic continuum simulation of mass arrival using a synthetic data set. The effect of hard and soft conditioning
Kung Chen Shan[1], Wen Xian Huan[1], Vladimir Cvetkovic[1], Anders Winberg[2]
[1] Royal Institute of Technology, Stockholm
[2] Conterra AB, Gothenburg
June 1992

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A review of the current state of the art
Mats Skålberg, Jan-Olov Liljenzin
Department of Nuclear Chemistry, Chalmers University of Technology
October 1992

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Importance of the bedrock for safety
SKB
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Geology and mobility during the last 1.5 Ga
Per-Gunnar Andréasson, Agnes Rodhe
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TR 92-22
Klipperås study site.
Scope of activities and main results
Kaj Ahlbom[1], Jan-Erik Andersson[2], Peter Andersson[2], Tomas Ittner[2], Christer Ljunggren[3], Sven Tirén[2]
[1]Conterra AB
[2]Geosigma AB
[3]Renco AB
September 1992