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A Preliminary Structural Analysis of the Pattern of Post-Glacial Faults in Northern Sweden

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ABSTRACT

Subvertical displacements of up to about 25m in the 8 to 9000 year old glacial topography of northern Scandanavia are obvious along 500km of discontinuous NNE trending fault scarps. Strike-line constructions for these scarps on maps, together with structural analysis of the rare exposures of Precambrian bedrock along them, suggest <1km thick thrust flakes extruded by oblique transpression along pre-existing steep ESE dipping mega-shears.

Such megalineaments are part of a cubic pattern of ductile shears, cataclasites, recrystallised pseudotachylites and fractures that have reactivated the 1.6-2Ga Proterozoic crustal fabric at various times. Oblique-slip slickensides, post-glacial pop-up and jostle-up horsts, short post-glacial scarps, and sections of sidewalls to the NNE trending thrust scarps, all point to post-glacial reactivation of other components of the cubic structural pattern inherited from Proterozoic times.

The post-glacial kinematics inferred from the structures suggest horizontal NW or WNW compression with lateral relief to the NE at depth below surficial upward relief. These kinematics are sufficiently similar to the kinematics throughout Europe north of the Alps to suspect the neotectonic motion of the Eurasian lithospheric plate over the last 38 or even 58(+/- 2)Ma as the causative force. Large displacements appear to have occurred within a hundred years or so(?) of the last ice retreating from any particular part of northern Scandanavia. This suggests a sudden relief during glacial unloading (and melting of ground water) of plate tectonic forces accumulated during glacial loading. Recent earthquakes in the region display similar kinematics to the post-glacial fractures on a regional scale but indications of ground movement along the forested fault scarps in the lifetime of the trees (about 100years?) is observed at only a few localities. Only geodetic strain measurements or small-earthquake monitoring will resolve whether current ductile or seismic motion is occuring along the most obvious post-glacial scarps. Such investigations are under way.

Whether the post-glacial near-surface displacements occurred in one large increment is uncertain. However, the forty or so 0.5-1 million cubic metre rock falls and soil slips, slides and flows in a zone which was probably between the contemporary highest marine shoreline and ice front suggest small numbers of large earthquakes. Attention is drawn to a less obvious but more general disturbance of bedrock exposures in the same zone. Such disturbances (labelled here the Jericho syndrome) could be due to periglacial ice activity but are considered more likely to provide further evidence for considerably ground shock during major earthquakes immediately following ice retreat. Both the lengths of the post-glacial fault scarps and the displacements along them in Sweden alone indicate at least three earthquakes with magnitudes (Ms) between 7.2 & 8.2.

1 INTRODUCTION

"And they blew with the trumpets and the walls of Jericho fell down flat" says the frequently quoted passage from the Bible about the double walls of Jericho, a fortified oasis in the wrench-fault-controled valley of the river Jordan north of the Dead Sea. Archeological excavations in the 1930's established that the blocks of the outer wall fell outwards and downhill, but that the inner wall along the crest of the hill had fallen the opposite way, burying the buildings which lay behind it. Moreover, the stumps of the walls still upright were cracked and fissured before the city burned. Such evidence is interpreted to indicate that the walls of Jericho were demolished by a large earthquake (Keller 1956).

Many of the hills and ridges of bedrock in northern Sweden also show evidence of what will be called here the Jericho syndrome. Before disruption, some of these hills and ridges appear to have survived the Quaternary glaciations and subsequent marine action as residual tor-like monadnocks rising above the Visingsö-Cambrian-Cretaceous peneplain of Scandanavia. Kujansuu 1972 records similar (tropical?) weathering in a 150km wide EW band beneath the former ice divide in Finland. What may be similar bedrock disruption of obscure origin is known on the crests of hills and ridges in parts of southern Sweden (Harald Agrell, pers. comm. 1986).

Figure 1 shows the location of post glacial landslides indentified in Finland by Kujansuu (1972) and in Sweden by Lagerbäck (1983). Many of these involved the sliding and flow of masses up to a million cubic m of glacial deposits down slopes between about 3 to 10 degrees. The till remained coherent in some circular earth slides but must have resembled porridge or "watery soup" in the flows. The asymetric shape of one example in Finland suggest it flowed around the irregular retreating margin of the ice front and Carbon 14 dating suggests that all occurred before about 8000 years ago (Kujansuu 1972 p.13).

These soil slumps and associated rock- and debris-slides appear to be confined to a zone through Finland and Sweden that probably represents the unfrozen ground between the highest marine shoreline and the contemporaneous (but so far un-delineated) ice front. Subaqueous slides of the same age below the highest marine shoreline may have too little relief to have been recognised. To these impressive large-scale phenomena can be added the less obvious Jericho syndrome which is observed in approximately the same area as the major slides and rock falls (Robert Lagerbäck, pers. comm. 1986).

Steep rock slopes exibit toppling failure on the steep joints and sliding failure on the subhorizontal lift joints (Fig. 13). Lagerbäck & Witschard (1983) have convincingly argued that the delicately poised jumbles of loose blocks along the toes of such steep rock slopes imply collapse soon after the last ice retreated from each site. However, more gentle soil-covered hillsides are irregular because the joint blocks jostled, separated and rotated as they slid downslope. Even the subhorizontal crests of hills and ridges a km or so across display open fractures where clear of soil, or irregular hollows where a soil cover has fallen down steep fractures which opened beneath. The sideways displacements by decimetres or more of metre thick rock slabs down slopes of a few degrees is impressive enough - but some of the slabs are jostled horizontally even where slopes are not noticeable.

Gravity alone can account for toppling of steep cliffs and even the sliding of substantial rock slabs down slopes as low as perhaps ten degrees as witnessed on the kopjes of Africa. But aditional agencies must be considered for post-glacial jostling of rock slabs to depths of over a metre on slopes less than a few degrees. Some of the thin thrust slabs to be described were jostled as they were pushed laterally over an irregular decollement (eg. Figs. 9 & 10). Some of the pop-up horsts extruded by transpression (see later, eg. Fig. 9) may have burst by destressing. High water pressure was probably involved. But the Jericho syndrome also occurs km away from known fault scarps and lineaments identified as probable faults.

Ground shock by one or more major earthquakes provides an obvious explanation for the Jericho syndrome, but the röle of periglacial ice activity suggests another, and both effects could have worked together (Robert Lagerbäck, pers. comm. 1986). However, the writer has worked in active periglacial terraines close to the ice sheet high in western Greenland as well as formerly periglacial terraines: in Jan Mayen, Scotland, and northern Canada as well as in Norway and Sweden. He is familiar with frost shattering, patterned ground and the like, but has only ever before encountered small-scale versions of the Jericho syndrome close to artificial bulk-blasted excavations dissaggregated by large volumes of high explosives. At this stage therefore, the writer tends to the opinion that earthquakes are necessary to account for the Jericho syndrome in northern Sweden, although he accepts the possibilty that periglacial effects may have contributed.

Over 500km of NNE trending fault scarps up to 25m high displace the precambrian bedrock and glacial drift in the north of Finland (Kujansuu 1964), Sweden (Lagerbäck 1979) and Norway (Olesen 1984). The Pärvie fault sytem is about 150km long and most of the fault scarps trend NNE or WNW (Fig. 2b). The 80km long post-glacial Finnmarksvidda fault scarp in Norway appears to be a similar structure approximately in line about 150km to the NE (Olesen 1984).

The discontinuous 360km long NE line of the post-glacial Pärvie-Finnmarksvidda fault scarp system is paralleled by another about 180km to the southeast (Fig. 1). This second line is 260km long and consists of two 50km long discontinuous post-glacial scarps: the Lansjärv fault in

Sweden (Lagerbäck 1979) and the Rautuskylä fault in Finland (Kujansuu 1964); a 'linear' NE segment of the river along the Swedish-Finnish border occurs in the intervening gap (Fig. 1).

Geomorphological analysis has shown the fault scarps to have developed at much the same time as the more restricted landslides (Fig. 1) and to have disrupted the region soon after the last ice melted about 8 to 9000 years ago (Kujansuu 1972 and Lagerbäck 1979). Various geophysical methods have shown that the obvious NE trending fault scarps are segmented between NW trending lineaments with wrench displacements of unknown age (Henkel and others 1983). Although comments have been made on the few bedrock exposures along the fault scarps (Lagerbäck & Witschard 1983), there has been no systematic structural analysis of this unexpected fault pattern.

This report is such an analysis of that part of the pattern in Sweden based on a desk study which followed reconnaisance field observations carried out in the week 28 September to 3rd October 1986.

The Pärvie fault system (Figs. 1 & 2) was overflown south to north by helicopter after the first snow of the autumn on 861001; occasional landings allowed hurried ground observation of some of the bedrock exposures. Section 2 of this report documents a strike line analysis of the Pärvie fault system augmented by the few ground observations available. This section demonstrates that, rather than consisting only of steep reverse faults as previously supposed, the Pärvie fault system also involves surficial thrust flakes or nappes which moved to both the WNW and ENE. The Laino fault (Fig. 1) was also overflown NS but there was time for only one landing along this 50km long scarp (at the location photographed in fig. 20 and described in Lagerbäck & Witschard 1983). More leisurely study was possible by travelling by car and foot to bedrock exposures along parts of the Lansjärv fault (Figs 1 & 9), an un-named example of the NW lineaments and one of the major NS lineament in the Lansjärv region. These observations are described in section 3 where it is argued that wrenching along the NS and NW lineaments accompanied the already recognised thrusting. The post glacial kinematics are summarised in section 4 where they are related to the Proterozoic fabric in the bedrock.

A final section speculates on the dramatic post-glacial dynamics of northern Scandanavia being a brief stage during which Fennoscandia 'caught-up' with the rest of the eurasian plate after being delayed by glacial loading during the Quaternary ice ages. Brief comparisons are made between the structures described here and the earthquakes, in-situ stresses and hydrological research elsewhere in Sweden.

2 THE PäRVIE FAULT SYSTEM

Figure 2 shows the locations of Figures 3 to 8 which are maps of those parts of the Pärvie fault system across which composite profiles can be constructed by interpolating strike lines.

Strike lines are constructed assuming that particular segments of the fault scarps lie along planar elements with constant strike. They can only be constructed where fault traces cross areas of significant topographic relief. These are labelled Sectors A to W from south to north (Figs. 2-8). The trace on the map of these scarp sectors is taken as the intersection of a planer fault with a more complex topography. One or more locations where a particular segment of a fault scarp crosses the same topographic contour are joined by a 'strike line' which is labelled with its height above sea level. The same process is repeated where the the same scarp element crosses other topographic contours. Sets of such strike lines are interpreted as contours not on the topography but on individual fault elements. They can be used either to construct vertical cross sections through the fault(s) or to extrapolate the surface trace of a fault beyond that already known. Such excercises offer potential checks on the local strike-line construction.

PROFILE P11 across sector C (Fig. 3) is a clear example of the method where the contours on the fault between two lakes indicate a straight planar fault dipping 70 degrees ESE. This seems reasonable for, as shown on the stereogram (Fig. 3) of the outcrop indicated in the vegetation free zone along the shoreline of Langas (see figure 26 in Lagerbäck & Witschard 1983 for photo), the most conspicuous fracture set also dips 70 degrees ESE, parallel to a strong gneissose to mylonitic foliation in the c.2Ga old quartz porphyries. The volumes of the joint blocks decrease from >1 cubic metre about 100m from the fault to about a cubic cm within 10m of where the fault extrapolates through the site. Seven years ago a metre or so wide strip brown fault gauge was exposed in the fault itself but this has since been eroded (Lagerbäck, pers. comm. 1986). Groove slickensides plunge 50 degrees to the south on epidote exposed on steep NNE fracture infillings indicating that recent movements involved oblique slip.

A few metres SE from the likely fault trace, a 1-2m wide cataclastic breccia is seamed by two anastomosing veins of largely recrystalised pseudotachylites (small veins of glass due to the quenching of total melts generated by friction). Thin sections of these former pseudotachylites display undulose colour banding in (multiple generations of?) the wider veins of melt which permeated the apparently contemporaneous cataclastic breccia. The wider veins have radiating crystallites (of muscovite?) but some of the thinnest may still be glass.

The joint blocks in this same exposure are also displaced laterally as though shaken by the Jericho syndrome and major slides are known locally (Fig. 1, for photo see fig. 5 in Lagerbäck & Witschard 1983).

PROFILE P1 (Fig. 3) shows the fault geometry at the southern extremity of the Pärvie fault to be more complex than between the lakes of Langas and Sautihaure. Two fault scarps in profile P1 are offset en-echelon without overlap but, as in many other profiles, have been projected into a single strike-normal profile to display their mutual geometric relationships. Sector A could be a southerly continuation of Sector C offset dextrally by over a km along a NW lineament through Langas. Sector B is interpreted to be listric (spoon-shaped) and to curl downwards to the ESE to a gentle dip above lake level. This curl could be confirmed if, as expected, the fault surface is exposed in the NE facing hillside south of Langas.

PROFILE P111 (Fig. 3) illustrates one of the potential difficulties of strike line constructions. The curl of the scarp of Sector D down the hillside to the SSW has to be interpreted as an unlikely dip in to the WNW. However, this is the only highly suspicious profile constructed using strike lines; all the remainder can be readily rationalised.

PROFILES PIV-PVI (Fig. 4) illustrate the potential of strike line constructions. Although local horsts have been recognised before (eg. Lagerbaäck 1979) the Pärvie fault system has previously been taken to consist mainly of steep reversed faults dipping steeply ESE (like Sector C on Fig. 3). Projecting Sectors F, H & I into a single composite profile (PIV), and relating these to profiles PV & PVI using a common strike line (Fig. 4), suggests that at least this portion of the Pärvie fault system consists of anastomosing gently dipping listric thrusts and normal faults defining shear pods or flakes up to hundreds of m thick, a few km wide and tens of km long. Smaller pods exist along the subhorizontal thrust of Sector M which projects just above the topography to the NE (PVIII on fig. 4). Sectors M & J1 could be offset sinistrally 800m along a NW lineament. The Pärvie fault system begins to look like a classical ESE-dipping system of thrusts and antithetic normal faults like the WNW-dipping sytem in the Caledonides just to the West.

However, if the 3m high fault scarps along Sectors O,P,R & Q really face eastward, then these sectors are gentle ESE-dipping normal faults while Sectors Q & O could be the same subhorizontal WNW dipping thrust (Fig. 5). Such relationships suggest the kinematics of the Caledonides and raise the spectre of the ESE dipping thrusts of the Pärvie system being reactivated back thrusts of the the Caledonian orogen not far to the west. A simpler and prefered alternative is that that the thrusts in the east (ie. Sectors O & P on Fig. 5) are themselves backthrusts in a Pärvie thrust system unrelated to the Caledonides.

Figure 6 includes a stereogram of ground observations in an isotropic metadolerite exposed in an EW river cliff immediately west of the 015 degree trending sector S. The fractures are unsystematic and the block volume is <1 cubic cm in the outcrop closest to Sector S. The fractures become systematic 15m further west and the block volume increases to >1 cubic m about 170m further west. Hackle marks on vertical NE fractures suggest that some of the fractures propagated horizontally. Slickenside grooves plunge about 40 degrees to both the NNW and SSE in steep NNE fractures paralleling the fault scarp emphasisng again that some of the displacements were oblique slip. Strike lines cannot be drawn on sector S but indicate that an unlettered Sector 6km to the south of the outcrop visited on Sector S is a WNW dipping thrust (Fig. 6).

PROFILES PX & PXI (Fig. 7) can be described using the terminology that refers thrust geometry to staircases consisting of flats and ramps. This is because both these profile illustrate comparitively small antithetic normal faults above where strike lines imply thrust ramps curl (convex upward) to flats in Sectors T,(V?) & W. The thickness of the nappe in sector U is a matter for speculation (see eg profile of Sector U on Fig. 7 for a thin-skinned interpretation which accounts for the surficial slumping of the leading NW edge). Strongly foliated granodioritic gneisses are exposed in a c.10m high cliff along the ESE trending sidewall represented by Sector U. This old penetrative foliation dips steeply N, perpendicular to old subhorizontal stress relief lift joints which decrease to a spacing of about 0.5-1m at the top of the cliff. Epidote infilling horizontal fractures forming overhangs at the foot of the cliff diplays subhorizontal slickensides which parallel the EW sidewalls despite developing on thrust flats. A set of conjugate shear fractures that dips about 30 degrees west is illustrated on Figure 7 but is not represented on the stereogram. A fault breccia a few dm wide dips steeply south, parallel to a conspicuous fracture set which parallels the sidewall. Here the post-glacial sidewall appears to be slightly oblique to the Precambrian fabric.

The tectonics of the Pärvie and Lansjärv fault systems will be summarised together in a later section.

3 THE LANSJäRV FAULT SYSTEM.

Figure 8 gives an overview of that part of the Lansjärv-Rautuskylä fault system which occurs in Sweden (after figure 3 in Lagerbäck & Witschard 1983) and also outlines Figures 9 to 12 where structural observations were made on bedrock outcrops close to examples of the faults in the Lansjärv area.

3.1 THE RISTRÄSKKöLEN EMBAYMENT

Figure 9a is a tracing from an air photo of the Risträskkölen plateau which is defined by fault scarps (about 30 degrees from the horizontal) in the top surface of the glacial drift and represents a conspicuous embayment in the general NE trend of the Pärvie fault system (Fig. 8). The plateau tilts down to the SE and merges with the peneplain about 3km behind its leading NW corner which has a NW-facing scarp about 22m high (Fig. 9b).

Precambrian granite gneiss is exposed in parts of the scarp where it faces north. The toes of these rock slopes are aproned with heaps of jumbled 2-3 cubic metre blocks which toppled into the mire below soon after the last ice retreated. The rock slopes above these delicately poised piles of blocks are between 50 and 80 degrees from the horizontal. None of the <5cm irregularites in any of the exposed fractures interlock implying that even the "bedrock" here has been disturbed by the Jericho syndrome.

In the base of the most westerly of these rock slopes a penetrative foliation dips 12 degrees to the SE (parallel to a shallow décollement beneath the plateau?) while a transgressive mylonite dips 75 degrees to the WSW parallel to the sidewall (Fig. 9c). The three most prominent fracture sets in this outcrop have been interpreted to consist of an extensional set asymmetric between two conjugate shear sets (Fig. 9c). This allows an interpetation in terms of the three principal axes of the stress field repsonsible for the fracturing. The maximum principal stress (sigma 1, starred on Fig. 9c) was horizontal WNW with a minimum principal stress (sigma 3) plunging about 45 degrees to the NNW. The intermediate stress axis plunged to the SW, subparalleling slickenside grooves on some of the exposed fracture surfaces. The stress field indicates a WNW directed thrust regime and the slickensides suggest relief to the sidewall once it rose above the land surface to form the scarp.

About 100m to the east, two fracture patterns (Fig. 9d) record a similar (but horizontal) thrust regime in combination with, or followed by, a dominant transpressive wrench regime with sigma 1 subhorizontal NS. The wrenching corresponds to a slight NS dextral offset in the northern edge of the Risträskkölen plateau near this site (Fig. 9b). Slickensides on wrench surfaces at this locality plunge gently NW in accord with the interpretation involving thrusting followed by wrenching.

The surface of the Risträskkölen plateau is crossed by furrows with orientations which parallel its margins. These may mark the sites of fractures down which the drift drained when they opened- either because of the Jericho syndrome or while the plateau was jostled northwestward over a slightly irregular shallow decollement surface. A similar jostling process is thought to be responsible for a small lunate hump of slightly foliated granite 2km NE of the plateau. This asymmatric hump (insert on Fig. 9a) is interpreted to represent what happens when a thin slab of bedrock is jostled along pre-existing fractures over a mound in the underlying decollement. The top veneer of loosened surface slabs were subsequently dispersed by the Jericho syndrome.

3.2 THE NORTHERN SECTION OF THE LANSJäRV FAULT SYSTEM

Another example of comparitively thin-slab-jostling (as a local facies of thrusting) is illustrated in an insert on Figure 10. Here the underlying obstruction appears to have been an inclined step for the regionally horizontal and vertical NS joints in the jostle-up are tilted beyond where they surmounted the step.

Ground observations confirm a strike line construction (see profile on Fig. 10) suggesting that the northern end of the Lansjärv fault dips gently to the SE. The upper levels of this thrust dip 8-10 degrees to the SE and projects upwards to the NW, parallel to the hillside of Precambrian pegmatitic granites in the footwall. The same thrust extrapolates just above the SE flank of Storberget about 2km to the SW. This suggests that the post-glacial scarp hereabouts represents only a small reactivation of a thrust which controled erosion in the region long before the Quaternary glaciations. No bedrock was found exposed in the hanging wall but that in the footwall on Märjavberget (top of Fig. 10) was too irregular to be the thrust surface and had a huge block volume (>10 cubic m?) and a foliation (dipping 43 degrees to the NW) unrelated to the thrust. Hills in both the hanging and footwalls have been bevelled by the highest marine shoreline suggesting that careful study of the height of this marker could be used to constrain what is probably a quite small vertical component of the post-glacial increment of displacement along the thrust(s?) profiled on Figure 10.

3.3 NW LINEAMENTS

Magnetic, electrical, EM and seismic studies have all delineated several major NW and N trending lineaments as well as some of the NE trending lineaments beneath the fault scarps in the Lansjarv fault system (Henkel and others 1983). Offset of geophysically indicated structures with other orientations suggest NW wrench displacements but the age of such wrenching has been obscure. Certainly some of the NW lineaments locally acted as sidewalls to thrust flakes in both the Pärvie and Lansjärv fault systems but this does not automatically mean that continuations of even these locally exploited NW lineaments wrenched on a regional scale since the last glaciation. It is difficult to answer this problem because any strike-slip displacements along the NW lineaments would parallel the grain of the glacial topography and are therefore unlikely to produce obvious scarps in the marshy ground along the lineaments.

The SW margin of the Risträskkölen plateau is the site of a pronounced NW geophysical lineament and the scarp along this obvious example of a sidewall increases from zero in the SE to about 20m in the NW. About 5km NW of the Risträskkölen plateau this same lineament is marked by a 2-3m high scarp facing NE which extends for about 90m. Such a scarp in the till (labelled location 5 on Fig. 8) is highly suggestive of post-glacial wrenching along a NW lineament far beyond where it acted as a sidewall to a thrust.

Figures 11b & c are stereograms of structural data collected on a 2km traverse across the same NW lineament (circled on Fig. 11a) where it passes between Vitberget and Smedeberget about 14km SE of Risträskkölen (Fig. 8). Here the geophysical lineament is about 200m wide and is marked by a corridor of low marshy ground between rounded ridges of graphic pegmatitic granite and gneissose granite.

Comparison of the orientation data on Figures 11b & c shows that the fracture patterns are essentially similar on either side of the lineament- but rotated 20 degrees with respect to each other about a horizontal axis along the lineament. The stress fields interpreted for the fracture patterns in each block independently indicate wrenching along a steep NW fault. Both fracture patterns are symmetrical about a penetrative foliation in the granitoid gneiss which varies in intensity and, closest to the lineament (in Smedeberget), becomes mylonitic in a dm wide zone parallel to the inferred fault.

All the NW trending bedrock ridges visited showed disturbance by the Jericho syndrome and, although the block volume varied from about 10 cubic metres to half a cubic metre, there was no systematic decrease towards the fault as was found within about 200m of the faults elsewhere.

Figure 11d illustrates a sketch map of the fracture orientations measured on the ground referred to their approximate distance from the lineament. Some of the fracture sets in either block curl irregularly from their regional orientations to others close to the lineament (and other shear zones sub-parallel to it). Thus an ENE trending set of conjugate shears in the NE block curls from a strike of 080 degrees 300m away from the margins of the lineament to a strike of 120 degrees within a hundred metres of it. Such curls towards the shear(s) of sets of brittle fractures strongly suggests that even the bedrocks exposed outside the geophysical lineament still lie within one or more dextral ductile shear zones. Furthermore, the ductile shearing was superposed on earlier sets of brittle fractures suggesting inconstant strain rate. The asymmetry in the strains in the two blocks is emphasised by the horizontal principal compressive stresses derived for each block being 10 degrees on either side of the trend of the lineament itself (insert on Fig. 11d). Such assymetry may indicate a steep SW dip of what was (and may still be) a transpressive zone of ductile shear.

3.4 NS LINEAMENTS

3.4.1 LILLA SNöRBERGET

Lilla Snörberget is the more northerly of two dissaggregated horsts of migmatites and granites exposed close to the southern end of a NS post-glacial fault scarp 5km east of Ristráskkölen (Fig. 9b). Lilla Snörberget is elongate NNW, en-echelon and intermediate in location between the NS scarp to the north and its offset southerly continuation as a NS lineament (Fig. 9b). The complex fracture pattern within Lilla Snörberget can be interpreted as recording the effects of both wrench and normal faulting with a common strike of 013 degrees (Fig. 9e). This suggests that this square-profiled ridge developed as a pop-up horst which collapsed by normal faulting (and the Jericho syndrome) after being squeezed to the free surface by oblique slip along the NS scarp (and the lineament to the south?). Both the pop-up and the oblique-slip wrenching it implies along the NS fault scarp are post-glacial. At least some of the NS lineaments have therefore been active since the last glaciation.

3.4.2 SOLKOBERGET

Figure 12 shows structural data collected from exposures of bedrock in the NS trending ridge of Solkoberget east of a marsh along a conspicuous NS strand of geophyisical lineaments some 45km to the NE of Ristráskkölen (Fig. 8).

Here the fracture pattern in the migmatitic bedrock is cubic and does not allow interpretation of a causative stress field. However, the kinematics indicated by slickenside grooves in epidote infilling both steep and subhorizontal fractures closest to the lineament are consistent with sinistral displacements along a NS sinistral strike slip transpressive shear zone. The grooves plunge gently within a partial great circle dipping about 40 degrees west. The steep easterly dipping migmatitic layering and foliation was rotated through 55 degress within 300m of the edge of the exposed bedrock adjacent to the geophysical lineament. This curl was about a steep SE axis suggesting a slight thrust component in the transpressive shear zone. The block volume decreases systematically from about 3 cubic m 100m from the lineament through about 1dm 20m from the fault to about a cubic cm along the bedrock edge closest to E side the lineament. Subvertical NS cataclasites and possible recrystallised pseudotachylites anastomose along the W edge of this exposure.

4 REACTIVATION OF A PROTEROZOIC CUBIC FABRIC

Essentially the same cubic pattern of sets of fracture as that seen near Solkoberget (stereogram on Fig. 12) is present in exposures of bedrock along all the other components of the fault pattern visited in the north of Sweden (see Fig. 14). It is rotated in the pop-up or jostle-up horsts (Figs. 9 & 10) and joined by extra conjugate shear fractures along the NW lineaments (Fig. 11), the NE fault scarps and their sidewalls of various orientations (Figs 13 & 14).

The underlying cubic fracture pattern throughout the region is defined by two subvertical sets of joints and a third set of subhorizontal relief joints (Fig. 12). The two steep NS-NNE & WSW-EW sets strike parallel and perpendicular to the penetrative foliation in the 2Ga bedrock (Fig. 1). They were therefore inherited from the original Proterozoic fabric and probably reactivated several times since. Berthelsen and Marker (1986 see eg. their fig. 3) describe NS and NW megashears in the region which reversed their senses of strike-slip shear between 1.9 and 1.8Ga ago. The post-glacial tectonics described here reactivated some of the same Proterozoic structures.

It is common for later kinematics on a regional scale to adapt to and reactivate pre-existing fracture systems. New fractures are only generated to flake off the corners of margins of blocks of the rock mass on any scale which obstructed the regional scale jostling of old blocks. Late movements along the NS lineament at Solkoberget appear to be unique in having been able to reactivate the old fabric without generating new fractures.

The local fracture patterns elsewhere are generally more complicated. Analyses of the stress fields in these localities may therefore interpret local variations where the regional stress field refracted (see stereogram bottom right on Fig. 13). This is likely in comparatively small flakes splintered from the corners and edges of blocks of the old regional pattern and either trapped and crushed- or expelled to the free surface where they collapsed.

Both the Pärvie and Lansjärv fault traces trend NE on scales of a hundred km but both locally reactivated subvertical EW, NW and NS and subhorizontal planar elements on the scale of km. Furthermore, both fault systems moved on younger (curled) fractures with a much larger range of orientations on the outcrop scales, although even these still relate to the underlying cubic pattern (see stereograms on Figs. 13 & 14).

5 DISCUSSION: NEAR-SURFACE DUCTILE STRAINS

An intriguing feature of the deformation patterns illustrated on Figures 11d & 12 is the apparent ductile distortion of older brittle fractures. Brittle fractures can often be inferred to have been present in old rocks- but they have usually been annealed by later metamorphism. Reports of old fractures (rather than veins or sheet intrusuives) being recogniseable after the superposition of ductile strains are rare in the literature. The writer has only previously noticed three minor examples of distorted planar joints in about 27 years of field experience. All three of these could, like the examples in the Lansjärv fault system (Figs. 11d & 12), be interpreted as indicating surprisingly ductile strains in near-surface (or at least non-metamorphic) conditions. Slunga (1985) raised a similar problem when he reported that half the small earthquakes monitored in southern Sweden between 1979-1984 occurred in the depth range 7-17km. Most of these earthquakes appear to have occurred along steep wrench faults which presumably extend down to the lower crust and up to the surface (Talbot & Slunga, in prep). Ductile aseismic shear along faults (or shear zones) is to be expected at depth because of the higher temperatures there. However, the ductile near-surface strains inferred in Sweden from both the earthquake data and Figures 11d & 12 are unexpected.

Two factors could together account for aseismic near-surface displacement along faults:

1. The top few km of the faults are likely to be marked by zones of comparativly soft breccia and gouge (a mechanical soil- see Fig. 15a).
2. Groundwater is known to soften most crystalline rocks as well as soils. Episodic ductile strains monitored along near-surface faults in water-saturated sediments beneath a water resevoir in California have been called aseismic "slow earthquakes" (Hudson & Scott 1965). Some of the shallow (pre-glacial?) displacements in the Lansjärv fault system may have been accompanied by "slow earthquakes".

The most obvious difference between the ductile near-surface strains in California and northern Sweden is that the Swedish rocks are old and crystalline rather than young sediments. Nonetherless, the old crystalline rocks are demonstrably permeable at shallow depths because of the fractures. Even quartzites, some of the most brittle crystalline rocks are known to soften when wet by a few weight per cent of water. The possibility of slow earthquakes still occurring in water-saturated Swedish bedrock is likely to be clarified by the geodetic monitoring planned for the Lanjärv fault system.

6 SUMMARY

Parts of the Pärvie and Lansjärv fault sustems have been shown independantly to involve gently dipping anastomosing thrusts with N to NE strikes and steep contemporaneous NW-EW-trending sidewalls as well as the previously known steep E or ESE dipping reverse faults (Fig. 13).

Most of the thrust strands diplay variable dips to the ESE and those dipping WNW in the Pärvie system are taken to be backthrusts with associated normal faults (Fig 13). Figures 2c & d suggest possible correlations between the scarp height and both their orientations and their lengths along the Pärvie system. The highest scarps (c. 12m) trend about NE and the lowest trend WNW (Fig. 2c); this correlation is poor but accords with the picture of thrusting to the NW (resulting in steep scarps) with wrenching without significant vertical displacements along WNW or NW trending sidewalls. The longest continuous scarps along the Pärvie sytem also tend to be highest (Fig. 2d). The steepest thrusts (or reverse faults) trend NNE and are also the longest, and the larger thrust flakes or nappes probaly root to them. The post-glacial fault scarps along the Lansjärv fault system are generally higher than those along the Pärvie system and reach a height of about 22m around the Risträskkölen plateau.

Slickenside grooves on epidote fracture infillings indicate oblique slip on the steep NNE-trending reverse faults. This raises the possibilty that both the Pärvie and Lansjärv fault strands are positive flower structures extruded by transpression along NE trending master zones of weakness inherited from Proterozoic times (see eg Fig. 13).

Slickenside grooves on epidote fracture infillings along the N and NW lineaments are indistinguishable from those along undoubted post-glacial fault scarps. A 90m long scarp in glacial soils is 2-3m high along a NW lineament known to be a sinistral sidewall to that part of the post-glacial Lansjärv thrust under the Risträskkölen embayment. Such a scarp suggests strongly that some of the NW wrench faults were active at the time of the post-glacial thrusting and NS wrenching. This is so even though the same fault 14km to the SE of Risträskkölen distorted both the old cubic fabric and younger fractures in a suite of dextral shear zones. The SINISTRAL post-glacial fault increment along the SW margin of Risträskkölen implies that the surprisingly ductile DEXTRAL shearing discernable along the same structure further SE was older.

All the recent structures studied throughout northern Sweden fit the same single general kinematic picture summarised on Figures 13 & 14. Post-glacial horizontal NW-WNW shortening and NNE-NNE relief in a wrench regime at depth was relieved along N and NNE-trending thrusts and backthrusts close to the surface. This contrasts to sigma 1 plunging 10-20 degrees to the SSW in the Vietas headrace tunnel (Fig. 1) where it penetrates the lower allochthon of the Caledonides just to the west, at the head of lake Langas (Martna & Hansen 1986). However it is remarkably similar to the situations in central Sweden, at the Finnsjön study site SW of Forsmark (Ahlbom and others 1986) and at Forsmark itself (Swedish State Power Board 1982). A cubic Proterozoic fabric is recognised as controling the current stress field at Forsmark. The in-situ rock stresses at both these sites involve subhorizontal NW compression which vary significantly in magnitude above and below significant gently dipping fractured mylonite zones at depths between 50-200m at Finnsjön and 320m at Forsmark. The example of such a fracture zone has been shown to control the stress intensity and hydrology at Finnsjön and is probably an analogoue of the shallow thrusts or decollement surfaces described here. Such fractured mylonite zone(s) separating a surficial destressed (thrust?) regime from a deeper (wrench?) regime has also been suggested on the basis of Swedish earthquakes (Båth 1985) and could account for the seismic reflectors known beneath part of the Siljan ring (eg Passchier 1986).

Some elements of the post-glacial fault pattern in northern Sweden parallel and exploit old penetrative foliations and lithological contacts while others transgress such old fabrics to variable degree. Some of the recent faults involved ductile shear zones and mylonite zones which presumably developed at high metamorphic grade long ago. Others involved more recent, less deeply buried, cataclastic crush zones, breccias, recrystallised pseudotachylites, epidote-infilled brittle fractures and fault gauges (Fig. 15a). Relating schematic block diagrams of both the Pärvie and Lansjärv post-glacial fault systems with compound stereograms of the structures along them (Fig. 14) demonstrates that both reactivated and modified a Proterozoic cubic fabric in the bedrock of the region.

Many of the post-glacial faults obviously have a long and complex history of repeated reactivation. However, the trees growing on the forested scarps are only noticably curled at two locations:1, where the arctic circle crosses the scarp immediately east of the Risträskkölen plateau and 2, on Mäjärvberget, 5km NE of Lansjärv-(Lagerbäck pers comm. 1986); no other indications of downslope movements within the last 100 or so years was recognised. No evidence was therefore found to contradict the suggestion that post-glacial displacement on both the widespread faults and the more localised landslides occurred in a short time interval between the ice front retreating generally northwestward and the shoreline retreating generally southeastward about 8-9000 years ago (Lagerbäck 1979).

7 SPECULATION

The dynamics behind the post-glacial kinematics are more problematic. Post-glacial uplift alone would presumably induce horizontal extension both radial and concentric to the centre of uplift near Luleå, not the NW or NNW horizontal shortening evidenced by the structures, earthquakes and in-situ stress determinations in the rising region (Klein & Barr 1986).

The most likely explanation of the dynamics at this stage invokes plate tectonic forces timed by glacial offloading.

If the post-glacial tectonic pattern is really confined to the north of Scandanavia, then it could support the recent suggestion that subduction of the oldest sea floor just to the NW is beginning to sag prior to subduction (Anderson 1984). This suggestion was based on a depression of the geoid off the coast of northern Norway revealed by SEASAT. Any such incipient subduction could reasonably be expected to induce ESE dipping thrusts with strikes parallel to the nearest continental margin.

However, the kinematics interpreted here for northern Sweden are essentially similar to those indicated by small earthquakes and active faults in southern Sweden (Talbot & Slunga, in prep.). Indeed, it can be argued that the same post-glacial horizontal NW-WNW comression now wrenching Scandanavia at depth (and thrusting shallow levels) is perpendicular to both the current spreading ridge in the north Atlantic and the subduction zone south of the Alps and is active throughout much of the continental crust of western Europe (Klein & Barr 1986). Similar kinematics appear to have been operating since about 38 or 58(+- 2)Ma ago when the northwards propagating Atlantic rift separated Greenland from Eurasia (Talbot & Slunga, in prep.).

'The correlations among earthquake magnitude and surface rupture length and displacement are well known' (Bonilla and others 1984). Inserting the lengths and scarp heights (as a measure of vertical displacement) of the (160km long 12m high) Pärvie, the (40km long and 22m high) Lansjärv, and the (50km long 30m high) Laino-Suijavaara fault scarps into figure 3 of Bonilla and others 1984 (see Fig. 15b) shows these ruptures to have similar dimensions to others known to have occured during major earthquakes elswhere in the world. Inserting the lengths of these scarps in graphs published by Bonilla and others 1986 relating surface rupture lengths to magnitude for all earthquakes (their fig 1a- see Fig. 15c here), for reverse and reverse oblique earthquakes(fig. 1b), and for plate interior earthquakes (fig. 1i) all indicate that at least three major earthquakes (with Ms between 7.2 and 8.2) occurred in sequence near the retreating ice front between about 8-9000 years ago in Sweden alone. Two others of similar magnitude presumably accompanied the formation of the Rautuskylä and Finmarksvidda in adjoining Finland and Norway.

The spectacular faults and landslides which moved immediately after the ice front receeded from any particular area can be attributed to the comparatively sudden release of stored plate tectonic forces. The long-term rate of straining of the Baltic shield could have been retarded by lateral compression induced by glacial downbending. The melting of the ice released both the elastic stresses temporarily restrained- and large quantities of water which could dramatically raise both the water table and the hydrostatic pressure in the rock mass. The immediate post-glacial burst of tectonic activity was demonstrably shortlived and probably represented the release of accumulated stresses which would otherwise have dissipated far more slowly continuously during the preceeding Quaternary ice ages. Whether the long-term rate of strain has been resumed requires the monitoring of any small earthquakes or ductile strains (and slow, aseismic earthquakes) by seismic and geodetic monitoring.

8 SUGGESTIONS FOR FURTHER WORK

Geophysical data already in hand (both air and ground) could probably be used to check some of the interpretations made here (eg. some of the shallow decollements?, some of the dipping faults? etc.).

Figure 16 is a cartoon illustrating some of the structures which may be expected in northern Sweden as a result of the deep NW directed transpression interpreted here. Many of these structures had already been recognised and others have been identified in this work. The remainder may yet turn up as a result of renewed systematic study of air photos, geophysical maps or detailed relief maps if they are actively sought.

An attempt should be made to use such data sets to recognise and map the Jericho syndrome and possible contemporaneous sub-aqueous soil flows below the highest marine shoreline. A map of the highest marine shoreline, the contemporaneous ice front and the Jericho syndrome together with the fault scarps and landslides would be revealing.

Ground observations and analyses of the structures should be extended.

9 ACKNOWLEDGMENTS

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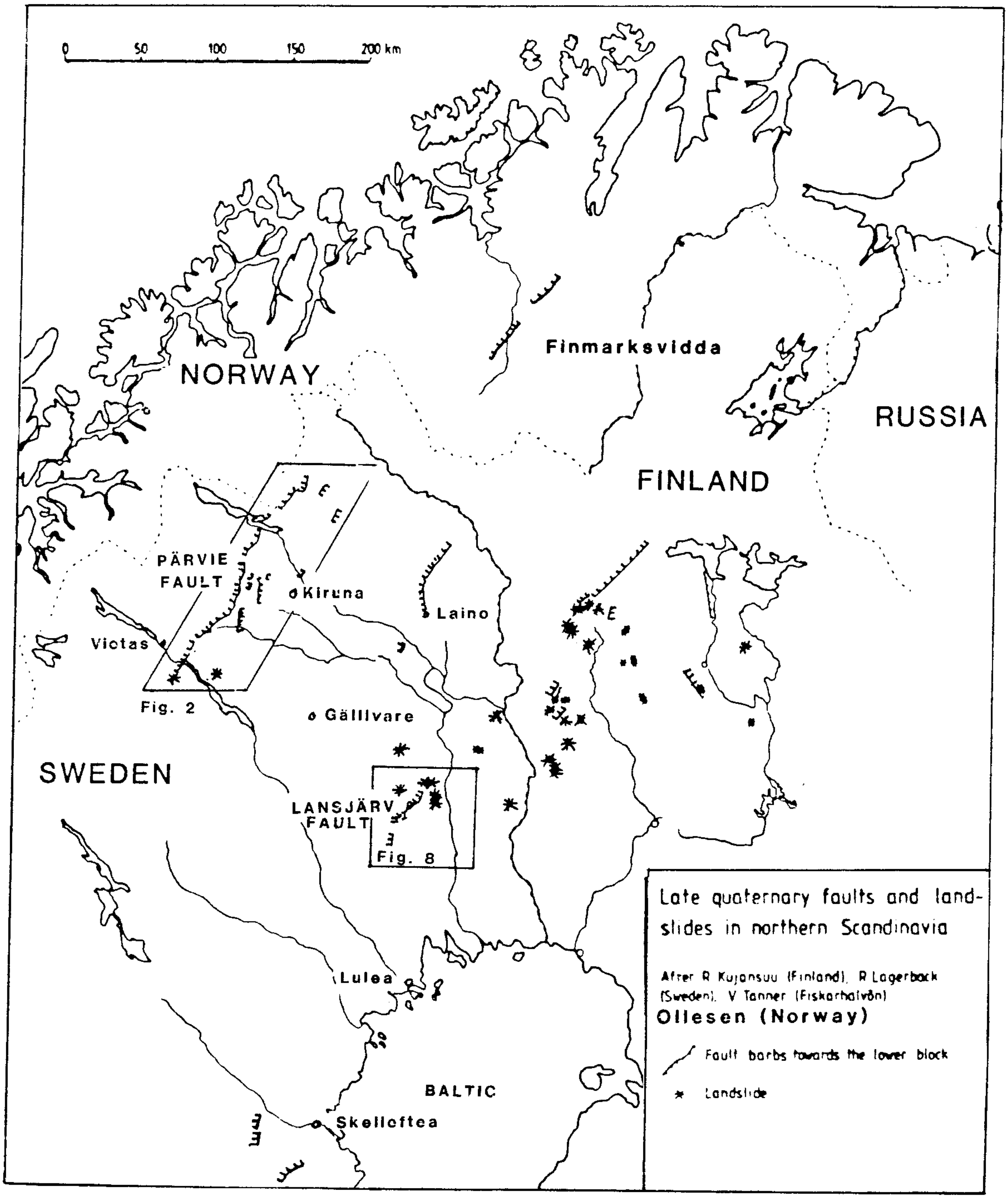


Figure 1: Post-glacial fault scarps (lines with ticks on foot walls) and landslides (stars) in northern Scandinavia after Kujansuu 1964 (Finland), Lagerbäck 1979 (Sweden) & Ollesen 1984 (Norway). The areas shown on Figures 2 & 8 are outlined. The insert shows geological contacts irrespective of age in Northern Sweden.

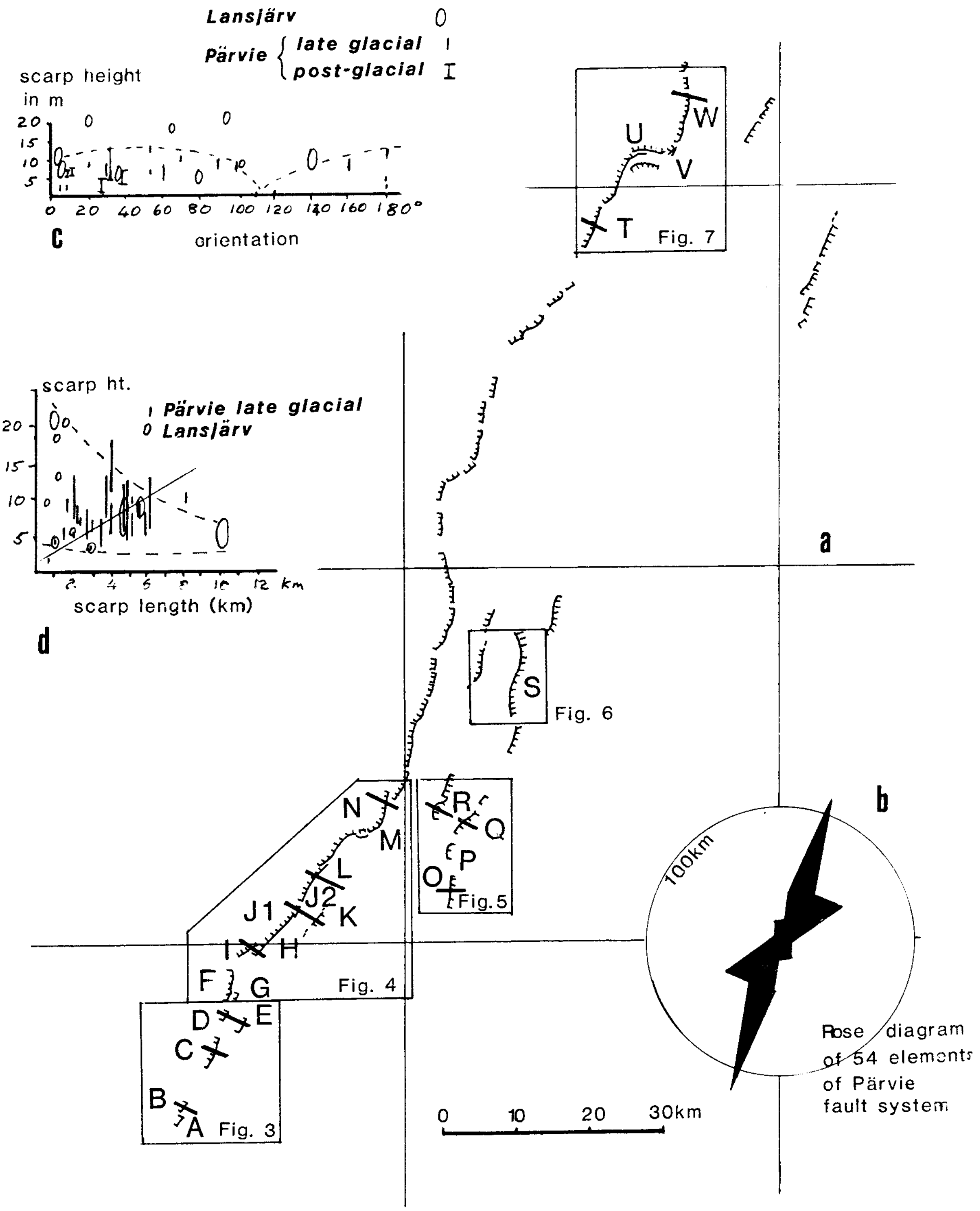


Figure 2: *a. The traces of post glacial fault scarps along Pärvie fault system in Sweden, ticks on the lower side of all scarps (see Fig. 1 for location).*
b. Rose diagram of trends of the 54 elements of the Pärvie fault system.
c. Height of the fault scarps along both the Pärvie and Lansjärv fault systems plotted against their orientation from north.
d. Scarp height plotted against length for both Pärvie and Lansjärv fault systems. Only those scarps described by Lagerbäck and Witschard 1983 having late- (as opposed to only post-) glacial increments are shown for the Pärvie fault.

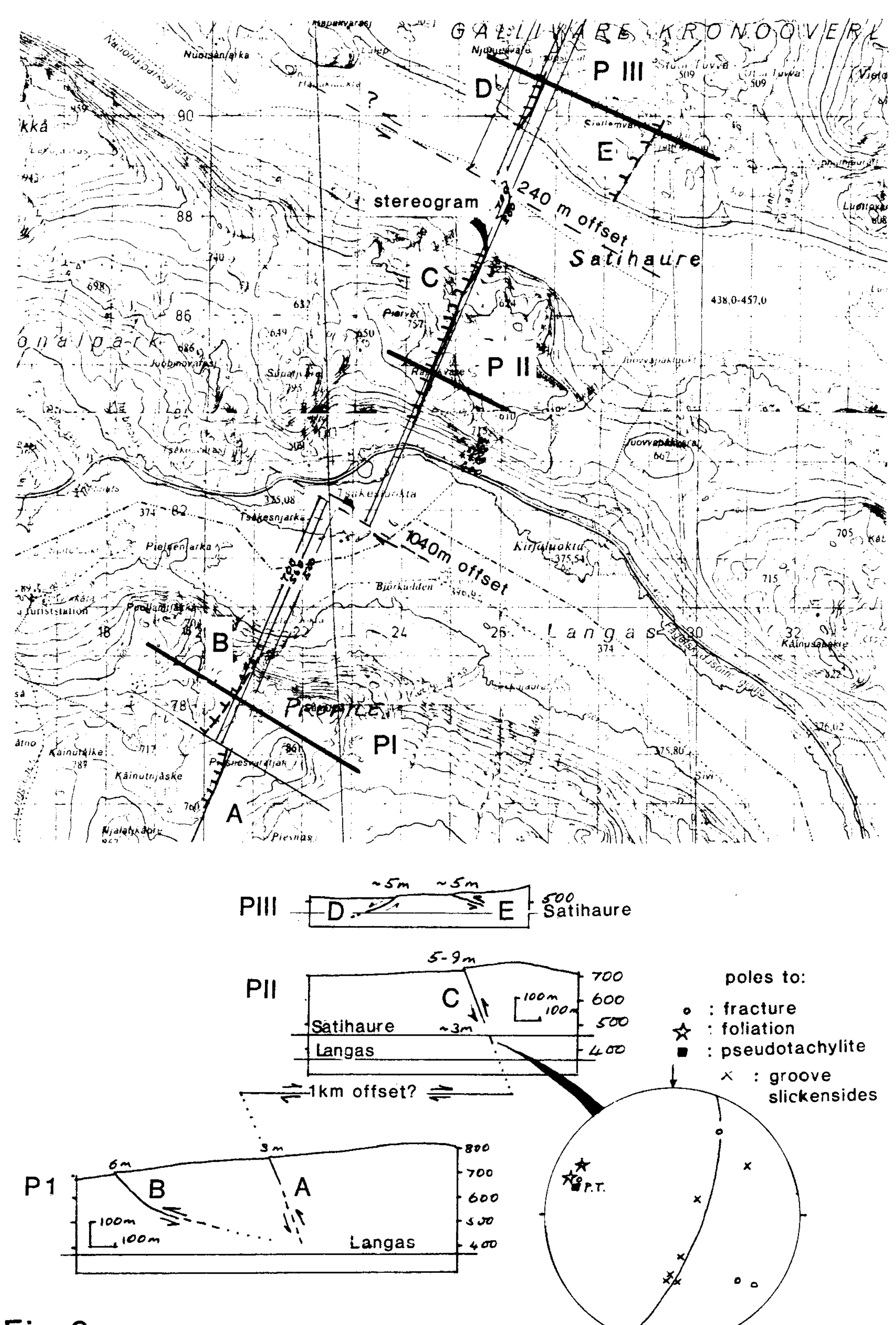
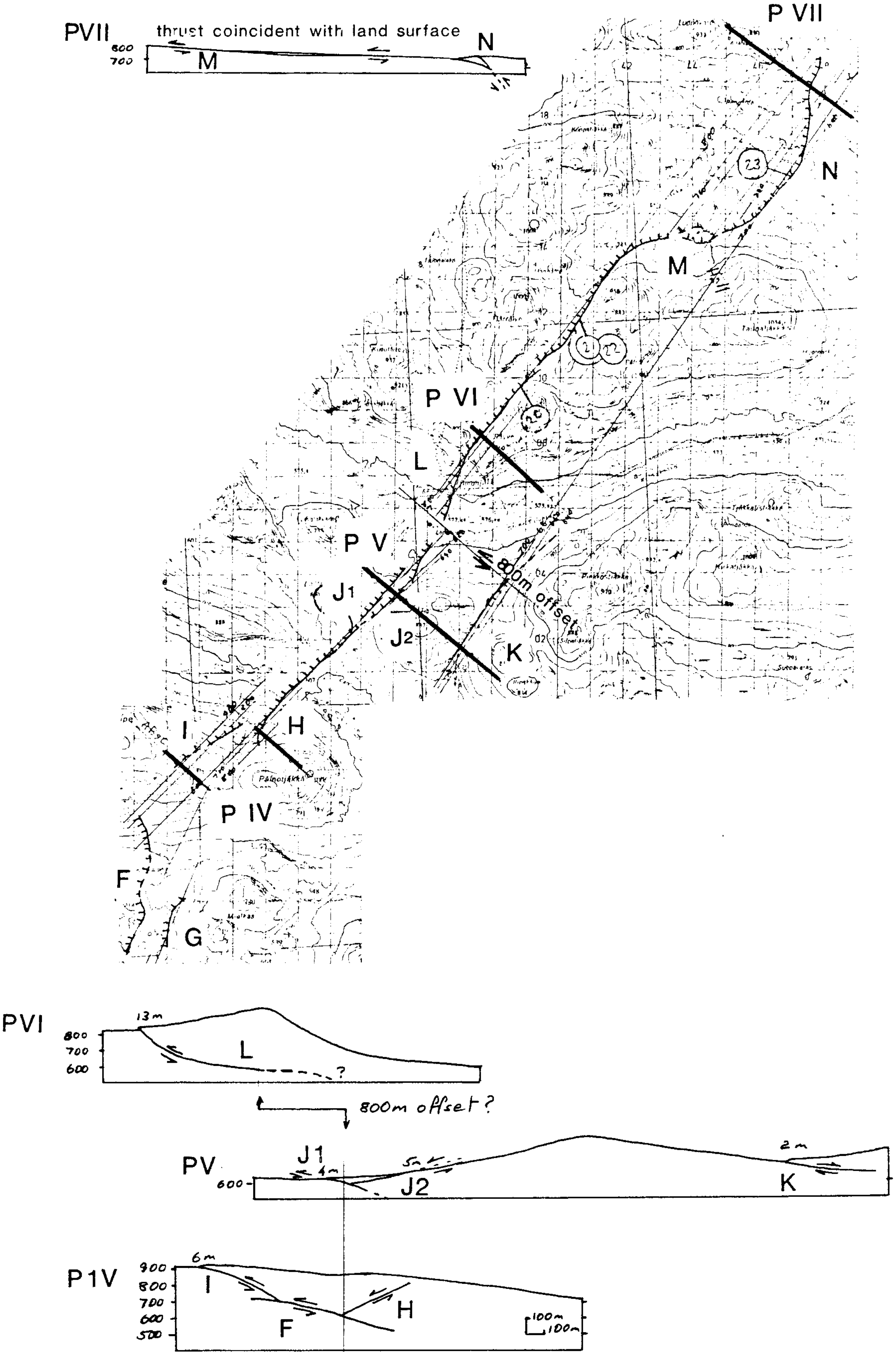


Fig 3.

Figures 3 to 7. Maps of those parts of the Pärvie fault system identified on Figure 2 showing strike line constructions for scarp sectors A—W and locations of profiles P1—X1 which are drawn with equal horizontal and vertical scales. All the stereograms are presented here on lower-hemisphere equal-area projections refered to magnetic North. The small amounts of data on most stereonets represents the brief time spent at the outcrop but in other cases is the result of small exposures, or few fractures and a large block volume in large expanses of the Precambrian migmatites, gneissose granitoids or metabasic rocks.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PVI
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800m offset?
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Fig. 4

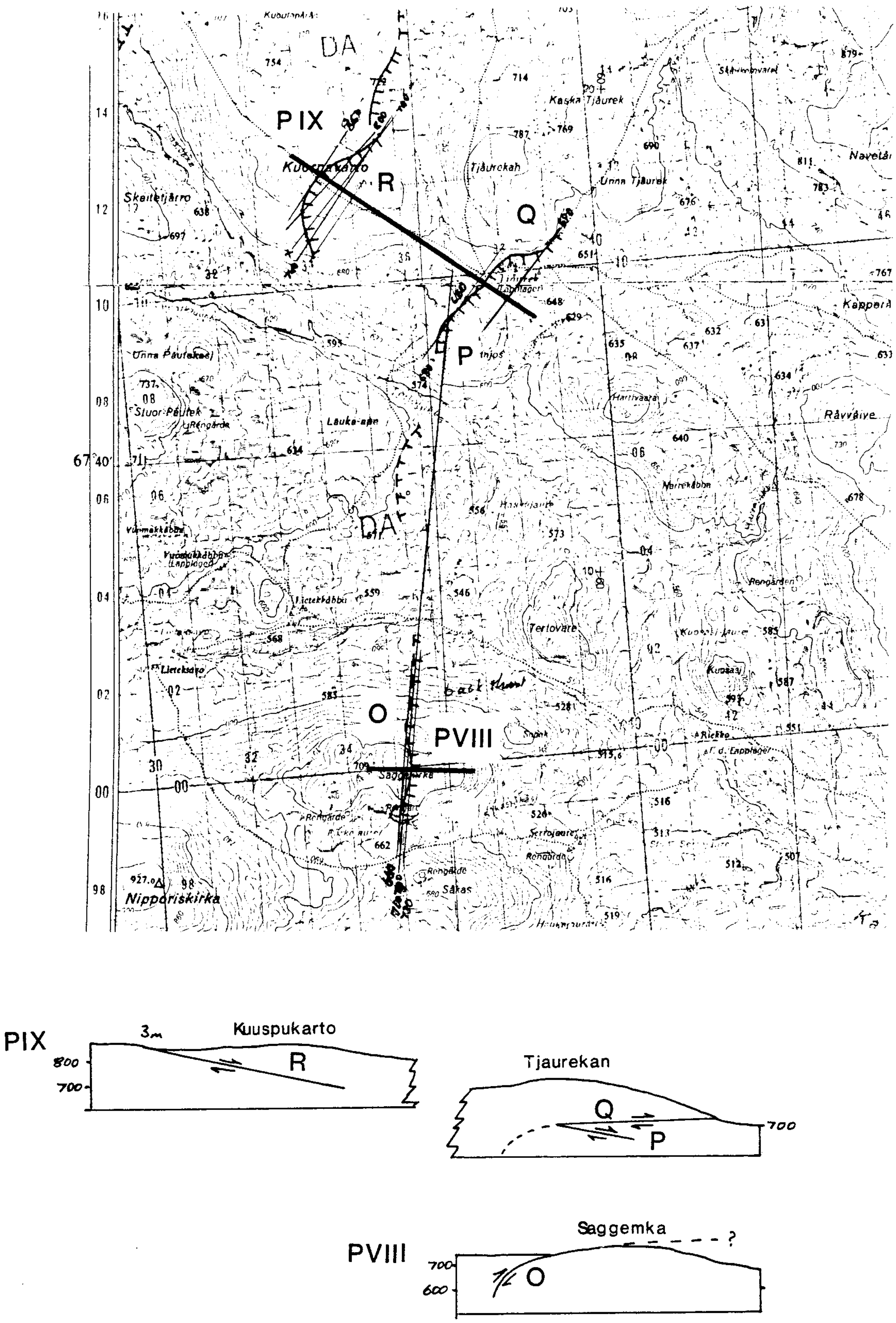
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Fig. 5

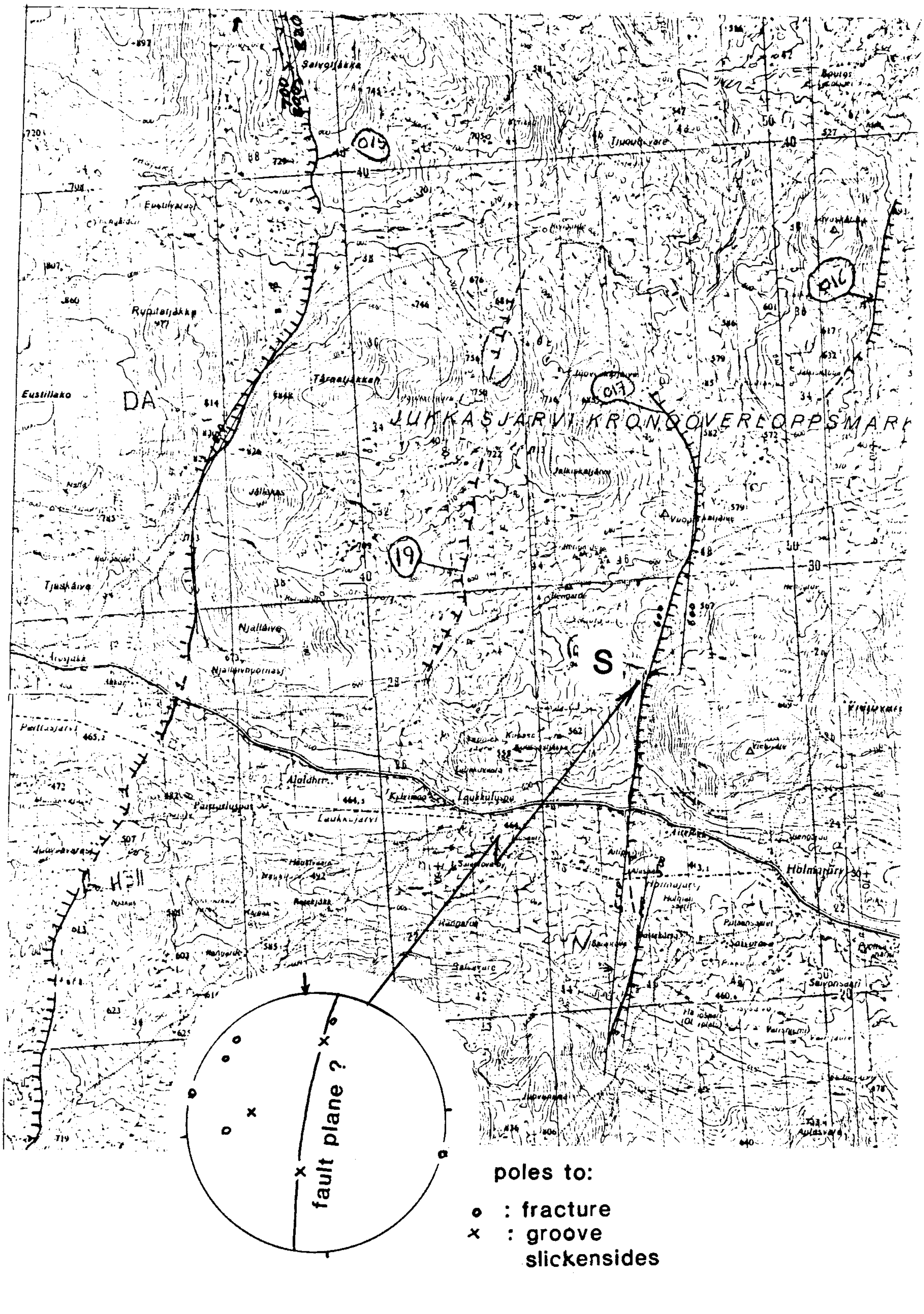
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Fig.6

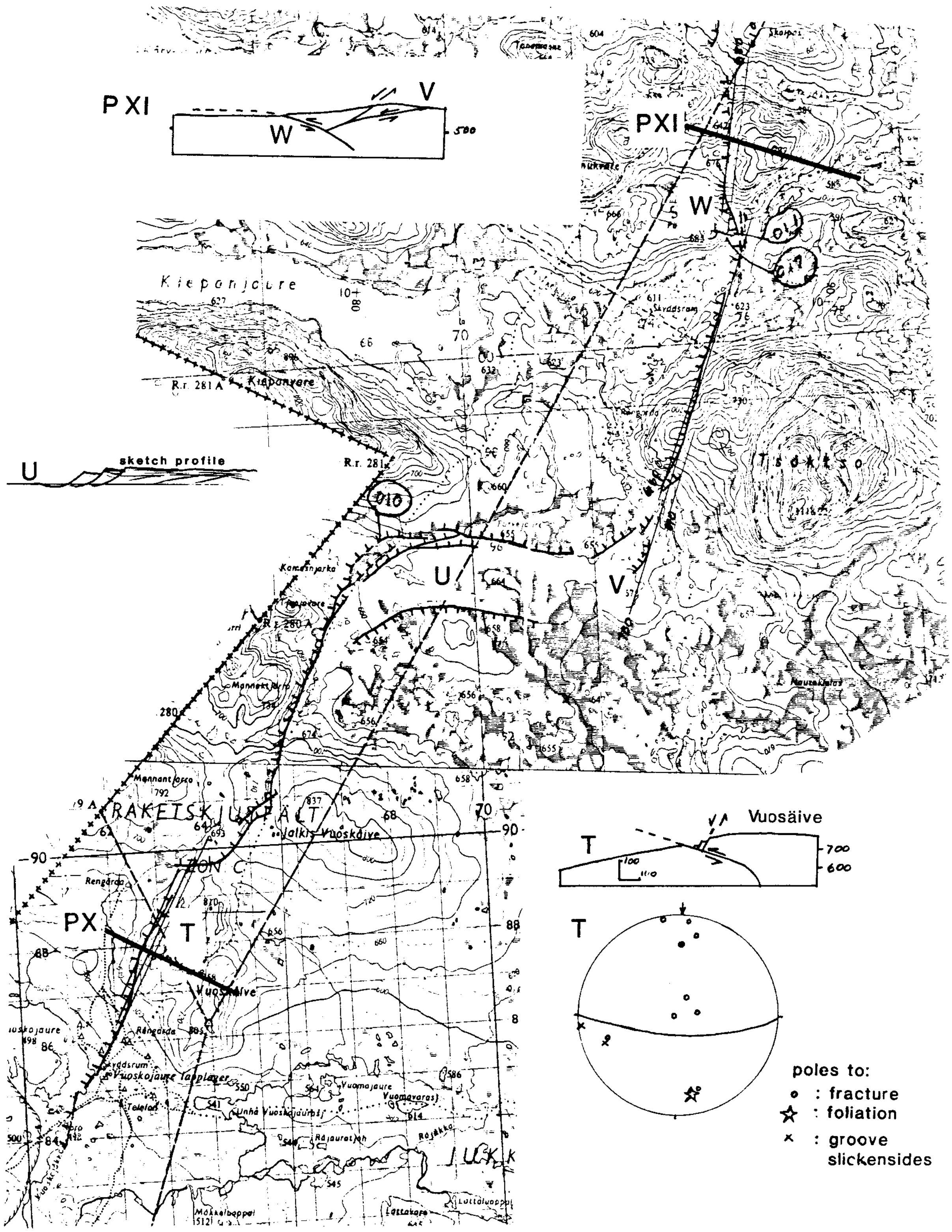
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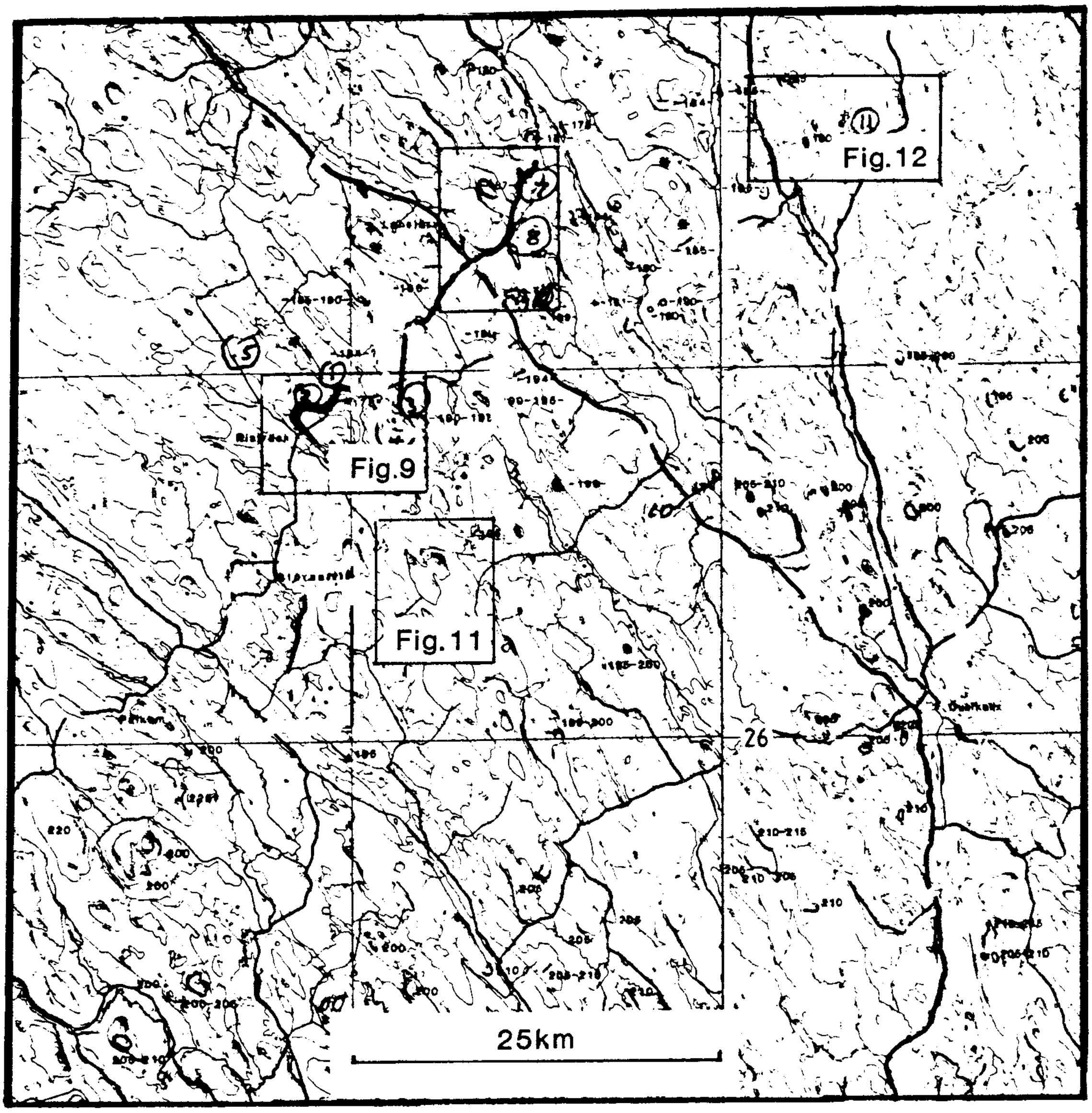
Fig. 7



Faults, landslides and shorelines in the Lansjärv region.
Fault • landslide ◦ landslide, less certain 210 shoreline level

Figure 8: *Map of the post-glacial scarps along the Lansjärv fault system in Sweden showing locations of Figures 9—12. See Figure 1 for the location of this area.*

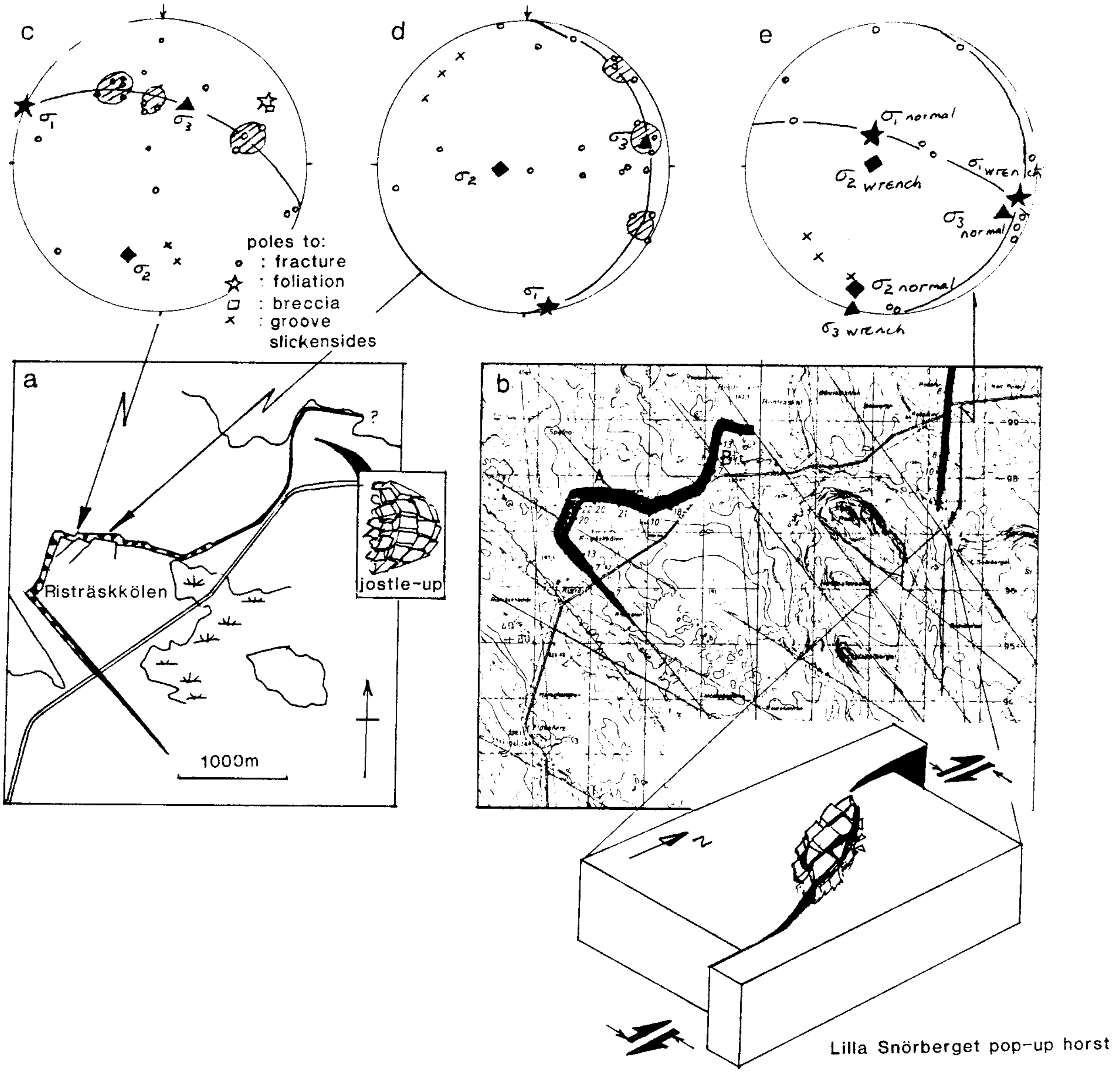


Figure 9: *Structures in and near the Risträskkölen plateau*

a. Tracing of the scarp from an air photo. Insert shows a cartoon of a jostle-up NE of the plateau.

b. Map of the plateau and its surroundings with topgraphic lineaments added (grid defines km squares). Insert illustrates schematically the relationship of two post-glacial pop-up horsts where a NS geophysical lineament is offset south of a East facing NS trading (oblique-slip?) scarp.

c—e. Sterograms showing structural data collected in the bedrock exposures indicated. Oblique ruling indicates clusters of poles to conjugate fractures used to interpret the fracturing stress field. In each sterogram sigma 1 is black star, sigma 2 is a black diamond, and sigma 3 a black triangle. Two stress fields are interpreted in stereogram e; these resulted in wrench and normal faults.

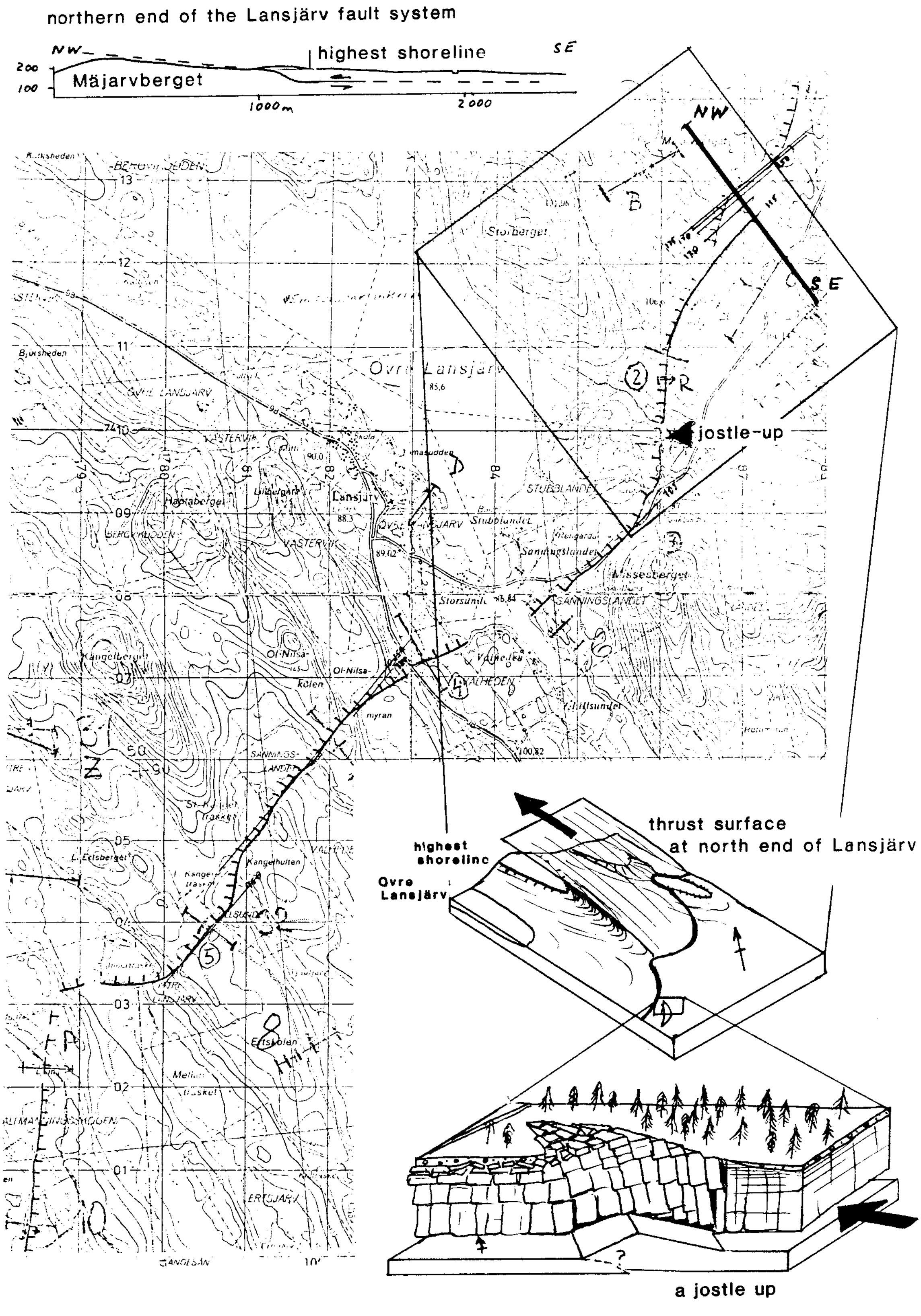


Figure 10: Map of part of the Lansjärv fault system and a profile constructed using strike lines near its northern end (see Fig. 8 for location).
Top insert is a schematic block diagram of the area outlined. Lower insert indicates how a particular exposure of fractured bedrock might have been jostled through the glacial soils by thrusting over an asymmetric irregularity on the underlying decollement.

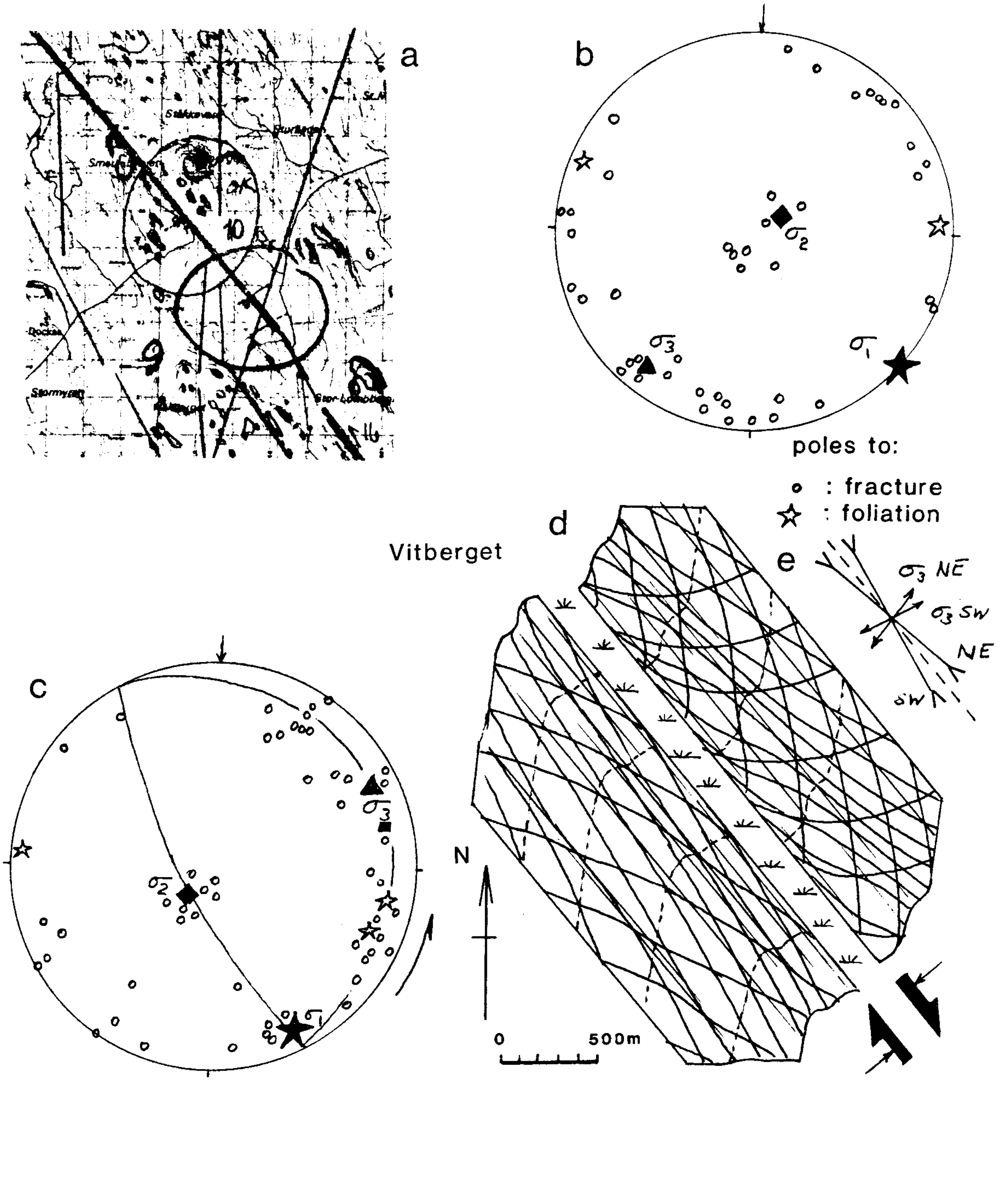


Figure 11: *a. The NW lineament defining the SW edge of Risträskkölen between Vitberget and Smedeberget 14 km to the SW (see Fig. 8 foe location). Outdrops visited are infilled.*
b&c are stereograms showing the orientations of the structural elements in the NE and SW blocks respectively. Stress fields interpreted independantly for each block are indicated by black stars (= sigma 1), black diamonds (= sigma 2) and black triangles (= sigma 3).
d. Schematic map indicating qualitative structural relations in each block. Notice that old fractures (continuous lines) have been distorted by ductile dextral transpression along subsidiary shear zones as well as the obvious topographic (and geophysical) lineament marked by a marsh.
e. the orientations of the stress fields in each of the two blocks is related to that of the lineament itself.

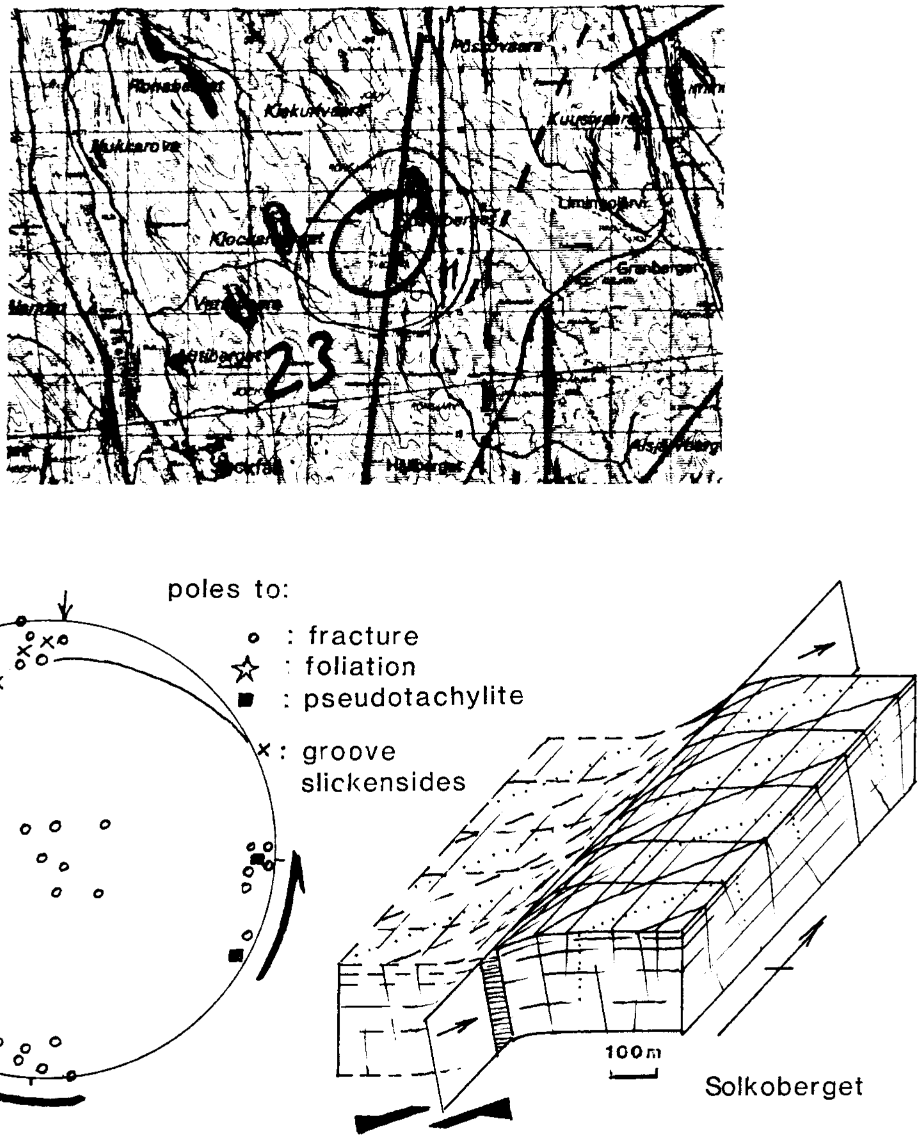


Figure 12: Structures on the eastern side of a NS lineament at Solkoberget (see Fig. 8 for location). Block diagram illustrates schematically oblique slip along a late brittle fault superposed on an earlier sinistral ductile shear zone which had in turn distorted a still older cubic fracture fabric (solid lines) and a penetrative foliation (dotted). The western block is beneath a marsh; its illustration is an extrapolation from exposures to the east.

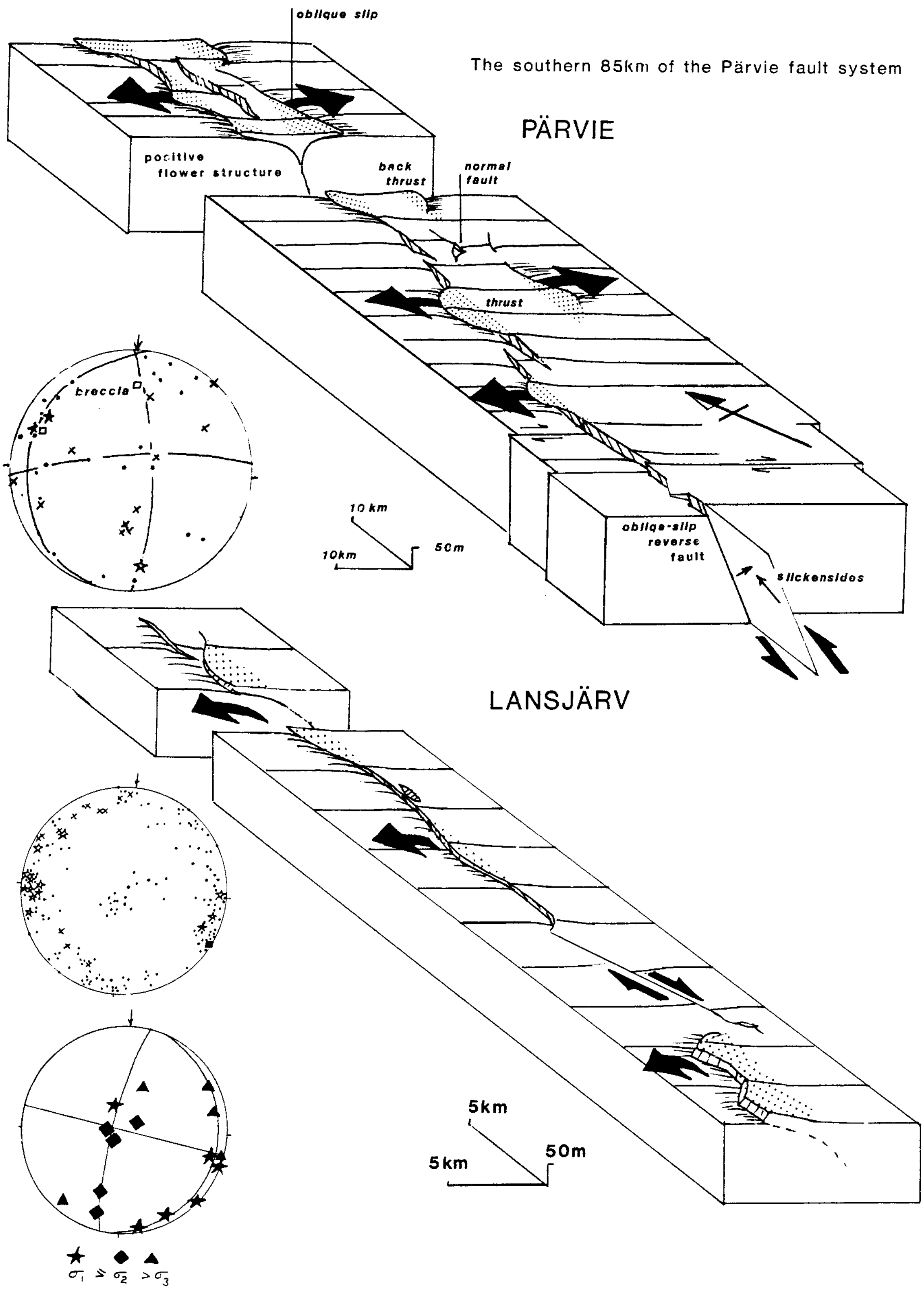


Figure 13: *a. A schematic block diagram of the southernmost 85 km of the 160 km long Pärvie fault system in northern Sweden. The post-glacial displacements along local thrust and back-thrust flakes or nappes (stippled) integrate on a regional scale into a positive flower structure rooted in en-echelon steep oblique-slip reverse faults. The regional picture is of transpression along a subhorizontal WNW shortening axis with surficial relief by thrusting.*
b. Compound stereogram of data along the Pärvie fault system emphasising how little field data is available (key as in Fig. 12).
c. A schematic block diagram of the Lansjärv fault system.
d. Compound stereogram of field data along the Lansjärv fault system (minus the Risträskkölen plateau) showing similarities to data available from the Pärvie system.
e. Principal stresses determined from various short segments of the Lansjärv fault system shown together to emphasis that thrust, wrench and normal fault regimes operated in different segments.

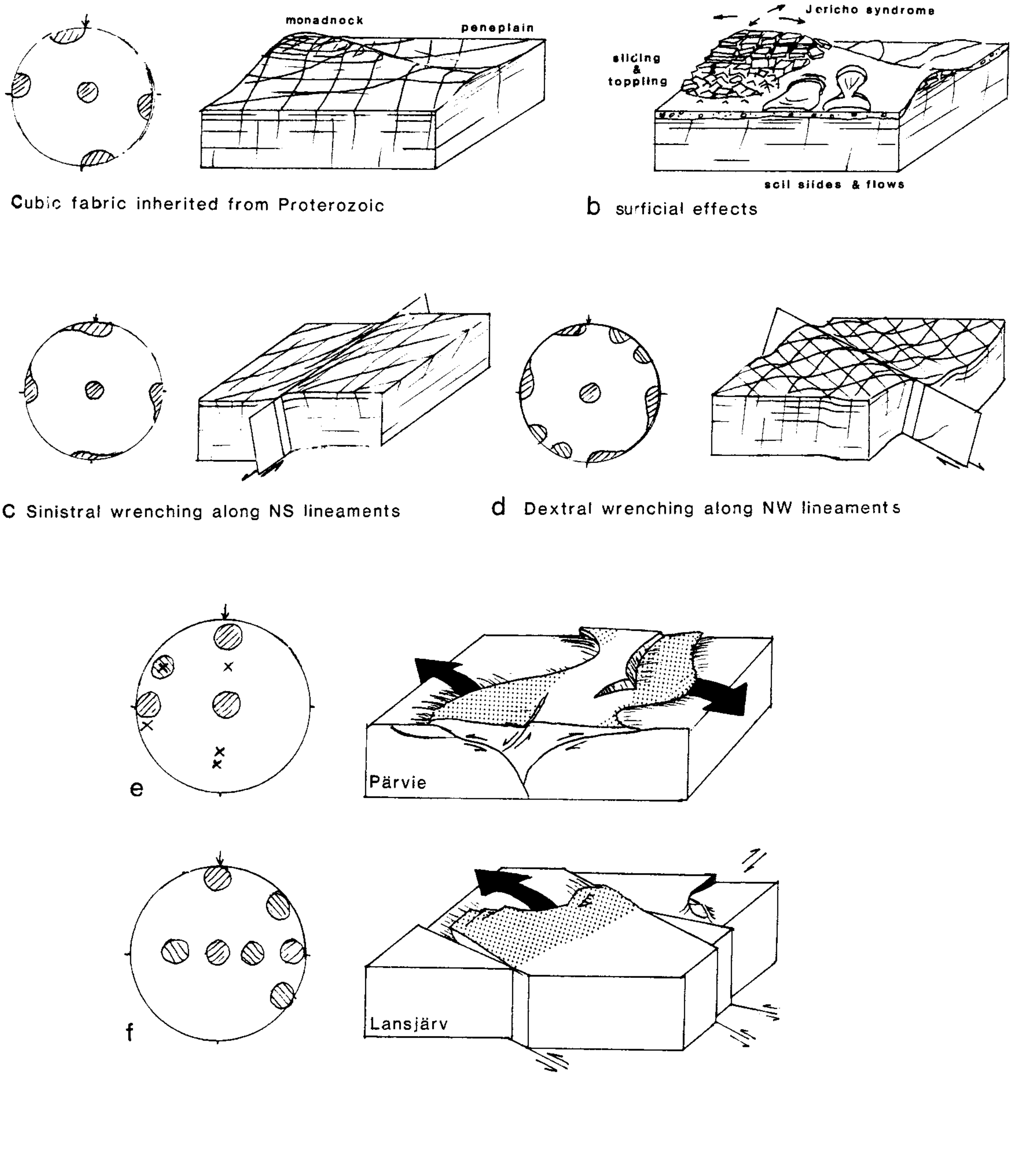


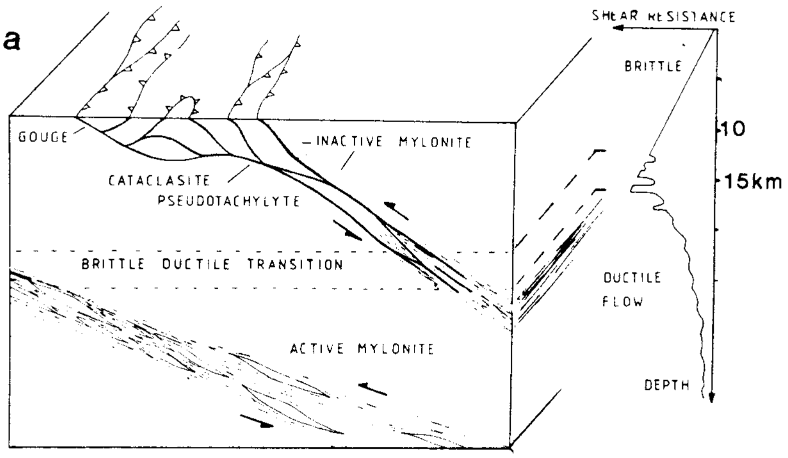
Figure 14: *Cartoons to illustrate how the post-glacial tectonics exploited a Proterozoic cubic fabric in the bedrock.*

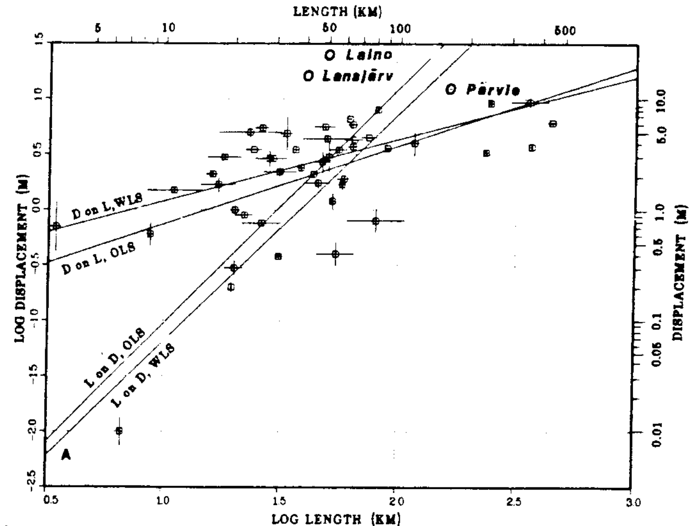
a. The inherited fracture fabric and its relation to the topography. (Clusters of poles to old joint sets are shown by oblique down-to-the-left ruling on all the stereograms).

b. Immediately post-glacial rock and soil slides and the Jericho syndrome (recording the surficial effects of ground shake?).

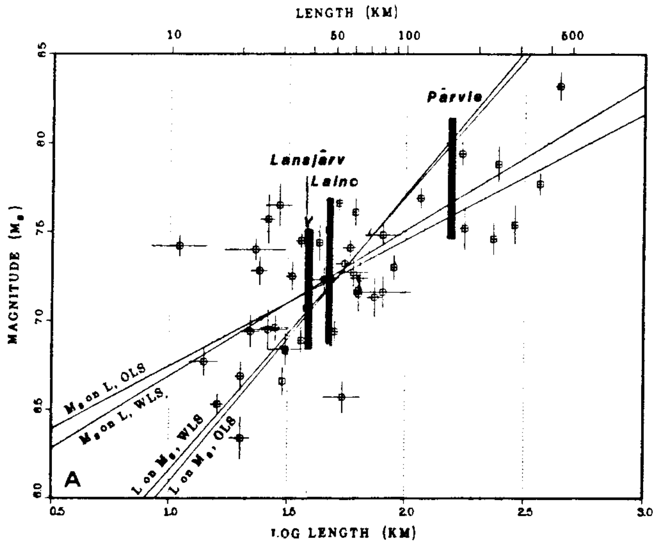
c and d record how deeper tectonics modified the inherited fabric and (in c) generated new fracture sets (oblique down-to-the-right ruling).

e&f. The positive flower structure along the Pärvie system is illustrated on a larger scale than the thrust flake at Risträskkölen along the Lansjärv fault system.





b Maximum fault displacement at the surface versus length of surface rupture, with regression lines for various fault groups. *D* on *L*, regression of log displacement on log length; *L* on *D*, regression of log length on log displacement; OLS, ordinary least squares; WLS, weighted least squares. Error bars are shown for each event. (A) All faults.



c Length of surface rupture versus surface-wave magnitude, with regression lines for various fault groups. M_S on *L*, regression of magnitude on log length; *L* on M_S, regression of log length on magnitude; OLS, ordinary least squares; WLS, weighted least squares. Error bars are shown for each event. (A) All faults.

Figure 15: *a. Schematic distribution and geometry of fault rocks along a constrictional shear zone, and, to right, plot of shear resistance against depth which could also be a plot of the frequencies of small earthquakes with depth in Sweden (after Passchier 1986).*
b. Scarp lengths plotted against scarp height (as a measure of vertical displacement) for the three major fault systems known in northern Sweden compared with similar data known to be due to major earthquakes elsewhere in the world (after Bonilla and others 1984, fig. 3).
c. Scarp lengths for the Swedish fault systems suggest that they were associated with earthquakes with M_S between 7.2 and 8.2.

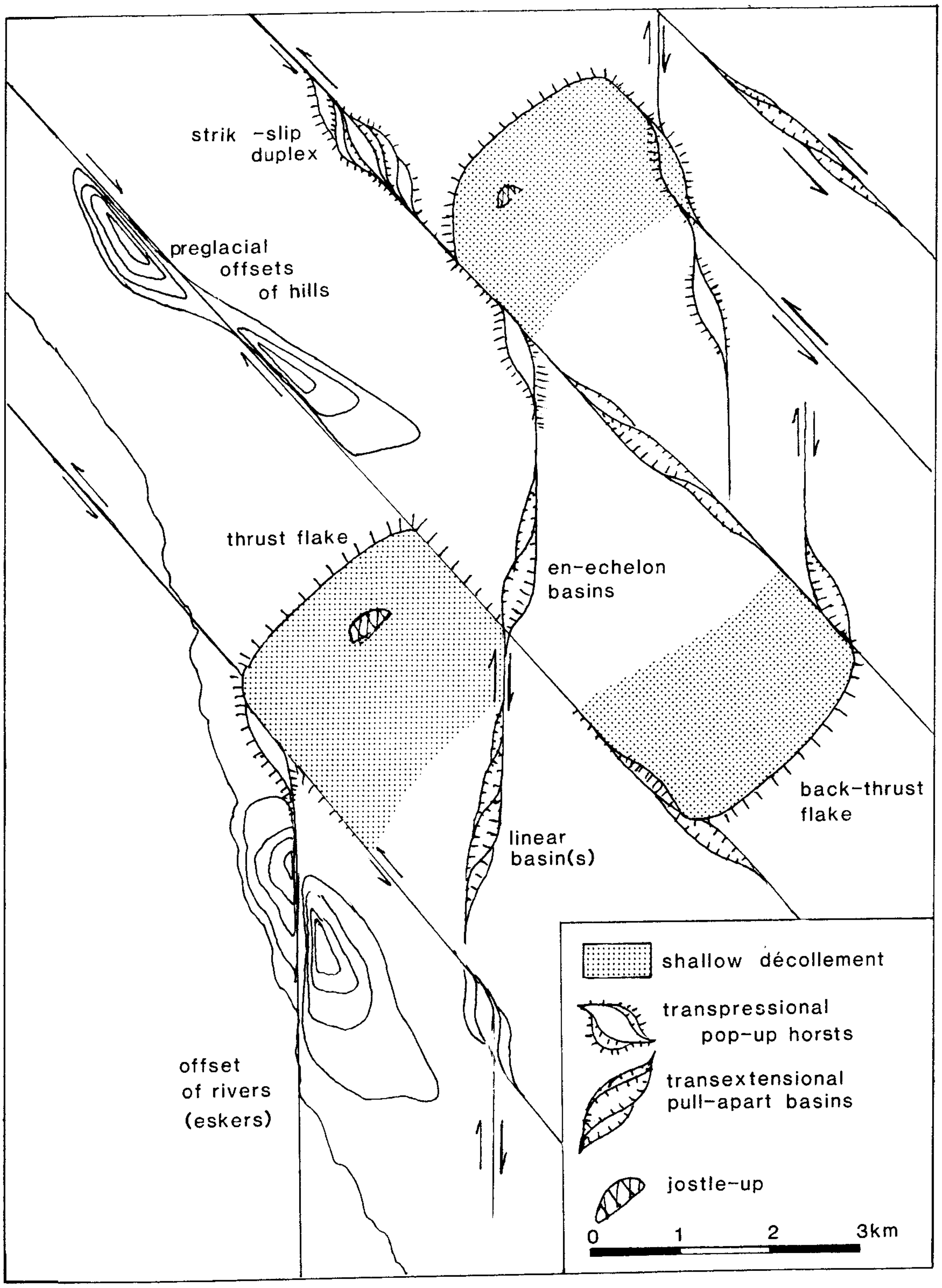


Figure 16: Speculative cartoon illustrating those structures which might be expected in a deep transpressive wrench regime with a shallow destressing zone. The scale indicated is only approximate. Many, but by no means all these potential structures have already been identified. The remainder may yet be recognised if they are actively.
Transpressive pop-up horsts (of shallow or bare bedrock) and transextensive pull-apart basins (infilled by lakes or marsh?) en-echelon along NS and NW wrench faults are particularly important as they could be dateable and should be recogniseable on air photos and/or geophysics.
Thrust flakes above shallow décollements are expected to have distinctive (broken or furrowed) topography with local jostle-ups. Geophysically such broken flakes can be expected to have generally low magnetics and seismic velocities and high electrical conductivity. The depth to décollement should be discernable by seismic refraction and ground radar traverses would be interesting.
The degree of displacement along such wrenches is unknown. The monadnocks may be about 900 Ma old and displacements as old may be tens or more km. Post glacial displacements are likely to be only tens of metres- and may have an opposite sense.

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B Allard
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D Kirk Nordstrom
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Trygve Eriksen
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Hilbert Christensen
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Erling Bjergbakke
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Börje Torstenfelt
Department of Neclear Chemistry, Chalmers University of Technology, Göteborg
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Department of water in environment and society, Linköping university, Linköping
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