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European Stress: Contributions from Borehole Breakouts [and Discussion]

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European stress: contributions from borehole breakouts

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Before about 1986 European measurements of rock stresses were sparse. The development of the borehole breakout method has facilitated a dramatic increase in the geographical distribution of rock stress orientations. These are derived from data collected routinely for other purposes by the oil, coal and gas industries over many years. Borehole breakouts can be interpreted in terms of the orientation of the stress field in boreholes as a function of depth, with the findings related to known stratigraphical boundaries, tectonic structures, fault and fracture occurrences, and to other geological and geophysical stress indicators. Geographical and depth distributions of stress on local and regional scales are beginning to provide the necessary base from which broad interpretive stress field models can be constructed.

1. Introduction

A growing awareness of the importance or rock stress measurements to the understanding of broad tectonic and deep geological processes has led to an increased effort of collating and analysing stress data throughout Europe. Until the mid-1980s the number of rock stress determinations was small and relied primarily on earthquake focal mechanisms or on relatively few near surface (less than 50 m) measurements. There is still a great paucity of data but, more importantly, our understanding of the geological origins of rock stress and of the interplay between stress, structure, tectonic evolution and other geological attributes on a variety of scales remains limited. One of the advantages of incorporating European rock stress determinations into a coordinated database is that subsequent regional and local stress maps, and the interpretations based upon them, will be subject to the rigours of the wider quality control procedure established for the World Stress Map.

Studies in recent years have demonstrated that borehole breakouts can be used as a reliable indicator of the orientation of principal horizontal *in situ* rock stresses (Zoback *et al.* 1989). The advent of stress measurements from breakouts and the ready availability of primary data from existing boreholes has permitted a rapid expansion of the European Stress Map database from which both regional and local stress fields can be derived.

For much of northwestern Europe there prevails a broadly consistent NW–SE maximum compressive stress orientation ($\sigma_{\mathrm{H,max}}$) from the Alps to northern Britain. This arises from plate movements and can be attributed to forces associated with the interaction between stress fields created by the east to southeasterly separation of Europe from North America and the north to northeasterly movement between the African plate and Europe.

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On a more pragmatic level, the energy industries are beginning to acknowledge the importance of stress field information as an aid to maximizing the economic development and exploitation of hydrocarbon, coal and geothermal resources. Low permeability, or 'tight', gas- and oil-bearing formations often require massive hydraulic fracture treatments to achieve economic rates of production. Hydraulically induced fractures will preferentially propagate in a direction parallel to the maximum stress orientation. In general, it is disadvantageous for zones of induced fracturing between adjacent wells to interfere with one another and thereby provide hydraulic short circuits. Local stress field information will allow optimum well field arrays to be designed to avoid this potential problem. On the other hand, stress field information will allow the prediction of whether off-target wells can be connected to a reservoir by fracturing or will enable the optimum location of relief wells to be drilled in blowout situations (Bell & Babcock 1986).

Hot dry rock geothermal energy depends upon the concept that water circulated between a couplet of boreholes will exchange heat with the rock and provide steam for electricity generation (Downing & Gray 1986). In this case, the water needs an efficient transmission path between the boreholes, usually provided by fracturing. A knowledge of the local stress field is required to predict the extent and direction of the induced fractures so that the borehole couplet can be properly oriented.

Rock stress orientations can have a significant influence on the economics of mining. Jackson *et al.* (1989) have shown that rectangular section coal mine roadways driven within 30° of the minimum horizontal stress direction can suffer marked deformation and support problems. Roadways at right angles to the minimum stress direction stood up well. Gale & Blackwood (1987) had arrived at comparable results after a series of three-dimensional analyses to determine stress distributions around a mine face when the roadway intersects the *in situ* stress field at different angles. Other large underground excavations such as electricity generator turbine halls and radioactive waste disposal facilities also require a comprehensive knowledge of the local stress field, preferably including relative stress magnitudes to allow the estimation of the likelihood of fault reactivation.

These examples of the scientific and commercial applicability of rock stress derivations serve to emphasize the importance of collating available data in the European Stress Map.

2. Scales of measurement

A complete characterization of the state of stress in a rock mass requires a three-dimensional description of both the stress orientation and stress magnitude. There is, however, no absolute method of measuring *in situ* rock stress against which other methods can be calibrated. This is in part because of the differences in scale over which the various measurement methods apply and the interplay between the forces at work within a rock mass; from the intergranular scale, through layered sediments, jointed blocks, plutons, major faults, and plates at the continental scale. Hyett (1990) visualized the state of stress in a rock mass as being assembled from self-equilibrating elements, stored within equilibrium volumes, superposed on one another over the complete spectrum of geological scales. Far-field stresses will be represented by an integration of all the near-field components. For fractured rock masses, the dimensions of the equilibrium volumes are controlled by fracture geometry; length, spacing, frequency of intersection, etc. In general, only that component of the residual stress, stored within equilibrium volumes greater than that of the measurement scale, will be sampled. When a rock mass is divided into units smaller than the equilibrium volume, part of that stress may be released. This may result in the determination of different stress tensors at different scales of measurement.

Stress measurement methods which work on hand-size samples, such as differential strain analysis, anelastic strain recovery or overcoring, will primarily relate to the intergranular and microfracturing scale. Earthquake focal mechanisms on the other hand, apply to scales of hundreds of metres to kilometres. Borehole methods, such as breakouts and hydrofracturing, are influenced by stresses stored on the more geologically representative layered scale and enable measurements from the near surface to depths of several kilometres.

Because of the influence of scale upon results derived from the various stress measurement methods, it is important to not only record a full range of results in databases such as the European Stress Map, but also to exercise caution when interpreting the data in geological terms. The scale of the interpretation, whether it be local, regional or continental, should take account of the scale of the measurements used to influence that interpretation.

3. Regional stress fields

The European subset of the World Stress Map database contains close to 1500 entries (Müller *et al.* 1991). These data are classified, according to reliability as tectonic stress indicators, into quality categories A to E, where A to C are regarded as very reliable. The database contains previously existing compilations including the Fennoscandian Rock Stress Database (Stephansson *et al.* 1986), the Catalogue of Focal Mechanisms for European Earthquakes (Udias *et al.* 1989) and other, previously unpublished listings. The majority of the data (59%) are from focal mechanisms, followed by overcoring measurements (19%), borehole breakouts (14%), hydraulic fracturing (5%), and fault slip orientations, which fall under the category of geological stress indicators (3%).

The geographical and depth distributions of the data are variable: focal mechanisms concentrate in seismogenic zones and occur mostly at depths greater than 5 km; borehole breakout and hydraulic fracturing data are, as a rule, from sedimentary basins usually to depths less than 5 km. Overcoring and fault-slip data are the shallowest, with the exception of some measurements taken in tunnels and mines. Although these stress indicators monitor different scales of stress, in places where it is possible to make comparisons Müller *et al.* (1991) showed that significant differences in the orientations of horizontal stresses are not apparent.

From the data coverage displayed in figure 1, Europe can be subdivided into three major stress provinces.

1. Western Europe, broadly covering an area between 45° N to 55° N and 10° W to 17° E. The stress orientation is generally very uniform with a mean of 145±26°. This homogeneous stress field is coincident with a thin to medium lithospheric thickness (50–90 km) and a medium to high heat flow (greater than 80 mW m^{-2}). A comparison of the observed horizontal stress directions with the trajectories of plate motion (Minster & Jordan 1978) indicates differences of about 17° compared with the absolute plate motion and about 2° compared with the relative plate motion between Eurasia and Africa. However, these relative motions

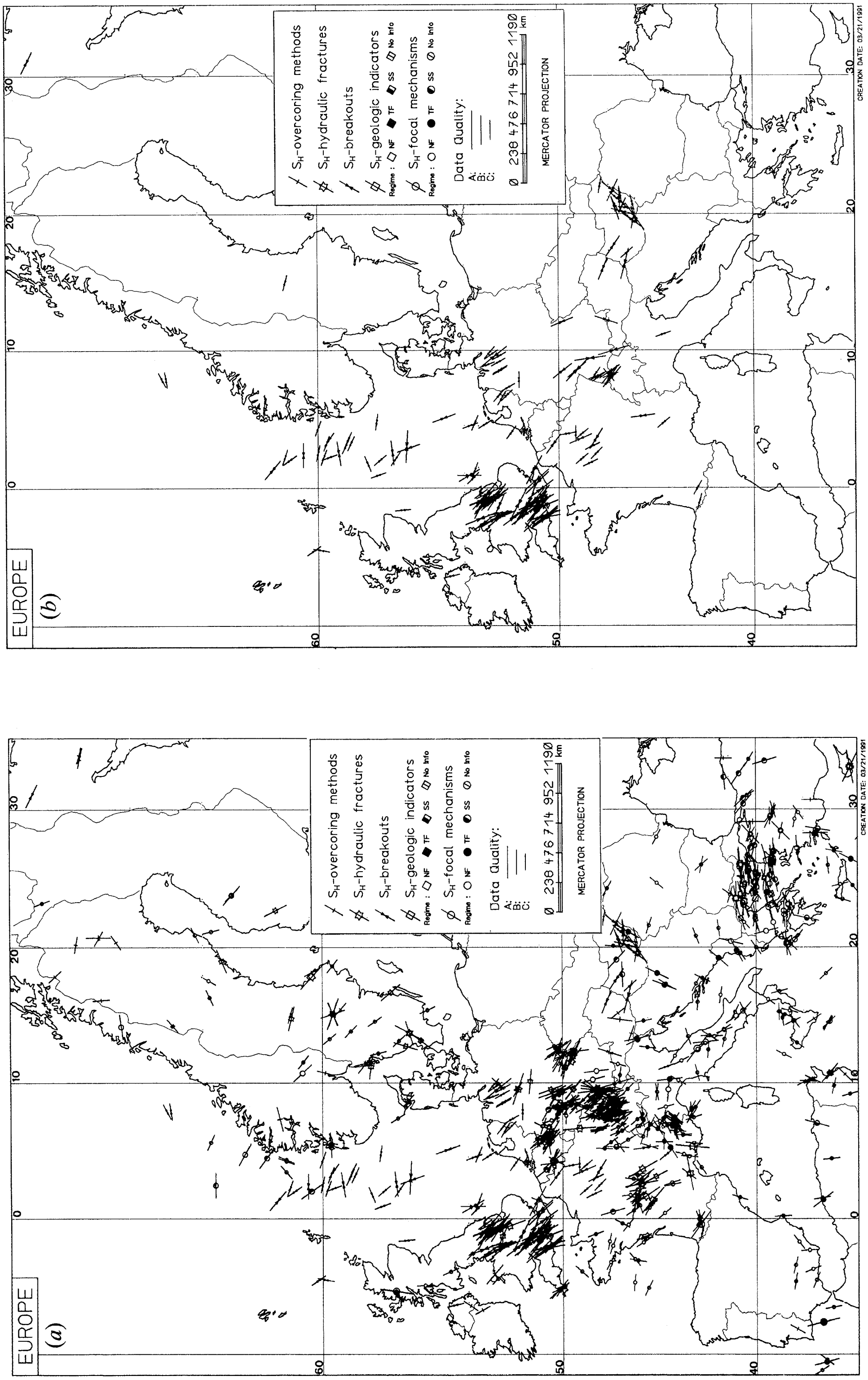

Figure 1. (*a*) European Stress Map. The symbols indicate the orientations of maximum horizontal compressive stresses for the quality categories 'A', 'B' and 'C'. The symbols represent the different types of stress indicator; longer symbols designate better qualities. (After Müller *et al.* 1991.) (*b*) All $\sigma_{H,\max}$ orientations deduced from borehole breakout observations.

depend very much upon how accurately the poles of plate motion can be determined, which is not very precise for Europe because of the very slow Eurasian plate movement.

2. Northern Europe covering latitudes greater than 55° N. The average orientation of $\sigma_{\mathrm{H,max}}$ is $120 \pm 45°$, similar to, but not as consistent as, that for western Europe. Most of the area is characterized by a thick lithosphere (110–170 km) and a relatively low heat flow (less than 50 mW m^{-2}). Modelling work by Kusznir & Bott (1977) has demonstrated a reverse relationship between stress magnitudes, lithospheric thickness and geothermal gradient: the thinner the lithosphere and the larger the thermal gradient then the greater is the stress amplification in the upper crust. Stresses are therefore expected to be lower in magnitude for a thick, cold lithosphere and subject to greater influence by local perturbations. Regional stress field influences which also need to be taken into account are: the effect of plate-boundary forces (discussed by Stephansson 1988); post-glacial uplift (Bungum *et al.* 1991) and post-glacial flexure due to sediment loading along the continental margins (Stein *et al.* 1989); and large topographical gradients. The spreading of thick crust would create tensions perpendicular to the continental margin and compressions in adjacent oceans. Similarly, deglaciation would create localized tensions and compressions elsewhere. Swolfs & Savage (1985) have demonstrated good agreement between measured stresses and analytical solutions used to assess the influence of topography (see also Liu & Zoback 1991). The superposition of these influences upon lateral plate-boundary forces being transmitted from the mid-Atlantic Ridge may account for the diversity of stress orientations observed in northern Europe.

3. The Aegean and western Anatolia are characterized by N–S extension and a $\sigma_{\mathrm{H,max}}$ orientation of $085 \pm 27°$. The tectonic setting of the eastern Mediterranean can be broadly described as a back-arc basin resulting from the northward movement of Africa relative to Eurasia. The basin is bounded by the Hellenic Trench to the west and south and by the North Anatolian fault to the north. Current lack of data prevents the easterly extrapolation of the stress field but it may well persist as far as the East Anatolian fault.

Further characteristics of the European stress field can be summarized as follows.

(*a*) The stress field is generally compressive with the intermediate principal stress being primarily vertical. This is suggested by the predominance of strike–slip faulting throughout much of Europe and accords with Anderson's (1951) hypotheses that, within the constraints of boundary conditions, the uppermost crustal stress field has one axis close to vertical: nearly 40% of the available data for which spatial orientations are given have one of the principal stress axes within 20° of vertical. Areas where the maximum stress orientation is vertical are the Lower Rhine Embayment, western France and the Aegean and western Anatolian region.

(*b*) The influence of regional-scale geological structures on stress field orientations is not ubiquitous. In the western Alps, for example, the horizontal stresses seem to align perpendicular to the Alpine front. On the other hand, the Rhinegraben rift system does not seem to perturb the regional-stress field. The graben can be subdivided into the Lower Rhine Embayment (striking NW) where normal faulting dominates, and the Upper Rhine Graben (mostly striking NNE) where strike–slip faulting is clear (Ahorner 1970, 1975). Even so, the stress orientation is constant within and across the graben system. Thus it seems that the relative geometrical juxtaposition of tectonic structures and stress orientations is responsible for the type of resultant deformation.

(*c*) On a broad regional scale, there seems to be no systematic variation of stress orientation with depth.

4. Borehole breakout contributions to the European stress field

Borehole breakout measurements have made a considerable contribution to our recent knowledge of the European state of stress. Breakouts describe the resultant elongation of a borehole cross section induced by the refraction and concentration of stress tensors near the free surface of a borehole wall. This stress concentration produces shear fracturing, microcrack propagation and associated spalling of material, in a direction parallel to the minimum stress orientation.

Breakouts are conventionally measured using information from the dipmeter logging tool. This is a four-arm pad device and will only provide X–Y caliper – and related pad resistivity information – at any particular depth in the borehole. The Borehole Televiewer (BHTV), on the other hand, is an acoustic imaging tool which is also able to give the full borehole cross-sectional shape. The BHTV can therefore be used to analyse breakouts in much more detail than can be obtained from the dipmeter. However, the BHTV is a relatively recent and novel device which is only run on special occasions, whereas the dipmeter is run almost always.

Breakout analyses can be performed not only by using caliper readings but also using the corresponding resistivity differences: referred to as caliper and resistivity eccentricity respectively (Brereton & Evans 1989; Brereton *et al.* 1990). Where microcrack propagation has allowed invasion of higher conductivity drilling fluids the formation resistivity will be reduced in the breakout azimuth. Resistivity eccentricity analysis can therefore be used to detect azimuthal zones of incipient spalling where rock material has not yet become dislodged. An effective method of displaying breakout data and enhancing dominant trends is the rose diagram. Results can also be weighted according to the relative size, or magnitude, of individual breakouts.

The principal advantages that the borehole breakout method has over other means of rock stress evaluation are (i) the large geographical distribution of appropriate data currently available; (ii) this type of data is routinely collected within the hydrocarbons and coal industries and as part of other deep geological investigations; (iii) it represents a very cost-effective means of providing detailed stress field measurements, always assuming the raw data have already been collected for other purposes; (iv) it helps to provide a tie between the shallow near surface stress measurements and the deeper focal mechanism stress indicators; (v) breakout data show the least variability in their regional scale mean orientation. In western Europe the mean $\sigma_{\mathrm{H,max}}$ orientation from breakout observations is $141 \pm 18°$.

Breakout analyses have been performed in nearly 200 boreholes drilled in a variety of European geological environments: sedimentary basins such as the Paris Basin, Pannonian Basin and the North German Plain; in the vicinity of the Rhinegraben and the Viking and Central graben structures of the North Sea; as well as into crystalline basement rocks (e.g. KTB and boreholes in the northern Alpine foreland). But, by far the most breakout measurements have been performed in Britain (Brereton & Evans 1989) where they form the majority of the stress map data. Here they are concentrated in the onshore exploration areas of the Midlands and central southern England. The overall picture is one of an average orientation of $\sigma_{\mathrm{H,max}}$ of $138 \pm 11°$(relative to geographic north) for the United Kingdom as a whole. In selected areas the results are a little more variable. In the Midlands there seems to be a bimodal trend at about 155° and 129°. The mean trend for southern England is 135 ± 10° while two subregions of the Hampshire Basin and Wytch Farm area have trends of 129° and 145° respectively. These directions concur with a system of northwest-striking mesofractures well developed throughout Upper Cretaceous and Palaeogene rocks in southern England and northern France (Bevan & Hancock 1986). The mean orientation for the whole country may reflect the averaging of a dominant trend of about 130° with a secondary trend of about 155°.

5. Local variations

Locally, lithospheric or regional stress fields can become significantly modified by the influence of both micro- and macroscale features. The most common are boundary effects associated with geological discontinuities or free surfaces, such as joints, faults, bedding planes, cavities, or the Earth's surface, which will cause stress trajectories to deviate.

Evidence suggests it is unlikely that a localized three-dimensional stress field in a complex geological setting would be uniform, homogeneous or simple. A spectrum of results is to be expected with features characteristic of both the micro- and macroscale influences but with dominant trends reflecting the larger regional-scale stress field.

The rotation of the horizontal stress field in the vicinity of the San Andreas fault is well documented (Zoback *et al.* 1989) and rotations relative to faulting along the Scotian Shelf can be inferred from Bell (1989). Breakout observations in coal exploration boreholes indicate that the free surface effect of the Earth's surface can extend to depths of 100–150 m and cause stress rotations away from the regional trend (K. R. Whitworth, personal communication). On the borehole scale gradual and discontinuous changes in breakout orientation have been associated with fractures and faults intersected by the hole and attributed to local perturbations of the stress field near the borehole due to its interaction with the fractured zones (Shamir & Zoback 1989).

Structurally controlled localized stress rotations were suggested by data presented by Springer (1987). Refraction of mean stress trajectories around a Precambrian basement high, producing a significant anticlockwise rotation relative to the surrounding regional trend, was ascribed by Bell & Lloyd (1989) to a contrast in the elastic properties between the crystalline basement and the overlying sediments. Bradshaw & Zoback (1988) argued that if a significant contrast in viscosity exists between two adjacent strata, such as a normally pressured sandstone and an underlying overpressured shale or evaporite, there will be a rotation of $\sigma_{\mathrm{H,\,max}}$ away from the vertical which will lead to the formation of low-angle normal faults.

Measured stress orientations, derived from borehole breakouts in wells around a salt dome in northern Germany (Schneider 1985), have been compared with the calculated principal stress directions using a finite element model: the shape of the salt dome was known from seismic investigations while representative material parameters were incorporated in the model (figure 2). There is clear agreement between the observations and calculated results. The principal stresses realign in the vicinity of the salt dome, whereas within the salt dome itself the near homogeneous stress is more representative of the far field stresses. The extent of the stress rotation is dependent upon the elastic parameter differences. Thus the salt behaves as a soft

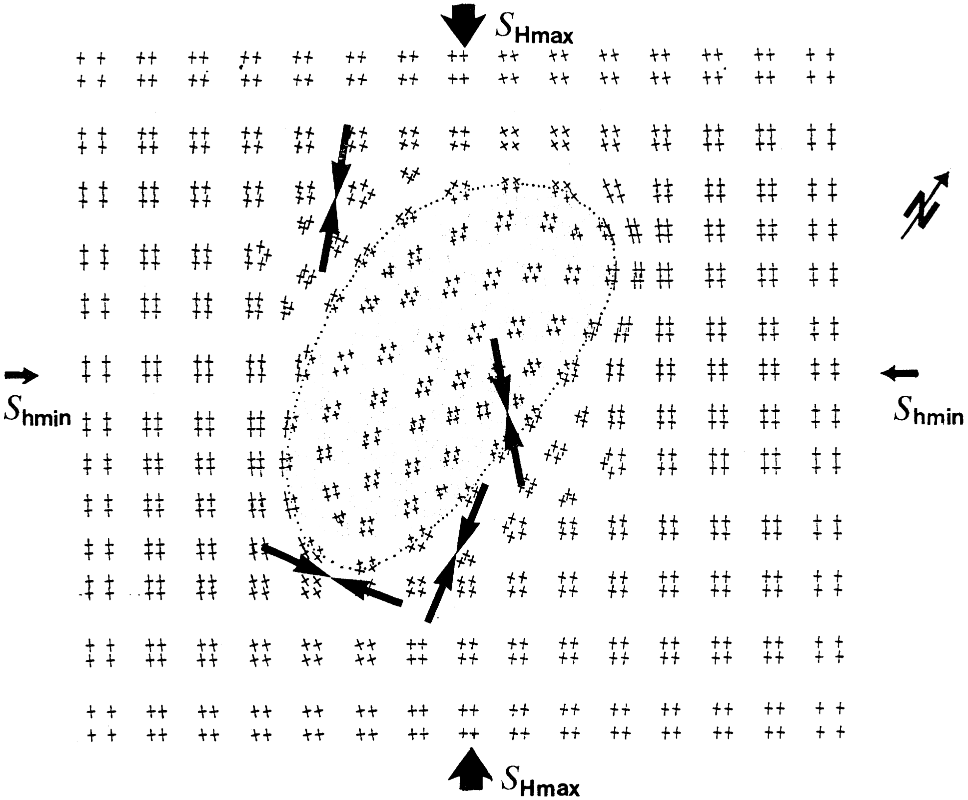

Figure 2. Observed orientations of principal horizontal stress around a salt dome in northern Germany compared with calculated stress orientations (crosses) using a finite-element model.

inclusion in the surrounding material (Goodier 1933). Stress rotations caused by bent dislocations and around elliptical inclusions have been comprehensively modelled by Ivins & Lyzenga (1986).

In contrast to these lateral and structural influences, the stress field of northern Switzerland exhibits changes primarily with depth (Clauss 1987; Müller *et al.* 1991). The block diagram in figure 3 summarizes current knowledge of the modern state of stress in an area between the Aare Massif and the folded Jura Mountains: (*a*) in the crystalline basement the stress orientation is about 140°, which is close to the western European mean; (*b*) in the Permocarboniferous Trough, situated to the north and east of the mountains, rock property contrasts seem to have caused the stress field to rotate to 160°; (*c*) south of the Jura Mountains the stress in the Molasse sediments is virtually N–S but changes, over a depth interval of less than 300 m, to 140°. Finite element modelling indicates that the Molasse stresses are caused by Alpine topographical effects, the Alps trend almost E–W in this area. This observed rotation of horizontal stress coincides with intensive plastic deformation of anhydrite layers, extending over a large horizontal distance, which is thought to vertically decouple the stress field.

Processes influencing localized variability have been studied near a British Coal colliery in the English Midlands (Brereton *et al.* 1990). The study area, of about 40 km^2, was chosen because of the large number of boreholes (over 30), and because the three-dimensional geology is well known. The tectonic evolution, from late

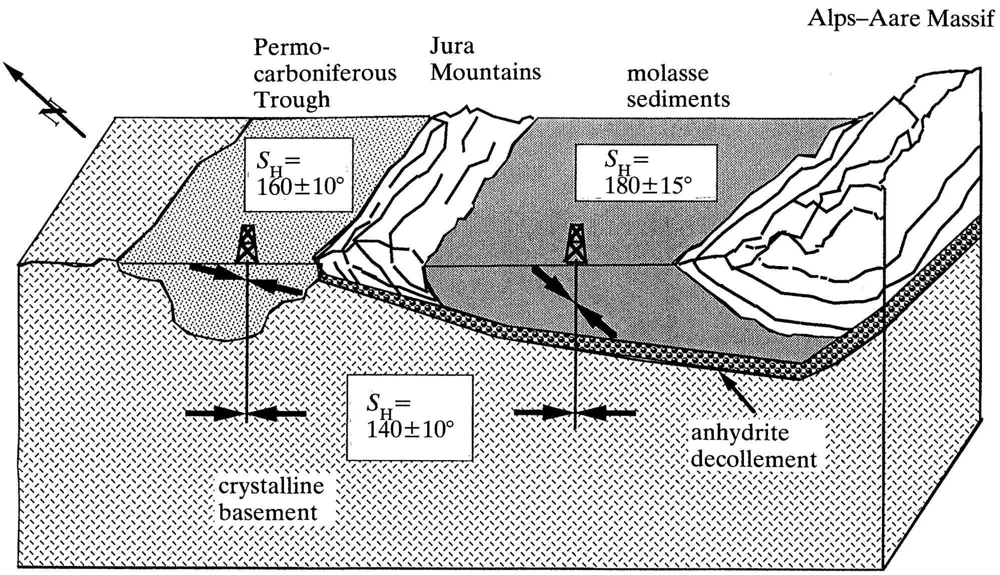

Figure 3. Sketch diagram of stress distribution in the folded Jura Mountains of northern Switzerland. The simplified block diagram shows stress orientation variations with depth due, in part, to an anhydrite decollement horizon between sediments of the Molasse Basin and the crystalline basement.

Carboniferous to early Permian times, resulted in the formation of horst and graben structures with segmented Coal Measures sequences. The grabens subsequently became depositional troughs and are sites of thick Permo-Triassic deposits. Two major faults, trending NE and N, abruptly displace the Coal Measures sequence with an associated downthrown-side thickening of the Permo-Triassic cover to the SE or E (of 130–200 m and 30–90 m respectively). Numerous northerly trending faults, with throws of only a few metres, are also known.

Fourteen boreholes were selected, clustered in two zones of contrasting geology. Cores exist for selected intervals only, but detailed lithostratigraphy from standard cuttings analysis or from using a combination of geophysical logs (British Coal ROCTEC: Halker *et al.* 1982) was available for all boreholes. The ROCTEC routines also provide a measure of relative rock strength from a fracture identification index (FIDX). Breakouts were determined from analyses of both caliper and resistivity data.

Almost all of the boreholes investigated displayed at least one conspicuous zone of breakouts. However, these zones often showed significant variations in depth, depth extent, host strata, orientation and magnitude of the associated breakouts. Even breakouts in boreholes a few hundred metres apart (e.g. Echills 1 and 2), do not correlate as consistently as might have been expected.

Despite the complexities of the breakout behaviour, several important observations could be made.

(*a*) Rose diagrams derived from the full depth extent of each borehole show two main trends of breakout elongation, ENE and NNW. The dominant ENE trend of minimum horizontal stress is consistent with breakout trends for Britain as a whole (Brereton & Evans 1989) and is also supported by overcoring studies performed in the local mine by British Coal. The secondary NNW trend was found primarily in a

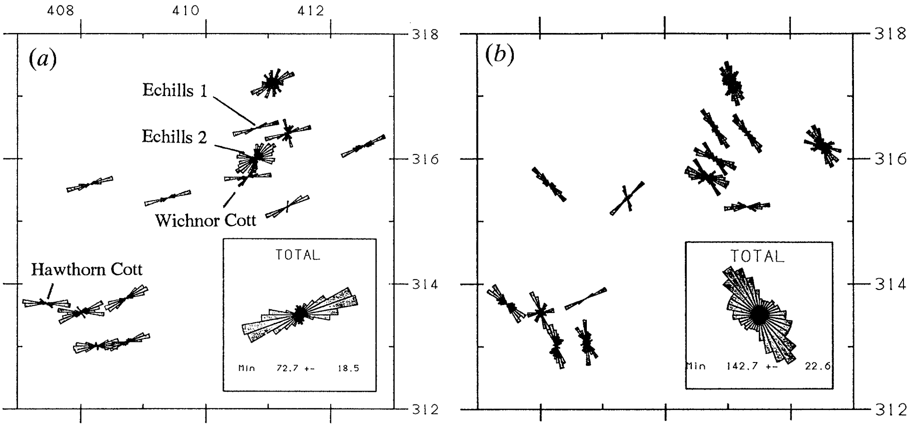

Figure 4. *Minimum* principal stress orientations (borehole breakout directions) for a study area in the English Midlands. Observations in (*a*) the Carboniferous are rotated by 70° compared with those in (*b*) the Permo-Triassic strata.

cluster of four boreholes in the NE corner of the study area. Maps of both the caliper and resistivity rose diagrams were very similar.

(*b*) Investigations of the Carboniferous and Permo-Triassic strata separately (figure 4) showed that the ENE trend is well defined in the Carboniferous strata (equivalent to an orientation of $\sigma_{\mathrm{H,\,max}}$ of $157 \pm 19°$), and the NNW trend is predominant in the Permo-Triassic strata. Further subdivisions of the Permo-Triassic into the Bunter Pebble Beds below and the Keuper Marl above results in a bimodal distribution for the Pebble Beds, with a generally NNW prevalence and a ENE trend for the Keuper Marl. Thus a *ca.* 70° rotation of stress orientation with depth, from NNW in the uppermost lithologies to ENE in the deeper strata, is evident.

(*c*) Low strength coal seams (FIDX values less than 30) were isolated in seven boreholes. The prevailing breakout orientation for these seams is the same as that for the Carboniferous as a whole. But individually, only in boreholes Echills 1 and 2 do all the seams show agreement with this trend. Nine seams in Hawthorn Cottage borehole show clear rotation with depth while in Wichnor Cottage borehole, the top three seams display a NE trend, reverting to ENE in the underlying four seams, below which eight seams show orientations of due east. These observed rotations are attributed to the relative proximity of particular seams to local faults.

Other interesting breakout behaviour was also observed, notably the following.

(*a*) It was common for the dipmeter tool to rotate as it passed through a coal seam (figure 5) and for the largest caliper eccentricities to occur at the contact between the coal and the underlying beds.

(*b*) Coal Measures breakouts showed a highly significant and consistent inverse correlation between rock strength and the magnitudes of both caliper and resistivity eccentricities: i.e. the weaker coal, seatearth and siltstone materials commonly produce the largest breakouts. However, this correlation was not so strong for the Permo-Triassic sediments.

(*c*) Towards the bottom of some boreholes there is a marked reduction in caliper eccentricities, relative to the corresponding resistivity eccentricities, demonstrating that in the upper borehole there are zones of coincident caliper and resistivity

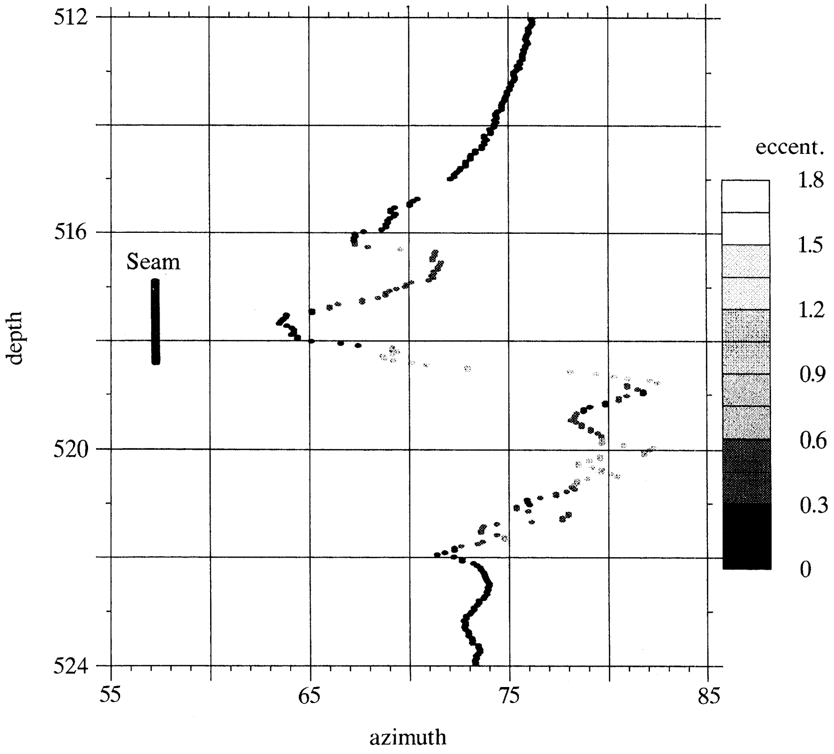

Figure 5. An example of stress rotation with depth (some 15°) across a coal seam. The figure shows the azimuth of breakout direction for the different eccentricities that are observed. The largest caliper eccentricity occurs at the contact between the coal and the underlying beds.

eccentricity where both microcrack propagation and material spalling have taken place, whereas in the lower sections the rock have not had time to dislodge. This observation (see also Kessels 1989) supports the suggestion that breakouts continue to develop with time and that borehole stability is not fully achieved during drilling.

6. Continuing work

It has been shown that Europe can be subdivided into three stress provinces within each of which the broad regional stress field is relatively consistent and indicative of major tectonic events. But to some extent this subdivision may be too simplistic because the data itself tends to be clustered into these same broad groupings. The diversity of stress orientations deduced, for example, from the Balkans indicates a very complex situation. In the Mediterranean region, where seismicity is closely related to plate-boundary effects, borehole breakout analysis is probably the main source of data for the study of the modern intraplate upper crustal state of stress. There are still big gaps in the database especially for much of eastern Europe, southern France, Spain, Italy and the Mediterranean. Even in the North Sea and other offshore areas around Britain, where the potential source of data is huge, the number of systematic borehole breakout analyses that have been performed is small.

Although regional-scale stress fields are relatively consistent, it has also been demonstrated that, when examined in detail, the stresses can be subject to the influences of small-scale local features and hence locally can be very variable. What is needed, therefore, is an expansion of the current database to provide not only a wide geographical distribution of stress data but also a high density distribution of data in three dimensions. The level of detail of the analysis of stress data will depend upon the application of the knowledge to be gained. The change of stress within and across a coal seam or around a salt dome is of considerable interest to the mining or hydrocarbons industry, as the case may be, and the time dependence of breakout evolution in boreholes may influence the economics of deep drilling. But it is the tectonic causes of, for example, stress rotations from one stratigraphic unit to another and the inter-relationships between stress and structure that are of primary interest to the research geologist.

Additional aspects of rock stress research which need to be taken further include (i) the influence of time-dependent breakout evolution on borehole stability; (ii) the use of borehole leak-off test data to help improve our knowledge of stress magnitude variations; (iii) the interdependence of rock stresses and interlayer pore pressure contrasts; their influence on the initiation and propagation of fractures and faults; and whether time-dependent pore pressure changes due to hydrocarbon production will cause changes in localized stress fields.

Collaborative studies are underway between the Universität Fridericiana Karlsruhe, the British Geological Survey and other institutes to help fill some of these database gaps and to improve our knowledge of stresses throughout Europe.

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Discussion

P. Hancock (*Bristol University, U.K.*). I would like to report some unpublished overcoring measurements. The first set were made in the central valley of Scotland and the second set were made in the middle of the Orcadian Plateau in Caithness. They gave reliable results showing a consistent NW–SE trend. In the Permo-Triassic rocks of the Midlands you showed one set of breakout directions in the Bunter Pebble Beds and another in the Keuper rocks. I wonder whether there is much greater dispersion of the data within the Bunter Pebble Beds because they are so extremely heterogeneous?

R. Brereton. The two breakout trends from the Midlands were from the Carboniferous and Permo-Triassic strata. Within the Permo-Triassic rocks there is a breakout trend which rotates by about 70° from NNW to ENE with depth. However, the dispersion of data within the Bunter Pebble Beds (Sherwood Sandstone Group) was not markedly different from that for the Keuper rocks (Mercia Mudstone Group).

T. Harper (*BP Research Centre, Sunbury, U.K.*). Are there any magnitude data from the coalfield where there are a lot of closely spaced directional data which might enable a generic model for that distribution to be developed?

R. Brereton. There is as yet insufficient stress magnitude data to enable a model to be developed at this stage.

M. H. P. Bott (*Durham University, U.K.*). With respect to possible reorientations of the stress system about a salt dome which Dr Brereton discussed, might this not also apply in the Alps, the Alps being a weak surface in the lithosphere?

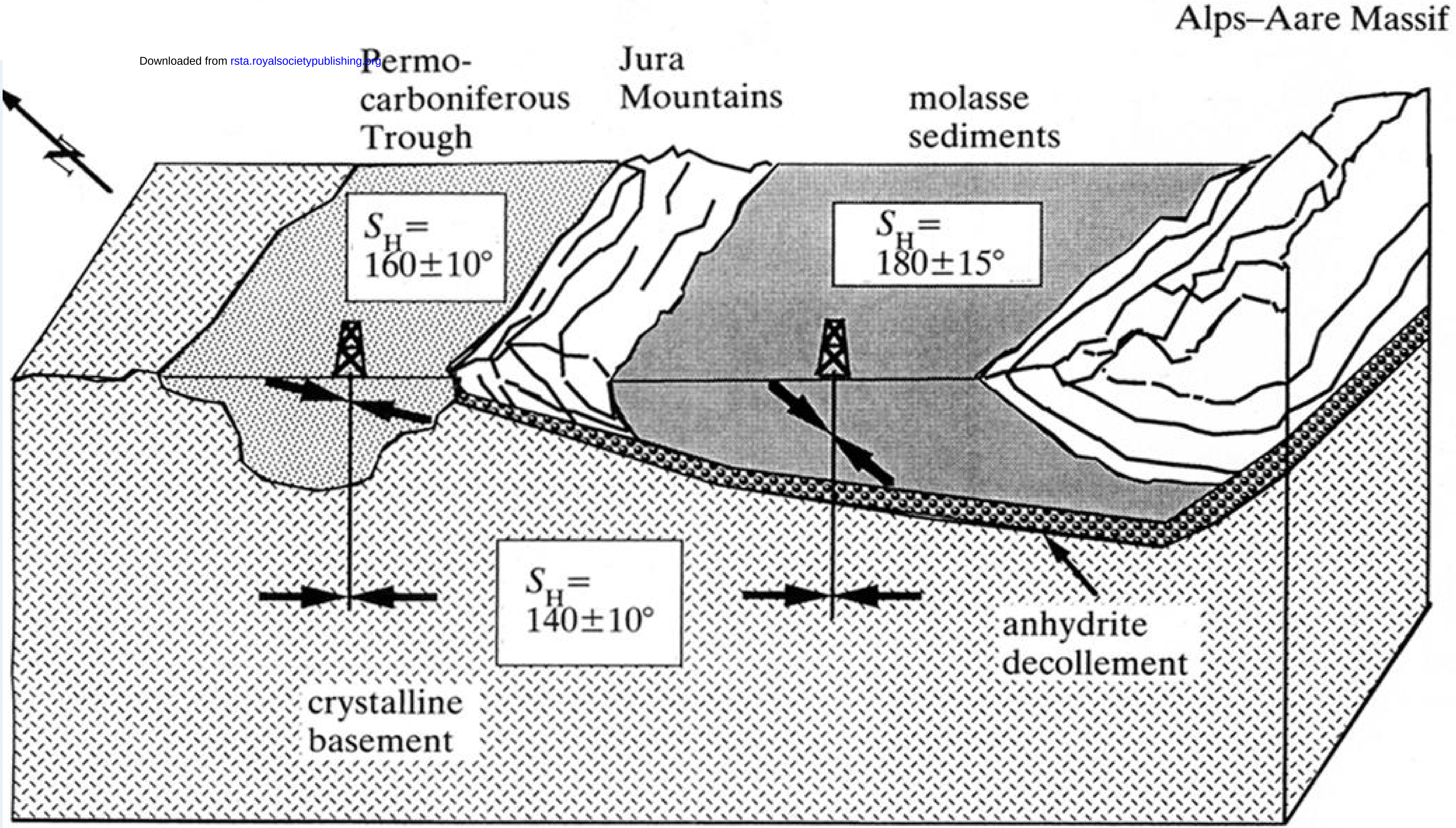
B. Müller. If the Western Alps, which show a roughly radial pattern of maximum horizontal stress with respect to the Alpine front, acts as a soft inclusion in the lithosphere we would expect to find (1) relatively homogeneous stress orientations within the Alps and (2) stress orientations which trend more or less parallel to the Alpine front outside the Alps. The available data do not show such a tendency. N. Pavoni interpreted the radial pattern as being due to a large-scale crustal indentation of the inner parts of the Alps towards the foreland in the west. Alternatively we suggest that the dense and thick lithosphere root could overcome the tension caused by the high topography and create an additional compression perpendicular to the trend of the lithosphere root.

D. Sanderson (*Southampton University, U.K.*). I am interested in the breakout results which showed a difference between the Trias and the Carboniferous because the two directions which Dr Brereton showed, the NW or NNW direction in the Trias and the more ENE direction in the Carboniferous, are precisely parallel to the main directions of extension fractures which developed in the Carboniferous and the Trias. I wonder whether the breakouts were not utilizing some pre-existing anisotropy.

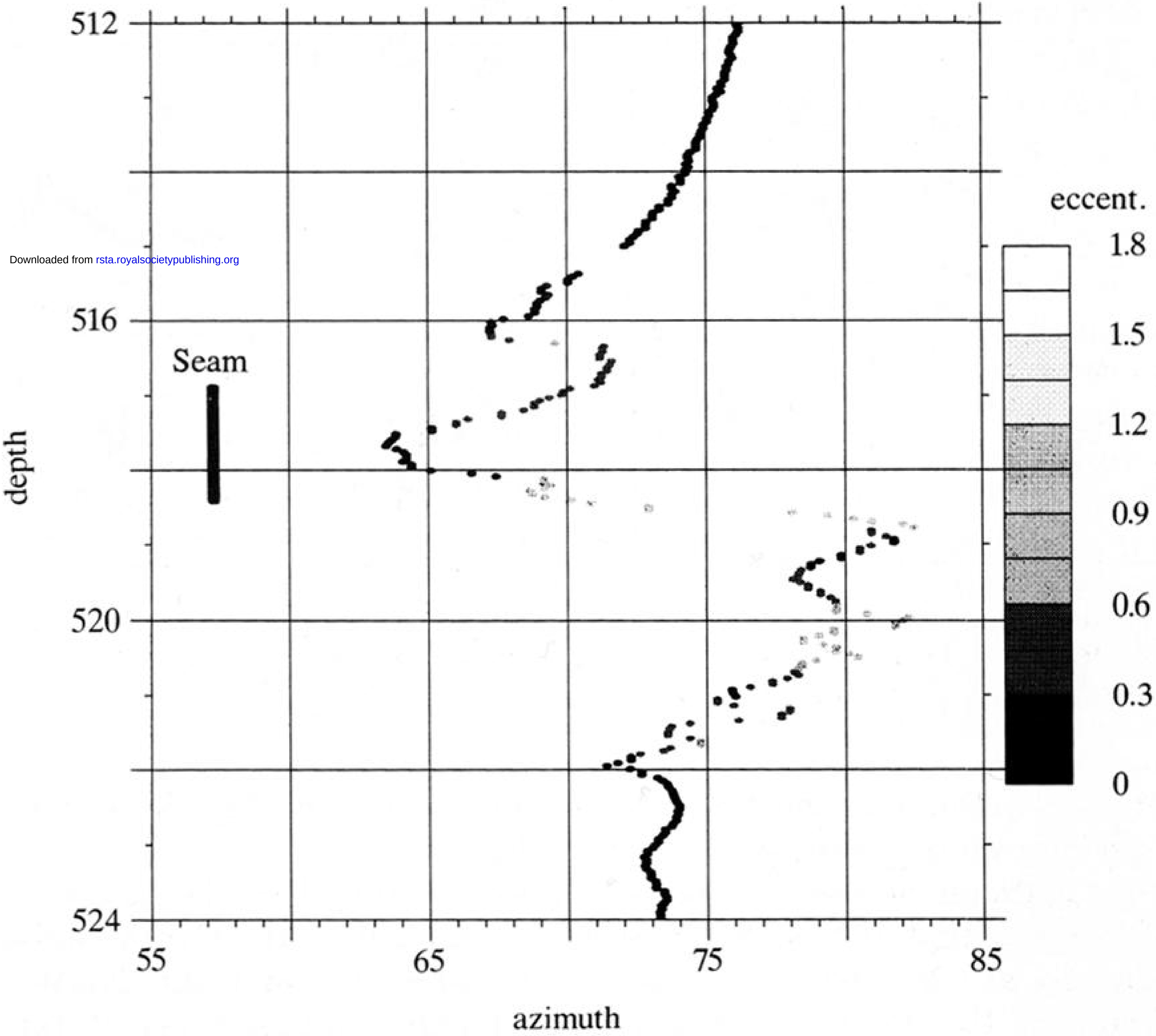
R. Brereton. There has been some debate in the literature as to whether breakouts reflect pre-existing fracture patterns or not. To some degree this question is about whether the stresses being measured today are modern or residual and if they are residual whether the observed fracture patterns in the rocks are themselves some manifestation of the residual stress field. If so some correspondence between the two sets of results might be expected. In an earlier paper Professor Kusznir discussed a stress 'memory effect' on a continental scale implying that there may indeed be a strong residual component to the stress orientations being measured by breakouts. In my view this debate has not yet been fully resolved.

N. Kusznir (*Liverpool University, U.K.*). I find the difference in orientation of stress between Scandinavia and the rest of NW Europe fascinating. Could Dr Müller explain this change in orientation?

B. Müller. A combination of different sources seems to be responsible for the variability of the stress orientations in Scandinavia: (*a*) ridge-push forces from the mid-Atlantic Ridge, possibly also an additional radial component of the Iceland Hot Spot; (*b*) flexure due to the deglaciation of wide areas of Scandinavia which may cause a tensile component in the area of deglaciation and a compressional component in the surrounding oceanic crust, both oriented radial to the area of deglaciation; (*c*) topography might be responsible for local variations. The magnitude of the broad-scale tectonic forces, e.g. the ridge-push forces, is strongly influenced by the variation of lithospheric thickness, causing stress amplification in those parts of the lithospheric plates with thin lithosphere. Areas of thick lithosphere show lower stress magnitudes that might be much more easily disturbed.



igure 3. Sketch diagram of stress distribution in the folded Jura Mountains of northern witzerland. The simplified block diagram shows stress orientation variations with depth due, in art, to an anhydrite decollement horizon between sediments of the Molasse Basin and the ystalline basement.



igure 5. An example of stress rotation with depth (some 15°) across a coal seam. The figure shows e azimuth of breakout direction for the different eccentricities that are observed. The largest liper eccentricity occurs at the contact between the coal and the underlying beds.