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Determining Contemporary Stress Directions from Neotectonic Joint Systems [and Discussion]

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Determining contemporary stress directions from neotectonic joint systems

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A neotectonic joint is a crack which propagated in a tectonic stress field that has persisted with little or no change of orientation until the present day. Investigating neotectonic joints is of value because the approximate orientation of the contemporary stress field can be inferred from them.

Although exposed neotectonic joints in the flat-lying sedimentary rocks of some cratons are related to regional stress fields, their initiation and propagation occurred close to the Earth's surface. For example, neotectonic joints in the centre of the Ebro basin (N. Spain) preferentially developed in a thin, near-surface channel sited within a sequence of weak Miocene limestones underlying the upper levels of plateaux. The Ebro basin joints strike uniformly NNW–SSE throughout an area of at least 10000 km^2 and they are parallel or subparallel to the direction of greatest horizontal stress extrapolated from *in situ* stress measurements and fault-plane solutions of earthquakes.

1. Preamble

This paper has three aims. Firstly, to review the general attributes of exposed neotectonic joints, secondly, to demonstrate that in S. England/N. France and the Ebro basin (Spain) the directions of greatest horizontal principal stress that were inferred from neotectonic joints are parallel to those determined later from geophysical observations, and thirdly, to discuss why neotectonic joints in the Ebro basin are better developed in weak limestones cropping out in the upper parts of plateaux.

In this paper the word neotectonic is used to indicate that a fracture was propagated in a tectonic stress field that has persisted with little or no change of orientation until the present day (Hancock & Engelder 1989). A fracture is called a joint if, at the scale of observation possible in the field, it is barren and there is no measurable offset related to shear, dilation or pressure solution. Because joints are the most abundant of non-penetrative geological structures they are of great potential value for tracking the orientations of principal stress axes at the time of failure. Confidence in the value of joints as stress indicators is greatest where they are uniformly arranged throughout a large area of flat-lying rocks.

2. Fracture classes and joints

On the basis of theory, rock mechanics and field observations, many geologists recognize three classes of fractures; extension fractures, hybrid-shear fractures and

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Figure 1

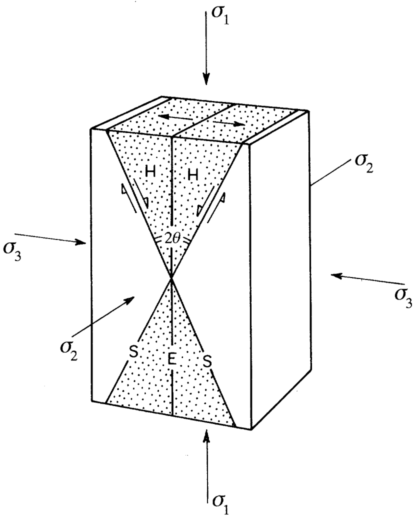

Figure 2

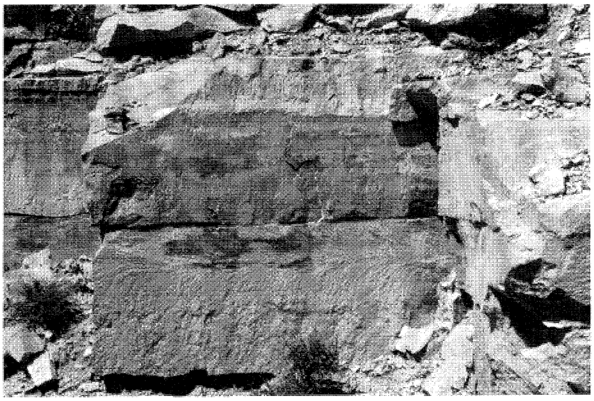

Figure 1. Relationships between fracture class and principal stress axes during the failure of brittle intact rocks. E, single extension fracture; S, conjugate Coulomb-shear fractures; H and stipple, field within which conjugate hybrid-shear fractures form at small angles to σ_1. Principal stresses are $\sigma_1 > \sigma_2 > \sigma_3$. 2θ is the conjugate shear angle.

Figure 2. A plumose marking with a horizontal axis on a NNW-striking neotectonic extension joint cutting a Miocene chalky limestone, Sancho Abarca, Zaragoza Province, Ebro basin, Spain. The joint, which is about 1 m high, propagated from right to left. View to the west.

Coulomb-shear fractures (Price & Cosgrove 1990). Figure 1 illustrates relationships between fracture classes and the orientations of principal stress axes, assuming the rock is brittle and does not contain pre-existing fractures. All the joints to be discussed in this paper formed in brittle rocks and many of them propagated in intact rocks. Even those that developed in already jointed rock possess many characteristics in common with those that formed in intact rocks.

Many joints are interpreted as extension fractures. From such joints the orientation of the σ_3 axis can be determined knowing that it was perpendicular to the joints. Unless a joint displays a plume axis it is not possible to determine the orientations of σ_1 and σ_2 within the plane. Plume axes and individual plume components (figure 2) develop parallel to σ_1 within a joint plane (Kulander *et al.* 1979).

Whether some joints are hybrid-shear or Coulomb-shear fractures is a controversial issue (see Pollard & Aydin (1988) and Price & Cosgrove (1990) for conflicting views). In the view of Price & Cosgrove (1990) and Hancock (1985) there is abundant field evidence in favour of the formation of conjugate hybrid-shear joints. From conjugate sets of joints it is possible to infer the orientations of all three principal stresses knowing that the acute and obtuse bisectors between sets yield σ_1 and σ_3, respectively. Although many joints belong to well-defined sets within which the angular dispersion of planes is small, others define a coaxial angular continuum enclosing a maximum 2θ angle of about 45°. Hancock (1986) has interpreted such continua as comprising a spectrum of extension and hybrid-shear fractures.

From the perspective of comparing the orientations of principal stress axes inferred from joint sets with those known from *in situ* stress measurements it is usually possible to compare only directions of horizontal stress. In this account, the direction of greatest horizontal stress is called S_{H}, while that of the least horizontal stress is referred to as S_{h}. S_{h} and σ_3 are identical in the examples discussed here, but S_{H} is equivalent to σ_1 in some situations and σ_2 in others.

Plumose markings and arrest lines are not only valuable indicators of stress axis orientations but they also allow the propagation sequence of the joint bearing them to be established. For example, only rarely do joint surfaces display more than about six arrest lines. This means that the final dimensions of many joints are achieved in no more than about seven propagation events during which significant rotations of the axes of a regional stress field are unlikely to occur.

3. Common attributes of exposed neotectonic joints

Exposed joints that have been interpreted as neotectonic have been described from Devonian rocks in the Appalachian Plateau of New York State, Ordovician rocks in the Valley and Ridge Province of Pennsylvania, Late Cretaceous–Early Tertiary rocks in southern England and northern France, Neogene rocks in eastern Arabia, and Miocene rocks in the Ebro basin of northern Spain (Engelder 1982, 1985; Bevan & Hancock 1986; Hancock 1987; Hancock & Engelder 1989). In addition, Holst & Foote (1981) have described joints cutting Devonian rocks in the Michigan basin that strike parallel to the contemporary direction of S_{H}. On the basis of these studies the following inventory of fundamental and field attributes of *exposed* neotectonic joints has been compiled.

1. Neotectonic joints either strike parallel to S_{H} or symmetrically enclose a small angle about S_{H} where its orientation is known from geophysical data. Parallelism or subparallelism of a joint set with S_{H} does not, by itself, indicate that a joint is neotectonic.

2. Most exposed neotectonic joints are thought to have propagated in the uppermost 500 m of the brittle crust because they are absent in cores taken from greater depths (Engelder 1985).

3. Regionally extensive neotectonic joint sets within a tectonic domain of several thousand square kilometres generally strike in a uniform direction.

4. Neotectonic joint systems are geometrically simple, mainly consisting of a single set of vertical systematic joints (figure 3*a*). Single sets are locally replaced by either conjugate sets at small dihedral angles to each other or a joint spectrum. Single sets of systematic neotectonic joints generally comprise extension fractures that were propagated when S_{h} was perpendicular to a set and S_{H} was parallel to its strike. When steeply inclined joints in conjugate sets or spectra were formed, S_{h} was slightly oblique to joint planes while S_{H} remained parallel to their strike (figure 3*b*). During the formation of vertical joints in conjugate sets or spectra, S_{h} and S_{H} subtended large and small angles, respectively, with the joint planes (figure 3*c*). The dominance of either extension or hybrid-shear joints enclosing small dihedral angles indicates that differential stresses were small during jointing.

5. Neotectonic joints are the youngest systematic joints (Hodgson 1961) in a rock although individual neotectonic joints may be linked by small irregular non-systematic joints abutting them (figure 3). Where neotectonic joints have formed in rocks containing older and sealed systematic joints they either cut or abut them. Regionally extensive and exposed neotectonic joints do not define orthogonal networks of roughly coeval systematic sets. Such networks are common where

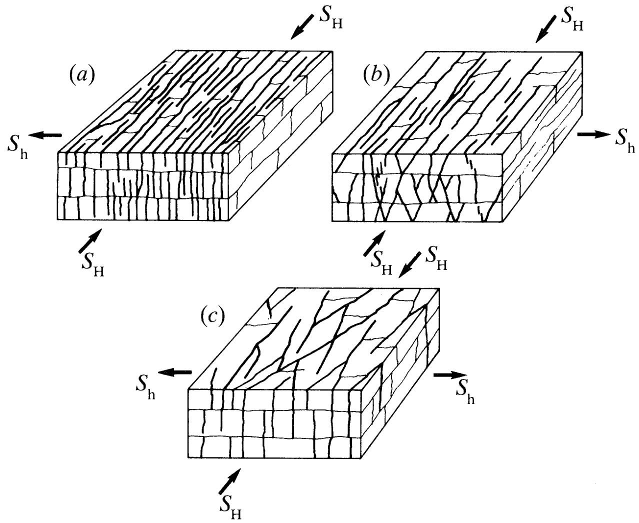

Figure 3. Characteristic neotectonic joint systems. (*a*) Single set of systematic vertical extension joints (heavy lines) linked by non-systematic cross-joints (thin lines). (*b*) Spectrum of systematic vertical extension joints and steep hybrid-shear joints linked by non-systematic cross-joints. (*c*) Spectrum of systematic vertical extension and hybrid-shear joints linked by non-systematic cross-joints. S_H, greatest horizontal stress; S_h, least horizontal stress (after Hancock & Engelder 1989, fig. 5).

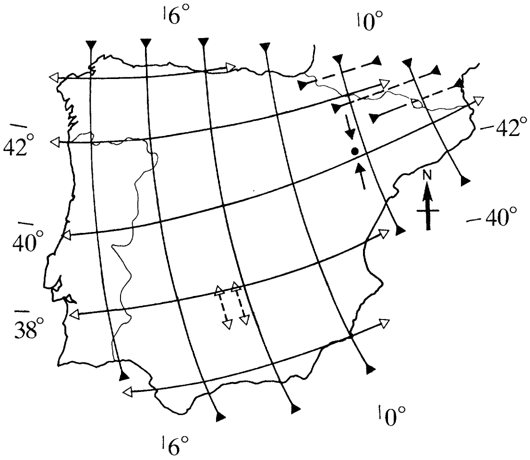

Figure 4. Contemporary regional stress trajectories (continuous and pecked lines) in the Iberian peninsula extrapolated from *in situ* stress measurements at nine sites, earthquake focal mechanisms, at four sites and the analysis of recent faults cropping out at four sites or visible on *Landsat* images at three sites (after Gonzalez de Vallejo *et al.* 1988, fig. 4). The direction of the greatest horizontal stress axis inferred by Hancock (1987, fig. 11) from the strike of neotectonic joints in the Candasnos area of the Ebro basin is also shown by arrows external to a solid circle. Projection: conical with two standard parallels.

ancient (i.e. palaeotectonic) joints have been exposed as a result of uplift and exhumation (Hancock *et al.* 1987). However, local networks of coeval orthogonal joints are formed adjacent to some neotectonic normal faults (Stewart & Hancock 1990). The general geometry of neotectonic joint systems is identical in both intact and previously fractured rocks although the orientation of a neotectonic joint may be locally deflected within a few centimetres of an old one.

6. Veins parallel to and of the same age as neotectonic joints are rare. Palaeotectonic joints are commonly accompanied by parallel vein sets. The absence of veins parallel to exposed neotectonic joints suggests that the joints formed when the fluid pressure to confining pressure ratio was low and significantly less than one.

7. Neotectonic joints commonly cut several beds. The principal exception to them being multilayer fractures is within sequences containing weak layers, such as clays or marls; joints in these sequences do not pass through the weak layers. Neotectonic joint zones containing several closely spaced joints within a narrow zone (centimetres wide) are common in rocks containing older joints. Large multilayer neotectonic joints are usually slightly gaping.

4. Successful estimates of the direction of S_H from neotectonic joints

In 1986 Bevan & Hancock reported the presence of NW-striking joints and small normal faults cutting Late Cretaceous chalks and Palaeogene sands and clays in S. England and N. France. They attributed the formation of the fractures to the influence of a stress field within which the regional direction of horizontal extension was orientated NE–SW, and they noted that the strike of the fractures was parallel to the direction of S_H determined from *in situ* stress measurements and fault plane solutions of earthquakes external to their study-area. One year after the appearance of Bevan & Hancock's article, Brereton & Evans (1987) published the results of an analysis of borehole breakout data that had become available to the British Geological Survey. Many of the boreholes are sited within the area surveyed by Bevan & Hancock (1986): from them Brereton & Evans (1987) concluded that the direction of S_h was mainly NE–SW (see Hancock & Engelder 1989, fig. 2, for details).

NNW-striking joints cutting flat-lying Miocene rocks near Candasnos in the east-central part of the Ebro basin (N. Spain) were interpreted by Hancock (1987, fig. 4) as neotectonic using the field criteria listed in §3. On the basis of *in situ* stress measurements by overcoring, earthquake focal mechanisms, and analyses of recent faults visible at outcrop or on *Landsat* images, Gonzalez de Vallejo *et al.* (1988) published a map of the Iberian peninsula showing smoothed contemporary stress trajectories. They showed the direction of S_H in the Candasnos area within 5° of the average strike of the joints that were first reported by Hancock (figure 4).

5. Neotectonic joints in the Ebro basin

Figure 5 shows average strikes of joints surveyed by the author in the flat-lying Miocene rocks of the Ebro basin, north Spain. The only fractures disturbing these horizontal rocks are small faults and joints. Most of the faults are normal, and those in a graben-field near Tudela strike NNE–SSW and were formed between the Aquitanian and Tortonian stages according to Garcia Prieta & Simón-Gómez (1986). The joint sets depicted in figure 5 are mainly vertical or nearly vertical but they are not all of the same age or type. Those striking WNW–ESE along the northern fringe of the basin are extension joints that Turner & Hancock (1990) interpret as being related to flexural loading of the basin during the early Miocene. NNE–SSW striking joint in the same tract are extensional cross-joints related to the WNW-striking Pyrenean joints.

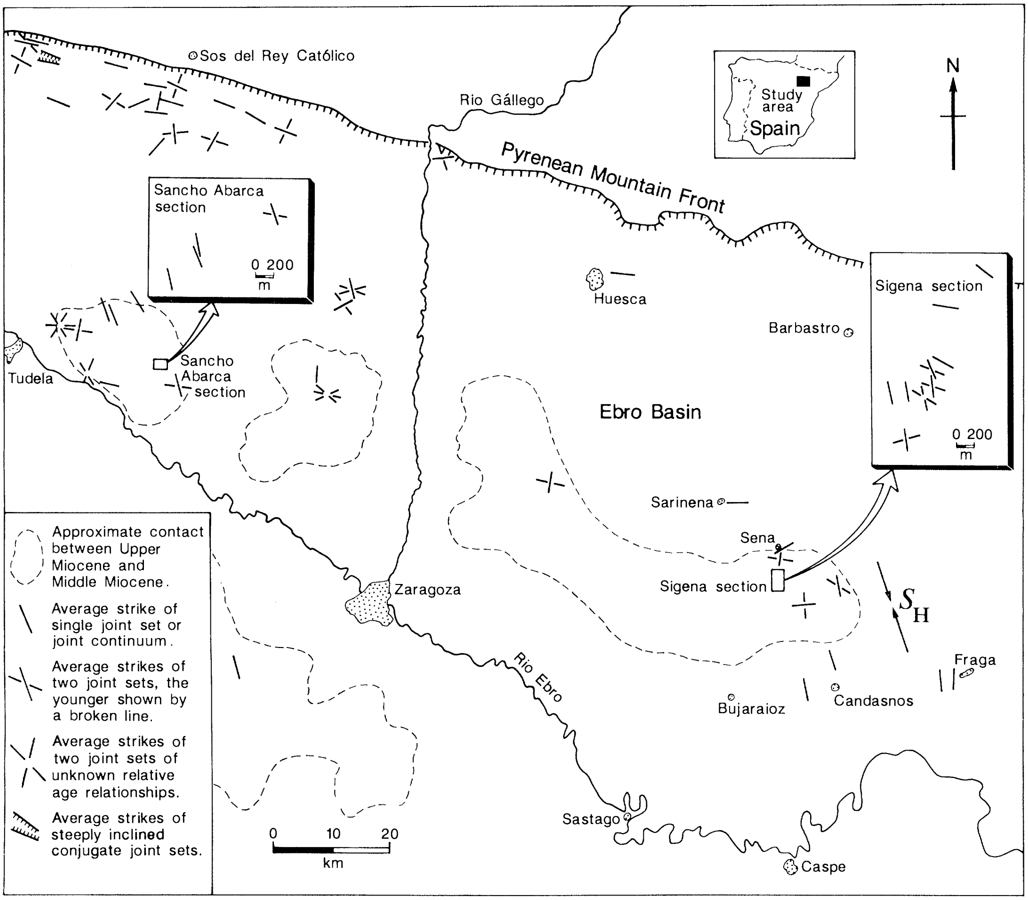

Figure 5. Average strikes and relative age relationships of joint sets in part of the Ebro basin, N. Spain. S_H, contemporary direction of the greatest horizontal stress according to Gonzalez de Vallejo *et al.* (1988, fig. 4). Upper/Middle Miocene contact after Riba, Puigdefabregas and Quirantes (in Julivert 1978, fig. 4.8). Strikes of joints adjacent to the Pyrenean mountain front derived from data in Turner & Hancock (1990, figs 4–6).

In the centre of the basin, joints of another trend cut lacustrine and fluvial rocks that Riba *et al.* (in Julivert 1978) dated as middle to late Miocene. Because these rocks are younger than the latest Pyrenean events, the joints that cut them must be related to younger deformation phases. Of particular interest in the context of this paper are NNW-striking joints cutting the youngest Miocene rocks cropping out in plateaux and mesas. Because NNW-striking joints abut NNE-striking normal faults and parallel shear fractures (figure 6) it is concluded that the joints are post-Tortonian (i.e. late Miocene) structures. Furthermore, because they are of late Cenozoic age and strike parallel or subparallel to the direction of S_H it is concluded that they are neotectonic. Nine attributes of these joints are noteworthy.

1. As reported in §4, the direction of S_H inferred from the joints is within 5° of that extrapolated from independent geophysical evidence.

2. The strike of joints, or the direction of the acute bisector between vertical conjugate hybrid-shear joints, is generally within 15° of an average strike of 165° throughout an area of about 10000 km^2 (figure 5).

Figure 6

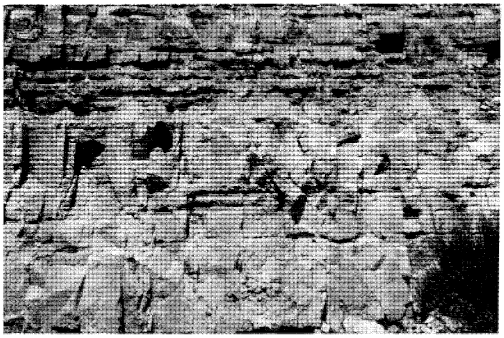

Figure 7

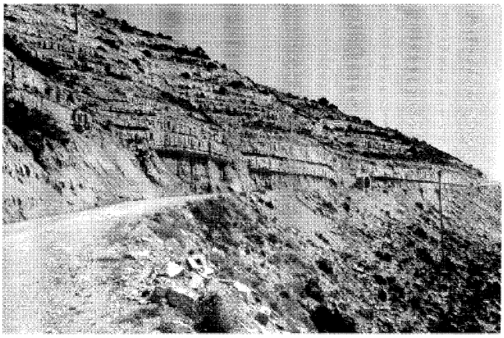

Figure 6. Vertical NNW-striking neotectonic extension joints abutting moderately inclined, NNE-striking shear fractures (sloping down to the right) cutting Miocene chalky limestones at Sancho Abarca, Zaragoza Province, Ebro basin (N. Spain). The joints are younger than the late Miocene shear fractures. The exposure is about 2 m high. View to the north.

Figure 7. Closely spaced and planar NNW-striking neotectonic joints cutting Miocene chalky limestones at Sancho Abarca, Zaragoza Province, Ebro basin (N. Spain). Individual joint planes are picked out by the dark shadows. View to the northeast.

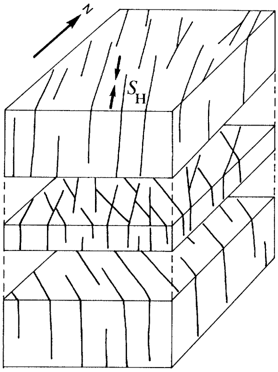

Figure 8. Exploded block diagram illustrating relationships between dominant systematic joint sets in the neighbourhood of the 20 m thick ‘joint transition zone’ within the Sigena section (see figure 5) in the Ebro basin. The highest beds (shown as one) are cut only by NNW-striking neotectonic joints. In the transition zone there are both NW- and NNW-striking joints. Layers immediately beneath the transition zone contain only NW-striking joints. S_H, direction of contemporary greatest horizontal stress according to Gonzalez de Vallejo *et al.* (1988, fig. 4).

3. A set of vertical extension joints is dominant at most localities but locally it is replaced by either steeply inclined or vertical conjugate hybrid-shear joints in sets or spectra.
4. NNW-striking joints are the youngest systematic joints in the study area.
5. The morphology of NNW-striking joints in limestones is the same throughout the area, thus enabling them to be identified by a field criterion distinct from azimuth. Although individual parts of joints are smooth many surfaces are composite and stepped. Many joints that strike in directions other than NNW–SSE are irregular.
6. A few joint planes in homogeneous limestones display plumose markings with horizontal plume axes (figure 2).

7. Systematic NNW-striking joints are absent in the weak clays and marls interbedded with chalky limestones.

8. Veins parallel to NNW-striking joints are absent or rare.

9. NNW-striking joints are best developed (i.e. most closely spaced and planar) within a sequence of chalks that underlie mesas capping plateaux (figure 7). NNW-striking joints become less closely spaced and less planar towards the tops and bases of most mesas. Beneath the higher levels of all mesas and in the youngest rocks, NNW-striking joints are the only systematic joints. These relationships are especially well displayed in the Sigena section (figure 5), which starts at about 250 m above sea level and rises to nearly 600 m. Joints striking NNW–SSE suddenly appear at the 490 m level and are present in all limestones up to the top of the escarpment. For about 20 m above their first appearance they co-exist with NW-striking joints (figure 8). These joints are identical in strike to those cutting beds immediately below and lacking NNW-striking joints. Thus in the Sigena section there is a thin 'joint transition zone' containing joints of both strikes, but otherwise joints of either NW–SE or NNW–SSE strike are restricted to the lower or upper parts of the section, respectively.

Three aspects of the exposed neotectonic joints in the Ebro basin require comment from the perspective of understanding their origin.

1. Why are the joints uniformly orientated throughout an area of 10000 km^2 and within a sequence containing limestones that are separated from each other by unjointed mudstones? Although the limestones containing the joints are of uniform thickness on the scale of an outcrop they are lenticular on the scale of a few hundred metres and were, thus, never, continuous across the basin. Hence it is impossible that they acted as basin-wide stress guides. It is more probable that the stresses responsible for generating the joints in the limestones reflect small strains in the enclosing muddy rocks. In their turn, these strains probably mirror small regional strains of uniform orientation beneath the centre of the basin, which is distant from the boundary conditions imposed from the framing mountain ranges (Simón-Gómez 1989).

2. Why, in the centre of the basin, do the exposed neotectonic joints, and hence the inferred direction of S_{H} (locally σ_1), trend NNW–SSE? Because the direction of S_{H} is oblique to the trend of both the Iberic and Pyrenean mountains it is unlikely to reflect the dominant direction of shortening in either of those domains. A more likely explanation, judging from figure 4, is that it reflects a large regional stress field affecting all of Iberia.

3. Why are neotectonic joints in the Ebro basin best developed in a relatively thin near-surface channel beneath the summits of plateaux and mesas? Two explanations can be put forward. One is that neotectonic joint development is controlled by lithology. In favour of this hypothesis is the observation that the most closely spaced and planar joints are restricted to fine-grained homogeneous marly chalks with a uniaxial strength of about 20 MPa (as estimated from point load tests by using the method of Bock & Franklin (1972)). However, the limitation of neotectonic joints to chalky limestones does not explain why they die out upwards in chalks which at the top of the sequence are little different to those 100 m below.

An alternative explanation for the restriction of exposed neotectonic joints in the Ebro basin to a near-surface channel is that for their development both a thin cover was required to provide a confining pressure, and they had to be uplifted to a level within which, after exhumation, tensile or hybrid-shear failure could occur without the aid of abnormally high fluid pressures. Thus neotectonic joints are absent at the tops of some mesas because there was either insufficient cover or there has been little exhumation. Neotectonic joints are, however, exposed at the tops of more denuded mesas from which a former cover has been removed. The observation that neotectonic joints are absent or less well developed in the lower slopes of some mesas is probably related to the rocks of such settings not having been sufficiently extended. Uplift is likely to have been the principal mechanism leading to horizontal extension. It is otherwise difficult to understand why NNW-striking neotectonic joints have not been superimposed on older joints cutting rocks lower in the sequence (e.g. see figure 8). In the context of Engelder's (1985) genetic classification of joints, the exposed neotectonic joints in the central part of the Ebro basin are typical *unloading joints* formed after burial, uplift and exhumation.

The work of Narr & Burress (1984) on the formation of fractures observed in core is significant in the context of the second hypothesis. They report fractures formed subparallel to S_H in Early Carboniferous limestones at greater than about 3000 m depth below the surface in North Dakota. Although they think that fluid pressures were normal-hydrostatic immediately after fracturing they do not rule out the possibility that fluid pressures could have been abnormally high during fracturing. Thus, jointing may occur simultaneously in both a thin near-surface channel and at greater depth. 'Dry' unloading joints form close to the Earth's surface where lateral relief is possible, and 'wet' tectonic joints, partly driven by high fluid pressures related to tectonic compaction, form at greater depths. Because shallow-formed joints may be exposed by modest denudation not long after their formation, stress directions inferred from them will generally be similar to those of the present day. More deeply formed, hydraulically driven, tectonic joints (possibly accompanied by parallel veins) will be exposed only after substantial exhumation.

The uniformity of strike of Ebro basin neotectonic joints throughout several plateaux and mesas bounded by slopes of different attitude indicates that local topography is not an important control. Discriminating between the hypotheses of control by lithology or altitude is not easy in the Ebro basin because the rocks are flat-lying and chalky limestones crop out only beneath the upper slopes of mesas. A regional survey of relative neotectonic joint development in relation to sedimentary facies and altitude in the basin is required.

6. Conclusions

1. Exposed neotectonic joints can be used to track approximately the horizontal axes of the contemporary stress field. The joints strike either parallel to the direction of the greatest horizontal stress or they symmetrically enclose a small angle about it. In both S. England/N. France and the Ebro basin (N. Spain), contemporary stress axes were successfully predicted from neotectonic joints before geophysical data became available.

2. The strikes of exposed neotectonic joint sets are generally uniform throughout areas exceeding 10000 km^2, reflecting the uniformity of orientation of the stress field to which they are related.

3. Abnormally high fluid pressures are not necessary to propagate neotectonic joints at very shallow (less than 500 m) crustal levels, but unloading consequent on denudation, and lateral relief resulting from uplift are, however, necessary prerequisites.

4. The majority of exposed neotectonic joints are extension fractures but a small proportion are hybrid-shear fractures. Differential stresses during neotectonic jointing are small and S_H is horizontal.

5. Neotectonic joints in the Ebro basin are best developed in a thin-near surface channel containing chalky limestones. The preferential development of joints in this channel is related to either the presence of weak but brittle limestones or uplift having raised the rocks to a height where lateral elongation is possible.

A. G. Becher, J. P. Turner and L. Arlegui assisted in the field and in many other ways. B. J. McConnell carried out the point load tests, and P. C. England made valuable suggestions for improving the paper. The Royal Society, the University of Bristol, King Abdul Aziz City for Science and Technology, Shell International Petroleum Company and the NERC funded fieldwork.

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Discussion

R. Maddock (*Geoscience Ltd, U.K.*). In the Ebro Basin example, how is extensional strain partitioned between the joints and the normal faults in percentage terms?

P. L. Hancock. Because the NNW-striking neotectonic joints in the Ebro basin can be shown, on the basis of field evidence, to be younger than the NNE-striking normal faults strain partitioning was not involved. Formation of the joints resulted in no more than 1% elongation. Although this strain is trivial the uniformity of the inferred ENE–WSW extension direction throughout an area of least 10000 km^2 permits confidence in the idea that the joints are reflections of a strain of regional significance.

M. L. Zoback (*US Geological Survey, Menlo Park, U.S.A.*). I never thought I would stand up in defence of joints, but I think Dr Hancock has made some really important observations regarding neotectonic joints and their relationship to the contemporary stress field. One thing that has always bothered me in the Appalachian Plateau is the question of the large stratigraphic window. If we look at Devonian rocks, why should they be recording the modern stress field when they have been sitting there so long?

P. L. Hancock. Dr Zoback's remarks about the potential of neotectonic joints for tracking contemporary stress trajectories are much appreciated. A simple answer to her question is that old rocks are just as capable of experiencing contemporary stresses as young rocks. Whether old rocks respond by developing new structures, or by reactivating pre-existing ones, depends on the orientations and characters of the old structures, and the orientations and magnitudes of the contemporary stresses. The influence of residual stresses that have been locked-in since an ancient deformation episode generally seems to be slight.

B. Skipp (*Soil Mechanics Associates, U.K.*). Has Dr Hancock made a close examination of the Crag in East Anglia? Can he comment upon reports there of large concentrations of joints which perhaps are more fault-related and furthermore has he examined flat lying caliche type deposits which I would have thought should also show something of the contemporary stress field?

P. L. Hancock. I have not seen the structures referred to and that were described by Balson & Humphreys (1986) as cutting Plio-Pleistocene Crags in East Anglia. However, judging from the photographs in their paper, the neotectonic joints cutting the Cretaceous chalks and Palaeogene sands and clays in S. England/N. France are unlike the fissures they describe. The neotectonic joints are closed, rather than open, fractures and, in Suffolk, they terminate upwards in London Clay at the unconformity beneath the Red Crag (Bevan & Hancock 1986).

I agree that some Quaternary caliches might contain systematic joints that record the influence of the contemporary stress field. Caliches dated as latest Pliocene–Pleistocene in eastern Arabia are cut by systematic joints of neotectonic trend but only within their basal parts. Furthermore, these joints are direct continuations of joints cutting underlying Miocene–early Pliocene bedrocks. Thus they might be reflection cracks rather than tectonic structures. Non-systematic joints are abundant in the east Arabian caliches but there is little correlation between their average strikes and those of systematic neotectonic joints cutting the underlying bedrocks.

C. VITA-FINZI (*University College, London, U.K.*). Could the window be narrowed even further by making a study of joint systems in Quaternary or even in Holocene rocks? You would then benefit from the tighter correlation with the contemporary stress field and from the knowledge that the structures formed at the surface and have not undergone reactivation.

P. L. HANCOCK. A thorough search for systematic joints in Quaternary, and in particular in Holocene, sedimentary rocks would be most worthwhile. Such rocks are commonly cut by faults and fissures in regions that are actively extending. Paradoxically, regionally extensive and regularly orientated joint sets are generally lacking in such young rocks. However, non-systematic, randomly organised joints commonly cut late Pleistocene and Holocene rocks. For example, cemented beach rock in the Corinth area, which is cut by normal faults, contains only non-systematic joints. Several colleagues have reported that they have seen systematic joints in a variety of mainly older Quaternary materials but detailed descriptions of them are few, a notable exception being Caputo's (1990) account of joints in the Thessaly area of Greece. One reason why systematic joints in late Quaternary rocks are relatively rare might be that they have not experienced a stress history that involves both loading during burial and unloading during denudation.

Additional references

Balson, P. S. & Humphreys, B. 1986 The nature and origin of fissures in the East Anglian Coralline and Red Crags. *J. Quat. Sci.* **1**, 13–19.

Caputo, R. 1990 Geological and structural study of the recent and active brittle deformation of the Neogene–Quaternary basins of Thessaly (central Greece). *Scientific Annals of the Geological Department of the Aristotle University of Thessaloniki* **12**, 1–252.

Figure 1

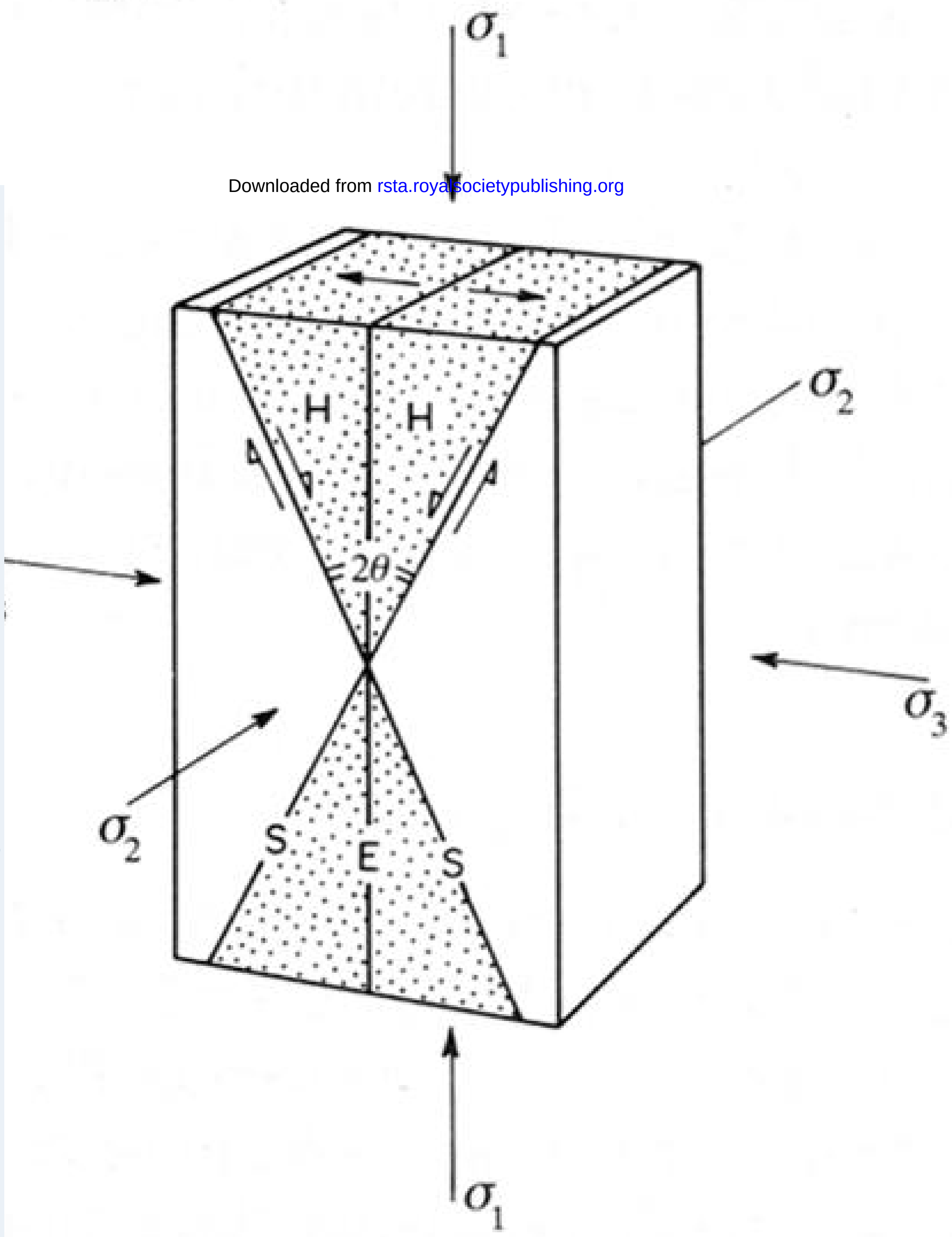
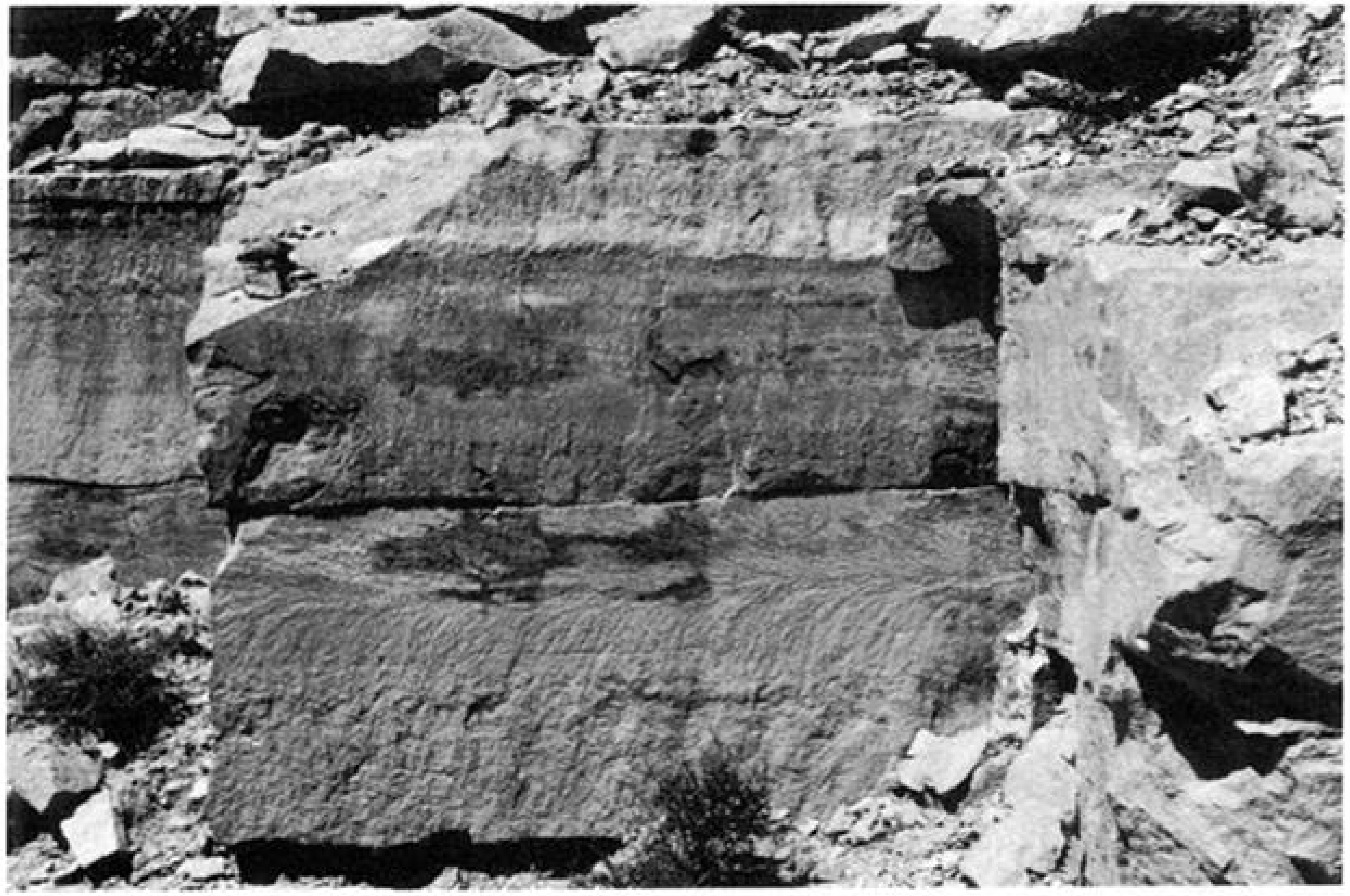


Figure 2



igure 1. Relationships between fracture class and principal stress axes during the failure of brittle tact rocks. E, single extension fracture; S, conjugate Coulomb-shear fractures; H and stipple, eld within which conjugate hybrid-shear fractures form at small angles to σ_1. Principal stresses re $\sigma_1 > \sigma_2 > \sigma_3$. 2θ is the conjugate shear angle.

igure 2. A plumose marking with a horizontal axis on a NNW-striking neotectonic extension joint itting a Miocene chalky limestone, Sancho Abarca, Zaragoza Province, Ebro basin, Spain. The int, which is about 1 m high, propagated from right to left. View to the west.

igure 6

Figure 7

igure 6. Vertical NNW-striking neotectonic extension joints abutting moderately inclined, NNE-
riking shear fractures (sloping down to the right) cutting Miocene chalky limestones at Sancho
barca, Zaragoza Province, Ebro basin (N. Spain). The joints are younger than the late Miocene
ear fractures. The exposure is about 2 m high. View to the north.

igure 7. Closely spaced and planar NNW-striking neotectonic joints cutting Miocene chalky
nestones at Sancho Abarca, Zaragoza Province, Ebro basin (N. Spain). Individual joint planes are
cked out by the dark shadows. View to the northeast.