Neotectonic joints

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ABSTRACT

Neotectonic joint systems are the most recent joint systems to form within a region subject to uplift and erosion. An inventory of neotectonic joint attributes was compiled from observations in case-study terrains containing flat-lying sedimentary sequences in the platform covers of cratons: the Appalachain Plateau, southeast England–northeast France, the Arabian platform, and the Ebro basin in Spain. Neotectonic joint systems are simple, generally consisting of sets of vertical extension fractures or less commonly steep conjugate fractures striking parallel to, or symmetrically about, the extension fractures. Shallow neotectonic joints propagate within the upper 0.5 km of the crust where effective σ_3 is both tensile and horizontal and $\sigma_1 - \sigma_3$ is small. These shallow joint systems generally form within the upper 0.5 km of the crust because unloading as a result of denudation and lateral relief consequent on uplift are prerequisites for their propagation. These structures are of potential value for tracking the contemporary stress field in regions where *in situ* measurements are not available. As a test of this possibility, late-formed joints were studied in the Appalachian Valley and Ridge of Pennsylvania. Outcrop studies showed that late-formed joints have the characteristics of neotectonic joints and, furthermore, propagated parallel to or approximately parallel (N75°–90°E) to directions of contemporary horizontal maximum stress (S_H) known from *in situ* stress measurements or fault-plane solutions of earthquakes. The latter study lends strong support to our notion that late-formed or neotectonic joints in some terrains are likely to reflect the orientation of the neotectonic or contemporary tectonic stress field.

INTRODUCTION

In 1982, T. E. asked the rhetorical question, "Is there a genetic relationship between selected regional joints and contemporary stress within the lithosphere of North America?" (Engelder, 1982). The question is necessary because in eastern North America, evidence supporting a positive response to the hypothesis is difficult to establish. Most of the North American craton east of the Mississippi River is covered with platform sediments no younger than late Paleozoic, so that dating joint sets based on stratigraphic arguments leaves a 250-m.y. window that cannot be narrowed. Subsequent work by P.L.H. and students in much younger rocks (everywhere <60, and <15 m.y. old in some settings) showed that stress axes inferred from joints correlated approximately with those of the contemporary stress field (for example, Hancock and others, 1984; Bevan and Hancock, 1986; Hancock and Bevan, 1987; Hancock, 1987).

In this paper, we summarize observations and inferences from our earlier work in New York, south England/north France, east Arabia, and the Ebro basin (north Spain) and synthesize them in a new inventory of the attributes of shallow-formed joints. We then comment on the previous prediction of the orientation of contemporary horizontal maximum stress, S_H, based on last-formed joints (Bevan and Hancock, 1986) in the light of recently published information about the orientation of the contemporary stress field in south England. Finally, we test our general hypothesis by correlating certain joints to the contemporary tectonic stress field in an area of the Appalachian Valley and Ridge, Pennsylvania, within which there had been no earlier attempt to define the relationship between the late-formed joints and the contemporary tectonic stress field.

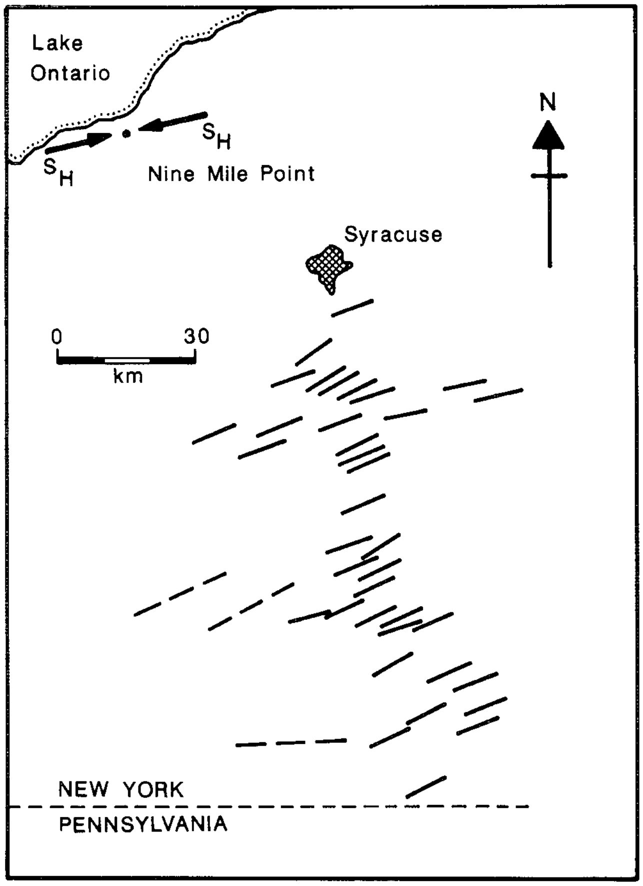

Figure 1. Average strikes of extension joints interpreted as having formed in a neotectonic stress field influencing Devonian rocks in part of the Appalachian Plateau of New York. Joints observed by Engelder (1982) in individual outcrops are shown as continuous lines; those reported by him from the work of Parker (1942) are shown as dashed lines. The orientation of S_H, which is subparallel to the strike of the joints, is generalized from 74 measurements of Dames and Moore (1974) and also reported by Engelder (1982).

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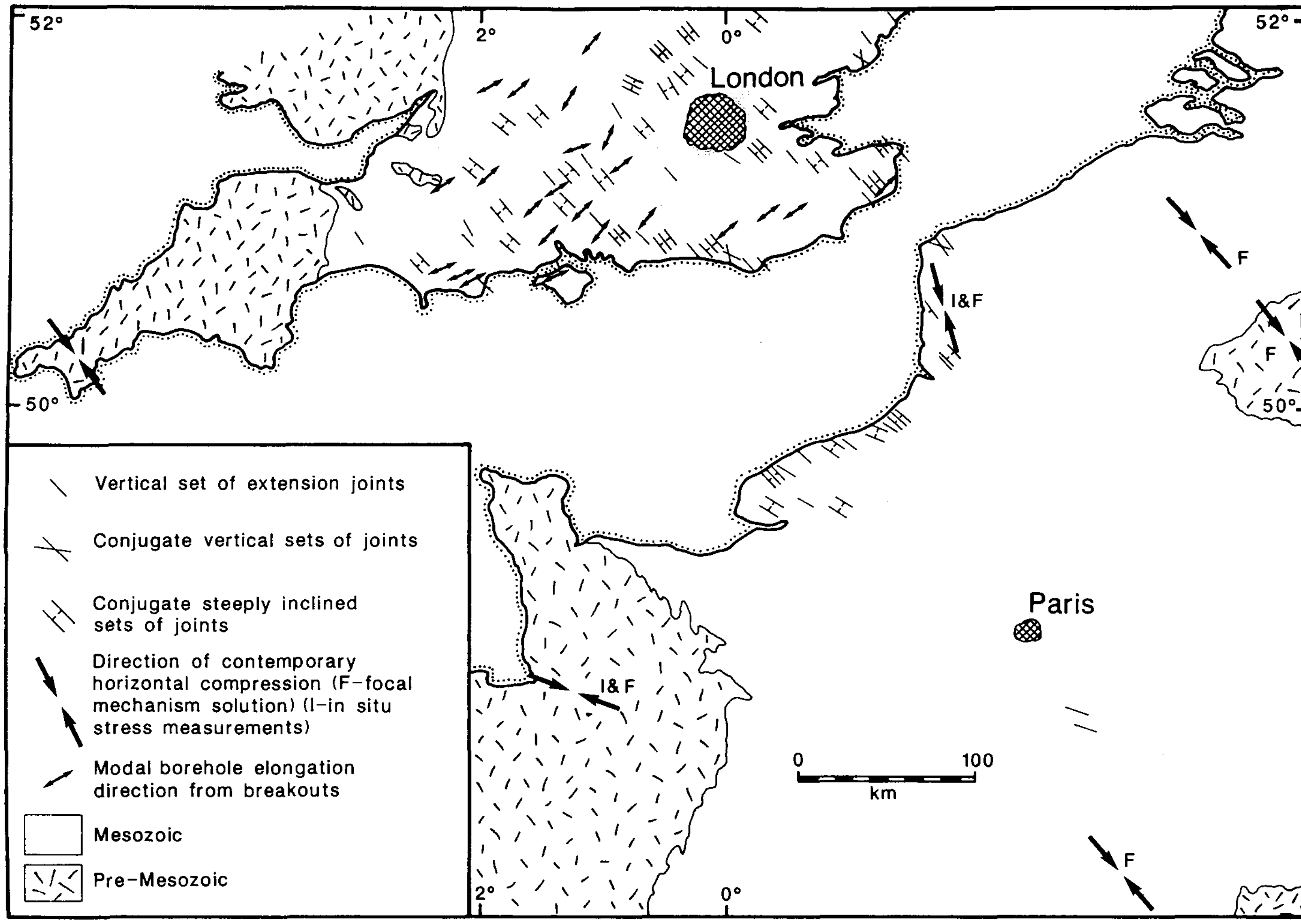


Figure 2. Northwest-striking late Cenozoic joints cutting Upper Cretaceous and Paleogene rocks in southeast England and northeast France. Each set is represented by a mean strike direction. Directions of contemporary horizontal compression determined from *in situ* measurement or focal mechanisms by various authors are taken from Bevan and Hancock (1986, Fig. 4), whereas joint directions have been taken from Figure 1 of Bevan and Hancock. Representative modal elongation directions of boreholes are from Brereton and Evans (1987, Fig. 9).

In all settings, the joints we discuss are the last systematic brittle structure to form, usually when differential stresses are less than those necessary for active faulting or the development of other mesoscopic structures. Although joints of this type occur in rocks of all ages, it is possible to be more certain of their youthfulness in young rocks, especially those of late Miocene or younger age. In this account, the term "joint" is used to describe a fracture that is not a stylolite or vein and on which, in the field, there is no evidence for offset related to shear (Hancock, 1985). This descriptive definition of a joint, which follows the classical one (see Challinor's dictionary, Wyalt, 1986), is broader than the genetic definitions used by Engelder (1985, 1987), who restricted the use of the term to only those fractures interpreted as propagating normal to σ_3, and by Pollard and Aydin (1988, p. 1186), who emphasized "field evidence for *dominantly* opening displacements." The adjective "neotectonic" is used as a qualifier to indicate that a suite of structures is interpreted as having evolved in a late Cenozoic stress field, the orientation of which is in harmony with, but not necessarily precisely parallel to (less than ~20°), the principal axes of the contemporary stress field.

Because some regional joints that are interpreted as neotectonic on the basis of field relationships strike parallel to or approximately parallel to the direction of S_H known from *in situ* stress measurements or fault-plane solutions of earthquakes (for example, Engelder, 1982, 1985; Bevan and Hancock, 1986), they are structures of potential value for tracking the contemporary stress field in regions where *in situ* measurements and fault-plane solutions are not available. It is for this reason that an inventory of the attributes of neotectonic joints would enhance the value of such a geologic approach to understanding contemporary stresses.

CASE-STUDY TERRAINS

The Appalachian Plateau

Vertical joints south of Syracuse, New York, in the Appalachian Plateau strike east-northeast, subparallel to the mean direction of contemporary horizontal maximum stress (Fig. 1) (Engelder, 1982; Hickman and others, 1985; Evans and Engelder, 1986). These joints, which cut Devo-

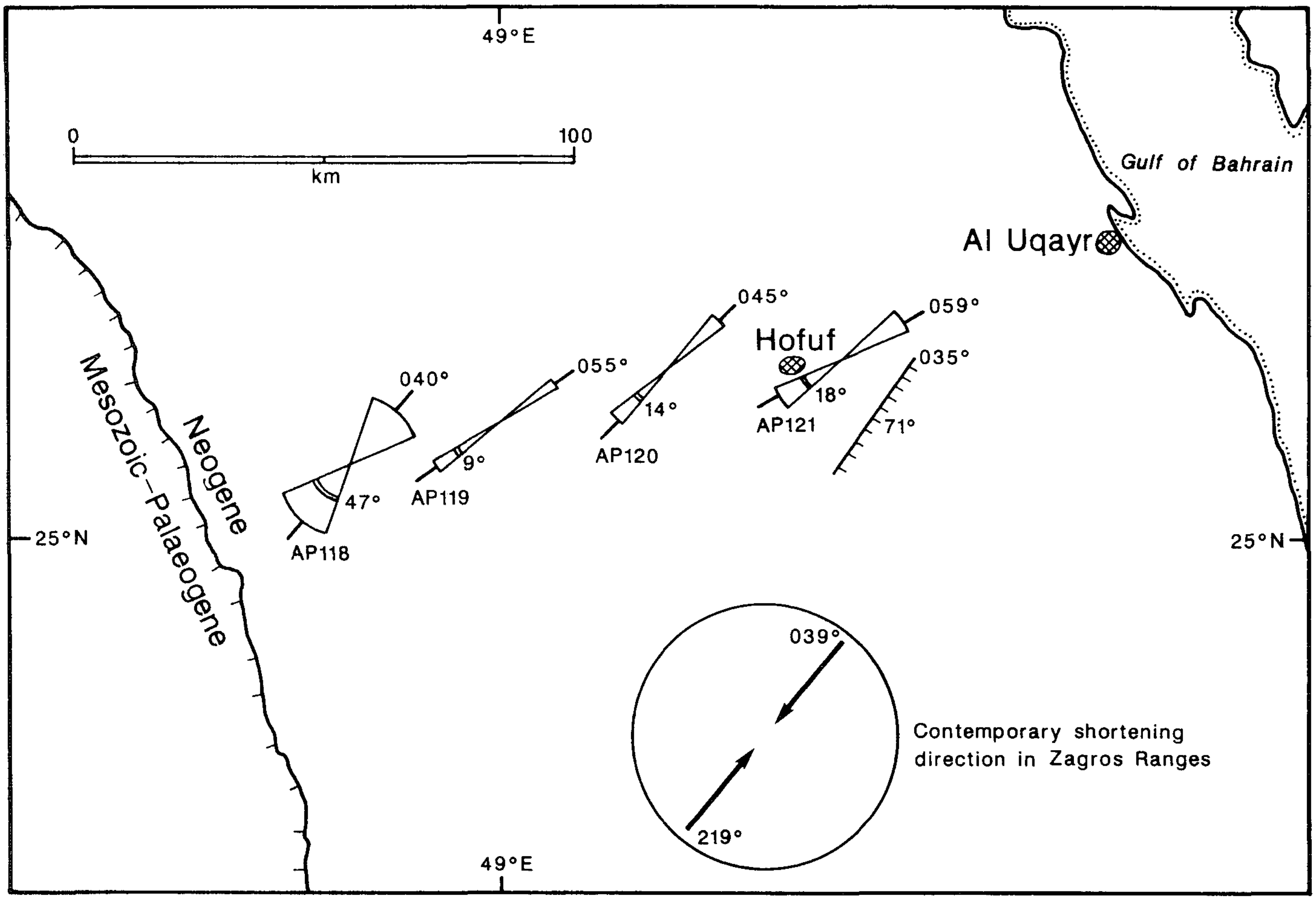


Figure 3. Strike directions of neotectonic vertical joints cutting the flat-lying Miocene-Pliocene Hofuf Formation in the east of the Arabian platform. The dispersion of strike directions in a set or spectrum is stated as an angle and depicted by a double "fan." The mean strike of joints in a set or spectrum is shown by a solid line and as an azimuth. The mean orientation of a set of steeply inclined joints at station AP121 is given separately. Inset shows the average direction (Jackson and McKenzie, 1984, Fig. 34) of slip vectors determined from fault-plane solutions of active thrusting events in the Zagros Ranges, on the northeast shore of the Arabian Gulf, and within the Arabian plate.

nian siltstones and shales, are superimposed obliquely on at least two cross-fold joint sets that relate to the late Paleozoic Alleghanian orogeny (Parker, 1942; Geiser and Engelder, 1983). Furthermore, they strike uniformly throughout a region of varied relief and, hence, are unrelated to purely topographic effects. Where abutting relationships can be established, these east-northeast joints postdate the two cross-fold sets (Engelder, 1982). Data from drill holes show that east-northeast joints are shallow, suggesting that they propagated during the final and most recent phase of Appalachian tectonics, uplift, and erosion (Engelder, 1985). The idea is that effective stresses necessary for propagation of shallow-formed joints are generated during uplift and erosion (for example, Narr and Currie, 1982).

Southeast England and Northeast France

The northwest-striking late Cenozoic joints cutting Upper Cretaceous chalks and Paleogene sands and clays in southeast England and northeast France are likewise superimposed on older joints, in this instance related to north-south contraction during the "Helvetic" phase of Alpine mountain building (Fig. 2) (Bevan and Hancock, 1986). *In situ* stress measurements and fault-plane solutions of earthquakes listed by Bevan and Hancock (1986) and published before their study appeared, indicate that external to the area investigated by Bevan and Hancock, the direction of contemporary horizontal maximum stress is commonly oriented northwest-southeast. The joints in southeast England/northeast France are uniformly oriented throughout a region of 10^5 km^2; they control rather than are controlled by local topography.

The Arabian Platform

Although no published *in situ* stress measurements or fault-plane solutions are available for the "stable" interior of the Arabian subplate, the northeast-southwest direction of slip vectors of active thrusting events in the neighboring Zagros Ranges on the northeast margin of the Arabian subplate is known from numerous fault-plane solutions (Fig. 3) (Jackson and McKenzie, 1984). In the Miocene-Pliocene Hofuf Formation of the eastern Arabian platform, the horizontal, massive sandy limestones are cut by a single system of east-northeast– to northeast-trending joints, which

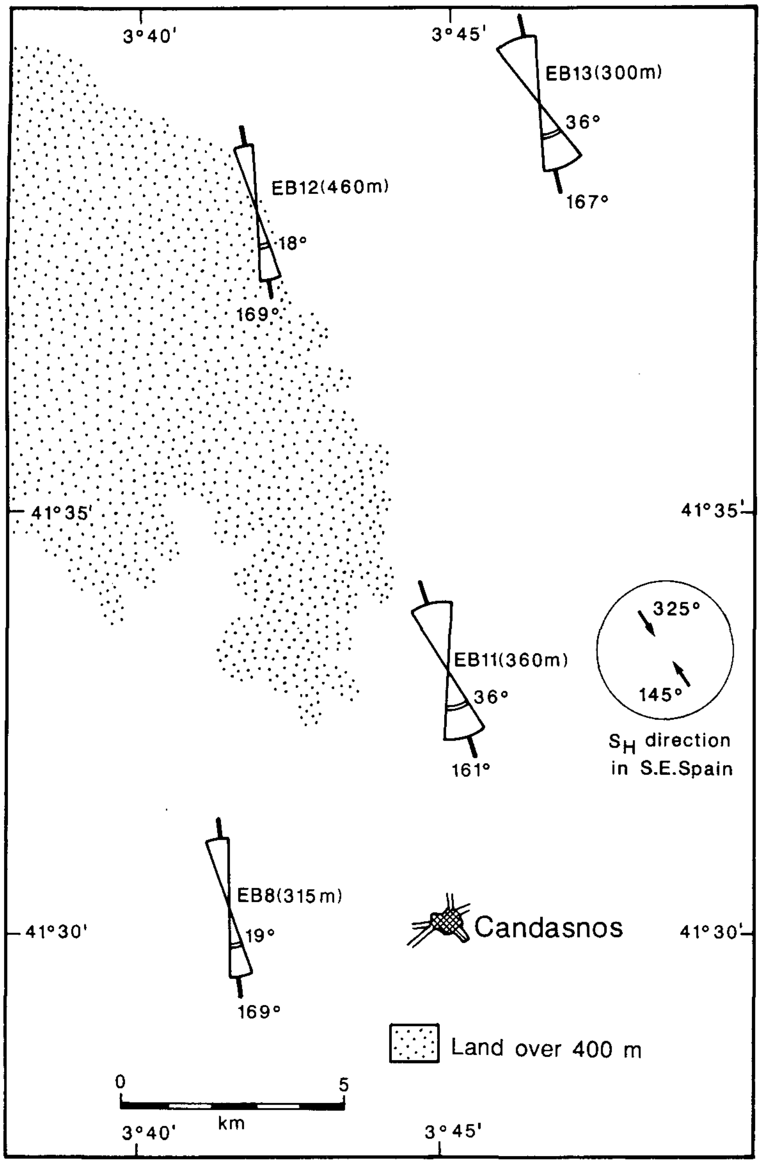


Figure 4. Strike directions of neotectonic vertical joints in flat-lying Miocene limestones in the Candasnos area, Ebro basin, Spain. The dispersion of strike directions in sets or spectra is stated as an angle and depicted by a double "fan." The mean strike of joints in a set or spectrum is shown by a solid line and as an azimuth. The approximate height above sea level of each station is given in meters. Longitudes are east of a datum meridian through Madrid and are taken from sheet 110 (Gelsa) of the Cartografía miltar de España (1954). S_H direction in southeast Spain (insert) from Letouzey (1986, Fig. 3).

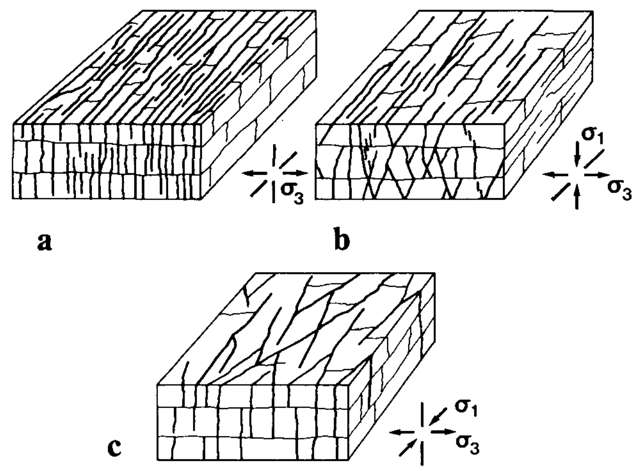


Figure 5. Characteristic neotectonic joint systems. (a) Single set of systematic vertical extension joints (heavy lines) linked by nonsystematic cross-joints (thin) lines. (b) A spectrum of systematic joints (heavy lines) comprising vertical extension fractures and steep conjugate fractures enclosing a range of dihedral angles of less than 45°. Two steep fracture directions are expressed by arrays of *en échelon* vertical joints. Nonsystematic joints (thin lines) link systematic joints. (c) A spectrum of systematic joints (heavy lines) comprising vertical extension fractures and vertical conjugate fractures enclosing a range of dihedral angles of less than 45°. Nonsystematic joints (thin lines) link systematic joints. σ_1, maximum effective principal stress; σ_3, minimum effective principal stress.

locally pass up into the lower levels of a thick duricrust (paleosol) layer, dated as latest Pliocene–Quaternary (see Hancock and others, 1984). The joints in the Hofuf Formation, which are uniformly oriented throughout an area of 10^4 km^2, only a small part of the region shown in Figure 3, were interpreted by Hancock and Bevan (1987) as products of early Pliocene lateral foreland extension that occurred just before the climax of northeast-southwest shortening in the Zagros Ranges.

Ebro Basin, Spain

North-northwest-striking joints cut Miocene fresh-water chalky limestones intercalated with unjointed calcareous mudstones near Candasnos, in the center of the Ebro basin, north Spain (Fig. 4). These late Cenozoic joints are regarded as neotectonic because, at a locality 18 km east of Candasnos, they are the last-formed systematic fractures and display no signs of having been reactivated within north-northeast-striking normal fault zones. In the western part of the Ebro basin, similar north-northeast-striking normal faults are thought to be middle late Miocene (Gracia Prieto and Simon Gomez, 1986). The north-northwest-striking joints near Candasnos are uniformly oriented throughout the area, their strikes being unrelated to the trends of slopes bounding mesas. The strike of the joints is unchanged in the western part of the Ebro basin near Tudela, 150 km west-northwest of Candasnos. Furthermore, the north-northwest joints strike subparallel (<20°) to the direction of the present maximum compressive stress axis as determined from microtectonic data in southeast Spain (Letouzey, 1986).

GEOMETRY OF JOINT SETS

The geometry of the neotectonic joint systems in the previously investigated case-study terrains is characterized by simplicity, irrespective of

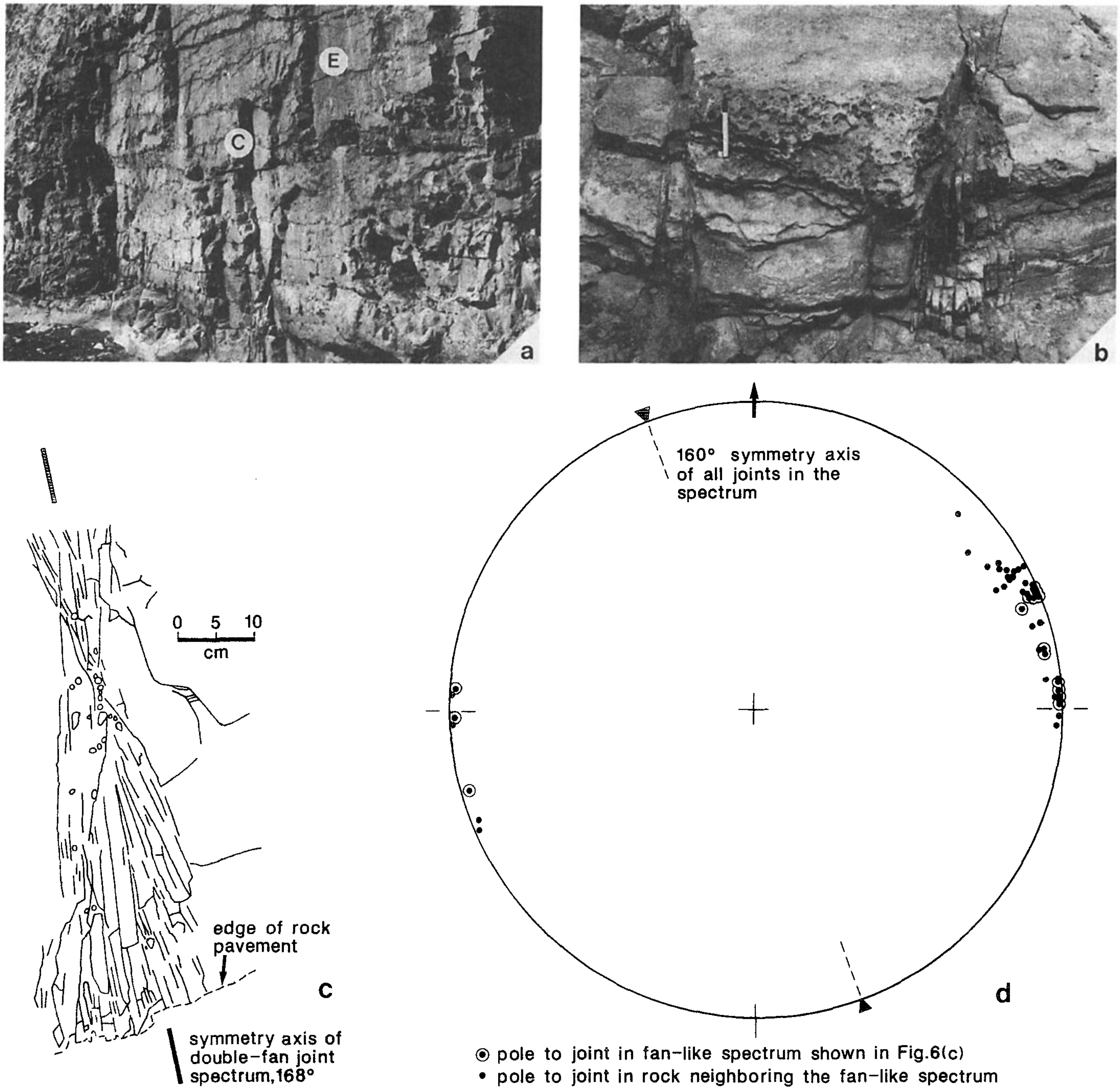


Figure 6. Neotectonic joints cutting horizontal limestones. (a) Vertical closely spaced northwest-striking systematic extension joints (E) within a joint swarm. Vertical nonsystematic cross-joints (C) abut the systematic joints. Upper Cretaceous chalk, Pegwell Bay, Kent, England. Exposure is about 2 m high. (b) Part of a double fan of fractures (right of the pen) belonging to a joint spectrum (angular continuum of joint orientations) cutting a bed of upper Miocene limestone. Las Bardenas area of the Ebro basin, north Spain. (c) Line drawing from a photograph, looking down on the double-fan joint spectrum shown in part b. The symmetry axis of the spectrum trends subparallel to the mean strike of all neotectonic joints in the Candasnos region (Fig. 4), about 150 km east-southeast of Las Bardenas. (d) Lower-hemisphere equal-area projection of poles to all systematic joints at the locality containing the double-fan joint spectrum illustrated in parts b and c.

whether they cut previously intact or already fractured rocks. The commonest assemblage comprises vertical joints that are either parallel to each other or dispersed less than 10° about the mean orientation of the set (Figs. 5a, 6a, and 7a). Joints belonging to a single vertical set are interpreted as extension fractures (that is, mode I cracks) formed perpendicular to the effective minimum principal stress axis (σ_3). The principal reasons for this interpretation are as follows. (1) Some joint planes bear delicate plumose marks. (2) Rare veins parallel to the joints contain growth fibers oriented normal to vein margins. (3) At many localities, the single set is the only systematic set in the sense of Hodgson (1961). (4) Where the set occurs in

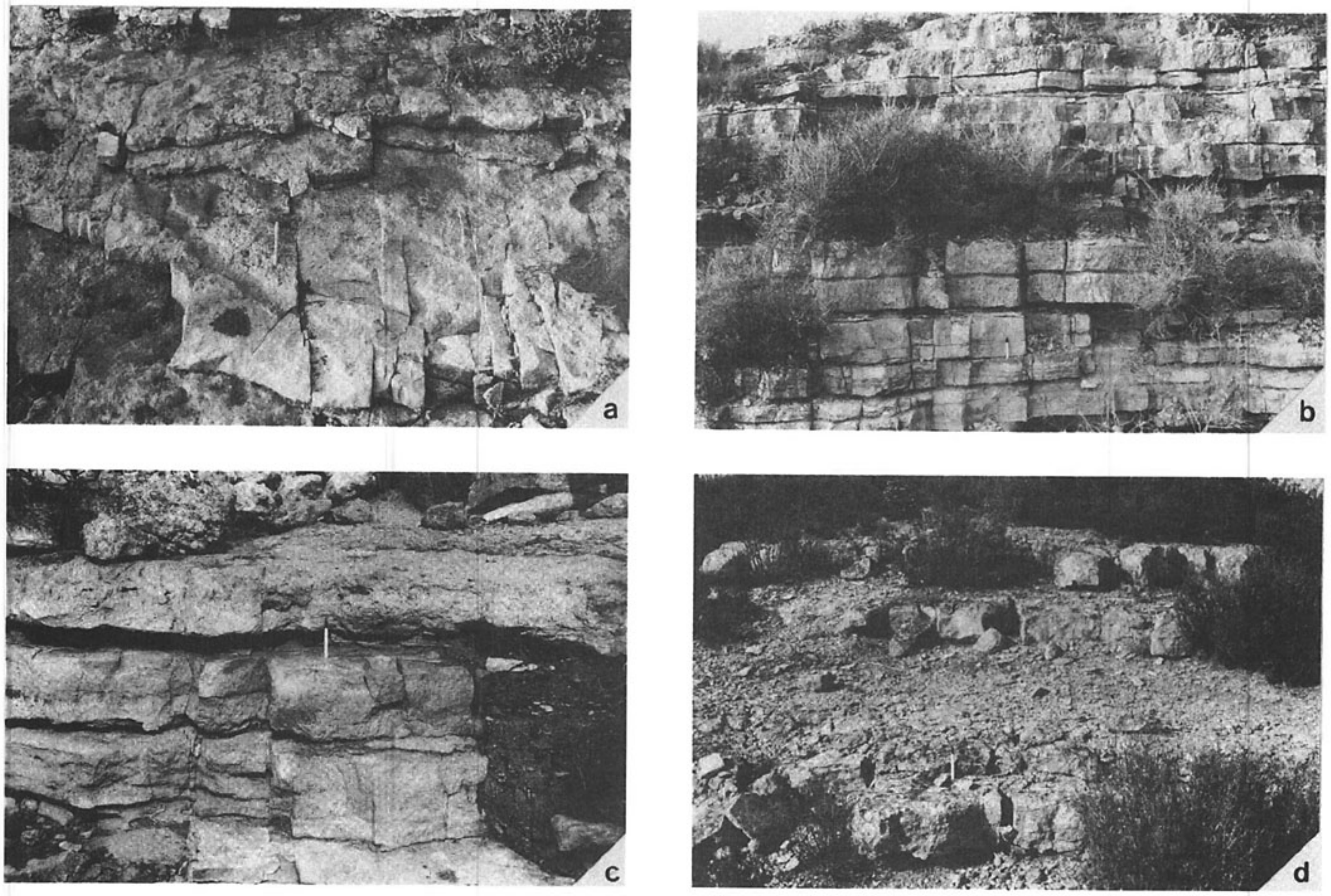


Figure 7. Vertical neotectonic joints cutting horizontal Miocene limestones in the Ebro basin, Spain. (a) Oblique view of closely spaced, planar systematic joints linked by poorly developed nonsystematic joints, at station EB8 (315 m above sea level), 5 km west of Candasnos. Pencil for scale. (b) Profile view of closely spaced, planar joints also at station EB8. The systematic extension joints are abutted by a few nonsystematic cross-joints parallel to the plane of the photograph. 13-cm pen for scale. (c) Profile view of moderately spaced joints at station EB11 (360 m above sea level), 5.5 km north of Candasnos. 13-cm pen for scale. (d) Profile view of widely spaced irregular joints at station EB12 (460 m above sea level), 16 km north-northwest of Candasnos. 13-cm pen for scale. Locations of stations are given in Figure 4. Note the increase in joint spacing from station EB8 through EB11 to EB12, as the horizontal succession is ascended.

conjunction with other neotectonic joints, it bisects the acute angle between conjugate sets.

In all four case-study terrains, a less abundant, but nevertheless typical, neotectonic joint pattern comprises steep conjugate joints striking parallel to a neighboring single vertical set (Fig. 5b). Steep conjugate joint sets, which have an outcrop pattern resembling chicken-wire fractures, appear in some upper but muddier parts of the Devonian succession of western New York State, whereas in the central part of the state, lower silt and shale units are cut by a single set of joints. Conjugate joints strike parallel to locally developed late Cenozoic topography in western New York and postdate cross-fold joint sets (Engelder, 1989). Those joints with a dip direction pointing downslope become more prominent in the near surface. The conjugate joints nevertheless strike parallel to the contemporary tectonic stress field. This correlation of dip with Cenozoic topography is the strongest evidence supporting a neotectonic age for the east-northeast joints of the Appalachian Plateau. Steep conjugate joints generally enclose dihedral angles (2θ) in the range of 10°–45°.

At a few stations in the Arabian platform (Fig. 3) and Ebro basin (Figs. 4, 6b, and 6c), well-ordered conjugate steep or vertical sets are replaced by a continuum of joint orientations with an angular dispersion of as much as 45° about a symmetry axis that is either vertical or trends parallel to the mean strike of a nearby single joint set (Figs. 5b, 5c, 6b, 6c, and 6d). Hancock (1986) has called a coaxial angular continuum of joints enclosing a dihedral angle up to a maximum of 60° a "joint spectrum" if it is interpreted as comprising more than one fracture class and is contained in a small (<5,000 m^3) volume of rock. At station AP121 in eastern Arabia (Fig. 3), there is a 24° difference between the mean strikes of vertical and steep joints, which may, because steep joints penetrate higher into the Pliocene-Quaternary duricrust, reflect an anticlockwise rotation of the horizontal maximum stress during the cycle of neotectonic jointing. It is noteworthy that the steep joints (Fig. 3) strike within 4° of the averaged contemporary shortening direction in the Zagros Ranges of Iran (Jackson and McKenzie, 1984) (Fig. 3).

JOINT ARCHITECTURE, SPACING, AND SURFACE MORPHOLOGY

The architectural styles (Hancock, 1985) of neotectonic joint systems are simple. In plan, the commonest pattern comprises short irregular nonsystematic cross-joints abutting but not crossing the members of a single set of neotectonic systematic joints (for example, Figs. 5a and 7a). Cross-joints are absent or rare at some localities. Systematic conjugate joint traces either abut each other (for example, Figs. 5b and 5c), or more rarely they cross (Figs. 6b and 6c). Nonsystematic cross-joints link but do not cut some vertical conjugate joints (Fig. 5c). The abutting relationships between conjugate neotectonic joints (Figs. 5b and 5c), which demonstrate that each set contains some members that are older and some members that are younger than those in the other one, are, in our experience, characteristic of most conjugate fracture sets. Although such sets are formed approximately simultaneously, each individual fracture reflects a separate failure event within a single structural phase.

The spacing of shallow neotectonic joints, like that of other joints, varies with such parameters as the bed thickness, lithology, structural setting, and depth of burial of the host sequence. Neotectonic joints are closely spaced (1–20 cm) in weak and relatively thin beds, such as the Cretaceous chalks of southeast England and northeast France (Fig. 6a) or the Miocene limestones of the Ebro basin (Figs. 7a and 7b). In stronger or more-massive beds, average joint spacing is commonly much greater (Fig. 8) and may, in rocks cut by older joints, be several meters. Whereas neotectonic joints cutting previously intact rocks are reasonably periodic (that is, evenly spaced), those superimposed on previously jointed rocks are commonly nonperiodic, with close joints restricted to narrow joint zones (Fig. 6a) that are themselves widely spaced. The spacing range of neotectonic joints in the Candasnos area of the Ebro basin varies with the present elevation of the outcrop (Fig. 4). At about 300 m (stations EB8 and EB13), beds of comparable thickness contain joints with average separations of 2–20 cm (Figs. 8a and 8b); between 350 and 400 m (station EB11), separation is 10–30 cm (Fig. 8c), whereas at >400 m (station EB12), a few meters below the summit level of the mesa, there are no closely spaced joints, separations commonly being 20–50 cm (Fig. 8d). The increase in spacing is accompanied by a corresponding decrease in planarity of joint surfaces.

The planarity of joints interpreted as neotectonic also decreases upward through the Devonian sequence of the Appalachian Plateau. In the lower shale and siltstone units of the succession, neotectonic joints are smooth planes, in contrast to the higher mudstone units in which many of the steep joints are irregular and anastomose with each other. Both vertical and steep neotectonic joints in the mudstone units are parallel to the contemporary tectonic stress field, despite being far less regular then their counterparts deeper in the section (Engelder, 1989). On the basis of core data, the neotectonic joints of the Appalachian Plateau are characteristic structures of only the uppermost 0.5 km of the crust. This suggests that the upward decrease in planarity in the Devonian rocks of the Appalachian Plateau is lithologically controlled. In contrast to the Ebro basin and Appalachian Plateau, all neotectonic joints in the chalks of southeast England and north France are smooth planar surfaces.

Average sizes of shallow neotectonic joints in the Appalachian Plateau and south England/north France are relatively great (for example, 10 × 5 m) compared with older joints in the same settings. Furthermore, most of the surveyed neotectonic joints in these two regions are also multiple-layer joints (Bahat, 1989). Neotectonic vertical joints in the Hofuf Formation of east Arabia are also large (Figs. 8a and 8b). The only small shallow neotectonic joints surveyed by us occur in the Candasnos and Bardenas areas of the Ebro basin, where systematic joints are limited to <2-m-thick limestones interbedded with mudstones not containing systematic joints (Figs. 7b and 7c).

Although rare, a few neotectonic joints in the Appalachian Plateau display a surface morphology that consists of plumose structures and arrest lines. Such a morphology is indicative of a mode I crack that opens in extension (Kulander and Dean, 1985). The orientations of the arrest lines indicate that on average, the propagation direction for Appalachian neotectonic joints was normal to bedding (that is, vertical). This is in contrast

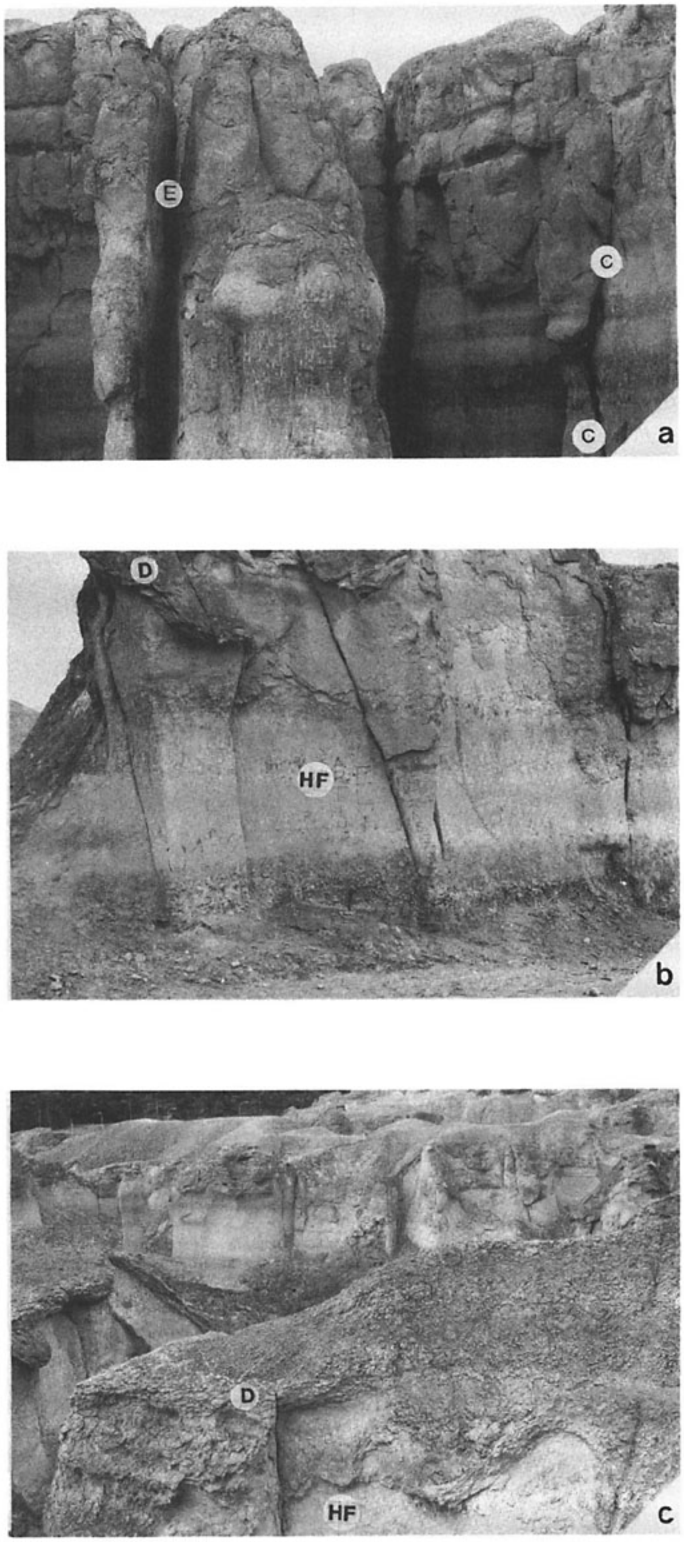


Figure 8. Neotectonic joints cutting the horizontal Miocene-Pliocene Hofuf Formation in the east of the Arabian platform. (a) Vertical extension joints (E) and steep, possibly conjugate, joints (C). Cliff is about 20 m high. (b) Steep joints cutting the Hofuf Formation (HF) and penetrating the duricrust layer (D). Hammer for scale. (c) Vertical extension joints cutting the Hofuf Formation (HF) and penetrating the lower part of the duricrust layer (D). All structures exposed at station AP121 (Fig. 3), 11 km west of Hofuf, Saudi Arabia.

to most Alleghanian tectonic joints, which propagated in a vertical plane in an over-all direction that was parallel to bedding, according to the orientation of the plume axes (Kulander and Dean, 1985). Plumose structure was not observed on joints in southeast England/north France, the Ebro basin, and east Arabia, perhaps because the host rocks are porous carbonates or carbonate-rich sandstones, lithologies unreceptive to plume development.

Systematic neotectonic joints are the youngest tectonic structures in all of the study areas. They are, however, older than superficial nonsystematic cross-joints of nontectonc origin that abut and link them (Figs. 5, 6a, and 7b). Although some systematic neotectonic joints in the Appalachian Plateau and south England/north France abut older systematic joints, many of them cut older systematic joints where the latter joints are partly sealed.

A noteworthy attribute of many large (>25 m^2) vertical neotectonic joints cutting older joints in the Appalachian Plateau and south England/north France is that they are slightly gaping (1–10 mm), rather than being tight and closed. Smaller neotectonic joints in these regions, and in the other study areas, are generally tight.

CONTEMPORARY STRESS FIELD AND NEOTECTONIC JOINT DIRECTIONS IN SOUTHEAST ENGLAND

When Bevan and Hancock (1986) wrote their account of late Cenozoic joints in southeast England/north France, there were no published *in situ* stress measurements for the region of southeast England that was surveyed by them. They based their hypothesis that the joints reflect the neotectonic stress field on the following two relationships. (1) Joints in the northwest-striking system are younger than those related to north-south Oligocene-Miocene contraction. (2) Joints in the northwest-striking system are parallel to the northwest-southeast direction of S_H as determined from overcoring and hydraulic fracture measurements, and earthquake focal mechanisms, in areas external to that surveyed by Bevan and Hancock.

Bevan and Hancock's (1986) prediction that S_H in southeast England might be oriented approximately northwest-southeast receives support from Brereton and Evans (1987), who have recently analyzed borehole breakout data made available to the British Geological Survey. They have shown that the average orientation of elongation azimuths in more than 50 wells is 052°–232°, that is, parallel to the direction of extension determined by Bevan and Hancock (1986) from geologic indicators (Fig. 2). The point is that a prediction of S_H was later justified with breakout data.

LATE-FORMED JOINTING IN THE APPALACHIAN VALLEY AND RIDGE

The inventory of attributes of neotectonic and late-formed joints compiled from regions of simple structure and where the rocks are either young or the arrangement of the contemporary stress field is known can be applied to the problem of identifying the orientation of the contemporary tectonic stress field in a structurally complicated terrain, such as the Valley and Ridge province of the central Appalachian Mountains, where *in situ* stress measurements are rare and widely spaced. The Valley and Ridge is extensively jointed, with several sets of Alleghanian joints rotated with bedding (Nickelsen, 1979). Joints and fractures were mapped in the Nittany anticlinorium in the vicinity of State College, Pennsylvania, in an effort to identify late-formed joints associated with the contemporary tectonic stress field.

The Nittany anticlinorium, the outermost (northwesternmost) fold in the Valley and Ridge province, is a first-order fold with a wavelength of more than 10 km. Data from drilling and reflection seismology suggest that the anticlinorium contains in its core a duplex of carbonate panels, the uppermost panel being exposed at the surface (Gwinn, 1970). In the vicinity of State College, the average strike of the first-order structures, including the Allegheny Front, is N57°E. The Nittany Mountain syncline is a second-order fold plunging to the east-northeast within the Nittany anticlinorium (Fig. 9). A traverse of outcrops in the Bellefonte dolomite and Axemann limestone across the southwestern nose of the east-northeast–plunging syncline permits observations of joints in beds with attitudes ranging from a north-northeast strike, dipping east-southeast, through a northwest strike, dipping gently to the northeast, to an east-northeast strike, dipping north-northwest. This range of bedding attitudes may be viewed along the Nittany Expressway east of State College. The following discussion focuses on three outcrops along the Nittany Expressway with different bedding attitudes: (a) southeast-dipping beds of the Bellefonte dolomite, (b) northwest-dipping beds of the Bellefonte dolomite, and (c) almost flat-lying beds of the Axemann limestone. These outcrops correspond to locations A, B, and C in Figure 9.

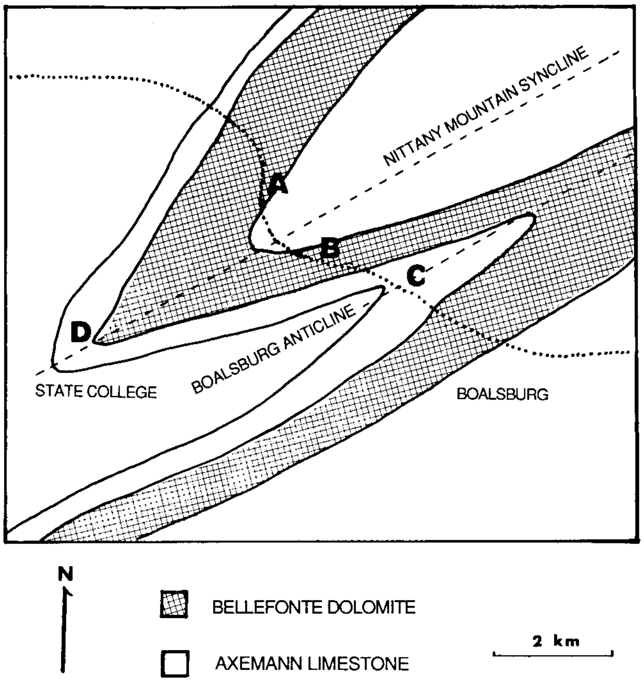


Figure 9. Map of the Nittany Mountain syncline in the vicinity of State College, Pennsylvania. Outcrop locations A–D refer to Figures 10 and 11.

Fractures in the Bellefonte dolomite and Axemann limestone in the Nittany anticlinorium include five distinct types, which can be identified, on the basis of their orientation, filling, size, and present aperture, as bedding-parallel veins, strike veins, cross-fold veins, cross-fold joints, and late-formed vertical joints (Srivastava and Engelder, 1989). Fracture orientation data are plotted in lower-hemisphere projection within which general joint sets are identified (Fig. 10). When bedding is rotated to horizontal, both strike veins and cross-fold joints are orthogonal to the major structural trend of the Nittany anticlinorium (that is, N57°E). These structures are pre-folding, as indicated by the lack of local congruence with the nose of the Nittany Mountain syncline and general orthogonality with bedding (Fig. 10). Strike veins are in many cases restricted to one bed and are normal to the bed regardless of the dip of that bed. Two sets of

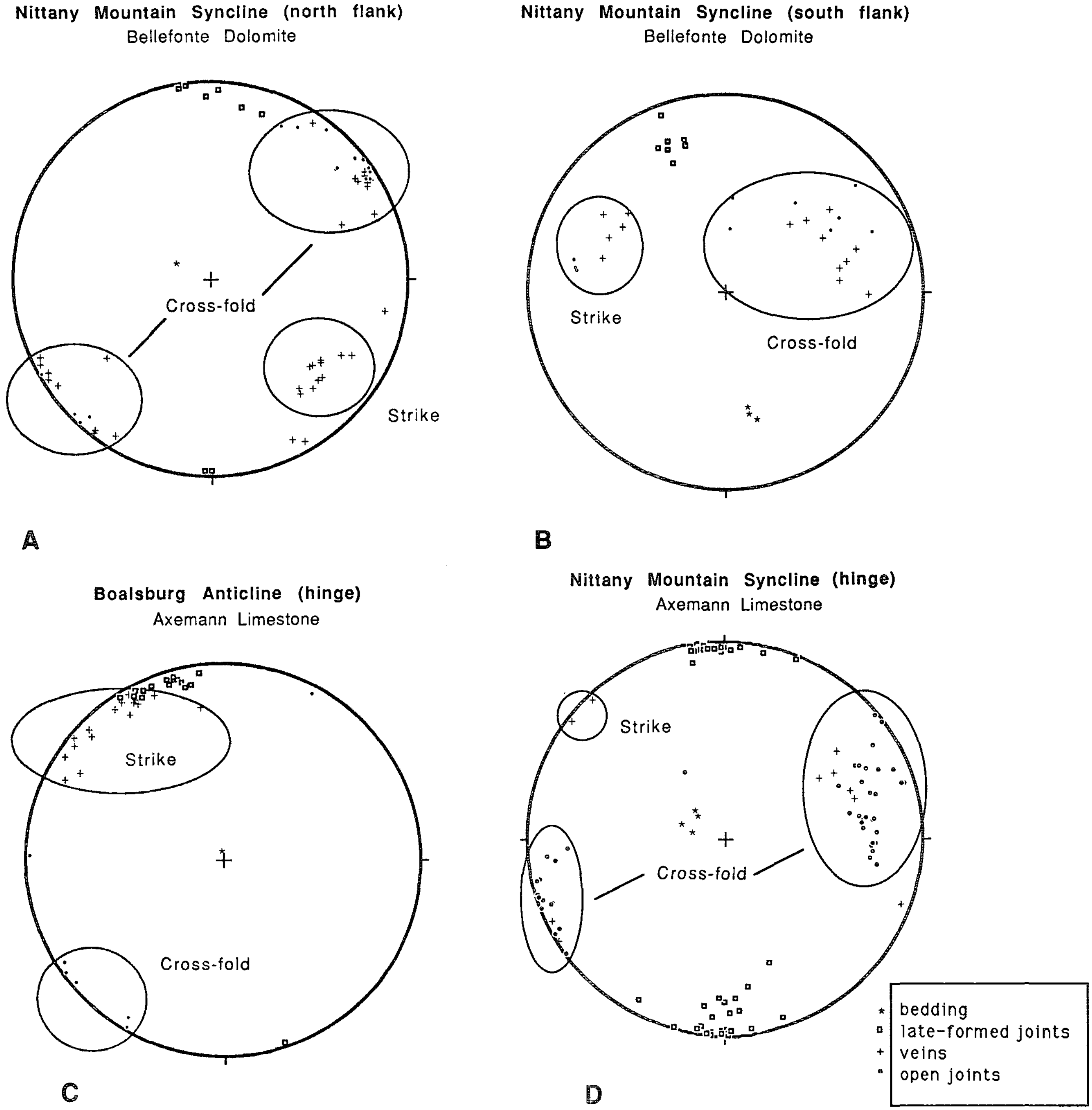
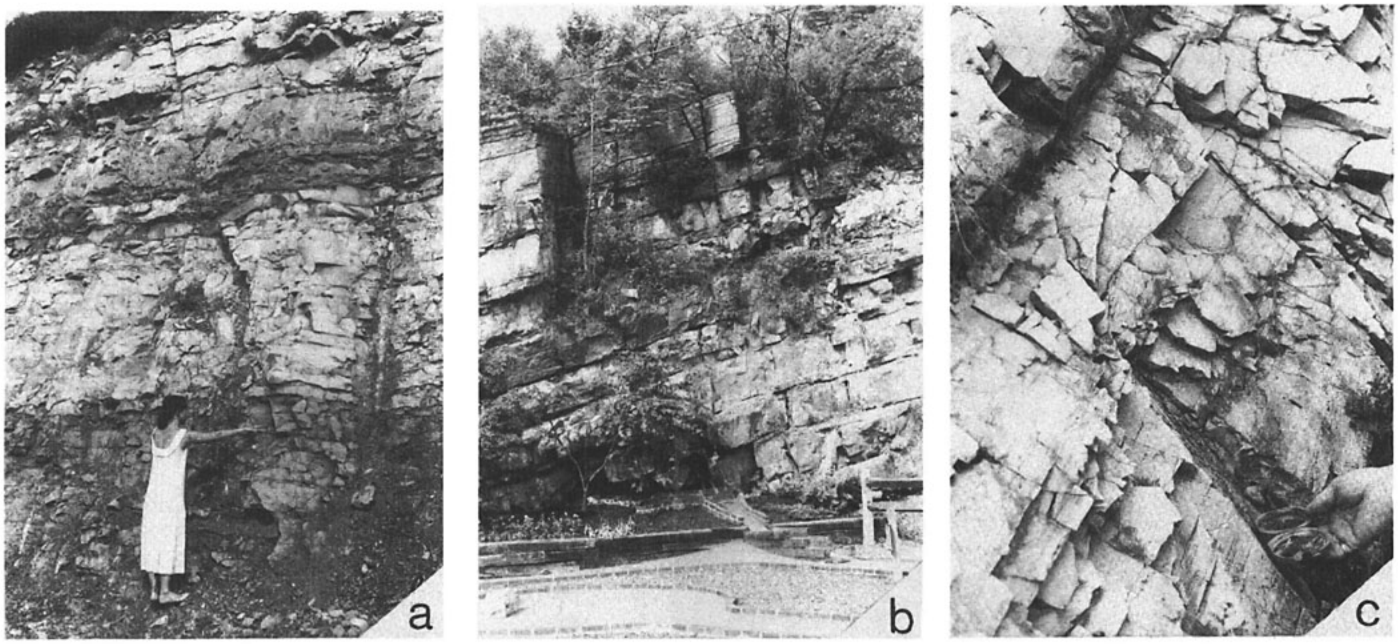


Figure 10. Lower-hemisphere equal-area projections of poles to fractures in the Nittany anticlinorium in the vicinity of State College, Pennsylvania. Ellipses indicate grouping of data and have no statistical significance. Although bedding-parallel veins are not shown, their poles would plot in the vicinity of poles to bedding. A, B, C, and D are station locations shown in Figure 9.

cross-fold joints are present, with one open and the other filled. Both cut and hence postdate the strike veins (Srivastava and Engelder, 1989). The presence of more than one cross-fold joint set is common in the Valley and Ridge as well as in the Appalachian Plateau (Nickelsen, 1979; Engelder and Geiser, 1980). As the beds of the Nittany syncline rotated about their fold axis, the cross-fold joints were tilted, depending on the attitude of the bed relative to the nose of the Nittany Mountain syncline (Fig. 10). Cross-fold joints are highly weathered and are potential grikes (Wyalt, 1986). Some cross-fold joints show large amounts of dissolution, which is a reflection of the initial stage of the development of a karst system of interconnected caves common in the Valley and Ridge.

Overprinted on the orthogonal joints and veins of pre-Alleghanian or



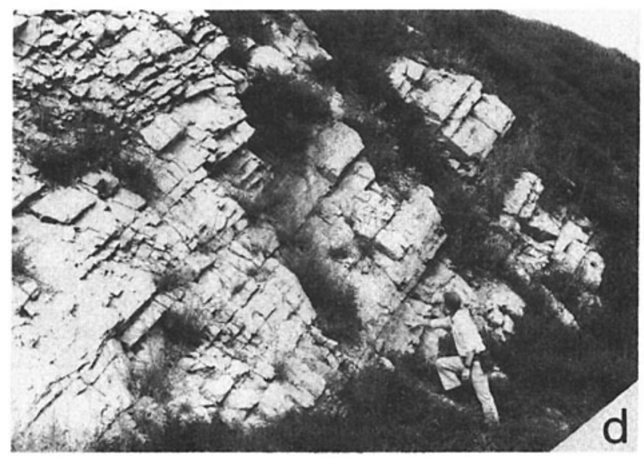


Figure 11. Outcrops of the Lower Ordovician carbonates in the Nittany anticlinorium in the vicinity of State College, Pennsylvania. (a) Bellefonte dolomite at outcrop A (Fig. 9) on the north flank of the Nittany Mountain syncline. Beds dip directly into the outcrop, and the face of the outcrop tilts back from the camera. A geologist points to a late-formed joint cutting vertically through the tilted face. (b) Axemann limestone at outcrop D on the nose of the Nittany Mountain syncline. In this outcrop, an angular continuum of open joints strikes parallel to the late-formed joints at outcrops A, B, and C. (c) Bellefonte dolomite at outcrop B on the south flank of the Nittany Mountain syncline where view is to the northeast. Beds dip to the north. The compass is on an example of a late-formed joint refracting parallel to bedding during propagation. (d) Bellefonte dolomite at outcrop B on the south flank of the Nittany Mountain syncline where view is to the northeast. The late-formed joints dip to the southeast (right), whereas strike joints are dipping at a much gentler angle to the east.

Alleghanian age there is a late set of joints that cuts vertically through many beds with outcrop means striking between N70°E and N91°E (Fig. 11a). These late-formed joints do not display karst-like dissolution. Evidence that this joint set postdates folding rests on the fact that in beds which dip at less than 30°, it is vertical and strikes N80°E ± 20° regardless of the local bedding dip or strike, and on the fact that it is not orthogonal to any fold-related structure. This joint set cuts without deviating through Alleghanian structures, including cross-fold veins. The set possesses different characteristics, depending on the attitude of the beds in which it occurs. In beds dipping 25°S at outcrop A, the late-formed joints cut the entire height of the outcrop in contrast to Alleghanian joints, which are more likely to be restricted to single beds (Fig. 11a). Late-formed joints are not filled, have relatively fresh surfaces with no cross-joints, but in some cases form with conjugate joints (Fig. 11b). Because of the lack of karst-like dissolution, these joints are interpreted as younger than the highly dissolved cross-fold joints. In beds dipping 55°NW, the same joint set is less common, and when it appears, it is canted in the direction opposite to bedding. Where the late-formed joints do not cut bedding planes, they curve into them (Fig. 11c). In contrast, none of the Alleghanian joints refract to be parallel to bedding, but rather they cut across bedding without deflection. When bedding is nearly horizontal, the open joints strike clockwise from strike veins (Fig. 11c). This sense of rotation indicates that the late-formed joints propagated in a different direction from that of strike veins. These late-formed joints compare with neotectonic joints as described in the previous section for the following reasons. (1) They postdate folding, (2) they are not restricted to single beds as compared with some pre-Alleghanian or Alleghanian joints, (3) some form conjugate sets absent in Alleghanian joints of the Nittany anticlinorium, (4) they are more widely spaced than many Alleghanian joints, (5) they have fresh surfaces not displaying karst-like weathering, and (6) they have formed in beds that may have been uplifted more than 3 km.

In the vicinity of State College, Pennsylvania, the outcrop with the most closely spaced late-formed joints is the Axemann limestone in the nose of the Nittany Mountain syncline (Fig. 11b). This outcrop contains a few strike veins as well as two cross-fold joint sets. The degree of last-formed joint development may be lithologically controlled, as indicated by those Axemann outcrops (Fig. 9), which contain more of these joints compared with outcrops of Bellefonte dolomite. In contrast, late-formed joints are impossible to recognize in some of the thin-bedded carbonates of the Valley and Ridge province.

Late-formed joints in the vicinity of State College, Pennsylvania, have an average strike of N80°E, which we use to predict the orientation of S_H of the contemporary tectonic stress field in central Pennsylvania. In fact, a prediction of N80°E for S_H in central Pennsylvania is in good agreement with other data on the stress field in the northeastern United States, where regional stress maps by Sbar and Sykes (1973) and Plumb and Cox (1987) show that the general orientation for S_H is about N75°E. This is part of a very large area of North America that is subject to a uniformly oriented east-northeast-trending S_H direction. The nearest deep hydraulic fracture measurements are each more than 100 km from State College, Pennsylvania, at Bradford, Pennsylvania (N60°E, Overby and Rough, 1968); Alma, New York (N77°E, Haimson and Stahl, 1970); South Canisteo, New York (N68°E in the Wilkins well and N80°E in the Appleton well, Evans and Engelder, 1986); and Auburn, New York (N83°E, Hickman and others, 1985). Measurements of S_H in central Pennsylvania come from borehole breakouts (elongations) showing S_H at N70°E in Clinton County, Pennsylvania, and N77°E in Indiana County, Pennsylvania (Plumb and Cox, 1987). The correlation between the regional S_H direction and the strike of last-formed joints in central Pennsylvania is consistent with the hypothesis that these joints formed under the current stress field. Although the correlation does not prove that these joints formed under the current stress field, we feel that such a correlation is not a coincidence.

DISCUSSION

The general attributes of the structures in the four case-study terrains plus the Appalachian Valley and Ridge might be characteristic of many neotectonic joint systems formed in indurated rocks experiencing horizontal extension at relatively shallow crustal depths. A critical line of evidence indicates development at shallow depth. As demonstrated by Engelder (1985), late-formed joints (that is, east-northeast-striking joints) in the Appalachian Plateau are abundant only to depths from the surface of about 0.5 km. Calculations such as those of Narr and Currie (1982) show that effective tensile stresses may develop in rocks that have more than 50% of their total overburden removed by erosion. These calculations depend on the assumption that rock properties change by diagenesis at or near the full depth of burial (Voight and St. Pierre, 1974). In the western portion of the Appalachian Plateau where burial was on the order of 2 km, effective tensile stresses are most likely to have developed at depths of less than 1 km (data from joints in core suggest that this depth was closer to 0.5 km), and so the propagation of late-formed joints in the northwestern Appalachian Plateau is restricted to depths from the surface of less than 1 km.

We hypothesize that the initiation and propagation of late-formed or neotectonic joints was a consequence of failure in the contemporary teconic stress field during unloading by removal of overburden; fluid pressure, even if it was less than hydrostatic, contributed to failure. Furthermore, we hypothesize that joint spacing is in part controlled by a combination of amount of uplift and ratio of uplift to total depth of burial. Of course, bed thickness, elastic properties, and other parameters also play a role in controlling joint spacing (for example, Ladeira and Price, 1981). The upward increase in spacing of joints in the Candasnos area of the Ebro basin lends support to this hypothesis because the highest beds will have been less deeply buried and have experienced less unloading than the lowest exposed beds have. Whether the propagagion of selected joints from the Hofuf Formation into the lowest levels of the overlying Pliocene-Pleistocene duricrust (Fig. 8) occurred as a result of reflection cracking (that is, the upward propagation of cracks into a weaker cover above a rigid basement) or continued tectonic activity is unknown.

The majority of the neotectonic joints in the study areas are vertical or symmetrical about the vertical. We conclude that they formed when σ_1 was vertical because (1) some steep conjugate joints are parallel or subparallel to nearby normal faults also interpreted as neotectonic, (2) the commonest conjugate joints are steeply inclined and symmetrical about layering, and (3) some vertical neotectonic joints display plumose structures and arrest lines indicating vertical propagation directions. Experiments in fractography indicate that crack propagation occurs normal to σ_3 and in the direction of σ_1 (Kulander and Dean, 1985).

The three types (Fig. 5) of shallow joint assemblages have in common their development in stress fields within which σ_3 is horizontal and effective stress ($\sigma_3 - P_p$) is tensile. The cause of effective tensile stresses in settings where fluid pressures are normal or low is related to lateral relief, itself a result of uplift and thermal cooling (Voight and St. Pierre, 1974). Removal of overburden after burial appears to be a prerequisite for shallow neotectonic jointing. Because extension fractures and small-dihedral-angle conjugate fractures dominate shallow neotectonic joint systems, differential stress during jointing appears to be small. Joint continua at some localities may, if they reflect spectra, attest to small changes in differential stress during failure sequences, or they may express small rotations in principal stress directions.

The 10° mismatch between the averaged direction of S_H and the average strike of late-formed vertical joints in the Appalachian Plateau (Fig. 1) may be a consequence of the contemporary field having rotated slightly during the time interval since the joints were formed. A comparable, but slightly greater, mismatch between the average strike of vertical joints and the inferred contemporary shortening direction in the Zagros Ranges also characterizes the eastern part of the Arabian platform. Despite the possibility of there being slight misalignments of S_H and neotectonic joints in other areas, surveying neotectonic joints remains a potentially valuable technique for the rapid assessment of the orientation of the contemporary stress field. Certainly, in the Valley and Ridge of Pennsylvania, the orientation of late-formed joints, which have the characteristics of neotectonic joints, reflects the orientation of the contemporary tectonic stress field on this area. Furthermore, where neotectonic joints can be discriminated from older joints, they can be removed from the total joint pattern. In the Appalachian Plateau and southeast England/northeast France, the mechanical anisotropy introduced by older joints does not appear to have influenced the orientation of the late-formed or neotectonic joints superimposed on them. Only locally, as for example, in the Appalachian Valley and Ridge, do pre-existing joints affect the orientation of neotectonic joints. This may have been the case in outcrop B (Fig. 10B).

Conjugate Joints with a Small Dihedral Angle

Some neotectonic joints comprise steep conjugate sets that enclose dihedral angles (2θ) in the range of 10°–45°. Hancock (1985) called joints that enclose small dihedral angles "hybrid-shear fractures" and interpreted them as belonging to a failure class transitional between extension fractures and Navier-Coulomb shear fractures showing a conjugate set with a dihedral angle greater than 45°. An empirical basis for in-plane propagation of joints at a small angle to σ_1 was recently established by Cox and Scholz (1988), who observed that in mode 3 loading, the angle between tensile cracking (that is, σ_1) and shear crack propagation decreases with a decrease in normal load (that is, confining pressure). Although Pollard and Aydin (1988) have argued that the following terms are misleading at best and sometimes wrongly applied, Dennis (1972) has called cracks that propagate at a small angle to σ_1 "oblique extension fractures," whereas Ladeira and Price (1981) and Etheridge (1983) have termed them "hybrid extension/shear fractures" and "extensional shear fractures," respectively. Suppe (1985) envisaged fractures of this type being formed during transitional tensile behavior. Price (1977) discussed in detail the conditions leading to the formation of conjugate joints with a small dihedral angle. Support for interpreting some conjugate, steep joints as cracks that propagate at a small angle to σ_1 occurs (1) where steep arrays containing vertical *en échelon* joints are parallel to nearby steep joints (Fig. 5b), (2) where small, steep normal faults are subparallel to the joints (Bevan and Hancock, 1986), and (3) where they enclose an acute dihedral angle symmetrically about vertical joints. Less abundant than conjugate steep joints in study areas other than the Ebro basin are vertical conjugate joints that enclose 2θ angles of less than 45° about an acute bisector parallel to the strike of nearby neotectonic joint sets (Fig. 5c).

PRINCIPAL CONCLUSIONS

(1) Shallow-formed systematic neotectonic joint systems are simple, generally consisting of sets of vertical extension fractures or, less commonly, steep or vertical conjugate fractures striking parallel to, or symmetrically about, the extension fractures. Joint spectra, comprising angular continua of coaxial extension and conjugate fractures, locally replace well-ordered sets.

(2) Many shallow-formed neotectonic systematic joints are large, slightly dilated fractures cutting several layers. Only where thin, weak beds occur in a sequence are large multiple-layer neotectonic joints absent.

(3) Shallow neotectonic joint systems generally form within the upper 0.5 km of the crust when effective σ_3 is both tensile and horizontal and $\sigma_1 - \sigma_3$ is small. Burial followed by unloading as a result of denudation and lateral relief consequent on uplift are prerequisites for the formation of shallow neotectonic joints.

(4) Shallow neotectonic joint systems are of potential value for tracking the orientation of the contemporary stress field even in structurally complex terrains, although there may be a slight misalignment between joint strike and the direction of the greatest horizontal stress.

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