Mesoscopic fault array of the northern Umbrian Apennine fold belt, Italy: Geometry of conjugate shear by pressure-solution slip

STEPHEN MARSHAK *Lamont-Doherty Geological Observatory and Department of Geological Sciences, Columbia University, Palisades, New York 10964*
PETER A. GEISER *Department of Geology and Geophysics, University of Connecticut, Storrs, Connecticut 06268*
WALTER ALVAREZ *Department of Geology and Geophysics, University of California, Berkeley, Berkeley, California 94720*
TERRY ENGELDER *Lamont-Doherty Geological Observatory of Columbia University, Palisades, New York 10964*

ABSTRACT

The strata of the northern Umbrian Apennine fold belt are cut by an array of mesoscopic faults that generally display strike- or oblique-slip offset. The majority of these faults have traces less than a few metres long and represent displacements of < 10 cm. Fault surfaces are associated with stylolites and are coated with elongate calcite fibers, suggesting that movement occurred by the mechanism of pressure-solution slip. Crosscutting relationships indicate that faulting occurred before, during, and perhaps after regional folding. The slip on the faults permitted translations of mesoscopic blocks with respect to one another, thereby accommodating regional strain. There is a great range among fault attitudes, but two clusters forming a conjugate set with about a 90° dihedral angle stand out. The mean trend of left-lateral faults of this pair is N72°E, whereas the mean trend of right-lateral faults is N16°W. The bisector between these two fault clusters is about 15° away from the normal to the regional fold axes. This unusual orientation pattern of mesoscopic faults of the study area may indicate that the mechanics of initiating faults in rocks undergoing pressure-solution deformation is different from that in rocks undergoing purely brittle deformation. Alternatively, the fault pattern may indicate that the faults represent slip on pre-existing fractures. If this latter situation is true, the geometry of the fault array may merely reflect the geometry of the pre-existing joint array.

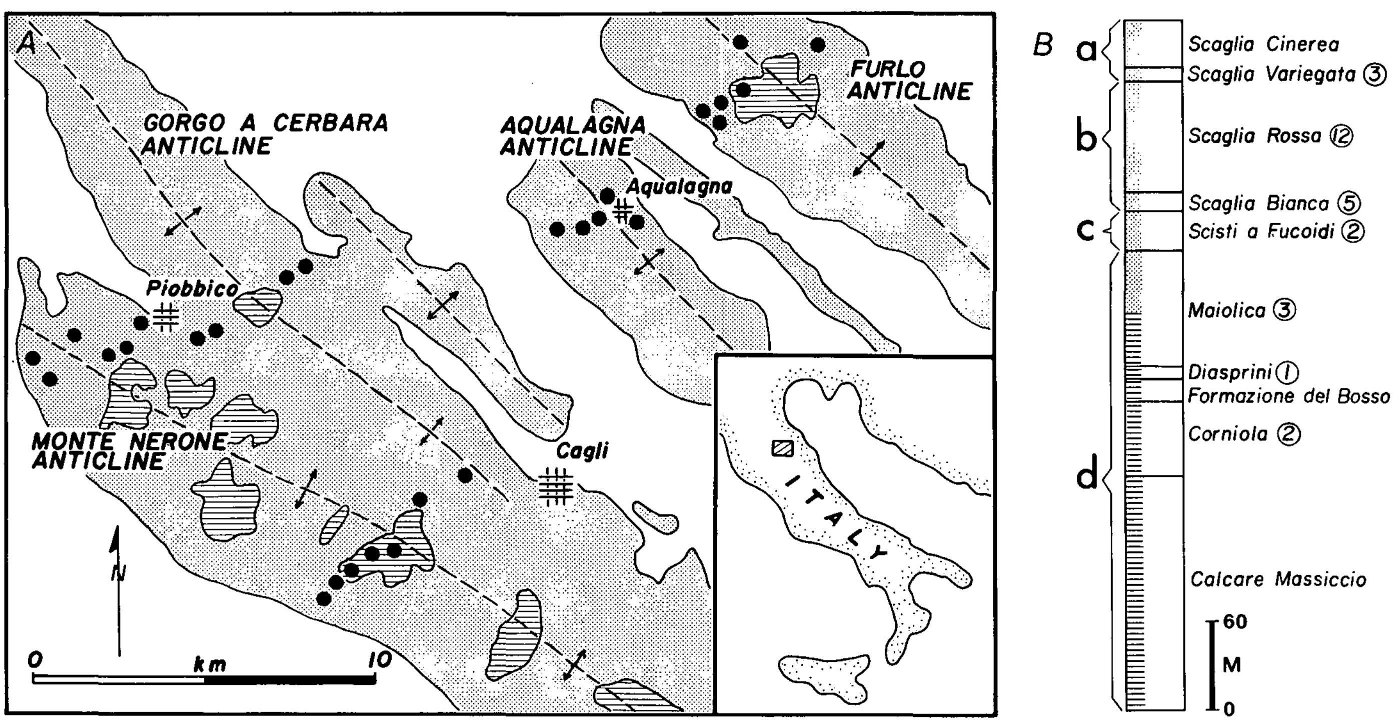

Figure 1. A. Generalized geologic map of the northern Umbrian Apennines. Large dots are sampling stations, white area is post-Eocene pre-flysch marl and turbidite flysch, and dashed lines are anticlinal hinges. In both the map and the column, the shaded area is Cretaceous through Eocene strata, and the ruled area is Jurassic strata. B. Schematic stratigraphic column of the study area. Circled numbers next to formation names indicate number of stations in the unit. Interval a = lower Miocene to Oligocene pre-flysch marl; Interval b = Eocene to Upper Cretaceous thin-bedded pelagic limestone; Interval c = mid-Cretaceous marl; Interval d = Lower Cretaceous to Jurassic limestone.

Geological Society of America Bulletin, v. 93, p. 1013–1022, 7 figs., October 1982.

INTRODUCTION

Mesoscopic faults commonly develop during the deformation of a sedimentary sequence. These faults sometimes define a tightly clustered conjugate set with an acute dihedral angle of 60° (Stearns, 1968). It is commonly implied that sliding on these faults involves brittle deformation (Engelder, 1974). Here we report a situation in which the fault array displays considerable orientation scatter, the dihedral angle between the members of a conjugate fault set in this array is much larger than 60°, and the sliding on the faults does not involve brittle deformation, but rather pressure solution.

Our field area is in the northern Umbrian Apennine fold belt of central Italy, which developed during Miocene-Pliocene time and is composed of large, open, asymmetrical anticlines separated from one another either by tight synclines or by faults (Fig. 1A) (Abbate and others, 1970; Carta Geologica d'Italia at 1:100,000, Gubbio sheet). Recent field studies by Alvarez and Geiser indicate that the folds developed in response to ramping on low-angle detachment faults. In stream-cuts and road-cuts throughout the belt, there are excellent exposures of Jurassic through lower Tertiary marine limestones, marls, and cherts (Fig. 1B) (Bortolotti and others, 1970). The folding and major faulting were accompanied by the development of a pervasive array of mesoscopic faults, stylolites, and veins. Alvarez and others (1976, 1978) have discussed the local occurrences of stylolitic solution cleavage in the area. The present paper focuses on the mesoscopic faults.

We measured 680 mesoscopic faults distributed among 28 stations on two northeast-southwest-trending lines that cross the fold belt approximately normal to the axes of four major northwest-trending anticlines (Fig. 1A). At each station, we measured all mesoscopic faults present in a 1- to 2-m-high band along a 10- to 40-m traverse. Large-scale faults, low-angle detechment surfaces, bedding-plane slip surfaces, and ramps were not included in our data set. Traverses were made at a variety of bearings to avoid sampling bias, and we attempted to obtain data from a variety of stratigraphic levels (Fig. 1B) and from hinge areas and both limbs of the folds, although, because of fold asymmetry, most of our stations were located on the gently dipping southwest limbs.

In this paper, we first describe the faults, then consider factors which might have controlled their orientation pattern. Finally, we discuss the importance of these faults in accommodating regional strain.

OBSERVATIONS

Description of Faults

Traces of the mesoscopic faults range in length from about 10 cm (about the thickness of one sedimentary bed) to several tens of

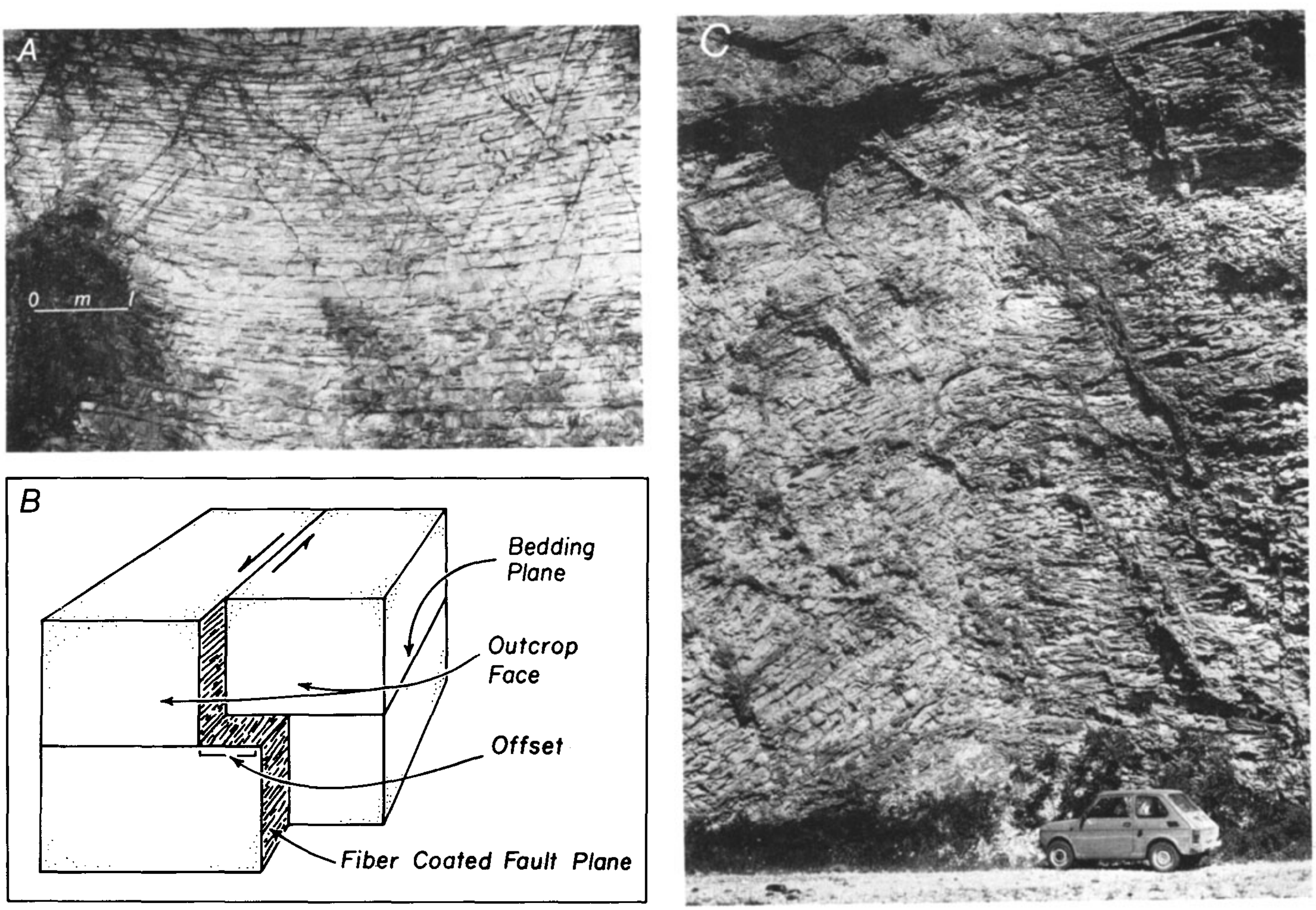

Figure 2. A. Photo of moderately faulted cliff face in Scaglia Rossa on southwest limb of the Aqualagna Anticline. Note the offset of the fault planes at bedding planes. B. Block diagram showing relation of linear fibers on bedding plane to those on offset fault plane. C. Photo of intensely faulted cliff face in Scaglia Rossa on southwest limb of the Monte Nerone Anticline. Fault zones stand out in relief.

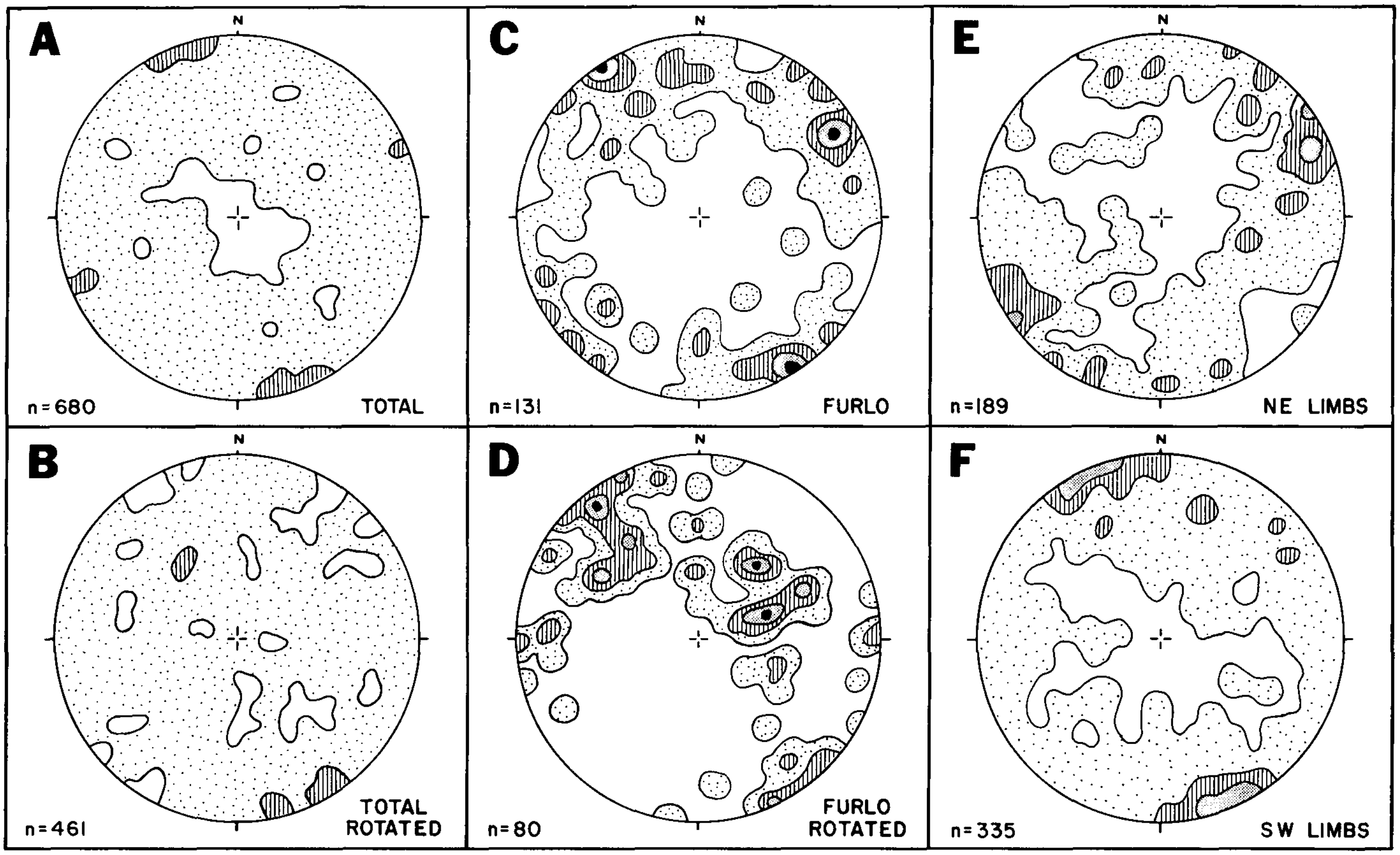

Figure 3. Lower-hemisphere equal-area plots of poles to fault planes contoured at 2%, 4%, 6%, and 8% per 1% area. A and B use total data set summed from 28 stations. C and D are plots of data from the Furlo Anticline alone. E and F distinguish poles of northeast limbs from those of southwest limbs (core areas of folds deleted). "Rotated" plots are those for which the faults have been rotated by the angle necessary to return bedding to horizontal. Faults from zones of mesoscopic folding were deleted in making the rotated plots.

metres (about the maximum observed dimension of an outcrop). The structural characteristics of the fault surfaces correlate to some degree with the trace length.

About 80% of our measurements were of faults whose traces are less than a few metres long. None of these faults has visible offsets exceeding 10 cm, and offset was commonly less than 5 mm. Features of similar trace length and displacement have been labeled "shear fractures" elsewhere (Stearns, 1968). We use the term "fault" for these features because even the smallest ones are coated with elongate calcite fibers, the existence of which implies slip (Durney and Ramsay, 1973), but by using this term, we do not intend to imply anything about the mechanism of fault initiation in an intact rock. Fault surfaces are locally disrupted by two kinds of steps: stylolitic (pressure-solved) or sparry calcite encrusted. Many of the smallest faults, in fact, terminate at such steps. The long axes of the solution pits on the stylolitic steps often parallel the calcite fibers on the fault surface, even where the step surface is not perpendicular to the fault surface.

The larger faults have traces in the range of several metres to several tens of metres but generally are not traceable from one outcrop to the next. Displacements on these faults range from several centimetres to several metres. They are generally curviplanar and locally splay into anastomosing suites of surfaces. All fault surfaces are coated with linear calcite fibers, sometimes in multiple layers with a cumulative thickness of 3 cm. There are a few examples where the orientation of fibers from each layer is different. On many faults, there are individual calcite layers which are 2 to 3 cm thick; the interiors of these thick layers are composed of white blocky crystals. Many of the larger faults are bordered by breccia and gouge zones as much as 30 cm thick; but even the largest fault surfaces are disrupted by stylolitic or spar-encrusted steps. Many of the faults are offset at intersections with bedding planes (Fig. 2A). Of note, the calcite-fiber layer of the fault surface is not disrupted at all of these bedding plane steps but wraps continuously around the steps. In such cases, the long axes of fibers coating the portion of the bedding plane between the offset fault segments parallel those on the fault surface itself (Fig. 2B).

Distribution of Faults

Our 28 stations were situated at various stratigraphic levels and structural positions in the folds. We observed mesoscopic faulting at all but one of these stations, suggesting that mesoscopic faulting almost pervades this portion of the Umbrian Apennine fold belt. Station averages for fault frequencies ranged from 0 to 1.8 faults/m^2 (measured as number of faults cutting each square metre of traverse, averaged over the traverse). High concentrations occurred locally, particularly near major faults (Fig. 2C). The fault arrays are best developed in the well-bedded, homogeneous pelagic limestones of the Scaglia Rossa and Scaglia Bianca, and in the shaly marls of the Scisti a Fucoidi.

Orientation Data

Figure 3A, a contoured, lower-hemisphere, equal-area plot of poles to all fault planes, shows a large scatter of fault attitudes with two vague concentrations. To test whether more clearly defined patterns existed locally, we divided our data into subsets based on location in the fold profile (measurements from northeast limbs, core areas, and southwest limbs were plotted separately) or on position in the fold belt (measurements from each of the four anticlines were plotted separately). The plots for the individual anticlines show two steeply dipping concentrations, one trending north-northwest and the other trending east-northeast. The clearest plot showing this feature, that of the Furlo Anticline, is presented in Figure 3C. Figures 3E and 3F indicate that there may be a preference of north-northwest–trending faults for northeast-dipping limbs and east-northeast–trending faults for southwest-dipping limbs. Rotation of the fault poles by the requisite amount to restore bedding to horizontal (Figs. 3B and 3D) did not decrease the scatter on the contour plots, but merely decreased the dip of one cluster and increased the rake of fibers on faults of the other cluster. Subsequent plots, therefore, are constructed using unrotated data.

We measured the rake of calcite fibers on 92% of the fault surfaces. Figure 4 demonstrates that the majority of faults presently have low-raking fibers; more than 60% have rakes of 20° or less. The mesoscopic faults in their present orientation thus display predominantly strike-slip or oblique-slip offset.

For 174 faults from throughout the field area, we were able to determine the sense of slip from the geometrical relation between the fault plane and its associated pressure-solved or spar-encrusted steps. (This relationship is explained in the next section.) Figure 5A is a lower-hemisphere stereoplot of poles to these fault planes, in which right-lateral and left-lateral faults are distinguished from one another. Figure 5B is a plot of bearing and plunge of fibers for the same data set. We did not contour these data because we have no basis for assuming that this plot is a statistically valid representation of the fault array. These figures demonstrate that left-lateral and right-lateral faults fall in separate clusters. The vector mean of left-lateral faults of Figure 5A strikes N73°E, whereas the vector mean of right-lateral faults strikes N16°W. Thus, the mean trends of these two clusters are 88° apart. A similar pattern is expressed by the plot of fiber lineations.

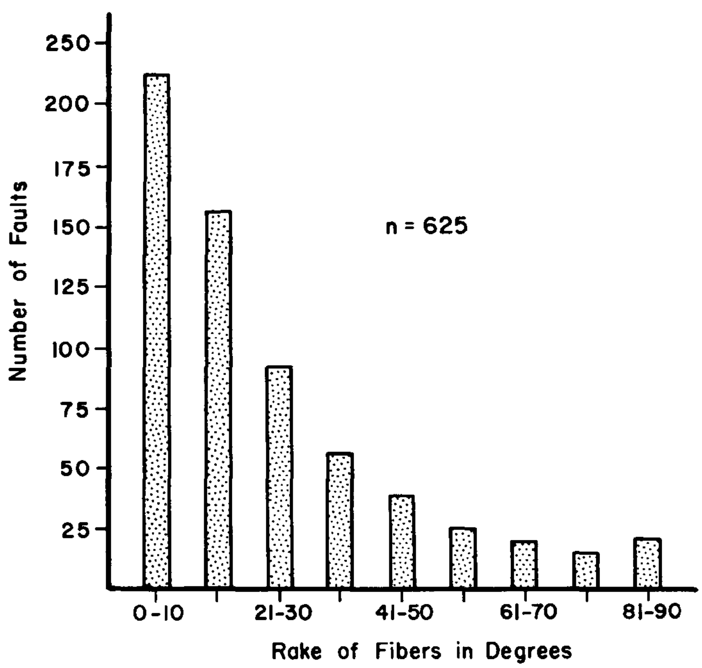

Figure 4. Histogram indicating number of faults that have fibers raking in the indicated range.

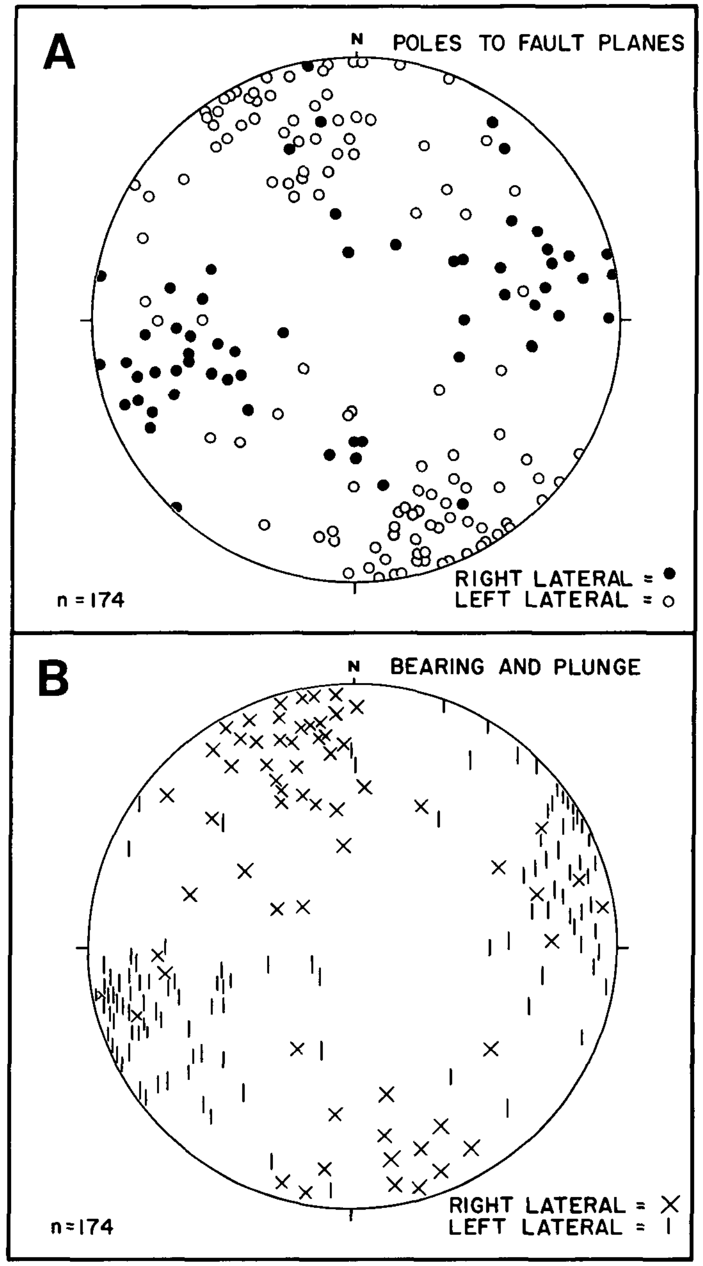

Figure 5. A. Stereoplot of poles to fault planes distinguished by sense of slip. This plot uses faults, for which we had sense of slip data, from both limbs of all the anticlines in the study area. B. Stereoplot of bearing and plunge of fibers on fault planes, using the same data set as in A.

DISCUSSION

Kinematic Relation of Fault Surfaces to Stylolitic and Spar-Encrusted Steps

The relationship of faults to stylolitic (pressure-solved) surfaces was first proposed by Blake and Roy (1949). Several more recent publications (Wagner, 1964; Price, 1967; Arthaud and Mattauer, 1969; Elliott, 1976; Hancock and Atiya, 1979; Laubscher, 1979) have discussed and illustrated this relationship and have also considered the relationship of faults to spar-encrusted steps. These relationships are briefly demonstrated here, in Figure 6A. Consider the continuous fracture X–X′, with rock body "1" (above the fracture) moving to the right with respect to "2". Surfaces parallel to the motion are the mesoscopic faults, and these are coated with linear calcite fibers. The surfaces of steps oriented at an angle to the direction of motion develop either pressure-solution pits or spar encrustations, depending on whether the surface faces toward or away from the direction of motion as illustrated in Figures 6A, 6B, and 6C. Thus, the steps are the mesoscopic equivalent of restraining and releasing bends on large transform faults such as the San Andreas (Crowell, 1974) and can be used to determine the direction of slip on faults. In a situation where the stylolitic step is kinematically related to slip on the fault, the long axes of the solution pits (P in Fig. 6A) parallel the fibers on the slip surface, regardless of whether the step is perpendicular to the slip surface (Blake and Roy, 1949). The fact that fault surfaces have such a wide range of orientations and yet often display the above geometric relationship with associated steps perhaps indicates that the relation between steps and fault surfaces is related to the local stress field as modified by the fault.

Small faults which terminate at stylolitic steps may be thought of as "stylolite transforms," in that the amount of offset that they represent equals the amount of shortening accomplished by pressure solution on the stylolitic step. Conceivably, the length of these transforms can increase, decrease, or remain unchanged through time.

Mechanism of Slip and Conditions of Deformation

The presence of fiber coatings on the faults and the association of stylolitic and spar-encrusted surfaces with the faults indicate that the predominant slip mechanism on the mesoscopic faults of the Umbrian Apennines is, according to the criterion of Elliott (1976), "pressure-solution slip." Pressure-solution slip refers to the process whereby obstacles (asperities) on the fault plane are "by-passed by diffusive mass transfer" (Elliott, 1976). The asperities are removed by dissolution, rather than by brittle fracture, as one wall of the fault moves across the other. The material that had composed the asperities is redeposited, perhaps as the elongate calcite fibers which coat the fault surface, rather than being converted into fault gouge. The mathematical relations describing pressure solution are different from those describing sliding by brittle failure (Elliott, 1976). According to Rutter and Mainprice (1976), pressure-solution slip obeys a viscous flow law in which the rate of slip is proportional to the shear stress parallel to the slip surface. It has been recognized that pressure solution commences under very low stresses (see, for example, Bathurst, 1971).

Pressure solution apparently could not accommodate all of the motion on some of the larger faults in the study area. These faults are bounded by breccia and gouge zones. It is not clear from our observations whether the breccia and gouge formed because faults slipped under conditions that did not favor pressure solution, or because pressure solution, being a slow process, could not remove asperities, particularly the step-bounded blocks, fast enough to avoid their being fractured in a brittle manner as slip progressed. Perhaps the presence or absence of breccia is a function of slip rate.

Whether faulting proceeds by brittle failure of asperities, by pressure-solution slip, or by both mechanisms simultaneously, is certainly a function of the deformational environment (Elliott, 1973, 1976) and slip rate. On the basis of field occurrence in the Canadian Rockies, Elliott (1976) proposed that pressure-solution slip becomes dominant only at depths greater than ~5 km. In our study area, however, stratigraphic measurements indicate that the faulted rocks that are now exposed were never buried more than 1 to 2 km deep (Alvarez and others, 1976). Clearly, the pressure-solution slip mechanism is active at relatively shallow levels in the crust; the exact level probably depends on local environmental conditions such as ground-water circulation and heat flow. Rutter (1974) proposed that a temperature of 400°C is the upper limit of a low-temperature deformation regime dominated by pressure solution. Groshong (1975), working in the Appalachians, and Droxler and Schaer (1979), working in the Jura Mountains, have described pressure-solution deformation and demonstrated that it developed under low overburden.

Significance of Orientation Pattern

Figure 4 indicates that the mesoscopic faults of the northern Umbrian Apennines are dominantly strike-slip or oblique-slip faults. Figure 5A displays scatter, but indicates that left-lateral faults cluster around a trend of east-northeast, whereas right-lateral faults cluster around a trend of north-northwest, and Figure 3 suggests that, at least regionally, the faults define a conjugate set with a dihedral angle of ~90°. The two principal features of this orientation data set which require explanation are, first, the wide range of fault orientations, and, second, the existence of fault clusters which define an orthogonal conjugate set.

In many published accounts of mesoscopic fault arrays, the orientation data cluster tightly (Price, 1967; Choukroune, 1969; Hancock and Kadhi, 1978; Nickelsen, 1979; Wise and others, 1979), and it is possible to define symmetry elements of the array (see, for example, Norris, 1964; Arthaud and Mattauer, 1969; Hancock and Atiya, 1979). This is not always the case, however, as indicated by our plot in Figure 3A and by plots presented in Erdman (1950), Fitzgerald (1963), Norris (1958), and Lindstrom (1962). Freund (1970) noted a range of 57° for trends of sinistral faults in southeast Iran. We emphasize that scatter is an important aspect of our data; the scatter may be due to reorientation of faults as folding progresses or to changes in the local stress field due to material anisotropy. We will propose an additional explanation later in this section.

The almost 90° dihedral angle between the two fault clusters of Figures 3A and 5A is unusually large for conjugate sets, although field examples of orthogonal or near-orthogonal conjugate sets, in addition to ours, have been described (Erdman, 1950; Hancock and Kadhi, 1978; and Hoffman and St. Onge, 1981). Both members of the conjugate set could not be found at all stations, but the dominance of one member of the conjugate set at a given locality is not a feature unique to our study area. Hoeppener, Kalthoff, and

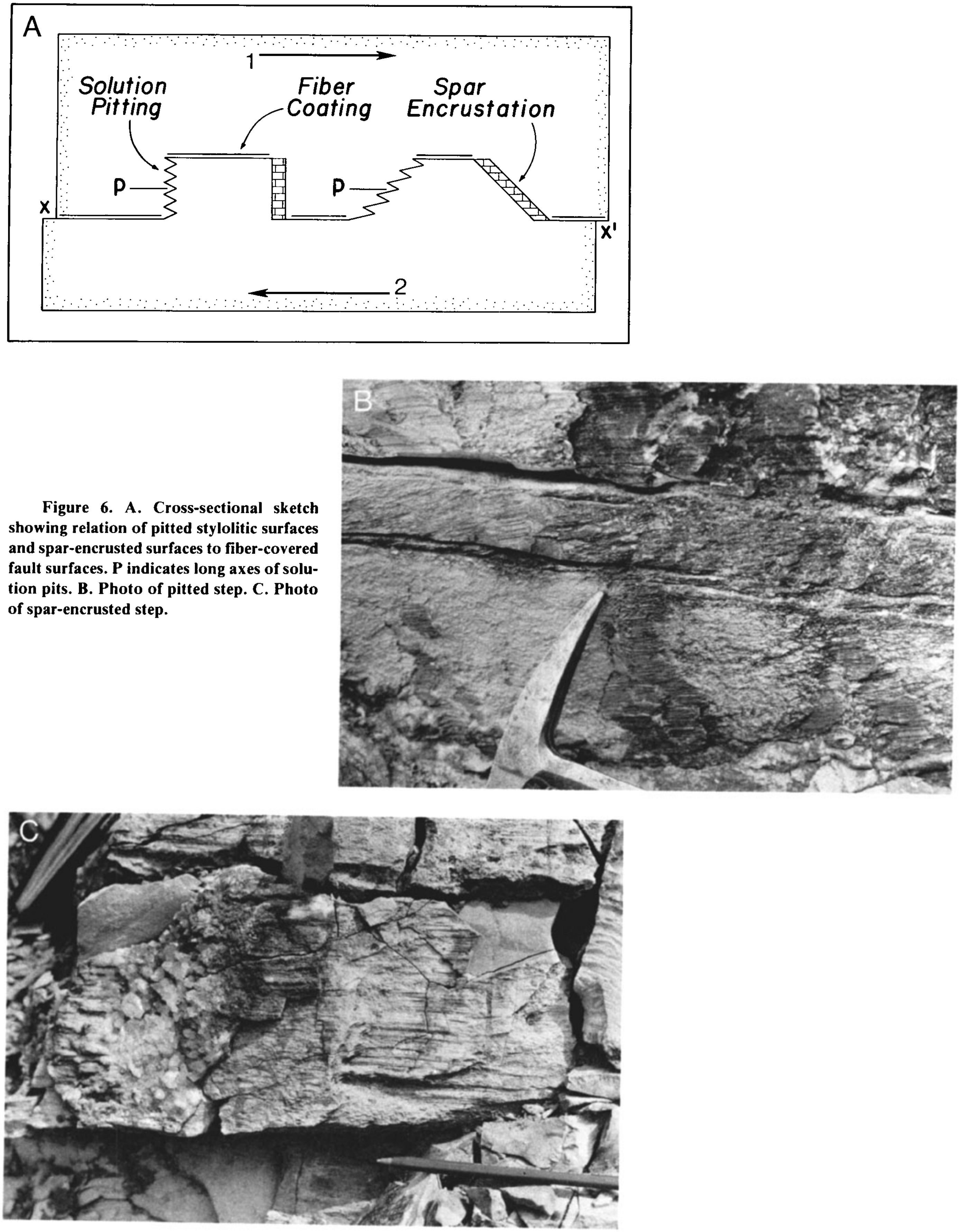

Figure 6. A. Cross-sectional sketch showing relation of pitted stylolitic surfaces and spar-encrusted surfaces to fiber-covered fault surfaces. P indicates long axes of solution pits. B. Photo of pitted step. C. Photo of spar-encrusted step.

Schrader (1969), in experiments with clay models, showed that, as deformation progressed, the members of conjugate pairs would not crosscut. Rather, domains developed which contain faults of only one orientation. Our Figures 3E and 3F suggest that domain geometry may be related to fold geometry. We will consider below four possible explanations for the large dihedral angle: (1) the faults initiated with a smaller dihedral angle, but rotation of the fault planes during shortening increased the angle; (2) the faults initiated while the Apennine carbonates were unlithified so that water entrapment effectively reduced the coefficient of internal friction; (3) pressure-solution processes may permit the initiation of orthogonal fault sets; and (4) the faults did not initiate as faults, but rather are reactivated joints.

1. It has been suggested that large dihedral angles are a consequence of rotation of fault surfaces around a vertical axis as shortening parallel to the maximum compressive stress (σ_1) progresses. Cloos (1955) and Duby (1980) demonstrated, in experiments with clay cakes, that conjugate shear planes initiate with a dihedral angle of 55°–60°, but that with continued compression, left-lateral faults rotate clockwise and right-lateral faults rotate counterclockwise. The magnitude of offset on the faults of the Apennines and the related shortening appear to be too small to permit significant rotation.

2. In standard triaxial compression experiments with rock cylinders, the planes of shear failure develop at about 30° to σ_1 (Paterson, 1978), and thus the dihedral angle between members of conjugate fault pairs is about 60°. The geometry of conjugate faults that initiate in intact rock by brittle failure can be described by the Coulomb-Mohr criterion for failure (Hubbert, 1951; Handin, 1969). Because the value of the coefficient of internal friction (η) for rock is not known to approach zero, the dihedral angle between members of conjugate pairs does not approach 90°, provided that the Coulomb-Mohr criterion applies. Thus, the orthogonal clusters of the fault array in the Apennines are unlikely to be the result of brittle failure on planes oriented at 45° to σ_1.

If the Apennine sediments were not lithified during deformation, however, the geometry of conjugate faults that could develop might be different. It has been demonstrated that wet clays that are loaded so that they cannot drain during loading behave as if $\eta = 0$ (Lamb and Whitman, 1960). There is sedimentological and paleomagnetic evidence that the Apennine sediments were at least partially lithified prior to deformation (Alvarez and Lowrie, unpub. data). Thus, we probably cannot use the $\eta = 0$ concept to explain the fault pattern of the Apennines.

3. The physical process by which mesoscopic shear fractures initiate in intact rock is not yet totally understood. Laboratory studies indicate that mesoscopic shear planes that develop in brittle rock follow a zone of extensional microcracks. If pressure solution is taking place in a rock body undergoing compression, however, the work done by external stresses goes into diffusive mass transfer at grain boundaries. One result of this process is the initiation and propagation of solution cleavage planes (Fletcher and Pollard, 1981). Perhaps pressure-solution slip planes could initiate and propagate as well. Such slip planes might nucleate at points where grain-boundary sliding encouraged by pressure solution is proceeding most rapidly. Work by Rutter and Mainprice (1978) suggests that pressure-solution slip follows a linear viscous flow law where the strain rate is proportional to the shear stress on the sliding plane. Because shear stress is greatest on planes oriented at 45° to σ_1, microslip planes in this orientation might develop most rapidly and perhaps could coalesce to form mesoscopic slip planes that are also in this orientation. This proposed process is distinct from the coalescence of a zone of extension microcracks to form a mesoscopic shear plane in brittle rocks. A rigorous analysis of the above conjecture is beyond the scope of this paper; we are merely noting that we cannot yet rule out the possibility that the mesoscopic faults of the Umbrian Apennines initiated with a high dihedral angle and, further, that perhaps the deformation mechanism responsible for sliding on a fault may control the orientation of the fault.

4. We finally explore the possibility that the pattern of faults displayed in the Apennines is a consequence of slip on a network of pre-existing fractures. It takes less work to cause slip on pre-existing fractures than it does to initiate new fractures (see references in Handin, 1969). Thus, if the Apennines were broken by numerous joints, the imposition of a deviatoric stress on the region would not initiate new faults but rather would cause slip on the pre-existing surfaces. If the fault array in the Apennines is a consequence of slip on pre-existing joints, the following question is relevant. In order to create the orientation pattern displayed by the faults, must the pre-existing fractures have described a specific pattern themselves prior to slip, or could they have been randomly oriented?

The Coulomb criterion does not govern slip on pre-existing fractures (Handin, 1969), but, as Byerlee (1978) has shown, when slip on fractures occurs by brittle mechanisms, the empirical law governing sliding takes the same form as the Coulomb criterion. Thus, if the region being deformed contained random fractures, fractures oriented at 30° to σ_1 would slip first, and a conjugate set with a dihedral angle of 60° should develop (Compton, 1966). If deviatoric stress remains sufficiently high even after slip on the preferred surfaces has begun, other less favorably oriented surfaces will slip too, and a plot of fault orientations will display scatter. If, however, the shear stress necessary to initiate sliding has some finite value but is independent of the normal stress across the surface, faults oriented at 45° to σ_1 would slip first, and a fault pattern such as the one we observed in the Apennines would develop. Reches (1978) demonstrated that for such conditions the fault pattern that minimizes the work done by external forces most efficiently depends only on strain ratios and that, for plane strain, an orthogonal conjugate set of strike-slip faults would develop. As mentioned in the previous section, the relations governing pressure-solution slip are different from those governing slip by brittle failure, but it is not clear whether the shear stress necessary to initiate sliding is independent of normal stress for pressure-solution slip. Furthermore, it appears that the yield stress necessary to initiate sliding by pressure solution is so low that essentially all fractures available for slip could slip; if fractures are randomly oriented, dominant clusters might not appear in the orientation data set. We also note that random joint sets have not been documented in fold belts. The preceding arguments suggest that the faults of our study area are probably not the result of reactivation of a random joint set.

A more reasonable explanation of the fault pattern, if the faults are reactivated joints, is that it is a direct reflection of the pattern of pre-existing joints. The scatter indicates that there was a wide range of joint orientations; most of these joints could slip because of the very low yield stress for pressure-solution slip. The presence of orthogonal clusters indicates that many of these joints were members of an orthogonal set.

Direct evidence of pre-existing fractures is not available, for it is difficult to determine if a fault surface which, at present, is decorated with calcite fibers was initiated by extension or by shear. Other authors have called upon reactivation of joints to explain complicated fault arrays, and there are many published descriptions of joint arrays characterized by a wide range of orientations but with a dominant orthogonal set (Nickelsen and Hough, 1967; Hancock, 1969; and Reches, 1976). Usually, however, one member of the orthogonal set is roughly parallel to regional fold axes and the other member is normal to regional fold axes. We do not see this geometry in the Apennines. We also note that many of the faults in our study area display oblique slip. Several authors (Williams, 1958; Bott, 1959) have suggested that oblique slip is characteristic of movements on a pre-existing plane under the influence of a stress system different from that which initially formed the plane. Thus, while we cannot prove the existence of pre-existing fractures, some of our observations are compatible with this possibility.

Timing of the Faulting

In the field, we observed several examples of mesoscopic faults that are offset at bedding planes. The offset was generally in the correct sense for it to have been caused by flexural slip during folding, or by removal of material by pressure solution on the bedding plane (see Fig. 5 in Alvarez and others, 1976). The offset, if it is a consequence of flexural slip, points to the possibility that some mesoscopic faults developed prior to regional folding. The fact that elongate calcite fibers parallel to those of the fault sometimes occurred on the segment of the bedding plane between offset segments of the fault (Fig. 2B) indicates that some slip on these faults did occur after offset on the bedding planes. Many faults were not offset, however, either because slip or pressure solution on bedding planes did not always occur, or because the faulting postdated such deformation. The failure of the rotation test (Figs. 3B and 3D) also suggests that faulting occurred later in the development of the fold belt. We tentatively conclude that faulting initiated prior to regional folding, but that it continued during folding and perhaps after folding. Faulting probably developed in response to the same regional stress that caused folding. A similar history of faulting was recognized by Nickelsen (1979) in the Alleghanian age folds of the Appalachian Mountains in Pennsylvania.

Geometrical Relation of Faults to Regional Folds

It has long been recognized that mesoscopic faulting plays an integral part in the development of fold belts. When the faults are geometrically related to folds, their symmetry can be described using the fold axis as a reference line. Steeply dipping, strike-slip conjugate shear faults for which the acute bisectrix is normal to the fold axis have been called "hk0 shears" (Hancock and Atiya, 1979). Movement on hk0 shears can permit volume-constant shortening normal to the fold axes and volume-constant extension parallel to the fold axes (Arthaud, 1969), and thus faulting is a mechanism into which strain is partitioned during regional deformation.

The bisector between two conjugate hk0 fault clusters and the normal to the associated folds are generally parallel and are thought to represent the orientation of σ_1. The bisector is also the mean of the calculated σ_1 vectors associated with the fault planes (Fig. 7A).

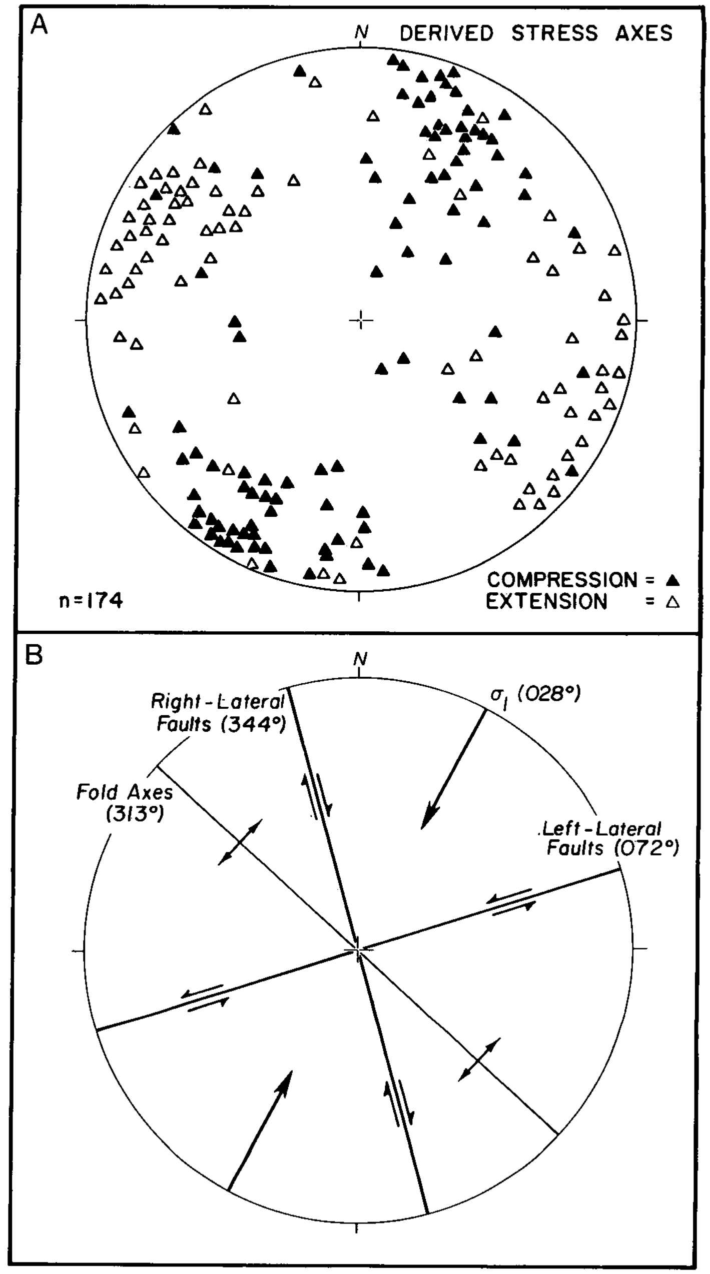

Figure 7. A. Stereoplot of derived stress axes, using the same data set as in Figure 5A. The σ_1 approximation for each fault for which we had sense of slip information is taken as the line 45° from the fault plane measured in the plane containing the normal to the fault plane and the slip fibers (R. Allmendinger and R. Fletcher, 1980, personal commun.; Compton, 1966; Ragan, 1968). The trend of the mean σ_1 associated with the folds is taken as the normal to the mean fold axis in the map plane. B. Synoptic diagram of mean trends of principal structures and derived stress axes in the study area, determined from Figures 1A, 5A, and 7A.

For our data from the Umbrian Apennines, the bisector and the normal to the regional fold axes are not exactly parallel (Fig. 7B). Reches (1976) found a similar discrepancy for folds that he measured in Israel. This discrepancy may be a further indication that the mesoscopic faults are reactivated joints; the joints might have been created in response to an earlier stress field which was not exactly parallel to the one which created the folds and caused slip on the joints. If so, the orientation data on the faults alone cannot be used to estimate the orientation of σ_1. Alternatively, the discrepancy may indicate that, in the Umbrian Apennines, stratigraphic inhomogeneities such as the abrupt thickness changes of the Jurassic strata (Centamore and others, 1971) control gross fold geometry, so that the mesoscopic faults may have accommodated strain that could not be accommodated by folding.

Mesoscopic Cataclasis

The general picture of deformation which we envision for the Umbrian Apennines is one in which strain is accomplished in part by means of translations and rotations of fracture-bounded mesoscopic-scale blocks, or, more concisely, by "mesoscopic cataclasis." Alvarez and others (1976) demonstrated that very little strain has been partitioned into penetrative distortion of the rocks. Movement on block boundaries progresses by means of pressure-solution slip, a form of diffusion creep (Elliott, 1973). This type of motion is simply a larger-scale version of grain-boundary sliding (Raj and Ashby, 1977), as was noted by Fletcher and Pollard (1981).

Mesoscopic cataclasis is not a new concept. Laubscher (1965, 1979) considered that the principal mode of deformation in the Jura fold belt was "shearing displacement of rigid masses" and that the strata of the folds had been broken into a "block mosaic." Droxler and Schaer (1979) described the folding of the Jura as "cataclastic by its nature." Compton (1966) suggested that basement folds in the Santa Lucia Range of California were the result of "piecemeal movements on minor faults." Price (1967) described this style of deformation where it affects the Canadian Rockies foreland belt: "Bulk deformation may have been somewhat analogous to 'cataclastic flow' in a granular or blocky aggregate in which the individual fragments are free to move relative to one another along their bounding surfaces during deformation."

Mesoscopic cataclasis is certainly important during layer-parallel shortening and extension in a fold belt (Arthaud and Mattauer, 1969). It is also probably important as a means of accommodation for local space problems and perhaps for oroclinal bending, such as that which apparently has affected the cover rocks of the Umbrian Apennines (Channell and others, 1978). The strain represented by arrays of mesoscopic faults should certainly be considered in the construction of balanced cross sections, but, in our study area, the strain due to the mesoscopic folds is small; assuming an average offset of about 2 cm per fault and a fault spacing of about 1 fault per metre, an approximate estimate of the strain due to faulting is between 1% and 2%.

CONCLUSIONS

The Jurassic through lower Tertiary strata of the northern Umbrian Apennines are cut by an array of mesoscopic strike-slip and oblique-slip faults. Structural features of the fault surfaces indicate that movement on the faults occurred predominantly by the mechanism of pressure-solution slip. When this mechanism is operative, slip can begin under very low deviatoric stresses, and the rate of slip on the faults is proportional to the shear stress parallel to the fault surface (Rutter and Mainprice, 1978). Thus, faults oriented at 45° to σ_1 may become the most prominent faults. There appears to be an upper limit to the strain rate for which this flow law can be extrapolated, for gouge occurs on the largest faults, suggesting that above a certain strain rate, pressure-solution is supplemented by brittle failure. Pressure-solution slip in the Apennines is manifested in rocks that were never buried deeper than about 1.5 km. Regionally, the movement of mesoscopic blocks bounded by these faults can be likened to "cataclastic flow of a blocky aggregate," but, in the Apennines, mesoscopic faulting probably does not account for more than a couple of percent of regional strain.

The orientation pattern of the faults displays considerable scatter, but there are clusters of faults which define a conjugate set with a dihedral angle of about 90°. We suggest two possible explanations for this orientation pattern, but we do not have sufficient information to determine which explanation is correct. First, the faults may have originated as pressure-solution slip surfaces, and in this case their geometry was controlled by the deformation mechanism. Second, the orientation pattern of the faults simply reflects the orientation pattern of pre-existing joints.

ACKNOWLEDGMENTS

Assistance in the field by Michael Carr, Kathryn Marshak, and William Leith and discussion in the field with Michael Carr, Steven Schamel, and William Leith are greatly appreciated. We would also like to thank R. Nickelsen, R. Allmendinger, I. Dalziel, R. Hatcher, Jr., S. Schamel, M. Winslow, T. Wilson, N. Bogen, and R. Forsythe for helpful discussions and reviews. Comments from R. Wheeler and Z. Reches were particularly useful. W. Menke and L. House helped to adapt computer programs for plotting the data. This work was supported by National Science Foundation Grants EAR-77-13000 and EAR-79-10849.

REFERENCES CITED

Abbate, E., Bortolotti, V., Passerini, P., and Sagri, M., 1970, Introduction to the geology of the northern Apennines: Sedimentary Geology, v. 4, p. 207–209.

Alvarez, W., Engelder, T., and Lowrie, W., 1976, Formation of spaced cleavage and folds in brittle limestone by dissolution: Geology, v. 4, p. 698–701.

Alvarez, W., Engelder, T., and Geiser, P., 1978, Classification of solution cleavage in pelagic limestones: Geology, v. 5, p. 263–266.

Arthaud, F., 1969, Methode de détermination graphique des directions de raccourcissement, d'allongement et intermédiaire d'une population de failles: Bulletin de la Société Géologique de France, ser. 7, v. 11, p. 729–737.

Arthaud, F., and Mattauer, M., 1969, Exemples de stylolites d'origine tectonique dans le Languedoc, leur relations avec la tectonique cassante: Bulletin de la Société Géologique de France, ser. 7, v. 11, p. 738–744.

Bathurst, R.C.G., 1971, Carbonate sediments and their diagenesis: Amsterdam, Elsevier, 620 p.

Blake, D. B., and Roy, C. J., 1949, Unusual stylolites: American Journal of Science, v. 247, p. 779–790.

Bortolotti, V., Passerini, P., Sagri, M., and Sastini, G., 1970, Development of the northern Apennines geosyncline—The miogeosynclinal sequences: Sedimentary Geology, v. 4, p. 341–344.

Bott, M.H.P., 1959, The mechanism of oblique-slip faulting: Geological Magazine, v. 96, p. 109–117.

Byerlee, J., 1978, Friction of rocks: Pure and Applied Geophysics, v. 116, p. 615–626.

Centamore, E., Chiocchini, M., Deiana, G., Micarelli, A., and Pieruccini, U., 1971, Contributo alla conoscenza del Giurassico dell'Appennino umbro-marchigiano: Studi Geologici Camerti, v. 1, p. 7–89.

Channell, J.E.T., Lowrie, W., Medizza, F., and Alvarez, W., 1978, Paleomagnetism and tectonics in Umbria, Italy: Earth and Planetary Science Letters, v. 39, p. 199–210.

Choukroune, P., 1969, Un example d'analyse microtectonique d'une series calcaire affectée de plis isopaque ("concentrique"): Tectonophysics, v. 7, p. 57–70.
Cloos, E., 1955, Experimental analysis of fracture patterns: Geological Society of America Bulletin, v. 66, p. 241–256.
Compton, R. R., 1966, Analyses of Pliocene-Pleistocene deformation and stresses in northern Santa Lucia Range, California: Geological Society of America Bulletin, v. 77, p. 1361–1380.
Crowell, J. C., 1974, Origin of late Cenozoic basins in southern California, *in* Dickinson, W. R., ed., Tectonics and sedimentation: Society of Economic Paleontologists and Mineralogists Special Publication 22, p. 190–204.
Droxler, A., and Schaer, J. P., 1979, Déformation cataclastique plastique lors du plissement sous faible couverture de strates calcaires: Eclogae Geologicae Helvetiae, v. 72, p. 551–570.
Dubey, A. K., 1980, Model experiments showing simultaneous development of folds and transcurrent faults: Tectonophysics, v. 65, p. 69–84.
Durney, D. W., and Ramsay, J. G., 1973, Incremental strains measured by syntectonic crystal growths, *in* DeJong, K. A., and Scholten, R., eds., Gravity and tectonics: New York, John Wiley & Sons, p. 67–96.
Elliott, D., 1973, Diffusion flow laws in metamorphic rocks: Geological Society of America Bulletin, v. 84, p. 2645–2664.
—— 1976, The energy balance and deformation mechanisms of thrust sheets: Royal Society of London Philosophical Transactions, ser. A, v. 283, p. 289–312.
Engelder, J. T., 1974, Cataclasis and the generation of fault gouge: Geological Society of America Bulletin, v. 85, p. 1515–1522.
Erdman, O. A., 1950, Alexo and Saunders map areas, Alberta: Geological Survey of Canada Memoir 254, 100 p.
Fitzgerald, E. L., 1963, Structural analysis along Toirens River, Alberta Foothills: Bulletin of Canadian Petroleum Geology, v. 11, p. 125–137.
Fletcher, R. C., and Pollard, D. D., 1981, Anticrack model for pressure solution surfaces: Geology, v. 9, p. 419–424.
Freund, R., 1970, Rotation of strike-slip faults in Sistan, southeast Iran: Journal of Geology, v. 78, p. 188–200.
Groshong, R. H., Jr., 1975, Strain, fractures, and pressure solution in natural single-layer folds: Geological Society of America Bulletin, v. 86, p. 1363–1376.
Hancock, P. L., 1969, Jointing in the Jurassic limestones of the Cotswold Hills: Geologists' Association Proceedings, v. 80, p. 219–241.
Hancock, P. L., and Atiya, M. S., 1979, Tectonic significance of mesofracture systems associated with the Lebanese segment of the Dead Sea transform fault: Journal of Structural Geology, v. 1, p. 143–153.
Hancock, P. L., and Kadhi, A., 1978, Analysis of mesoscopic fractures in the Dhruma-Nisah segment of the central Arabian graben system: Geological Society of London Journal, v. 135, p. 339–347.
Handin, J., 1969, On the Coulomb-Mohr failure criterion: Journal of Geophysical Research, v. 74, p. 5343–5348.
Hoeppener, R., Kalthoff, E., and Schrader, P., 1969, Zur physikalischen tektonik; bruchbildung bei verschiedenen affinen deformationen im experiment: Geologische Rundschau, v. 59, p. 179–193.
Hoffman, P. F., and St. Onge, M. R., 1981, Contemporaneous thrusting and conjugate transcurrent faulting during the second collision in Wopmay orogen: Implications for the subsurface structure of post-orogenic outliers: Current Research, Part A, Geological Survey of Canada, Paper 81-A, p. 251–287.
Hubbert, M. K., 1951, Mechanical basis for certain familiar geologic structures: Geological Society of America Bulletin, v. 62, p. 355–372.
Lambe, T. W., and Whitman, R. V., 1969, Soil mechanics: New York, John Wiley & Sons, 553 p.
Laubscher, H. P., 1965, Ein kinematisches modell der Jurafaltung: Eclogae Geologicae Helvetiae, v. 58, p. 231–318.
—— 1979, Elements of Jura kinematics and dynamics: Eclogae Geologicae Helvetiae, v. 72, p. 467–483.
Lindstrom, M., 1962, A structural study of the southern end of the French Jura: Geological Magazine, v. 99, p. 193.
Nickelsen, R. P., 1979, Sequence of structural stages of the Alleghany orogeny at the Bear Valley Strip Mine, Shamokin, Pennsylvania: American Journal of Science, v. 279, p. 225–271.
Nickelsen, R. P., and Hough, V. D., 1967, Jointing in the Appalachian Plateau of Pennsylvania: Geological Society of America Bulletin, v. 78, p. 609–630.
Norris, D. K., 1958, Structural conditions in Canadian coal mines: Geological Survey of Canada Bulletin, no. 44, 54 p.
—— 1964, Microtectonics of the Kootenay Formation near Fernie, British Columbia: Bulletin of Canadian Petroleum Geology, v. 12, p. 383.
Paterson, M. S., 1978, Experimental rock deformation—The brittle field: Heidelberg, Springer-Verlag, 254 p.
Price, R. A., 1967, The tectonic significance of mesoscopic subfabrics in the southern Rocky Mountains of Alberta and British Columbia: Canadian Journal of Earth Sciences, v. 4, p. 39–70.
Ragan, D. M., 1968, Structural geology, an introduction to geometrical techniques: New York, John Wiley & Sons, 155 p.
Raj, R., and Ashby, M. F., 1971, On grain-boundary sliding and diffusional creep: Metallurgical Transactions, v. 2, p. 1113–1127.
Reches, Z., 1976, Analysis of joints in two monoclines in Israel: Geological Society of America Bulletin, v. 87, p. 1654–1662.
—— 1978, Analysis of faulting in three-dimensional strain field: Tectonophysics, v. 47, p. 109–129.
Rutter, E. H., 1974, The influence of temperature, strain rate, and interstitial water in the experimental deformation of calcite rocks: Tectonophysics, v. 22, p. 311–334.
Rutter, E. H., and Mainprice, D. H., 1978, The effect of water on stress relaxation of faulted and unfaulted sandstones: Pure and Applied Geophysics, v. 116, p. 634–654.
Stearns, D. W., 1968, Certain aspects of fracture in naturally deformed rocks, *in* Rieker, R. E., ed., National Science Foundation Advanced Science Seminar in Rock Mechanics, Special Report, Air Force Cambridge Research Laboratories, Bedford, Massachusetts, p. 97–116.
Wagner, G. H., 1964, Kleintektonische Untersuchungen im Gebiet des Nordlinger Rieses: Geologisches Jahrbuch, v. 81, p. 519–600.
Williams, A., 1958, Oblique-slip faults and rotated stress systems: Geological Magazine, v. 95, p. 207–218.
Wise, D. U., Hozik, M. J., Goldstein, A. G., and Piepul, R. G., 1975, Minor fault motions in relation to Mesozoic tectonics of southern New England: EOS (American Geophysical Union Transactions), v. 56, p. 451.

MANUSCRIPT RECEIVED BY THE SOCIETY MAY 1, 1981
REVISED MANUSCRIPT RECEIVED OCTOBER 19, 1981
MANUSCRIPT ACCEPTED NOVEMBER 16, 1981
LAMONT-DOHERTY GEOLOGICAL OBSERVATORY CONTRIBUTION NO. 3351