Postcrystalline Deformation of the Pelona Schist Bordering Leona Valley, Southern California

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By JAMES G. EVANS

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Detailed study of fabric of Pelona Schist of Portal and Ritter Ridges in the San Andreas fault zone

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POSTCRYSTALLINE DEFORMATION OF THE PELONA SCHIST BORDERING LEONA VALLEY, SOUTHERN CALIFORNIA

By James G. Evans

ABSTRACT

Detailed structural investigations in part of the Leona Valley segment of the San Andreas fault zone, 5–16 km west of Palmdale, focused on the postcrystalline deformation of the block of Mesozoic(?) Pelona Schist underlying Portal and Ritter Ridges. The early fabric of the schist is modified and in places obliterated by cataclasis along shear zones near the San Andreas fault and the Hitchbrook fault, a major west-striking branch of the San Andreas fault system. Anastomosing shear foliations, fabric elements of the postcrystalline deformation, intersect at small angles to one another and are generally vertical or steeply dipping to the north-northeast; they are subparallel to the Hitchbrook fault. Many of these shear foliations are nearly parallel to the compositional layering and schistosity, which commonly dip at moderately steep angles to the northwest. Folds in the shear foliation, commonly intrafolial, generally plunge at moderately steep angles to the north-northeast or are nearly vertical. Other folds, various in form, have axes parallel to the intersections of the early schistosity and the shear foliations and plunge in many other directions.

Faults, roughly similar in orientation to the shear foliations, have orientations subparallel to large-scale structures and structural features in the Leona Valley area and in southern California: the San Andreas fault zone in Leona Valley, the Hitchbrook fault, the Garlock fault zone, steep northward-striking faults, the San Andreas fault zone north and south of the Transverse Ranges, and the generally northwest-dipping early compositional layering of the schist.

Slickensides on some of the minor faults indicate that the latest movements on the steep faults are predominantly strike slip with indications of less common episodes of predominantly dip slip. The low-angle faults have oblique slip with a large dip component.

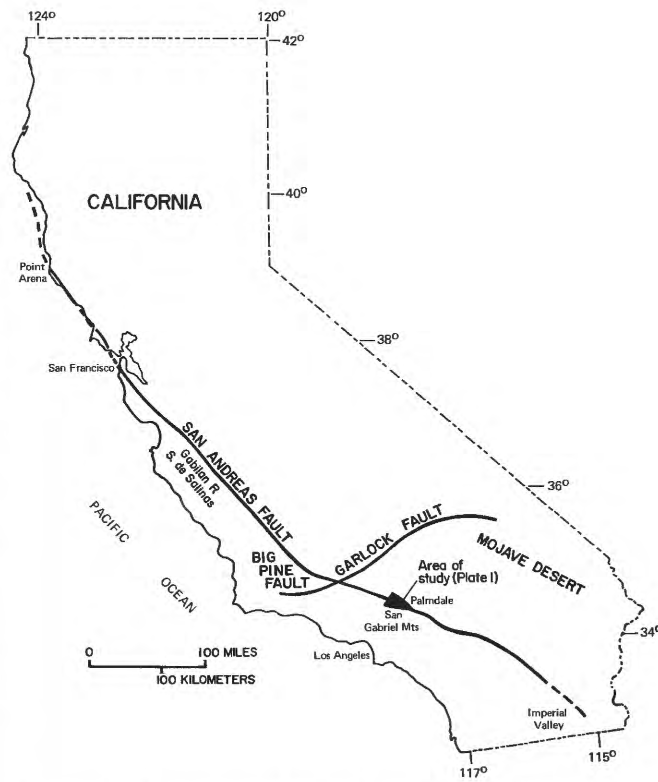


Figure 1.—Index map showing location of study area.

INTRODUCTION

Much of the regional geology along the San Andreas fault zone, one of the best known large active strike-slip fault zones of the world, has been mapped. Yet to this time, the style of the deformation and the orientation of the minor structures within the fault zone have not been documented in detail. Following a reconnaissance of several areas along the San Andreas fault zone between Imperial Valley and Point Arena, the Leona Valley segment of the fault zone (figs. 1, 2; pl. 1 and Evans, 1976) 5–16 km west of Palmdale, was selected for a detailed structural study. Exposures of the fractured rock and breccia zones at Leona Valley, though not uniformly good, are among the best in the fault zone. They include a large sliver of the Mesozoic(?) Pelona Schist, a rock old enough to have been subjected to much of the deformation associated with the faulting.

ACKNOWLEDGMENTS

The author is particularly indebted to J. C.

FIGURE 2.—Panoramic view showing the San Andreas fault zone from the mouth of Leona Valley to the San Gabriel Mountains. View east-southeast. LV, Leona Valley; RR, Ritter Ridge; AV, Antelope Valley; SG, San Gabriel Mountains; SA, San Andreas fault; AvV, Anaverde Valley.

Crowell, University of California, Santa Barbara, who pointed out parts of the San Andreas fault zone of special interest. Fruitful discussions with G. Oertel, J. M. Christie, and W. G. Ernst, University of California, Los Angeles, helped clarify some aspects of this work.

This study constitutes part of Evan's work toward a doctoral degree at the University of California, Los Angeles (Evans, 1966), and was continued by him as a geologist with the U.S. Geological Survey.

The Leona Valley area lies along the segment of the San Andreas fault for which Crowell (1962, p. 36-38) postulated at least 210 km of right-lateral strike slip since the early Miocene. This segment of the fault has been inactive since the great Fort Tejon earthquake of 1857 (Lawson, 1908, v. 1, p. 449-451; Wood, 1955; Iacopi, 1964, p. 96). Displacements and seismicity of the 1857 event are believed to have rivaled those of the catastrophic San Francisco earthquake of 1906. Kahle (1975) documented many minor geomorphic features related to faulting in the Leona Valley that were formed during or before the 1857 earthquake. The Leona Valley lies along the axis of uplift recently discovered in the western Mojave Desert (Castle and others, 1976). The uplift apparently began in 1960 near the junction of the San Andreas and Garlock faults and grew east-southeastward to include the Leona Valley area, which, coincidentally, lies along the zone of maximum uplift (0.25 m). Evidence bearing on large separations, seismicity, and very recent movements along the San Andreas fault are beyond the scope of this detailed study, which focuses on the fabric of a small part of the San Andreas fault zone.

The fabric data presented here were plotted as points on the lower hemisphere of an equal-area projection. Azimuths are referred to a 360° compass with 0°=north and 90°=east. Point diagrams were contoured by the Schmidt method. In order to estimate the statistical significance of the point concentrations, the contours illustrated below can be compared with contours that would result from employing the contouring method suggested by Kamb (1959, p. 1908-1909). Using Kamb's method, a point density greater than 3σ, where σ is the standard deviation of the number of points expected in a unit area of the equal-area projection for a particular sample taken from a population that is randomly distributed, is considered to be a significant deviation from a random distribution. In a 100- or 150-point sample, the contours 2 and 4 percent per 1-percent area are crudely equivalent to 2σ and 4σ. In a 300-point sample, the contours 1, 3, and 5 percent per 1-percent area are approximately equivalent to 2σ, 4σ, and 8σ. In a 450-point sample, the contours 1, 2, and 4 percent are approximately equivalent to 2σ, 4σ, and 9σ.

GENERAL GEOLOGY OF LEONA VALLEY AREA

Leona Valley is an elongate valley parallel to and formed by erosion along two major splay faults of the San Andreas fault zone, the San Andreas fault itself, the most recent break, and the Portal fault, parallel to it (pl. 1; Evans, 1976). In fact, most of the area shown on the geologic map (pl. 1) from the San Francisquito fault on the south to the Hitchbrook fault on the north can be considered part of the San Andreas fault zone, as the major faults are parallel or subparallel to the zone and have most likely participated in the strike-slip faulting that is a characteristic of at least Holocene tectonism along the San Andreas fault zone.

The oldest rocks of the Leona Valley area are granodiorite, diorite, gneiss, and the Pelona Schist, juxtaposed in fault slivers and all of pre-Tertiary age. The most important unit for purposes of this study is the Pelona Schist, which crops out on both sides of the San Andreas fault, on Portal and Ritter Ridges on the northeast, and in the northern Sierra Pelona on the southwest (pl. 1). The ages of the metamorphism of the Pelona Schist and of the sedimentary and volcanic rock assemblage that the schist represents are not clearly known. A Precambrian age for the schist has been accepted by a number of workers (Hershey, 1902, p. 273; Simpson, 1934, p. 380-381; Wallace, 1949, p. 787; Dibblee, 1960, 1961, 1967, p. 9). Ehlig (1958, p. 33-40, 1968, p. 294, 300-301) has argued, however, that the metamorphism of the Pelona Schist probably occurred during the Late Cretaceous and that the deposition of the protolith of the schist may have occurred at some earlier time during the Mesozoic. The Pelona Schist of the eastern San Gabriel Mountains, 69 km southeast of the study area, is intruded by Miocene (14.2-14.6 m.y. by K/Ar method) plutonic rocks (Miller and Morton, 1974). Accordingly, the Pelona Schist in Leona Valley is certainly pre-Miocene and is assigned a Mesozoic(?) age in this paper.

The Pelona Schist underlying Portal and Ritter Ridges on the northeast side of the fault includes rocks of several lithologies, in order of diminishing abundance, quartzo-feldspathic muscovite schist, chlorite-muscovite schist, amphibolite, augen gneiss, quartzite, talc schist, marble, and actinolite schist. The widespread presence of plagioclase, An_{35}, in apparent equilibrium with epidote, suggests that physical conditions characteristic of the amphibolite facies of regional metamorphism were attained (Turner and Verhoogen, 1960, p. 544-553; Turner, 1968, p. 307-309). In contrast, the Pelona Schist of the northern Sierra Pelona on the southwest side of the fault contains assemblages of albite, epidote, and blue-green hornblende that define the albite-epidote amphibolite facies (Turner and Verhoogen, 1960, p. 533; Turner, 1968, p. 303-304). The possibility, suggested by Ehlig (1958, 1968, p. 301), that the schist exposed in these two areas may be different parts of a once larger regionally metamorphosed terrane and subsequently juxtaposed by movements along the San Andreas fault is consistent with the observed small differences in the metamorphic grade of the two schist bodies. Ross (1976), noting the modal and chemical similarities of the schist on Portal and Ritter Ridges and the schist in the Sierra de Salinas and the Gabilan Range, has suggested that these two bodies of schist, now 320 km apart and on opposite sides of the San Andreas fault, were once contiguous.

A fault sliver of lithic lapilli tuff is shown in the north corner of the geologic map (pl. 1) northeast of the Hitchbrook fault. Earlier workers (Wiese, 1947; Wallace, 1949; Dibblee, 1961) have assigned the tuff a Miocene(?) age. This age designation is accepted here.

The lithic lapilli tuff and the Pelona Schist are intruded by fine-grained hornblende diorite dikes. The single dike in the tuff, too small to appear on the geologic map, occurs in the southern part of the tuff outcrop area. Therefore, these dikes must be post-Miocene(?).

Leona Valley is underlain chiefly by arkose and shale of the Pliocene (Wallace, 1949, p. 790; Axelrod, 1950) Anaverde Formation (pl. 1). Although the valley is flanked on both sides by Pelona Schist, the Anaverde Formation in the trough contains no schist fragments. The buff arkose member of the Anaverde Formation south of the San Andreas fault contains abundant gneiss cobbles, whereas gneiss does not crop out north of the San Andreas fault in Leona Valley. The base of the Anaverde Formation is not exposed. Diapiric intrusions of sheared monzonite and diorite into rocks of the formation suggest that the rock underlying the Anaverde Formation is like the diorite and gneiss south of the San Andreas fault. Pleistocene to Holocene alluvial fan deposits and alluvium cover large expanses of Leona Valley and Antelope Valley.

Two lines of evidence suggest relative horizontal separations in Leona Valley: (1) The lack of schist clasts in the Anaverde Formation is most likely explained by the juxtaposition of the schists and the Anaverde Formation along large lateral-slip faults since the Pliocene (see discussion in Wallace, 1949, p. 802); (2) gaps in the line of low ridges that lie between the San Andreas and the Portal faults are not alined with the mouths of canyons descending from Portal Ridge. The mismatch of the canyon mouths and the gaps in the ridge line suggest a Holocene strike separation of several hundred feet along the Portal fault.

Relative vertical separations are suggested chiefly by the trenches that Armagosa Creek has cut through the low ridges between the San Andreas and Portal faults. Wallace (1949, p. 795-796) calls this line of ridges the "center-trough ridge" and envisages its formation by periodic upward movement of the sheared rock between the San Andreas and the Portal faults.

STRUCTURAL GEOLOGY

INTRODUCTION

Several deformations are recorded in the Pelona Schist of Portal and Ritter Ridges. An early crystalline deformation was followed by minor episodes of fracturing associated with intrusion of diorite dikes and later by the postcrystalline deformation related to the major faulting in the area.

CRYSTALLINE DEFORMATION OF THE PELONA SCHIST

The crystalline deformation of the Pelona Schist is recorded at Portal and Ritter Ridges by two stages. An initial stage of deformation, the major one, resulted in the development of the dominant foliation, commonly parallel to the compositional layering of the schist. The layering and foliation were both folded into tight folds. In the second stage of deformation, the early foliation and the compositional layering were again folded but not as tightly as they were during the first folding. In places, a second weak foliation was developed along the axial surfaces of these later folds.

The dominant structural element of the Pelona Schist is the compositional layering, which may be transposed bedding. The layering of the schist on Portal and Ritter Ridges outlines several large early folds, designated B_1, that plunge at small angles to the east and west (pl. 1). The hinge zones of the folds are narrow, and their axial surfaces dip at moderately steep angles (40°–50°) to the northeast. A large, sharp antiformal hinge lies near the southwest edge of Ritter Ridge within the muscovite-chlorite schist unit (see *B–B′*, pl. 1). Marble and amphibolite and augen gneiss layers on eastern Portal Ridge outline what appears to be part of an open synform with minor folds superposed on it.

The dominant foliation, designated S_1, is defined by the planar preferred orientations of biotite, muscovite, and chlorite and by the plane of flattening of other mineral grains (plagioclase, quartz, and calcite). This foliation is generally parallel to the compositional layering; in places it is at large angles to it. The minor folds in S_1 are tight similar folds, much more closely appressed than the large folds in the compositional layering. The minor folds, like the large ones, plunge at low angles, predominantly to the east and west. The axial surfaces of the minor folds are subparallel to S_1. Profiles of some of these minor folds, also designated B_1, are shown in figures 3*A*, *B*.

Other folds with an open, more concentric style, are present at many places but are most abundant in northern Portal Ridge and southeast Ritter Ridge. Orientations of these folds vary widely. Where their orientations are most uniform, on northern Portal Ridge, they generally plunge steeply and moderately steeply in easterly directions. In other areas, the folds plunge in many different orientations. Large folds of this later group were too small or not well marked for mapping. Either they are obscured by faulting, poor exposures, or lack of marker horizons in the schist, or large folds were not formed in the later deformation. The early folds, B_1, in northern Portal Ridge appear to be rotated about an axis coincident with the predominant orientation of later folds, B_2. This relation is shown on an orientation diagram as a small circle distribution of the early folds about an axis plunging 50° E. The relative ages of the folds were established on this evidence. The axial surfaces (S_2) of these later folds, B_2, are marked in places by the planar preferred orientation of biotite and muscovite and by veins of milky-white quartz.

Areas in which the linear fabric elements, B_1 and B_2, are homogeneous are commonly small and have irregular-shaped boundaries. In the eastern part of Portal Ridge, where a detailed study of these minor structures was made, the overall crystalline fabric is inhomogeneous and probably largely reflects the inhomogeneity of the crystalline deformation. Rotation of blocks of schist as a result of the Tertiary faulting subsequent to the crystalline deformation may have further disrupted the already inhomogeneous fabric. Slumping of large blocks of schist does not seem to be a significant influence on the inhomogeneity of the fabric, as map units in the schist are not disrupted by slumping. The lack of geomorphic evidence eliminates at least Holocene slumping as a factor.

STRUCTURES PRODUCED BY SHEARING

In shear zones on Portal and Ritter Ridges, the early fabric of the schist is partly or completely obliterated by the postcrystalline deformation associated with the shearing. Some of the rocks are cataclastically deformed to gouge and breccia, especially near the Portal fault and the Hitchbrook fault. In other zones of deformation, a new fabric element is superposed on the crystalline structures in the area; it is dominated by a shear foliation, designated S_3, which is itself locally folded. The new structures are best developed in the sheared micaceous schist along the southern side of Portal and Ritter Ridges.

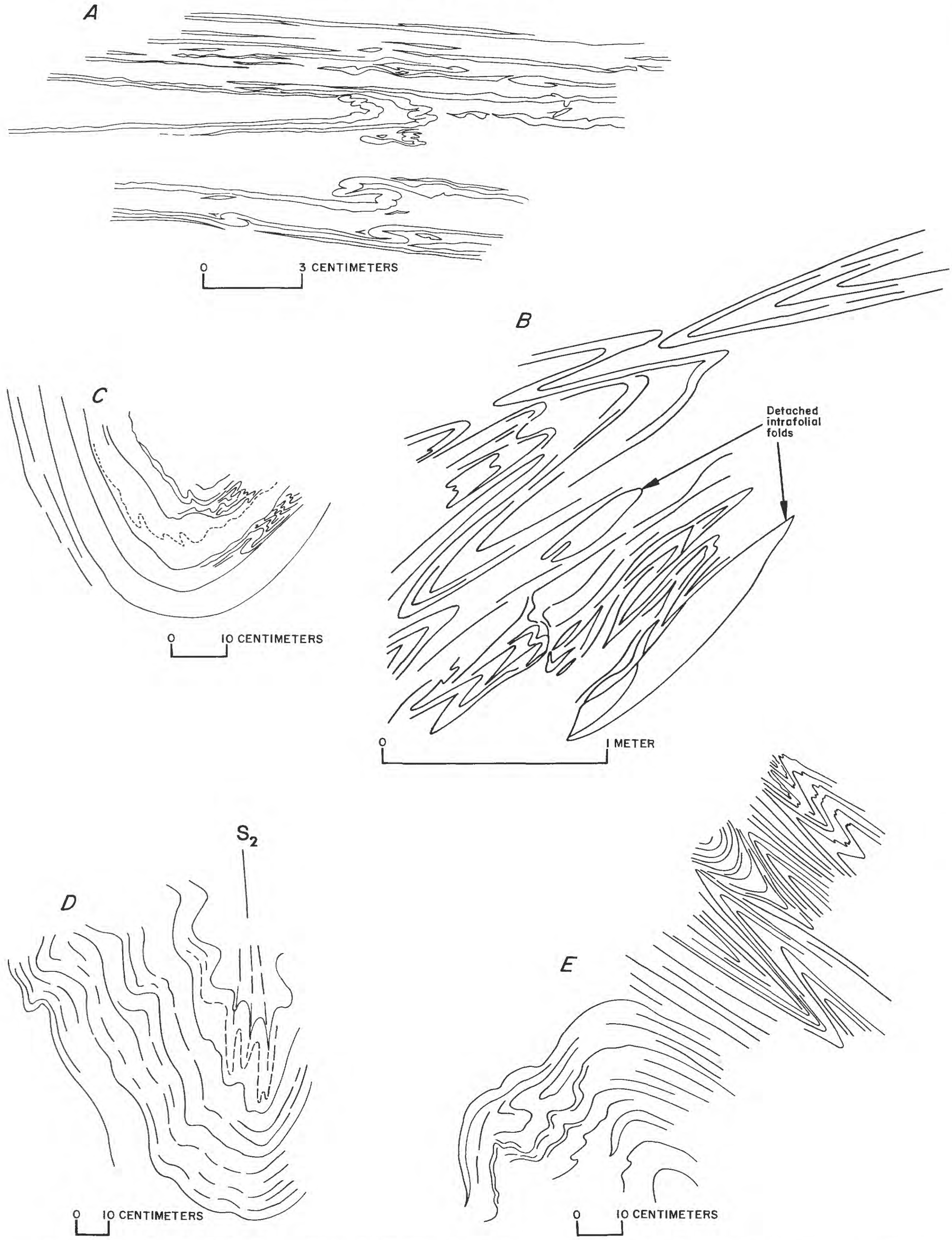


FIGURE 3.—Profiles of early folds (B_1) and later folds (B_2). *A*, tightly appressed B_1; folded quartz laminae in muscovite schist. *B*, tightly appressed B_1; folded quartz laminae and boudinage in quartzite. *C*, B_2; minor intrafolial folds on the limb of a larger fold in amphibolite. *D*, B_2; folded quartzo-feldspathic muscovite schist with axial surfaces (S_2) developed in the core of the fold. *E*, B_2; chlorite-muscovite schist with a variety of fold forms.

In this study, an effort was made to differentiate shear foliations, penetrative surfaces along which displacements have occurred, from minor faults. Locally, the shear foliations obliterate all earlier crystalline structures, and the schist between shear foliations generally is intensely granulated. The minor faults, in contrast to the foliations, are discrete surfaces that for the most part are not penetrative; the schist on either side is generally not granulated, although it may be fractured. A fault may consist of a thin zone of gouge and breccia in which some shear foliations are present. The shear foliations are not easily distinguished from minor faults everywhere in the sheared chlorite-muscovite schist, owing to the similarity in the characteristics of the two kinds of surfaces.

Shear foliations generally intersect at small angles, although some sets are at large angles to one another (fig. 4). Movements along the shear foliations inclined at low angles to the early compositional layering, S_1, favor the formation of thin tabular layers parallel to S_3 and at low angles to S_1. This crude compositional layering is not persistent. Resistant nodules and lenses of quartz and schist, also generally elongate parallel to S_3, occur in clusters and may be intensely fractured; S_3 wraps around them.

Latest folds, designated B_3, occur in S_1 parallel to the intersections of S_1 and S_3, and also in S_3. These two kinds of folds are not easily differentiated because postcrystalline slip may have occurred on S_1, which then becomes, in effect, indistinguishable from S_3. Because of the anastomosing character of the foliations and the lenticular character of the

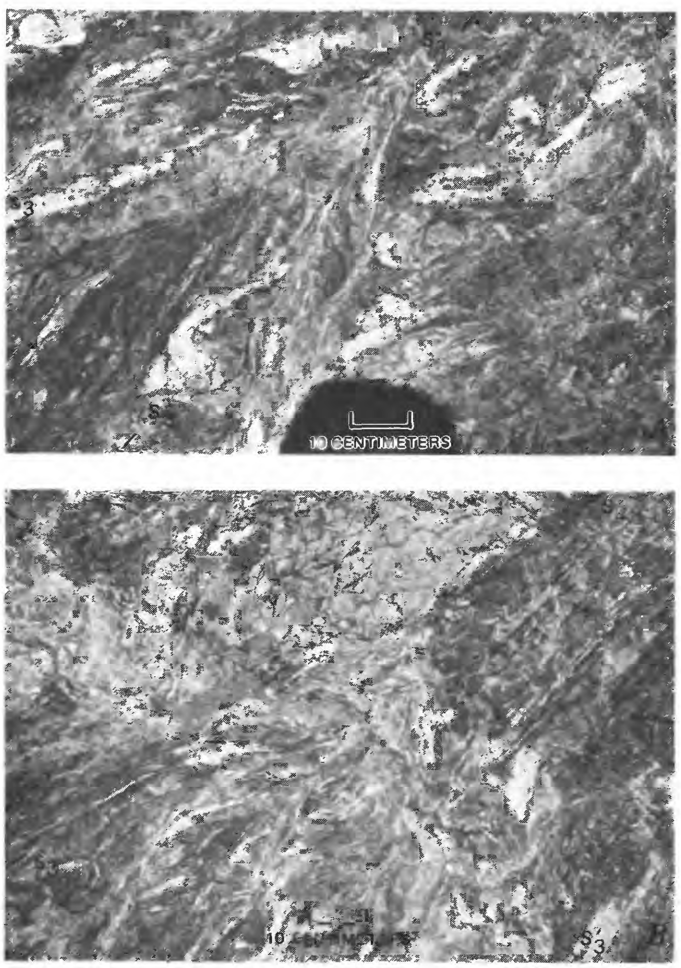


FIGURE 4.—Dominant (S_3) and subordinate (S_3') sets of shear foliations in sheared muscovite-chlorite schist, eastern Ritter Ridge. Traces of S_3 and S_3' are drawn on the photographs. *A*, S_3 and S_3' intersecting at a low angle. *B*, S_3 and S_3' intersecting at a high angle. Movement along S_3 has been intermittent, as indicated by the offset in S_3'.

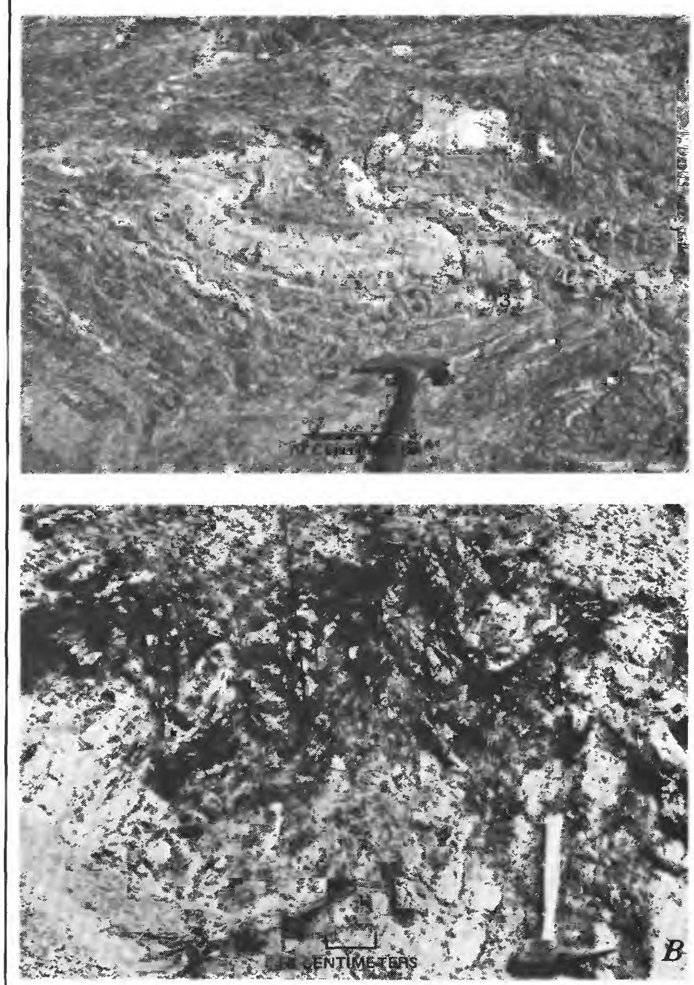


FIGURE 5.—Latest folds (B_3) in shear foliations (S_3) in sheared chlorite-muscovite schist, eastern Portal Ridge. Folds plunge at moderate to large angles to the north-northeast. *A*, Intrafolial folds in S_3. S_3 is warped around the rounded, streamlined, relatively little sheared blocks of schist. White spots are masses of granulated quartz. *B*, Folds in S_3 at a locality adjacent to the Portal fault. Layering defining the folds is partly compositional (flat, resistant lenses of quartz-rich schist and quartz vein material) and partly mechanical (closely spaced, anastomosing groups of shear foliations).

marker horizons in the sheared rock, the folds are not cylindrical. Moreover, fold styles are highly varied owing to the presence of numerous rounded, streamlined angular pieces of schist (fig. 5). Many of the folds in S_3 are intrafolial bounded by planar shear foliations. Overturning of these generally northward-plunging folds is both toward the east and toward the west.

Locally, although S_1 is preserved, the rock is intensely fractured; the early crenulations on S_1 do not have a high degree of preferred orientation, and the style of the folds in S_1 differs in some aspects from that of the earlier sets of folds (fig. 6). Small-scale faulting is common in the hinges, and the cores are made up of schist fragments. In figure 6, slip along S_1 is shown by (1) a small folded shear zone at the northern end of the exposure, (2) a fault zone parallel to S_1 near the center, and (3) quartz veins displaced along S_1 south of the central fault zone. The general forms of the folds crudely resemble some of the early folds, B_1, and their orientations are like those of B_1 in the unsheared terrane nearby.

ANALYSIS OF THE POSTCRYSTALLINE FABRIC

The fabric elements of the postcrystalline deformation are not penetrative features in all outcrops. Generally, anastomosing shear zones separate lenses of little-sheared schist and resistant quartzose nodules. The orientations of the late fabric elements, S_3 and B_3, may vary widely, even in a single outcrop because of (1) inhomogeneity of the late deformation, (2) the interactions among several sets of shear foliations, (3) the interactions between shear foliations and early foliation, S_1, and (4) slip on the early foliation during the late deformation. The inhomogeneity of the deformation is partly accounted for by the local influence of large blocks of unsheared schist. Nevertheless, the data from individual exposures of shear zones show many similarities in orientations of the structural elements classified as S_3 and B_3.

Data from the shear zones located near the Portal and Hitchbrook faults were gathered and analyzed as two separate groups in order to find the orientations of the late fabric elements characteristic of the shear zones of the respective faults and to determine the relations of the minor structures in each of these two fault zones.

FABRIC OF SHEAR ZONES NEAR THE SAN ANDREAS FAULT

The poles to the shear foliations, S_3, define a point maximum with some spread along a great circle (fig. 7*A*). The center of the 5-percent concentration (fig. 7*A*) corresponds to the normal of a shear foliation that dips 65° NNE. and has a strike of 100°. Although this strike is close to the trend of the San Andreas fault in Leona Valley (115°), it is more nearly parallel to most of the major west-northwest faults in the Pelona Schist and to a segment of the Hitchbrook fault (pl. 1).

The poles to the mean attitudes of S_1 at localities in the vicinity of the shear zones near the San Andreas fault form a broad girdle (fig. 7*C*). Some of the poles to the shear foliations coincide with poles to the early foliation, S_1. This association illustrates the field

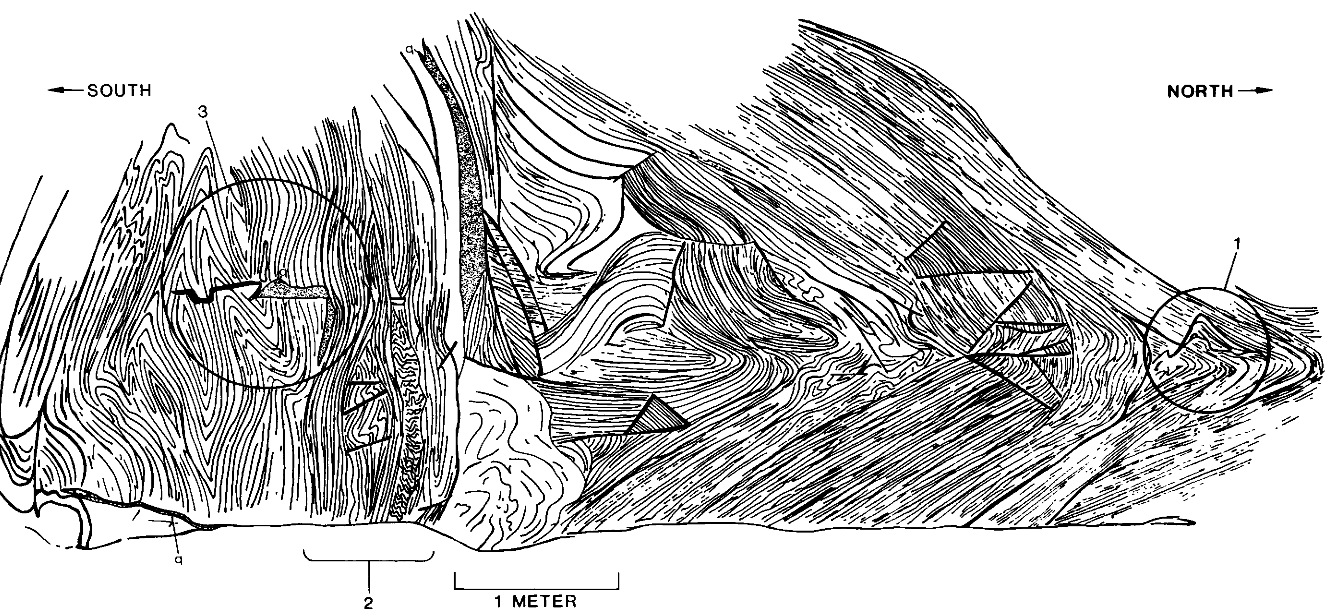


FIGURE 6.—Profiles of early folds modified by postcrystalline deformation in exposure along eastern Portal Ridge. Axes of these folds in micaceous schist plunge at low angles to the west-northwest. Breccia is in fold core, and kink bands are locally at large hinge. q, quartz vein. 1, small fold shear zone at northern end of exposure; 2, fault zone parallel to S_1 near center of exposure; 3, quartz veins displaced along S_1 south of central fault zone shown in 2.

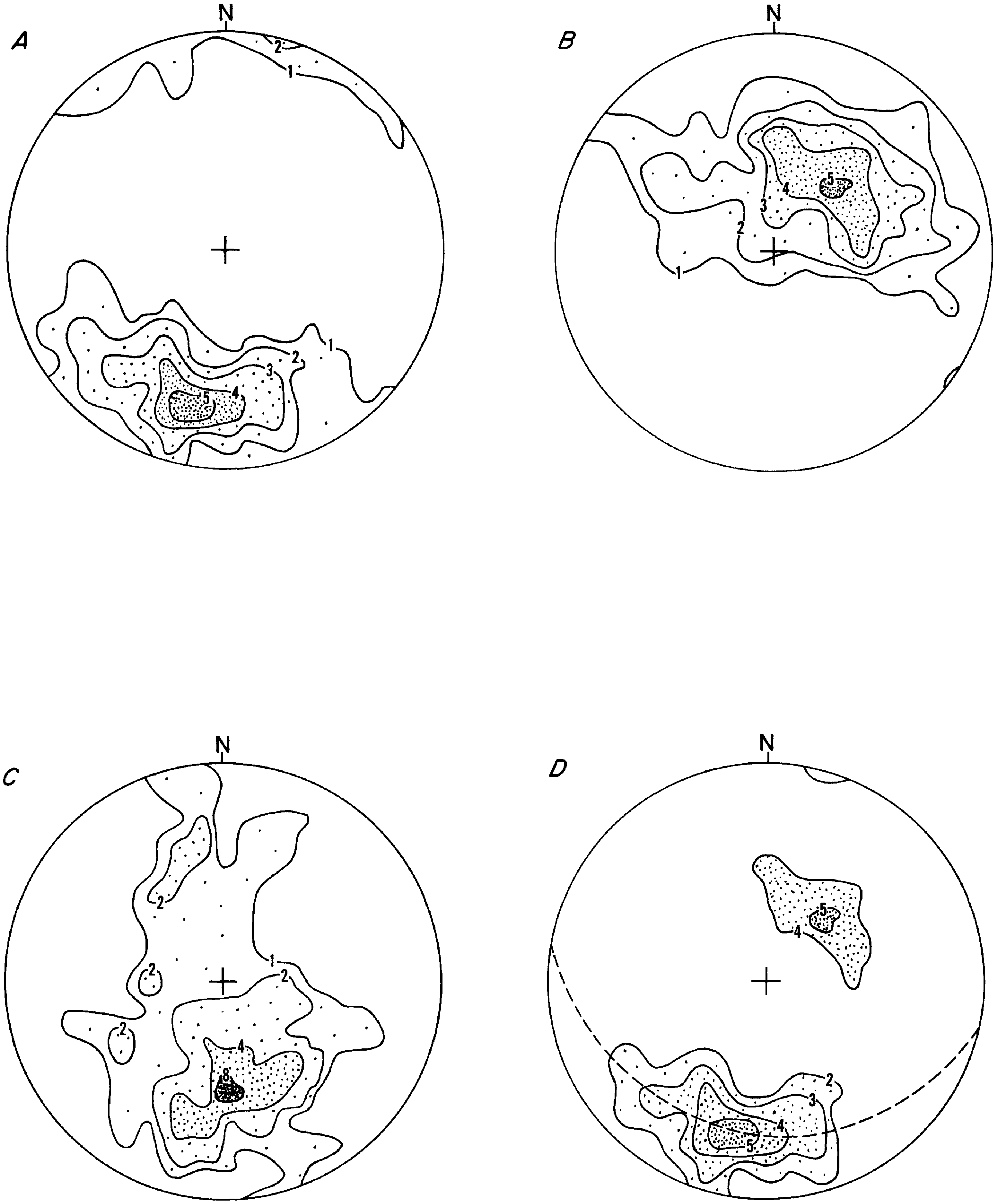


FIGURE 7.—Contoured fabric diagrams showing shear foliations (S_3), fold axes (B_3), and mean attitudes of dominant foliations (S_1) of shear zones near the San Andreas fault. Contours are shown in percent per 1-percent area. *A*, poles to S_3; 322 points. *B*, B_3; 321 points. *C*, poles to mean attitudes of S_1; 102 points. *D*, relations between S_3 and B_3. Black dot is the normal to the great circle (dashed line) distribution of poles to S_3.

observation that some of the shear foliations are approximately parallel to S_1, although in general they are inclined to the preexisting schistosity of the schists.

The fold axes, B_3, form a weak girdle on figure 7*B*. These axes include those of folds in S_3 and late folds in S_1 formed at the intersections of S_1 and S_3. As noted, these two kinds of folds cannot be easily differentiated everywhere because of slip of S_1. Whereas numerous steep intrafolial folds plunging steeply northeast were observed in the shear zones, other folds, some of which formed at the intersections of S_1 and S_3, plunge in other directions, in particular, west-northwest and north. The weak girdle distribution is probably a result of folding at the intersections of the sets of S_3 with S_1 having a wide range of orientations. In addition, the girdle formed by the fold axes, B_3, is subparallel to a representative attitude of S_3. The broad fold-axis concentration, the center of which plunges 60° in the direction 45°, is near the normal to the great circle distribution of the poles to S_3 (fig. 7*D*).

Slickensides are rare in the shear zones. Some were found at one locality in schist adjacent to the Portal fault (fig. 8). These slickensides are on a block of relatively unsheared mica schist that has different physical properties from the sheared matrix. The relative ages of the minor faults with the slickensides and shear foliations are uncertain, but both types of structures developed during the postcrystalline deformation. Most of the slickensides plunge at low angles to the west, northwest, and southeast (fig. 9*A*). Their mean trend is close to the strike of the San Andreas and Portal faults in Leona Valley. A few slickensides plunge in other directions. Most of the minor faults with these slickensides are steeply dipping and strike northwest-southeast (fig. 9*B*). A few dip steeply southeast and strike northeast-southwest. The slickensides suggest that movements in the fault zone, though complex in detail, are consistent with the lateral slip deduced from the strike separations of geologic units along the San Andreas fault.

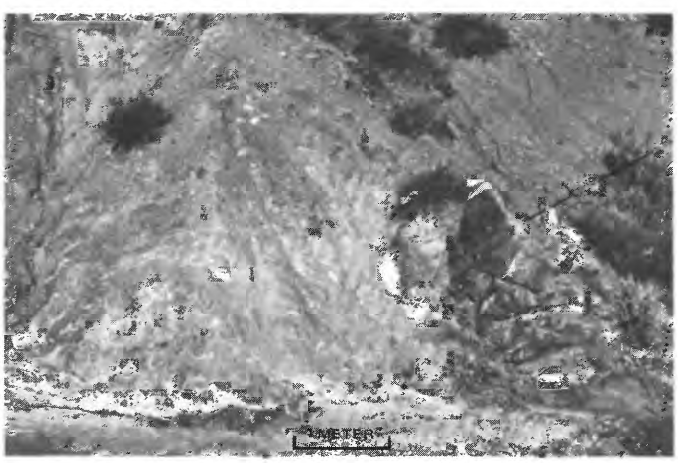


FIGURE 8.—Slickensides in sheared Pelona Schist adjacent to the Portal fault. In block of schist to the right, several minor faults can be seen; each exhibits slickensides that trend parallel to the Portal fault and plunge 25° WNW. Inked line shows the trace of the slickensides visible on the face of the block.

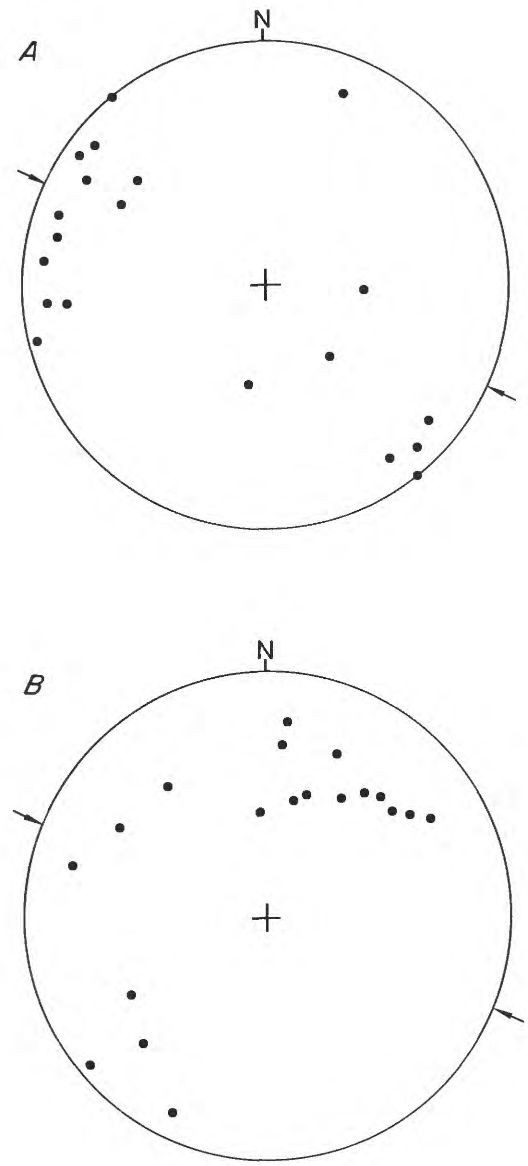
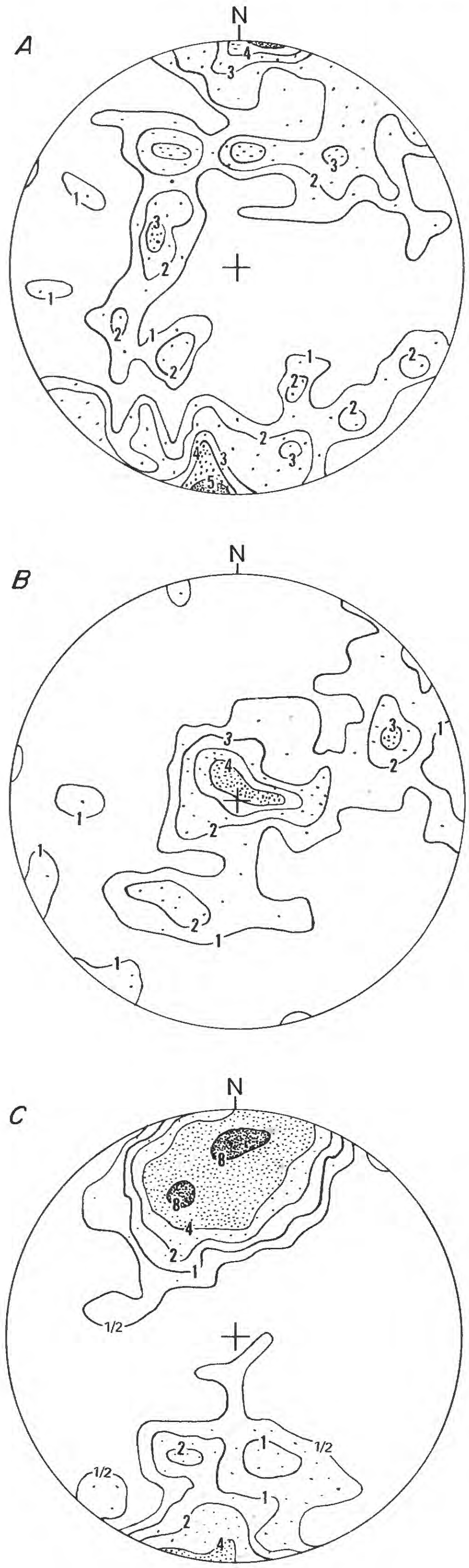


FIGURE 9.—Fabric diagrams of slickensides and minor faults with slickensides of shear zones near the San Andreas fault. *A*, slickensides; 19 points. Arrows in northwest and southeast quadrants mark the strike of the San Andreas fault in Leona Valley. *B*, poles to minor faults with the slickensides of 9*A*; 19 points.



FABRIC OF SHEAR ZONES NEAR THE HITCHBROOK FAULT

The shear zones exposed in the Pelona Schist on northeastern Portal Ridge are within 100 m of the Hitchbrook fault. The fabric of the zones here broadly resembles the fabric of the shear zones near the Portal fault. Near the Hitchbrook fault, however, the predominant orientations of the shear foliations and late fold axes (fig. 10) are different from the principal orientations of these fabric elements near the Portal fault. There appears to be greater inhomogeneity of the late fabric in the shear zones near the Hitchbrook fault than in the shear zones near the Portal fault, as the orientations of the shear foliations and late folds near the Hitchbrook fault vary more widely than the orientations of these late fabric elements near the Portal fault.

The latest fold axes, B_3, are widely scattered in orientation but form one major and two minor concentrations (fig. 10*B*). The 4-percent fold axis concentration plunges nearly vertically. These folds are chiefly in the shear foliation S_3. The smaller 3- and 2-percent concentrations plunge at low to moderately steep angles to the east-northeast and southwest, respectively. Some of the folds having these orientations clearly formed at the intersections of S_1 and S_3.

The poles to the mean attitudes of the early foliation S_1 in the vicinity of the shear zones in northern Portal Ridge form a broad concentration that coincides in part with the major concentration of poles to the shear foliation S_3 (fig. 10*C*). In these shear zones, as in the ones near the San Andreas fault, the early foliation appears to have exerted a strong control over the attitudes of many of the shear foliations and possibly the orientation of the fault itself.

SUMMARY

Although the early foliation, S_1, as a preexisting plane of weakness in the Pelona Schist, has exerted a strong influence over the orientation of the later shear foliations, S_3, and some of the folds produced during the last recorded deformation, a general

FIGURE 10.—Contoured fabric diagrams showing shear foliations (S_3), fold axes (B_3), and mean attitudes of dominant foliations (S_1) of the shear zones near the Hitchbrook fault. Contours are shown in percent per 1-percent area. *A*, poles to S_3; 85 points. *B*, B_3; 141 points. *C*, poles to mean attitudes of S_1; 168 points.

pattern defined by the new elements that evolved during the postcrystalline deformation can be seen. A large proportion of shear foliations, S_3, lie at a small angle to S_1 and dip steeply to the north or are vertical. The strike of these foliations is commonly close to the trend of the Hitchbrook fault and subparallel to the major westward-trending faults mapped in the Pelona Schist. Late folds, B_3, plunge in several directions, but many plunge steeply to the north and northeast or are vertical. The slickensides found adjacent to the Portal fault plunge generally at low angles to the west-northwest, at high angles to the steep fold axes. Little can be deduced from the similarities that the subfabrics in the shear zones have to orthorhombic or monoclinic symmetry except that individual episodes of the deformation in the fault zones may also have been characterized by these symmetries. The symmetry of the total postcrystalline fabric is triclinic.

FAULTS

ANALYSIS OF THE LARGE STEEP FAULTS

The attitudes of the large faults are not easily measured in the field because the fault planes are poorly exposed and because many of the faults are not discrete features but zones in which the rocks have been intensely fractured and sheared. Their

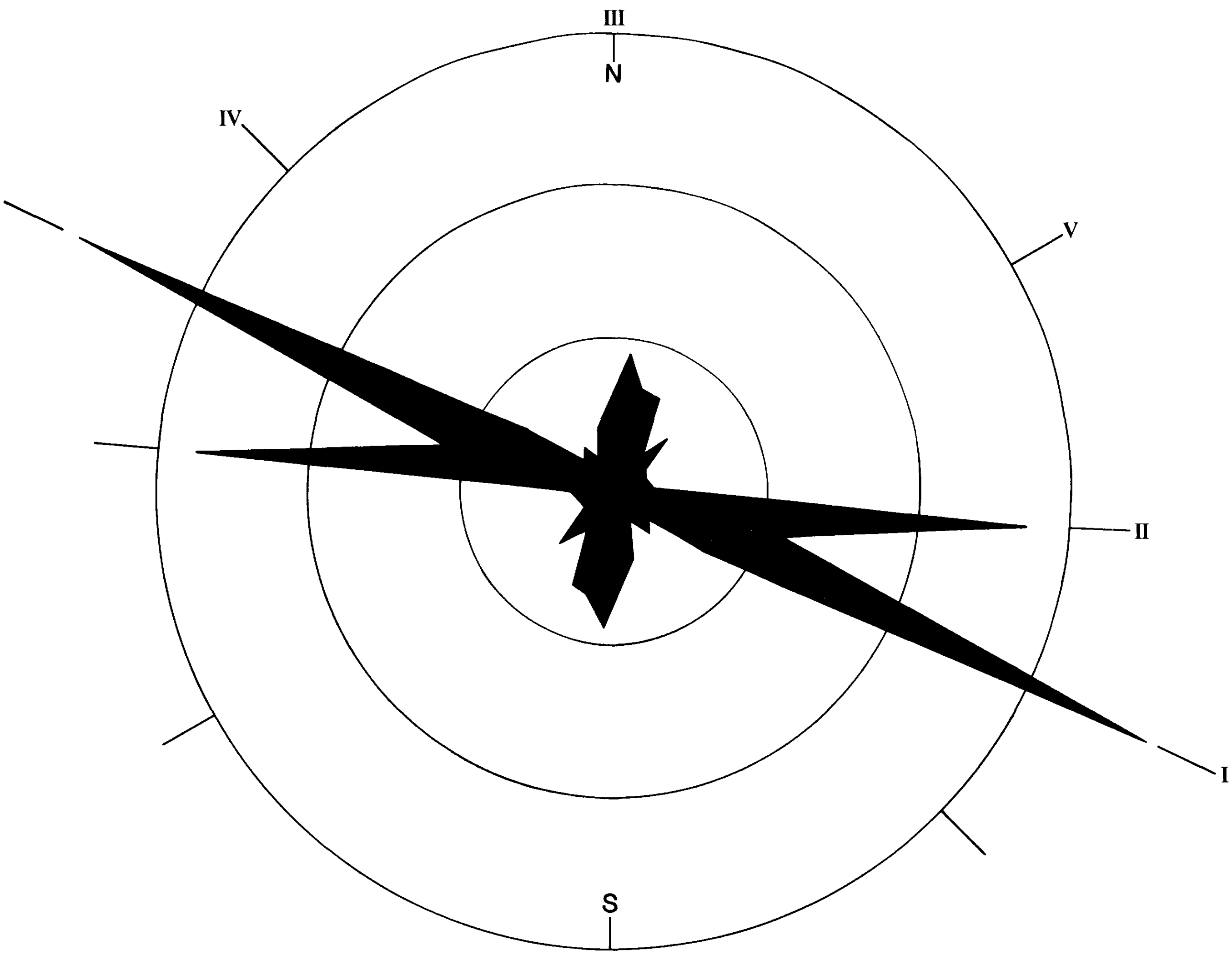


FIGURE 11.—Rose diagram of large steep faults. Faults appear to fall into groups I–V; see text for explanation. Radius of innermost circle, 5 fault-miles.

rectilinear traces across steep canyons imply that many of the faults are steeply dipping or vertical. In order to study the variation in the attitudes of these faults, the dip angles were assumed to approximate 90°. The azimuths of the strikes of the faults were measured from the geologic map and assumed to approximate the strike of the faults. Each fault was weighted by its length of exposure or inferred trace. The faults were then separated into groups wherein the strikes of the faults are within 10° intervals. The total length of the faults in each group is plotted in fault-miles in a rose diagram, figure 11. The rose diagram is biased in favor of the better exposed and more recent faults and shows the preference given to the west-northwesterly faults, which are parallel to the long dimension of the study area.

The faults appear to fall into five groups:

Groups I and II. The groups of faults parallel to the San Andreas fault in Leona Valley (I) and to the general strike of part of the Hitchbrook fault (II), represented on figure 11 chiefly by a small number of long, relatively recently active and well-marked faults.

Group III. Numerous faults that strike in northerly directions.

Group IV. A few faults that strike about 140°, close to the general trend of the San Andreas fault zone north and south of the Transverse Ranges.

Group V. A small, but conspicuous group of faults that strike 45°, close to the general trend of the Garlock fault zone.

LARGE THRUSTS

Thrusts along the northeastern side of Ritter Ridge are at small angles to the early schistosity and compositional layering in the Pelona Schist. The hanging walls cover steep north-trending faults and include at least one vertical fault which strikes west-northwest (pl. 1). Other north-trending faults that dip steeply to the east, or are vertical, truncate and offset the thrusts. A distinctive zone of amphibolite and marble that occurs in the upper plates of the thrusts is several hundred meters closer to Leona Valley than it is in western Ritter Ridge, where few thrusts were mapped. This distribution of the amphibolite and marble points to a large dip component of separation on the thrusts, or shortening along a northeast trend.

MINOR FAULTS AND SLICKENSIDES

The minor faults studied in detail are from a series of roadcuts through the quartzo-feldspathic mica schist along Goode Hill Road in east-central Portal Ridge and are not shown on the geologic map (pl. 1). These faults vary widely in orientation (fig. 12*A*). The faults whose poles make up the large 3-percent concentration of figure 12*A* generally dip steeply to the northeast and have a mean strike of approximately 135°, nearly parallel to the mean strike of the San Andreas fault zone north and south of the Transverse Ranges. The poles to S_1 in the vicinity of the minor faults form a large 16-percent concentration (fig. 12*B*). The small 3-percent concentration of poles to faults on figure 12*A* coincides with part of the 16-percent maximum. This relation emphasizes the control that S_1 has on the attitudes of some of the minor faults.

Slickensides are present on 25 percent of the faults. Most slickensides plunge about 15° to the northwest (fig. 12*C*). The orientation diagram that shows the poles of the faults with slickensides (fig. 12*D*) is somewhat similar to figure 12*A*, suggesting that this smaller sampling of minor faults may be about as representative of the minor faults as is the larger sample. The faults with slickensides were divided into six sets, each of which represents one of the pole concentrations on figure 12*D*.

Set *1* (fig. 13*A, B*). The mean strike of these steep faults is 120°, close to the trend of the San Andreas fault in Leona Valley. Most of the slickensides plunge at low angles to the northwest and southeast, but a few are steep.

Set *2* (fig. 13*C, D*). The faults strike nearly east-west, close to the west-northwest faults of eastern Portal Ridge, and are nearly vertical. Most of the slickensides plunge to the east and west at low to moderate angles. A few are steep.

Sets *3* (fig. 13*E, F*) and *4* (fig. 14*A, B*). The mean strike of these steep faults is north-northwest, parallel to many of the large steep northward-trending faults (fig. 11). Slickensides generally plunge at low angles to the north-northwest, although a few are steeper.

Set *5* (fig. 14*C, D*). These faults have a mean strike of 50°, close to the general trend of the Garlock fault zone. Most of the slickensides plunge at low angles to the northeast, and a few are steep.

Set *6* (fig. 14*E, F*). These faults are parallel to the early compositional layering and schistosity, S_1. The slickensides on them plunge at low angles to northeast, north, and northwest.

If the northwestward-plunging slickensides that are at high angles to the axes of the intrafolial folds in S_3 that plunge steeply to the northeast can be accepted as indicators of major directions movement on S_3, then the form of the intrafolial folds may be useful in determining the sense of major slip. Some of the intrafolial folds resemble the ones described by Kienow (1953; fig. 5*A*). The sense of overturning of the folds described by Kienow gives the sense of

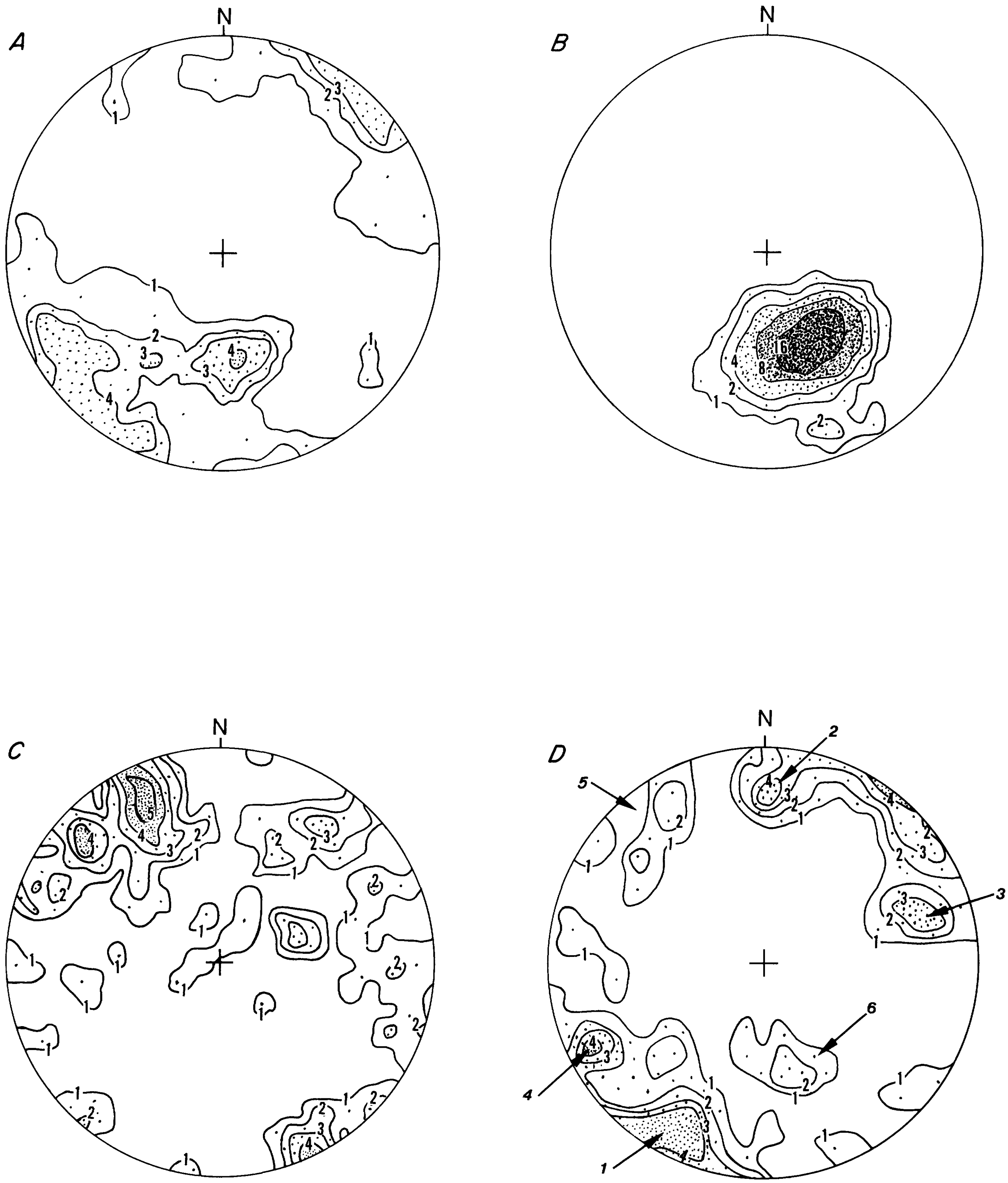


FIGURE 12.—Contoured fabric diagrams of minor faults, early foliations (S_1), and slickensides, eastern Portal Ridge. Contours are shown in percent per 1-percent area. *A*, poles to minor faults; 469 points. *B*, poles to S_1; 156 points. *C*, slickensides; 133 points. *D*, poles of faults with slickensides; 133 points. Numbers *1* through *6* refer to sets of faults discussed in text.

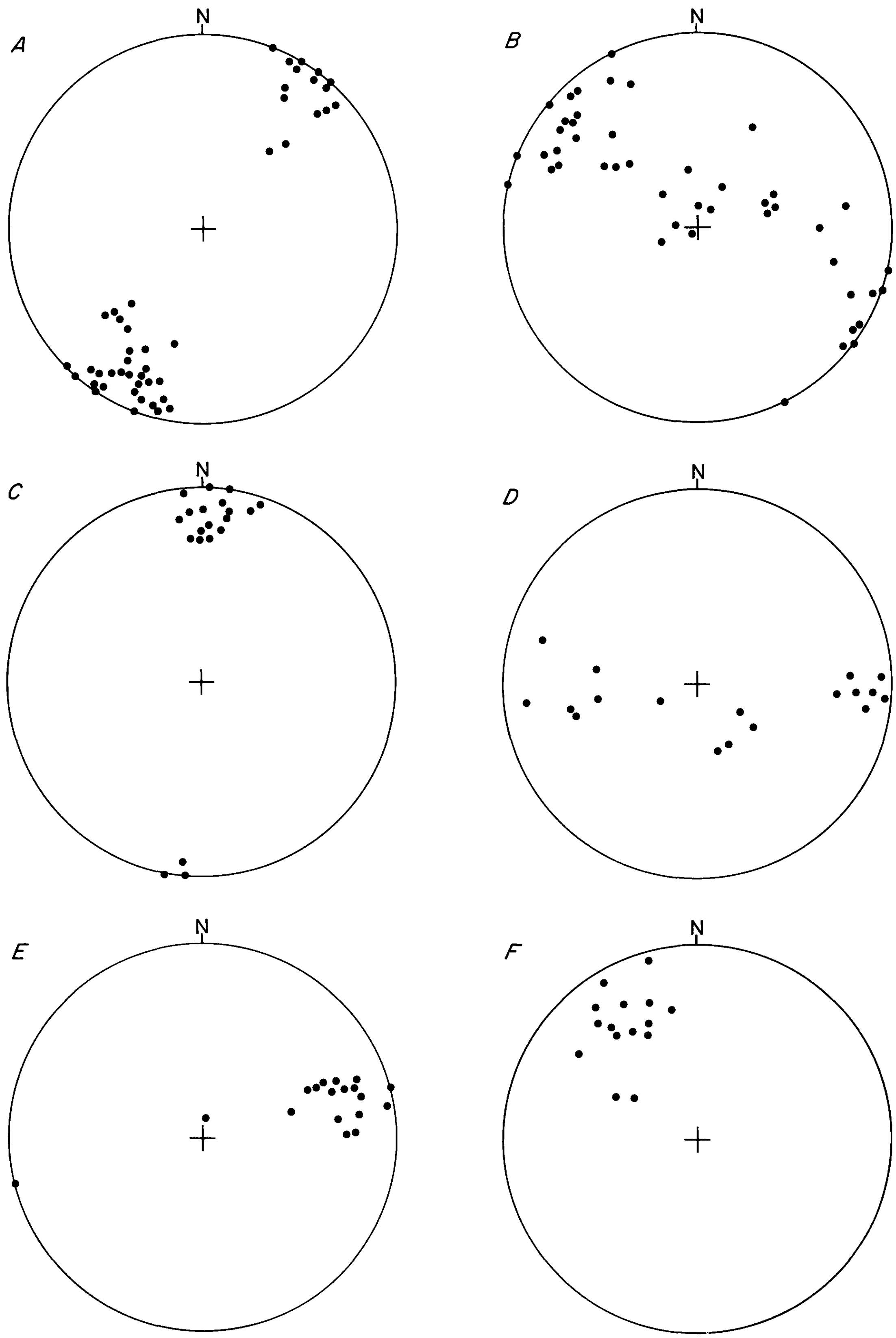


FIGURE 13.—Fabric diagrams of minor faults and slickensides from sets *1-3* (fig. 12*D*). *A*, poles to faults of set *1*. *B*, slickensides on faults of set *1*. *C*, poles to faults of set *2*. *D*, slickensides on faults of set *2*. *E*, poles to faults of set *3*. *F*, slickensides of faults of set *3*.

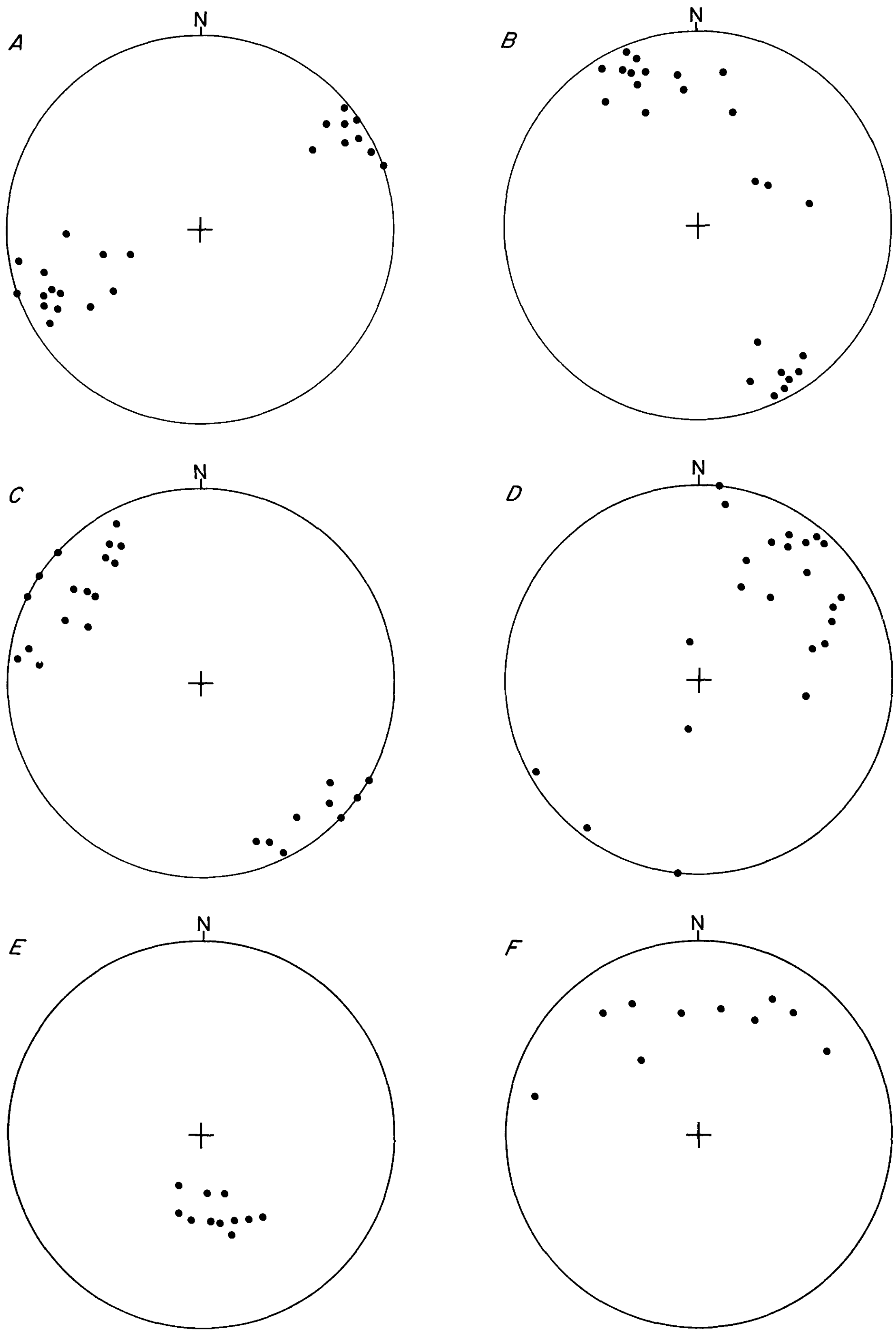


FIGURE 14.—Fabric diagrams of minor faults and slickensides from sets *4-6* (fig. 12*D*). *A*, poles to faults of set *4*. *B*, slickensides on faults of set *4*. *C*, poles to faults of set *5*. *D*, slickensides of faults of set *5*. *E*, poles to faults of set *6*. *F*, slickensides of faults of set *6*.

shearing during the movements in which the folds were formed. Using this criterion in the shear zones near the Portal fault in Leona Valley, where the folds are overturned to the southeast and northwest, no preferred sense of overturning is indicated in the direction of the numerous northwestward-plunging slickensides.

Schist breccia, an important feature of the deformation, locally controls the orientation of the shear foliations and is involved in defining the style of some of the intrafolial folds in S_3. Possibly overturning of the intrafolial folds is not a reliable criterion of sense of shear within these shear zones. Alternatively, movements within minor shear zones like these with triclinic fabric symmetry may be so complex that the sense of shear was not consistent while overall right-lateral slip occurred along major faults within the San Andreas fault zone.

CORRELATIONS OF SHEAR SURFACES AND LATE MOVEMENTS WITHIN THE SHEAR ZONES

Many of the large and minor faults in the study area have similar orientations. Likewise, many of the shear foliations are parallel or subparallel to large nearby faults chiefly to large nearby east-west faults in the Pelona Schist and to the San Andreas fault, and have orientations like those of the minor faults. This parallelism and near parallelism of the three kinds of shear surface (compare figs. 7A, 8, 10A, 11, 12A) suggest that these fabric elements are genetically related to the same shearing deformation.

The slickensides on the minor faults indicate slip directions associated with some phase or phases of this postcrystalline deformation and suggest that these slip directions may be characteristic of the deformation within the shear zones. According to this evidence, strike slip is dominant. Other movements must have occurred, including vertical movement that may include extension parallel to the steeply plunging folds, B_3.

The slickensides on some of the minor thrust faults subparallel to the early schistosity of the schist indicate oblique slip with a large dip component. The orientations of these slickensides are consistent with the northeastward-directed crustal shortening shown by the large thrust faults of northeastern Ritter Ridge. Both large and minor thrust faults suggest that crustal shortening for the San Andreas fault zone as a whole is approximately perpendicular to the San Andreas fault.

SUMMARY

The Pelona Schist of Portal and Ritter Ridges, though pervasively fractured and locally intensely brecciated, exhibits most of the minor features of the crystalline fabric. Strong overprinting with the postcrystalline fabric is confined to shear zones near the San Andreas and Hitchbrook faults. Brecciation of the schist and granulation of the quartz and feldspar are characteristic of this later deformation. Further, the postcrystalline fabric is dominated by an anastomosing group or groups of shear foliations inclined at low angles to one another and to the early compositional layering and schistosity of the schist. Characteristic orientations of the shear foliations are subparallel to large nearly east-west faults (vertical, strike 95°) in the schist as well as to the early schistosity (generally dipping northwest at low to moderately steep angles).

Folds of the shear foliations, commonly of the intrafolial type, plunge steeply or moderately steeply to the north and northeast or are nearly vertical. Other folds, generally similar to the tightly appressed and open folds of the early crystalline fabric and with axes parallel to the intersections of the shear foliations and the early schistosity, plunge in many other directions.

The slickensides on faults of sets *1* through *5* indicate that these minor faults have had a predominantly strike-slip character that includes a small component of dip slip. The less numerous steep slickensides indicate that movements of a predominantly dip-slip nature probably have been less common. The parallelism of these minor fault sets and other faults in the area (the San Andreas fault, the Hitchbrook fault, and the north-trending faults) and some outside the area (the Garlock fault) suggests that the large faults shown on the geologic map (pl. 1) have had similar kinds of movements. Such a conclusion is consistent with the strike-slip character generally accepted for the San Andreas and Garlock fault zones. Slip of this kind, combining a dominant horizontal component and less important vertical components, has been documented for the Atera fault, Japan (Sugimura and Matsuda, 1965), and for the Wairau fault, New Zealand (Lensen, 1968).

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