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Composite planar fabric of gouge from the Punchbowl Fault, California

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Abstract—The structure of clay-bearing gouge from the Punchbowl Fault zone, a brittle fault of the San Andreas system in southern California, is examined at the microscopic scale. The right-lateral, oblique-slip fault consists of a single, continuous gouge zone bounded by a zone of damaged host-rock. The gouge has a statistically homogeneous, composite planar fabric that consists of a foliation defined by the preferred orientation of clay, porphyroclasts and compositional lamination, and a planar anisotropy defined by zones of localized high shear strain (shear-bands). The foliation appears to be related to the accumulation of finite strain and to rotate towards the shear-band orientation with an increase in shear strain. In the Punchbowl gouge the sense of shear on individual shear-bands, and the asymmetric disposition of the planar fabrics with respect to each other and to the boundaries of the zone, appear to be valid indicators of the overall sense and direction of shear. Local variation in preferred orientation of fabric elements exists in the gouge, and therefore statistically based sampling and analysis of the fabric is necessary to infer shear sense and direction.

INTRODUCTION

ROCK IN ductile shear zones commonly exhibits a schistosity (*S*-foliation) defined by preferred alignment of inequant grains and mineralogic differentiation and a planar anisotropy defined by localized zones of high shear strain or displacement discontinuities (*C*-surfaces, shear bands, extensional crenulation cleavage; e.g. Lister & Snoke 1984). In some cases schistosity reflects the accumulation of finite strain, and its orientation may be used to infer sense of shear, finite strain and total displacement across the zone (Ramsay & Graham 1970). If schistosity and some other planar anisotropy coexist, then the rock is said to have a composite planar fabric, and fits the broad definition of *S*–*C* tectonites given by Lister & Snoke (1984). There appear to be many geometric and temporal relations between *S* and *C* structures in ductile shear zones (Berthé *et al.* 1979, Platt & Vissers 1980, White *et al.* 1980, Lister & Snoke 1984).

It has long been recognized that planar anisotropies also are formed in shear zones of clay and clay-bearing rock (Skempton 1966, Morgenstern & Tchalenko 1967, Tchalenko 1968, Mandl *et al.* 1977, Logan *et al.* 1981). In addition, some geometric similarity between fabrics in low- and high-grade shear zones has been noted (Chester *et al.* 1985, Rutter *et al.* 1986). However, detailed characterization of the fabric in natural clay-bearing shear zones is lacking. As such, mechanisms for fabric development and relationship of fabric to strain are poorly known. The purpose of this paper is to present a detailed description of the microstructure of clay-bearing fault gouge from a brittle fault zone of the San Andreas system in southern California. The gouge fabric is compared to that of other low- and high-grade shear zones. The development of the fabric and the use of fabric elements as shear-criteria are addressed. Study of shear-zone microstructure is aided by knowledge of the shear direction (e.g. Simpson & Schmid 1983). Because mesoscopic structures indicative of shear direction, such as stretching lineations, are not present in the gouge, slip direction of the fault is inferred from the host structure.

REGIONAL GEOLOGY AND DEFORMATION HISTORY

The Punchbowl Fault is a segment of the Punchbowl–Nadeau system, located at the juncture of the San Gabriel Mountains and Mojave Desert, 4 km from the historically active trace of the San Andreas. The Punchbowl and San Andreas faults are approximately parallel and join to the northwest and southeast (Dibblee 1968). The Punchbowl Fault was possibly the main trace of the San Andreas system during much of the Quaternary, and accounts for approximately 20 km of right-lateral displacement (Sharp & Silver 1971, Woodburne 1975).

The 5-km segment of the Punchbowl Fault investigated juxtaposes arkosic Miocene–Pliocene strata of the Punchbowl Formation and a zone of intensely fractured basement (Fig. 1). The basement consists of biotite-rich gneiss, and diorite, tonalite, granodiorite and biotite monzogranite plutonic rocks. The facture zone ranges up to 0.5 km in width, and marks the extent of the Punchbowl–Nadeau system. Other faults of the system occur within the basement, but are not as clearly defined or as continuous as the Punchbowl Fault (Noble 1954, Cox *et al.* 1983). Structures in the intensely fractured basement indicate a complex history with episodes of deformation by brittle and ductile mechanisms.

The Punchbowl Formation consists of an interbedded sequence of moderately-indurated conglomerate, sandstone and siltstone. The present stratigraphic thickness of the Punchbowl Formation and overlying units is

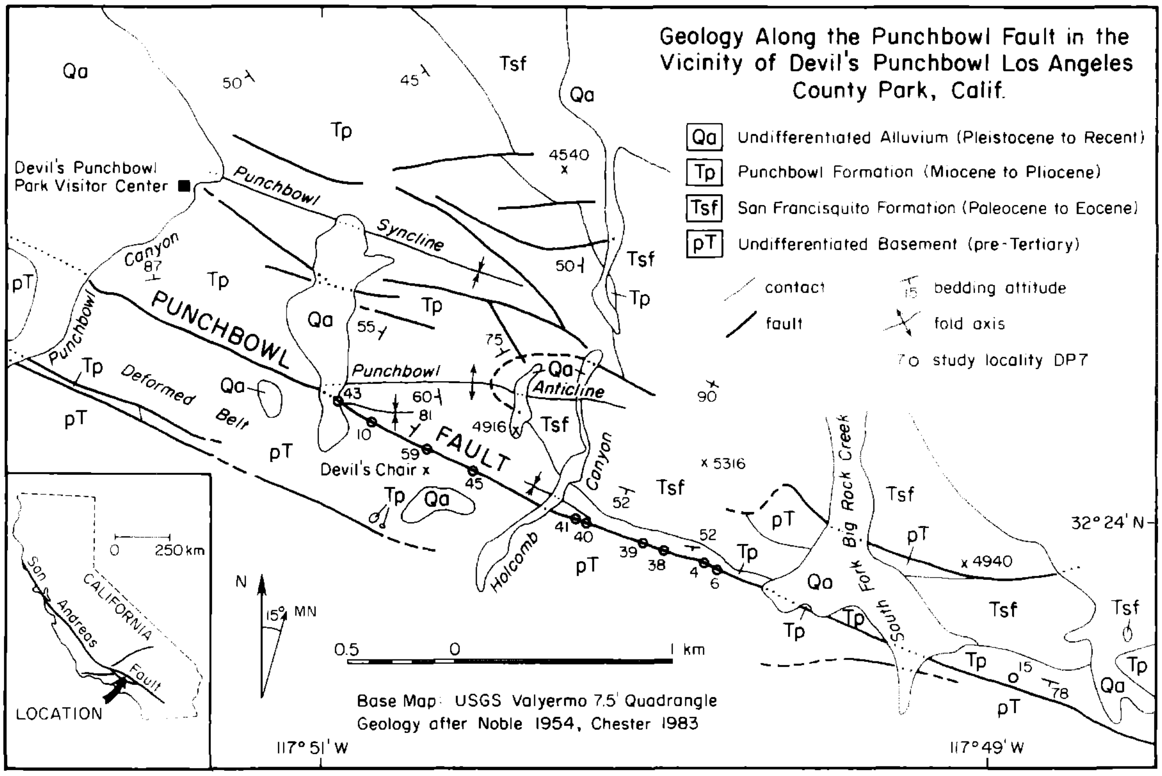

Fig. 1. Geologic map of the Punchbowl Fault in the vicinity of Devil's Punchbowl Los Angeles County Park, California. Gouge outcrop and study locations are indicated.

approximately 1800 m in the study area (Noble 1954). Due to the presence of several unconformities, however, the stratigraphic thickness at the time of faulting is unknown (Noble 1954, Woodburne 1975). The depth of faulting, estimated from the stratigraphic thickness, is 2–4 km, corresponding to temperatures and over-burden pressures of 75–125°C and 22–45 MPa. The depth estimate takes into account possible additional section and/or tectonic thickening from folding and faulting at the time of fault activity. The mineralogy of the Punchbowl Formation and gouge is consistent with the stratigraphically inferred pressure and temperature conditions (Chester & Logan 1986). Consequently, deformation in the fault zone is expected to have been by cataclastic mechanisms with minor pressure solution (e.g. Sibson 1977, Rutter 1983).

FAULT ZONE STRUCTURE

Within the study area the Punchbowl Fault is a single, continuous gouge zone bounded by damaged host-rock. The gouge is exposed between locations DP43 and DP45, DP4 and DP6, and at isolated outcrops elsewhere (Fig. 1). At the macroscopic scale the gouge zone defines the Punchbowl Fault surface. The orientation of the surface was determined by three-point calculations from mapped gouge outcrop locations and by direct measurements of fault exposures. The average orientation is N66°W, 70°SW; the orientation determined for 17 different segments, ranging from 5 m to over 1 km in length, varies 13° in strike and 28° in dip (Fig. 2). Discontinuities in the surface are not apparent at the scale of individual exposures which range up to 50 m in length.

The width of the damaged zone bounding the gouge is variable, but averages 30 m. In the Punchbowl Formation the damaged zone is defined primarily by the presence of subsidiary faults. In the basement it is defined

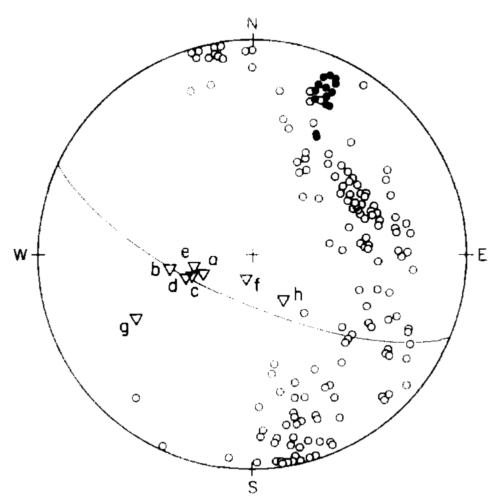

Fig. 2. Orientation of normals to bedding (open circles) and best-fit axes to folds (triangles) in the Punchbowl Formation, and normals to the Punchbowl Fault (solid circles); lower hemisphere, equal-area projection. Great circle shows average orientation of Punchbowl Fault. Fit of fold axes to bedding described in text. (a) Best fit axis to all bedding-normal data (n = number of measurements = 150). (b)–(e) Axes to the four largest folds, the Punchbowl Syncline (n = 70), Punchbowl Anticline (n = 30), DP10 Syncline (n = 28), and DP40–41 Syncline (n = 16). (f)–(h) Axes to small folds in the damaged zone at locations DP38–39 (n = 8), DP10 (n = 4) and DP59 (n = 4).

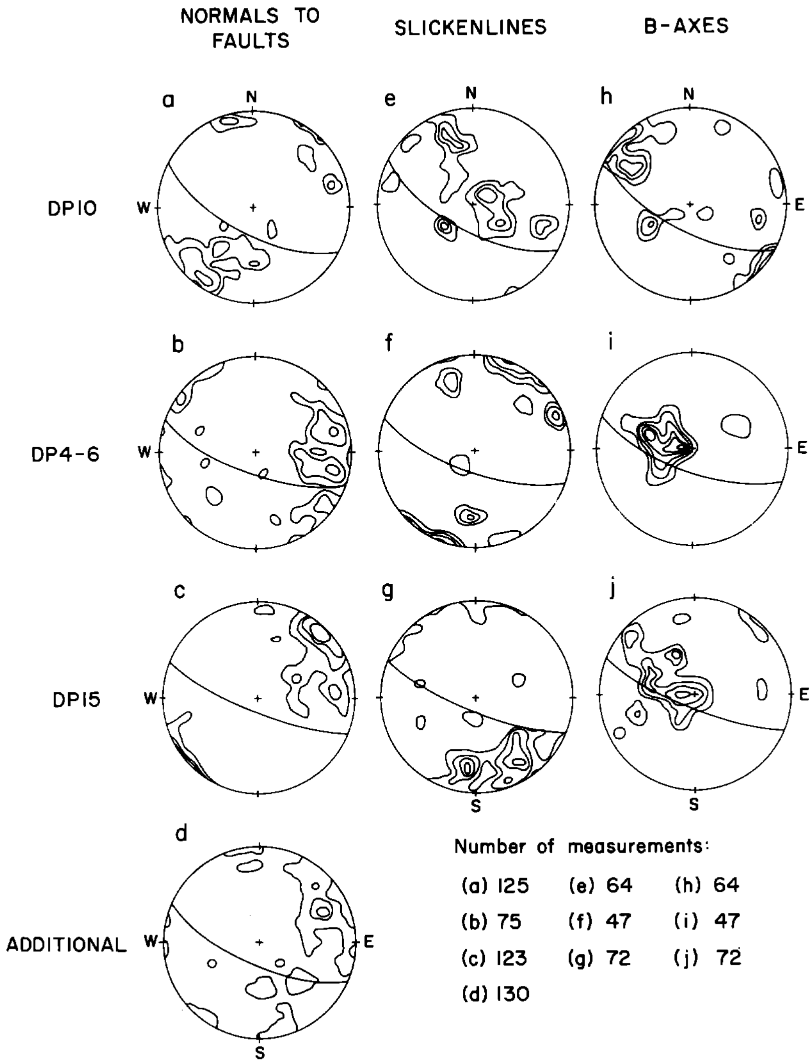

Fig. 3. Subsidiary fault fabric in the damaged Punchbowl Formation adjacent to the Punchbowl Fault at localities DP10, DP4–6, DP15, and elsewhere in the study area. Data are contoured in equal-area, lower-hemisphere projection at 2, 4, 6, 8, 10 and 12% per 1% area. Great circle shows orientation of Punchbowl Fault.

by an increase in fracture intensity and by a greater degree of disruption of igneous and metamorphic structures relative to that within the fracture basement as a whole. The intensity of deformation in the damaged zone increases towards the gouge (Chester & Logan 1986).

Folds in the Punchbowl Formation

The folds within the Punchbowl Formation and in other sedimentary rocks northeast of the Punchbowl Fault are asymmetric, imperfectly-cylindrical folds that plunge NW. The Punchbowl Syncline is the largest and northern-most fold (Fig. 1) The northern limb is longer than the southern limb; this asymmetry is shared by all folds in the area. Fold wavelength and amplitude decrease with proximity to the Punchbowl Fault. The smallest folds, having limbs several meters in length, occur within the damaged zone of the fault.

The orientation of bedding in the Punchbowl Formation was measured within 0.5 km of the Punchbowl Fault to supplement the areal coverage of Noble (1954). The orientation data are grouped into subsets representing specific folds within the area, and the orientation of axes and apical angles for cones of best fit to bedding-normals were determined using standard statistical methods (Ramsay 1967, pp. 14–22).

The best-fit axis to the combined data set trends 247° and plunges 69°SW. Best-fit axes to subsets of the data have nearly the same orientation (Fig. 2). The normals to bedding in the three largest and best-sampled folds are fit by conical surfaces with half apical angles of 70–80°.

Subsidiary faults in the damaged Punchbowl Formation

The subsidiary faults within the damaged zone of the Punchbowl Formation range up to 50 m in length, but are typically 2–5 m in length with offsets of 2–20 cm. The surfaces of the subsidiary faults are usually semi-polished and contain lineations (slickenlines) defined by iron oxide streaks and corrugations. Only rarely can

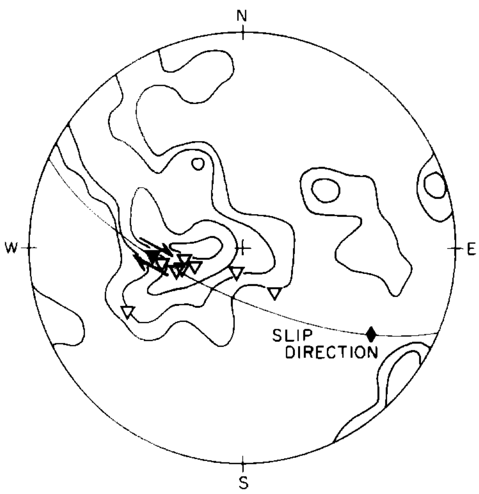

Fig. 4. Summary of host structure showing all subsidiary fault B-axes (contoured at 1, 2, 4 and 6% per 1% area, from Fig. 3h–j), and best-fit axes to folds in the Punchbowl Formation (triangles, from Fig. 2) in lower-hemisphere, equal-area projection. Subsidiary fault measurements weighted so each sample locality contributes equally (179 measurements total). Great circle shows average orientation of Punchbowl Fault; solid triangle and diamond show inferred B-axis and slip-direction, respectively.

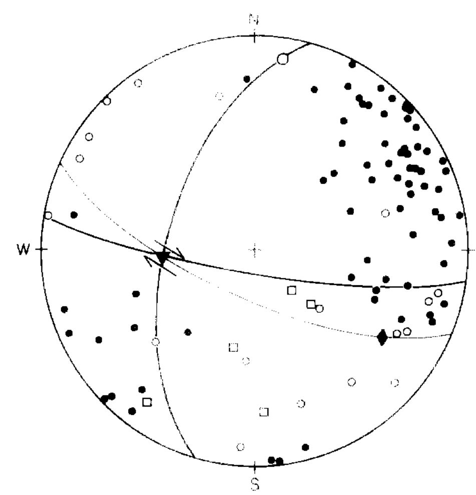

Fig. 5. Orientation of normals to all subsidiary faults for which sense of shear could be determined; solid circles are right lateral, open circles are left lateral, and open squares are reverse faults. Lower-hemisphere equal-area projection showing 94 measurements. Great circle with solid triangle and diamond are same as in Fig. 4. The other two great circles separate fields of right- and left-lateral faults. Orientation of the maximum compressive stress axis that is consistent with the fault fields is indicated by large open circle.

more than one slickenline orientation be observed on a single surface. Sense of offset on the faults can often be determined from offset of small-scale sedimentary structures. All fault sets observed are mutually offsetting. Although the density of subsidiary faults increases towards the gouge zone, there are no obvious changes in orientation or character of the faults with proximity to the gouge.

The orientation of subsidiary fault planes and associated slickenlines were measured at four or five domains at three locations (DP4–6, DP10 and DP15) within the damaged zone of the Punchbowl Formation. Additional measurements were made at other localities. Fault poles, slickenlines and inferred B-axes are plotted in equal-area projection (Fig. 3). The *B-axis* is an imaginary line within a fault plane that is perpendicular to the slickenline orientation, and has the orientation of the intermediate principal strain axis for slip on that fault parallel to the slickenlines (Angelier 1984, Hancock 1985).

The preferred orientation of subsidiary faults and slickenlines varies between locations (Fig. 3). At DP4–6 and DP15 the majority of faults strike NW–NE and dip steeply W (Fig. 3b & c); slickenlines are subhorizontal (Fig. 3f & g). The B-axes are disperse, but define point maxima that are nearly coincident and are concentrated about a line that plunges steeply W (Fig. 3i & j). The normals to faults measured elsewhere in the study area (Fig. 3d) form a pattern grossly similar to that seen in the plots of DP4–6 and DP15 (Fig. 3b & c).

Subsidiary faults at DP10 generally strike NW and dip NE (Fig. 3a). A majority of the slickenlines are oriented approximately vertical (Fig. 3e). The B-axes form two point-maxima; one similar to the B-axis maxima at DP4–6 and DP15, and the other centered on a near-horizontal line (Fig. 3h–j).

Slip direction of the fault

The composite plot of all subsidiary fault B-axes shows a point maximum that lies approximately within the Punchbowl fault plane (Fig. 4). The best-fit axes to folds in the Punchbowl Formation cluster about this same maximum. The subsidiary faults clearly are related to slip on the Punchbowl Fault because they occur within, and define, the damaged zone. All of the folds also are probably related to slip on the Punchbowl Fault, because their axes are approximately parallel and some folds occur within the damaged zone. The approximate colinearity of fold axes and subsidiary fault B-axes is consistent with fold and fault formation under the same displacement field. Because the folds and subsidiary faults are related to displacement on the Punchbowl Fault, we infer a slip direction for the Punchbowl Fault that is sympathetic to the host structure. This suggests a B-axis for the Punchbowl Fault that is parallel to the point maximum defined by the fold axes and subsidiary fault B-axes, and a slip direction that rakes approximately 30° SE (Fig. 4).

The Punchbowl Fault is known to be right-lateral by association with the San Andreas, as well as by correlation of offset stratigraphic units (e.g. Dibblee 1968, Woodburne 1975). A plot of all subsidiary faults for which the sense of shear could be determined shows that the majority are right-lateral, sympathetic to the right-lateral slip on the Punchbowl Fault (Fig. 5). The distribution of both right- and left-lateral faults suggests that the greatest principal compressive stress was nearly normal to the fault surface.

The inferred slip direction suggests that there was a significant component of dip-slip motion on the Punchbowl Fault. This is consistent with the reverse geometry of the Punchbowl Fault and with the fact that basement

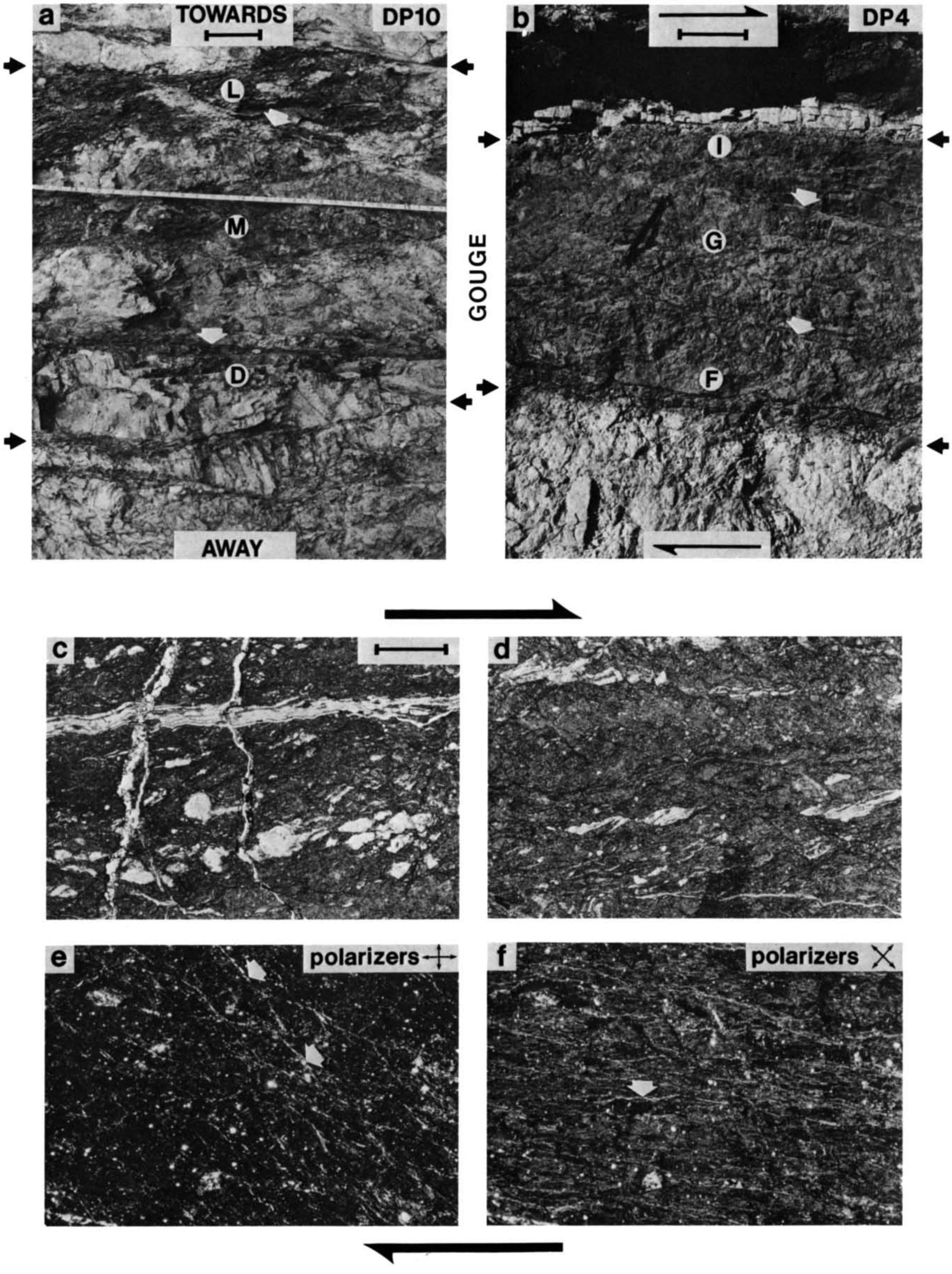

Fig. 6(a) and (b). Excavations of the gouge zone at DP10 and DP4. Sense of fault displacement indicated; scale bar is 0.1 m. Small black arrows identify gouge–host contacts; basement is at top and Punchbowl Formation at bottom of photos. Sample locations are indicated with letters, and mesoscopic shear-bands identified by small white arrows. Note the gouge–Punchbowl Formation contact at DP10 changes orientation by 15°. (c)–(f) Micrographs of gouge sample DP10D in slip-parallel section. All views oriented for dextral shear; scale bar is 0.4 mm and applies to all micrographs. (c) Intact fractures filled with quartz and calcite cement; plane polarized light (ppl). (d) Offset segments of filled fractures; ppl. (e) and (f) Same view of gouge under crossed polarized light, orientation of polarizers indicated by arrows. Clay foliation is evident from the change in intensity of light transmitted through the matrix with a change in the polarizer orientation. Microscopic shear-bands (arrows) are also highlighted.

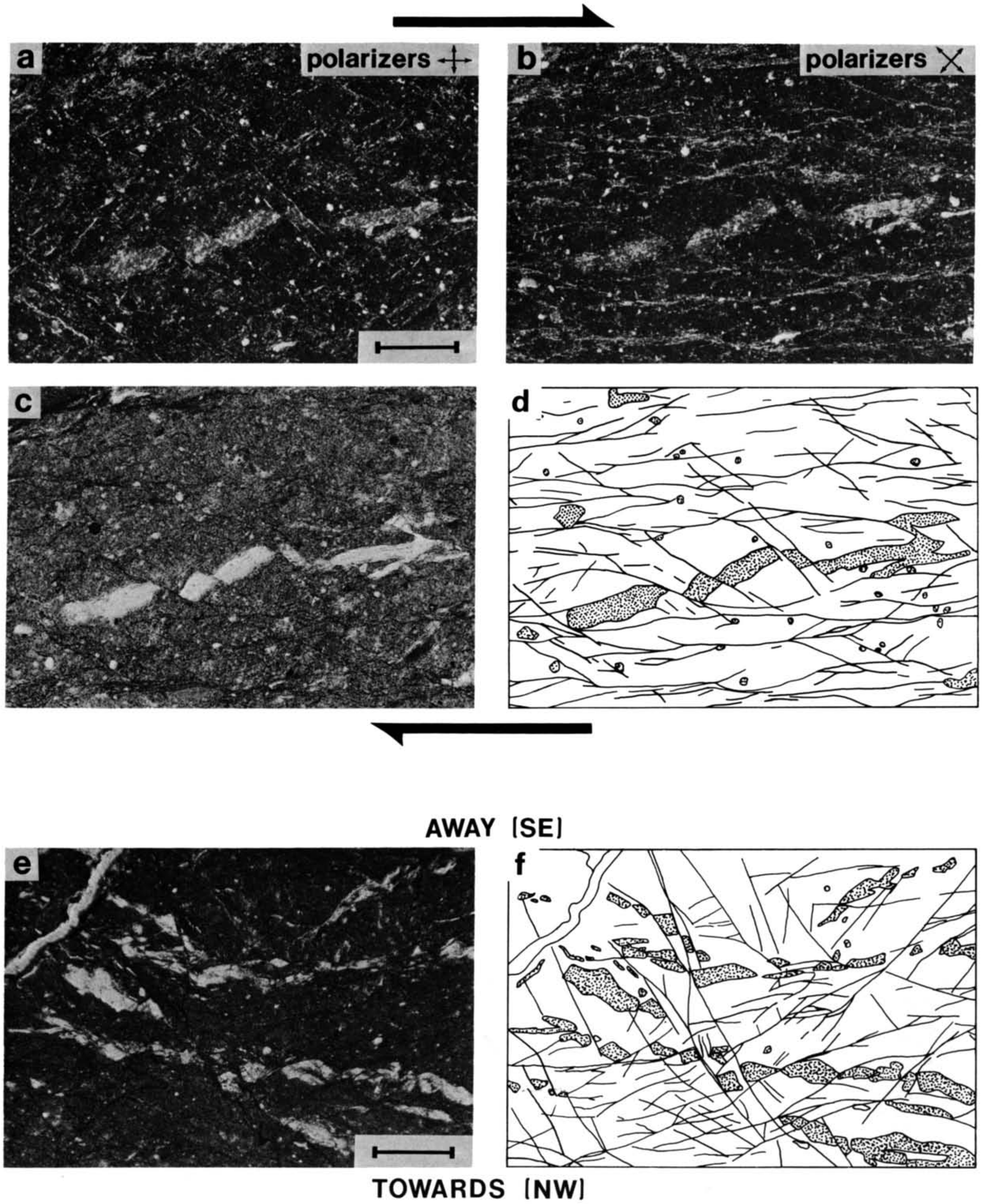

Fig. 7. Geometry and offset on microscopic shear-bands in the (a)–(d) slip-parallel section, and in the (e) and (f) slip-normal section of sample DP10D. Sense of shear is indicated; scale bar is 0.4 mm and applies to all micrographs. (d) and (f) Superposed tracings of shear-bands and porphyroclasts from photomicrographs of gouge viewed through crossed polarized light with polarizers at different orientations and through plane polarized light. Only dextral offset evident in slip-parallel sections; dextral and sinistral offset in slip-normal sections.

is faulted over the Punchbowl Formation. A significant component of dip-slip movement also is in agreement with the southern block (San Gabriel Mountains) having been a topographic high, and the northern block (Devil's Punchbowl) having been a topographic low and the site of sedimentation, during Punchbowl Fault activity (e.g. Woodburne 1975).

GOUGE FABRIC

Mesoscopic scale

The gouge zone can be distinguished from the host-rock on the basis of texture and color. It is typically 45 cm wide, but varies from 5 cm to 1 m (Fig. 6a & b). The composition at localities DP4 and DP10 is similar (Chester & Logan 1986). The gouge is usually dark brown, poorly indurated, and very-fine grained; porphyroclasts are not generally evident in the hand specimen. Even though the variation in color, induration and texture is subtle, it defines crude layering that is approximately parallel to the fault surface. The contact of the gouge and host deviates up to 25° from the average orientation of the zone over length scales typically less than one meter (Fig. 6a) (Chester & Logan 1986, fig. 7b).

The gouge is extensively fractured normal and parallel to the zone and is easily eroded. In 0.5-m deep excavations the fracture density is reduced; however, curviplanar discontinuities are still present throughout the zone and at the contacts with the host. The discontinuities are oriented parallel or slightly oblique to the gouge–host boundaries (Fig. 6a & b) Some discontinuities that parallel the zone are greater than 10 m in length, and juxtapose gouge of different color and induration. These relations suggest that the discontinuities are sites of shear; herein they are termed mesoscopic shear-bands.

Microscopic scale

Three oriented samples were collected from across the zone at both DP4 and DP10 (Figs. 1 and 6a & b). Two petrographic sections oriented normal to the gouge zone were prepared from each sample. The two sections are oriented parallel and perpendicular to the inferred slip direction of the fault, and are referred to as slip-parallel and slip-normal sections, respectively.

The presence of water-swelling clay in the gouge, and the poor induration, necessitated special section preparation techniques. Samples were cut by a diamond saw using isopropyl alcohol and impregnated with epoxy between cuts. Dehydrated kerosene was used as a lubricating agent during polishing.

The constitution and fabric of the gouge were characterized via point counts and orientation measurements at 100 evenly spaced locations in an area 20 mm square on each of the slip-parallel sections. Orientation measurements were also made at 25 locations in each of the slip-normal sections. All fabric elements measured are planar features. At each location (1 mm field of view), the orientation of the element in the plane of the section was measured with respect to the shear plane, i.e. the macroscopic orientation of the gouge zone at the sample location (angle conventions are shown in Figs. 8 and 11). Statistical analyses of the orientation-distributions use a pre-assigned level of significance of 0.05, and follow Mardia (1972) and Batschelet (1981).

The gouge is composed of very-fine grained ($<10\,\mu m$) matrix (72%), fractures filled with microcrystalline quartz and calcite (8%), and porphyroclasts of single crystals of quartz and feldspar (5%) or of microcrystalline quartz and calcite (13%) (Table 1, Fig. 6c & d). Matrix grains that can be optically distinguished are typically equant, angular porphyroclasts of quartz or feldspar. The filled fractures occur as (1) veins having segments with different thicknesses and orientations, or (2) planar, tapered cracks with high aspect ratios. Some veins form an orthogonal pattern (Fig. 6c). Quartz fill is often fibrous, occurring in several bands symmetric about the center of the fracture, which suggests formation by a crack–seal process (Ramsay 1980).

Fabric elements present in the gouge include: (1) compositional lamination defined by changes in color, and by shape and distribution of porphyroclasts (Fig. 6d); (2) preferred crystallographic orientation of clay in

Table 1. Occurrence (%) of textural features and fabric elements in the Punchbowl fault gouge

Sample number		DP10D	DP10M	DP10L	DP4F	DP4G	DP4I	Average
Matrix (grains $<10\,\mu m$ diameter)		72	59	71	73	79	79	72
Single crystal porphyroclasts		4	3	7	5	5	3	5
Microcrystalline porphyroclasts		21	28	9	7	5	8	13
Filled fractures (intact)		3	9	12	12	5	8	8
Open fractures		0	1	1	3	6	2	2
Compositional Lamination		30	19	16	15	5	7	15
Clay foliation	Well developed	23	78	21	44	70	67	50
	Moderately developed	73	22	39	53	30	27	41
	Not present	4	0	40	3	0	6	9
Shear-band sets	High intensity	72	75	16	61	88	66	63
	Moderate intensity	64	60	36	72	84	95	69
	Low intensity	82	81	64	87	83	86	81
	Not present	0	1	23	1	3	0	5

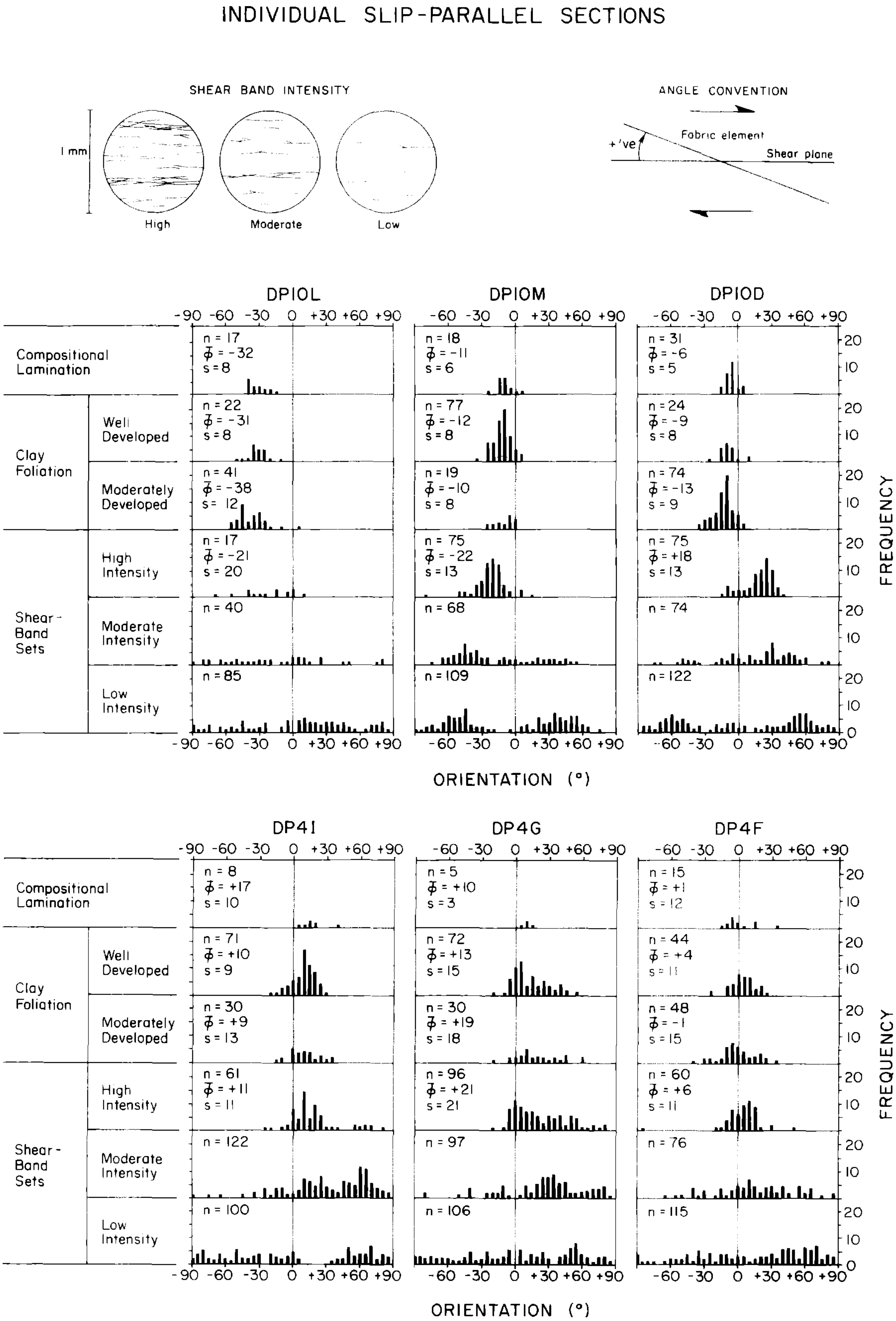

Fig. 8. Orientation-distributions of fabric elements in the individual slip-parallel sections. For each fabric element in each section, n indicates the total number of measurements, ϕ the mean orientation, and s the angular deviation. Orientation measurements are grouped into 5° intervals. Standard used to judge shear-band intensity and angle convention are shown at the top of the diagram.

the matrix, distinguished by uniform extinction (Fig. 6e & f); and (3) microscopic shear-bands, distinguished by the strong alignment of clay within the bands (Fig. 7). The latter features are referred to as shear-bands rather than fractures because shear displacements can be documented by offset of other fabric elements, and because they do not show any indication of extension normal to the bands.

The microcrystalline porphyroclasts appear to be offset remnants of once-continuous, filled fractures. This is suggested by the presence of a complete progression from fractures filled with quartz or undeformed calcite cement, to fracture segments offset along shear-bands, to completely separated, irregular-shaped porphyroclasts of quartz or extensively twinned calcite (Figs. 6c & d and 7). Many isolated quartz porphyroclasts are fibrous and banded, similar to intact quartz-filled fractures. Cross-cutting relations between quartz- and calcite-filled fractures, and between filled fractures and shear-bands, indicate at least several episodes of fracture with quartz and/or calcite cementation followed by shear on newly created or reactivated shear-bands. The calcite cement in some filled fractures is not mechanically twinned, and must represent cementation after the final stage of deformation locally.

Slip-parallel sections

A compositional lamination defined by changes in color was noted at 15% of the measurement locations in the slip-parallel sections (Table 1). The orientation-distribution of the lamination is unimodal in each sample; mean orientations range between −32° and +17°, and angular deviations range between 3° and 12° (Fig. 8). The orientation-distribution of the lamination for the combined sample (all six samples combined) is also unimodal, and has a mean orientation of −8° and angular deviation of 15° (Fig. 9).

The clay foliation was classified at each measurement location as *well-developed* if the extinction angle was uniform and the foliation was present throughout the field of view, *moderately-developed* if the foliation was present throughout the field of view but the extinction angle was variable (but a representative angle could be determined), or if the extinction angle was uniform but the foliation was present only in part of the field of view, or *not present* if the foliation was not developed, or if a representative extinction angle could not be determined.

A clay foliation is present at greater than 90% of the measurement locations in all but one of the slip-parallel sections (DP10L; Table 1). A well developed clay foliation was noted at 50% of the measurement locations. The distributions of the well- and moderately-developed foliations are unimodal in each sample, and have a similar range in mean orientation and angular deviation as the compositional lamination (Fig. 8). The combined sample distributions are also unimodal; the mean orientation of the well-developed foliation is parallel to the shear plane, whereas that of the moderately-developed foliation is −8° (Fig. 9).

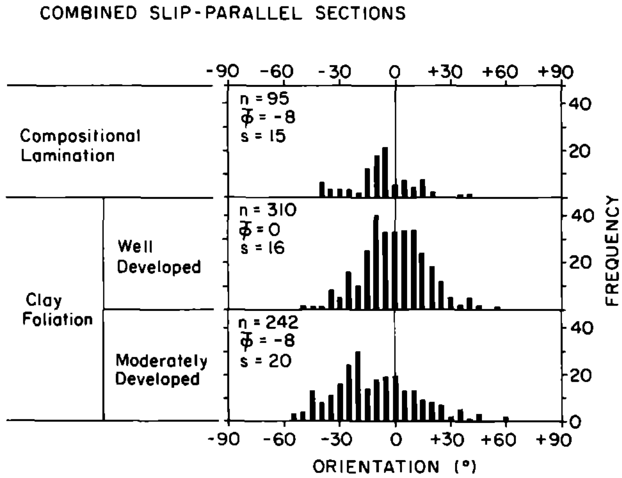

Fig. 9. Orientation-distributions of compositional lamination and clay foliations in the combined slip-parallel sample. Angle convention, grouping interval and symbols are the same as in Fig. 8.

Combining the compositional lamination and clay-foliation measurements (combined foliation) for all samples produces an orientation-distribution with a mean of −4° and an angular deviation of 18° (Fig. 10). The combined foliation of the combined slip-parallel sample is normally distributed; it is satisfactorily described by the von Mises distribution (Batschelet 1981, p. 71).

The shear-band sets in the field of view of each measurement location were qualitatively judged by comparison with a standard to be of *high-intensity, moderate-intensity* or *not present* (Fig. 8). Orientations of only one high-intensity set, and up to two moderate- and low-intensity sets, were measured (if present) at each location.

Except for one sample (DP10L), shear-bands are present at greater than 95% of the measurement locations (Table 1). The orientation-distribution of the shear-bands varies systematically with intensity of development (Fig. 8). The high-intensity distributions are unimodal in each sample, with means and angular deviations ranging from −22 to +21° and 11 to 21°, respectively. The orientations of the moderate-intensity shear-bands are more disperse than the high-intensity set. The low-intensity shear-bands occur in all orientations; however, in some samples (DP10M and DP10D) they have a distinct bimodal distribution with concentrations at approximately +50° and −50° (Fig. 8).

The high-intensity shear-bands in the combined sample have a unimodal orientation-distribution with a mean of +7° and angular deviation of 21° that also is satisfactorily described by the von Mises distribution. Overall, all of the shear-band sets are more prevalent in the positive orientation (Fig. 10).

Offset of porphyroclasts, filled fractures and compositional lamination by the shear-bands document the sense of displacement in the plane of the section. In all slip-parallel sections only dextral shear is observed (Figs. 6d and 7a–d).

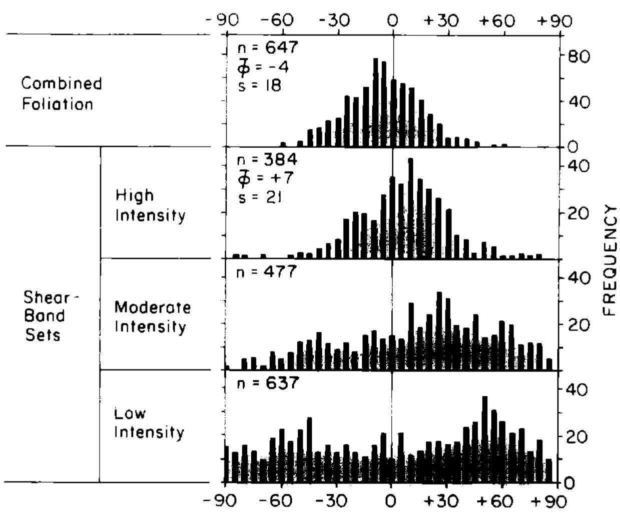

Fig. 10. Orientation-distributions of combined foliation and shear-band sets in the combined slip-parallel sample. Angle convention, grouping interval and symbols are the same as in Fig. 8.

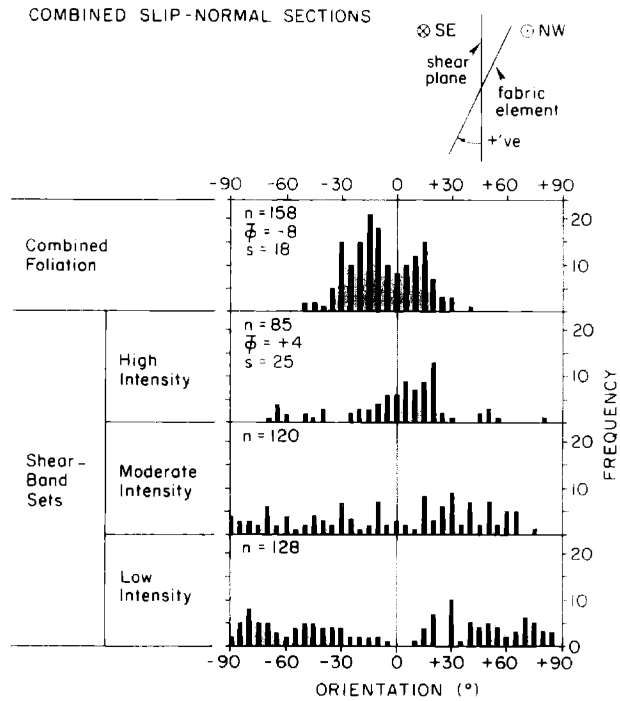

Fig. 11. Orientation-distributions of combined foliation and shear-band sets in the combined slip-normal sample. Angle convention is shown; grouping interval and symbols are the same as in Fig. 8.

Based on the occurrence of the well-developed clay foliation and the high-intensity shear-bands in the individual slip-parallel samples (Table 1), and the location of the samples in the gouge zone (Fig. 6a & b), the fabric elements appear to be best developed in the center of the zone.

Slip-normal sections

The combined foliation in the slip-normal sections has a mean of −8° and an angular deviation is 18° (Fig. 11). In contrast to the combined foliation in the slip-parallel sections, the distribution is neither distinctly unimodal or symmetric.

The orientation-distributions of the shear-bands are similar to those in the slip-parallel sections. The high-intensity set has a unimodal orientation distribution with a mean of +4° and an angular deviation of 25°. In contrast, the moderate- and low-intensity shear-band orientation-distributions are less suggestive of a preferred positive orientation (Figs. 10 and 11).

The most notable difference between the slip-parallel and slip-normal sections is the apparent displacement on individual shear-bands. The shear-bands in the slip-normal sections display examples of both dextral and sinistral shear (Fig. 7e & f).

DISCUSSION

Composite planar fabric of the gouge

In the study area, most of the displacement on the Punchbowl Fault was accommodated by deformation in the gouge zone. At a macroscopic scale the gouge zone boundaries were approximately parallel and the host remained relatively rigid during faulting. At this scale the strain condition in the gouge may be approximated as statistically homogeneous, non-coaxial laminar flow (Paterson & Weiss 1961, Lister & Snoke 1984).

At the mesoscopic and microscopic scales, bulk flow was partitioned between slip on shear-bands (discontinuous) and flow of the intervening gouge matrix (continuous). Deviation from simple-shear would have been caused by slip on shear-bands or other planar anisotropies oblique to the zone (e.g. Platt 1984). In addition, flow of the gouge around boundary irregularities would have caused spatial and temporal changes in the shear direction and orientation of the shear plane (Lister & Snoke 1984). Thus a variation in mean orientation of the fabric elements between individual samples is expected. In fact, means vary by as much as 45°, similar to the variation in orientation of the gouge zone boundaries. As such, the combined sample probably best represents the average fabric of the gouge zone in the study area, and will best demonstrate preferred angular relations of fabric elements to the gouge zone boundaries.

Both the combined foliation and the high-intensity microscopic shear-bands define statistically planar anisotropies. Together these anisotropies constitute a composite planar fabric within the gouge (e.g. Simpson & Schmid 1983). The mean orientations and variance of the planar fabrics are well constrained because several hundred orientation measurements were made in the combined slip-parallel sample, and the orientation-distributions are satisfactorily described by the von Mises distribution. Statistical tests (Mardia 1972, pp. 152, Batschelet 1981, p. 95) indicate that the mean orientation of the combined foliation is significantly different than that of the shear-bands. Additionally, the 95% confidence interval for the means does not include 0° (average orientation of the shear plane). Thus, the mean orientation of the shear-bands and of the combined foliation are significantly shifted in a positive and negative orientation, respectively.

Foliations defined by the same elements as the combined foliation in the gouge have been reported for other natural (Skempton 1966, Rutter *et al.* 1986) and experimental (Morgenstern & Tchalenko 1967, Tchalenko 1968, Mandl *et al.* 1977, Logan *et al.* 1981, Rutter *et al.* 1986) clay-bearing shear zones. In all cases these foliations form a negative angle with the shear plane. In clay-bearing zones the foliation has been referred to as a compression texture (Tchalenko 1968) and *P*-foliation (Rutter *et al.* 1986). However, the fact that these foliations are defined by the preferred alignment of grain boundaries and/or lithologic layering, makes them also similar to schistosity (*S*-foliation) in ductile shear zones (Paterson and Weiss 1961, Berthé *et al.* 1979, Lister & Snoke 1984, Rutter *et al.* 1986). In ductile shear zones the *S*-foliation is thought to be related to the accumulation of finite strain, and is oriented between −45 and 0° to the shear plane. In some cases the *S*-foliation may be parallel to the *XY* plane of the finite-strain ellipsoid (Ramsay & Graham 1970, Lister & Snoke 1984).

The microscopic shear-bands consist of zones of higher shear strain in which the clay is preferentially oriented parallel to the band. The shear-bands are very similar to structures produced in experimental shear zones of clay (e.g. Tchalenko 1968). Such structures found in clay or clay-bearing rock have been often classified as elements of the Riedel array (Skempton 1966, Morgenstern & Tchalenko 1967, Tchalenko 1968, Logan *et al.* 1979, Rutter *et al.* 1986). Typically the R_1 Riedel shear, which is oriented at a small positive angle to the shear plane, and the *Y*-shear (or D-shear of Skempton 1966) which is oriented parallel to the shear plane, are the best developed (e.g. Rutter *et al.* 1986). The orientation-distribution of the shear-bands in the Punchbowl fault gouge is somewhat disperse, so classification as a particular element of the Riedel array is not possible. However, the mean orientation of the high-intensity shear-bands in the combined slip-parallel sample does occur between the R_1- and *Y*-shear orientation, and therefore may represent a combination of these two elements. Because the shear-bands consist of localized zones of high shear strain, they are also similar to *C*-surfaces in mylonites (Berthé *et al.* 1979, Lister & Snoke 1984). In fact, the statistically defined composite planar fabric of the gouge fits the broad definition of *S–C* tectonites proposed by Lister & Snoke (1984, p. 637). Conjugate shear-bands geometrically similar to the conjugate Riedel shears in clay-bearing shear zones (Rutter *et al.* 1986), or similar to the conjugate shear-bands or extensional crenulation cleavage of ductile mylonites (White *et al.* 1980, Platt & Vissers 1980), were not observed in any of the slip-parallel sections.

Clay orienting mechanisms

Preferential alignment of clay in gouge may occur by rotation and/or mechanisms of controlled oriented growth (Williams 1977, Oertel 1983, Rutter *et al.* 1986). The latter mechanism may have been important during Punchbowl faulting because the clay content was apparently increased during syntectonic alteration of the gouge (Chester & Logan 1986). Consistent with the clay-foliation having developed primarily by rotation, however, is the fact that the mean orientation of the moderately-developed clay foliation is more negative than the well-developed clay foliation, and that the acute angle defined by the composite planar fabric is smaller in samples with greater occurrence of well-developed foliation. This interpretation is based on the assumption that rotation of clay in gouge may be approximately described by March's model, which for simple shear predicts a decrease in dispersion of orientation and a rotation of the mean orientation towards the shear plane with an increase in strain (Oertel 1983).

At each measurement location the distinction between the moderately- and well-developed foliations is a qualitative judge of dispersion in clay orientation. If dispersion is reduced by rotation with shear strain, then the moderately-developed clay foliation should occur at a greater negative angle to the shear plane. Standard statistical tests (Mardia 1972, p. 152, Batschelet 1981, p. 95) indicate that the mean orientation of the moderately-developed clay foliation is oriented significantly more negative than the well-developed foliation in the combined slip-parallel sample (Fig. 9).

If the occurrence of the well-developed foliation in the individual slip-parallel sections reflects bulk shear strain in the samples, then the mean orientations of the combined foliation and of the high-intensity shear-bands approach equality with an increase in shear strain (Fig. 12). A similar relationship has been documented for

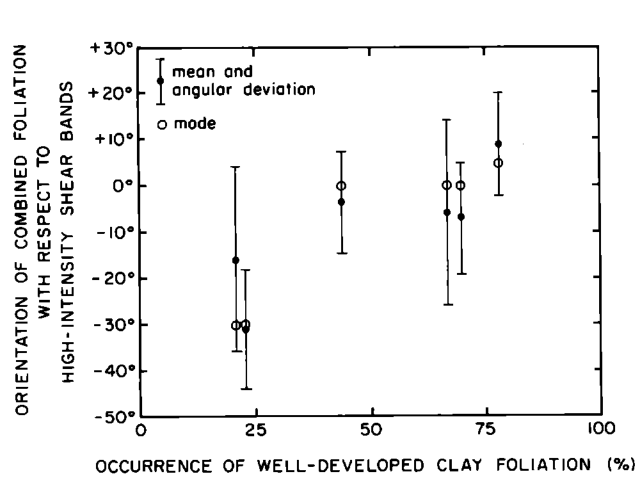

Fig. 12. Orientation of the combined foliation measured with respect to the high-intensity shear-band set (acute angle of the composite planar fabric) versus the occurrence of well-developed clay-foliation (from Table 1) for each of the six slip-parallel sections. Mean orientation, angular deviation and mode of the orientation-distribution in each section is indicated. Angle convention shown in Fig. 13(a).

some S–C composite planar fabrics in ductile shear zones (e.g. Berthé *et al.* 1979, Simpson & Schmid 1983). In these cases the S-foliation rotated towards the C-surfaces, the latter being fixed in orientation parallel to the shear plane (Berthé *et al.* 1979). Although it can not be demonstrated that the shear-bands in the gouge had a fixed orientation with respect to the shear plane during progressive shear, the similarity in evolution of the composite planar fabric in the gouge to that in ductile shear zones suggests that the combined foliation could be kinematically similar to S-foliations and could reflect the accumulation of strain.

The mean orientation of the well-developed clay foliation in the combined slip-parallel sample is parallel to the shear plane, which is the limiting orientation of S-foliation with high shear strain. That the clay foliation in low-grade shear zones rotates towards the shear plane with progressive shear does not agree with experimental findings of Tchalenko (1968) and Rutter *et al.* (1986).

The formation of the Punchbowl fault gouge must have involved extensive cataclasis to reduce the grain size and mix the components. Whether the clay foliation developed during this stage is unknown. Once grain size was reduced other flow mechanisms might have been promoted, such as particulate flow by intergranular slip or pressure solution (Rutter 1983). Either of these mechanisms can produce flow during which clay grains could act as passive markers and rotate under the influence of strain (Oertel 1983). If pressure solution occurred in the gouge it might have provided a source for the silica filling fractures and contributed to the generation of the compositional lamination. Features indicative of pressure solution, such as stylolites or partially dissolved grains, are not evident in the gouge but may be masked by cataclasis.

Shear criteria

There are several asymmetric structures in the Punchbowl fault gouge that appear to be useful as shear criteria. For simple shear, asymmetric structures should be best developed in the plane normal to the zone and parallel to the shear direction (orientation of the slip-parallel sections herein; e.g. Ramsay & Graham 1970, Simpson & Schmid 1983). If fabric elements are viewed in planes at other orientations, the asymmetries may not be developed, or more likely may show contradictory shear sense.

Possibly the best indicator of shear sense in the gouge is provided by the offset of fabric elements by individual shear-bands. In the slip-parallel sections, offsets are always dextral, consistent with the known sense of shear on the Punchbowl Fault.

Based on the geometric similarity of the gouge fabric with planar fabrics in other clay-bearing shear zones (Skempton 1966, Tchalenko 1968, Logan *et al.* 1981, Rutter *et al.* 1986), and to S–C tectonites (Berthé *et al.* 1979, Simpson & Schmid 1983, Lister & Snoke 1984), the negative mean orientation of the combined foliation, the positive mean orientation of the high-intensity shear-

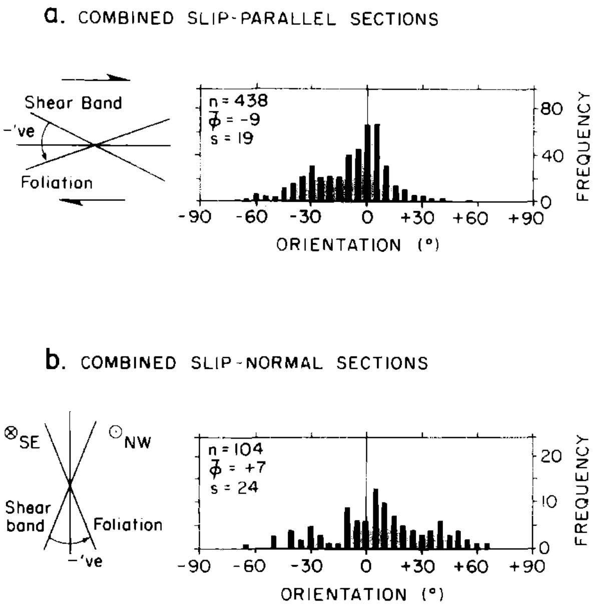

Fig. 13. Angular-distribution of the combined foliation measurement with respect to the high-intensity shear-band set (acute angle of the composite planar fabric) for the (a) combined slip-parallel sample and (b) combined slip-normal sample. Angle conventions are shown: grouping interval and symbols are the same as in Fig. 8.

bands, as well as the positive preferred orientation of the medium- and low-intensity shear-bands, are all consistent with dextral shear (Fig. 10). These determinations are dependent upon the assumption that there has been statistically valid sampling of orientation data to overcome the local variation. The orientation-distributions from individual samples clearly show that limited sampling could be misleading (e.g. DP10M slip-parallel section, Fig. 8).

The orientation of the combined foliation relative to the high-intensity shear bands is a sense of shear indicator that is less sensitive to the local variations in shear direction, assuming that both anisotropies rotate together in response to changes in shear direction. Although the mode for this measure in the combined slip-parallel sample is near 0°, the orientation-distribution is distinctly skewed with a greater frequency of measurements at negative angles, as expected for dextral shear (Fig. 13a).

The consistent shear criteria in the slip-parallel sections suggests that these sections are oriented essentially parallel to the shear-direction, and that the slip-direction for the Punchbowl Fault inferred from the structures in the host is appropriate for the gouge zone. The orientations of fabric elements in the slip-normal sections are also consistent with such an interpretation. For a shear zone with statistically parallel boundaries and relatively rigid host, the plane normal to the zone and parallel to the shear direction is a plane of symmetry (Ramsay & Graham 1970). Planar fabrics viewed in the plane normal to the shear-direction should be symmetric about the symmetry plane. The two best shear criteria, the offset of fabric elements on individual shear-bands and the orientation of the combined foliation with respect to the high-intensity shear-bands are compatible with this symmetry requirement. In the slip-normal sections both dextral and sinistral shear are observed on shear-bands (Fig. 7e & f). In addition, the angular-distribution of the combined foliation with respect to the shear bands is approximately symmetric, and 0° is within the 95% confidence interval for the mean orientation (Fig. 13b).

CONCLUSIONS

The microstructures present in the Punchbowl fault gouge are similar to structures noted in other natural and experimental clay-bearing shear zones. The Punchbowl gouge fabric is characterized by two statistically planar anisotropies: the combined foliation and microscopic shear-bands. The combined foliation is defined by the preferred alignment of clay, porphyroclasts and compositional lamination. It appears to reflect the accumulation of strain, and rotates towards the shear plane with an increase in shear strain, analogous to schistosity in ductile shear zones. Although the microscopic shear-bands occur at all orientations, the longest and best developed bands are preferentially subparallel to the gouge zone boundaries. The shear-bands are similar to *C*-surfaces in ductile shear zones, and together with the combined foliation define a composite planar fabric that fits the broad definition of *S–C* tectonites given by Lister & Snoke (1984).

The gouge fabric is statistically homogeneous at the macroscopic scale. At the mesoscopic and microscopic scales, however, the preferred orientations of the shear-bands and combined foliation appear to rotate together in response to variations in shear direction caused by the irregular gouge zone boundaries and slip on mesoscopic shear-bands. The acute angle defined by the composite planar fabric decreases in magnitude with an increase in strain, primarily from the rotation of the foliation towards the shear bands, analogous to that of the *S–C* structures in orthogneiss observed by Berthé *et al.* (1979).

The offset on individual shear-bands, and the asymmetric disposition of the two planar fabrics to one another and to the average orientation of the gouge zone, may be useful shear criteria if viewed in a plane normal to the zone and parallel to the shear direction. The orientation of the planar fabrics in the plane normal to the shear-direction appears to satisfy the symmetry requirements for zones of simple-shear in rigid host-rock (Ramsay & Graham 1970). Use of the gouge fabric as shear criteria requires statistically based sampling and analysis of orientation data because significant heterogeneity in strain exists at the mesoscopic scale.

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SHEAR CRITERIA IN ROCKS

Section III:

Patterns of faults or shear zones