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Kinematic indicators on active normal faults in western Turkey

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Abstract—Quaternary normal fault zones in western Turkey comprise multiple slip planes and zone-parallel layers of fault breccia. They also contain several little-known kinematic indicators that are probably typical of many formed at shallow levels in extending terrains. The recent exhumation by contractors of about 2000 m^2 of slip planes in a SSE-dipping fault zone separating Quaternary colluvium from bedrock carbonates at Yavansu (7 km SE of Kuşadasi) permits an unusually complete inventory of the indicators to be compiled. The most spectacular indicators are metre-scale 69°W-pitching corrugations in slip planes and recemented breccia sheets underlying them. Corrugations, characterized by sinusoidal profiles normal to their long axes and, less commonly, culminations and depression along their axes possibly developed as a result of upwards-propagating slip planes seeking undemanding pathways through heterogeneous fault-precursor breccias that formed in advance of tip lines. Parallel to corrugation long axes are those of gutters, flat-floored, steep-sided channels a few centimetres wide, probably related to the abrasion of subslip-plane breccia sheets. Centimetre-scale tool tracks scored in the uppermost subslip-plane breccia sheet by resistant colluvial clasts are irregular at their proximal ends but distally they swing into alignment with corrugation axes. Frictional-wear striae, centimetres long but only a few millimetres wide and pitching 78°W, are superimposed on the other slip-parallel lineations. Comb fractures nearly perpendicular to slip planes define an intersection lineation which is normal to corrugation axes. Fault-plane solutions of earthquakes on SSE-dipping active faults in the West Anatolian extensional province indicate that mainly normal, combined with minor dextral slip is the dominant mode, a conclusion in accord with the sense of slip inferred from the indicators exposed on the Yavansu slip planes.

INTRODUCTION

Well-exposed late Quaternary faults provide opportunities for assessing whether 'slickenside lineations' and other fault-plane phenomena, so commonly employed in palaeostress analysis, are trustworthy kinematic indicators. For example, senses of inferred slip can be compared with those calculated from fault-plane solutions of earthquakes or known from ground surface deformation. In addition, some fault-plane features may be related to amounts of displacement known to have accompanied recent seismic events. Furthermore, because we know that the observable features of active fault scarps were formed within a few tens or hundreds of metres of the ground surface, it is likely that some of them are characteristic structures of deformation at such depths of burial.

Although the general characters, including the pitch (rake) of lineations on active faults have been reported by several after-shock teams and neotectonicians, relatively few of them document in detail the range of fault-plane phenomena or discuss their mechanical significance. However, Angelier (1977, 1979), Dumont *et al.* (1981) and Jackson *et al.* (1982), whose investigations, like the present one, were based in the Aegean region, have published photographs showing that more than one class of lineation is present. Furthermore, Vita-Finzi & King (1985) emphasize the role of brecciation as a mechanism of deformation ahead of upwards-propagating active normal faults in the Corinth region of Greece.

During a reconnaissance survey of the West Anatolian extensional province (Fig. 1) we discovered a site at Yavansu (37° 48′N, 27° 17′E), about 6.5 km southeast of Kuşadasi, where a fault zone separating Quaternary colluvial sediments from bed-rock carbonates had been freshly exhumed by contractors exploiting the colluvium for aggregate. Excavation had been carried out with a minimum of machine damage to slip planes. During the few months since exhumation and our recording of the site (late September 1985) there had been little rain either to erode patches of fault rocks still adhering to slip planes or partly cover them by wash material. Our purpose in this note is to report and interpret outcrop-scale phenomena that were investigated in detail in the Yavansu fault zone, and were also observed during reconnaissance surveys of the Manisa and Ephesus fault zones within the same extensional province. We believe that their characters may be typical of the shallower levels (<1 km depth) of other active normal fault zones.

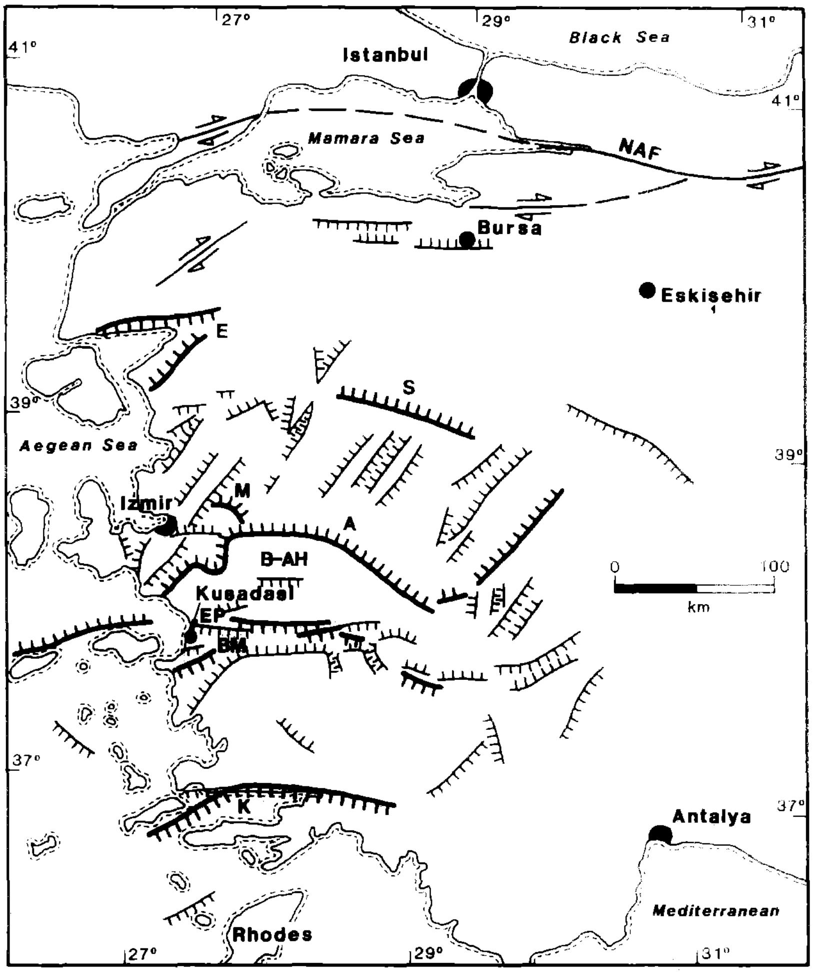

Fig. 1. Map of neotectonic faults in the West Anatolian extensional province of western Turkey. Barbs are shown on the downthrow sides of normal faults and arrow-couplets are shown astride strike-slip faults north of the extensional province. Thick lines indicate principal normal faults. *Grabens*: E. Edremit; EP, Ephesus (Efes); S, Simav; M, Manisa; A, Alasehir; BM, Büyük Menderes; K, Kerme. *Horst*: B-AH, Bozdag-Aydin. Modified from Şengör (1987, fig. 1).

SEISMOTECTONIC SETTING

Kuşadasi is situated in the western part of the West Anatolian extensional province (Sengör 1987) (Fig. 1); a neotectonic (i.e. post-Serravalian in Turkish terms) domain within the larger Aegean extensional region. According to McKenzie (1972, 1978), Dewey & Şengör (1979), Le Pichon & Angelier (1981) and Şengör (1987), the province is experiencing roughly N–S contemporary extension within the westwards escaping Anatolian *scholle* or crustal flake.

The fault zone discussed in this paper is located west of the Büyük Menderes graben, which turns from its dominant ENE-trend to follow a NE–SW direction 20 km east of the site (Fig. 2). The trend of the investigated fault zone is ENE, that is parallel to the greater length of the Büyük Menderes graben. Neotectonic normal faults close to the studied one also strike ENE. The fault zone at the investigated site dips and downthrows at least 200 m to the SSE and can be regarded as the northern framing fault to a subsidiary graben, the southern boundary of which is the Dilek Fault (Fig. 2).

The epicentres of historical (Soysal *et al.* 1981) and instrumental earthquakes (McKenzie 1972, 1978 and computer output data of the Kandilli Observatory, Istanbul) in the study-site area are shown in Fig. 2. Although the historical record is a long one, spanning the interval from BC 2100–AD 1900, Soysal *et al.*'s (1981) catalogue indicates that reported events in the Kuşadasi area occurred in the interval AD 1751–1893. Figure 2 shows that the majority of the events occurred close to the western extension of the Yavansu fault zone. The nearest approximately located epicentre to the studied fault zone is for an intensity VIII event in 1890, although no evidence links this event with an increment of displacement on the Yavansu Fault. Since instrumental records began there have been several $M > 4$ events in the study area. The largest ($M > 7$) earthquake occurred in 1955. According to McKenzie (1978) its epicentre lay close to the Dilek Fault but Ocal (1958), using macroseismic data, located it on the Söke–Balat Fault, which strikes and dips subparallel to the Yavansu Fault. Şengör (1987) also argues for the 1955 event having been on the Söke–Balat Fault and hence this location of its epicentre is shown in Fig. 2.

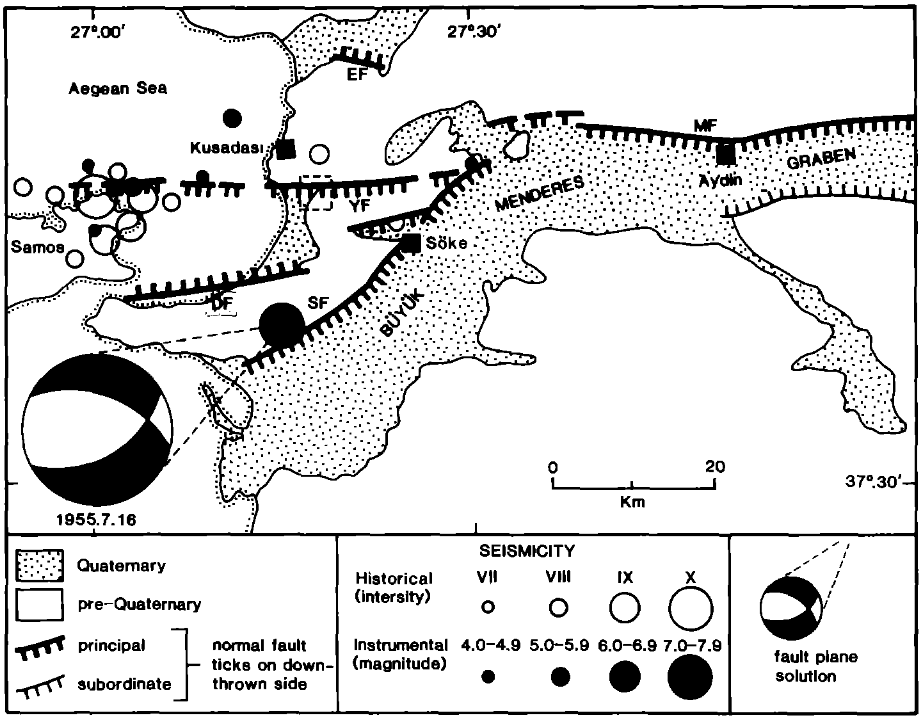

Fig. 2. Seismotectonic map of the western part of the Büyük Menderes graben. Sources: *geology*: 1:500,000 Denizili sheet of M. T. A., Ankara (1964); Landsat 5 image (28/06/1984) path 180 row 034; Şengör (1987, fig. 1); *seismicity*: historical—Soysal *et al.* 1981; instrumental—computer output data of Kandilli Observatory, Istanbul; fault-plane solution of 1955 event from McKenzie (1978, fig. 8) and its epicentral location from Şengör (1987, fig. 1). DF, Dilek Fault; EF, Ephesus Fault; MF, Menderes Fault; SF, Söke-Balat Fault; YF, Yavansu fault zone. The studied sector of the Yavansu fault zone is enclosed by pecked lines.

ARCHITECTURE OF THE STUDY SITE

The 600 m-long and 50 m-wide study site, occupying only a small part of the Yavansu fault zone, contains several ENE- and WNW-striking slip planes inconsistently offset a few metres in plan from each other within an ENE-trending belt (Fig. 3). Although most slip planes strike ENE (052–098°, mean 080°) a few short segments, connecting or interrupting them, strike WNW (092–132°, mean 109°). ENE-striking slip plane inclinations average 58° (42–78°) S, dips generally being steeper in the east. WNW-striking slip planes dip at an average angle of 49° S. The relatively smooth slip planes are exposed 10–40 m above sea level at the base of an ENE-trending topographic scarp which to the north of the site rises at an average slope angle of 25–35° to an elevation of about 150 m (Fig. 4a).

Across the fault zone at the study site it is possible to recognize six components in its architecture (Fig. 5): (A) massive unbrecciated bedrock (Mesozoic) limestones, dolomites and marbles within which bedding is obscure but dips gently south at one locality; (B) broad belts of coarse fault breccia containing carbonate clasts, calcite cement and some void spaces; (C) thin sheets of compact zone-parallel mineralized and recemented fault breccia, here called subslip-plane breccia sheets; (D) corrugated slip planes on the upper surfaces of subslip-plane breccia sheets, the principal one being the uppermost slip plane separating footwall breccias from hangingwall colluvium; (E) linear trails or locally tabular sheets of

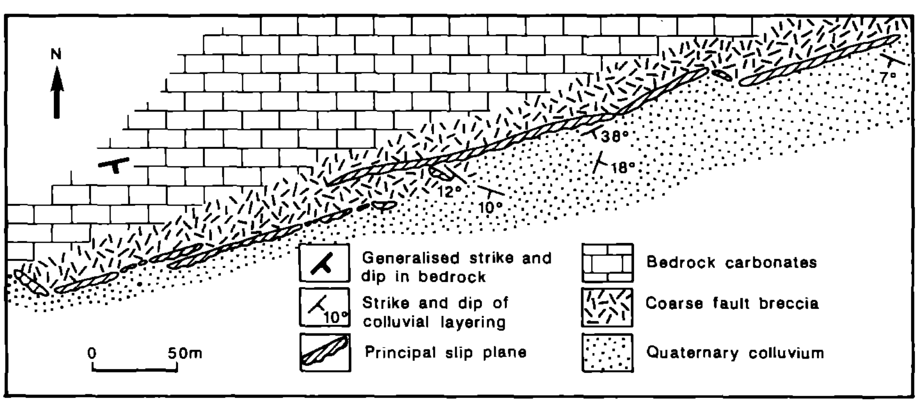

Fig. 3. Sketch map of the principal architectural elements at the study site in the Yavansu fault zone, western Turkey.

brecciated colluvium; and (F) unbrecciated colluvium beneath the modern scree slope. Other active normal fault zones in the region (e.g. Manisa, Fig. 1) are characterized by an even better-developed layered architecture comprising multiple slip planes separating alternating zone-parallel belts or sheets of coarse and recemented breccia, respectively. Most slip planes at Yavansu and elsewhere are smooth and where freshly exposed they are polished surfaces; that is they are the 'miroirs de failles', of French workers (e.g. Angelier 1979) or slickensides *sensu stricto*. A characteristic feature of the Yavansu and many other circum-Aegean (Angelier 1979, Dumont *et al.* 1981) slip planes is that in addition to being smooth they are traversed by several size orders of undulations up to several metres in wavelength, and resembling those in a sheet of corrugated iron (Figs. 4 and 5). These linear structures are here called corrugations, without implying that their formation involved shortening of previously planar slip surfaces.

The total width of the breccia belt at Yavansu varies from a few to more than 20 m but is difficult to assess precisely because the footwall junction between it and the bedrock is gradational and exceptionally indistinct. Long axes of subangular to rounded clasts in coarse breccia belts (B in Fig. 5) range from 0.5 to 20 cm and clasts show no preferred orientation. Interclast spaces are either voids or filled by calcite and fine-grained, iron oxide-rich matrix material. Contacts between coarse breccia belts and subslip-plane breccia sheets are generally sharp but markedly irregular and rough.

Subslip-plane breccia sheets (C in Fig. 5) vary in thickness from 3 to 15 cm, upper contacts being markedly smooth in contrast to lower contacts. Breccias comprise crazed mosaics of angular marble clasts from 1 mm to 10 cm long (but exceptionally 20 cm), set in a compact cement of strained drusy (i.e. cavity filling) calcite plus silt and fine sand. Variably orientated stylolitic sutures separate clasts and some clast/cement areas. Voids are not present in these stylobreccias and a preferred clast-shape fabric was not observed except locally where some clasts of about 6:1 aspect ratio are orientated with their long axes pitching about 22°E, an orientation that is approximately perpendicular to corrugation long axes. Although the corrugated morphology of slip-planes is well displayed as a consequence of the exhumation of the colluvium, the shapes of the lower contacts of subslip-plane breccia sheets are more difficult to establish because they lie within footwall breccias. However, where breccia sheets have been breached and up to 1 m^2 of their lower contacts are exposed they are generally subparallel to the overlying slip plane. Pluck holes (Figs. 4b and 5) penetrate breccia sheets in a few places and indicate that locally the breccias are less well cemented than normal.

Structures exposed on slip planes (D in Fig. 5) are discussed in detail in the next section: here attention is focused on three of their general attributes. (1) A polished mirror-like finish is present only where slip planes are corrugated and have been recently exposed by exhumation. (2) Where the principal slip plane is best exposed it extends as a smooth (but no longer mirror-like) surface for over 2 m above the former upper limit of the scree slope (Fig. 4a, Y in Fig. 5). It is also noteworthy that corrugations extend into the slightly weathered smooth part of the fault scarp but that their troughs no longer contain colluvial breccia trails. The approximately 2 m-high smooth slip plane above the former limit of the scree slope may reflect the amplitude of the last increment of displacement or it may be a consequence of either recent erosion or the scree slope not having been built higher. (3) Above the upper limit of the smooth but slightly weathered slip plane the fault scarp continues as an irregularly stepped and cavitated surface underlain by coarse fault breccias (Fig. 4a, and Z in Fig. 5). This slope represents a fault scarp in the early stages of its denudation. The reason why traces of bedding planes in footwall carbonates are not visible on the fault scarp (Fig. 4a) is largely because it is underlain by breccias within which the original layering is now disorganized.

Trails or tabular sheets of brecciated colluvium range in thickness from zero to more than 50 cm, greatest thicknesses being preserved in depressions along corrugation troughs, especially on their E-facing sides (5 in Fig. 5, Figs. 4b & c and 6a). Minimum or zero thicknesses coincide with culminations along corrugation crests. Unlike the two varieties of footwall breccia, hangingwall brecciated colluvium contains both carbonate and quartz–arenite clasts, and is less-well indurated than either of them. The approximately equant, angular to subrounded and poorly ordered clasts range in size from 1 to 30 cm across and are set in a fine-grained matrix. Well-ordered fractures in brecciated colluvium are relatively rare but matrix and clasts are cut in a few places by small joints whose traces on slip planes are normal to corrugation long axes (Fig. 6b). Slip planes locally penetrate brecciated colluvium (Fig. 6d). Mud smears, no more than a few millimetres thick, occupy the troughs of some very low-amplitude (<0.5 cm) corrugations and are lineated by fine striae.

Fig. 4. Structures within the fault zone at Yavansu. (a) View from the SSE of the recently exhumed portion of the corrugated principal slip plane [X] formerly beneath the now-terraced colluvial slope [C]. Immediately above the exhumed area, the fault plane continues as a 2-m-high smooth but dark-weathered surface beneath an approximately 150-m-high degraded fault scarp [Z]. Culminations and depressions along corrugation axes within the slip plane are visible. (b) Plan view of the crestal area of a mega-corrugation bearing parallel gutters [2] and a slightly sinuous tool track [3]. Part of a colluvial breccia trail [E] and a pluck hole [7] are also visible. Damage marks made by contractors are nearly horizontal. Nine cm of the scale rule are visible. (c) View east of the sharp contact between the principal slip plane [D] and crudely stratified colluvial sediments [C]. A colluvial breccia trail [5] occupies a mega-corrugation trough and the location of a deep asymmetrical depression within the trough of another mega-corrugation is indicated by a curved arrow. The exposed slip plane is about 15 m high.

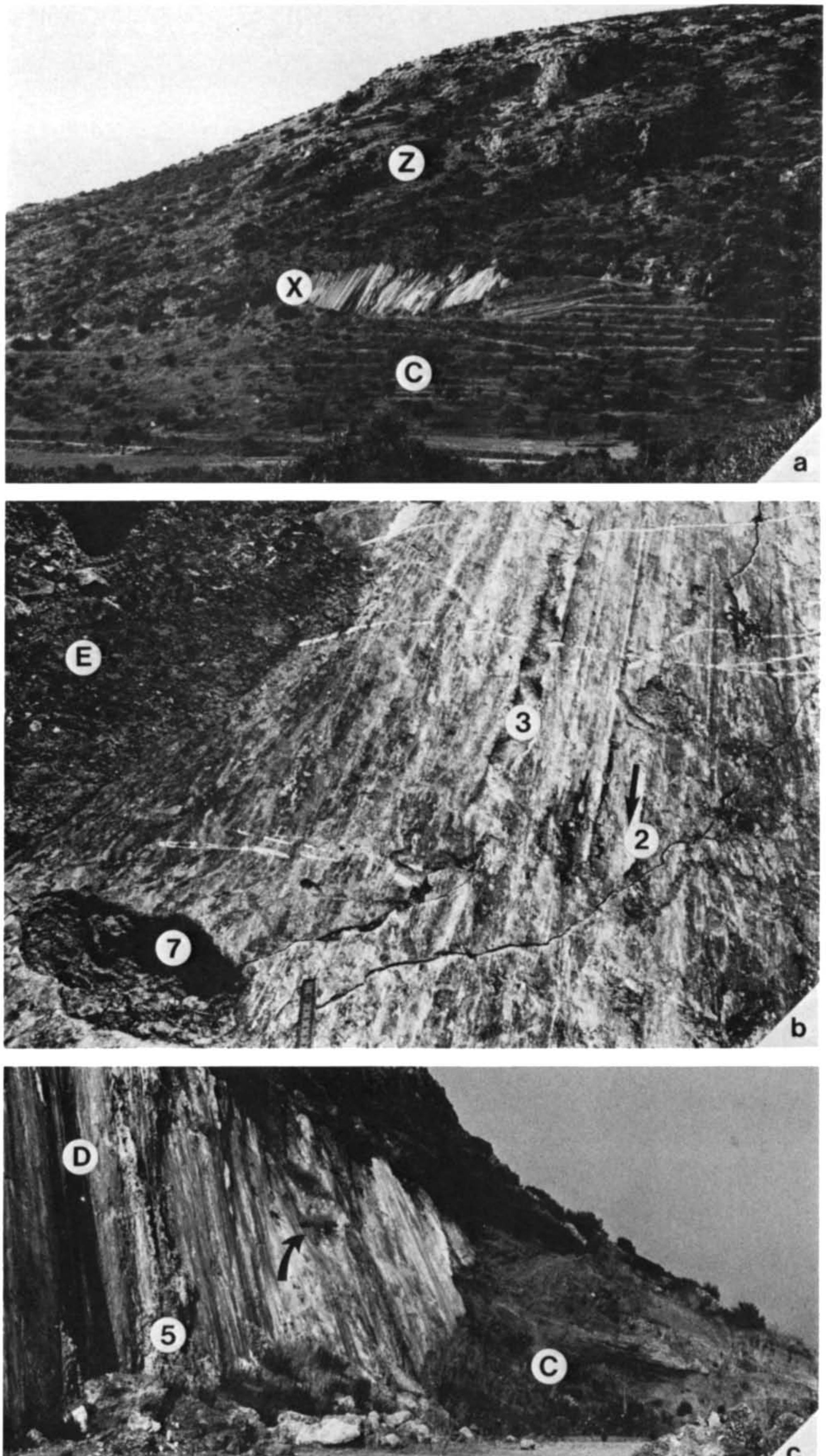

Fig. 4.

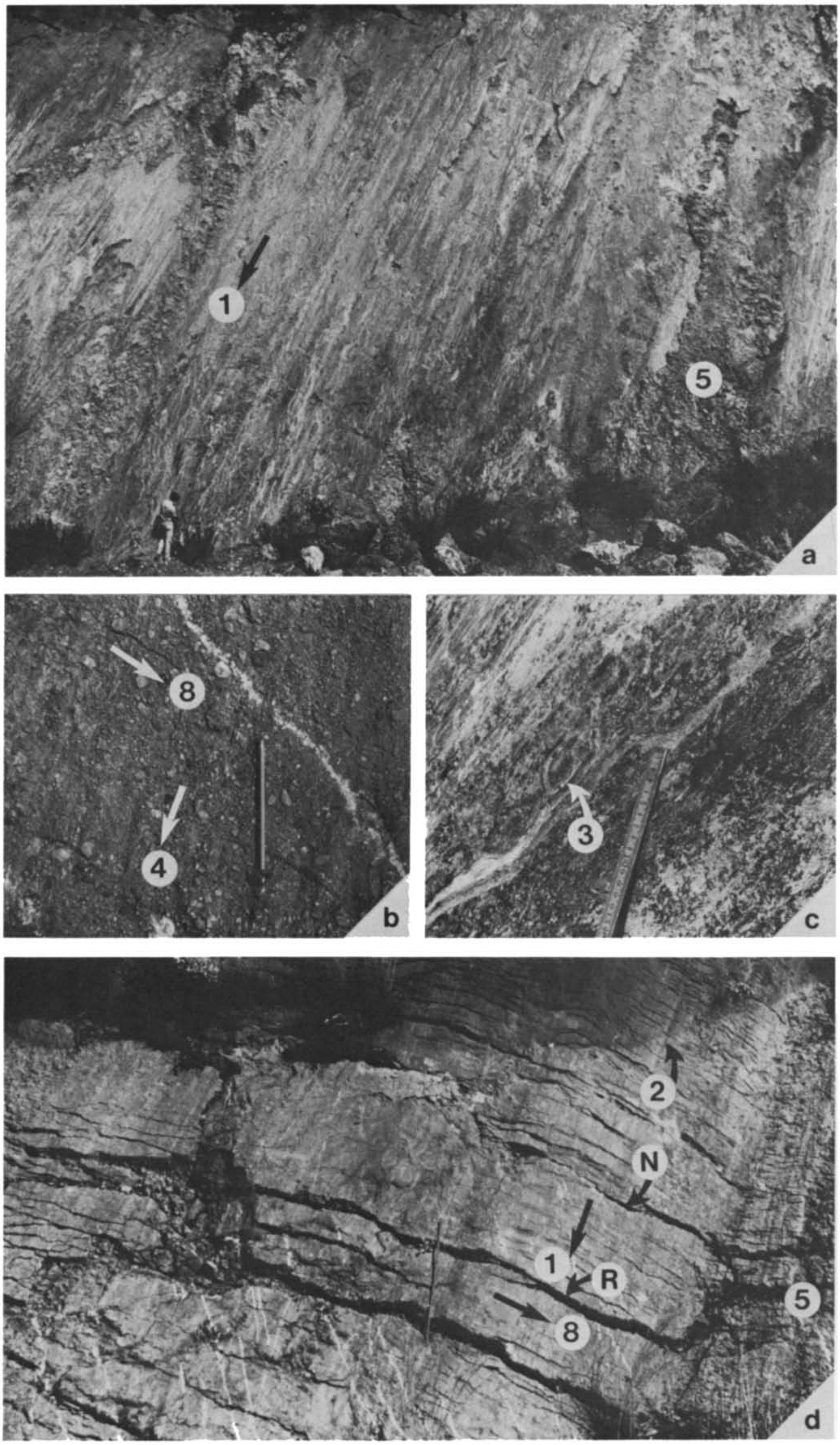

Fig. 6.

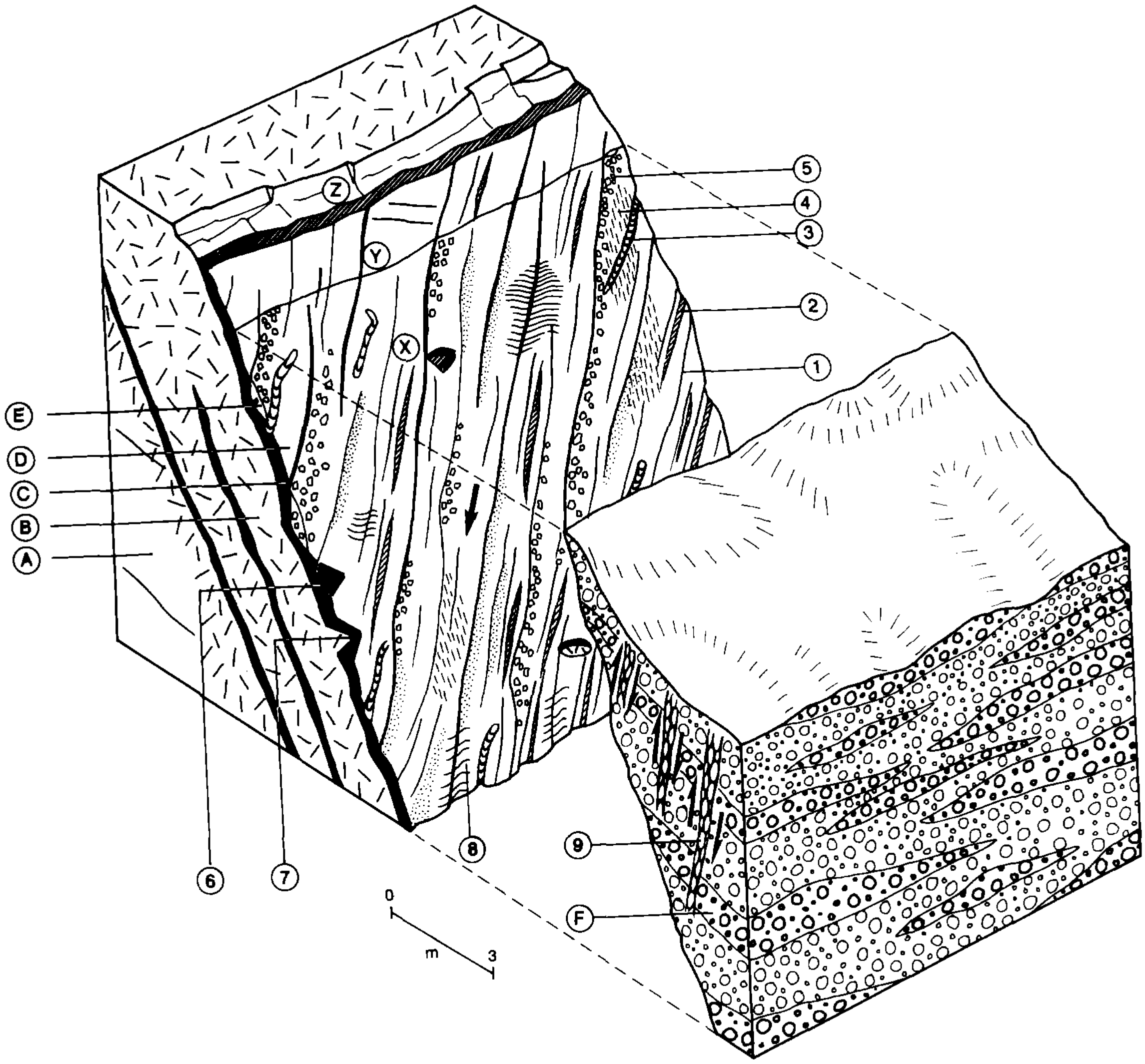

Fig. 5. Schematic exploded block diagram illustrating relationships between structures in neotectonic normal fault zones in western Turkey. Based largely on phenomena exposed in the Yavansu fault zone. *Key*: A, unbrecciated bedrock: B, coarse fault-precursor breccia: C, subslip-plane breccia sheet: D, corrugated slip plane; E, brecciated colluvium: F, unbrecciated Quaternary colluvium; X, artificially exhumed slip plane; Y, fresh fault scarp above level of exhumation: Z, degraded fault scarp: 1, corrugation axis; 2, gutter: 3, tool track: 4, frictional-wear striae; 5, trail of brecciated colluvium [open symbol] or mud smear [stipple]; 6, spall mark; 7, pluck hole; 8, comb fracture traces; 9, reverse fissure-fault in colluvium. Structures are not all to scale but the scale bar gives an idea of approximate dimensions. Large arrow indicates direction of slip of hangingwall.

The hangingwall of the uppermost slip plane is occupied by poorly indurated colluvial sediments of Quaternary age (Figs. 4a & c, and 5). The colluvial sequence comprises crudely stratified gravel and scree (C in Fig. 4c). Colluvial layering is locally radial but disturbed by relatively few structures of tectonic origin except some fissures across which there are reverse displacements up to a maximum of about 20 cm (9 in Fig. 5). There is also one obliquely striking fault which cuts back-rotated colluvium.

STRUCTURES ON SLIP PLANES AND IN SUBSLIP-PLANE BRECCIA SHEETS

Striae, tool tracks, gutters and corrugations

Morphology. Although slip planes locally display a mirror-like finish they are not perfectly planar, being traversed by a variety of lineations including striae and tool tracks, which are well-known structures on many fault planes (e.g. Hancock 1985), and gutters and corrugations whose forms are reported in this paper.

Fig. 6. Structures on slip planes in the Yavansu fault zone. (a) Plan view of the principal slip plane exposing rectilinear corrugation axes [1] and colluvial breccia trails [5]. The man is about 1.7 m tall. (b) Plan view of a small area of a slip plane to which a sheet of brecciated colluvium adheres. Note the comb fractures cutting the breccia matrix and giving rise to an intersection lineation [8] normal to a steeply pitching, but weakly developed, striae lineation [4]. The pencil is approximately 15 cm long. The pale streak from top left to bottom right is a damage mark made during excavation. (c) Oblique plan view of a slip plane exposing the proximal (up-slope) ends of two irregular intersecting tool tracks [3] flanked by levee-like ridges. Sixteen cm of a scale rule is visible. (d) Plan view of a slip plane exposing corrugation axes [1], parallel gutters [2] and an orthogonal lineation [8] formed by the intersection of irregular comb fractures on the slip plane. Across some comb fractures there are small reverse [R] or normal [N] offsets. Part of a colluvial breccia trail cut by minor slip planes bearing gutters is also visible [5]. Scale rule is 25 cm long.

Table 1. Average dimensions of slip-parallel lineations

	Width or wavelength (mm)	Depth or amplitude (mm)	Length (mm)
Scratch-like striae	1	0.5	≤200
Groove-like striae	20	5	≤300
Tool tracks	30	15	≥1140
Gutters	45	25	*ca* 2500
Minor corrugations	50	20	*ca* 3000
Major corrugations	450	60	*ca* 10,000
Mega-corrugations	4500	250	*ca* 15,000

The smallest lineations are striae ranging in size from scratches to minor grooves (4 in Fig. 5, Table 1), scratches being the variety of striae most characteristic of polished areas of slip planes. It is rarely possible to trace an individual striation for more than about 40 cm along its length and areas of slip planes crossed by striae are relatively small compared with the total area of slip planes. Striae are locally superimposed on tool tracks, gutters and corrugations but not vice versa, indicating that striae are younger than them.

Tool tracks (3 in Fig. 5. Figs. 4b and 6c) [the prod marks of Tjia (1972) and Engelder (1974)] are not pervasive lineations but isolated score marks preferentially developed in the uppermost slip plane. Because not all tool tracks are completely exposed their 1140 mm average maximum length (range 350–2000 mm) (Table 1) may be a slight underestimate of their true average maximum length. Some tool tracks are deeper at their up-slope ends whereas others are deeper at their down-slope ends, and some tool tracks are characterized by irregular up-slope ends and nearly rectilinear down-slope ends that swing into alignment with down-dip lineations (Fig. 6c). Levee-like ridges, a few millimetres wide and high, flank the edges of some tool tracks and in one case a young track cuts an old one (Fig. 6c). Gutters are rectilinear, steep-sided, flat-floored channels a few centimetres wide incised in the uppermost 1–2 cm of subslip-plane breccia sheets (2 in Fig. 5 and Figs. 4b and 6d). Although more abundant than tool tracks they do not, unlike striae, define a pervasive lineation on slip planes.

Although within small areas ($<100^2$ m) of slip planes there are generally two or three well-defined size orders of corrugations (Table 1) there is a continuum of sizes if the total area of surveyed slip planes is considered. In addition to possessing sinuous profiles perpendicular to their lengths, corrugations on the uppermost slip plane also show whale-back-like culminations and depressions along their lengths (Figs. 4a & c and 5). Culmination crests are up to 5 m apart and depressions range up to 1 m deep. Depressions are roughly symmetrical with the exception of the largest one (Fig. 4c), which is markedly asymmetric, its short steep side facing up-slope in the footwall. A few mega-corrugations traverse the full height (*ca* 15 m) of the largest slip plane (Fig. 6a) but generally they replace each other in an unordered fashion (Fig. 5). Although most mega-corrugations and some major corrugations affect both the upper and lower contacts of subslip-plane breccia sheets, minor corrugations are restricted to their upper surfaces.

Geometry. The four types of down-dip lineation are parallel or subparallel to each other within ENE-striking slip planes (Fig. 7). Mean observed pitches of the long axes of corrugations, gutters, tool tracks and striae are 69, 69, 67 and 78°W, respectively. The orientations of stereographically determined mega-corrugation axes generally pitch 2–10° more gently west than observed axes (Figs. 7b & c).

Comb fractures and fissure-faults

Areas up to 10 m^2 of subslip-plane breccia sheets are cut by rows of closely spaced fractures which are roughly perpendicular to slip planes and give rise to an intersection lineation statistically normal to corrugation and gutter long axes (Figs. 5, 6d and 7c). The angle between these fractures and slip planes is 75° or more, the acute bisector lying closer to the vertical than the horizontal. In common with pinnate joints (Hancock 1985) they are structures restricted to narrow zones adjacent to faults but unlike pinnate joints, which generally subtend angles of about 45° with faults (Fig. 8a), comb fractures are nearly orthogonal to them (Fig. 8b) and hence, in profile, resemble the teeth of a hand-comb. Although the average pitch of the intersection lineation on slip planes is 20°E it is rarely straight, most commonly being curvilinear where crossing corrugation troughs and crests. Where comb fractures are preferentially restricted to corrugation crests, or more rarely corrugation troughs, the intersection lineations are generally crescentic and individual traces are arranged in rows up to 2 m long and parallel to corrugation axes (Fig. 5). A few, small, comb fractures cut brecciated colluvium (Fig. 6b).

The majority of comb fractures are joints or fissures but a few are small faults achieving up to 7 cm of reverse or normal offset of slip planes (Fig. 6d). Some fissures remain unfilled with irregular matching walls while others are partly filled by colluvium (Fig. 6d). Comb fracture separations average 10 cm and their trace lengths are commonly 30–150 cm although at least one exceptionally large comb fracture extends for 4 m. Wide-spaced, but long comb fractures, cut the slightly weathered but smooth slip plane above the former upper level of the scree slope although they are not visible as traces on the mirror-like finish of the freshly exhumed surface immediately beneath it (Fig. 5).

Although few tectonic structures cut the unbrecciated colluvial sediments of the hangingwall they are locally displaced by a set of five fissures across which there are also offsets. These fissure-faults are spaced about 3 m apart and achieve about 20 cm of offset each (Fig. 5). Within each 40 cm-wide, downwards-tapering fissure-fault, clasts are reordered so that their long axes are now subparallel to fissure walls. As Fig. 7(d) shows, the stereographically calculated intersection between the mean orientation of fissure-faults and the slip plane to which they are related lies about 90° away from the striae lineation.

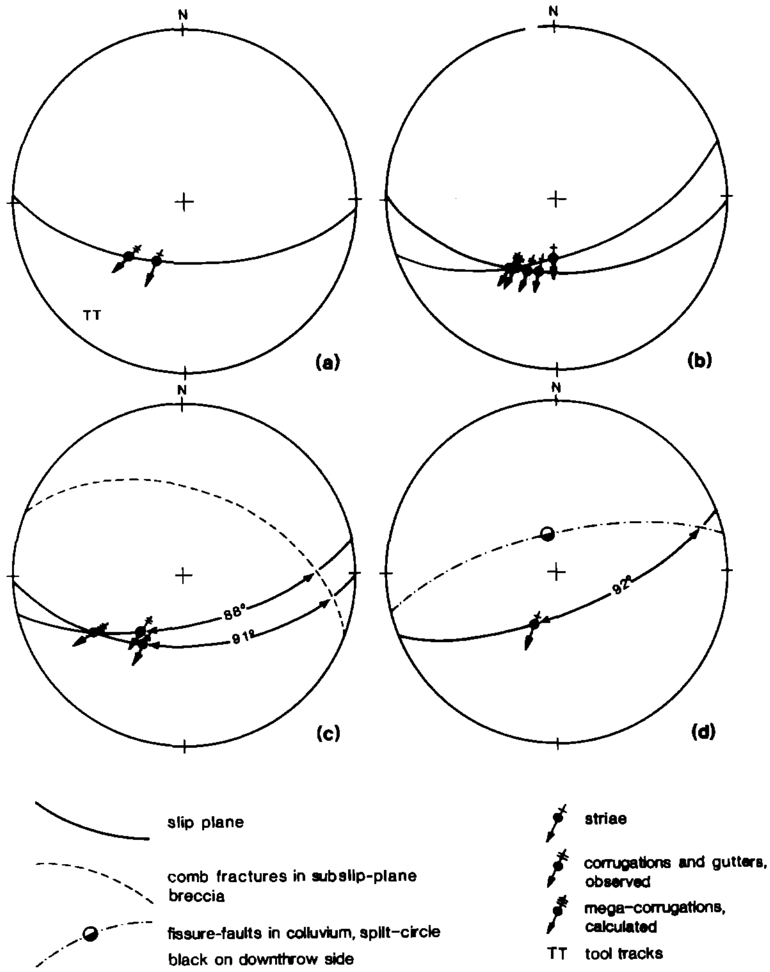

Fig. 7. Lower-hemisphere Lambert projections of structures in the Yavansu fault zone. (a) Tool track, gutter and corrugation axes pitching slightly more gently than striae axes within a slip plane. (b) Adjacent obliquely striking parts of a slip plane bearing corrugation axes and striae. (c) Slip-plane segments intersecting comb fractures at 90° to corrugation and gutter axes on the flanks of a mega-corrugation. (d) Slip plane–fissure fault intersects at 90° to striae on a slip plane.

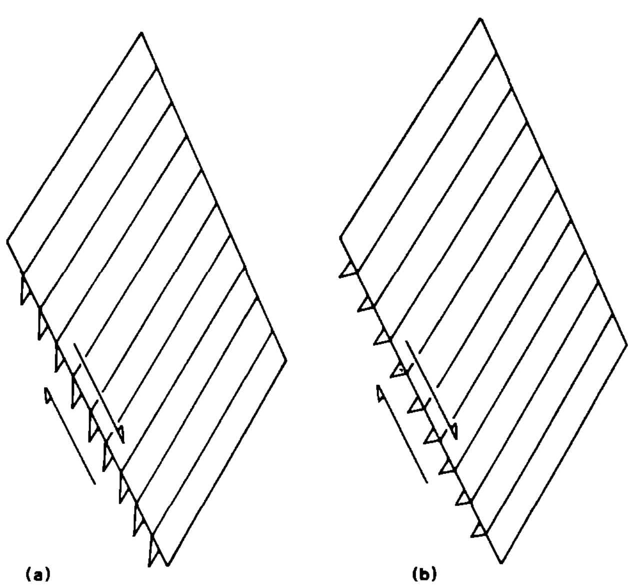

Fig. 8(a). Geometrical relations between footwall pinnate joints and a normal fault. (b) Geometrical relations between footwall comb fractures and a normal fault.

Miscellaneous structures cutting subslip-plane breccias

Pluck holes penetrating the entire thickness of subslip-plane breccia sheets are generally equant in plan but those that are inequant generally possess long axes orientated approximately normal to corrugation axes (Figs. 4b and 5). The local removal of flakes a few centimetres thick from the upper parts of subslip-plane breccia sheets has given rise to spall marks (Tjia 1972) (6 in Fig. 5), which are partly framed by a steep riser which faces down the footwall of a slip plane. Spall marks occur preferentially in mega- and major-corrugation troughs and possess floors that are rough and irregular. The majority of the remainder of structures cutting subslip-plane breccia sheets are poorly ordered, gently pitching veins and joints orientated at high angles or normal to sheet margins.

INTERPRETATION AND DISCUSSION

The principal reasons for thinking there has been at least one increment of Quaternary slip on the Yavansu fault zone are: (1) colluvium adjacent to the uppermost

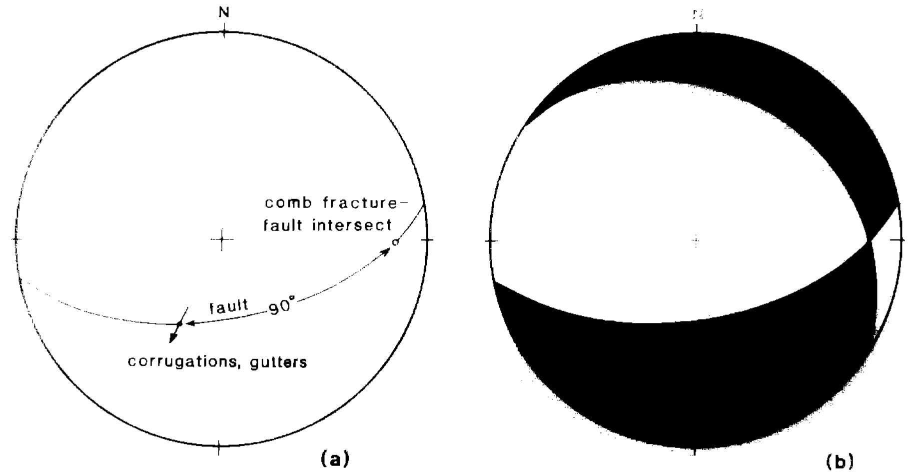

Fig. 9(a). Lower-hemisphere Lambert projection of average ENE-striking fault planes, corrugation and gutter axes, and comb fracture–fault intersects in the Yavansu fault zone. (b) Average Yavansu fault plane orientation data replotted with the addition of a 90° auxiliary plane passing through the comb fracture – fault intersect.

slip plane is locally brecciated; (2) a few minor slip surfaces penetrate brecciated colluvium; (3) comb fractures cut matrix and clasts in some patches of brecciated colluvium; (4) some colluvial mud smears in corrugation troughs are striated; and (5) colluvial layering is locally displaced by minor reverse faults intersecting slip planes normal to the principal down-dip lineations. Figure 9(a) shows for the Yavansu data a great circle representing the average orientation of ENE-striking slip planes, a pole representing the average orientation of the lineation defined by corrugation and gutter axes, and a pole representing the average orientation of comb fracture-fault intersects. In Fig. 9(b) the average fault plane has been replotted and an auxiliary plane at 90° to it constructed through an imaginary null point as determined from a pole normal to corrugation axes and the pole of comb fracture–fault intersects. Comparing Fig. 9(b) with the fault-plane solution for the 1955 earthquake given in Fig. 2 the similarity of the two is clear. Hence it is concluded that the pitches of the long axes of corrugations and gutters, and the pitches of normals to comb fracture–fault intersects yield a reasonably reliable estimate of directions of displacement at Yavansu. Figure 9 also indicates that motions on S-dipping, ENE-striking faults in the region were dominantly normal but involved a subordinate component of dextral strike–slip.

Reliably determining shear sense, as opposed to direction, from the Yavansu fault-plane phenomena is less straightforward, even knowing that stratigraphic relationships indicate that the net displacement is dominantly normal. Tool tracks are, however, unambiguous shear-sense indicators, being markedly irregular up-slope (i.e. proximally for normal slip) and swinging into alignment with corrugation axes down slope (i.e. distally) (Fig. 5). The single example of an asymmetrical depression containing ponded and brecciated colluvium within a corrugation trough possesses a short 'steep' side facing up-slope in the footwall, and hence, it is incongruous with respect to slip sense. In contrast, spall mark risers face down-slope in the footwall. Although comb fractures are nearly perpendicular to slip planes the large acute angle they subtend with them closes against the sense of shear.

Vita-Finzi & King (1985) provided an elegant model, based on observations near Corinth, that explains why some active normal fault zones at high crustal levels are characterized by a wide zone of breccia cut by a slip plane. They proposed that if increments of displacement at depth significantly exceed 1 m the response beyond the slip-plane tip line is near-surface brecciation followed by the slip plane propagating upwards through its own breccia during later increments of movement.

We follow Vita-Finzi & King (1985) and interpret the belts of coarse breccia with voids as brittle accommodation phenomena developed in advance of upwards-propagating normal fault planes. Likewise, we also consider the slip planes and subslip-plane breccia sheets to be younger than these coarse cataclastic rocks, which we call *fault-precursor breccias*. Figure 10 is a freeze-frame cartoon sequence suggesting how layered normal fault zones, such as those in the West Anatolian extensional province, might evolve via repeated slip increments generating and propagating slip planes within precursor breccias. The direction of slip-plane migration is into hangingwalls, within which brecciation is greater than in footwalls. At Yavansu the last increments of slip probably occurred on the plane separating the footwall breccias from the hangingwall colluvium.

The corrugated shapes of slip planes and subslip-plane breccia sheets are a distinctive feature of the Yavansu fault zone. Slip planes characterized by sinuous large amplitude/wavelength corrugations are also typical of some of the other active normal fault-zones in the Aegean region; for example at Ephesus (Fig. 2) (Dumont *et al.* 1981, fig. 1b and our observations) in Crete (Angelier 1979, plate 2) and near Manisa (Fig. 1) (our observations). Because the shapes of the upper and lower contacts of subslip-plane breccia sheets mimic each other the origin of fault-plane corrugations is considered here to be more complex than that of the other

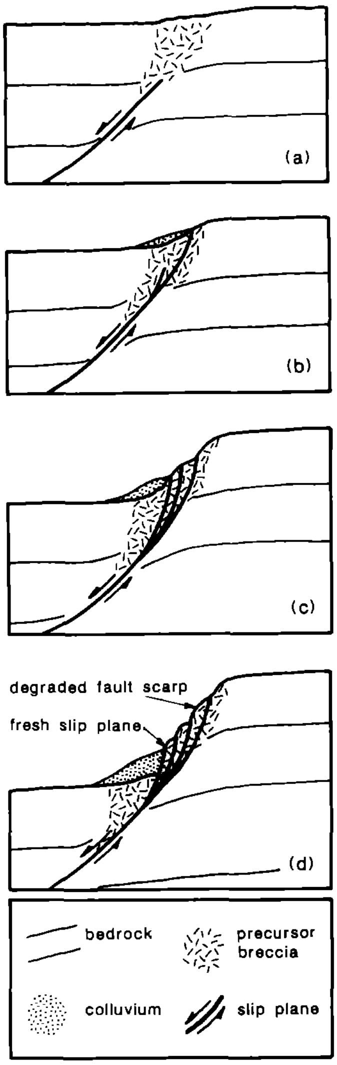

Fig. 10. Cartoons illustrating a possible evolutionary sequence (a)–(d) of an active normal fault zone separating bedrocks from Quaternary colluvium. Note the upwards propagation of slip planes combined with hangingwall collapse involving slip-plane migration into the hangingwall within which precursor breccia preferentially occurs. The cartoons are developed from an idea of Vita-Finzi & King (1985, fig. 6) to take an account of relationships observed in western Turkish fault zones.

slip-parallel lineations. A comprehensive interpretation of them must await reports of whether they are exclusively a feature of shallow faults or whether they also form at greater depths. An explanation tentatively advanced for the origin of the Yavansu corrugations is that they formed when the slip planes were propagating upwards through their own precursor breccias. The pathways sought by advancing slip planes in such heterogeneous bodies are likely to be through the weak matrix, and hence irregular, with perturbation long axes (i.e. corrugations) being orientated parallel to the direction of motion. Within a few tens of metres of the ground surface, where confining pressures will be very low as a result of both shallow depth and the possibility of lateral freedom, additional perturbations in the form of culminations and depressions along corrugation axes may have been introduced as the planes propagated not only around, but also over or under, large clasts and within material capable of flowing. Once the shapes of large corrugations have been established they are unlikely to be tectonically erased. The preferential development of colluvium-derived fault breccia in corrugation troughs and ponds is probably a reflection of a process such as debris streaking (Means 1987) and possibly also, the ability of the colluvium to flow and hence ride over irregularities and fill hollows.

The histories of the Yavansu slip-plane breccia sheets are not known in detail. The slight diminution of average clast size from precursor to slip-plane breccias, the occurrence of moderately twinned sparry calcite and the presence of microstylolitic seams all indicate that more than one episode of displacement was involved. A form of hydraulic pumping (Sibson *et al.* 1975) with resultant episodes of calcite crystallization during repeated increments of seismic slip was probably responsible for mineralizing the sheets.

Gutters are interpreted here as products of the abrasion of subslip-plane breccias by portions of overlying breccia masses. The ploughing action of individual resistant colluvial clasts is thought to be responsible for forming tool tracks. Tool tracks at Yavansu are features of the uppermost slip plane and hence they were probably scored during the latest increments of slip when colluvium and bedrock breccias were juxtaposed (Fig. 10d). The angularity of some of the clasts may have prevented them from following an initially rectilinear path and hence proximally (i.e. up-slope) they are irregular. During continued displacement they probably became more efficiently arranged for scoring a straight track. The 1.14 m average maximum length of tool tracks is probably less than the average displacement during a slip increment.

Striae, both scratches and grooves, were also probably formed as a consequence of abrasion (i.e. frictional wear), not by large clasts but by the relatively fine-grained colluvial sand and silt matrix. The observation that locally they are superimposed slightly obliquely on corrugations, gutters and tool tracks indicates that the slip event, or events, to which they are related occurred late in the history of the fault zone.

The geometry of the reverse fissure-faults, intersecting slip planes normal to the displacement direction inferred from slip-parallel lineations (Fig. 7d), suggests that they too are products of one or more displacement increments, perhaps above a locally convex-up portion of a slip plane. The genesis of comb fractures is also probably linked to that of displacement episodes; fracture traces on slip planes are perpendicular to corrugation and gutter axes, and preferentially developed across corrugation crests. Unlike pinnate joints (Hancock 1985), that subtend angles of about 45° with faults, fractures at nearly 90° to fault planes have not been described except by Suppe (1985, figs. 8–12) who illustrates veins of this type which he interprets as transverse tensile fractures. We agree with Suppe that fractures of such geometry are probably initiated as tension cracks and hence at Yavansu they reflect the down-dip stretching of subslip-plane breccia sheets, perhaps during post-slip stress reorientation since their distribution is not related to the occurrence of dilational or antidilational jogs (Sibson 1986). Despite uncertainty about the mechanism responsible for their initiation, comb fractures, which also cut slip planes at Ephesus and Manisa, appear to be distinctive structures of some high-level fault zones. The offset of principal slip planes across some comb fractures indicates that succeeding the last episode of normal displacement there was stress relief involving extension oblique to the horizontal. Likewise, the occurrence of fractures of other geometries cutting slip-plane breccia sheets also shows that local stresses operated into recent times.

From the perspective of estimating the average amount of slip that occurred close to the surface during each increment of movement, the two most significant observations are that the average maximum length of tool tracks exceeds 1 m, and that the approximate value of the maximum height of the fresh fault scarp (Y in Fig. 5) above the upper level of colluvium exhumation is greater than 2 m. Because average tool-track lengths are probably somewhat shorter than increments of displacement we consider that each increment was probably of the order of 2 m.

CONCLUSIONS

(1) Several active fault zones in the West Anatolian extensional province comprise multiple slip planes and alternating zone-parallel layers of coarse fault-precursor breccias, formed ahead of upwards-propagating tip lines, and recemented subslip-plane breccias related to mineralization accompanying increments of slip. Layering of the fault-zone rocks influences fault-scarp retreat and decline and leads to the formation of irregular cavities within it.

(2) The Yavansu fault zone contains three neglected classes of kinematic indicator which are probably characteristic of other active normal fault zones. The most spectacular indicators are metre-scale *corrugations* traversing slip planes and affecting subslip-plane breccia sheets. Corrugations possess sinuous profiles normal to their long axes and are up to 15 m in length. Corrugations in the uppermost slip plane, immediately beneath colluvium in the hangingwall, display marked culminations and depressions along their lengths. Corrugations may have developed during the upwards progagation of slip planes that were seeking undemanding pathways through coarse precursor breccias. Parallel to corrugation axes are those of *gutters*, rectilinear, steep-sided, flat-floored channels within subslip-plane breccia sheets. Accompanying some corrugations are rows of closely spaced *comb fractures* offsetting subslip-plane breccia sheets and intersecting them along a lineation normal to corrugation axes. Unlike pinnate joints which subtend angles of about 45° with slip planes, comb fractures subtend angles of nearly 90° with them. In addition to these 'new' indicators the Yavansu fault zone also contains centimetre-scale tool marks scored into the uppermost subslip-plane breccia sheet and frictional-wear striae.

(3) Corrugation, gutter, tool track and striae long axes are parallel or subparallel to each other and the inferred direction of slip. Comb fracture-slip plane intersects are normal to the slip direction.

(4) Individual increments of near-surface displacement on the Yavansu fault zone were probably about 2 m.

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