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Evolution of monolithological breccia deposits in supradetachment basins, Whipple Mountains, California

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ABSTRACT

Extensive sheets of monolithological breccia (megabreccia) within detachment-fault systems of the North American Cordillera have been identified as large landslides. Although the origin of the megabreccia deposits is controversial, their spatial and temporal association with detachment-fault systems implies a causal relationship between the initiation of such landslides and motion along detachment faults. Emplacement may have been catastrophic following seismic activity, or slow, as the result of gravity gliding. Nevertheless, comprehensive analysis of these deposits provides important constraints on the evolution of supradetachment basins by detailing the unroofing history, palaeotopography and palaeoseismicity of detachment-fault systems. An extensive Miocene landslide deposit, the War Eagle landslide, in the north-eastern Whipple Mountains, provides an opportunity for such an endeavour to elucidate: (1) the cause and timing of its initiation; (2) mechanism for its emplacement; (3) nature of the apparent association of the landslide with detachment-fault development; and (4) role of the megabreccia in the development of supradetachment basins. Cross-sections were drawn through the deposit to determine the geometry and kinematic development of the landslide. Additionally, a simple mechanical model based on limit equilibrium force balance was designed to explore physical mechanisms that controlled its creation. The results of this model combined with field relationships suggest that the Whipple detachment fault was active at an angle of less than 30° with displacement most likely accompanied by the release of seismic energy. Continued extensional evolution of the Whipple detachment fault caused tilting of the upper-plate strata and the formation of numerous half and full grabens as well as roll-over structures. Rocks from the lower plate were brought to the surface during the later stages of detachment-fault activity thereby producing sufficient topographic relief for large landslides to be seismically activated. Increased pore-fluid pressure in the footwall subjacent to the Whipple detachment fault probably aided landslide initiation. The landslide was emplaced onto the upper plate of the detachment fault, providing a significant amount of material into the evolving supradetachment basin. Although the rate of emplacement of the megabreccia remains uncertain, penetrative fracturing throughout the breccia sheet is evidence that emplacement occurred catastrophically. The results of this study indicate that Tertiary megabreccias were emplaced during continued detachment-fault evolution, implying oversteepened topography and seismicity of these low-angle systems.

INTRODUCTION

Deposits of monolithological breccia are common in the hangingwalls of detachment faults in the North American Cordillera (e.g. Miller & John, 1988; Yarnold & Lombard, 1989; Nielson & Beratan, 1990; Dickinson, 1991; Yin & Dunn, 1992). On the basis of their overall sheet-like geometries, relative coherence in preserving primary structures and intense deformation along the base of the deposits, the breccia deposits have often been interpreted as landslides (e.g. Miller & John, 1988; Nielson & Beratan, 1990; Yin & Dunn, 1992). Field relationships indicate that the occurrence of monolithological breccia was synchronous with detachment faulting, and that the deposits were commonly derived from the footwalls of detachment faults. Thus, the initiation

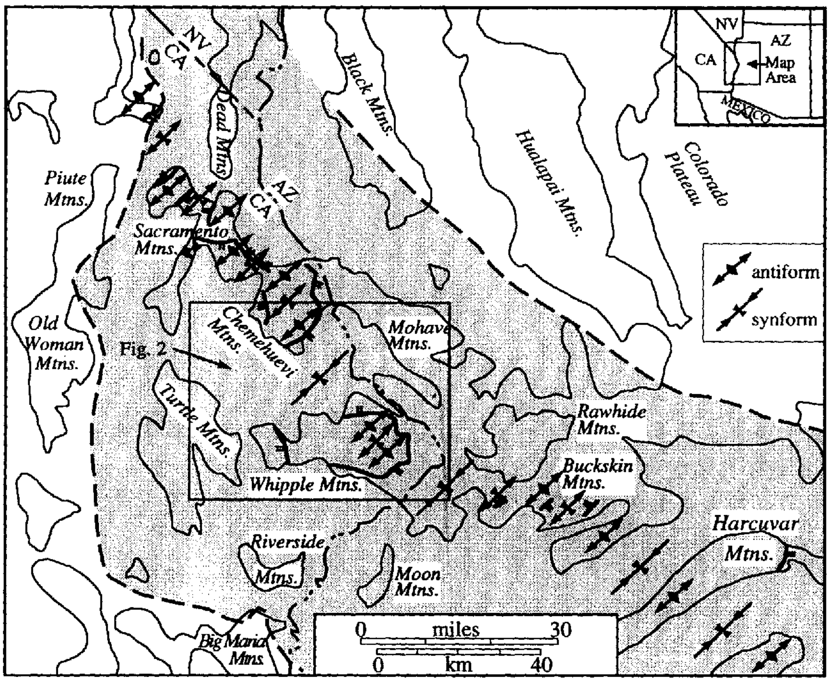


Fig. 1. Colorado River extensional corridor (shaded), and doubly plunging antiformal and synformal geometries of detachment faults within extensional corridor (modified from John, 1987; Yin, 1991).

and emplacement of the monolithological breccias were closely related to the unroofing history of a detachment-fault system.

The Whipple Mountains in south-eastern California (Fig. 1) expose one of the best-studied detachment-fault terranes in the North American Cordillera (e.g. Davis, 1988, and references therein). Recent field mapping in the northern Whipple Mountains and central Chemehuevi Valley reveals the presence of a large landslide that was initiated from the footwall of the Whipple detachment fault, transported across the fault and emplaced into a hangingwall basin (Yin & Dunn, 1992). The relationship between the occurrence of this landslide and movement along the Whipple detachment fault is critical in addressing whether the Whipple detachment fault was seismically active at a low-angle (<35°) geometry. Resolving this problem has profound implications for the mechanical behaviour of the crust during continental extension (Jackson, 1987; Axen, 1992; Yin, 1994). To investigate this issue, we conducted detailed mapping in the north-eastern Whipple Mountains and Central Chemehuevi Valley, south-eastern California. In particular, our work emphasizes: (1) internal deformation of the landslide; (2) relationships between landslide initiation and the mylonitic foliation in the footwall; (3) relationships between structural development and formation of sedimentary basins in the hangingwall of the Whipple fault; and (4) the mechanism for the initiation and emplacement of the landslide.

REGIONAL GEOLOGICAL SETTING

The Whipple Mountains lie in the 100-km-wide Colorado River extensional corridor (Fig. 1; Howard & John, 1987) which underwent mid-Tertiary extension along a system of regional low-angle normal (detachment) faults. This system, in turn, is part of a larger sinuous belt of isolated metamorphic 'core complexes' in western North America that extends from north-western Mexico to southern Canada (Coney, 1980; Armstrong, 1982). The detachment faults in the corridor are interpreted to root into mid-crustal ductile shear zones under the Colorado Plateau (Fig. 1; John, 1987), as inferred from the sheared mylonitic rocks brought to the surface in their footwalls (e.g. Davis, 1988). These detachment faults, together with numerous high-angle normal faults in their hangingwalls, accommodated a large (>100%) Tertiary extensional strain (Davis & Lister, 1988; Miller & John, 1988).

Detachment faults in the Colorado River extensional corridor exhibit doubly plunging antiformal and synformal geometries (Fig. 1; Spencer, 1982; Yin, 1991). John (1987) suggested that the faults initiated as curviplanar surfaces. Yin (1991) and Yin & Dunn (1992), however, proposed that the detachment faults were initially relatively planar, in comparison with their present geometries, and were warped during the later stages of their development. The long axes of these regional antiforms and synforms are parallel to the regional extension direction, approximately N60°E (Fig. 1). Development of the antiformal and synformal detachment faults may have played a critical role in controlling the distribution and geometry of supradetachment basins (e.g. Yin & Dunn, 1992).

The geology of the Whipple Mountains region has been studied extensively (e.g. Davis *et al.*, 1980, 1982, 1986; Davis, 1988; Davis & Lister, 1988; Yin & Dunn, 1992). Major Tertiary structural features within the study area are the Whipple and Chemehuevi detachment

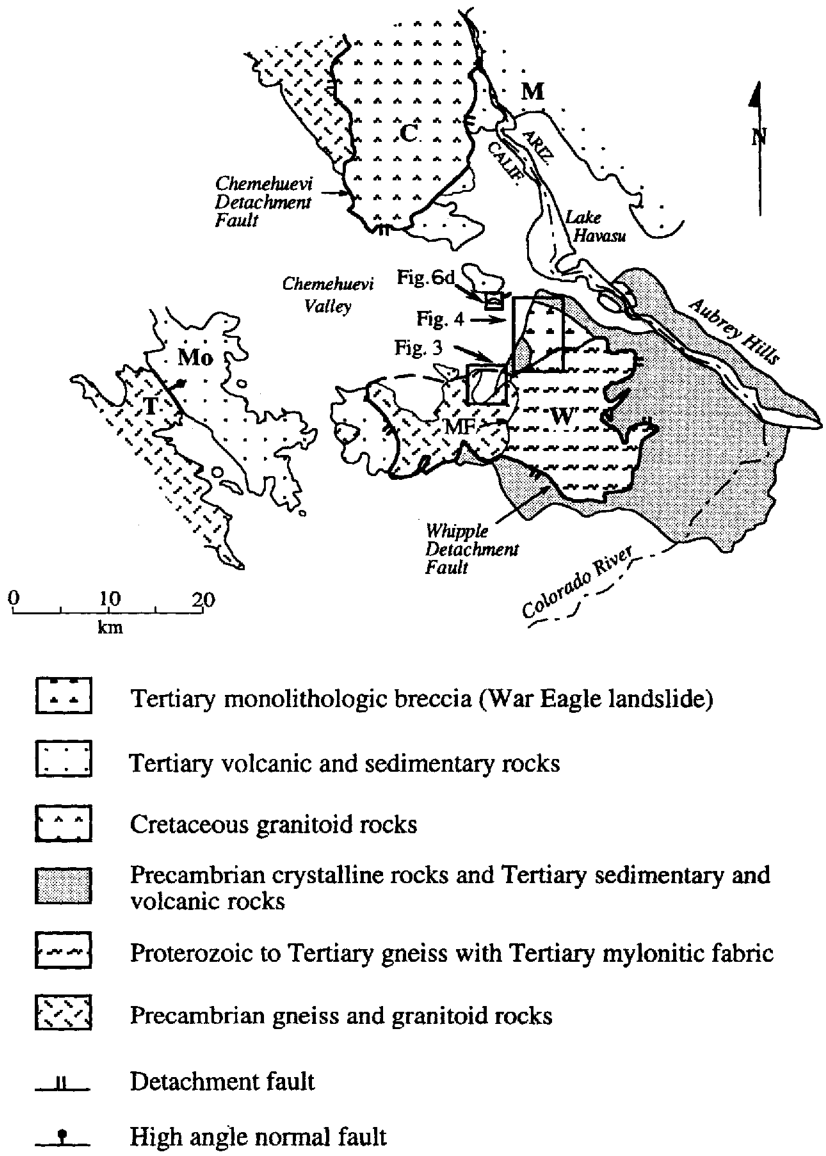


Fig. 2. General geological map of the Whipple Mountains area. T, Turtle Mountains; Mo, Mopah Range; W, Whipple Mountains; C, Chemehuevi Mountains; M, Mohave Mountains; MF, mylonitic front (modified from Yin & Dunn, 1992).

faults, exposed in the Whipple and Chemehuevi Mountains, respectively (Fig. 2). The Chemehuevi detachment fault has a large displacement (>8 km; Miller & John, 1988). Additionally, Yin & Dunn (1992) have inferred a gentle, east-dipping normal fault under Chemehuevi Valley (the Chemehuevi Valley detachment fault). The Whipple detachment fault has a displacement of ~40 km (Davis & Lister, 1988), and the Chemehuevi Valley detachment fault is assumed to accommodate a portion (~15 km) of this displacement.

The hangingwall of the Whipple detachment fault consists of Precambrian granitic gneiss, Cretaceous plutonic rocks, and Tertiary sedimentary and volcanic rocks, whereas Precambrian metamorphic and igneous rocks, Mesozoic igneous rocks and Tertiary dykes comprise the lower plate (Figs 2 and 3; Davis *et al.*, 1980; Davis & Lister, 1988; Anderson & Cullers, 1990). Rocks within the eastern part of the lower plate commonly contain a mylonitic foliation (generally subparallel to the Whipple detachment-fault surface; Dunn, 1986), and exhibit stretching lineations parallel to the north-eastward direction of transport inferred for the upper plate of the Whipple detachment fault.

The lower-plate mylonitic front is defined as the transition from the generally SW-dipping non-mylonitic rocks to their structurally deeper mylonitic counterparts (Fig. 2; Davis & Lister, 1988). A Tertiary dyke swarm, the Chambers Well dykes, containing both mylonitic and non-mylonitic dykes (Fig. 3; Davis *et al.*, 1982; Anderson & Cullers, 1990), intrudes across the mylonitic front. Dating of a non-mylonitic dyke indicates cessation of lower-plate mylonitization by 21.5 Ma (Davis & Lister, 1988).

GEOLOGY OF THE NORTH-EASTERN WHIPPLE MOUNTAINS

Geological mapping at a scale of 1:12 000 was conducted in the north-eastern corner of the Whipple Mountains

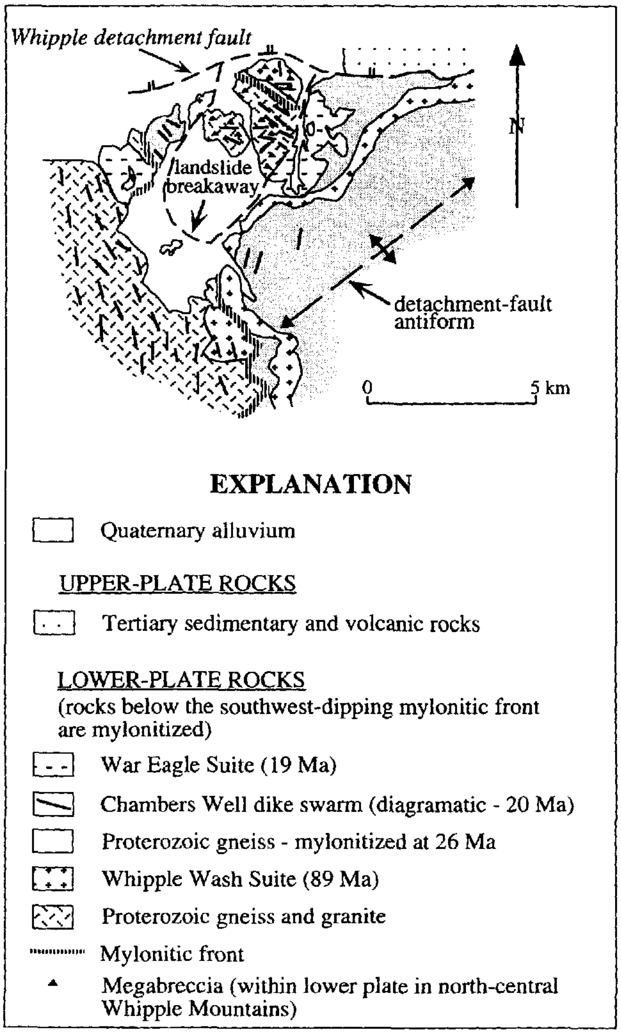


Fig. 3. General geology of breakaway area for War Eagle landslide in north-central Whipple Mountains (modified from Anderson & Cullers, 1990). See Fig. 2 for location.

and compiled at a scale of 1:24 000 (Fig. 4). Note that this area was studied by Dunn (1986) in reconnaissance, and Yin & Dunn (1992) suggested that the large sheet of monolithological breccia in the north-eastern Whipple Mountains originated from the footwall of the Whipple detachment fault as a landslide. This study focuses on the internal deformation of the landslide and structural styles in its substrata to determine the initiation and emplacement mechanisms of the landslide.

Stratigraphy

The stratigraphy of the north-eastern Whipple Mountains was described in Dunn (1986) and Yin & Dunn (1992). The lithological units used in this study follow their division into footwall (lower-plate) and hangingwall (upper-plate) units with the latter further divided into: (1) pre-megabreccia deposits; (2) megabreccia; and (3) post-megabreccia deposits.

Footwall units

The footwall of the Whipple detachment fault in the northern Whipple Mountains consists of Proterozoic gneisses, Cretaceous plutons (Whipple Wash Suite – 89 ± 3 Ma) and Tertiary intrusive rocks (Chambers Well dyke swarm – 20 Ma; War Eagle Suite – 19 Ma) which are variably overprinted by the mid-Tertiary mylonitic fabric (Fig. 3). The Whipple Wash Suite includes metaluminous to peraluminous granitic plutons which occur as sills up to 0.5 km thick in the upper parts of the mylonitic lower plate. The Chambers Well dyke swarm primarily consists of north-trending andesite, dacite and diabase dykes which occur both structurally above and below the mylonitic front. The volume of dykes locally exceeds that of the host rock. The War Eagle Suite contains gabbro–diorite and granodiorite and was emplaced at upper crustal levels (5–6 km; Anderson & Cullers, 1990). We did not study the footwall units in detail because it is not the main goal of this research. Readers may obtain further information from Anderson & Cullers (1990).

Hangingwall units

In our study area, hangingwall units consist of Tertiary sedimentary and volcanic rocks and the megabreccia. Although Precambrian basement rocks are not exposed here, they are found in areas immediately to the north and south (Davis, 1988; Yin & Dunn, 1992).

Pre-megabreccia units include interbedded sandstone and andesitic flows (units Tmv_1, $Tmss_1$, Tmv_2, Tmb and $Tmss_2$ in Figs 4 and 5). The minimum thickness of this sequence is approximately 800 m, as its lower limit is not exposed. Post-megabreccia units include conglomerate interbedded with sandstone and mudstone, volcanic breccia, and Quaternary alluvium deposits (units Tmcs, Tvb, Tc, Qoal and Qal in Fig. 4). Their thickness varies from several tens of metres to about 350 m.

The most regionally extensive unit in the hangingwall is the monolithological breccia (megabreccia) deposit which consists of penetratively fractured mylonitic Precambrian granitic gneiss (unit gn in Fig. 4), mylonitic Cretaceous (?) quartz monzonite (adamellite; unit ad in Fig. 4), and several generations of dykes (both mylonitic and non-mylonitic). It overlies a succession of interbedded Tertiary basalt flows and sandstone. The megabreccia deposit is sheet-like and is cut by numerous hangingwall normal faults. Locally, the breccia sheet is at least 1 km thick. The megabreccia is penetratively fractured, and locally displays crackle breccia facies and jigsaw breccia facies (e.g. Shreve, 1968a; Yarnold & Lombard, 1989). Dunn (1986) called the megabreccia complex, in the area to the south, the Copper Canyon allochthon. Similar megabreccia deposits were also found in the Aubrey Hills (Nielson & Beratan, 1990; Roberts, 1992) to the east and in the central Chemehuevi Valley to

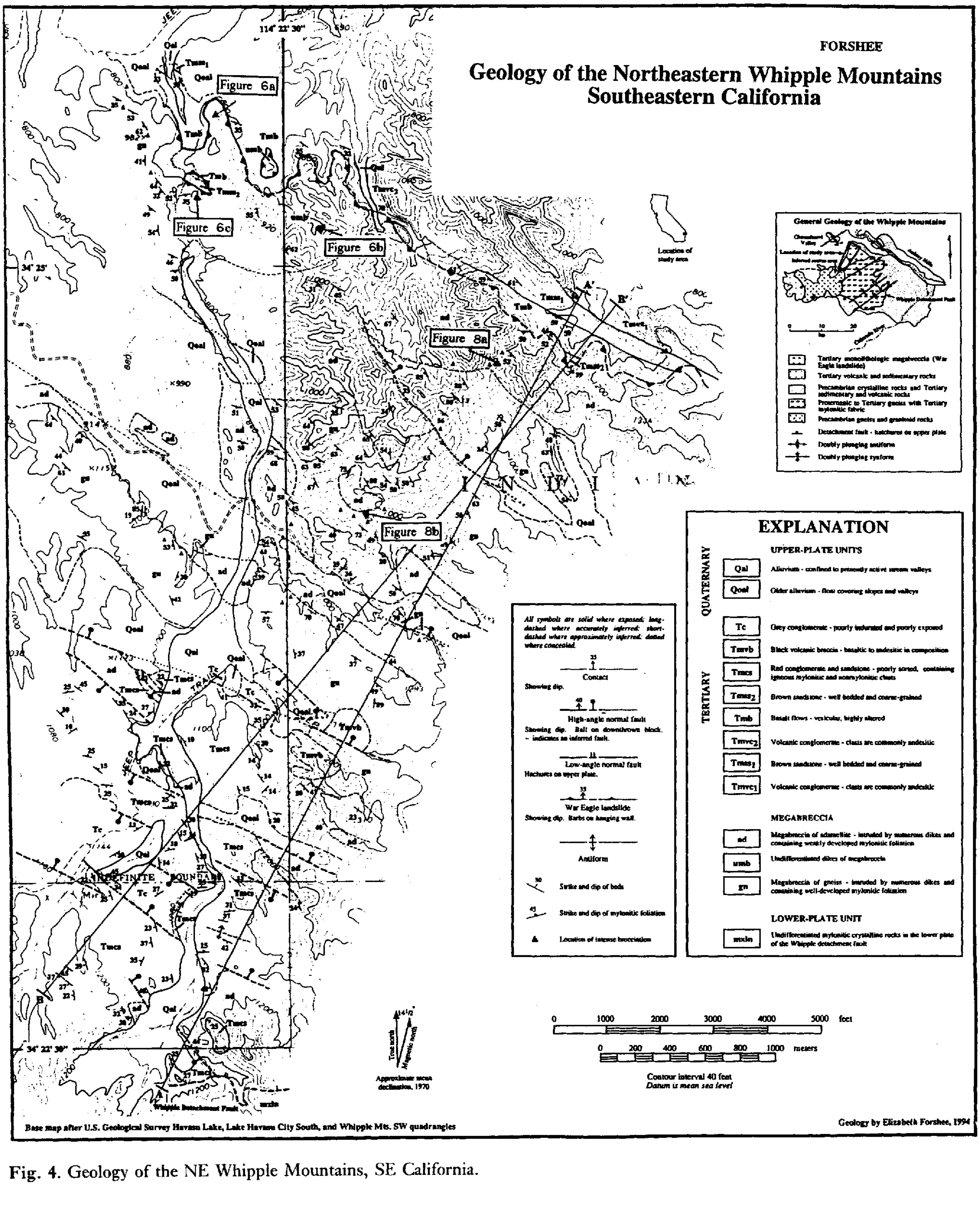


Fig. 4. Geology of the NE Whipple Mountains, SE California.

the north (Yin & Dunn, 1992). These exposures were interpreted by Yin & Dunn (1992) to all be part of a single extensive deposit, the War Eagle landslide. This interpretation is based on compositional similarity of the megabreccia deposits to lithologies found in their inferred source area and the absence of other interbedded sedimentary units within the megabreccia deposits (see below for additional lines of evidence).

The basal contact of the megabreccia is generally sharp and planar. Locally, it is a thick zone (>500 m) of highly sheared and mixed rock fragments derived from both the landslide and its substrata. Striations along the

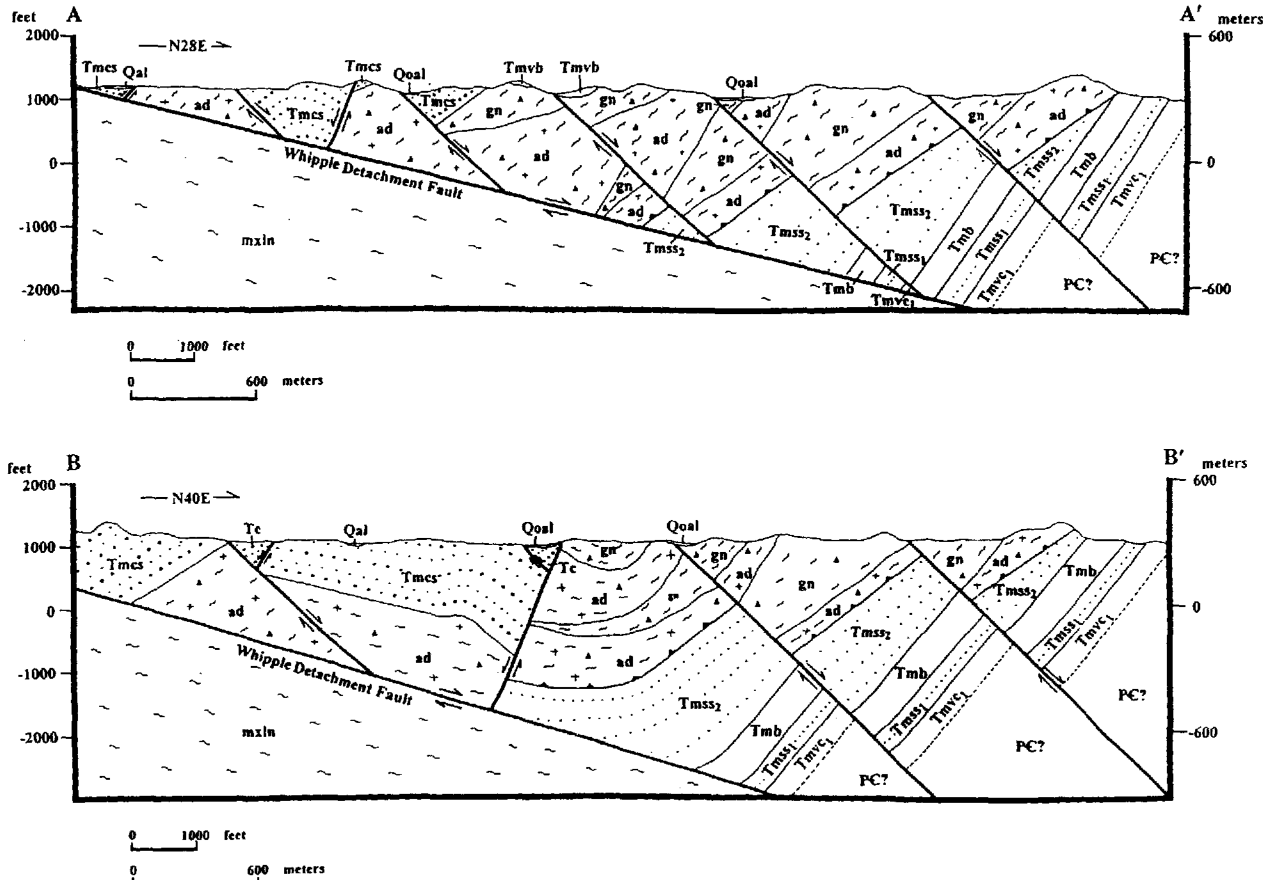


Fig. 5. Cross-sections from the NE Whipple Mountains, SE California. Location of sections shown on Fig. 4.

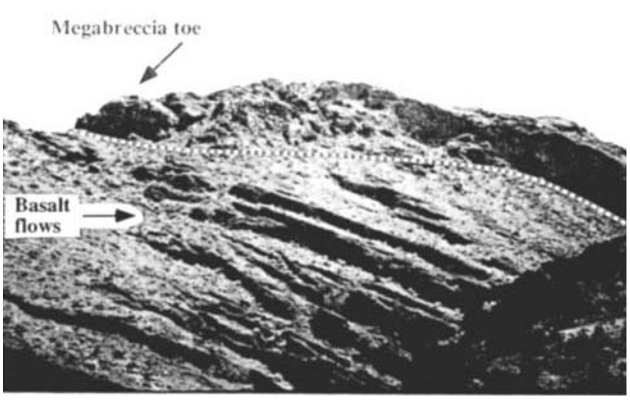
base with a trend of N68°E were observed by Dunn (1986). The attitude of the basal surface was recorded at several locations, both in this study (N9°W/44°SW, N80°E/39°SE) and in Dunn (1986) (N11°W/51°SW, N62°W/31°SW and N66°W/26°SW). The basal surface of the megabreccia commonly parallels the regional foliation of the deposit but generally dips less steeply than the underlying sedimentary and volcanic units (Fig. 6a). Sills <1 m thick (inferred to be from the Chambers Well dyke swarm and derived from the source area) and subparallel to the regional foliation are observed above the base. Megabreccia above the basal contact is coherent, although shattered. Locally, clastic dykes derived from a sandstone in the substrate were observed along the base (Fig. 6b).

In the northernmost part of the map area (Fig. 4) basalt flows directly below the megabreccia deposits are little deformed, whereas fine-grained sandstone units are highly folded (Fig. 6c). Similarly, highly deformed and folded lake beds occur below an outcrop of megabreccia in the central Chemehuevi Valley (Fig. 6d). The non-uniform distribution of bedding-plane attitudes of the substrate (Fig. 7) suggests that deformation directly below the megabreccia was turbulent during landslide emplacement.

Although most of the megabreccia in the map area is coherent with ubiquitous SW-dipping foliation, penetratively fractured zones of intense brecciation, a few metres to tens of metres thick, are common (Fig. 8). Within these zones, the megabreccia consists of tightly packed, coarse, angular fragments with highly variable orientation, cemented together by a thin, fine-grained matrix of crushed gneiss and adamellite. Thus, these zones are similar to the matrix-rich breccia facies of Yarnold & Lombard (1989), but dissimilar in that they occur throughout the deposit, rather than only locally near the base. They commonly are developed near a contact between the adamellite and the gneiss but also occur near the base of the megabreccia.

Evidence for landslide interpretation

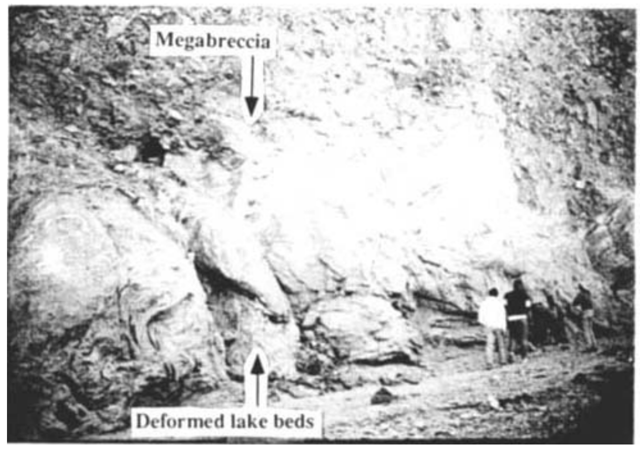
Mapping of the hangingwall units shows that the megabreccia body is a coherent unit inferred to have been placed essentially instantaneously. Several lines of evidence imply that the megabreccia in the north-eastern Whipple Mountains was emplaced as a landslide. The observation that the basal contact generally parallels the foliation in the breccia, but dips less steeply than the underlying sedimentary and volcanic rocks (Fig. 6a), suggests that: (1) the megabreccia was emplaced along a surface subparallel to the regional foliation inherited from the source area; (2) the megabreccia was emplaced after some tilting of the volcanic and sedimentary units;



(a)

(c)

(b)



(d)

Fig. 6. (a) Toe of megabreccia overriding basalt flows (Tmb in Fig. 4). Note that basalt flows dip more steeply than the base of landslide implying tilting of the stratigraphy prior to megabreccia emplacement. View to the south. See Fig. 4 for photograph location. (b) Clastic dyke of sandstone (Tmss in Fig. 4) injected into megabreccia near the base of the deposit. See Fig. 4 for photograph location. (c) Folded sandstone beneath megabreccia in the north-eastern Whipple Mountains. View to the south. See Fig. 4 for photograph location. (d) Highly deformed lake beds in central Chemehuevi Valley. See Fig. 2 for location.

and (3) the megabreccia was translated on the ground surface without significant rotation about the horizontal axis.

If the basal contract is interpreted as a fault, then the 'older rocks over younger rocks' relationship would imply a reverse fault. This seems unlikely, however, since evidence from striations and the location of likely source rocks indicates displacement in the same direction as, and concurrent with, regional extension. Additionally, a thrust-fault interpretation would require the basal surface to have a root, which has not been found.

The inferred breakaway for the landslide is a broad cirque-like valley located within a synformal corrugation of the Whipple detachment fault in the north-central Whipple Mountains (Figs 2, 3 and 9). The north-easterly transport direction of the landslide measured from slickensides along the base (N68°E, Dunn, 1986) corresponds to the present position of the megabreccia complex with respect to this inferred source area. This transport direction also corresponds closely with the extension direction of the Whipple detachment fault (N50°E, Davis & Lister, 1988) and to the axes of the wavelike corrugations of the fault surface.

The landslide breakaway was previously mapped as the War Eagle detachment fault (Davis, 1988; Davis &

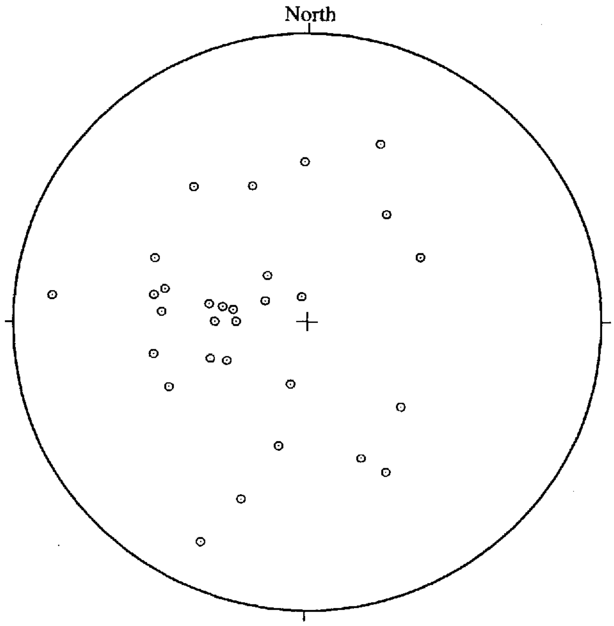


Fig. 7. Equal-area stereonet plot of poles to bedding planes of folded lake beds within Chemehuevi Valley. Poles do not lie along a great circle, and therefore folds are non-cylindrical. View to the south.

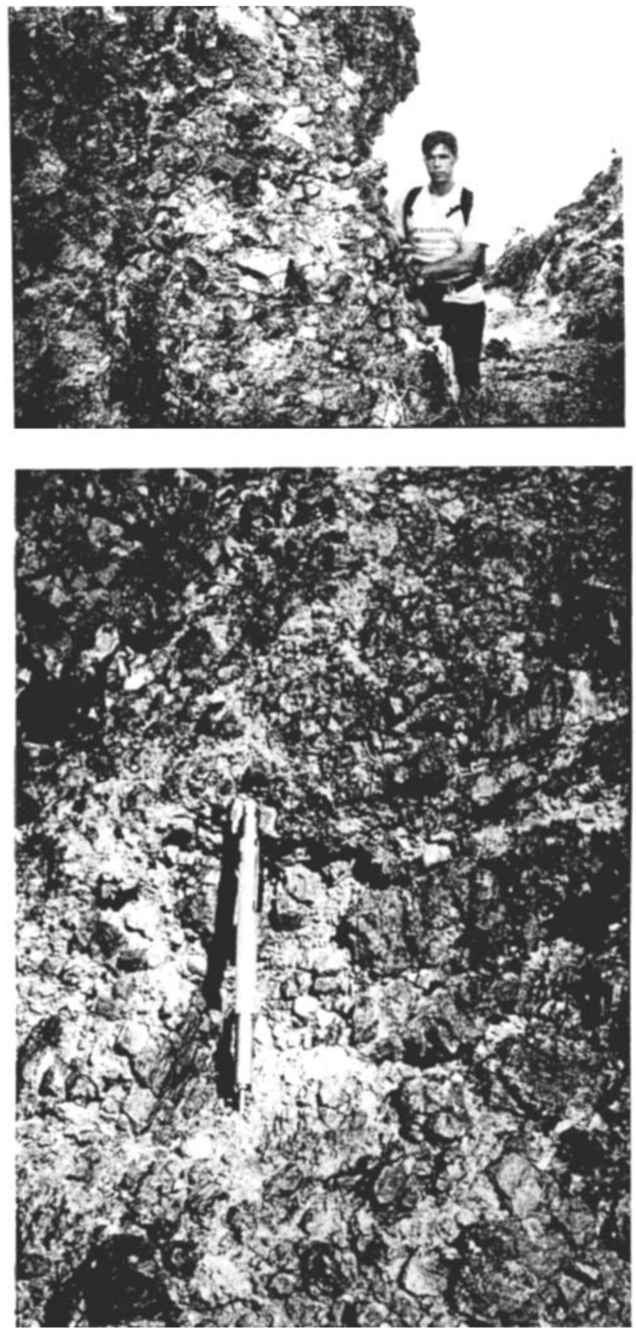


Fig. 8. Zones of intense brecciation within megabreccia. See Fig. 4 for photograph locations.

Lister, 1988; Anderson & Cullers, 1990), along which the mylonitic front was offset approximately 4.5 km to the north-east. Davis (1988, fig. 2) shows the War Eagle detachment fault displaced by the higher, younger Whipple detachment fault. With the interpretation in this study that the War Eagle fault is, in fact, the breakaway for the War Eagle landslide, the 4.5 km offset of the mylonitic front is a minimum transport distance for the landslide (Fig. 3). Yin & Dunn (1992) estimated 9.5 km to be the minimum transport of the landslide based on restoration of the original shape of the landslide. Earlier workers concluded that the War Eagle fault was truncated by the Whipple detachment fault. In this study, this conclusion is interpreted as post-landslide movement along the Whipple detachment fault, which tectonically transported the megabreccia deposit further from the landslide breakaway. The breakaway of the landslide should not be confused with that for the Whipple–Chemehuevi detachment-fault system located in the region between the Old Woman and Turtle mountains (Fig. 1).

Possible source for the megabreccia

The compositional character of the upper-plate megabreccia clearly reflects derivation from a lower-plate, north-central Whipple Mountains provenance. The adamellite megabreccia shows strong affinities to the leucocratic rocks of the Whipple Wash Suite and the mylonitic gneiss megabreccia is likely derived from the Proterozoic gneiss in the lower plate (Figs 2 and 3; see Anderson & Cullers, 1990). Additional lines of evidence for derivation from the Cretaceous Whipple Wash Suite and Proterozoic rocks include: (1) east–northeastward thinning of adamellite megabreccia sills (Fig. 5). This reflects an inherited trend in that leucocratic Cretaceous plutonic rocks (Whipple Wash Suite), which sub-horizontally intrude lower-plate Proterozoic gneisses in the north-central Whipple Mountains, pinch-out eastward (see Davis, 1988, Davis *et al.*, 1982, fig. 2; Anderson & Cullers, 1980); and (2) the Chambers Well dyke swarm intrudes the Whipple Wash Suite and older rocks found in the north-central Whipple Mountains

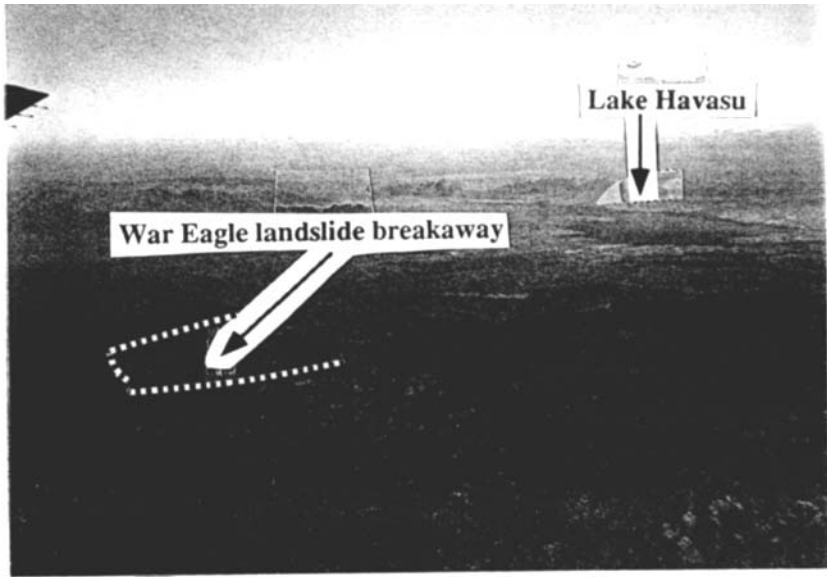


Fig. 9. Aerial photograph of breakaway of War Eagle landslide. Note Lake Havasu in centre-right of photograph. Photograph courtesy of Jack F. Dunn.

(Davis *et al.*, 1982; Anderson & Cullers, 1990). The dyke rocks occur as parts of the megabreccia deposit and thus record pre-landslide intrusion (Fig. 3; Yin & Dunn, 1992).

Structural geology

The Whipple detachment fault is the major structure in the study area. Numerous minor normal faults in the hangingwall of the Whipple fault join the Whipple detachment fault in plan view in an adjacent area mapped by Dunn (1986). Thus, the high-angle faults must merge with the detachment at depth (Figs 4 and 5). Although most of the minor normal faults dip towards the north-east, a few SW-dipping normal faults are also observed. Displacement along these faults ranges from several hundreds of metres to several kilometres. NE-dipping faults have tilted Tertiary stratigraphy in their hangingwalls to the south-west, forming a series of half grabens. SW-dipping antithetic faults are locally present and have tilted Tertiary strata to the north-east. Together with NE-dipping normal faults, synthetic to the detachment, they have created full grabens and broad anticlines. The anticlines were developed as roll-over structures, coeval with movement along high-angle hangingwall faults and the low-angle Whipple fault.

DISCUSSION

Mechanisms for the initiation of the War Eagle landslide

Although significant attention has been given to the transport mechanisms of large landslides (see Yarnold & Lombard, 1989, for a review), little investigation of the forces necessary to mobilize such large masses of material has been conducted. An understanding of the initiation mechanism may provide important constraints on the transport mechanism. Initiation of the War Eagle landslide during the Miocene may have occurred in response to one or more of the following factors: (1) antiformal warping of the Whipple dome; (2) increased pore-fluid pressure in the lower plate of the detachment fault resulting in reduced shear strength; and (3) momentary changes in loading conditions such as those following an earthquake.

Antiformal warping of the Whipple dome

Detachment-fault evolution in the Colorado River extensional corridor was complicated by the occurrence of numerous domal and basinal corrugations of the fault surface (Fig. 1; e.g. John, 1987; Davis & Lister, 1988; Yin, 1991). These undulations have resulted in the synextensional development of antiforms and synforms with their major axes parallel to the extension direction. Linear, subparallel, half-graben basins of the extensional corridor developed around the antiformal uplifts within the synformal corrugations (Fig. 10). The megabreccia complex in the north-eastern Whipple Mountains initiated in the War Eagle area adjacent to the crest of an antiformal corrugation of the Whipple detachment fault. This suggests that formation of the Whipple dome could have enhanced the gravitational instability of the uplifted footwall rocks.

Increased pore-fluid pressure

Increased pore-fluid pressure reduces the shear strength of rocks, and may have contributed to initiation of the War Eagle landslide. An increase in pore-fluid pressure possibly occurred in the lower plate of the Whipple detachment fault by two mechanisms: (1) migration of fluids was likely along the detachment-fault surface; (2) fluids may have been added to the system during the

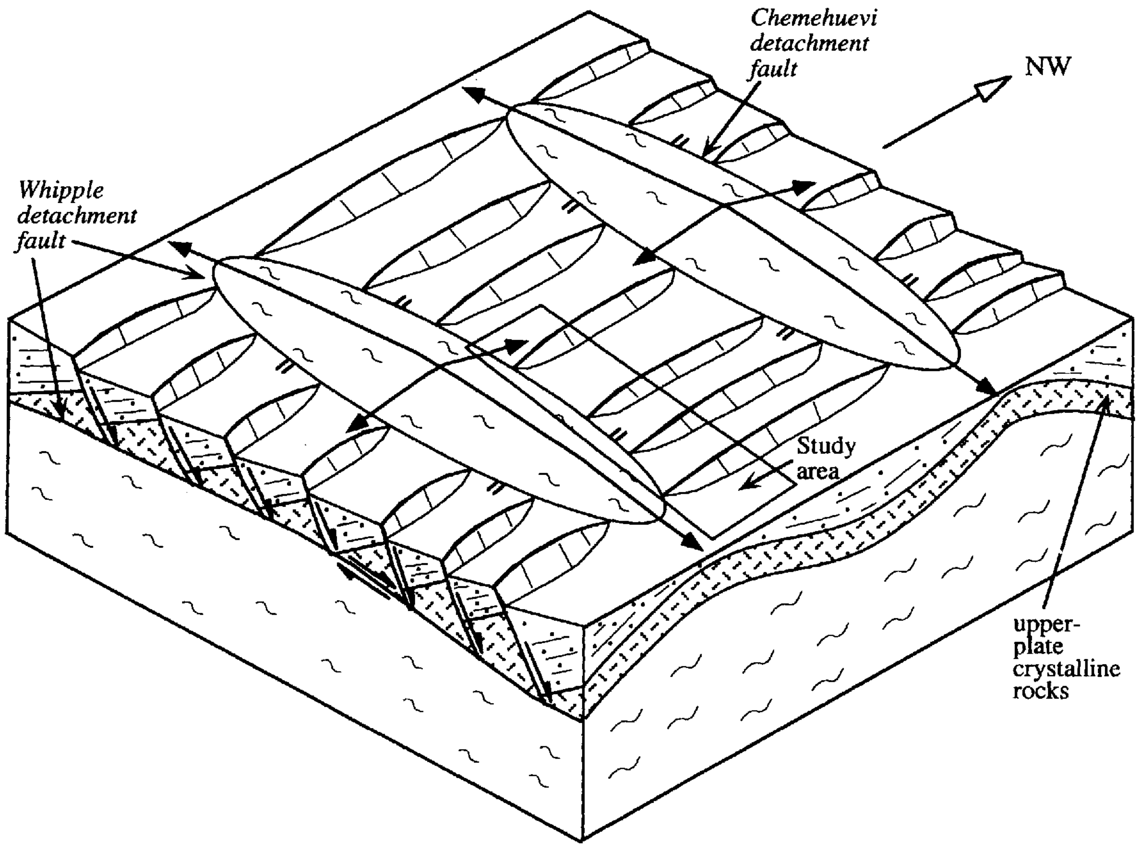


Fig. 10. Whipple Mountains region during Miocene time, showing antiformal uplift around Whipple detachment fault, and geometry of half-graben basins (modified from Teel & Frost, 1982).

intrusion of the Chambers Well dyke swarm or Miocene plutons such as the War Eagle Complex, and fluid pressures may have been maintained if the permeability of the rocks was sufficiently low.

The occurrence of mineralization spatially related to the detachment fault implies the communication of fluids along the fault surface (e.g. Ridenour *et al.*, 1982; Wilkins & Heidrick, 1982). Additionally, the character of the cataclasite developed along the Whipple detachment fault indicates a mechanism for formation which may have been aided by higher-than-normal fluid pressures (Phillips, 1982). Axen (1992) also argued that detachment faulting favours the generation of high pore-fluid pressure.

The intrusion of the Chambers Well dyke swarm at ~20 Ma and/or the War Eagle Complex at ~19 Ma in the vicinity of the inferred breakaway of the War Eagle landslide may have provided fluids into the lower plate of the Whipple detachment fault, thereby increasing pore-fluid pressures. The War Eagle Complex was emplaced at shallow crustal levels (6 ± 2 km, Anderson & Cullers, 1990). Updip fluid migration would have been aided by dilatancy pumping (e.g. Reynolds & Lister, 1987), where microcracking during the buildup of stress allowed the dilating fault zone to draw pore fluid from the country rock. During seismic events, this dilatancy would collapse thereby releasing fluids. High rates of displacement along the fault surface may have resulted in an increase in the frequency of the dilatancy creation–collapse cycles (Reynolds & Lister, 1987).

The landslide was initiated at shallow depths (<3 km), and maintaining significant pore fluid pressure at these shallow crustal levels is unlikely. However, only slightly increased pore-fluid pressure ratios, in combination with seismic forces and topography, are necessary to initiate an instability.

Earthquake accelerations

Several workers in the Colorado River extensional corridor have assumed that megabreccia emplacement was linked to palaeoseismicity of detachment-fault systems (e.g. Fedo & Miller, 1992). A simple mechanical model developed by Forshee & Yin (1993) incorporated the effects of maximum horizontal ground acceleration generated during earthquakes on the instantaneous stability of a rock mass. Given the strong anisotropy of the gneiss and adamellite, and of foliation planes along micaceous surfaces (Dunn, 1986), the compressive failure strength of these rocks would have been effectively reduced (e.g. Gottschalk *et al.*, 1990).

The mechanical model presented below implies four important assumptions: (1) we only consider the landslide for a two-dimensional case, and hence the

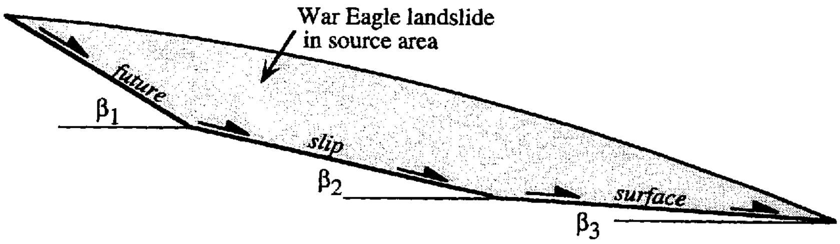


Fig. 11. Schematic cross section of War Eagle landslide breakaway prior to initiation of landslide.

frictional resistance along the side walls of the landslide shown in Fig. 9 is not accounted for; (2) blocks resting above different inclined surfaces do not interact at the time of landslide initiation; (3) earthquake acceleration during the landslide initiation is the acceleration of the landslide mass; and (4) the frictional failure occurs simultaneously along all the inclined basal surfaces which have different dip angles. Figure 11 shows the cross-sectional geometry of the landslide in two dimensions where the basal surface for each segment of the landslide is inclined at an angle, β_i ($i = 1$, 2 and 3). These angles are based on present topography: β_1 is the angle in the inferred breakaway in the north-central Whipple Mountains (25°); β_3 is the current topographic gradient between the source area and megabreccia outcrops (1°) and β_2 is an angle selected in between (15°).

A rock mass of approximate volume (11 km^3), density (approximately 2.8 g m^{-3} – see Coulson, 1972) and geometry to replace the present space in the landslide breakaway region is shown in Fig. 11. The forces due to gravity, friction and a seismic horizontal acceleration are balanced. In the model, the coefficient of horizontal acceleration necessary to create momentary instability is determined. The coefficient of horizontal acceleration, a_h, is defined as seismic acceleration divided by the gravitational acceleration. The effects of variations of the pore-fluid pressure ratio, λ, and the coefficient of internal friction for the rock mass, μ, were considered. We neglected cohesion in the calculation, because we believe, based on field relationships, that the landslide was initiated along the footwall foliation surfaces.

In the model, the role of seismically generated acceleration contributing to the initiation of landslides was given particular attention. The total force-balance equation involves the summation of static and dynamic forces. The condition of equilibrium is

$$F_g + F_f + a_h F_s = 0 \qquad (1)$$

where F_g is the force due to gravity, F_f is the frictional force, F_s is the 'seismic force', induced by seismic acceleration, and a_h is the coefficient of horizontal acceleration. Vertical acceleration affects both the driving and the resisting forces in such a way that they effectively cancel each other (Ghosh & Haupt, 1989); therefore, the effect of vertical acceleration on the force balance, averaged over the course of an earthquake event, is not as significant as that of the horizontal acceleration and is assumed to be inconsequential. However, the vertical acceleration may be important when we consider an instantaneous instability. In addition, dilatancy along the basal surface of the landslide due to vertical acceleration may enhance pore-fluid pressure along the basal zone, thus reducing its effective coefficient of friction.

In the model, the total forces were calculated for three segments of the sliding block, one over each basal slide surface, and then summed together. The model was limited because the forces were not distributed over the side walls of the slide block, and only the force due to the total volume of each segment was resolved in the direction of the landslide along its basal surfaces. A complete treatment of the problem will be presented in a separate paper.

The gravitational force, F_g, on the block is equal to

$$F_g = \sum W_i \sin \beta_i \quad (i = 1, 2, 3) \qquad (2)$$

where W_i is the weight of a segment of the block above a portion of the basal surface with a dip angle of β_i (Fig. 11). Because the landslide mass could have been saturated with fluid, we define $W_i = V_i \rho_e g$, where $\rho_e = \rho(1 - \lambda_0)$, V_i is the volume of a segment of the landslide block above a portion of the landslide surface with a dip angle of β_i, ρ is the density of the landslide, g is the gravitational acceleration and λ_0 is the pore-fluid pressure ratio within the landslide.

The frictional force, F_f, is equal to

$$F_f = \sum W_i \cos \beta_i \cdot \mu(1 - \lambda) \quad (i = 1, 2, 3) \qquad (3)$$

and acts in the directions opposite to landslide transport; μ is the coefficient of friction and λ is the Hubbert–Rubey pore-fluid pressure ratio for the entire landslide block. Coefficients of friction from 0.4 to 0.47 were considered. These values are reasonable for the mylonitic rocks containing mica directly above the base of the landslide (Coulson, 1972). Pore-fluid pressure ratios from 0 to 0.6 were evaluated.

The seismic force, F_s, is equal to

$$F_s = \sum [W_i \cos \beta_i + W_i \sin \beta_i]\mu(1 - \lambda). \quad (i = 1, 2, 3) \qquad (4)$$

Solving for a_h, the coefficient of horizontal acceleration, in Eq. (1) produces a horizontal acceleration coefficient in terms of gravitational acceleration.

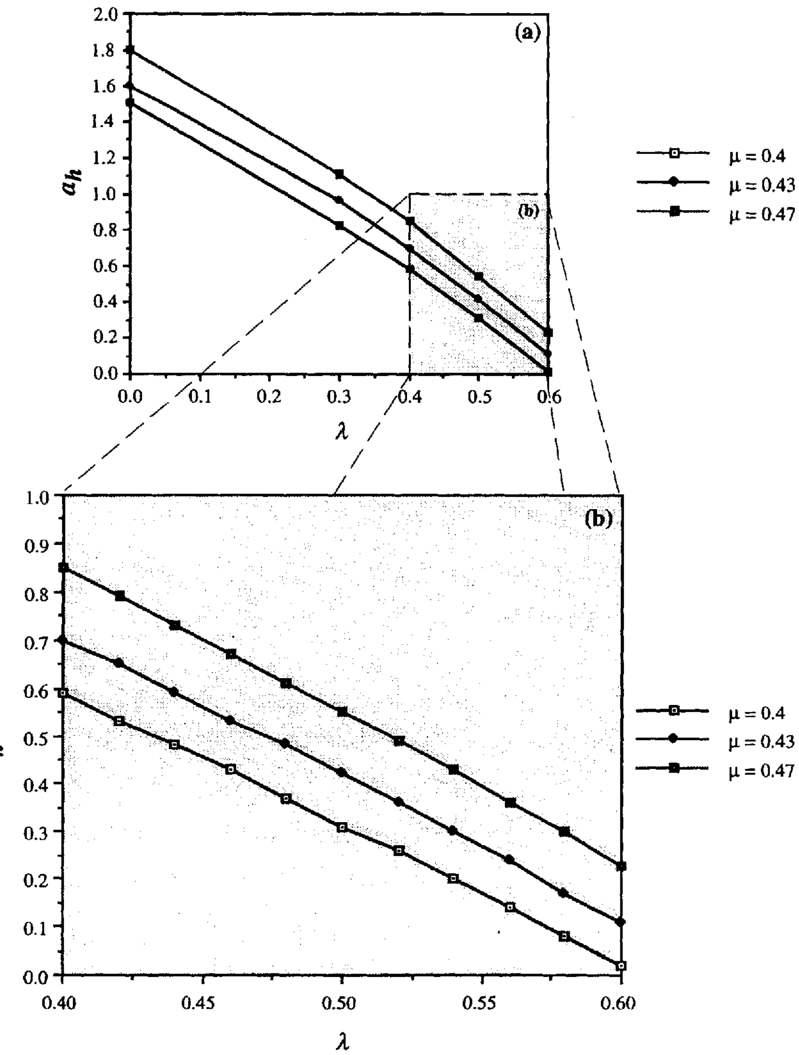


Fig. 12. Results of War Eagle landslide initiation model. Coefficient of horizontal acceleration, a_h, vs. λ (pore-fluid pressure ratio), with different coefficients of friction, μ. Lower coefficients of friction result in lower values of acceleration necessary to initiate movement.

Figure 12 is a plot of the results and shows the required coefficient of horizontal acceleration for landslide initiation vs. pore-fluid pressure ratio at the landslide base. Using the War Eagle landslide as an example, values of the coefficient of horizontal acceleration, a_h, were calculated at various pore-fluid pressure ratios, λ, and with various coefficients of internal friction, μ (Fig. 12). Lower coefficients of friction result in lower values of acceleration necessary to initiate sliding. It was found that coefficient of horizontal acceleration values exceeding 1.5*g* are required to mobilize the landslide if pore-fluid pressure along the basal slip surface is assumed to be zero (Fig. 12). Acceleration values of this magnitude have not been observed in bedrock even during very large earthquakes (e.g. Northridge earthquake, Shakal *et al.*, 1994). However, when pore-fluid pressure is considered, more reasonable acceleration values are obtained. The presence of pore-fluid pressure is essential for decreasing the amount of seismic energy necessary to generate sliding motion and is critical to the model. Assuming a coefficient of internal friction, μ, of 0.4, hydrostatic pore-fluid pressure ratio, λ, of 0.4 (Hubbert & Rubey, 1959) would be sufficient to initiate an instability given horizontal accelerations of 0.6*g*. Slightly elevated pore-fluid pressures (0.6) bring the necessary acceleration down to 0.02*g*. Note that in the model, the coefficient of internal friction of the rock material must be low (0.4–0.47), for reasonable values of horizontal acceleration to be obtained. It seems unlikely that a significant increase in pore-fluid pressure could be maintained at the shallow crustal levels where the landslide was initiated. Thus, we conclude that significant seismic horizontal acceleration, greater than 0.5*g*, may have induced an instability and triggered the initiation of the War Eagle landslide.

Results of these calculations have important implications concerning whether low-angle detachment faults were seismically active during their development. For the case of the Whipple detachment fault, previous workers have established that the fault was initiated and was active at an angle of less than 30° (Davis & Lister, 1988; Yin, 1991). Additionally, Davis & Lister (1988) documented pseudotachylite along the surface of the Whipple detachment fault as an indication of seismicity; also, Phillips (1982) suggested that the presence of injection features along cataclasite zones of the Whipple detachment fault may represent episodes of very rapid seismic faulting. If the above conditions are at all analogous to those during initiation of the War Eagle landslide, the model results strongly suggest that the Whipple detachment fault was a seismically active low-angle normal fault during the mid-Tertiary.

Mechanisms for the emplacement of the War Eagle landslide

A set of characteristic features of megabreccia deposits in detachment-fault systems in the western USA are identified in Yarnold & Lombard (1989). The landslides commonly have travelled into lake deposits or other soft sediments and created a zone of concentrated shearing within the substrate. The basal zone of the megabreccia is of mixed composition, incorporating substrate and breccia material, and is overlain by a region of matrix-supported breccia. This grades upward into a zone of highly fractured but coherent megabreccia where matrix is poor or non-existent. In some locations, a concentration of large avalanche blocks rests on top of the deposit.

Similarities between several deposits of large landslides have led many workers to attempt to formulate a general mechanism for their emplacement. Numerous models have been presented to explain the transport of rock-avalanche deposits found worldwide: fluidization of the breccia by entrapped air (Kent, 1966), interstitial dust (Hsü, 1975), a thin layer of molten rock (Erismann, 1979) and acoustic waves (Melosh, 1986) have been proposed, as well as air-layer lubrication (Shreve, 1968a,b), collisional grain flow (Davies, 1982) and transport on a low-density layer of highly active particles (Campbell, 1989). A contrary view held by other workers is that the megabreccia deposits were emplaced slowly, of the order of millimetres per year, by gravity gliding (e.g. Parke & Davis, 1990). All models have met with varying degrees of criticism as none has seemingly accounted for the diversity of observed features of the megabreccia deposits. Nevertheless, based on a set of characteristic features shared by numerous Basin and Range megabreccia deposits, Yarnold (1993) proposed that during transport, a basal zone of shear was generated, with some shear distributed vertically throughout the deposit on discrete slip surfaces. The results of this study imply a similar mode of emplacement for the War Eagle landslide. The physical mechanisms accommodating this style of transport remain to be explored in future work.

Yarnold (1993) proposed that megabreccia bodies were initiated as subaerial rock avalanches and were transported across dry substrate materials. Limited substrate materials were incorporated into the overlying breccia lobe because they were generally too coarse and lacked sufficient pore-fluid pressure. Yarnold & Lombard (1989) observed an increase in coherence upward in the deposits. This description of transport is similar to that inferred for the War Eagle landslide. However, a systematic increase in coherence was not observed in the megabreccia; instead, the shear is distributed throughout the deposit within zones of intense brecciation (Fig. 8) developed throughout the megabreccia. These areas represent shear zones within the deposit along which large coherent blocks of the megabreccia were transported. The original orientation of the megabreccia rocks within the footwall of the Whipple detachment fault was such that subhorizontal sills and subhorizontal foliation planes provided weak zones along which fracture of the basal landslide surface occurred. Transport was facilitated by simple shear along foliation planes distributed vertically through the deposit, effectively transporting the mass like a sliding deck of cards. This is in contrast to observations by Yarnold & Lombard (1989) which imply that transport was facilitated along zones near the base of the landslide with diminishing shear distributed upward. Parallelism between the landslide base and foliation in the landslide implies translation of the block, instead of granular flow as suggested by Yarnold & Lombard (1989).

The presence of clastic dykes (derived from the substrate) in the upper plate of the War Eagle landslide and in similar megabreccia deposits in the southern Basin and Range (Yarnold & Lombard, 1989; Yarnold, 1993) indicates a probable reduction of pore pressure along the basal surface (e.g. Guth *et al.*, 1982). It seems unlikely, therefore, that gravity gliding (Hauge, 1990) could be invoked as a mechanism for the emplacement of the megabreccia sheet (see Guth *et al.*, 1982). The intense deformation of the substrate in the central Chemehuevi Valley and the folding of sandstone beds in the north-eastern Whipple Mountains imply rapid deposition into water-laden sediments. Additionally, pervasive fracturing of the megabreccia deposit implies catastrophic deposition because the megabreccia would have needed to confine fluid pressures within the basal surface to facilitate gravity gliding (e.g. Guth *et al.*, 1982). Pervasive fracturing of the rocks would indicate that the megabreccia was too permeable to maintain such fluid pressures.

Structural and sedimentological evolution of the north-eastern Whipple Mountains

Miocene evolution of the north-eastern Whipple Mountains was similar to that of other detachment-related basins in the Colorado River extensional corridor. NE-directed extension of the Whipple detachment fault was accommodated along numerous subparallel high-angle normal faults and associated half grabens. The uplifted footwall blocks and SW-tilted hangingwall blocks provided sedimentary input to the basins.

Miocene evolution of the north-eastern Whipple Mountains is shown in Fig. 13. Initial deposition into the supradetachment basin is documented with con-

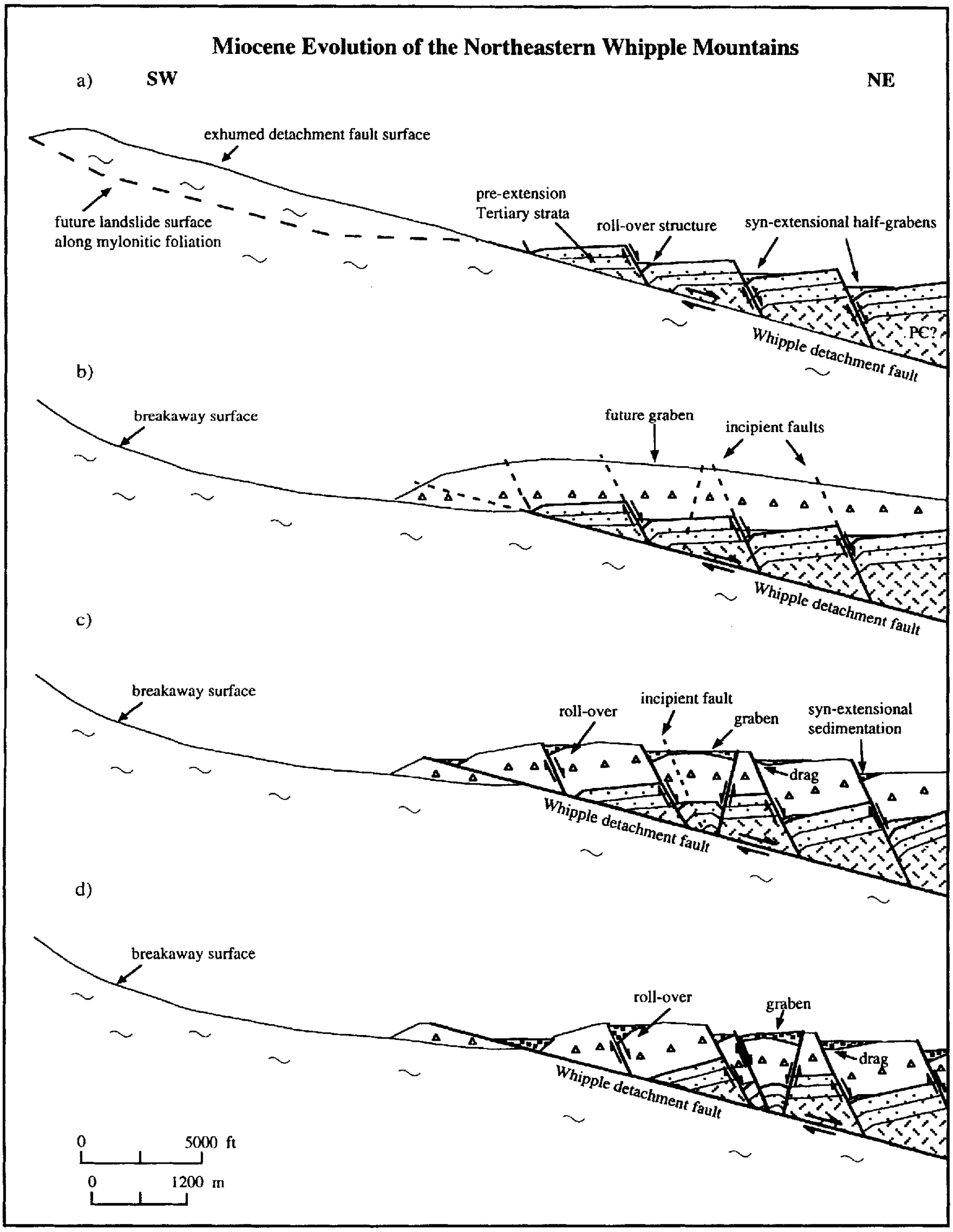


Fig. 13. Miocene evolution of the north-eastern Whipple Mountains. (a) Extension along the Whipple detachment fault produced synextensional half grabens in the hangingwall and brought lower-plate rocks to the surface. (b) A large landslide was initiated along subhorizontal planes of the mylonitic foliation. (c) and (d) Continued faulting and extension along the upper plate tilted and segmented Tertiary stratigraphy while tectonically transporting the megabreccia further from breakaway area. Compare (d) with cross-sections of Fig. 5.

glomerate, sandstone, limestone and volcanic rocks (Dorsey & Dunlap, 1993). Tilting of these sequences was followed by emplacement of the megabreccia complex. This relationship is indicated by the steeper dips of the pre-landslide strata compared with the attitude of the basal surface of the megabreccia deposit. Extension of the upper plate continued, and the megabreccia complex was tilted and segmented by subparallel high-angle normal faults. Post-landslide conglomerates and volcanic rocks were deposited in the continuously evolving half-graben basins. Growth–faulting relationships imply synextensional sedimentation.

In the Basin and Range Province, extension is generally accommodated by rotational, planar normal-fault systems (Wernicke & Burchfiel, 1982; Axen, 1988). Planar normal faults are also documented in the north-eastern Whipple Mountains, and occur along with the development of roll-over structures (Fig. 5). Roll-over structures are most commonly associated with listric normal-fault systems (Wernicke & Burchfiel, 1982; Dula, 1991). Where a high-angle normal fault in the hangingwall of a detachment-fault system joins the low-angle detachment at depth it exemplifies a continuous slip surface and approximates a listric fault (Xiao & Suppe, 1992). It is, therefore, not surprising to see roll-over structures associated with planar normal faults, as observed in the north-eastern Whipple Mountains (Figs 5 and 13).

Palinspastic cross-section reconstruction in the north-eastern Whipple Mountains proved to be problematic due to growth–faulting relationships. In fact, balanced cross-section restoration has not been possible in previous studies of the Whipple Mountains area (e.g. Gross & Hillemeyer, 1982; Davis & Lister, 1988). However, this shortcoming is actually supportive of synextensional sedimentation relationships. The cross-sections shown in Fig. 5 are consistent with all observable field relationships. Detailed examination of the cross-sections emphasizes several features which have important implications for the kinematic development of the landslide: (1) the basal surface of the landslide is subparallel to the foliation of the megabreccia; (2) the adamellite occurs as sills within the gneiss with a foliation subparallel to the gneiss and to the basal landslide surface; and (3) the foliation attitude was not disrupted significantly during emplacement of the megabreccia.

CONCLUSIONS

The results of this study have important implications for the evolution and basin architecture of supradetachment basins. The Whipple detachment fault was active at an angle of less than 30° and displacement along the fault was likely accompanied by the release of seismic energy. Numerous half grabens in the upper plate of the Whipple detachment fault were formed as NE-directed extension continued. Detachment faulting was active long enough for rocks from the lower plate to reach the surface. Sufficient topographic relief was produced, allowing generation, from the footwall of the detachment fault, of a large landslide, with the same transport direction as tectonic transport, following continued seismic slip along the fault. Antiformal warping of the Whipple dome may have also contributed to the oversteepened topography. The megabreccia deposit was emplaced during later stages of detachment-fault activity, and suggests a very seismically active period in the evolution of the Whipple detachment-fault system.

Initiation of the landslide may have been facilitated by increased pore-fluid pressure, and/or warping of the Whipple dome, but the primary cause of instability is attributed to the release of seismic energy along the detachment-fault system. The widespread occurrence of monolithological megabreccia deposits in the Basin and Range province suggests that the emplacement of large landslides in supradetachment basins is an integral part of the evolution of many detachment-fault systems.

Dynamics of transport of the megabreccia are still uncertain. However, intensely brecciated zones within the deposit imply that kinematic development involved slip by simple shear along planes of inherent weakness (foliation). The landslide was probably emplaced catastrophically, as suggested by penetrative fracturing of the megabreccia and local substrate deformation features. Detailed sedimentological studies of the megabreccia, and other sedimentary and volcanic deposits in the north-eastern Whipple Mountains, will further define the basin architecture of this supradetachment basin.

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