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Notes

Structural and stratigraphic development of the Whipple-Chemehuevi detachment fault system, southeastern California: Implications for the geometrical evolution of domal and basinal low-angle normal faults

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ABSTRACT

Recent debates on the development of detachment faults during continental extension have been centered on whether they were active at low angles and initiated as relatively planar faults. In addition, intense investigations have concentrated on how the detachment-fault geometry evolved in time and space and how the extension was accommodated in their upper and lower plates. The superb exposure of the mid-Tertiary Whipple Mountains detachment fault system in southeastern California provides an unusual opportunity to address these questions. Analysis of the stratigraphy and structures of upper-plate rock units constrains the three-dimensional kinematic evolution of the mid-Tertiary Whipple-Chemehuevi detachment fault system in southeastern California. Tertiary volcanic strata in the northwestern Whipple Mountains and central Chemehuevi Valley consist of similar rock types that have undergone about 15% extensional strain. In contrast, a different succession of Tertiary volcanic and sedimentary rocks underlies the northeastern Whipple Mountains along the structural trend of central Chemehuevi Valley; these strata have been extended by 40%. Differences in magnitudes of extension and mid-Tertiary stratigraphies between these two areas argue for the presence of a synformal, gently east-dipping normal fault above the Whipple fault in the central Chemehuevi Valley. This fault accommodates 15 km of the total 40-km extension along the Whipple-Chemehuevi detachment fault system. In addition, tilting patterns of upper-plate strata and the presence of an areally extensive syn-extension landslide ($>70 \text{ km}^2$)

show that (1) the Whipple detachment fault was active at low angles ($<30^\circ$); (2) the Whipple detachment fault was relatively planar at the time of its initiation and became antiformally warped during its late stage of development; and (3) the antiformal warping of the Whipple detachment fault produced enough topographic relief to expose the lower-plate mylonitic rocks and to initiate a large landslide ($>70 \text{ km}^2$) from the north side of the Whipple Mountains; its emplacement occurred before the end of detachment faulting.

INTRODUCTION

Detachment faults (regional low-angle normal faults) in Cordilleran core complexes commonly exhibit doubly plunging antiformal (domal) and synformal (basinal) geometries with axes both perpendicular and parallel to the extension direction. To understand how they formed and evolved, the following questions must be addressed. (1) Did they initiate and move at low angles (for example, Jackson, 1987; Burchfiel and others, 1987; Lister and Davis, 1989; Yin, 1989a)? (2) Were they relatively planar when they initiated and later became warped into domes and basins, or were they initiated as curvilinear surfaces (for example, Spencer, 1982, 1985; John, 1987a; Yin, 1989b, 1991)? (3) How did the three-dimensional geometry of detachment faults evolve in time and space, and what effect did this have on the pattern of structures in upper and lower plates? (4) How was the extension accommodated in hanging walls and footwalls during detachment faulting?

Various models have been proposed to ex-

plain the low-angle domal and basinal detachment-fault geometry, each predicting a specific geologic relationship between the detachment fault and the structures above and below it. Most workers concluded that the domal and basinal detachment-fault geometry is related to superposition of two mechanically independent processes. The extension-perpendicular antiforms and synforms are interpreted to be the result of such processes as (1) isostatic response to tectonic denudation (for example, Rehrig and Reynolds, 1980; Howard and others, 1982; Spencer, 1984; Hamilton, 1988; Wernicke and Axen, 1988; Buck, 1988; Weissel and Karner, 1989); (2) reverse drag caused by movement on an unrelated, structurally deeper detachment fault or a younger, high-angle, normal fault (Spencer, 1984; Bartley and Wernicke, 1984; Wernicke, 1985; Davis and Lister, 1988); (3) formation of antithetic shear zones in the lower plate of a detachment fault (Reynolds and Lister, 1990); and (4) movement along a flat-ramp fault surface (John, 1987a). All four models predict that detachment faults, as well as structures in their upper and lower plates, are warped concordantly. The word "warping" used in this paper refers to changes in geometry of planar or curvilinear structures and does not imply a mechanism (buckling, bending, faulting, and so on) for such changes.

The extension-parallel antiforms and synforms are interpreted to have formed as (1) folds of planar detachment faults (Spencer, 1982; Davis and others, 1980, 1982), or (2) original fault corrugations (Davis and Hardy, 1981; John, 1987a; Spencer, 1985; Davis and Lister, 1988). The first interpretation requires that the warped detachment-fault geometry be concordant with attitude patterns of structures in the upper and lower plates. In contrast, the second

interpretation implies that the curvilinear detachment-fault geometry is independent of attitude patterns of structures in the upper and lower plates.

Single-process models for the formation of domal and basinal detachment faults have been also proposed, such as (1) emplacement of syn-extension plutons (Thompson and White, 1964; Yin, 1989b, 1991; Reynolds and Lister, 1990; Holt and others, 1986), (2) uncompensated undulatory Moho topography (Yin, 1989b, 1991), and (3) compressive deviatoric stresses perpendicular to the extension direction (Yin, 1989b, 1991). All of these models predict that the warped detachment-fault geometry should be compatible with attitude patterns of structures in both the upper and lower plates.

Previous investigations on the origin of domal

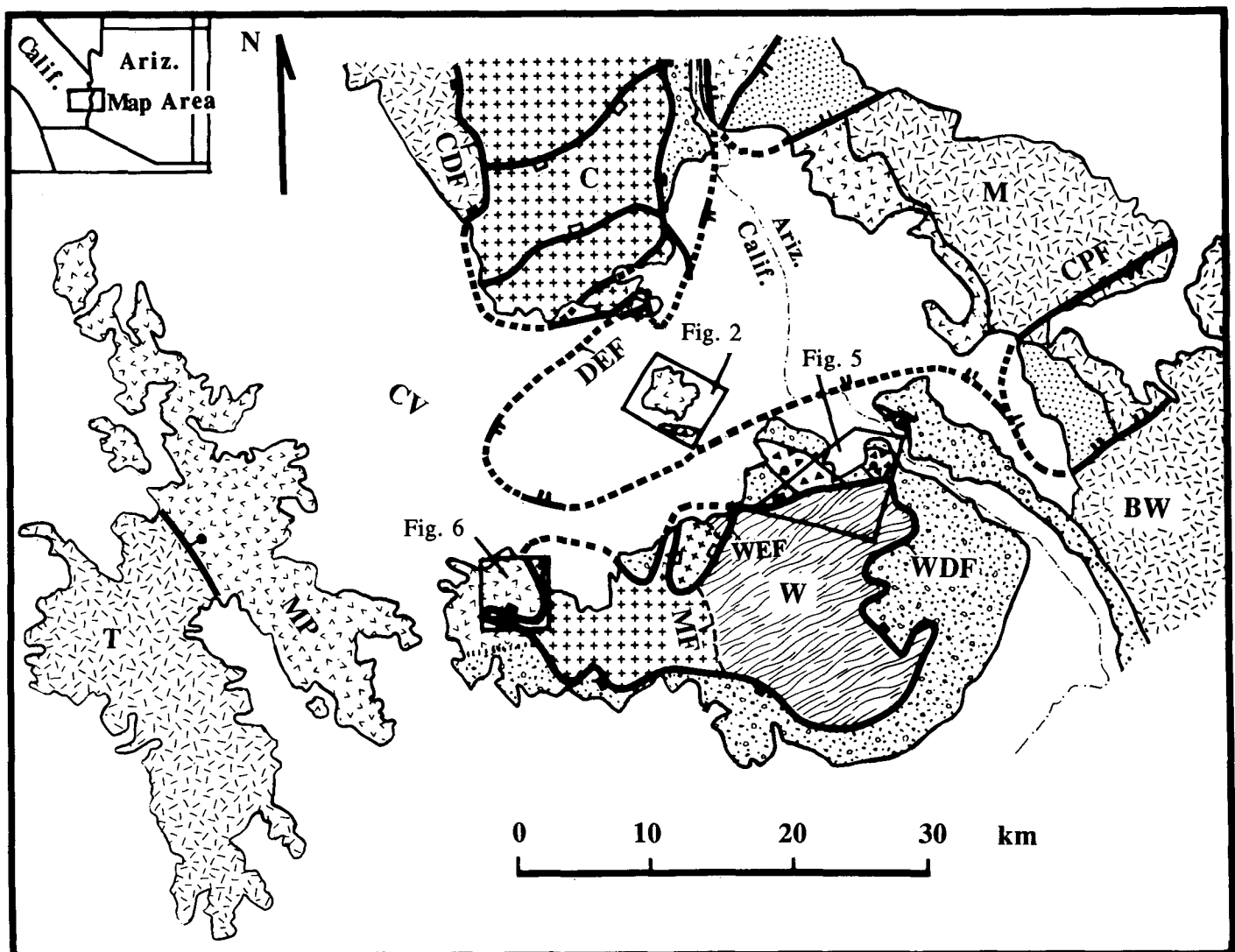
and basinal detachment faults have emphasized relationships between the detachment faults and lower-plate structural elements, for example, lower-plate, low-angle faults (John, 1987a), dikes (Spencer, 1985), and mylonitic foliation (Davis and Lister, 1988). An independent test of this interpretation is to examine the relationship between the detachment-fault geometry and the pattern of bedding attitudes in the upper plate to differentiate the above models. This paper presents the findings of our study in a classic, well-exposed, detachment-fault terrane: the mid-Tertiary Whipple detachment fault system in the northern Whipple Mountains, California. Geometric relations between the Whipple detachment fault and upper-plate structures and strata are used to construct the evolving three-dimensional geometry of the Whipple detach-

ment fault in both time and space. Implications of our findings for the correlation of regional structures and stratigraphy are also discussed.

REGIONAL SETTING

The study area is located in the central part of the Colorado River extensional corridor, which extends from southern Nevada to southeastern California and western Arizona (Fig. 1; Davis and others, 1980, 1982; Reynolds and Spencer, 1985; Howard and John, 1987; Davis and Lister, 1988; Spencer and Reynolds, 1990). The corridor itself is part of the greater sinuous belt of Cordilleran core complexes (Coney, 1980).

The Whipple and Chemehuevi detachment faults, exposed in the Whipple and Chemehuevi Mountains, respectively, are the major Tertiary



structures in, and adjacent to, the study area (Fig. 1). Both have large displacements (>8 km along the Chemehuevi fault, Miller and John, 1988; and ~40 km along the Whipple fault system, Davis and Lister, 1988) and exhibit an overall domal geometry. The domes are superposed by minor northeast-trending antiforms and synforms with wavelength of 6–8 km and amplitudes of 200–400 m.

In the Whipple Mountains, the upper-plate rocks of the Whipple fault consist of Precambrian granitic gneiss, Cretaceous plutons, and Tertiary sedimentary and volcanic rocks (Fig. 1; Davis and others, 1980, 1982; Davis and Lister, 1988). The lower-plate rocks consist of a heterogeneous assemblage of interlayered Precambrian metamorphic and igneous rocks, Mesozoic igneous rocks, and voluminous Tertiary dikes.

The lower plate is separated into two structural domains by the gradational, southwest-dipping Whipple mylonitic front (Fig. 1; Davis and others, 1980; Davis, 1988). The domain below the front contains a gently dipping Tertiary mylonitic fabric, whereas the domain above the front is nonmylonitic. The lower-plate mylonitic foliation is subparallel to the domal Whipple detachment fault (Davis, 1988).

The lower plate of the Chemehuevi fault consists of Precambrian crystalline rocks lithologically similar to those in the Whipple Mountains and a suite of Jurassic(?)–Cretaceous plutons (Fig. 1; John, 1987a, 1987b; John and Mukasa, 1990; John and Wooden, 1990), all of which are variably mylonitized in the northeastern and eastern part of the range. The mylonitic rocks are intruded by Upper Cretaceous plutons which

bear no mylonitic fabric, suggesting that mylonitization is of pre-Tertiary age (John and Mukasa, 1990). In contrast, lower-plate mid-Tertiary dikes and plutons of the Whipple fault are variably mylonitized in the Whipple Mountains (Wright and others, 1986; Anderson and Cullers, 1990). The apparent difference in the age of mylonitization between the two ranges raises the question of how the Whipple and Chemehuevi detachment faults correlate (compare John, 1987a; Howard and John, 1987; Davis and Lister, 1988). One way to address this problem is to compare the stratigraphy and structures in the upper plates of the Whipple and Chemehuevi faults.

STRUCTURE AND STRATIGRAPHY OF THE STUDY AREAS

Three areas were mapped for this study: (1) the central Chemehuevi Valley, (2) the northeastern Whipple Mountains, and (3) the northwestern Whipple Mountains.

Central Chemehuevi Valley

The central Chemehuevi Valley is located between the Whipple and Chemehuevi Mountains (Figs. 1 and 2) above the synformal part of the Whipple and Chemehuevi detachment faults.

Stratigraphy. Pre-Quaternary rocks consist of Tertiary volcanic rocks that overlie Precambrian granitic gneiss (see Figs. 3 and 4 for detailed description). Two of the lithologic units are well dated in the region: the 18.4 ± 0.2 Ma Peach Springs Tuff (sanidine, $\text{Ar}^{40}/\text{Ar}^{39}$; Nielson and others, 1990) and the 8.1–5.5 Ma Bouse Formation (Metzger, 1968; Damon and others, 1978; Buisson, 1990).

Landslide. A landslide complex lies in the southern part of the area with a thickness of at least 50 m (Figs. 2 and 3). It consists of amphibolite dikes and mylonitic diorite rich in hornblende and biotite. The rocks are highly fractured and are different from the *in situ* Precambrian crystalline rocks in that the rocks of the landslide are rich in mafic minerals and have mylonitic foliation. These differences suggest that the landslide was not locally derived. The

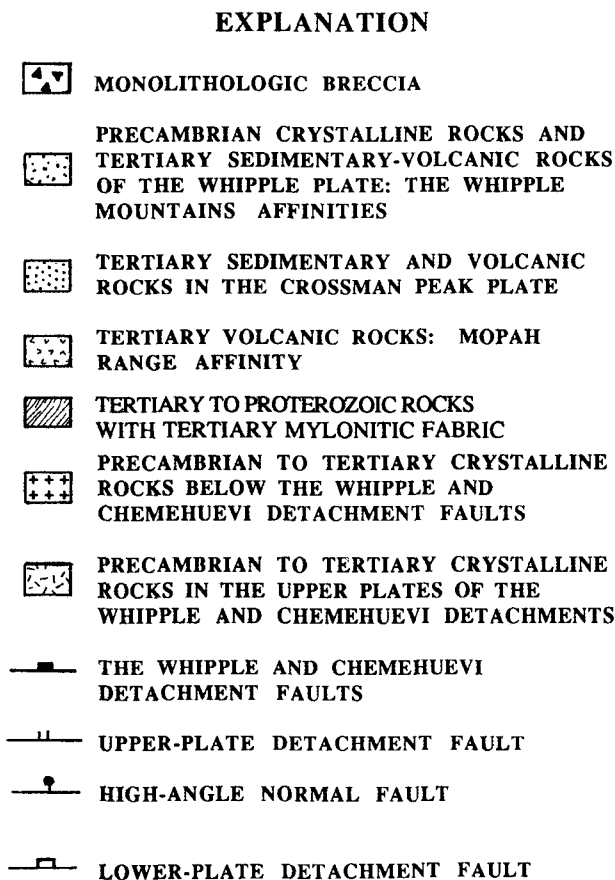


Figure 1. Simplified tectonic map of the Whipple Mountains and adjacent mountain ranges. Locations of Figures 2, 5, and 6. CDF, Chemehuevi detachment fault; CPF, Crossman Peak fault; DEF, Devils Elbow detachment fault; WDF, Whipple detachment fault; WEF, War Eagle detachment fault. BW, Bill Williams Mountains; C, Chemehuevi Mountains; CV, Chemehuevi Valley; M, Mohave Mountains; MF, mylonitic front; MP, Mopah Range; T, Turtle Mountains; W, Whipple Mountains.

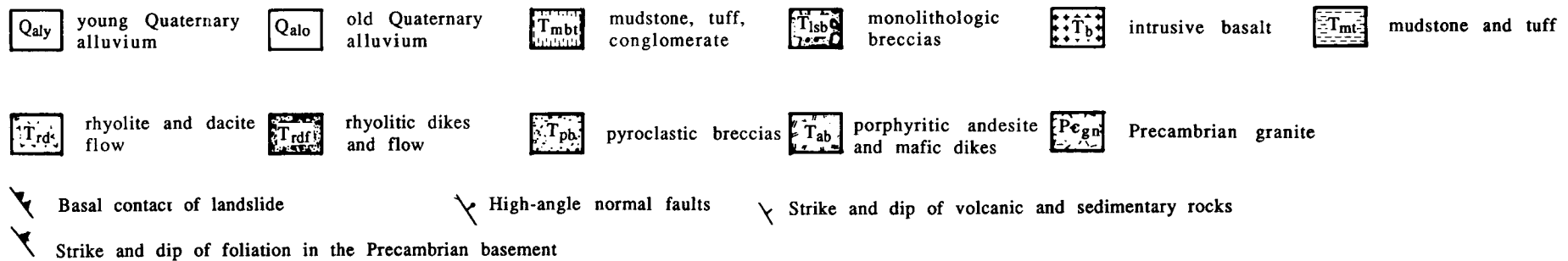
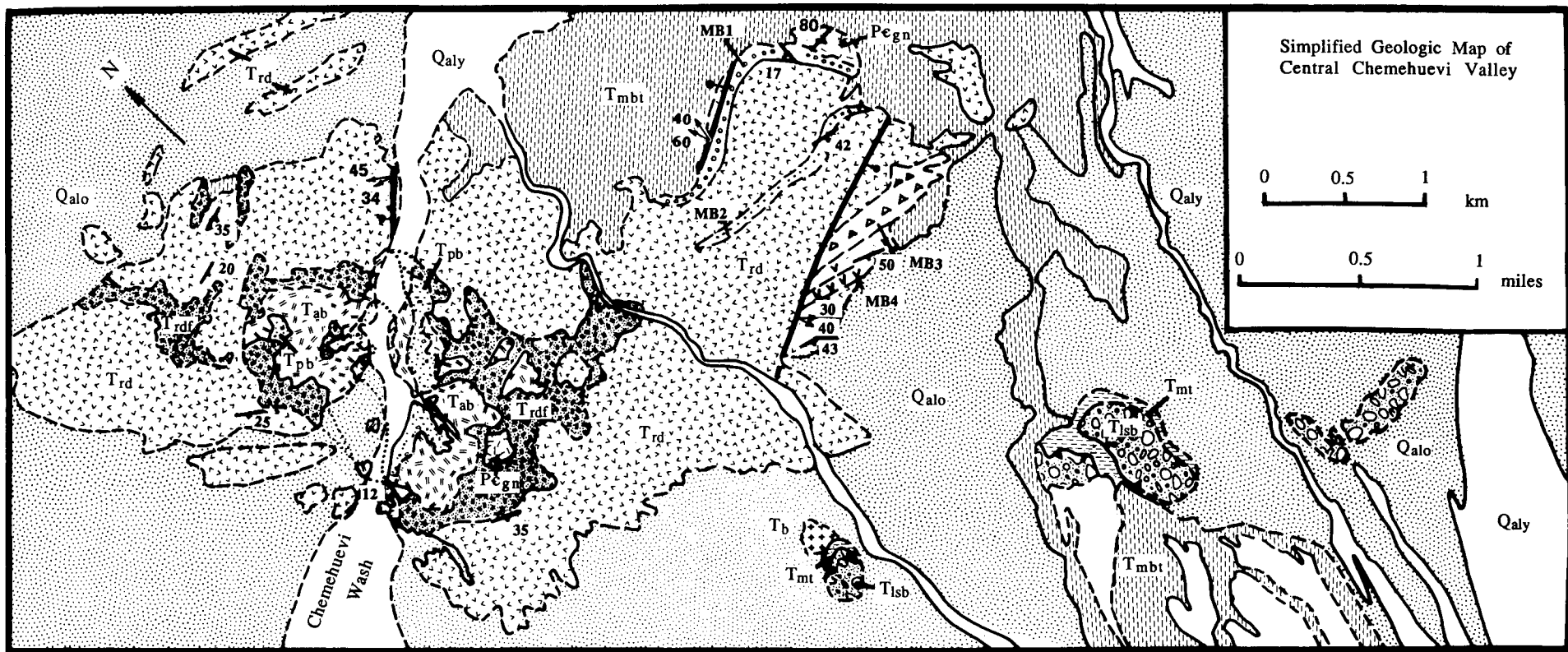


Figure 2. Geologic map of central Chemehuevi Valley. MB1, 2, 3, and 4 are layers of vitric tuffs used as marker beds within the volcanic sequence. See Figure 1 for location.

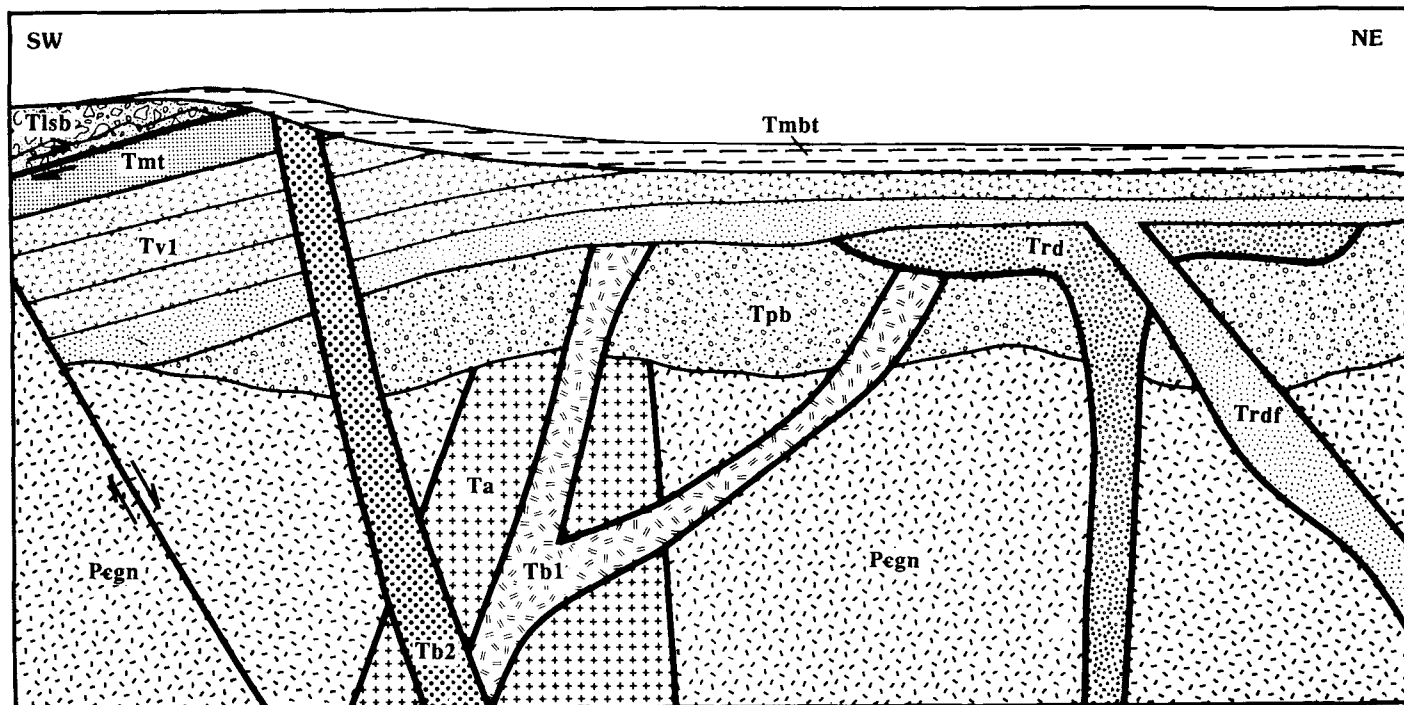


Figure 3. Schematic cross section through the central Chemehuevi Valley area. Cross-cutting relationships and stratigraphic units in ascending order: Ta, intrusive andesite; Tpb, pyroclastic breccias; Tb1, mafic dike swarms and small mafic hypabyssal plugs; Trd, rhyolitic dikes; Trdf, rhyolitic and dacite flows; Tv1, rhyolite flow including Peach Springs Tuff (Young and Brennan, 1974; Glazner and others, 1986; Nielson and others, 1990); Tmt, lenticular tuffaceous sandstone layers interbedded locally with the rhyolite sequence below the Peach Springs Tuff, lacustrine deposits interbedded with tuffs and tuffaceous sandstones; Tb2, intrusive basalt; Tlsb, a large landslide complex; and Tmbt, lacustrine deposits interbedded with tuffs, tuffaceous sandstone, and mudstone. PCgn, Precambrian basement consists of banded granitic gneiss.

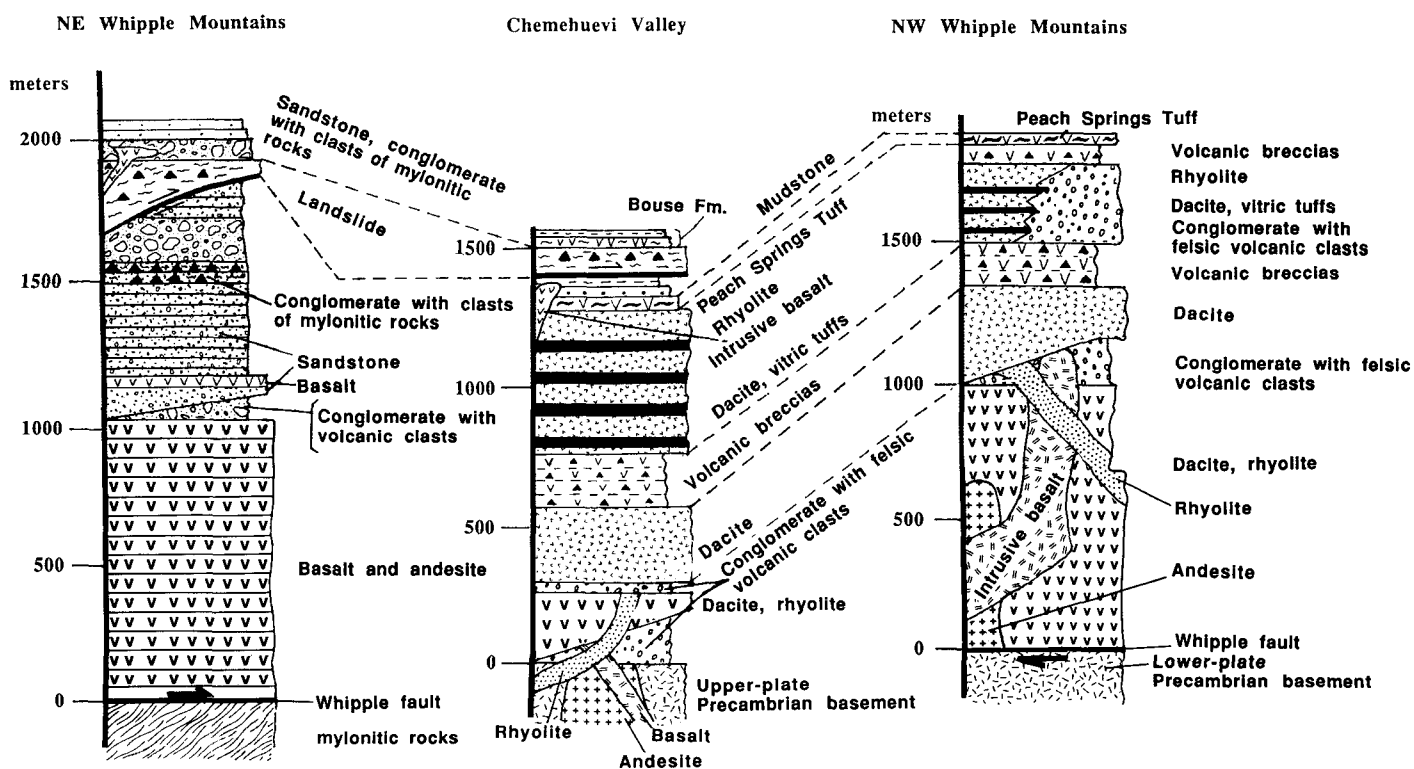


Figure 4. Generalized stratigraphy of central Chemehuevi Valley, northwestern Whipple Mountains, and northeastern Whipple Mountains. Note the similarity in the intrusive sequence and lithology between central Chemehuevi Valley and northwestern Whipple Mountains.

mafic rocks and the mylonitic diorite in the landslide are, however, similar to the Tertiary hornblende-biotite quartz diorite and hornblende gabbro in the lower plate of the Whipple fault in the north-central Whipple Mountains (Dunn, 1986; Anderson and Cullers, 1990).

The base of the landslide is subhorizontal and irregular. A zone about 3–5 m thick along the base of the landslide consists of both the hanging-wall (with respect to the base of the landslide) crystalline rocks and footwall sedimentary rocks. Above the mixed zone, the crystalline rocks are penetratively shattered (crackle breccias of Yarnold and Lombard, 1989). The landslide postdates the 18 Ma Peach Springs Tuff and predates the 8–5.5 Ma Bouse Formation (Fig. 3).

Structures. In the northern and central parts of the Chemehuevi Valley, the Tertiary strata strike from about due west to west-northwest (N70°–80°W) and dip gently (mostly less than 30°) to the south and south-southwest (Fig. 3). This strike is as much as 40°–50° more westerly than the regional structural trend (N40°W) in the upper plates of the Whipple and Chemehuevi faults (John, 1987b; Davis and others, 1980; Davis and Lister, 1988). Normal faults in the area strike east and east-northeast, much more easterly than the regional strike of normal faults (N45°W). Paleomagnetic data show that the Peach Springs Tuff in this area has rotated about $51^\circ \pm 10^\circ$ counterclockwise (Well and Hillhouse, 1989). This direction and magnitude of rotation are consistent with the rotation of Tertiary strata and faults from original northwest strikes to the present due west, west-northwest, and northeast strikes. The overall magnitude of extension in the area represented by the gently tilted strata is less than 15%.

Northeastern Whipple Mountains

The northeastern Whipple Mountains area is located on the northeastern limb of the Whipple dome (Figs. 1 and 5) and is separated from central Chemehuevi Valley by an alluviated wash about 5 km wide.

Stratigraphy. The lower plate of the Whip-

ple fault in the area consists of mylonitic Precambrian and Cretaceous granitic rocks (Dunn, 1986). A major landslide, the Copper Canyon landslide, is present in the upper plate (Fig. 5). Its base is used as a dividing horizon to separate the Tertiary section into lower and upper sequences (Fig. 4). The lower one consists of andesite-basalt flows and a thick clastic sequence of volcanic conglomerate and arkosic sandstone. The composition of the clastic sequences changes upward abruptly from primarily volcanic composition to predominantly clasts of mylonitic rocks, recording unroofing of the lower plate. The upper sequence includes the main body of the landslide and coarse clastic sediments deposited on it (Fig. 4).

Landslide. The Copper Canyon landslide extends across an area of at least 70 km² and it is as much as 1 km thick. It consists of Precambrian granitic gneiss and amphibolite dikes, Cretaceous (?) quartz monzonite (Anderson and Rowley, 1981), and five generations of dikes, all of which have been mylonitized except the youngest dikes. Two of the five groups of dikes and a plutonic complex have distinctive compositions: (1) mylonitic biotite tonalite; (2) andesite, dacite, and diabase; and (3) hornblende-biotite quartz diorite and hornblende gabbro pluton (Dunn, 1986). The temporal variation of the dike composition is similar to the lower-plate Chambers Well dike swarm in the north-central Whipple Mountains (G. A. Davis, 1985, personal commun.; G. A. Davis, *in* Anderson and Cullers, 1990). In Chambers Well rocks, both the mylonitic biotite tonalite dikes and nonmylonitic hornblende-biotite quartz diorite and hornblende gabbro dikes are abundant (Anderson and Cullers, 1990). This similarity in lithology suggests that the Copper Canyon landslide was derived from the lower plate in the north-central Whipple Mountains. The land-slides in the central Chemehuevi Valley and the northeastern Whipple Mountains may be correlative, because both share rock types similar to those in the north-central Whipple Mountains.

The basal contact of the landslide is from subhorizontal to gently southwest-dipping (Fig. 5b). The contact varies from sharp, planar, and

locally striated, to gradational and irregular. The mylonitic Precambrian gneiss and Cretaceous (?) quartz monzonite above the basal contact are intensely shattered. Breccia clast size ranges from a few tens of centimeters to a few meters in diameter within an ~10-m-thick zone above the basal contact. Coherent blocks are, however, commonly preserved a few meters above the basal breccia zone.

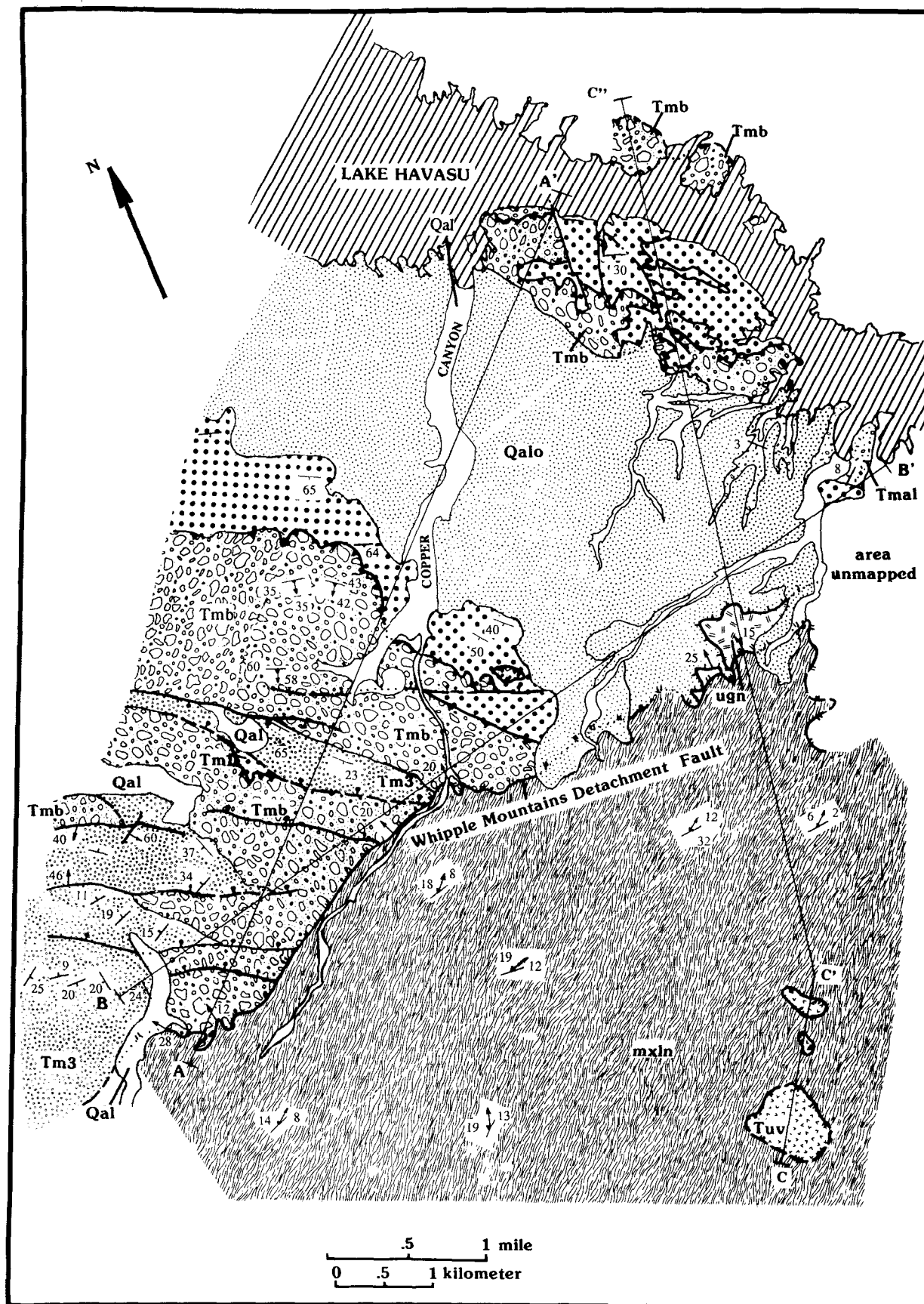
The landslide is cut by a series of northwest-striking normal faults that merge with, or are truncated by, the Whipple detachment fault (Fig. 5). By restoring post-landslide extension in this area, the minimum horizontal size of the landslide in the northeast direction is 9.5 km, which may be used also as its minimum displacement. This estimated displacement is similar to the 7 km displacement of the mylonitic front along the War Eagle fault in the lower plate (Davis and Lister, 1988), along which the landslide moved.

Structures. The Whipple detachment fault in the northeastern Whipple Mountains (Fig. 5) is curvilinear. It dips northward east of Copper Canyon and northwestward west of Copper Canyon. Such changes in dip direction define the geometry of the northeastern Whipple dome and are broadly concordant with attitudes of mylonitic foliation in the lower plate (Fig. 5a). The dominant direction of the stretching lineation on the mylonitic foliation, defined by plastically stretched quartz and cataclastically deformed feldspar, is N45°E–S45°W (Dunn, 1986).

Despite the fact that central Chemehuevi Valley and northeastern Whipple Mountains lie along the same regional structural trend, the magnitude of upper-plate extension is about 50% in the northeastern Whipple Mountains, much greater than the 15% extension in central Chemehuevi Valley. The difference in magnitude of extension suggests that a fault may lie between the two areas; this is supported by the lateral variation in stratigraphy between the areas (Fig. 4).

Beds directly below the base of the landslide dip gently (Fig. 5b, section A–A'). They steepen downsection to 60°–70°, consistent with a

Figure 5a. Geologic map of northeastern Whipple Mountains, see Figure 1 for location. Stratigraphic units from older to younger: ugn, upper-plate Precambrian granitic gneiss; mxln, lower-plate Proterozoic to Tertiary crystalline rocks with Tertiary mylonitic fabric; Tm1, pre-landslide sequence; Tmb, landslide complex; Tm3, post-landslide sequence; Tmal, Tertiary alluvium; Qal, old Quaternary alluvium; Qal, Quaternary alluvium. Note that the attitude of the Whipple Mountains detachment fault is broadly concordant with mylonitic foliation in the lower plate. Upper-plate, high-angle, normal faults cut the landslide. Note also that the strike of the post-landslide strata in the western corner of the area is subparallel to the local strike of the Whipple detachment fault.



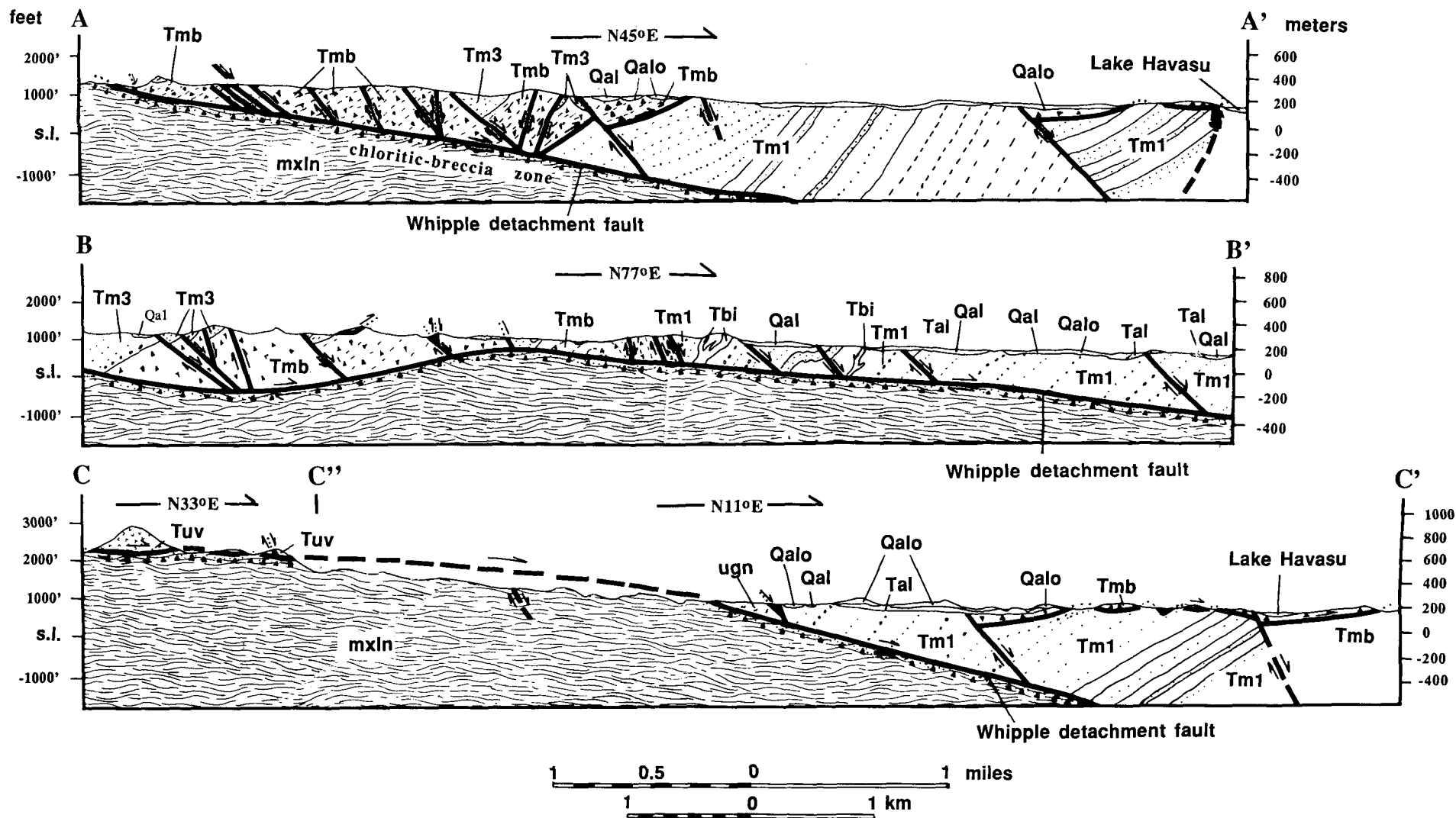


Figure 5b. Detailed cross sections through northeastern Whipple Mountains. Some stratigraphic units are omitted from the map. The Whipple detachment fault is broadly warped about northeast-trending axes as shown in cross section B-B'.

growth-fault origin. Post-landslide strata dip between 10° and 40° southwestward, about 30° – 40° more shallow than the lowest pre-landslide strata. Their strikes vary from northwest in the eastern part of the area to east and northeast in the western part of the area. Such a change in strike of the post-landslide, upper-plate strata coincides spatially with the change in the strike of the Whipple detachment fault and mylonitic foliation in the lower plate (Fig. 5), suggesting that all three features were concordantly warped.

Northwestern Whipple Mountains

The northwestern Whipple Mountains area is on the west-dipping, northwestern limb of the Whipple dome (Figs. 1 and 6).

Stratigraphy. The lower plate of the Whipple detachment fault comprises nonmylonitic Precambrian granitic gneiss and Tertiary basalt and dacite dikes. The upper-plate strata of the Whipple fault consist of, in ascending order (Fig. 4): (1) rhyolite and dacite interbedded with pyroclastic breccia and tuffaceous sandstone; (2) intrusive andesite, dacite, and basalt; and (3) shallow-dipping rhyolite interbedded with vitric tuff and basalt flows. No pre-Tertiary rocks are known in the upper plate in this area. These upper-plate units are similar to upper-plate Miocene strata described by Hazlett (1986, 1990) in the Mopah Range to the west (Fig. 1). There the lower part of the section consists of basalt-andesite-rhyolite flows, felsic dikes and plugs, and pyroclastic breccia with little sedimentary rocks, and the upper part of the section consists of basalt-andesite flows. The stratigraphy in the northwestern Whipple Mountains is also similar to that in central Chemehuevi Valley in that (1) both areas lack sedimentary rocks, (2) both areas are extensively intruded by andesite and basalt that are in turn intruded by rhyolite-dacite dikes, and (3) the upper part of the rhyolite-dacite flows are characteristically associated with distinctively similar vitric tuffs. The rhyolite-dacite flows in the northwestern Whipple Mountains are interlayered with extrusive basalt and andesite to the south (Stewart, 1988; Carr and others, 1980), suggesting that felsic and mafic volcanism occurred synchronously.

In the west-central Mohave Mountains 30 km to the northeast, Nielson and Beratan (1990) described a sequence of Tertiary volcanic rocks that resemble the lithologic succession of the Mopah Range, northwestern Whipple Mountains, and eastern Chemehuevi Valley units. On the basis of this correlation, we conclude that the Tertiary volcanic rocks in these three areas are of Mopah Range affinity (Fig. 1).

Structures. Two major low-angle faults sepa-

rate Tertiary rocks from Precambrian basement rocks in the study area: (1) a southwest-dipping fault in the eastern part of the area and (2) an antiformal northeast- and southwest-dipping fault in the southwestern part of the area (Fig. 6). The northeastern fault can be traced southward to connect with the main trace of the Whipple detachment fault mapped by Stewart (1988). The southwestern fault is not connected with the southwest-dipping fault in the study area. The two faults, however, are probably the same fault connected at depth because they share a similar basement lithology, highly altered granitic gneiss (Fig. 6a). This interpretation implies that the Whipple detachment fault is warped also into short-wavelength, northwest-trending (extension-perpendicular) antiforms and synforms.

DISCUSSION

Devils Elbow–Chemehuevi Valley Detachment Fault

Pre-Peach Springs Tuff strata are similar in the northwestern Whipple Mountains, central Chemehuevi Valley, and central Mojave Mountains. The detailed stratigraphy and the sequence of the intrusive events match. In contrast, the stratigraphies of the northeastern Whipple Mountains and the eastern Chemehuevi Valley differ significantly (Fig. 4). The thick sequence of clastic sedimentary rocks is absent in central Chemehuevi Valley. Conversely, the extensive intrusions of andesite, basalt, and rhyolite are not found in the northeastern Whipple Mountains area. The similarities and differences in the Tertiary stratigraphy among the three mapped areas may be explained by changes in sedimentary and volcanic facies. This interpretation requires a series of compositionally identical intrusive centers lying along Chemehuevi Valley in the northeast direction, because felsic volcanic flows commonly travel short distances due to their high viscosity.

Alternatively, the abrupt change in stratigraphy along the structural trend between the northeastern Whipple Mountains and central Chemehuevi Valley and the similarity of the Tertiary stratigraphy between central Chemehuevi Valley and the northwestern Whipple Mountains could be caused by a large top-to-the-east offset along a shallowly dipping, northeast-striking fault located along the southeastern edge of Chemehuevi Valley (Fig. 1). We favor this interpretation for the following reasons: (1) the magnitude of extension within upper-plate rocks changes dramatically between the northeastern Whipple Mountains and central Chemehuevi Valley, and (2) a regional detachment fault, the Devils Elbow fault, has been

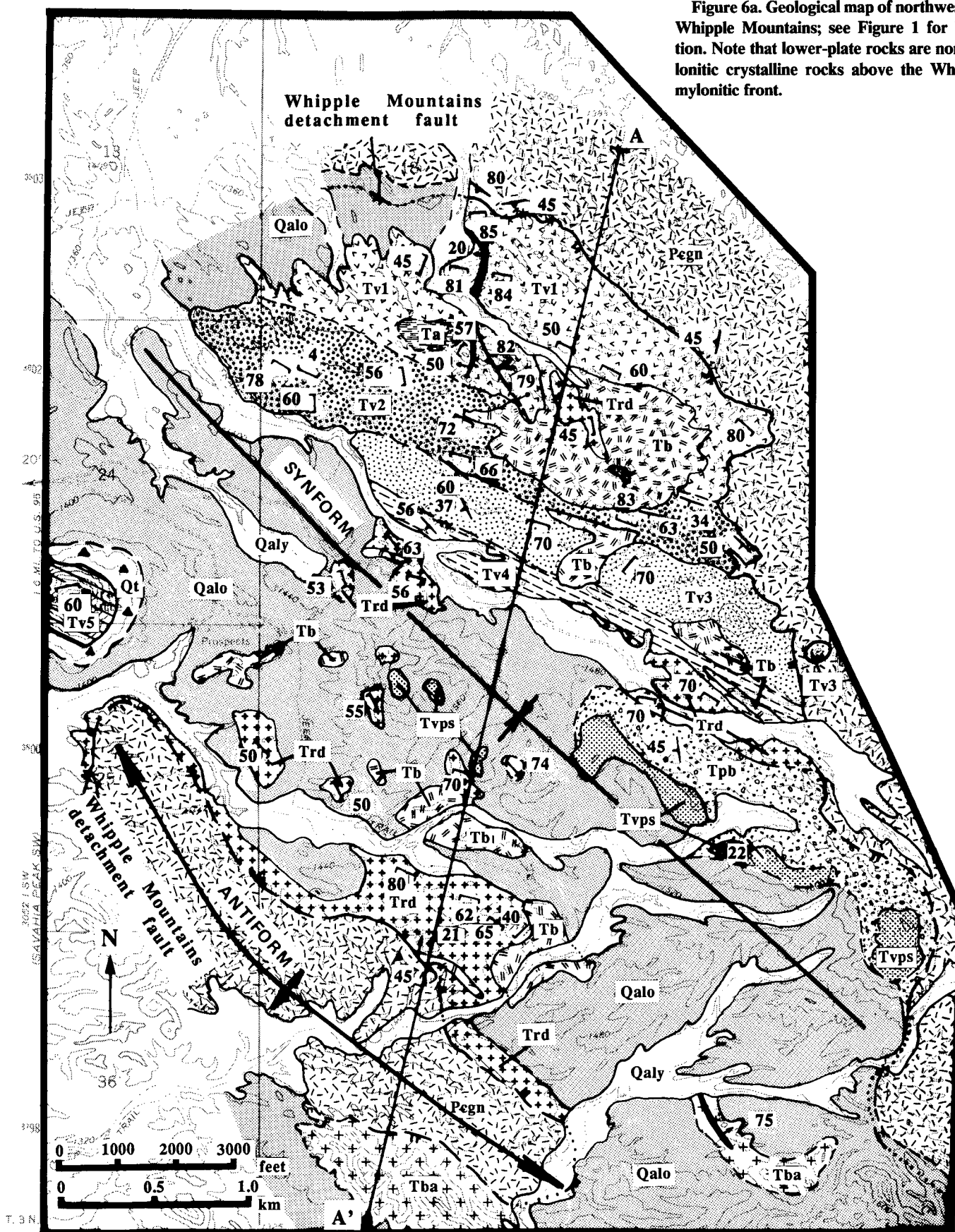
mapped in the upper plate of the Chemehuevi fault by John (1987a) north of central Chemehuevi Valley. Because the Devils Elbow fault dips gently southward and is not present in the northeastern Whipple Mountains, it must lie underneath central Chemehuevi Valley and may correlate with the proposed fault (Fig. 1). This interpretation implies that the Devils Elbow fault, with undulatory geometry similar to the Whipple and Chemehuevi faults, is a synform below the Chemehuevi Valley. The stratigraphic correlation between the northwestern Whipple Mountains and central Chemehuevi Valley suggests a 15-km displacement along the proposed fault. Therefore, the 40-km extension along the Whipple–Chemehuevi detachment fault system (Davis and Lister, 1988; Howard and John, 1987) was distributed as 15 km along the Devils Elbow fault and 25 km along the Whipple–Chemehuevi fault.

Complex Rotational History of the Upper-Plate Strata

The predominant southwestern dip of upper-plate strata in the Whipple Mountains is due to southwestward tilting along northeast-dipping normal faults (Davis, 1986). The general strike of the Tertiary strata in central Chemehuevi Valley is at least 20° – 40° more westerly than that of upper-plate normal faults ($N40^{\circ} \pm 10^{\circ}W$) and the tilted Tertiary beds in the eastern Whipple Mountains (Davis and others, 1980). In the northeastern Whipple Mountains, post-landslide strata strike north to northeast, a direction considerably east of the regional structural trend. These abnormal strikes of Tertiary strata may be related to warping of the Whipple and Chemehuevi detachment faults along an extension-parallel axis after significant upper-plate extension. A rotational history in the northeastern Whipple Mountains is proposed as follows: (1) the pre-landslide strata were tilted about 40° – 50° along northwest-striking normal faults as indicated by the angle between the dip of the base of the landslide and the dip of the lowermost part of the strata beneath it (Fig. 5b), (2) the base of the landslide and strata above and below it were further tilted about 20° to 30° along younger or reactivated northeast-dipping normal faults, and (3) all of the upper-plate strata were tilted about 20° northwestward due to formation of the northeast-trending Whipple dome/antiform.

The proposed rotational history is illustrated stereographically in Figure 7. Assuming the attitude of pre-landslide strata was $N45^{\circ}W$ $60^{\circ}SW$ before warping of the detachment fault, and that northwestward tilting by warping was achieved by rotation of 20° about a horizontal axis trending $N45^{\circ}E$ parallel to extension, the final atti-

Figure 6a. Geological map of northwestern Whipple Mountains; see Figure 1 for location. Note that lower-plate rocks are nonmylonitic crystalline rocks above the Whipple mylonitic front.



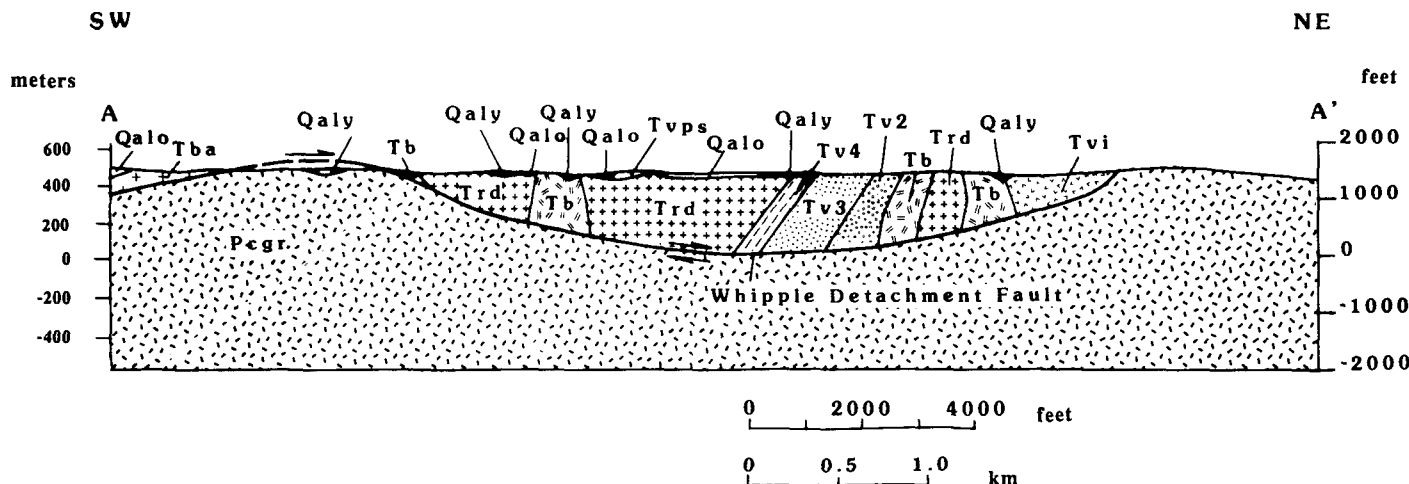


Figure 6b. Geologic cross section through line A-A'. The Whipple detachment fault is warped and pre-Peach Springs Tuff, upper-plate strata are tilted more steeply than the Peach Springs Tuff. Patterns and symbols are the same as those in Figure 6a.

EXPLANATION FOR FIGURE 6

	Qaly	Young Quaternary alluvium
	Qalo	Old Quaternary alluvium
	Qt	Quaternary talus
	Tvps	Tertiary Peach Spring Tuff
	Tba	Tertiary andesite and basalt flows
	Tv5	Tertiary rhyolite and dacite flows
	Trd	Tertiary rhyolite dikes
	Tb	Tertiary basaltic flows
	Tpb	Tertiary Pyroclastic breccia
	Tv4	Tertiary tuff and tuffaceous sandstone
	Tv3	Tertiary dacite flows
	Tv2	Tertiary latite flows
	Ta	Tertiary intrusive andesite
	Tv1	Tertiary rhyolite flows
	Pegn	Precambrian gneisses
		Detachment fault
		High-angle normal fault
		Volcanic flow banding
		Foliation
		Dikes

tude of the strata becomes either N54°W 60°SW or N36°W 60°SW, depending on the direction of tilting caused by warping (see points A, A', and A" in Fig. 7). The result of this rotation shows that the original strike of the tilted beds changes only about 9°. This result can also be applied to rotation of high-angle (>60°) faults due to the same gentle warping; that is, the strike of the high-angle faults would not change significantly due to extension-parallel warping. A similar exercise can be performed for the rotation of the post-landslide strata. Assuming that their attitude before warping is N45°W 30°SW and that the strata were later rotated 20° due to warping about an axis trending N45°E, the final attitude of the strata is either N76°W 35°SW or N14°W 35°SW, depending on the direction of warping (see points B, B', and B" in Fig. 7). This shows that the strike of shallow-dipping strata would change their strike significantly (~30°), which is consistent with the wide range of variation in strike for the post-landslide strata in the northeastern Whipple Mountains and central Chemehuevi Valley. The effect of late warping on even more shallow-dipping strata is also shown (see points C and D in Fig. 7).

The influence of warping on the attitude of both upper-plate faults and strata are shown by a series of block diagrams in Figure 8 with special reference to the Whipple-Chemehuevi Mountains region. The Chambers Well dike swarm (Davis and others, 1980, 1982; Davis, 1988) is used as an offset marker along the Whipple detachment fault system. The Whipple fault is shown in Figure 8 to be correlative with both the Sacramento fault (Davis and Lister,

1988), a major mid-Tertiary detachment fault exposed in the Sacramento Mountains northwest of the Chemehuevi Mountains (McClelland, 1982, 1984; Simpson and others, 1991), and the Chemehuevi fault (John, 1987a; Howard and John, 1987; Fig. 8a). Regional low-angle normal faults (detachment faults) were initiated as broadly listric to planar surfaces (Fig. 8a). Displacement along detachment faults and upper-plate normal faults resulted in tilting of the upper-plate strata in the direction opposite to the regional dip direction of the faults (Fig. 8b). Isostatically induced antiformal warping along a northwest-trending axis perpendicular to the extension direction may also have occurred (Spencer, 1984) and caused more southwestward rotation of the upper-plate strata west of the warping axis and a slightly northeastward rotation for the upper-plate strata east of the warping axis (not shown in Fig. 8). Later warping of detachment faults along an axis parallel to the extension direction deflected strikes of the upper-plate faults and strata (Fig. 8c). The strike of beds directly south of the Chemehuevi dome rotated counterclockwise, whereas the strike of strata directly north of the Whipple dome rotated clockwise (Fig. 8c). The predicted bedding attitudes and fault pattern are broadly compatible with those observed in the northern Whipple Mountains and central Chemehuevi Valley.

Implications of the Landslide

The landslide in both the central Chemehuevi Valley and northeastern Whipple Mountains appears to have originated in the north-central

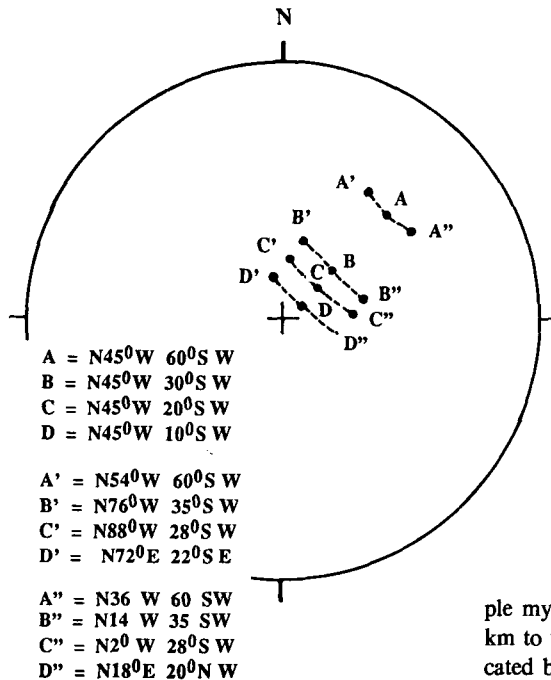


Figure 7. Stereographic projections showing paths of multiple rotation of upper-plate strata. The initial attitudes of the strata are N45°W 10°SW, N45°W 20°W, N45°W 30°SW, and N45°W 60°SW as represented by points A, B, C, and D, respectively. The rotational axis is northeast trending, and the magnitude of rotation about this axis is 20°. The consequence of this rotation of points A, B, C, and D are shown as A', B', C', D', A'', B'', C'', and D''. See text for discussion.

Whipple Mountains where a major low-angle fault, the War Eagle "detachment" fault, was mapped (Fig. 2; Davis and Lister, 1988; Davis, 1988). The gently dipping fault is scoop shaped, and its trace defines a broad U-shaped valley. The War Eagle fault offsets the Tertiary Whip-

ple mylonitic front in the lower plate about 7 km to the northeast. The fault is, in turn, truncated by the Whipple detachment fault. These relations indicate that this structure is coeval with movement along the Whipple detachment fault system. The hanging-wall block of the War Eagle fault consists of Precambrian gneiss, a large quartz monzonite pluton, seven types of mafic and felsic dikes, and a hornblende-biotite quartz diorite pluton; all of the units are mylonitized except the latest three types of dikes (G. A.

Davis, 1985, personal commun.). This same assemblage of rocks is mostly present in the landslide of the northeastern Whipple Mountains and is partially present in the landslide of central Chemehuevi Valley, suggesting that the War Eagle fault is equivalent to the basal contact of the landslide, and that the War Eagle allochthon of Davis (1988) is the upper reaches of the landslide in the northeastern Whipple Mountains and central Chemehuevi Valley.

The emplacement of the landslide postdates the 18 Ma Peach Springs Tuff and predates the end of detachment faulting and may signal the episode of doming of the Whipple detachment fault. The landslide occurred after significant upper-plate extension as indicated by the discordant relationship between the base of the landslide and the steeply tilted strata beneath it and by the fact that rocks with Tertiary mylonitic fabrics were at the Earth's surface (Fig. 5b).

A rock-avalanche complex mapped by Miller and John (1988) in the southeastern part of the Chemehuevi Mountains occurred after the 18 Ma Peach Springs Tuff was deposited but prior to the last motion along the Chemehuevi detachment fault. This broadly similar age interval to that in the northeastern Whipple Mountains and central Chemehuevi Valley area suggests that the uplift of both the Chemehuevi and Whipple domes/antiforms may have been synchronous.

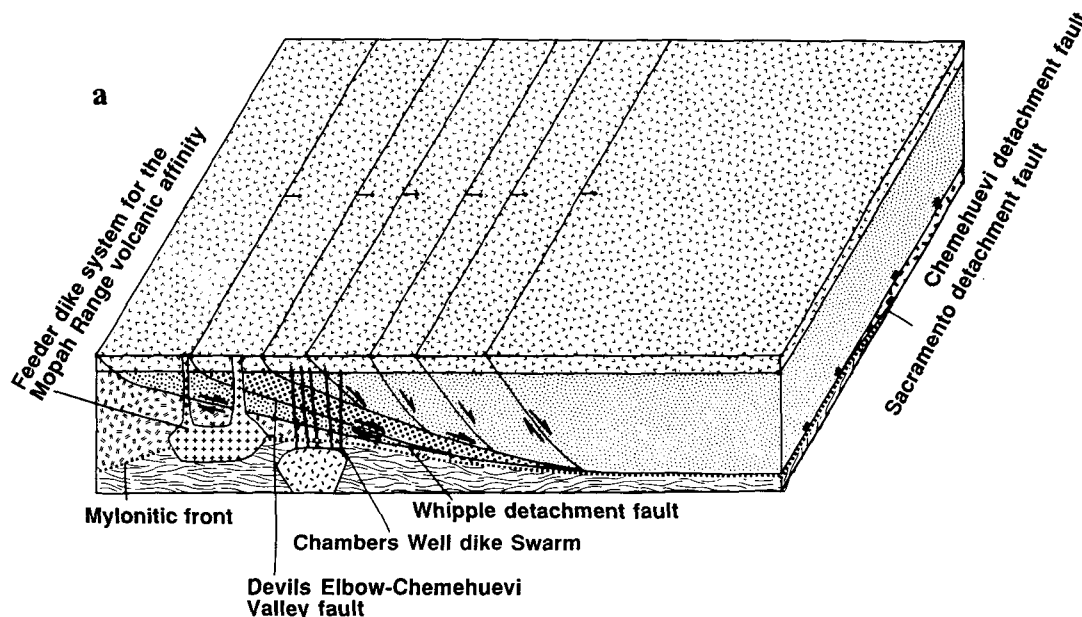


Figure 8. Effect of warping of detachment faults on the attitudes of upper-plate strata and faults with specific reference to the Whipple-Chemehuevi Mountains region. The Chambers Well dike swarm and the feeder dike system for the felsic volcanic strata in the central Chemehuevi Valley are used to show the distribution of upper-plate extension. The presence of plutons beneath the Whipple Mountains implies that the brittle-plastic transition zone may have not been subhorizontal during detachment faulting. (a) Regional low-angle normal faults, that is, the detachment faults initiated as planar surfaces.

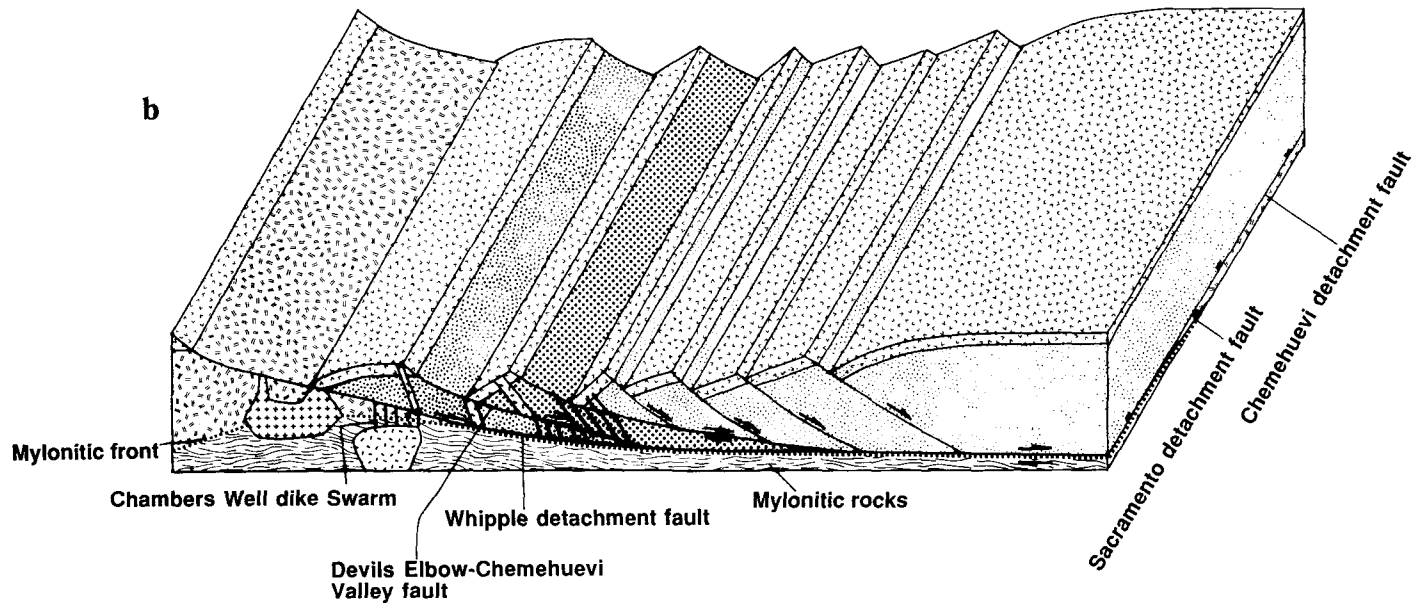


Figure 8b. Displacement along the detachment faults and the high-angle normal faults resulted in rotation of the upper-plate strata in the direction opposite to the dip direction of the faults.

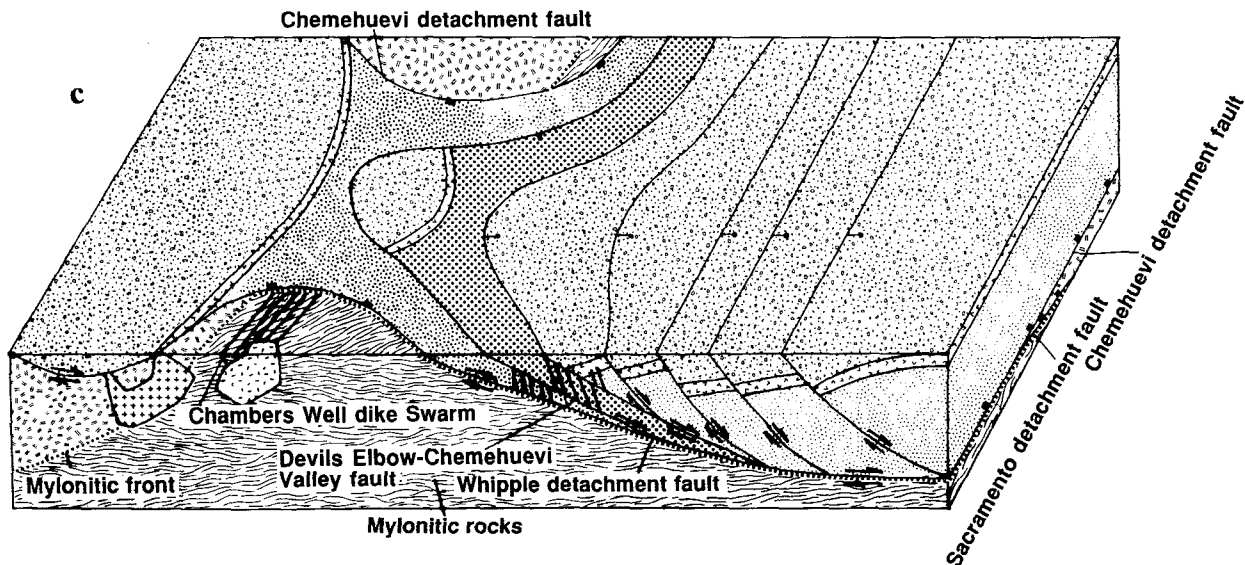


Figure 8c. Warping of detachment faults caused deflection of strikes of the upper-plate faults and strata. During doming of detachment faults, the strike of beds immediately south of the Chemehuevi antiform rotated counterclockwise, whereas the strike of the strata immediately north of the Whipple antiform rotated clockwise. The rational direction for the strike of the faults is opposite to that of the strata.

Whipple Detachment Fault Was Active at a Low Angle

Two critical field relationships observed in the study area suggest that the Whipple detachment fault was active at a low angle, $<30^\circ$: (1) the low-angle relationship between the shallow-dipping Whipple detachment fault and

the subhorizontal base of the landslide in the northeastern Whipple Mountains (Fig. 5b) and (2) the crosscutting relationships among upper-plate, high-angle normal faults that cut the landslide but terminate at the Whipple detachment fault (Fig. 5b). Thus, although the rolling-hinge models of Hamilton (1988), Wernicke and Axen (1988), and Buck (1988) clearly explain

evolution of some detachment fault systems (for example, Bartley and others, 1990), they are not consistent with our field observations in the Whipple Mountains. Movement along the low-angle Whipple detachment fault implies that the effective coefficient of friction along the Whipple fault was much lower than that determined by the experimental rock mechanics, because

the maximum compressive stress, if vertical (compare with Yin, 1989a), was at a high angle ($\sim 60^\circ$ – 70°) to the fault surface (Zoback and others, 1987).

STRUCTURAL AND STRATIGRAPHIC EVOLUTION

On the basis of geologic relations discussed above, the geologic history of Chemehuevi Valley and the northern Whipple Mountains is interpreted as follows (Fig. 9):

1. Initiation of the Whipple, Chemehuevi, Sacramento, and Devils Elbow faults was followed by the development of upper-plate, high-angle, normal faults. A dacite-rhyolite sequence and an andesite-basalt sequence were deposited simultaneously during the early stage of extension (Fig. 9a). The two sequences were erupted from different extrusive centers, but they interfinger in the west-central Whipple Mountains (Stewart, 1988).

2. The dacite-rhyolite and the andesite-basalt sequences were extended by slip along both detachment faults and upper-plate, normal faults (Fig. 9b). The Peach Springs Tuff was deposited on the top of the tilted volcanic sequences (not shown in Fig. 9).

3. The Whipple and Chemehuevi domes started to rise synchronously, and the relatively planar Devils Elbow, Whipple, and Chemehuevi faults were all broadly and concordantly warped into undulatory surfaces. Erosional denudation related to simultaneous extension resulted in exposing lower-plate mylonitic rocks, which were in turn eroded, transported, and deposited in basins in the upper plate as seen in the clastic sequence of the northeastern Whipple Mountains (Fig. 9c). As doming continued, a steeply dipping, north- to northeast-facing slope was developed in the northern Whipple Mountains and was apparently the source of the landslide that slid across the gently dipping Whipple fault into the central Chemehuevi Valley and northeastern Whipple Mountains (Fig. 9d).

4. Upper-plate, high-angle, normal faults cut and tilted the landslide. Post-landslide strata were deposited and then tilted along the upper-plate, normal faults. Further doming caused northeastward tilting of post-landslide strata in the northeastern Whipple Mountains and rotation of strike of Tertiary strata in central Chemehuevi Valley. The Bouse Formation was deposited over the trace of the landslide (not shown in Fig. 9).

CONCLUSIONS

1. The low-angle relation between the Whipple detachment fault and the subhorizontal

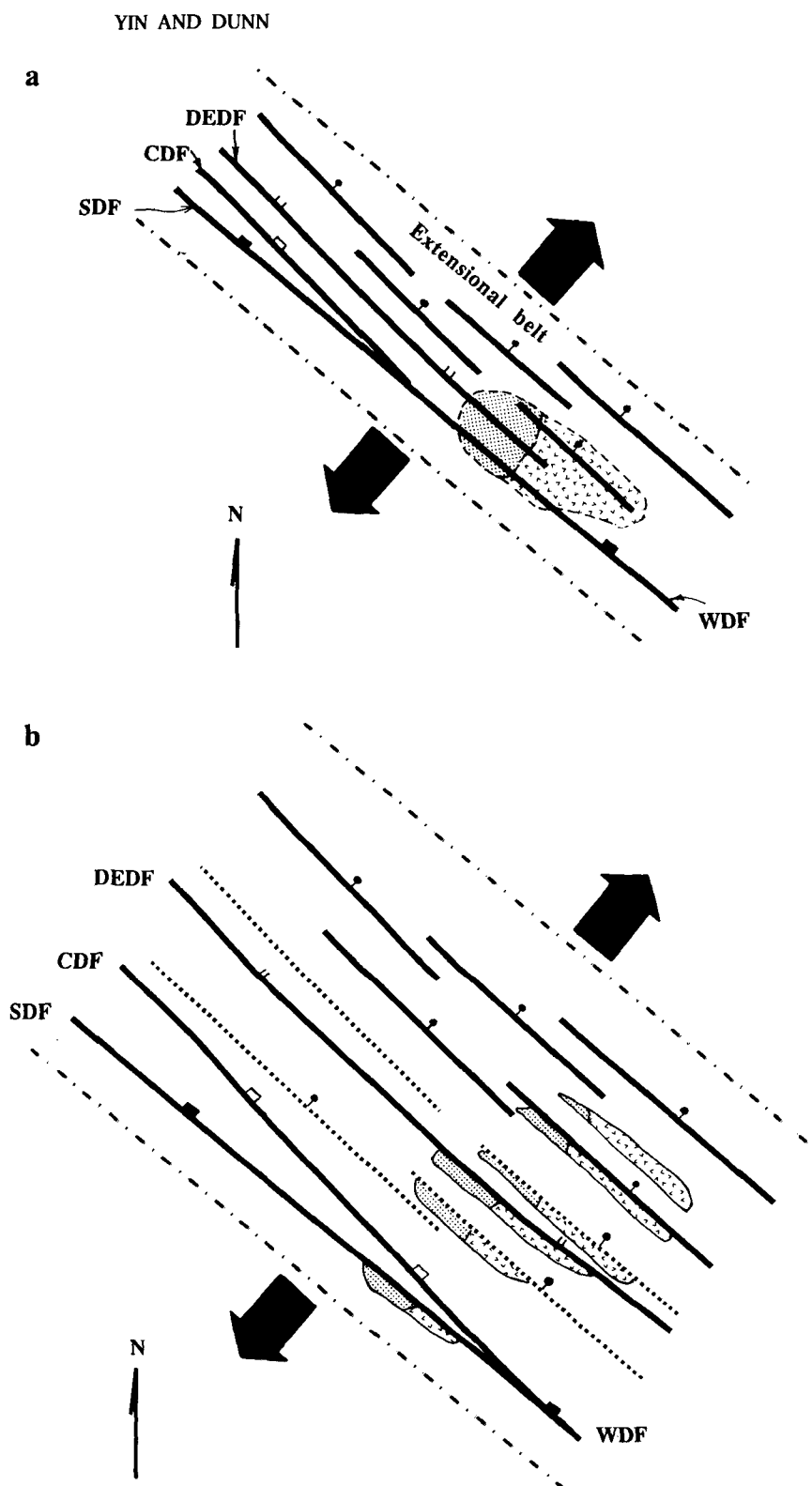












Figure 9. Kinematic models for development of the Whipple Mountains detachment fault system in northern Whipple Mountains and eastern Chemehuevi Valley.

(a) Initiation of the Whipple, Sacramento, Chemehuevi, and Devils Elbow faults followed by development of high-angle normal faults in their upper plate. Deposition of dacite-rhyolite and andesite-basalt sequences.

(b) Extension of dacite-rhyolite and andesite-basalt sequences by both detachment faults and upper-plate, high-angle normal faults.

EXPLANATION
FOR FIGURE 9

-  Whipple and Sacramento detachment faults
-  Chemehuevi detachment fault
-  Devils Elbow detachment fault
-  Upper-plate high-angle normal fault
-  Andesite-basalt flow
-  Dacite-rhyolite flow
-  Lower-plate crystalline rocks
-  Mylonitic gneisses
-  Landslide
-  Tertiary sedimentary sequence with clasts of Mylonitic gneisses

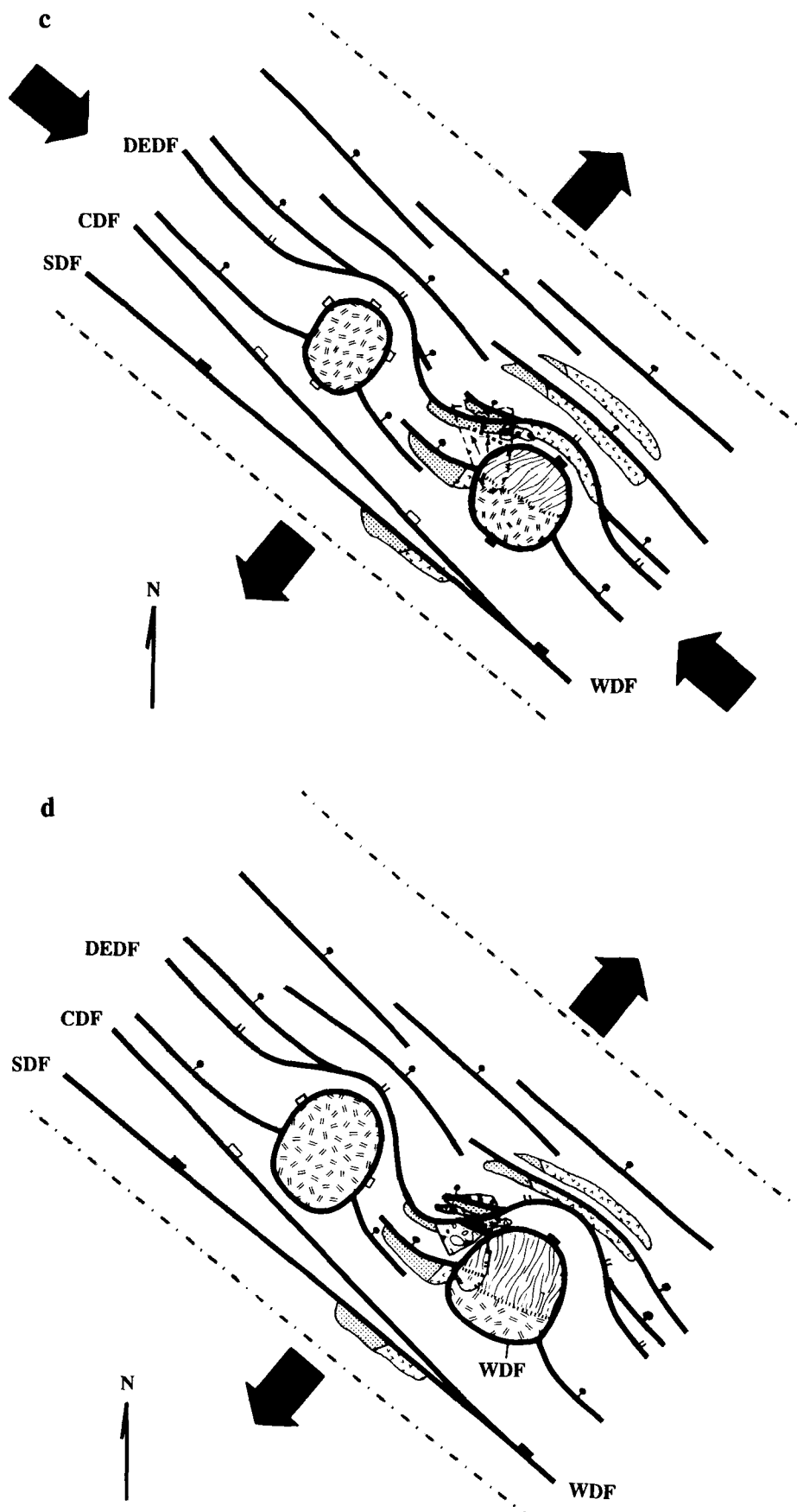


Figure 9. (Continued). (c) Development of Whipple and Chemehuevi domes and warping of Devils Elbow fault. Coeval extension along detachment and upper-plate normal faults resulted in exposing the lower-plate mylonitic rocks. Deposition of clastic sequence with mylonitic clasts in the northeastern Whipple Mountains. Emplacement of landslide.

(d) Continuation of doming and upper-plate extension. Upper-plate, high-angle, normal faults cut and locally tilted the landslide.

base of a syn-extension landslide demonstrates that the Whipple detachment fault was active at low angles, $<30^\circ$. This implies that the effective coefficient of friction along the Whipple fault was much lower than that determined from experimental rock mechanics.

2. The Whipple detachment fault was relatively planar at the time of its initiation and became antiformally warped during its late stage of development. This is documented by concordantly systematic variation of attitudes of upper-plate Tertiary strata, lower-plate mylonitic foliation, and the Whipple detachment fault.

3. The antiformal warping of the Whipple detachment fault produced enough topographic relief to expose the lower-plate mylonitic rocks and to initiate a large landslide, $>70 \text{ km}^2$. Similarly, a topographic depression was created above the synformal Whipple fault in the central Chemehuevi Valley into which the landslide

was emplaced. Its occurrence predates the end of detachment faulting.

4. The upper-plate extension in the Whipple-Chemehuevi detachment fault system was not only accommodated by high-angle, normal faulting and slip along the Whipple-Chemehuevi fault, but also by other major, low-angle, normal faults. Correlation of Tertiary strata between the northern Whipple Mountains and central Chemehuevi Valley suggests that 15 km of the total 40-km extension in the Whipple-Chemehuevi detachment was accommodated by a gentle, east-dipping, normal fault that lies underneath Chemehuevi Valley.

5. Analysis of upper-plate structures and stratigraphy provides critical constraints on the evolution of three-dimensional, detachment-fault geometry that cannot be determined from examination of lower-plate fabrics alone.

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