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Rapid upward transport of mid-crustal mylonitic gneisses in the footwall of a Miocene detachment fault, Whipple Mountains, southeastern California

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With 14 figures

Zusammenfassung

Im metamorphen Komplex der Whipple Mountains sind unterhalb der Whipple-Abscherung mylonitische Gneise der oberen Grünschieferfazies und mittleren Amphibolitfazies aufgeschlossen. Gefügeuntersuchungen innerhalb der mächtigen (> 3.5 km) Mylonitsequenz zeigen, daß hier eine intrakrustale Zone nichtkoaxialen laminaren Fließens mit vorherrschend nordost gerichtetem Schersinn repräsentiert ist. Den obersten Teil dieser Scherzone bildet die Whipple Mylonitfront. Sie überspannt kontinuierlich innerhalb weniger Meter die Obergrenze durchdringender duktiler Deformation bis zu eindeutig nichtmylonitisierten Abfolgen kristalliner Gesteine und ihren tieferen mylonitisierten Äquivalenten. Es wird angenommen, daß die Mylonitisierung während des Oligo-Miozäns (26 ± 1–5 Ma) in einer Tiefe von 16 ± 4 km (4,4 ± 1,1 kb) und bei Temperaturen zwischen 460–535 °C stattgefunden hat. Spaltspurenuntersuchungen und ^{40}Ar/^{39}Ar-Datierungen aus den mylonitischen Gesteinen belegen zusammen ein rasches Abkühlen von über 450 °C auf unter 200 °C im Zeitraum vor 20 bis 18 Ma. Die rasche Abkühlung wird dem vor 20 Ma beginnenden Aufstieg der mylonitischen Gneise am Fuß eines sich entwickelnden flachwinkligen, dehnungsbedingten Abscherungssystems zugeschrieben. Das nordost verwurzelte Whipple-Störungssystem und die Mylonite sind kinematisch gleichgerichtet, sie haben dieselbe Richtung und denselben Schersinn, dennoch haben die Störungen die Mylonite einige Millionen Jahre nach ihrer Bildung überschnitten. Tiefere Plattenmylonite erreichten so die Erdoberfläche und wurden vor 16 Ma erodiert. Die Minimalraten für den Aufstieg der Mylonite und die Bewegungen entlang der Abscherungssysteme für den Zeitraum vor 20 bis 16 Ma liegen jeweils zwischen 3 und 7,2 mm/yr. Dies unter der Annahme, daß die Mylonite in einer Tiefe von mindestens 12 km von einem mit 25° einfallenden Störungssystem geschnitten wurden. Aus den verfügbaren Daten müssen für den Zeitraum vor 20–18 Ma höhere Bewegungsraten angenommen werden. Der kumulative Versatz der Gesteinseinheiten entlang der Hauptstörungen des Whipplesystems scheint damit 40–45 km zu überschreiten.

Abstract

Mylonitic gneisses of upper greenschist to middle amphibolite facies grade are exposed below the Whipple detachment fault in the Whipple Mountains metamorphic core complex. Fabric and microstructural analyses of the thick (> 3.5 km) mylonitic sequence indicate that it represents an intracrustal zone of non-coaxial laminar flow with a predominant sense of northeastward shear. The top of this shear zone is the Whipple mylonitic front, the abruptly gradational (locally within several meters) upper limit of pervasive ductile strain between a distinctive sequence of non-mylonitized crystalline rocks and their lower, mylonitized equivalents. Mylonitization of Oligo-Miocene age (26 ± 5 Ma) is estimated to have occurred at depths of 16 ± 4 km (4.4 ± 1.1 kb) and at temperatures between 460–535 °C. Fission track and ^{40}Ar/^{39}Ar age determinations from the mylonitic rocks collectively document their rapid cooling from above 450 °C to below 200 °C between 20 and 18 Ma ago. Rapid cooling is attributed to post-20 Ma uplift of mylonitic gneisses in the footwall of an evolving low-angle detachment fault system of extensional origin. The NE-rooting Whipple fault system and the mylonites are kinematically coordinated (same sense and direction of shear), but the faults of the system appear to have cut across the mylonites several million years after their formation.

Lower-plate mylonites reached the earth's surface, where they were eroded, prior to 16 Ma ago. Minimum uplift rates for the mylonites and detachment fault system slip rates for the period 20–16 Ma ago are 3 and 7.2 mm/yr, respectively, assuming that the mylonites were captured at a minimum depth of 12 km by a fault system that dipped 25° through the upper crust. From available cooling data, higher rates for 20–18 Ma ago are likely. Cumulative displacement of rock units across major faults of the Whipple system appears to exceed 40–45 km.

Résumé

Une série épaisse (>3.5 km) de gneiss mylonitiques allant du facies supérieur des schistes verts au facies moyen des amphibolites affleure sous la faille de décollement de Whipple dans le complexe métamorphique des Whipple Mountains L'analyse des fabriques et des microstructures de cette séri mylonitique montre qu'elle représente une zone intracrusta

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de flux laminaire non coaxial, avec un glissement prédominant vers le nord-est. Le sommet de cette shear-zone est le front mylonitique de Whipple, qui marque l'apparition brusque (localement en quelques mètres) de la déformation ductile pénétrative, entre une série supérieure cristalline non mylonitique et ses équivalents mylonitiques inférieurs. La mylonitisation, d'âge oligocène-miocène (26 ± 5 Ma) a dû s'effectuer à une profondeur de 16 ± 4 km (4,4 ± 1,1 Kb) et à des températures comprises entre 460° et 535 °C. Les traces de fission et des datations ^{40}Ar/^{39}Ar montrent que les mylonites ont subi un refroidissement rapide de plus de 450 °C à moins de 200 °C entre 20 et 18 Ma. Ce refroidissement rapide est attribué à la montée, à partir de 20 Ma, des gneiss mylonitiques lors du développement du système de failles de décollement extensionnelles, dont ils formaient le mur. L'ensemble des failles, à pied NE, et les mylonites sont cinématiquement coordonnés; le glissement s'y est effectué dans la même direction et le même sens; cependant, les failles ont coupé les mylonites plusieurs Ma après la formation de celles-ci. Les mylonites de la plaque inférieure ont atteint la surface du sol et y ont été soumise à l'érosion avant 16 Ma. Si on admet une surface de décollement inclinée à 25° coupant les mylonites à une profondeur d'au moins 12 km, les vitesses minimales de la montée des mylonites et du mouvement de long du décollement entre 20 et 16 Ma, ont dû être respectivement de 3 mm/an et 7,2 mm/an. D'après les données fournies par le refroidissement, les vitesses devaient être plus élevées pendant la période de 18 à 20 Ma. Le déplacement des masses rocheuses de long des failles majeures du système de Whipple semble exéder 40 à 45 km.

Краткое содержание

В метаморфном комплексе гор Whipple Mountains милонитизированные гнейсы верхней фации зеленого сланца и средней фации амфиболитов обнажены ниже срыва Whipple. Данные исследования текстуры и мощность (3,5 км) милонитной свиты указывают на то, что здесь представлены внутрикристаллическая зона некоаксиально-ламинарного течения при господстве направления срыва на северо-восток. Верхняя часть этой зоны срыва образует фронт милонита Whipple. Она охватывает непрерывной мощностью в несколько метров верхнюю границу пластичной деформации до явно немилонитизированной свиты кристаллиновых пород и их милонитизированных эквивалентов, расположенных ниже. Считают, что процесс милонитизации происходил в олигомиоценовом периоде (26 + / — 1-5 миллионов лет тому назад) на глубине 16 + / — 4 км (4.4 + / — 1.1 кб) при температурах между 460–535 °С. Исследование следов трещин и датировка с помощью аргонового метода (^{40}Ar / ^{39}Ar) милонитизированных пород говорит о быстром охлаждении за период от 20 до 18 миллионов лет с более чем 450 °С до менее 200 °С. Такое быстрое охлаждение приписывают поднятию милонитизированных гнейсов, начавшееся еще ранее 20 миллионов лет тому назад у подошвы систем срыва, простирающихся полого и вызванных растяжением. Система разломов Whipple, связанная с северо-востоком, и милониты имеют одно и тоже направление и ту же плоскость скола, но нарушения разорвали милониты несколько миллионов лет позже, после их образования. Более глубоко залегающие милониты платформы появились т. о. на поверхности и подверглись эрозии в период до 16-ти миллионов лет тому назад. Минимальная скорость подъема милонитов и сдвигов вдоль системы сколов в период от 20 до 16 миллионов лет тому назад составляет от 3 до 7,2 мм/год. При этом считают, что милониты залегали, по-крайней мере, на глубине 12 км и их разрезала система разрывов, имеющая угол падения в 25°. На основании полученных данных считают, что за период от 20 до 18 миллионов лет тому назад подъемная скорость была больше. Смещение слоев пород вдоль главного разрыва системы Whipple, кажется, т. о. превосходящим 40–45 км.

Introduction

Cordilleran »metamorphic core complexes« in western North America are distinctive structural associations of Tertiary age and extensional origin (Davis & Coney, 1979; Crittenden et al., 1980). More than twenty geographically separate complexes have been recognized from southwestern Canada to northwestern Mexico (Sonora). Although most core complexes lie geographically within the Miocene and younger Basin-and-Range province, some do not. All, however, have developed in areas of profound Cenozoic crustal extension. These complexes include a characteristic structural association of (1) domal or antiformal mountain ranges, (2) flanking low-angle normal faults (detachment faults) of subregional to regional extent, (3) lower-plate (»core«) assemblages of crystalline rocks, commonly including mylonitic gneisses, and (4) upper-plate rocks highly distended by closely spaced normal faults. Typically, the low-angle normal (detachment) faults separate upper- and lower-plate rock assemblages that have experienced dramatically different Tertiary histories of metamorphism and deformation, including ductile shear. Upper-plate rock assemblages commonly include supracrustal rocks, as young as late Tertiary, which were deposited on a crystalline basement that escaped Tertiary metamorphism and/or mylonitization.

In marked contrast, lower-plate rocks characteristically exhibit the effects of mid-crustal metamorphism and deformation of Tertiary age. Mylonitic gneisses of upper greenschist to middle amphibolite facies grade are exposed in the lower plates of most Cordilleran metamorphic core complexes. Although some mineral components of the mylonitic rocks have deformed

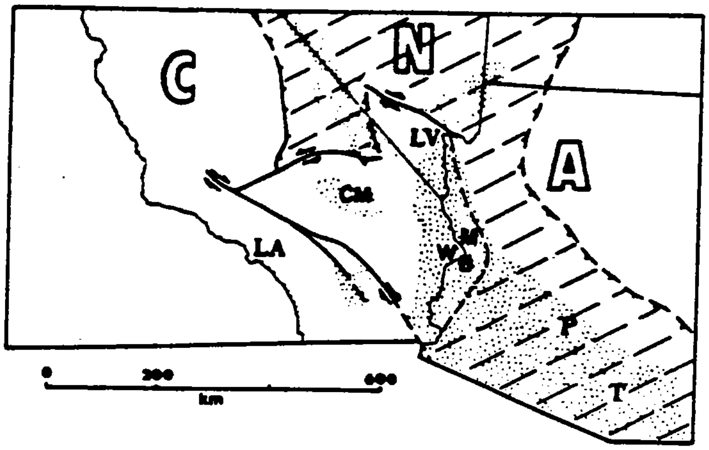

Fig. 1. Location map of southwestern U.S. Cordillera showing area of Basin and Range province (diagonally ruled pattern) and locations of Cenozoic detachment fault complexes (stippled pattern). Large open block letters: C = California; N = Nevada; A = Arizona. Large black letters: LA = Los Angeles; LV = Las Vegas; P = Phoenix; T = Tucson. Small black letters: CM = Central Mohave detachment terrane; W = Whipple Mountains; M = Mojave Mountains; B = Buckskin Mountains.

brittlely (feldspars, amphibole, garnet), quartz and micas exhibit crystal-plastic deformational behavior; bulk rock strain during deformation was ductile. Most of the mylonitic gneisses of the southwestern Cordillera are derived from pre-existing crystalline rocks, e.g. Precambrian gneisses and Mesozoic granitic plutons, but some complexes include Tertiary igneous rocks intruded during deformation. The mylonitic rocks are foliated and possess regionally-consistent stretching lineations most typically defined by elongate quartz grains and linear trains of feldspar porphyroclasts. In the Whipple Mountains of southeastern California (locality W, Fig. 1) mylonitic fabrics are most prominent in quartzo-feldspathic rocks that had not been previously deformed (e.g. Cretaceous and Tertiary intrusive rocks), but are also overprinted on older crystalline rocks affected by deformations of both Precambrian and Mesozoic age. Mylonitic gneisses (for brevity, simply »mylonites« elsewhere in this paper) exhibit two mineral assemblages — one relict from the preexisting igneous or metamorphic rock, the other a re-equilibrated, new and recrystallized assemblage formed during the mylonitic deformation. Temperatures and pressures during mylonitization can be deduced from mineralogic analysis of the latter assemblages (e.g. Anderson, 1985, and in press). Thicknesses of mylonitic rocks in the lower plates of Cordilleran Tertiary detachment faults vary from as little as 50 to 100 meters (South Mountain, Arizona; Reynolds, 1982, 1985) to 1 km (Ruby Range, Nevada; Dallmeyer et al., 1986), to more than several kilometers (Whipple Mountains, California; Davis et al., 1980, 1986).

The nature and origin of mylonitic gneisses in the lower plates of Tertiary detachment faults has been much discussed in recent Cordilleran literature and continues to be controversial. Three principal scenarios (among many) have been proposed by various workers:

I. The mylonitic gneisses existed in the crust prior to Cenozoic extension and are unrelated to that extension. During extension, they are transported upwards in the footwalls of detachment fault systems (G. A. Davis et al., 1980, 1982; Rhodes & Hyndman, 1984; Simpson, 1984; Engel & Schultejann, 1984; Schultejann, 1984; Erskine, 1986). Most pre-Cenozoic mylonites are generally known, or generally thought to have formed during Mesozoic thrust faulting.

II. The mylonitic gneisses form during coaxial, pure-shear strain of an extending crust at depths appropriate to their largely ductile behavior. Rocks at higher crustal levels experienced synchronous brittle behavior, primarily manifested by one or more generations of normal faulting. The boundary between the two deformational domains reflects a brittle/ductile transition in the crust and is represented physically by subhorizontal detachment faults which need not be surfaces of major translation (Eaton, 1980; Miller et al., 1983; Gans, 1987; Lee et al., in press).

III. The mylonitic gneisses form at depth along inclined extensional shear zones that cross or root into the lithosphere (Wernicke, 1981, 1985; Luchitta & Suneson, 1981; Reynolds, 1982, 1985; G. H. Davis, 1983; Lister & G. A. Davis, 1983; G. A. Davis et al., 1983, 1986; Howard & John, in press). At high crustal levels the shear zones are represented by brittle detachment faults with large translations; these detachments pass downward into ductile zones of broadly distributed simple shear and intracrustal laminar flow (Fig. 2) — the tectonic regime in which the mylonitic gneisses form.

In scenario I, the sense and direction of shear in older mylonitic gneisses need not have any predictable relationships to the sense and direction of shear of the younger detachment fault. In some instances (e.g. Simpson, 1984; Engel & Schultejann, 1984) different senses of shear clearly indicate the kinematic incompatibility and different ages of lower-plate mylonitic gneisses and the detachment faults above them. In scenario II, with its emphasis on synchronous coaxial deformation of both upper and lower plates, there should be no consistent sense of shear throughout lower-plate mylonites, but both plates should share a parallel direction of maximum extension. Scenario III requires that the sense and direction of simple shear within the mylonitic gneisses be the same as that along the kinematically related, but structurally higher detachment faults. This relationship is, in fact, observed

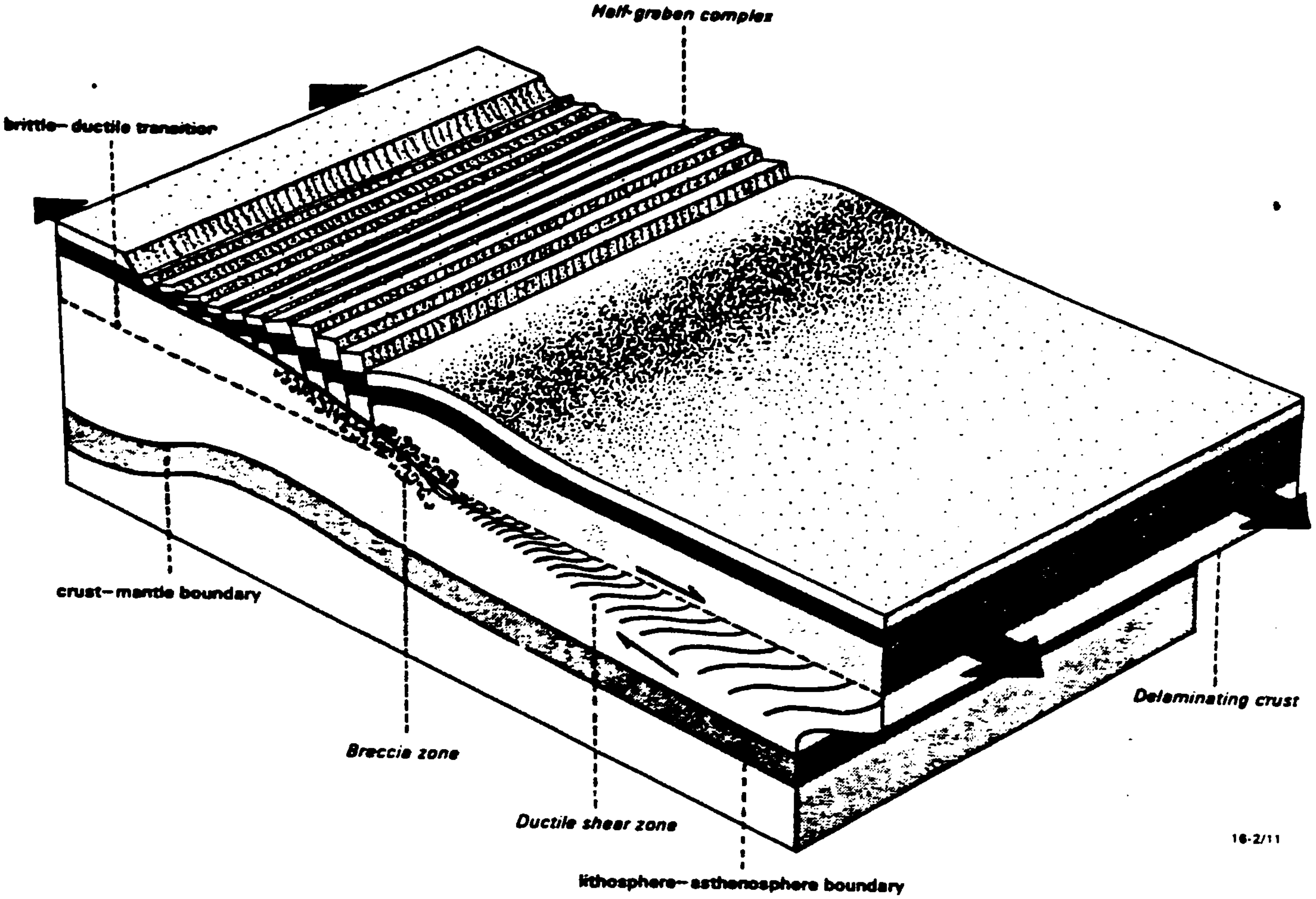

Fig. 2. Diagrammatic view of evolving low-angle extensional shear zone. In this interpretation, the one of several possible geometries most favored by Lister & Davis (in review), a brittle upper crustal detachment fault roots at depth into a ductile shear zone below the stress guide defined by the brittle-ductile transition. Mylonitic gneisses formed in the lower part of the shear zone are transported upward in the active footwall of the detachment fault system. At levels above the brittle-ductile transition the mylonites are sheared and retrograded to form lower-plate chloritic breccias.

through fabric and microstructural analyses of mylonites from more than a dozen metamorphic core complexes in the southwestern United States (Lister in Lister & Davis, in review).

Field relationships in the Whipple Mountains of southeastern California (Fig. 1), supplemented by geochronologic studies in the lower plate of that core complex, require the existence of a fourth scenario for the relationship between mylonitic gneisses and the Whipple detachment fault above them. Scenario IV, a variant of III, proposes that mid-crustal Tertiary mylonites formed at depth within an evolving ductile shear zone were crosscut by a somewhat younger shallow-dipping detachment fault and were transported upwards in the footwall of that fault to surface and near-surface levels. The mylonitic gneisses and the detachment fault exhibit kinematic coordination (i.e. same sense of shear, same direction of extension), but the two did not develop synchronously. Rather, they represent two separate phases of a protracted extensional deformation. Scenario IV does not refute evolving shear zone models of scenario III, but does indicate that in some cases this scenario is overly simplistic. Scenario IV has been introduced elsewhere (Davis & Lister, in press), but field relationships supporting it are developed in greater detail in this paper.

The Whipple Mountains core complex

Geologic overview

The Whipple Mountains of eastern San Bernardino County, California, contain one of the best exposed and most intensively studied metamorphic core complexes in the U.S. Cordillera. The mountain range, in an arid region of the southwestern United States, extends over an area >900 km^2, has a topographic relief of approximately 1 km, and affords spectacular exposures of the Whipple detachment fault (Fig. 3) and lower-plate mylonitic gneisses (Fig. 4). Details of the geology of the range are described by Davis et al., 1980, 1982; Anderson & Rowley, 1981; Davis & Lister, in press).

Fig. 3. Exhumed Whipple detachment fault surface, south-central Whipple Mountains (field trip locality 4A, ANDERSON et al. 1979, p. 113, 116). Cholla cactus in a pained G. S. LISTER's left hand provides scale. The detachment fault surface dips 14° to the south and is underlain by a resistant, 12 cm-thick microbreccia at this locality; chloritic breccias underlie the microbreccia. Overlying rocks are shattered Precambrian quartzo-feldspathic gneisses and a narrow aplite dike.

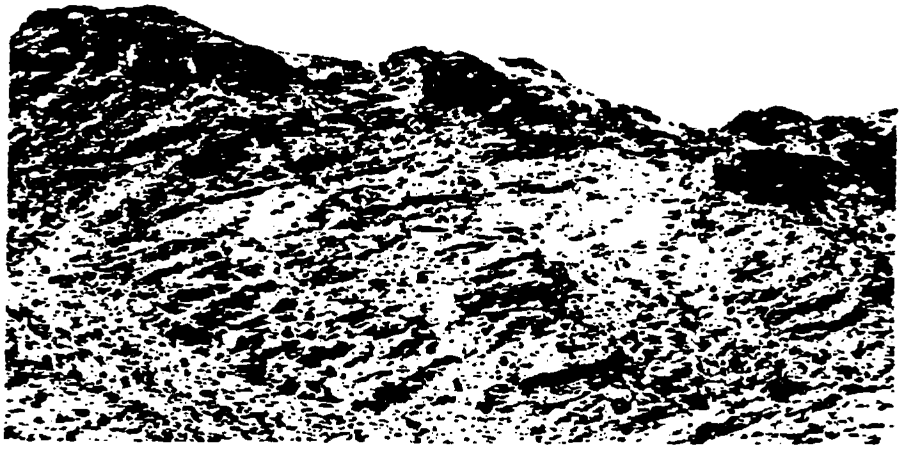

Fig. 4. Structural discordance in the south-central Whipple Mountains between SW-dipping mylonitic gneisses and a lower-plate detachment fault below resistant, cliff-forming chloritic breccias. View is to be north-northwest. The Whipple fault lies parallel to the lower detachment fault, but is just above the horizon here. It and chloritic breccias below it have an angular discordance to lower-plate mylonitic foliation throughout most of the range.

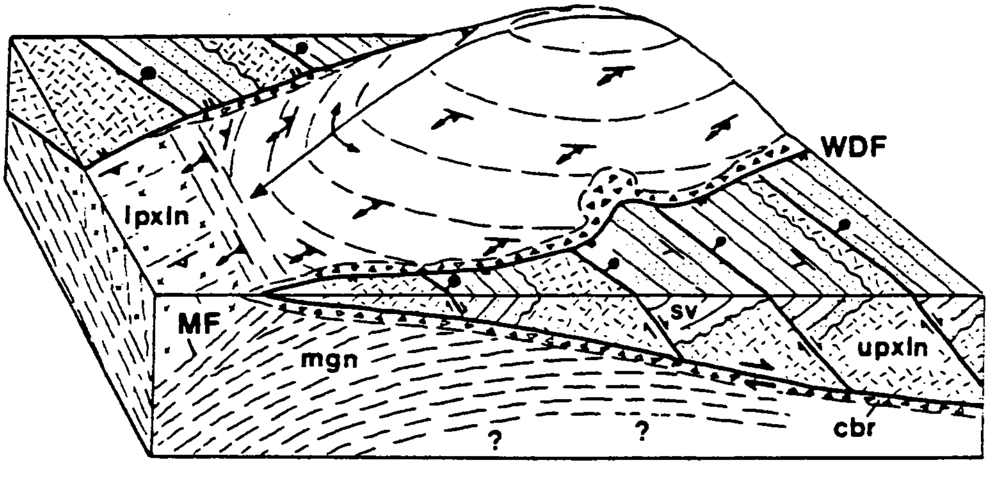

Fig. 5. Diagrammatic representation of geologic relations, Whipple Mountains, southeastern California, viewed to north. Width of block diagram is approximately 30 km; vertical topographic relief, ca 1.1 km, is highly exaggerated in the diagram. Structural features designated by symbols: WDF = Whipple detachment fault; MF = mylonitic front. Rock units: lpxln = lower plate crystalline rocks (predominantly Precambrian gneisses); mgn = undifferentiated mylonitic gneisses showing mylonitic foliation and lineation; cbr = chloritic breccias; upxln = upper plate crystalline rocks (predominantly Precambrian, but not correlative with »lpxln« within area of figure); sv = Miocene sedimentary and volcanic rocks.

Fig. 6. View to the north of antiformal foliation arch in mylonitic rocks of the Whipple Mountains lower plate (cf. Figs. 4, 5, 12). The lower dark layer above a recessive slope consists of mylonitized Proterozoic gneisses. It is overlain by three cliff-forming layers (see especially left of center), each a sheetlike pluton of mylonitized hornblende-biotite quartz diorite (73 Ma) separated by older gneisses. The composite thickness of the quartz diorite sheets is approximately 480 m (ANDERSON & ROWLEY 1981).

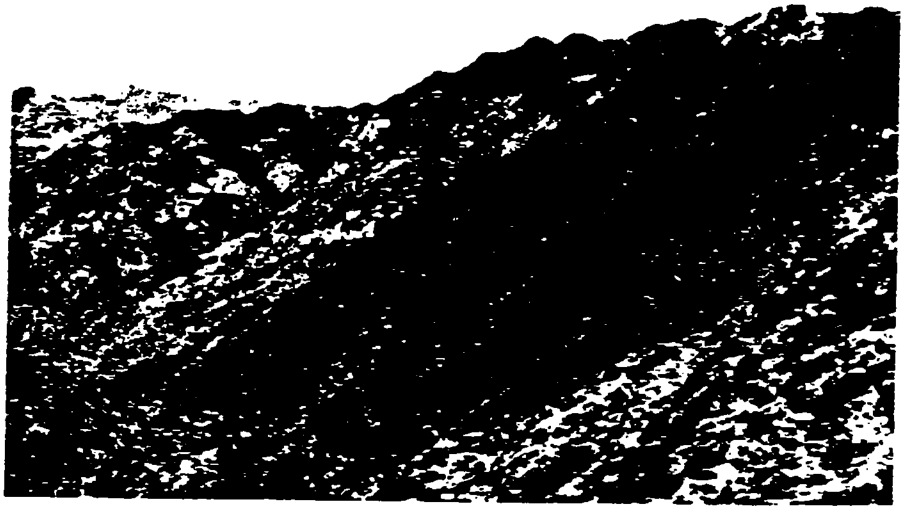

Fig. 7. View to west in south-central Whipple Mountains. Homogeneous-appearing, dark, foliated rocks that dip to left (WSW) in central part of photo are mylonitic gneisses that lie below the mylonitic front (Figs. 5, 9–12). Rocks in distance above the front are heterogeneous, lighter-colored crystalline units that are nonmylonitic and generally equivalent to rocks immediately below the front. Light-shaded rocks in lower right-hand foreground are mylonitic porphyritic granodiorite in the upper part of a sheet-like Cretaceous pluton (mgr, Fig. 9; unit 3, Fig. 10).

Fig. 5 is a diagrammatic block diagram, viewed to the north, of the central and eastern Whipple Mountains. It illustrates the major structural features of the range: (1) the Whipple Mountains antiform (Fig. 6), a major foliation arch in thick (> 3.5 km) lower-plate mylonitic gneisses (»mgn«); (2) the southwest-dipping mylonitic front (»MF«) which separates NE-striking and SE-dipping lower-plate crystalline rocks (»lpxln«) from their structurally deeper, mylonitic counterparts (Fig. 7); (3) the Whipple detachment fault (»WDF«) and retrograde, chloritic breccias (»cbr«) developed beneath it (Fig. 4); and (4) the characteristic pattern of upper-plate faulting — a series of closely-spaced (1–2 km), northeast-dipping normal faults that repeatedly offset and rotate to the southwest Tertiary sedimentary and volcanic rocks (»sv«) and their largely Precambrian crystalline basement (»upxln«). The figure illustrates the strong discordance seen in the range between the Whipple fault and both upper- and lower-plate structural elements.

Mylonitic gneisses

Mylonitic gneisses in the lower plate of the Whipple detachment fault are developed non-uniformly (see below) throughout a structural sequence in excess of 3.5 km thick. The gneisses have two major protoliths (not differentiated in Fig. 5) — Proterozoic quartzofeldspathic banded and augen gneisses and sheetlike

Cretaceous peraluminous (89 ± 3 Ma) and metaluminous (73 ± 3 Ma) plutons (ANDERSON & ROWLEY, 1981; WRIGHT et al., 1986). In northeastern portions of the lower plate the gneisses and plutons make up approximately equal parts of the section, although in southwestern areas Proterozoic gneisses are greatly preponderant.

G. S. LISTER and the writer have collected oriented samples of mylonitic rocks from several traverses that in the aggregate cross most of the > 3.5 km-thick section of mylonitic gneisses and intervening, less deformed panels (see below). Fabric and microstructural analyses of these samples by LISTER (ms. in preparation) reveal a variety of kinematic indicators, including S-C fabric relations (cf. DAVIS et al., 1986, Fig. 2b), oblique foliation in dynamically recrystallized quartz aggregates, and asymmetric mica »fish«, pressure shadows, and quartz c-axis fabrics (cf. DAVIS et al., 1986, Fig. 3). Analyses of 114 samples indicate that 65% record the effects of NE-directed shear parallel to the penetrative mylonitic lineation (N 45 ± 10°E) and to the direction of transport along the Whipple detachment fault; 18% exhibit evidence for SW-directed shear. and 17% were kinematically not definitive. LISTER & DAVIS (1983) and DAVIS & LISTER (in press) interpret this data as indicating formation of the Whipple mylonitic rocks in an intracrustal zone of non-coaxial laminar flow (i.e., flow that is dominantly progressive simple shear).

Subisoclinal, recumbent mesoscopic folds of at least two ages (Proterozoic and Tertiary) are common in some parts of the mylonitic sequence. Fold hinges characteristically parallel the NE-SW stretching lineation in mylonitic gneisses or have more south-southwesterly trends (most within 20 – 25° of the lineation); most (80% of 40 measured hinges) are overturned to the southeast (DAVIS et al., 1982, Figs. 9, 10). Some folds that postdate and clearly deform the mylonitic foliation and lineation in country rock gneisses have had fine-grained Tertiary (26 ± 5 Ma; WRIGHT et al., 1986) biotite tonalite dikes injected along their axial surfaces. These non-folded dikes have a planar internal mylonitic fabric (Fig. 8), thus demonstrating that they were intruded during a protracted period of Tertiary mylonitization. At other localities, the synkinematic Oligo-Miocene dikes are themselves folded. »Eye«-shaped (in cross-section perpendicular to the hinge) sheath folds have been observed, but are rare.

The Whipple mylonitic front

The Whipple mylonitic front is the sharply defined (locally within several meters) upper limit of the thick sequence of lower-plate mylonitic gneisses, although within that sequence the degree of development of mylonitic fabrics is variable. Above the southwest-dipping front, Proterozoic gneisses and amphibolites have predominant NE strikes and SE dips (Fig. 9); these rocks are extensively intruded by Cretaceous and Tertiary plutons, dikes, and sills (Fig. 10). Panels or tectonic lenses, up to 0.1 – 0.2 km thick, of Proterozoic gneisses with steeply dipping foliation (S_1) are locally preserved below the front, especially between mylonitized Cretaceous plutonic sheets (cf. DAVIS et al., 1982, Fig. 2). These relict, unsheared domains indicate that SE-dipping (> 45°) gneisses and amphibolites had been discordantly intruded by subhorizontal Cretaceous plutonic sheets prior to mylonitization. The Cretaceous plutons later became preferential sites of shear strain, quite likely because of their favorable subhorizontal geometry and their quartz-rich composition. In lower-plate areas below the mylonitic front

Fig. 8. Mylonitic foliation (S_2) in Oligo-Miocene (26 ± 5 Ma) biotite tonalite porphyry dike viewed on surface that lies parallel to stretching lineation. Light gray layer above lens cap is highly foliated chilled (?) contact of the dike. Shear sense in this outcrop is that higher levels are displaced from left (NE) to right (SW) with repect to lower levels. Thus, this is an example of antithetic shear compared with the opposite, predominant sense of shear characteristic of the thick mylonitic sequence.

where Cretaceous plutonic sheets are not present and could not, therefore, act as preferential strain guides, the Proterozoic gneisses show strong uniform rotation into shallow dipping orientations and pervasive development of mylonitic fabrics.

The mylonitic front is most sharply defined where it lies entirely within a leucocratic Cretaceous granitic pluton (ANDERSON et al., 1979, p. 130−131, field trip stop no. 24). Mylonitic fabrics (S_2, L_2) are penetratively developed in the lower part of the pluton, but disappear upward over a distance of three or four meters (Fig. 11); only discrete thin (< 2−3 m) foliated zones are present in the pluton above the front. Elsewhere, the NE-striking orientation of preexisting gneissic foliation documents the structural transition across the front where it (the front) occurs wholly within Precambrian gneisses and amphibolite. Along one well-exposed ridge, south of field locality no. 24, the older foliation S_1, N 50−65°E, swings eastward into an orientation of N 55−60°W through a structural thickness of about 20−30 m. As the foliation acquires a northwest strike it also acquires, through transposition, a mylonitic foliation (S_2) with a southwest-plunging lineation (L_2). The mylonitic fabrics are initially confined to a narrow (ca 5 m) shear zone. Below this local zone of transposition and ductile shear, the older foliation reemerges with its preexisting northeast strike. At the mylonite front, eastward rotation and transposition of this foliation occurs again in the same fashion as described (Fig. 10).

The mylonitic front is not a discrete fault. Rather, it is the abruptly gradational upper limit of pervasive ductile strain between a distinctive sequence of nonmylonitized rocks and their mylonitized equivalents. Mylonitic rocks occur locally hundreds of meters above the front. Fine-grained, shallow- to moderately-dipping Tertiary dikes with an internal mylonitic fabric are present at some localities as high as 1 km above the mylonitic front (Figs. 9, 10 [unit 4]); steeply-dipping, NE-striking country rock gneisses above and below these dikes generally lack visible fabric development in outcrop. Tertiary dikes of the same intermediate to silicic composition but with steep dips generally lack a mylonitic fabric, although some exceptions do oc-

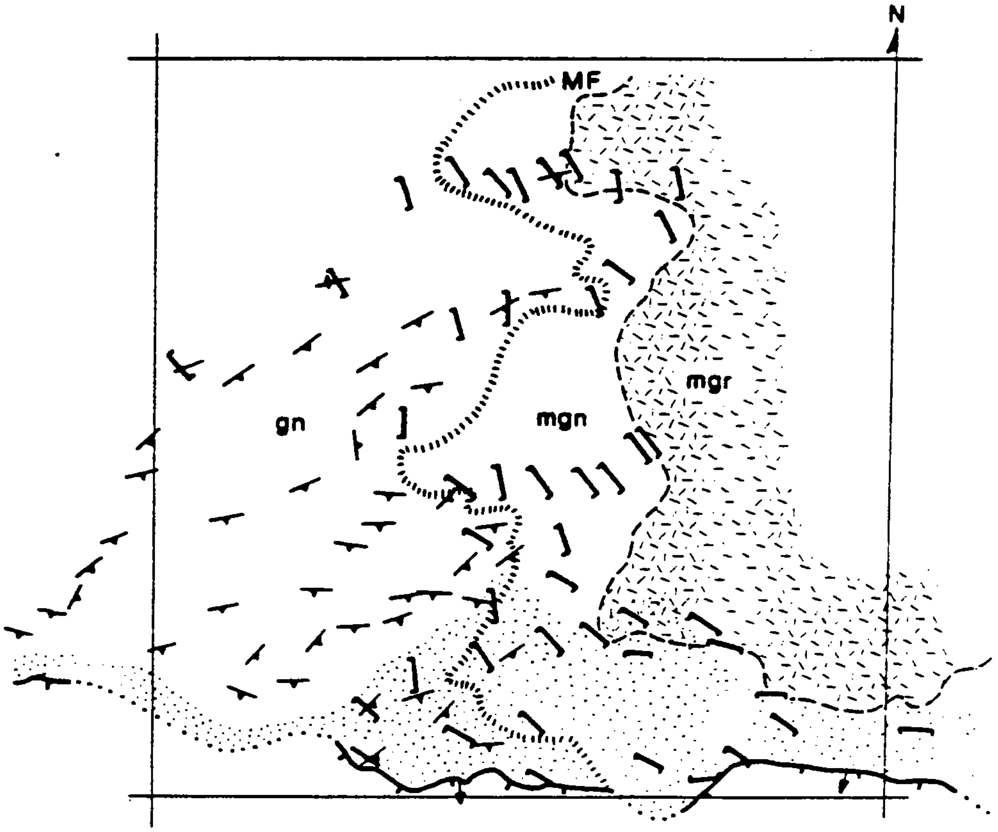

Fig. 9. Highly simplified geologic map of 4 sq. mile area in south-central Whipple Mountains (DAVIS et al. 1980, Fig. 16). Fig. 7 is a westward view across the northern part of the area. Map shows major geologic relations across west-dipping mylonitic front (MF). Map units: gn = undifferentiated gneisses and intrusive igneous rocks above mylonitic front; mgn = mylonitized equivalents of »gn« below the front; mgr = upper part of mylonitized porphyritic granodiorite pluton. Pre-mylonitic foliation (S_1) shown by attitudes with triangular barbs; younger mylonitic foliation (S_2) shown by heavier lined attitudes with double dip symbols. Stippled pattern designates chloritic breccia zone of shattered, sheared, and retrogressively altered rocks below the south-dipping Whipple detachment fault (hatchured line, south edge of map). The chloritic breccias are overprinted on lower-plate rocks both above and below the mylonitic front.

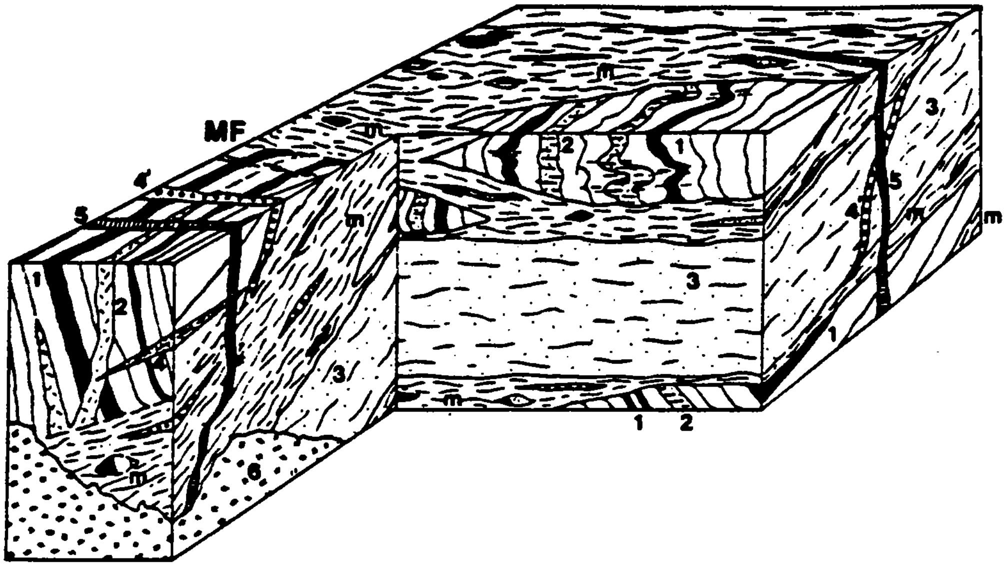

Fig. 10. Diagrammatic view toward the northeast of geologic relations across the west-dipping Whipple mylonitic front (MF) within the area of Fig. 9. Height of block is approximately 800 m; width is approximately 1.5 km. Rock units are numbered from oldest to youngest: 1 = Proterozoic gneisses (white) and amphibolite (black); 2 = Cretaceous monzogranite; 3 = Cretaceous porphyritic granodiorite (mylonitized; mgr of Fig. 9): 4 = Tertiary andesite and tonalite (26 Ma) with mylonitic fabric, both above and below mylonitic front; 4′ = Tertiary dacite, mylonitized below the front; 5 = Miocene diabase (21.5 Ma); 6 = Miocene composite diorite (19.8 Ma)/gabbro pluton: m = mylonitic gneisses below the front, primarily units 1 and 2. Steep pre-mylonitic foliations (S_1 and $_2$, see text) that have escaped transposition and rotation into parallelism with the mylonitic foliation (S_3) are preserved, but folded, in a large tectonic lens below the mylonitic front.

cur in dacites within several hundred meters of the front. One explanation for these field relations is that the dikes were emplaced during pervasive mylonitization at deeper structural levels. Ductile deformation leading to mylonitic fabrics above the front occurred primarily within thermally weakened (i.e. still hot) and

Fig. 11. View west-northwest of WSW-dipping mylonitic front within leucocratic Cretaceous granitic pluton, central Whipple Mountains. The mylonitic front is a sharply gradational contact zone, three to four meters thick, that extends diagonally upwards from the lower left corner of the picture to its right hand margin. It separates lower, penetratively deformed mylonitic granitic gneiss from compositionally identical granitic rocks in which mylonitic fabric elements are only sparsely and non-penetratively developed. Mylonitic foliation (S_3) at this locality (N 7W, 34°SW) lies parallel to the front. The thickness of the mylonitic section in this photograph is approximately 20 m; the total thickness of the mylonitic sequence below the front is in excess of 3.5 km.

favorably oriented (i.e. shallow-dipping) dikes. Conversely, mylonitic foliations at high structural levels (above the mylonitic front) could generally not be developed within hot, steeply-inclined dikes because of the resistance to shearing of the colder, more competent enclosing gneissic wall rocks.

Steeply-dipping diabase dikes were emplaced throughout the lower plate after mylonitization, but prior to detachment faulting (Fig. 10, unit 5). Although these dikes lack an internal mylonitic fabric, some (not all) experienced partial recrystallization and limited deformation after intruding hot mylonites below the front. Field relations demonstrating this include (1) the development of contact parallel or subparallel schistosity within the chilled border zones of some dikes, (2) broad, wavy distortion of once more planar geometries, and (3) northeastward displacement of the dikes along late, shallow-dipping slip surfaces (Fig. 10). The diabase dikes and the mylonitic front are crosscut in the north-central Whipple Mountains by a composite mafic pluton (biotite-hornblende quartz diorite to olivine gabbro) that lacks a mylonitic fabric and is considered to be post-tectonic (Figs. 10 [unit 6], 12). Absolute age relationships between the various intrusive units and the mylonite-forming event are discussed in a later section.

Fig. 10 illustrates many of the geologic relations for rocks above and below the mylonitic front. Of special note is a large tectonic lens of steeply-dipping Proterozoic gneisses (unit 1), amphibolites (unit 1, black), and Cretaceous monzogranite sills and dikes (unit 2), that is completely enclosed by the sheared, mylonitic equivalents of these rocks (locality 6D, Fig. 1 in Davis et al., 1982; a larger, similar lens labeled »mostly gn« is shown in Fig. 12). Structures within this isolated, relict domain of subvertical gneisses and weakly

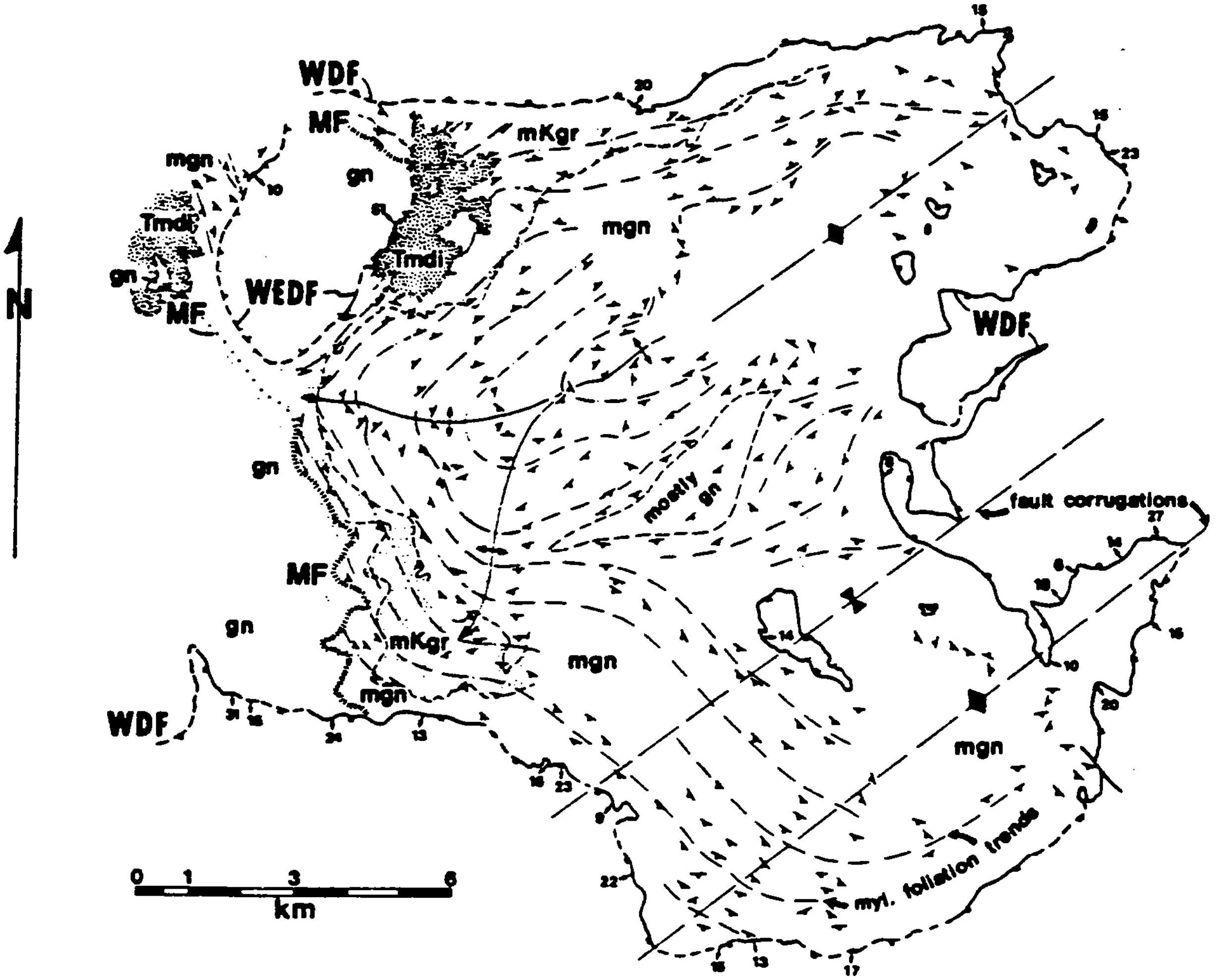

Fig. 12. Geologic map of the lower plate of the Whipple detachment fault (WDF), central and eastern Whipple Mountains. Map emphasizes undulatory or corrugated geometry of the Whipple fault, and foliation trends in mylonitic gneisses (mgn) and a composite Cretaceous granitic pluton (mKgr, light stippled pattern) — the latter with a sheetlike geometry (now folded). The dips of mylonitic foliation are generally steeper than subparallel dips on the overlying Whipple fault (see text). A major northeast-trending antiformal foliation arch in the mylonitic gneisses is not reflected in structurally higher, northwest-striking gneisses directly below the mylonitic front (MF). Non-mylonitized gneisses (gn) overlie the mylonitic front, which is intruded by a composite Miocene diorite/gabbro pluton (Tmdi, heavy stippled pattern). The War Eagle detachment fault (WEDF) offsets the front and the diorite/gabbro pluton ca 4.5 km to the north-northeast, and is in turn displaced by the higher, younger Whipple fault.

foliated Cretaceous sills clearly demonstrate that the lens has experienced a significant component of downward flattening (shortening). Internal strain within the lens appears to be more compatible with coaxial pure-shear strain mechanisms than with simple shear, in contrast to that within the enclosing mylonitic gneisses. The steeply inclined layers have undergone buckle-type folding, presumably in response to downward, layer-parallel shortening. The resulting structures are disharmonic, recumbent folds with axial surfaces that now dip westward generally parallel to the mylonitic front (Fig. 10; cf. Davis et al., 1982, Fig. 6D, for details of fold geometry). Fold hinges trend and plunge to the SW, an orientation controlled by the pre-existing NE-SW strike and subvertical dip of the gneiss, amphibolite, and monzogranite layers.

The most interesting relation in the folded sequence is the pervasive development of a shallow-dipping mylonitic fabric only within the steeply inclined sills of monzogranite (unit 2, Fig. 10). A faint layer-parallel foliation of Cretaceous age in these sills (S_2) did not inhibit the development of a crosscutting mylonitic foliation (S_3') as was apparently the case in the subvertical, more strongly foliated (S_1) older gneisses and amphibolites where S_3' did not develop. S_3' is parallel to the axial surface of the folds and to a surface of transposition in some fold hinges. Thin (< 1 m) dikes of Tertiary tonalite were intruded discordantly across the folds, but parallel to their axial surface; these syntectonic dikes exhibit a mylonitic fabric, S_3'', that is parallel to S_3' in the monzogranite sills. The confinement of S_3' to the monzogranite layers and the geometry of the folds within the tectonic lens strongly support that S_3' and the coeval folds formed in response to downward, layer-parallel shortening and that the finite strain was largely coaxial. Such internal strain for a tectonic lens within a much thicker mylonitic shear zone is not unexpected and is not incompatible with the conclusion of Davis & Lister (in press) that the mylonitic foliation (S_3) of the zone itself formed largely in response to simple shear processes.

Ages of mylonitization and detachment faulting

Field relationships and geochronologic studies in the region of the Whipple Mountains clearly indicate that mylonitic gneisses in the lower plate of the Whipple detachment fault are older than the fault. Major lines of evidence supporting this conclusion include:

1) truncation of inclined mylonitic foliation by the less steeply-dipping Whipple fault throughout much

2) lower-plate mylonitic gneisses in the nearby Buckskin Mountains (B, Fig. 1) were folded into large, upright, open folds with NW-SE trends prior to detachment faulting (Osborne, 1981); the largest folds have wavelengths of 900 to 1500 m and limb dips ranging from 10 to 45 °; the overlying Buckskin (= Whipple) detachment fault cuts discordantly across the folds and is itself not folded;

3) mylonitic foliation in the Whipple lower plate forms a major, NE-trending antiformal foliation arch (Figs. 6, 12); formation of the antiform appears to predate development of the more planar, NW-striking mylonite front and mylonitic gneisses directly below the front — both are discordant to the foliation arch (Fig. 12); the mylonitic front is in turn offset approximately 5 km by the War Eagle detachment fault and truncated by the still younger Whipple fault. The curviplanar geometry of the Whipple fault (Figs. 5, 12) is believed not to be the result of folding, but a primary reflection of the previously developed fold structure in the mylonitic gneisses that it (the fault) propagated across (Davis & Lister, in press);

4) chloritic breccias derived from the mylonites (Fig. 4) are locally offset by moderately-dipping lower-plate normal faults that are truncated upwards by the Whipple fault; the chloritic breccias apparently formed beneath an earlier detachment fault (War Eagle?) which is no longer preserved; the normal faults are interpreted as having formed in the upper-plate of a pre-Whipple detachment fault that lies at depth and is not presently exposed; and,

5) diabase dikes (21.5 ± 0.7 Ma, hornblende ^{40}Ar/^{39}Ar, E. DeWitt, written comm., 1984) and a still younger composite mafic pluton (19 ± 2 Ma, zircon, Wright et al., 1986; 19.8 ± 0.1 Ma, hornblende ^{40}Ar/^{39}Ar, ibid.) that intrude the Whipple mylonitic front (Fig. 10) are truncated and displaced northeastwards by the Whipple fault;

Given the Oligo-Miocene age for late stages of mylonitization (26 ± 5 Ma for late synkinematic tonalite dikes), the 19 – 21.5 Ma age of post-tectonic intrusives, and the post 19 – 20 Ma age for the Whipple fault, detachment faulting may have followed the end of mylonitization by as much as 6 or 7 Ma (or as little as 2 or 3). Nevertheless, structures formed during both brittle and ductile deformational events are kinematically compatible. NE-trending stretching lineations in the mylonitic gneisses are statistically parallel to the trend of striae on the Whipple fault and to striae on steeper upper-plate and lower-plate faults. Furthermore, the predominant northeastward sense of shear in the mylonitic gneisses matches the northeastward displacement of upper-plate rocks (with respect to lower-plate) on offset units and the drag folding of Tertiary strata adjacent to the fault. It is to an explanation of these geochronologic, geometric, and kinematic relationships that we now turn.

The capture of older mylonites by a younger detachment fault

Davis & Lister (in press) believe that Cordilleran detachment faults are best explained as evolving low-angle shear zones that root into lower upper crustal or mid-crustal structural levels during continental extension; the concept was originally proposed Wernicke (1981) in the context of shear across the entire lithosphere. The detachment zones propagate upward across the overlying crust and either reach the surface directly as low-angle faults or terminate at shallow depths in pull-apart complexes of closely-spaced normal faults (Fig. 2). At any given time during their development the higher level detachment faults are presumably continuous down-dip into progressively wider and deeper zones of brecciation, shearing, and ductile flow (mylonitization at mid-crustal levels). Lower-plate rocks are drawn rapidly upwards along the evolving shear zones (see discussion below) and out from beneath brittlely extending upper-plate rocks (e.g. Wernicke, 1981, 1985; G. H. Davis, 1983; Reynolds & Spencer, 1985; G. A. Davis et al., 1983, 1986). Footwall mylonitic gneisses formed at considerable depth now lie in fault contact beneath diverse supracrustal units. In the Whipple Mountains, Tertiary sedimentary and volcanic strata lie tectonically above broadly synchronous mylonitic gneisses that formed at depths characterized by an average estimated pressure of 4.4 ± 1.1 kb (i.e.> 12 km; Anderson, in press).

But the inclined extensional shear zone scenario (III), although probably correct for some (if not most) Cordilleran core complexes, is too simple an explanation for field relations between the Whipple detachment fault and lower-plate mylonitic gneisses. It is not simply that the mylonites are older than the detachment fault that now lies above them. Mylonites that form at depth along an evolving low-angle shear zone and that are transported upwards in its footwall, will of necessity be older than the fault surface that is now exposed above them and the brittle structures and fault zone products (chloritic breccias, cataclasites) that are superimposed on them. This age difference is equal to the length of time needed for transport of mylonites out of the ductile regime in which they form and into their structurally high position beneath supracrustal rocks. The critical relationship suggesting the inadequacy of scenario III to the Whipple core complex is that the mylonitic front and the underlying mylonite sequence exhibit an angular discordance with respect to the overlying Whipple fault. The mylonitic front, which represents the top of a zone of intracrustal laminar flow, leaves the detachment fault and dips below the ground surface to the southwest (Fig. 5). It cannot, therefore, have formed downdip and in lower portions of a ductile shear zone related to the present Whipple detachment system.

From relationships described above, the Whipple fault system probably did not exist at the time of the penetrative deformation which formed the mylonitic gneisses now exposed in the Whipple Mountains. These mylonitic gneisses may represent the downdip continuation of a more westerly evolving shear zone (Fig. 13, detachment system I). The scenario (IV) proposed here (and in Davis & Lister, in press) is that a younger, more easterly Whipple detachment fault system (Fig. 12, detachment system 2) crosscut the ductile shear zone at depth and carried mylonites captured in its footwall rapidly upward. As can be seen in Figs. 5 and 13, the displaced mylonitic front and mylonites below it leave the capturing fault and dip westward. This is a geometric necessity since only directly beneath and near the capturing detachment fault are footwall rocks, including those at and below the front, elevated to high structural levels. Farther west, the older mylonites should return to their originally deep structural position. It appears likely that they and the front above them are imaged in Calcrust (California Consortium for Crustal Studies) seismic reflection profiles 16 to 60 km west of the surface trace of the mylonitic front (Davis, 1986a; Okaya, & Frost, 1986; Frost & Okaya, in review). The front may be represented by a well-defined boundary from 3 to 4 seconds deep (E to W) between a transparent (non-reflective) crystalline upper crust and a deeper zone of prominent, subhorizontal, discontinuous seismic reflections that appears to extend downwards to the Moho (Frost & Okaya, in review).

The angle now observed in outcrop between the Whipple fault and the mylonitic front in its footwall records approximately the angle of initial discordance between deep, shallow-dipping mylonitic gneisses and the somewhat steeper, younger detachment zone which transected the mylonites and captured them in its rising footwall. This angular discordance is approximately 10–25° (cf. Fig. 17 of Davis et al., 1980), essentially the same range of angles at which high structural levels of the Whipple detachment fault cut through upper-plate crystalline basement and into subhorizontal Tertiary strata (cf. Figs. 13 and 14 of Davis & Lister, in press). These angular and geologic relationships at upper and lower levels of the Whipple detachment fault

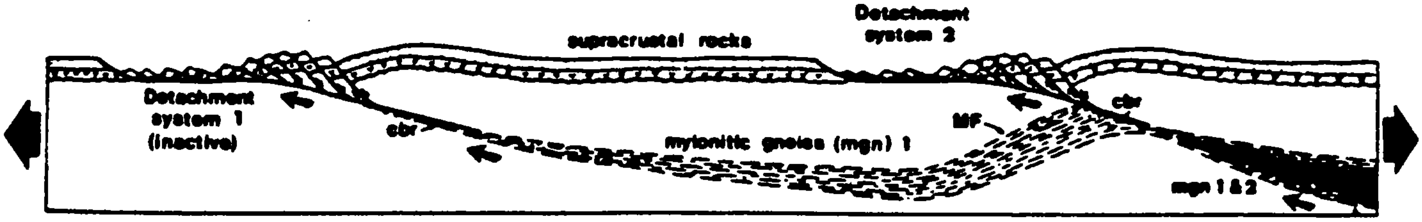

Fig. 13. Diagrammatic SW (left)-NE (right) cross-section illustrating hypothetical geometric relations between detachment fault systems 1 and 2. Depth of section approximately 20 km: width approximately 175 km. Detachment fault system 1 roots at depth into a thick zone of non-coaxial laminar flow, the tectonic regime in which mylonitic gneisses form (cf. Fig. 2). A younger, more easterly splay of the evolving shear zone, detachment system 2, has the geometry of system 1, but crosscuts and captures the previously formed mylonitic gneisses of system 1 in its footwall. After capture, the kinematically »dead« mylonitic sequence is transported upwards: its structural top is a mylonitic front (MF). Mylonitic gneisses that form at depth along evolving shear system 2 presumably overprint mylonitic gneisses formed during earlier phases of intracrustal ductile shear within the evolving zone.

system support the Wernicke hypothesis (1981) that extensional detachment faults are capable of transecting upper crustal rocks as primary, low-dipping (< 30°) shear zones uncontrolled by pre-existing, shallow-dipping structural anisotropies.

Presumably, mylonitic gneisses were also formed at depth along the Whipple fault during its period of activity, but these mylonites have not yet been exposed at the earth's surface (Fig. 13). Surficial geologic evidence for the existence of a northeast-rooting, pre-Whipple detachment system (system 1, Fig. 13) to the southwest of the Whipple Mountains has not yet been recognized, but Dokka (1986) and Dokka & Baksi (1986) have documented the existence of a major northeast-rooting detachment fault system in the central Mohave region to the west (CM, Fig. 1). This system was apparently active between ca 24–20 Ma ago, and could conceivably have been linked kinematically with the lower Colorado River detachment system (R. K. Dokka, personal comm., 1986). However, the present east-west geographic separation of the two areas (Fig. 1), coupled with the NE-SW extension that was characteristic of both, complicates a picture of possible linkage.

If a pre-Whipple detachment fault system does not lie southwest of the Whipple system, then a modification of Fig. 13 would obviously be required. In that modification, mylonitic gneisses formed in a non-coaxial zone of intracrustal laminar flow might represent a midcrustal zone of delamination (higher levels displaced preponderantly northeastward with respect to lower) without direct or obvious connection to structural levels now exposed in the southwestern Cordillera. Such non-surfacing zones have been postulated beneath the present Basin-and-Range province to the north (e.g. Eaton, 1980; Klemperer et al., 1986; Gans, 1987), but discussion of their validity is beyond the scope of this paper. What does appear clear is that mylonitic gneisses that are now exposed in the Whipple Mountains formed at depth during profound Tertiary crustal extension and were carried upwards in the footwall of a kinematically-related younger detachment system. The mylonitic gneisses were not formed in an environment of pure shear or coaxial deformation — at least within the > 3.5 km structural thickness now exposed in the Whipple Mountains. The geometry of strain at deeper levels remains unresolved since the lower limit of the Whipple mylonitic sequence is not exposed. It is not known, for example, whether a lower mylonitic front defines the base of the shear zone (as in the Ruby Mountains/East Humboldt Range complex: Dallmeyer et al., 1986) or whether mylonitic tectonites simply grade downward into flow-banded gneisses formed during Tertiary reworking of the extended continental crust (as favored by the pattern of mid- to lower-crust reflections seen in Calcrust profiles; cf. Frost & Okaya, in review.

The Whipple detachment fault and the mylonitic front: an alternative hypothesis

The angular relationship between the Whipple detachment fault and the mylonitic front in its footwall (Fig. 5) is here interpreted as the consequence of the capture of older, deep-seated mylonites by a younger, more steeply dipping detachment fault system. This interpretation has been questioned by several workers. They propose, both directly (G. H. Davis, 1983) and indirectly (Spencer & Reynolds, 1986), that the angular relationship is an expression of the normal geometry of a ductile shear zone (Ramsay, 1980), i.e. that the inclined mylonitic foliation below the detachment fault represents the lower half of a sigmoidal pattern of internal foliations that are characteristic of such zones. The geometry envision-

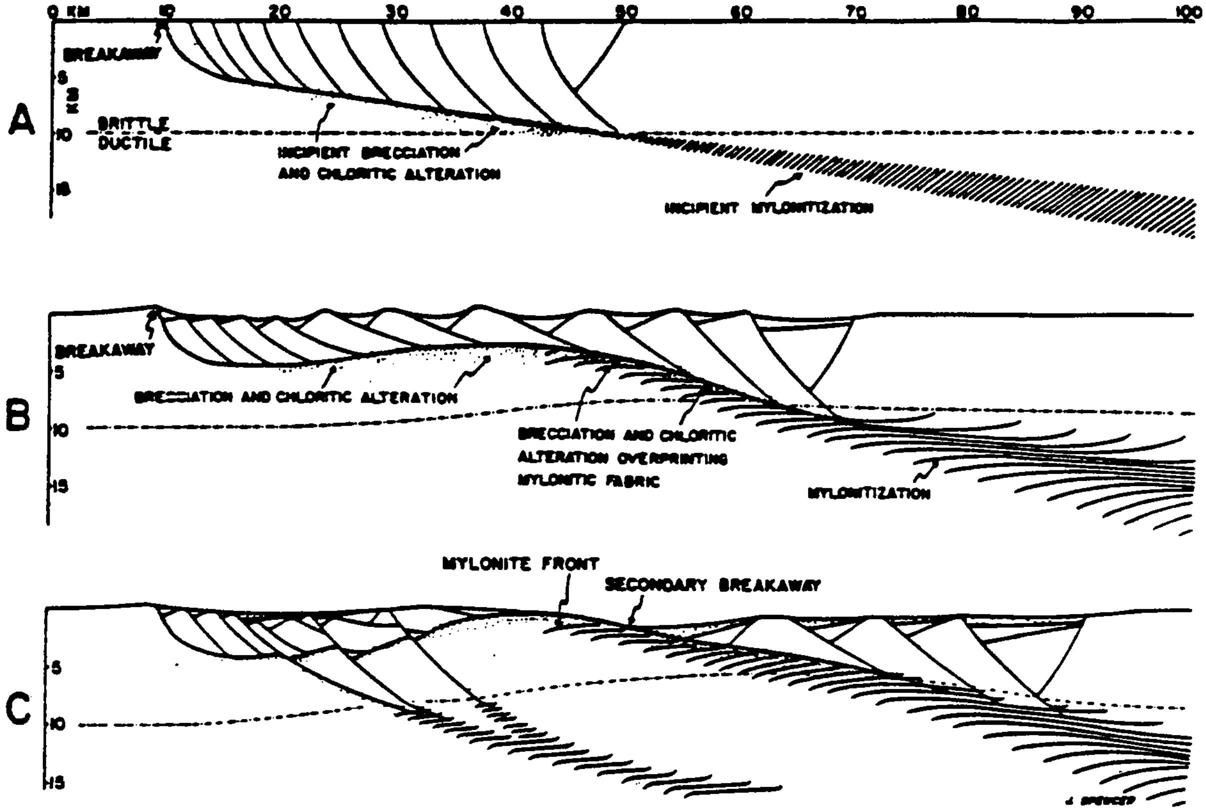

Fig. 14. Fig. 1 of SPENCER & REYNOLDS (1986). »Schematic cross sections showing the evolution of detachment faults and mylonitic detachment complexes; (a) initiation of movement on the detachment zone; (b) isostatic uplift and arching due to variable amounts of upper-plate distension; and (c) one-sided denudation of original detachment zone, and arching caused by reverse drag above structurally deeper, listric normal faults« (ibid., p. 103).

ed is illustrated in Fig. 14 (from SPENCER & REYNOLDS, op. cit., their Fig. 1) and by this quotation from G. H. DAVIS (1983, p. 346):

»Sigmoidal patterns arise when a shear zone gradually increases in thickness as deformation progresses (RAMSAY, 1980). Early formed foliations in the middle of such shear zones are rotated by progressive simple shear into near-parallelism with the boundaries of shear .... Late-stage, non-rotated foliations that form near the upper and lower margins of shear zones retain their original 45° angular relationship with the boundaries of shear .... Such a downward ›feathering‹ of foliation in a direction opposite to that of the movement sense of upper-level rocks is not unique to the Rincon Mountains. Similar patterns can be seen in cross sections ... by DAVIS et al. (1980) for the Whipple Mountains.«

Thus, interpretations of the kind proposed above consider the inclined mylonitic foliation in the footwalls of some detachment faults (e.g. the Whipple fault) to be the product of only late, relatively minor flattening strains developed adjacent to major through-going shear zones (the s-surfaces, or »schistosité«, of BERTHE et al., 1979). As illustrated in Fig. 14, such foliation or schistosity should weaken downward below the detachment fault and »feather« out into unsheared rocks. The mylonitic front is simply the upper limit of »late-stage, non-rotated« sigmoidal foliations, and it too, like the mylonitic foliation below it, should not extend to significant depths below the causative Whipple detachment fault.

Although the simplicity of the inferred geometry between detachment fault and mylonitic foliation pictured in Fig. 14 is appealing, the structural characteristics of both the mylonitic front and underlying foliation in the Whipple Mountains suggest that this interpretation is in error.

Among these characteristics are the following:

(1) the mylonitic front is an extremely abrupt upper limit for the thick (> 3.5 km) mylonitic gneisses of the Whipple lower-plate (Fig. 10); it is neither a narrow (as measured perpendicularly to the detachment fault) nor diffuse boundary between foliated and unfoliated rocks as is implied by the model presented in Fig. 14;

(2) the foliation of older gneisses and amphibolites that crosses the mylonitic front from above exhibits abrupt rotation (up to 90° or more in strike) and extreme transposition (Fig. 11) — both strain phenomena indicate the translatory nature of the mylonitic front, here interpreted to be the sharply defined upper limit of an intracrustal zone of non-coaxial laminar flow;

(3) the shear zone nature of the mylonitic gneiss se-

quence in the Whipple Mountains is clearly demonstrated by the tectonic lenses of non-mylonitized rocks contained within it (Fig. 10); these lenses, within which the steep, northeast-striking orientation of Precambrian foliation is preserved, vary in thickness from a few meters to several hundred meters; geometrically, they are analogous to shear-surface-bounded phacoids of undeformed rock seen within brittle shear zones developed at any scale;

(4) the interpretation that the southwest-dipping Whipple mylonitic front and underlying mylonitic gneisses project to depth (Fig. 13) gains support from recently acquired seismic reflection data in areas west of the Whipple Mountains; as mentioned briefly above, the mylonitic front may be represented on Calcrust reflection profiles as the abrupt top of a zone of subhorizontal, subparallel (anastomosing?), noncontinuous reflections that extend downward through the crust from a depth of 3 seconds (ca 9 km), 16 km SW of the mylonitic front, to a depth of 4 seconds (ca 12 km), 60 km to the SW.

Evidence for the rapidity of upward transport of the Whipple fault footwall

[redacted] The time of onset of mylonitization is unknown, but late syntectonic tonalite dikes were emplaced 26 ± 5 Ma ago. Much of the PT determinations come from study of reequilibrated and new mineral assemblages in Cretaceous plutons below the Tertiary mylonitic front. The deepest plutons, ca 2.5 km below the mylonitic front, are three closely spaced sheets (Fig. 6) of metaluminous hornblende-biotite quartz diorite with a composite thickness of 480 m (Anderson & Rowley, 1981) and an age of emplacement of 73 Ma (zircon, Wright et al., 1986). It is largely from the mineral assemblages of these plutons that the highest temperatures of mylonitization (535 °C) were estimated. The assumption is made here that these peak temperatures are a reasonable estimate of temperatures present at 26 Ma when the tonalite dikes were intruded into the quartz diorite plutons.

The mylonitized quartz diorite presumably remained at considerable depth for the next six or seven million years. An ^{40}Ar/^{39}Ar plateau age of 19.2 ± 0.2 Ma for neomineralized hornblende in the mylonitiz- until that time (E. Dewitt, written comm., 1986; Dewitt et al., 1986). But, neomineralized muscovite from a closely adjacent wallrock mylonite has a plateau age of 18.0 ± 0.1 Ma, an age compatible with cooling below 275 °C. The closely associated hornblende and muscovite samples thus indicate that this level of the mylonitic assemblage had cooled 175 °C in only one million years! Orthoclase from a structurally higher mylonitized granitic rock collected elsewhere in the range has a near plateau age of 18.5 Ma. This age indicates cooling of the rock below 150 °C, less than one million years after the hornblende in deeper rocks had cooled below 450°.

These Ar/Ar ages corroborate the conclusions of an earlier fission-track dating study of three Whipple mylonites collected from just below the Whipple fault by Dokka & Lingrey (1979). They found that five fission-track age determinations (three from zircons, one each from apatite and sphene) yielded concordant ages that varied from 17.9 to 20.4 Ma, with an overlap of error bars between 18.4 and 19.5 Ma. Because the three analyzed mineral species have different fission track closure temperatures their concordant ages led Dokka & Lingrey (ibid.) to conclude that the mylonitic gneisses had experienced a significant temperature drop (> 80°, < 220 °C) between 18 and 20 Ma (this early temperature estimate is still compatible with more recently accepted closure temperatures: sphene, ca 285 °C, Zeitler et al., 1982; zircon, ca 205 °C, ibid.; apatite, 70 – 130 °C depending on the rate of cooling, Dokka et al., 1986). Dokka & Lingrey attributed this sudden cooling to rapid uplift and tectonic denudation, although in 1979 the role of the Whipple fault in accomplishing this uplift was not known.

Rapid upward transport of mylonitic gneisses in the footwall of the Whipple detachment fault system, suggested by the rapid cooling of these rocks, is supported by field studies indicating (1) high collective rates of slip along Whipple system faults after 20 Ma, and (2) the incorporation of lower-plate mylonitic gneisses — as eroded clasts and an extensive landslide (?) block (Dunn, 1986) — into now-detached upper-plate Miocene strata older than 16 Ma. The Whipple fault truncates a distinctive lower-plate assemblage of rocks that includes a major Tertiary dike swarm and a younger composite mafic pluton (19.8 Ma) that intrudes both it and the mylonitic front (Fig. 11; Davis & Lister, in press). An upper-plate dike swarm in the Mohave Mountains of Arizona to the northeast (M, Fig. 1) appears to be the offset equivalent of the Whipple swarm. If so, at least 40 km of displacement (horizontal component) has occurred between rocks of the two ranges after approximately 20 Ma (the age

We can calculate the rate of slip along an inclined Whipple fault during the interval 20 – 16 Ma if a constant rate of slip is assigned to the Whipple fault system between 20 Ma and 16 Ma (the approximate age of post-detachment volcanic rocks in the nearby Buckskin Mountains, Fig. 1). If certain assumptions are made — (1) that the Whipple fault had an average dip through the upper crust of 25° (see earlier discussion), and that (2) mylonitic gneisses captured by the fault were displaced from a minimum depth of 12 km to near surface levels during the four million year time interval — an average slip rate of approximately 7.2 mm/Yr (ca 28.6 km in 4 Ma) is obtained, certainly not a geologically unreasonable value. These same assumptions give an average uplift rate over the 4 million year interval of 3 mm/yr. Even higher slip and uplift rates are probable for the period 20 – 18 Ma in order to explain (1) the observed rapid cooling of footwall mylonites during that interval, and (2) the fact that most major tilting of Tertiary strata along upper-plate normal faults in the Whipple-Mohave region occurred just before or after the deposition of a widespread ash-flow tuff unit with a probable age of 18.3 Ma (GLAZNER et al., 1986; DAVIS, 1986b).

DAVIS & LISTER (in press) attribute most of the rapid cooling of Whipple mylonitic gneisses to the upward transport of mylonitic gneisses from mid-crustal to near surface levels in the active footwall of the inclined Whipple fault system. During detachment faulting, the Whipple upper plate behaved relatively passively. Tectonic attenuation within it by brittle normal faulting is locally pronounced, but overall, upper-plate attenuation is a totally inadequate mechanism to effectively bring lower-plate mylonites formed at depths > 12 km to surface or near surface levels (cf. Whipple cross-sections. Figs. 10, 11 and 13 in DAVIS & LISTER, in press).

Isotopic age data and geologic relations indicating rapid uplift of mid-crustal rocks in the Whipple region during Miocene time are in close accord with the conclusions of recently published studies of the Ruby Mountains/East Humboldt Range metamorphic core complex in eastern Nevada (DALLMEYER et al., 1986; DOKKA et al., 1986). Relying largely upon ^{40}Ar/^{39}Ar hornblende and biotite plateau ages, DALLMEYER et al. (ibid.) conclude that lower-plate rocks of the Ruby-East Humboldt detachment fault — amphibolite grade metamorphic rocks and mylonitic gneisses derived from them — experienced rapid, but diachronous cooling from above 500 °C to below 300 °C between 45 to 20 Ma ago (between 26 and 21 Ma ago in one area of the range). In a companion fission track study (the most complete in any Cordilleran core complex to date),

lonitic rocks in the upper part of the Ruby-East Humboldt detachment zone indicate cooling from temperatures above 285 °C to below 70 °C between 25.4 and 23.4 Ma ago (DOKKA et al., ibid.).

Conclusions

A thick (> 3.5 km) sequence of mylonitic gneisses in the footwall of the Miocene Whipple detachment fault, southeastern California, was formed at mid-crustal depths (16 ± 4 km) and at temperatures compatible with upper greenschist to lower amphibole facies metamorphic grade (485 ± 35 °C to 535 ± 44 °C; ANDERSON, in press). The protoliths of the mylonitic rocks include Proterozoic gneisses and amphibolites, subhorizontal sheetlike Cretaceous granitic plutons of peraluminous and metaluminous composition, and synkinematic (26 ± 5 Ma) tonalite dikes and sills. Microstructural analysis of the mylonitic gneisses by G. S. LISTER indicates that most have fabrics compatible with formation in a non-coaxial ductile shear zone within which structurally higher levels were displaced northeastwards with respect to lower.

Two extensional tectonic settings are deemed most likely for the ductile shear zone: (1) it represents the down-dip, mid-crustal portion of an evolving low-angle shear system of WERNICKE (1981)-type (cf. DAVIS et al. 1986); or (2) it represents a zone of intracrustal delamination below the stress guide defined by the continental brittle-ductile transition, a zone which lacks direct or obvious connection to structural levels now exposed in the southwestern U.S. Cordillera. The geometry of strain at structural levels below the Whipple mylonitic sequence is unknown.

Whatever their specific environment of formation, the mylonitic gneisses were crosscut by the low-angle Whipple detachment fault system at depth and rapidly transported to surface levels in the active footwall of that evolving shear system. The gneisses and the Whipple detachment system exhibit kinematic coordination (same sense of shear, same direction of extension). However, the angular truncation by the Whipple fault of the footwall mylonites and the mylonitic front which represents their structural top indicate that the fault is younger than the ductile shear zone — perhaps 6 to 7 million years younger based on recent geochronologic information (WRIGHT et al., 1986; DEWITT et al., 1986). Fission track and ^{40}Ar/^{39}Ar age determinations collectively document rapid cooling of the mylonitic gneisses from above 450 °C to below 200 °C between 20 and 18 Ma ago. Lower-plate mylonites reached the earth's surface during detachquence, and younger, detachment fault-related chloritic breccias were deposited in upper-plate Miocene fanglomerates and debris flows in the northeastern Whipple Mountains (DUNN, 1987). These Tertiary units were later rotated along upper-plate normal faults and truncated from below by the youngest detachment fault in the Whipple system. The SW-tilted, mylonite clast-bearing Miocene units are older than 16 Ma, the approximate oldest age of subhorizontal, post-tectonic alkaline basalt flows in the Buckskin Mountains, southeast of the Whipple Mountains, Fig. 1 (cf. DAVIS and others, 1982).

If the capturing Whipple fault system had an average dip of 25° throughout the upper crust — an angle compatible with field relations in the Whipple Mountains as described above —, and if the mylonites lay at a minimum depth of 12 km at the time of capture, then their transport to the surface could have been accomplished by fault displacements of 7.2 mm/Yr during the 20 to 16 Ma interval. The vertical uplift component of this displacement would be equal to or greater than 3 mm/Yr. From fission track and argon-argon cooling data, higher rates of both uplift and slip along the Whipple fault system are likely for the period 20 to 18 Ma ago. Cumulative offset of a Tertiary dike swarm across detachment faults of the Whipple system probably exceeds 40 km, a displacement value compatible with the consequences of high slip rates over several million years. The results of recent studies in the Whipple Mountains by the writer and his colleagues ANDERSON, LISTER, DEWITT & WRIGHT documenting rapid, detachment-related uplift of mid-crustal rocks to the earth's surface are not unique in the U.S. Cordillera. Our results are closely corroborated by recently published studies from the Ruby Mountains and East Humboldt Range of northeastern Nevada (DALLMEYER et al., 1986; DOKKA et al., 1986). Here, too, lower-plate mylonitic rocks show rapid cooling attributed to rapid uplift and tectonic denudation.

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