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The origin of metamorphic core complexes and detachment faults formed during Tertiary continental extension in the northern Colorado River region, U.S.A.

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Abstract—Metamorphic core complexes form as the result of major continental extension, when the middle and lower continental crust is dragged out from beneath the fracturing, extending upper crust. Movement zones capable of producing such effects evolve in space as well as with time. Deforming rocks in the footwall are uplifted through a progression of different metamorphic and deformational environments, producing a characteristic sequence of (overprinted) meso- and microstructures. The movement zone is folded as the result of the bowing upwards of the lower crust to form a broad basement culmination, as the result of isostatic rebound due to tectonic denudation, but most likely also as the result of local isostatic adjustments due to granite intrusion in the middle crust. A succession of splays branch off from the master detachment fault at depth, excising substantial portions of the lower portions of the upper plate as successive detachment faults eat upwards through it. At the same time, detachment faults incise into progressively deeper levels of the lower plate, although the amount of incision is limited, because the locus of movement remains at approximately the same level in the lower plate. The detachment faults presently observed in the metamorphic core complexes are relatively young features, formed late in the geological evolution of these bodies, and are only the last in a succession of low-angle normal faults that sliced through the upper crust at the upward terminations of major, shallow-dipping, ductile shear zones in the extending Cordilleran orogen. Excisement of listric fault bottoms can explain some of the enigmatic domino-like fault blocks, and other structural relations observed in these terranes. Evidence in support of this model is illustrated from detachment terranes in the northern Colorado River region of southern Nevada, southeastern California and western Arizona, where multiple generations of detachment faults have produced remarkable excisement and incisement geometries.

INTRODUCTION

DURING the last decade, considerable research has been carried out on curious geological terranes in the western United States known as Cordilleran "metamorphic core complexes" (Crittenden *et al.* 1980, Frost & Martin 1982). This work has attracted increasing attention as it becomes clearer that core complexes constitute a newly recognized phenomenon in the earth sciences with far ranging implications for the tectonics of continental extension. Cordilleran metamorphic core complexes appear to be bodies from the middle crust that have been dragged out from beneath fracturing and extending upper crustal rocks, and exposed beneath shallow-dipping (normal-slip) faults of large areal extent.

The detachment fault is probably the most spectacular, as well as the most controversial, feature of the Cordilleran metamorphic core complexes. The shallow-dipping Whipple detachment fault of southeastern California, and western Arizona, for example (Fig. 1), has an areal extent in excess of 10,000 km^2, involves a relative displacement of at least 40 km, and juxtaposes rock types with radically different geological histories (Davis & Lister 1988). In the Whipple Mountains, just the exposed portion of the detachment fault is more than 30 km long in the direction of relative transport. We term these large-area low-angle normal faults 'detachment faults' mainly for historical reasons, as discussed by Davis & Lister (1988).

In all of the core complexes, the upper plate (above the detachment fault) is intensely fractured. It has clearly been subjected to significant horizontal extension, utilizing multiple generations of high-angle normal faults, some of which now have shallow-dipping orientations. These fault blocks comprise rocks from the upper crust (at the time of extension). In Arizona and California such rocks include Precambrian metamorphic and igneous rocks which acted as basement for varied Cambrian through Miocene supracrustal sequences. Multiple generations of faults of various types can be found in the upper plate, including listric normal faults, sub-parallel sets of planar, variably-dipping high-angle normal faults, as well as planar low-angle normal faults. The sub-parallel arrays of planar, moderate- to high-angle, normal faults are often referred to as domino faults. Fault-bounded blocks often as large as 1–2 km across have undergone large rotations, usually in the order of 20–60° but locally (for example in parts of the Whipple Mountains) rotations in excess of 90° are observed.

The intention of this paper is to discuss specific questions concerning the origin of metamorphic core complexes, attempting to explain detachment faults, and associated structures. We have used the results of fabric and microstructural work in more than a dozen of the metamorphic core complexes in Arizona and California. The model has been synthesized primarily as a result of field investigations in the Whipple Mountains, California, and the South Mountains, Arizona (Davis *et al.* 1986, Reynolds & Lister in review), but detailed observations have been made in several other core complexes (for example in the Ruby and Snake Ranges in Nevada). We are convinced the model is more widely applicable than just to the Whipple and South Mountains.

MODELS FOR THE GEOMETRY OF EXTENSION OF THE BRITTLE UPPER CRUST

The upper part of the continental crust appears to extend through the operation of normal faults. Early models (Fig. 2) envisaged the transition between the region of brittlely stretching upper crust and the ductilely stretching lower crust as a flat fault. Such models (e.g. see Miller *et al.* 1983) sought to explain the detachment fault observed in the metamorphic core complexes as equivalent to this brittle–ductile transition, since the detachment fault apparently separates the brittlely deformed upper plate from the ductilely stretched crust underneath. This model brought with it many problems, mostly of a mechanical nature, and in its simplest form, it has now been discarded. First, the nature of the brittle–ductile transition is considerably more complex than such a diagram implies. Second, in all the core complexes, the ductilely deformed rocks beneath the shear zone, once thought to have been deformed by stretching of the crust in pure shear (e.g. Davis *et al.* 1982, Miller *et al.* 1983) now appear to be the result of ductile deformation in crustal-scale shear zones.

We will return to these points, but first we introduce simple mechanical concepts and develop some background information.

The continental stress guide

The fracture strength of rock increases gradually downwards (in the absence of significant amounts of lithostatically pressured pore fluid). It may attain a maximum value in the region where gradually increasing temperature allows significant ductile flow (e.g. as the result of crystalline plasticity). Ductile relaxation at these depths may prevent the build up of large deviatoric stresses necessary for seismic failure (Chen & Molnar 1982). The strength properties of the continental crust might be approximated in terms of elastic–perfectly plastic yield envelopes, using the concept of the depth dependence of the rheology of the continental crust (e.g. Meissner & Strehlau 1982, Chen & Molnar 1983, Sibson 1983, Smith & Bruhn 1984). The strength maximum at about the depth of the brittle–ductile transition has been suggested in order to explain the distribution of seismic activity in continental crust. This proposed depth dependence of 'yield stress' implies that a diffusely bounded layer in the continental crust at about the depth of the brittle–ductile transition has superior strength properties, and therefore this layer will act as a crustal-scale stress guide (Fig. 3).

If the continental crust was extended by an instantaneous increment of uniform stretching, the deviatoric stress increase would be the same at any depth, regardless of the strength. Rocks at depth would relax this deviatoric stress build-up by ductile flow, and the hotter the rock, the quicker it would relax away any stress increase. In the surficial regions (i.e. down to 8 km), if this build-up of deviatoric stress continued, it will be relieved periodically by small seismic events. Gradually, with time, the load will be transferred to the strongest region, at about the depth of the brittle–ductile transition. The magnitude of earthquakes must therefore slowly increase, until finally, in a major catastrophic event, the stress guide itself is faulted, by a rupture which cuts through it, into the zone in which rocks for most of the time deform ductilely.

Stress is concentrated into a stress guide as the result of failure or yield or flow of the material on either side, since this results in transfer of load to the stronger, and hence still elastically deforming material. Such stress transfer can be envisaged by considering the effect of steel rods in progressively loaded reinforced concrete. Deformation results in failure or flow in weaker levels of the crust, so stress transfer takes place to the layer in which maximum load-bearing capacity resides. This diffusely bounded layer (from 8 to 15 km depth) will have the highest levels of deviatoric stresses, contain the maximum elastic potential energy, and it will be the source of most continental seismicity (Sibson 1982, 1983). The largest earthquakes occur when this continental stress guide catastrophically fails (Chen & Molnar 1982, Sibson 1983). The focus of such earthquakes is generally at depths between 8 and 12 km. The seismic rupture propagates upwards, towards the surface, as well as propagating downwards, reaching depths of 15–16 km in a large magnitude seismic event (Jackson 1987).

Steeply-dipping deeply-biting planar normal faults

The behaviour of the stress guide fundamentally influences how the crust responds to orogeny. One particularly apt example of the effect of a stress guide comes from mesoscopic shear zones. Competent layers in the stretching field are boudinaged, or they develop domino-like arrays of tilted blocks. The same type of phenomenon may apply on a crustal scale when the lithosphere is extended.

Modern-day active continental extension apparently involves deeply-biting planar normal faults (Fig. 4). Seismological observations show that major steeply-dipping normal faults remain planar to 10–16 km depth

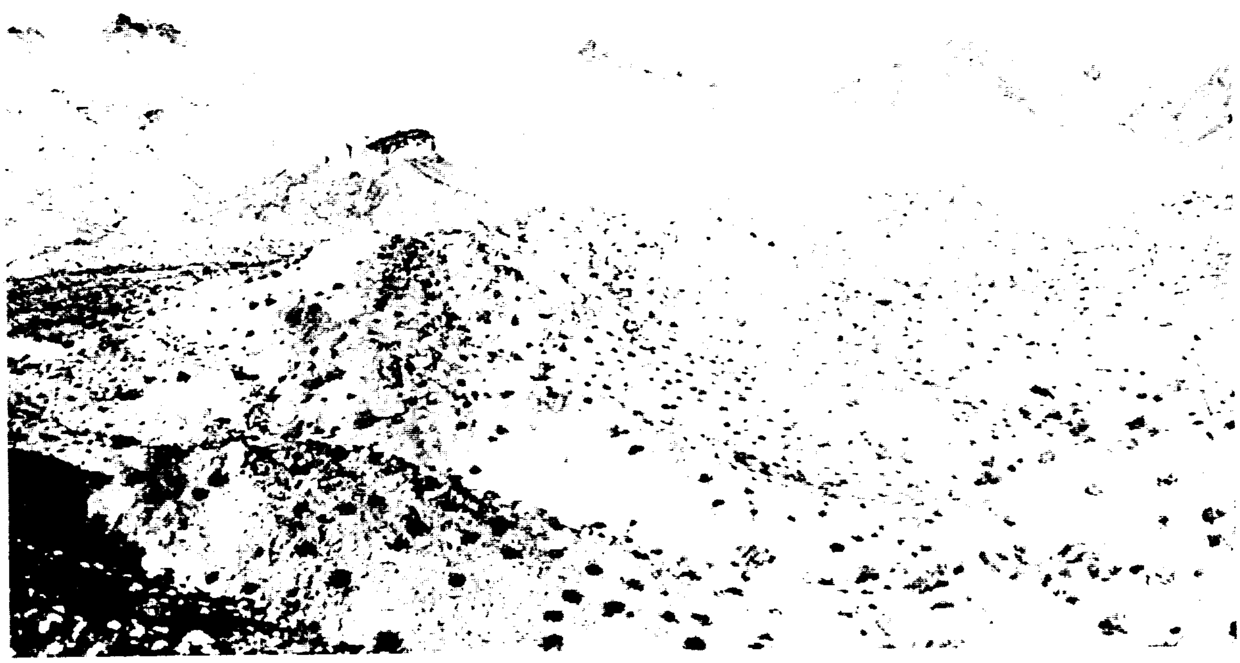

Fig. 1. The detachment fault is one of the most spectacular features of the Cordilleran metamorphic core complexes. This photograph of Whipple detachment fault (areal extent >10,000 km^2), taken from a powerline road in the eastern Whipple Mountains, shows klippen of Miocene volcanics overlying Precambrian metamorphics.

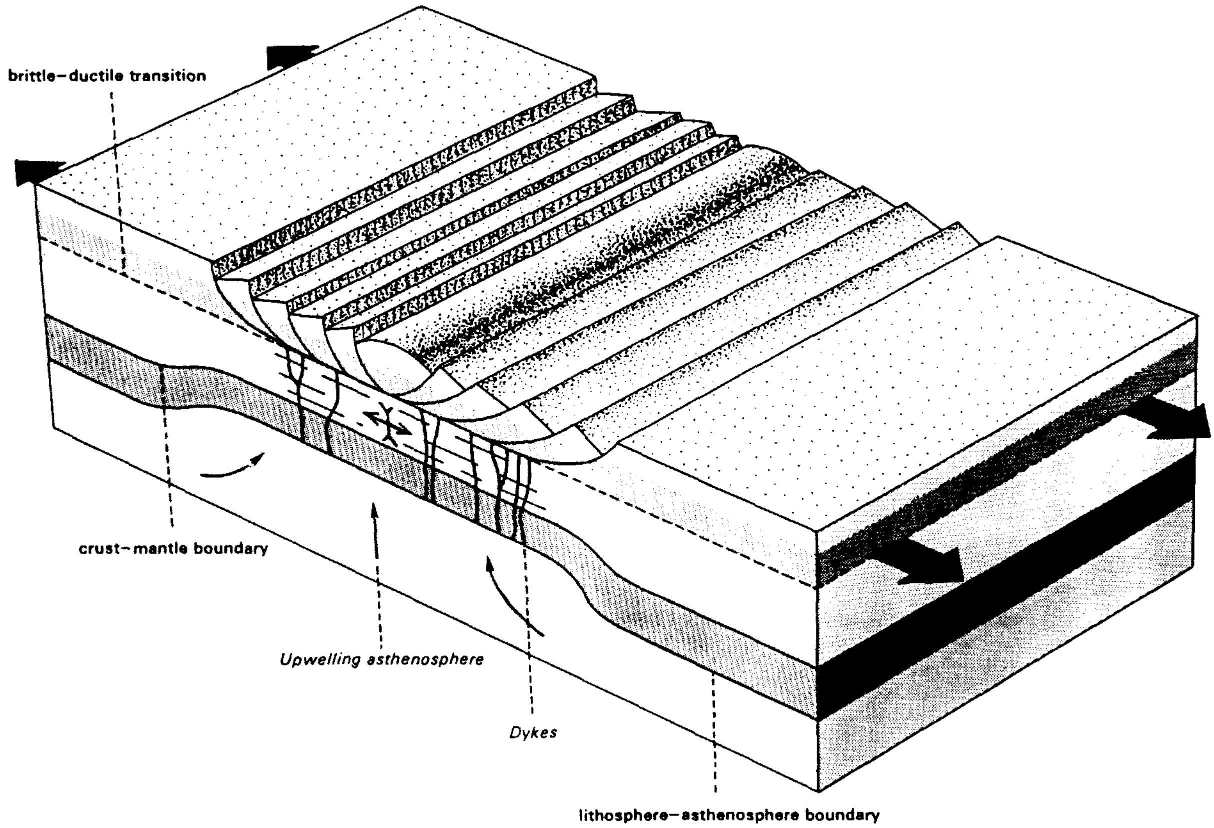

Fig. 2. Three-dimensional illustration of the symmetric pure shear model for continental extension. The detachment fault is seen as representing an ancient brittle–ductile transition in the Earth's crust. Brittle deformation in the upper plate is synchronous with ductile deformation in the underlying lower plate, which is the result of bulk coaxial extension as the entire lower part of the lithosphere uniformly stretches.

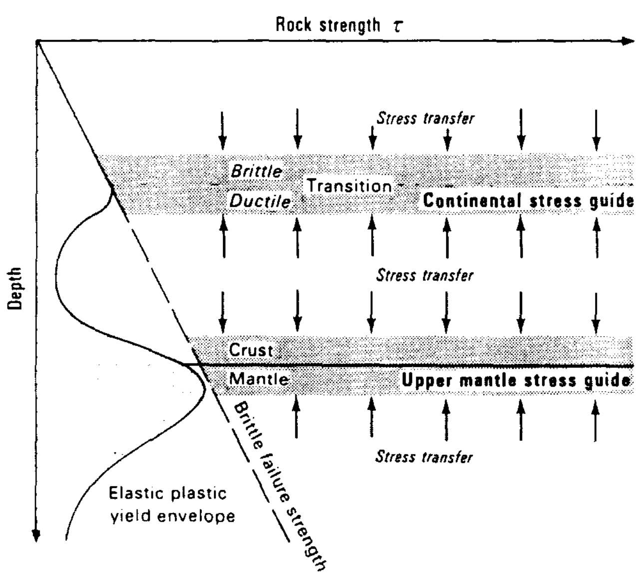

Fig. 3. Depth-dependent rheology of the continental crust, assuming the concept of an elastic–perfectly plastic rheology (after Chen & Molnar 1983). The strength maximum around the depth at which the brittle–ductile transition takes place defines the continental stress guide.

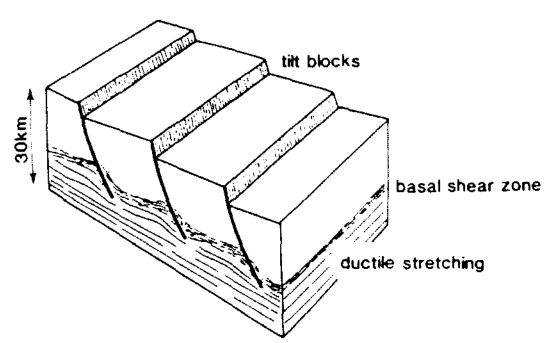

Fig. 4. Seismological observations tell us that the continental crust extends now as the result of arrays of steeply-dipping, deeply-biting normal faults. Crustal-scale rotating tilt blocks are bounded at depth by ductile shear zones that relax stresses built up around the base of a normal fault after a seismic rupture. The shear zones must be shallow dipping to accommodate strain incompatibilities between the ductilely stretching lower crust and the brittlely extending upper crust.

(Eyidogan & Jackson 1982, Jackson & McKenzie 1983, Nábelek & Eyidogan in press). The fault plane in such ruptures does not appear to be listric (Eyidogan & Jackson 1984, Jackson 1987, Nábelek & Eyidogan in press), although curvatures of up to 10–15° are not ruled out. Nábelek has shown that the dip of one such large normal fault varied less than 10° in this entire depth range. If arrays of such faults are involved, they are spaced 15–40 km apart. There is a complete lack of seismological evidence for active large-area, low-angle (i.e. less than 30° dip), crustal-scale normal faults in these extending terranes (Jackson 1987).

In the period preceding the largest earthquakes, there must be a gradual build up in the level of deviatoric stress in the crust. Above the diffusely bounded stress guide discussed in the previous section, the crust fails by faulting, but the faults are relatively small, and they do not penetrate deep into the crust. Below the stress guide, ductile flow relaxes the accumulating elastic stresses, so that lower stress levels are maintained. When the great earthquake occurs, it breaks the stress guide and bites deep into the rocks below. Prior to this time these rocks were ductile. The propagation of the rupture into this region means that a stress rise must occur. In the period of post-seismic relaxation, these stresses must be relaxed, in large part by ductile creep.

Prior to failure, as the stress reaches critical levels (relative to the local fracture stress), dilatancy increases, and fluids are sucked into the region of the stress guide (Sibson 1977). After the seismic rupture has propagated, these fluids are expelled, upwards along the fault plane, where they become involved in shallower level circulation systems, but also downwards, below the normal level of the brittle–ductile transition, into regions where fluid pressures are generally lithostatic. Since the seismic rupture propagated downwards from the stress guide into regions which normally flow ductilely, dilation on this fault will suck fluid from higher levels in the crust downwards, into the zone below the stress guide.

In the period of post-seismic relaxation, the stress rise at the base of the fault will be dissipated. The stress rise could be relaxed by attempting to drive the normal fault backwards, with a reverse motion. Alternatively, a shallow-dipping ductile shear zone could form, with the conjugate sense of shear, coincidentally the same as that during the primary motion. The fluids which have been driven downwards into the lower parts of the fault zone will be sucked into this ductile shear zone, as the result of the small but penetrative grain-scale dilatancy that accompanies crystal–plastic behaviour in the transitional region, allowing retrograde metamorphic reactions to take place. The operation of these large faults drives cycles of fluid motion.

The ductile shear zones formed at the base of a large normal fault must accommodate strain incompatibility between the brittle upper crust, and the ductile lower crust (Fig. 4). In this figure the upper crust is shown extending as the result of the operation of an array of steeply-dipping deeply-biting normal faults, dividing the crust into a sequence of tilt blocks which slowly rotate (domino-style) to allow extension to proceed. At the deepest levels, the crust is subject to ductile stretching, approximating bulk pure shear. In the transition zone, ductilely stretching rocks are cut periodically by faults when large earthquakes take place. When such a catastrophic event occurs, the normally ductile rocks at depth are cut by the downwards propagating normal fault. A transient stress rise results, which must be subsequently relaxed by ductile flow. If the crust beneath is subject to continuous stretching, then strain incompatibility requirements demand that *shallow-dipping ductile shear zones must form at the base of these large normal faults.*

Should one of these large fault blocks be tilted to such an extent that its base was exposed at the surface, what we would see would look very much like a metamorphic core complex (Fig. 5). There would be a large flat normal fault, tilted over from *ca* 60° to an orientation somewhat less than 30°. The metamorphic grade would increase in the down-dip direction of the fault. The fault would cut through mylonites in the lower plate that had been rapidly uplifted. These mylonites would curve towards parallelism with the fault, and increase in their metamorphic grade downwards. The amount of strain recorded in the mylonites would increase in the down dip direction of the fault. There would be a retrogressive overprinting sequence of microstructures in a shear zone, culminating in all structures being transected by brittle faults.

There is some support for such a model. Davis (1983) describes crustal-scale fault blocks bounded by shear zones at deeper levels. As extension proceeds, the domino-like blocks are rotated, and the once high-angle normal faults and ductile shear zones are rotated into shallower orientations. Some metamorphic core complexes might turn out to be examples of the phenomenon (e.g. the Pinaleno Mountains in Arizona). However, we do not believe this to be the origin of the core complexes exposed in the extensional terrain bordering the Colorado River in California and Arizona.

We emphasize that field data from this region support the notion that detachment faults form in shallow-dipping orientations (Davis & Lister 1988). There are no

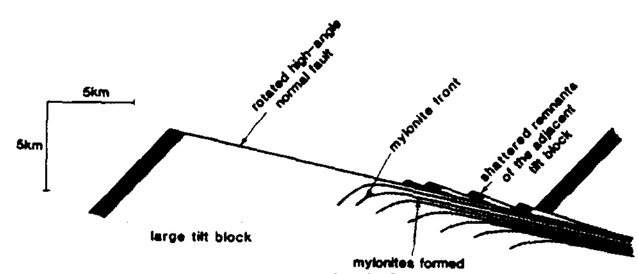

Fig. 5. One model for the origin of metamorphic core complexes is the domino-like rotation of crustal-scale tilt blocks. One such tilt block lying on its side would have many of the characteristics exhibited by a metamorphic core complex. The model supposes that the detachment fault is a rotated high-angle normal fault, but this requires a much larger variation in metamorphic grade along the crustal section thus exposed than is actually observed. (This is not the interpretation we propose. A more realistic model is shown in Fig. 20.)

major changes in the metamorphic grade of the lower plate across terrains exposed in excess of 20–30 km in the 'down-dip' direction of the detachment fault. Using fracture analysis, the orientation of σ_1 in the upper plate can be constrained to have been steep to vertical (Reynolds & Lister 1987, Reynolds & Lister in review). Segments of the upper plates are shallow-dipping over significant areas. The youngest faults are shallow-dipping. These observational data constrain the possible modes of origin of the detachment faults, and eliminate the crustal-scale domino model as a *panacea*. We are forced to look at the question of the origin of metamorphic core complexes and detachment faults in the light of the field data which leads inexorably to the conclusion that shallow-dipping faults of large areal extent (maybe as steeply dipping as 30°) have been formed in extending continental crust (Davis & Lister 1988).

The formation of a shallow-dipping (thrust) fault is easy to explain in compression, but more difficult to explain (from the point of view of rock mechanics) during extension. To date, in analogue experiments, no-one has succeeded in making a detachment fault without use of a *décollement* horizon. The preferred mode of deformation is the formation of arrays of steeply-dipping domino-faults.

Listric normal faults vs domino-faults

In the light of the above, with the increasing emphasis placed in the literature on domino-faults in extending terrains, it is worth again stepping back, and re-examining what we know about how the upper crust extends. Two general models for the fault geometry have been proposed. One model proposes that extension of the upper plate is caused by arrays of listric normal faults (see Davis *et al.* 1980). Rotation of the upper plate strata occurs in the hangingwalls of listric faults as the result of reverse drag caused by gravitationally induced sag (Hamblin 1965). This model for extension of the upper plate supposes the formation of several successive generations of listric normal faults, with new faults forming as geometric constraints impede the continued operation of older structures. Simultaneous operation of arrays of closely spaced listric normal faults has *not* been envisaged. Nor is it likely.

The other model (described above for the crustal scale) involves closely spaced arrays of parallel high-angle normal faults, and domino-like rotations of intervening fault blocks as extension takes place (e.g. Proffett 1977, Gans & Miller 1983). Older faults lock up as fault blocks rotate, because resolved shear stress on the fault planes is thereby diminished. New arrays of domino-faults eventually form, cutting across older fault blocks. This type of behaviour has been reported in the upper plate of the Snake Range 'décollement', where the youngest normal faults are always the steepest dipping, and these cut older, more shallow-dipping normal faults. This data is consistent with simple mechanical concepts of how faulting takes place during continental extension, and the seismological data summarized briefly above. The domino-fault model has been given new popularity (on a crustal scale) with recent emphasis on the significance of seismological observations.

It is unlikely that one type of fault operates exclusively of the other. A general scenario for extension of the uppermost continental crust probably includes simultaneous operation of listric normal faults as well as parallel arrays of domino-faults. Both fault types are commonly inferred in seismic sections showing the effects of syndepositional listric normal faulting (e.g. Christensen 1983). Such a geometry was probably also applicable in the early history of the Basin and Range province. Many authors (e.g. Wernicke & Burchfiel 1982, Gans & Miller 1983, 1984, Jackson & McKenzie 1983) have suggested the master faults in the extensional terranes are listric normal faults with domino-like arrays of normal faults operating in their hangingwalls. In any case the seismological data does not demand that all major normal faults are originally steeply dipping. It merely constrains the orientation of major normal faults that have been seismogenic, to lie typically in the range 30–60°. A normal fault which formed at 30°, and penetrated 16–20 km deep into the crust could be the precursor of detachment faults observed today in the Basin and Range. Such a shallow-dipping normal fault may well become listric in the upper few kilometers of the crust.

Detachment faults

Finally we turn to the question of the origin of detachment faults, hoping that by now the reader is not thoroughly confused, and not still looking for a simple solution. How does a detachment fault relate to the above? There are many enigmatic aspects to consider.

The domino-model is consistent with modern seismological observations. Some 'detachment faults' may well turn out to be rotated high-angle normal faults, and thus fit the domino-concept. Other data convinces us that particular detachment faults formed at shallow-dipping orientations. We make particular reference to the Whipple detachment fault. Contrary to what the domino-model predicts, *the youngest faults are not always the steepest upper plate structures*. In fact, *the youngest faults in the metamorphic core complexes appear to be (portions of) the presently visible detachment faults*. These shallow-dipping normal faults cut (and abruptly terminate) many older, more steeply-dipping normal faults.

This single fact forces one to accept that the domino-fault model is limited and that serious attention needs to be given to alternative models. For the domino-fault model is based on the assertion that the youngest structures are always those which are the steepest dipping. Although the domino mechanism proposed by Gans & Miller (1983) may apply to large segments of the upper plate above the detachment fault, it is by no means generally applicable. Domino-faulting might eventually be shown to have little bearing on arguments concerned with the nature and origin of detachment faults.

Crustal-scale ductile shear zones formed during continental extension and their relation to detachment faults

Several workers have now proposed models for continental extension based on the operation of shallow-dipping crustal shear zones and/or low-angle normal detachment faults (Rehrig & Reynolds 1980, Davis & Hardy 1981, Wernicke 1981a, b, 1983, 1985, Reynolds 1982, 1985, Brun & Choukroune 1983, Davis 1983, 1987, Davis *et al.* 1983, 1986, Lister & Davis 1983, Bartley & Wernicke 1984, Lister *et al.* 1984a, b, 1986, Howard & John 1987, John 1987, Davis & Lister 1988). The simplest such model (Fig. 6) involves a narrow zone of relative movement which passes through the entire crust or lithosphere, such as the low-angle normal faults first proposed by Wernicke (1981a, b).

The concept that detachment faults represent whole lithosphere dislocations is attractive, but it requires the faults to have remarkable persistence. An alternative is that detachment faults are merely upper crustal manifestations of shallow-dipping, normal-slip shear zones which widen with depth, as suggested by Reynolds (1982, 1985), Davis *et al.* (1983, 1986), Lister *et al.* (1984a, b) and Wernicke (1985). The essence of all these models, however, is that continental extension takes place primarily as the result of relative movement on low-angle normal faults and shallow-dipping shear zones, as one half of the extending terrane is pulled out from underneath the other. Invariably, these models envisage the detachment fault as the upward extension of the crustal-scale ductile shear zones.

The controversy?

We are moving (slowly) towards the statement that although field data suggest that normal faults of large areal extent actually *do* form during continental extension, there is little understanding of why this should be so. That such a phenomenon should exist, seems contrary to basic principles of rock mechanics. It seems also to contradict modern seismological observations, particularly if one is of the point of view that any very large fault which cuts the crust should be seismically active. The problem is confounded by the difficulty of making field observations which truly constrain the argument. As a result, many different theories have been put forward for the origin of detachment faults, none of which so far appear to have completely resolved the issues at hand.

As we noted above, modern-day active continental extension apparently involves deeply-biting planar normal faults (Fig. 4). If detachment faults are active in these terranes, they do not produce major earthquakes. Seismically active large normal faults do not appear to have significant listric character. If they flatten with

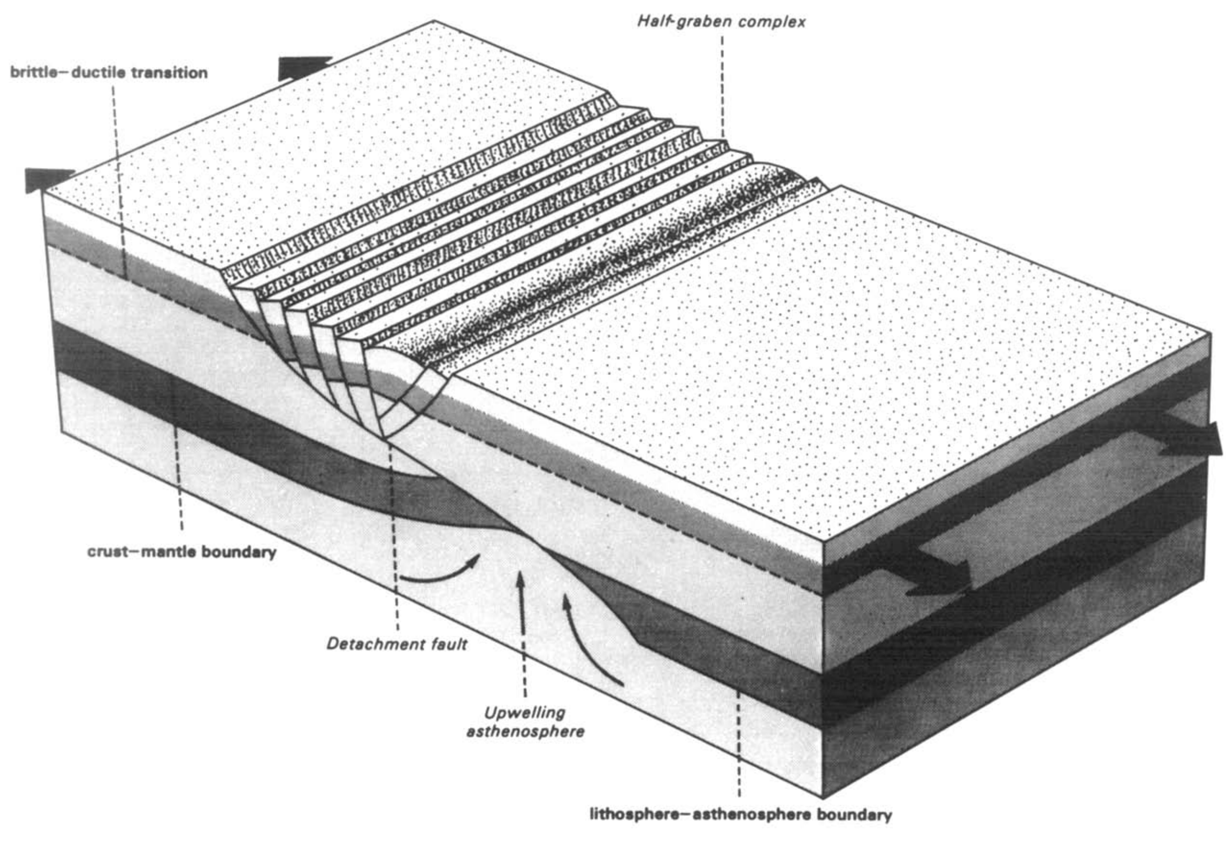

Fig. 6. Extension of the continental crust using a single lithospheric dislocation, after a model presented by Brian Wernicke at the Geological Society of America convention at Salt Lake City in 1983. The detachment fault represents the upper levels of a shallow-dipping shear zone that passes all the way through the lithosphere.

depth, they must do so beneath the depths at which earthquakes nucleate. It is difficult to imagine simultaneous operation of detachment faults which remain shallow-dipping over distances in excess of 15–40 km in such terranes, since the detachment faults would be cut by these major normal faults and rendered inactive.

Conversely, data from ancient extending terranes preclude closely spaced steep arrays of deeply-biting normal faults. It is difficult to imagine large-area, low-angle normal 'detachment faults' in such terranes, without them being chopped up by steeper fault arrays. Yet as shown for the Whipple Mountains in Fig. 1, areally extensive detachment faults overlying relatively undisrupted lower plates are characteristic of the detachment terranes, which underwent continental extension less than 20 Ma ago. In these detachment terranes, contrary to expectations based on simple mechanical models for fault geometry during continental extension, the youngest normal faults are not in general those which are the steepest dipping. This is very difficult to explain in mechanical terms.

Detachment faults have been interpreted as unconformities, thrust faults, thrusts re-activated as low-angle normal faults, high-angle normal faults that have been rotated into gently inclined attitudes, as surfaces representing an ancient brittle–ductile transition in continental crust, and as low-angle normal faults in their own right. The symmetric *pure shear* model (Fig. 2) envisages the detachment fault as representing an ancient brittle–ductile transition in the crust. The model proposed by Wernicke (1981a, b, 1983, 1985) envisages the detachment fault as representing the upper part of a major, through-going, lithospheric dislocation (Fig. 6), which may be represented by a narrow ductile shear zone in its lower levels.

THE BRITTLE–DUCTILE TRANSITION

Critical to the discussion of the tectonic setting for detachment faults and their mylonitic lower plates is the nature of the brittle–ductile transition, and the possible relationships detachment faults or ductile shear zones might have to this transition. At first sight, the detachment fault itself might be taken as representing the brittle–ductile transition, since it separates brittlely deformed from ductilely deformed rocks. This simple model, however, is highly unlikely.

The importance of scale

The term 'brittle' is one which is scale dependent, and it has different implications applied on the scale of a thin section compared to when it is applied on the scale of the crust. When we use 'brittle' in this paper, we mean 'formation of a macroscopic plane of failure', or in other words that 'faults form'. On the scale of a thin section, this usage is also correct, but it is important to qualify the scale on which the assessment of mechanical behaviour is made. In the case of a mylonite deforming both by crystal–plastic behaviour of quartz, and cataclastic behaviour of feldspar, the rock is nevertheless deforming ductilely on the mesoscopic scale. The 'brittle–ductile transition' is a term coined to describe the transition from faulting to flow (see Paterson 1978).

The seismic–aseismic boundary

It has been suggested that the brittle–ductile transition is equivalent to the seismic–aseismic boundary in continental crust (e.g. Meissner & Strehlau 1982, Chen & Molnar 1983, Smith & Bruhn 1984). This may be in large part correct, but it is misleading to assume that brittle behaviour is restricted to above the seismic–aseismic 'boundary', and *vice versa*. Brittle–ductile transitions depend on a wide range of parameters, and they therefore take place over a wide range of conditions applicable in the lowermost portions of the crust. Moreover, the transition from seismic to aseismic behaviour on a single fault is by no means equivalent to the brittle–ductile transition. For example, some faults may propagate aseismically, especially in the presence of lithostatically pressured pore fluids. At other times a large normal fault system may bite deeply into the crust in a single large magnitude seismic event (e.g. as far as 16–20 km deep), cutting into rocks which under normal conditions were flowing in a ductile fashion. These rocks will slowly relax the stress rise caused by the seismic event in a ductile fashion, so that there will be an alternation between brittle faulting and ductile flow at these levels.

The role of pressured fluids

In a dry rock, the brittle–ductile transition takes place under conditions primarily governed by rock composition, temperature and pressure. For example, a carbonate rock behaves in a markedly different way from a quartzite, and the two materials undergo the brittle–ductile transition at very different levels in the Earth's crust. However, although composition, pressure and temperature are significant variables, other variables under many circumstances may be of considerably greater importance. The most significant variable determining the rheological behaviour of the continental crust is probably the presence of pressured pore fluids.

The transition from ductile to brittle behaviour is most readily induced by the presence of pressured pore fluid (Etheridge 1983), with the important variables being the pore fluid pressure, and the magnitude of the pore fluid reservoir. Effective (normal) stress is the major factor which determines whether or not a macroscopic fracture will form and propagate, assuming deviatoric stress levels high enough to drive fracture migration. This is because the magnitude of the difference between pore fluid pressure and mean stress determines the ability of cracks to dilate. The length of the fractures formed is dependent on the magnitude of the pore fluid reservoir.

Increasing temperature increases the ability of a rock to dissipate built-up deviatoric stresses by ductile flow, and thus may prevent deviatoric stress levels necessary for catastrophic failure being reached. However, rocks which are deforming ductilely under one set of circumstances may suddenly become brittle if they are brought into contact with pressured pore fluid emanating for example from a crystallizing granite. Considerable igneous activity accompanied extension in the Basin and Range province, and crystallization of granites must have provided very large volumes of fluid, which then migrated through the rock pile (e.g. a 1 km thick sill of two-mica granite with areal extent 10 km square which rose into the footwall of a ductile shear zone could readily provide 10 km^3 of fluid to rise through the shear zone). In the South Mountains, ductilely deforming mylonitic gneisses became brittle approximately coincident with the arrival of fluids of igneous derivation. In these examples the ductile to brittle transition may have been induced solely as the result of fluid activity (Reynolds & Lister 1987).

Alternations between brittle and ductile behaviour due to transitory increases in strain rate

Another reason that ductilely deforming rocks might suddenly become brittle is if strain rate abruptly increases, because deviatoric stress levels rapidly rise. Such changes may occur under major normal faults in extending terranes. Plastic dissipation of small relative movements may involve a brittle–ductile transition at relatively shallow depths (e.g. 8–11 km). However, in the event of a seismic event of large magnitude, rapid displacement on a large high-angle normal fault will cut down through this so-called brittle–ductile transition to a much greater depth (e.g. to 15–16 km). Movement on such a fault will be associated with a seismic stress drop above 11 km, where deviatoric stresses had accumulated in the strongest region of the crust, but a stress rise will occur in the rocks surrounding the fault plane beneath this depth, since little deviatoric stress was present before the rupture in these normally ductilely flowing rocks. These stresses will be subsequently relaxed by solid-state flow (i.e. crystal–plastic deformation) and ductile shear zones will form in the rocks adjacent to the downwards terminations of these faults.

Since pore-pressure and strain-rate dependent variations in the brittle–ductile transition are not determined by temperature alone, *it is impossible to define a precise depth which marks a brittle–ductile transition relevant to all situations.* Seismic fault propagation locally may involve strain rates as high as 10^1 s^{-1}, whereas the strain rates involved in shear zones rarely could exceed 10^{-10}–10^{-12} s^{-1}. It is therefore difficult to imagine that the brittle–ductile transition will take place at a particular temperature and remain fixed to a particular material plane as extension proceeds. Models that envisage detachment faults separating brittlely deforming crust from ductilely deforming crust require the brittle–ductile transition to take place abruptly at a particular temperature, and for the transition to be 'anchored' to a particular material plane. This is unlikely, since all available evidence points to a gradual rather than an abrupt increase in ductility with pressure and temperature (see Paterson 1978).

DETACHMENT FAULTS DO NOT REPRESENT THE BRITTLE–DUCTILE TRANSITION

The discussion above suggests that it is improbable that detachment faults in metamorphic core complexes represent the brittle–ductile transition, as suggested by the 'pure shear' model in Fig. 2. There are a number of additional observations that invalidate the 'pure shear' model.

First, such a model implies that mylonites in the lower plate should develop synchronously with brittle deformation in the upper plate. However, when we examine the brittlely deformed rocks of upper plates, now tectonically juxtaposed against ductilely deformed lower plate rocks, we observe fabric and microstructural data which imply a time lag between ductile deformation in the lower plate and brittle deformation in the adjacent upper plate. This time lag is inconsistent with 'pure shear' models in which brittle rocks of the upper plate are separated from synchronously deforming ductile rocks of the lower plate by a detachment fault across which no significant relative displacement has taken place.

Second, in the Whipple Mountains, for example, the mylonitic foliation in the lower plate can be demonstrated by field relations to be older than the presently visible detachment faults, since the major detachment fault typically transects mylonitic foliation, and locally truncates upright folds in the mylonitic rocks. Hence these mylonitic gneisses were kinematically inactive at the time detachment faulting took place. Brittle structures in the lower plates of detachment faults consistently overprint ductile fabrics. Hence, the brittle and ductile fabrics of the upper and lower plates (respectively) cannot have formed synchronously in immediately adjacent locations. They must have been tectonically juxtaposed.

A third argument against the hypothesis that detachment faults represent ancient brittle–ductile transitions is that some detachment faults formed under conditions which would not have permitted significant ductile deformation of the lower plate. Some detachment faults formed in relatively surficial environments, where mean stress and temperature would have been quite insufficient to allow significant crystal–plastic behaviour. For example, Davis & Lister (1988) show that the Whipple detachment fault propagated to surface, or near surface levels during its development. Spencer (in Spencer & Turner 1982) reached the same conclusion for the master detachment fault in the Sacramento Mountains, California. Moreover (in the Whipple Mountains), lower plate high-angle normal faults exist which not only cut through the mylonitic rocks, and the chloritic breccias which have been superimposed on them, but are themselves abruptly terminated by the overlying detachment fault, demonstrating that *both upper and lower plates were well into the brittle field at the time of detachment faulting.*

These temporal relations between mylonitization and detachment faulting are confirmed by geochronologic studies reviewed in Davis & Lister (1988) for the Whipple Mountains area. These studies demonstrate that mylonitization was occurring during syntectonic emplacement of tonalite dikes at 26.5 Ma, and deformation had ceased by the time of emplacement of post-tectonic dikes and plutons (at *ca* 19–20.5 Ma). The present Whipple Fault offsets the post-tectonic igneous assemblage, and is clearly younger than the mylonitic gneisses in its lower plate.

It has generally been assumed that detachment faults as we see them today are structures that formed from the onset of the extension process, and which remained active throughout the period in which the core complexes formed. However, field evidence does not support this assumption (Davis & Lister 1988). The present detachment transects mylonitic foliation. Brittle structures in the chloritic breccias are superimposed on mylonitic gneisses in the lower plate. There are multiple generations of different types of normal faults in both upper and lower plates, and high-angle normal faults in both the upper and lower plates abruptly terminate against the detachment fault. The simplest explanation of these relations is the most obvious one. Arrays of high-angle normal faults in the upper plate are abruptly truncated at the master detachment fault. Hence the detachment fault is younger. The steep normal faults must have been kinematically inactive from the time they were truncated by the presently observed shallow-dipping detachment faults. Moreover, since these steep normal faults truncate brittle structures in both upper and lower plates, the detachment fault must have formed subsequent to all of these structures.

Although it has generally been assumed that detachment faults as we see them today are structures that formed from the onset of the extension process, and which remained active throughout the period in which the core complexes formed, *we must conclude that portions of the presently observed detachment faults are essentially the youngest structural features formed during the extensional history of the metamorphic core complexes.* Conversely, the present visible detachment faults did not exist in the early stages of the extension event(s). This same conclusion can be reached by examining detachment faults in other core complexes in Arizona and Nevada, as well as in the Whipple Mountains. Such observations force considerable revision of current detachment and shear zone models for continental extension.

We advocate the hypothesis that the presently observed master faults are merely the youngest in a *succession of major detachment faults* emanating from the same movement zone at depth during the complex evolution (both in space and time) of crustal shear zones formed in the extending Cordilleran orogen.

THE ROLE OF 'PURE SHEAR' VS 'SIMPLE SHEAR' DURING DEFORMATION OF THE LOWER PLATE

The brittle phenomena in the upper plate of the metamorphic core complexes contrast markedly with what is observed in the lower plates, which generally exhibit the effects of intense ductile deformation. The upper levels of the lower plate usually contain zones of shallow-dipping mylonites and associated mylonitic gneisses. These rocks have been subject to considerable horizontal extension, and initially it was supposed that this continued through the entire crust or lithosphere (e.g. Davis *et al.* 1980, Bally *et al.* 1981, Miller *et al.* 1983). It is now not at all clear that this is the case. Fabric and microstructural analysis of the metamorphic tectonites of the lower plates of more than a dozen core complexes in Arizona, California and Nevada suggests merely that the upper levels of the lower plates were once caught in major shallow-dipping normal-slip shear zones.

This conclusion has been reached by examining tectonites from the lower plates of the Whipple, and Chemehuevi Mountains in California, the Harcuvar, Harquahala, White Tank, South and Coyote Mountains in Arizona, and the Ruby Mountains and the Snake Range in Nevada (Davis & Hardy 1981, Reynolds 1982, 1985, Davis 1983, Davis *et al.* 1983, 1986, Lister & Davis 1983, Lister & Snoke 1984, Marks 1984, Davis *et al.* 1987, Lee *et al.* 1987). The sense of shear can be checked systematically in the field, using a variety of kinematic indicators, because type I and type II *S–C* mylonites are common throughout the core complexes (Lister & Snoke 1984). There *are* significant complexities in the inferred movement pictures. For example, narrow antithetic shear zones are numerous within the mylonitic zones. However, these local features do not detract from the general conclusion that the movement picture for the main mylonitic horizons is strongly translational. Major zones of intracrustal laminar flow are involved, since the zones of mylonitic gneisses can be as thick as 4 km (Davis *et al.* 1979, 1980). Although, there is some controversy remaining concerning the significance of the data from the Snake Range (see Lee *et al.* 1987), it is clear that models which envisage core complexes forming solely as the result of *in situ* coaxial extension of the entire crust (i.e. horizontal pure shear immediately below detachment faults representing the brittle–ductile transition) are incompatible with present observational data. The shear zones we describe cause considerable horizontal extension of the rocks within them without any overall extension of still deeper rocks in the lower plate being necessary.

However it must be recognized that the fabric and microstructural data we have collected does *not* eliminate the possibility that the crust was extended by 'pure shear' at depth before being cut into by shallow-dipping ductile shear zones. In some ranges (e.g. the Whipple and South Mountains), the base of the main shear zones is actually exposed, and the rocks underlying these zones can be examined. These rocks have been subject to limited ductile deformation, but the intensity of fabrics developed precludes large magnitude early extension by 'pure shear'. Strains below the main shear zone are probably less than 30–40% in the South Mountains (Reynolds & Lister in review). Lee *et al.* (1987) suggest they can detect evidence for an early history of 'pure shear' in the western part of the Snake Range, on the basis of quartz petrofabric data, and that up to 40–50% extension may be involved at these early stages of extension. In contrast, on the east side of the range, fabric and microstructural data (Marks 1984, Lee *et al.* 1987) demonstrate only the presence of a major shear zone (at least 500 m thick), and no constraints concerning the kinematics of the early history of extension can be offered. Considerably more stretching of the crust by early 'pure shear' may have taken place, but this can neither be proven nor disproven at the moment. Until a drill hole encounters the base of the ductile shear zone exposed on the east side of the Snake Range, we will not be able to constrain the magnitude of any early coaxial stretching of the crust which may have occurred in this part of the Basin and Range province.

Let us therefore return to consider the alternative to the 'pure shear' model, namely the model of a narrow movement zone passing all the way through the crust or lithosphere (Wernicke 1981a, 1985).

From the point of view of rock mechanics, there are no major conceptual difficulties with this model, except those which concern the existence of flat faults of large areal extent in an extensional regime. Narrow movement zones may exist at depth, since strain localization in a shear zone is favoured by strain-softening of the ductilely deforming rock. Strain-softening localizes relative movement even in situations where the surrounding rocks are capable of exhibiting considerable ductility, as would be the case in the middle to lower crust and upper mantle. There are numerous mechanisms which lead to strain-softening in shear zones, for example thermo-mechanical effects associated with 'shear heating', and rheological softening associated with the onset of dynamic recrystallization, the development of preferred crystallographic orientation leading to fabric-induced anisotropy, metamorphic transformations, or the effect of reduction in grain size. In retrograde conditions, while P and T both decrease, factors such as fluid content, or fluid flow-through, will also have important effects. The abrupt transformation of mylonitized granodiorite to chlorite schist in many shear zones is an excellent example of the dramatic effects of fluid on shear zone behaviour. Under such circumstances, a major movement zone could penetrate a considerable distance into the lithosphere. In this case, no attendant stretching of the continental lithosphere by 'pure shear' is necessary.

On the other hand, there is no evidence which directly supports the concept of a single narrow shear zone passing all the way through the crust as suggested by Wernicke (1985). It has always been difficult to apply such a model to the Whipple Mountains detachment

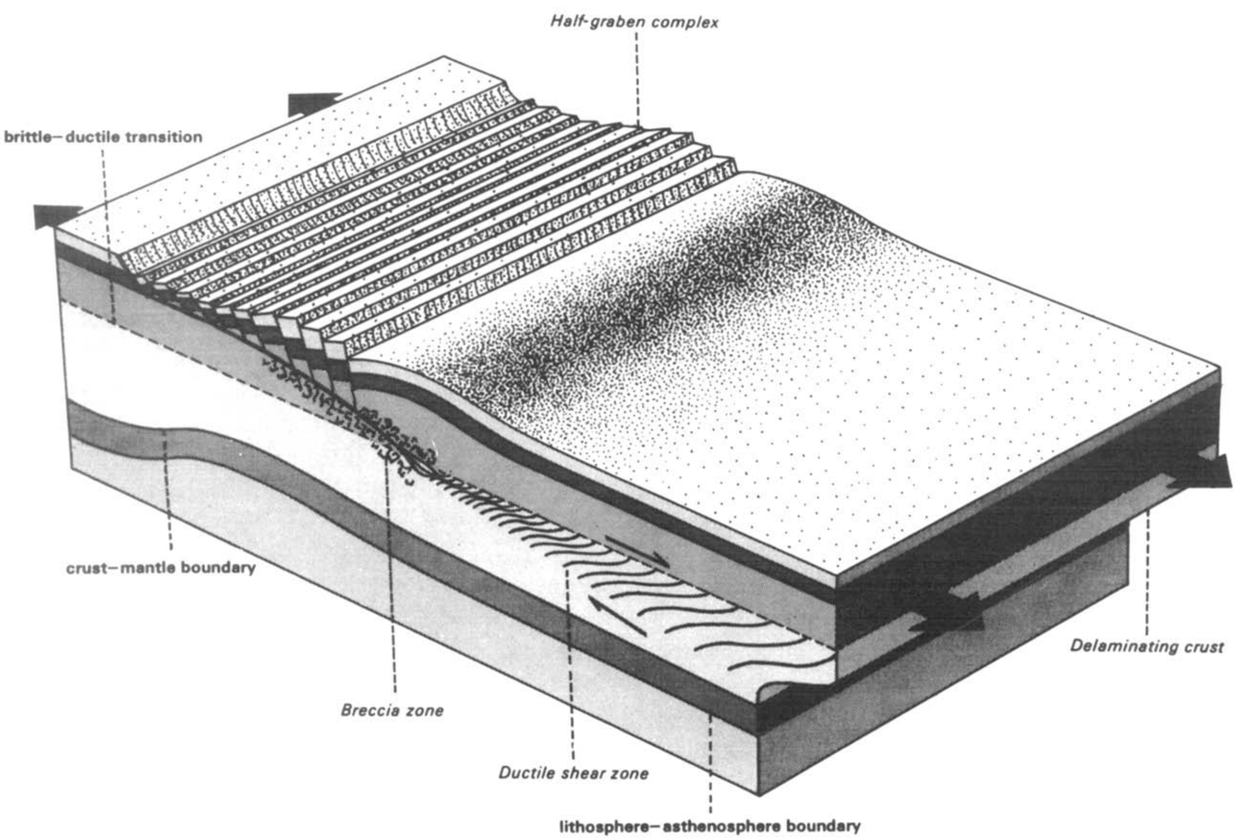

Fig. 7. An alternative model for continental extension involves the concept of a crustal shear zone which detaches the continental crust below the stress guide defined by the brittle–ductile transition. The shear zone broadens with increasing depth, and terminates within the crust.

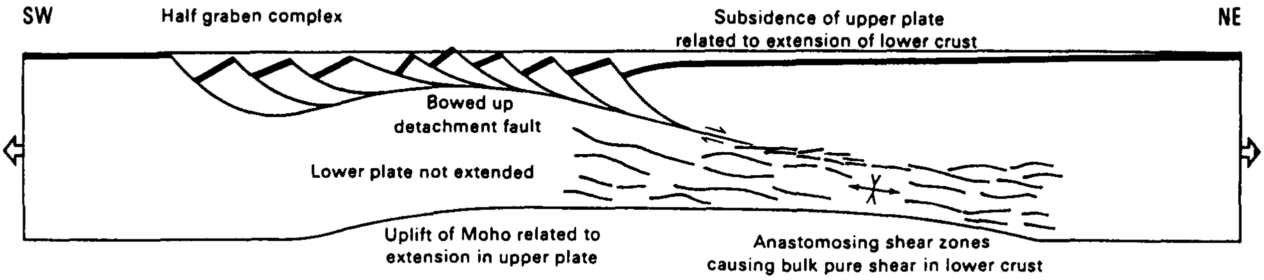

Fig. 8. Model of detachment of the upper crust during horizontal extension, involving a shallow-dipping detachment fault which disappears with depth into a ductile shear zone. The lower crust, however, is subject to pure shear at the termination of the movement zone. Uplift of the crust–mantle boundary is caused by a combination of bowing upward of the (undeformed) lower plate (dominant in the west), and the results of ductile attenuation of the lower part of the lithosphere (dominant in the east).

fault system, since in spite of a large displacement on this system (in the order or 40–50 km), lower crustal rocks (as opposed to mid-crustal rocks) have not been brought to the surface. Because of this, we (Lister & Davis 1983, Davis *et al.* 1983, 1986, Lister *et al.* 1984, Davis & Lister 1988) have favoured a geometry for evolving shear zones rooted in the crust, at structural levels beneath the brittle–ductile transition (Fig. 7). These evolving shear zones may widen with depth and terminate in a zone of complex anastomosing shear zones involving bulk pure shear in the middle and lower crust, as suggested by Rehrig & Reynolds (1980), Davis & Hardy (1981) or Hamilton (1982).

'Detachment + pure shear' models, as suggested by these early workers, have the added advantage that they allow explanation of the distinct uplift–subsidence histories of the several distinct architectural styles observed on passive margins (Lister *et al.* 1986, in press). Figure 8 shows how a zone of mid-crustal detachment underlain by a zone of 'pure shear' creates a broad zone of surface subsidence underlain by a corresponding large wavelength bulge in the crust–mantle boundary. Such a model can be readily applied to explain relatively 'symmetric' extension, as inferred from the variation in crustal thickness across an extended zone. Mid-crustal detachment leads to subsidence of the surface of the relatively unstructured upper plate (after thermal anomalies decay), because the lower crust is attenuated. Subsidence of the surface of the highly-structured lower plate adjacent to this domain takes place because the upper crust is effectively thinned. A relatively symmetric bulge in the crust–mantle boundary is produced, although on one side of the extended terrane, uplift of the Moho is due to upwards flexure of the lower crust, whereas on the other side, uplift of the Moho has taken place because the lower crust was thinned by ductile stretching.

Wernicke-type models involving through-going shear zones or detachment faults predict relatively minor thermal anomalies during the rift phase, and post-extension subsidence is therefore limited. Lithospheric wedge models are not able to adequately explain the observed uplift–subsidence histories on many passive margins.

THE SPACE–TIME EVOLUTION OF THE MAJOR SHEAR ZONES EXPOSED BENEATH THE DETACHMENT FAULTS

Major shear zones evolve in complexity, both in space as well as with time. Large shear zones evolve laterally, and with depth, because material properties change with ambient environmental conditions such as pressure, temperature, deviatoric stress, fluid content, fluid pressure and fluid composition. These changing modes of material response to applied deviatoric stress determine the fashion in which relative movement in a major shear zone is accommodated at different crustal levels. Major shear zones evolve with time primarily because operation of the shear zone carries rock from one structural level to the next (unless the movement vector is precisely horizontal). Thus in a normal-slip shear zone, as the lower plate moves out from underneath the upper plate, mylonites formed at depth are translated to progressively shallower levels, suffering brecciation, cataclasis, and retrograde alteration in the process (Davis *et al.* 1983, 1986).

Spatial evolution of a shear zone with increasing depth

Because the downward increase of pressure and temperature leads eventually to the brittle–ductile transition, major shear zones evolve with increasing depth from zones involving cataclastic rocks into regions in which mylonites and phyllonites are formed as the result of intense penetrative plastic deformation (as noted by Sibson 1977, 1983). In the uppermost levels of the crust, faults tend to be associated with zones of gouge and/or breccia. Gouges may indurate as the result of mass transfer accompanying fluid migration through the fault zone, since the presence of water in the fault zone facilitates growth of quartz and other minerals in dilation sites in the gouge and/or microbreccia. The resultant cataclasites may then undergo complex cycles of ductile deformation, fracture, and vein formation (as recognized by Stel 1981), or they may suffer repeated cycles of intense brecciation followed by induration as the result of mineral growth (e.g. in the microbreccia of the Whipple Fault; Green & Lister work in preparation).

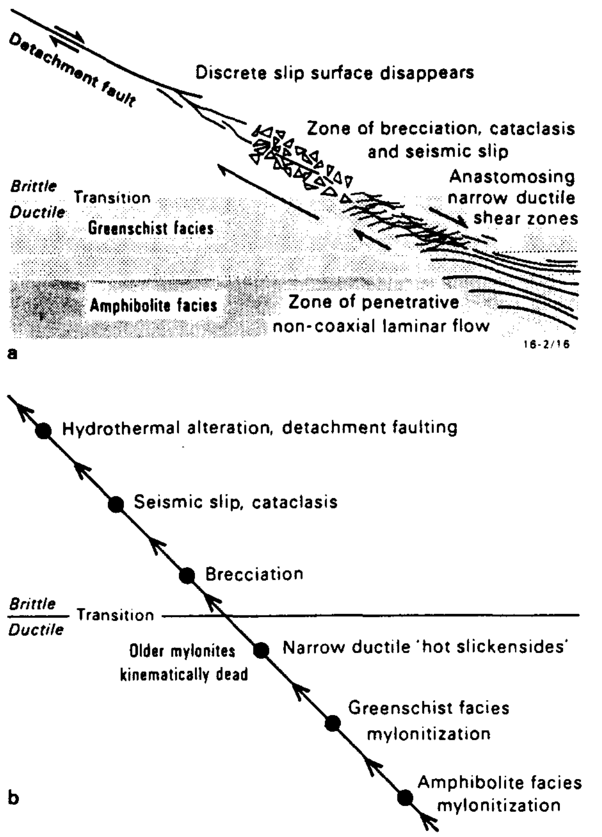

Fig. 9. The concept of an evolving shear zone implies spatial and temporal variation. Diagram (a) shows the spatial variation of material behavioural fields expected with increasing depth, with detachment faults disappearing into zones of brecciation, cataclasis and seismic slip, and then passing into ductile shear zones. A rock transported upwards in the footwall of a detachment fault transposes the spatial sequence of material behavioural fields in (a) into a time sequence of material response (b).

In circumstances where fault movements are rapid enough to generate seismic activity, and significant amounts of pore fluid are not present, fault melts may be generated (Sibson 1977). Alternatively, sintered cataclasites may develop if slightly less kinetic energy is dissipated close to the fault surfaces. These fault products are usually later altered, but pseudotachylites can be recognized if specific structures such as generation surfaces and injection veins are present (Sibson 1977).

In the crust, the brittle–ductile transition takes place progressively, marked by increasingly ductile behaviour at the margins of fractures, and by the development of narrow ductile shear zones. Some of these shear zones are so discrete that they are referred to as 'hot slickensides' (as recognized by S. J. Reynolds). Simpson & Segall (1985) and Segall & Simpson (1986) showed that some fractures actually change into ductile shear zones, with time, presumably because water which percolates to the fracture site is capable of inducing ductility in quartz. Ductility (measured by the percentage strain before failure) also gradually increases in experiments as pressure and temperature increase (Paterson 1978). At the same time the nature of the 'yield' or 'failure' mode changes from relative movement on discrete surfaces to a broadening zone of penetrative deformation. The same pattern of broadening shear zones with increas-zones with increasingly penetrative ductile behaviour is also observed in the shear zones in the upper levels of the lower plates of the metamorphic core complexes. This spatial variation of material behaviour in a major shear zone is illustrated in Fig. 9(a). The brittle–ductile transition is shown occurring at lowest greenschist facies conditions (cf. Sibson 1977, 1982, 1983).

Time-evolution of the lower plate shear zones of the metamorphic core complexes

In any major shear zone, a particular volume of rock moves slowly through a sequence of material behavioural fields, transposing the spatial variation of material response into a time-sequence which can be discerned by subsequent fabric and microstructural analysis. In an extensional shear zone, pressure and temperature gradually decrease in the lower plate while the shear zone operates. Consequently, rocks which once deformed ductilely will begin to deform brittlely. Eventually, if the extensional shear zone continues operating, these rocks will be exposed at the surface, allowing recognition of the major changes in material response that took place during the history of the shear zone.

Evolving shear zone models imply that the flowing rock is transported through a succession of different metamorphic and deformational environments. These involve progressively decreasing metamorphic grades, with deformation apparently taking place under progressively increasing deviatoric stress intensities, until finally the rock passes through the brittle–ductile transition, and further relative movement must be accomplished by brittle failure. As the lower plate is drawn from deeper levels towards the surface, the rocks it contains will pass from environments where they are deforming in the amphibolite facies to environments where they are deforming in the greenschist facies, and substantially different modes of deformation will apply.

As the result of this movement, spatial variation of material behavioural fields are translated into specific temporal sequences. This interdependence of space and time sequences is a notable feature of all major shear zones. The spatial sequence illustrated in Fig. 9(a), for an evolving shear zone, is thereby reflected in the time-sequence of events undergone by any particular volume of rock, and can be recognized by studying the sequence of mesoscopic and microscopic overprints on rock fabric. The time sequence for a particular volume of rock passing upwards through an evolving shear zone is illustrated in Fig. 9(b). Note the brittle–ductile transition is again shown as an abrupt transition for simplicity of representation.

In most of the metamorphic core complexes of the North American Cordillera, the succession begins with penetrative non-coaxial laminar flow in amphibolite or high greenschist facies conditions, as is evidenced by fabrics and microstructures observed throughout the 0.1–4 km thick sequences of lineated and foliated (*LS*) tectonites in the upper levels of the lower plates of most metamorphic core complexes (Lister & Davis 1983, Lister & Snoke 1984). The most important microstructures in these *LS* tectonites are mica 'fish', and oblique foliations in adjacent dynamically recrystallized quartz aggregates. Quartz *c*-axis fabrics measured in these regions show conclusive evidence of intense non-coaxial laminar flow (with a high simple shear component). If overall coaxial deformation had taken place, and the 'mica' fish and mica 'fish' trails merely represented passively stretched local shear discontinuities, the quartz *c*-axis fabrics would form symmetrically with respect to the foliations in the dynamically recrystallized quartz aggregates. The central part of the fabric skeleton, around the *Y*-axis, would form perpendicular to the plane of the grain shape foliation in these aggregates. Moreover, the overall extension axis would be parallel to the axis of incremental extension. This is *not* what is observed in any of the dozen or so metamorphic core complexes yet examined (e.g. see Davis *et al.* 1986, Davis *et al.* 1987). The measured *c*-axis fabrics exhibit considerable asymmetry with respect to the foliation in the quartz aggregates. Since the central part of the fabric skeletons around the *Y*-axis are almost orthogonal to the discontinuities defined by the mica 'fish' trails, it can be inferred that *C*-surfaces (Lister & Snoke 1984) are almost parallel to the flow plane of the bulk deformation. Moreover, the axis of incremental extension can be inferred from dynamically recrystallized quartz aggregates, and this is not parallel to the finite strain axis of extension, allowing the pure shear hypothesis for production of these fabrics to be eliminated.

The penetratively developed microstructures described above are locally overprinted by (increasingly) narrow (0.1–10 cm) ductile shear zones which transect the older fabric. Recrystallized grain size decreases in these zones, suggesting higher deviatoric stresses were involved during their development (Etheridge & Wilkie 1981). This observation is consistent with the notion that the rock, travelling upward in the footwall of the detachment system, is about to pass through the brittle–ductile transition, and is thus near the crustal level in which deviatoric stresses are the highest. The overall sense of shear generally remains constant in these later ductile shear zones.

The mylonitic foliation generally contains a well-developed stretching lineation. Variation in orientation of the lineation is usually gradual from one place to another, and is characteristically parallel in trend to striae on adjacent brittlely deformed upper plate rocks. The mylonitic stretching lineation is warped across elongate open domes defined by the mylonitic foliation. Since the sense-of-shear for the mylonites is invariably the same as for detachment faulting, and the inferred movement vectors for both brittle and ductile events are parallel, Davis *et al.* (1986) suggest kinematic continuity throughout the time frame in which mylonites and detachment faults formed. This offers further support of the evolving shear zone model (Reynolds 1982, 1985, Davis *et al.* 1983, 1986).

In the Whipple Mountains, subsequent to the stage at which narrow ductile shear zones formed transecting older fabric, widespread hydrothermal alteration appeared to take place, forming ubiquitous 'chloritic breccias'. The 'chloritic breccias' are always confined to the lower plate, and are derived from its rock components. We suggest that continuing ductile deformation was prevented by the arrival of pressured pore fluids, which led to embrittlement, and thus to the formation of breccias, and ultracataclasites. The shallow portions of the shear zones were seismically active at about this time, since pseudotachylites also formed, although these rocks have themselves been later altered. The magnitude of the implied seismic events may not have been very large, since only very small areas of contiguous pseudotachylite have ever been reported.

Once the rocks passed through the ductile–brittle transition, brittle microstructures continue to overprint the older more ductile fabrics. Ultracataclasites formed beneath the detachment faults which slice into the chloritic breccia. The basal detachment fault is usually a planar surface capping these ultracataclasites. Below them lie the chloritic breccias derived from lower plate rocks. The origin of microstructures in the ultracataclasites is enigmatic (see Phillips 1982). From work in preparation, Green & Lister observe evidence for numerous cycles of repeated brecciation, cataclasis and subsequent induration.

MULTIPLE GENERATIONS OF DETACHMENT FAULTING AND IMPLICATIONS FOR THE ORIGIN OF METAMORPHIC CORE COMPLEXES

The presently exposed detachment faults are very young features

The simplest form of an evolving crustal shear zone model (Reynolds 1982, Lister & Davis 1983, Lister *et al.* 1984a, b, Wernicke 1985) implies that mylonites formed in the deeper levels of an extensional shear zone are dragged to the surface through different levels of the same movement zone. In this case, mylonites formed at deeper levels in the shear zone should always underlie detachment faults formed at more surficial levels of the movement zone, and these detachment faults should be structures formed at the onset of movement, remaining active throughout the history of the shear zone.

However, many of the segments of the detachment faults we observe today cannot belong to the detachment faults which once existed at the upward terminations of the extensional shear zones in which the now exposed mylonites and mylonitic gneisses of the lower plate were deformed. Deformation of the lower plate generally took place at high amphibolite to middle greenschist metamorphic conditions. These tectonites were cut by detachment faults only *after* metamorphic grade had been reduced to low greenschist conditions. Moreover, brittle micostructures consistently overprint ductile fabrics. This indicates that the mylonites and mylonitic gneisses had become kinematically inactive *before* the rock was transected by the segments of the detachment faults we see today, and more importantly *these segments did not exist at the time of the penetrative ductile deformation which formed the mylonites and mylonitic gneisses.* Presumably older detachment faults lay updip of the termination of the ductile shear zones in which the presently exposed mylonitic rocks were once deformed. By the time the now visible mylonitic rocks had been drawn upwards to the point at which they were cut into by the presently observed detachment faults, these older detachment faults presumably had become inoperative.

These observations force us away from evolving shear zone models that are based on the concept of single movement zones, towards models that are considerably more complex. In fact we had already raised the spectre of multiple generations of detachment faults emanating from the same extensional shear zone when we pointed out that portions of the detachment faults observed today are features developed relatively late in the geological history of individual metamorphic core complexes. These portions of the presently observed detachment faults must be merely the youngest in a succession of low-angle normal faults which sliced through the extending terrane as the movement zone evolved in its complexity.

How can multiple generations of detachment faults splay from the same movement zone at depth?

The isostatic response to heterogeneous extension of the upper plate, and the intrusion of granitic bodies at depth causes the lower plate to bow upwards (Fig. 10). The original detachment surface becomes more and more curved as this process continues. Eventually, geometric difficulties associated with the operation of this curved fault become so great that a splay must develop, propagating from the pre-existing curved detachment surface (Fig. 11). The previously active detachment fault becomes kinematically inactive, and the splay becomes the new master detachment fault. It is impossible to develop a broad culmination in the lower plate without considering the effects of such multiple detachment, since as these new faults cut upward, the upper plate becomes progressively more fractured. The result is that extension of the upper plate above a developing culmination naturally tends to increase, and since there is greater tectonic denudation at this point, there is consequently an even greater tendency for the culmination to continue to develop.

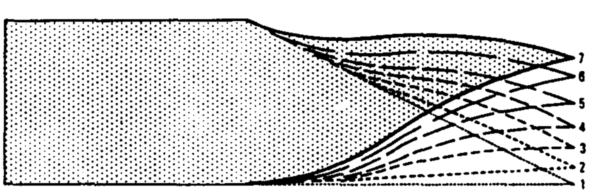

Fig. 10. Schematic illustration of the progressive uplift of a lithospheric wedge as the load exerted by the upper plate is slowly removed, assuming zero flexural rigidity.

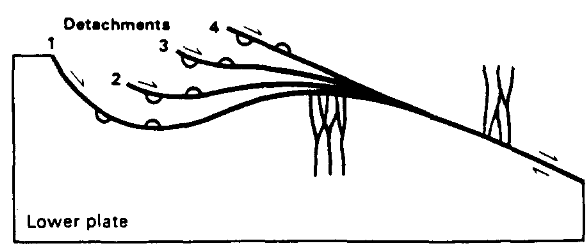

Fig. 11. Development of a basement culmination means that the master detachment faults become progressively more bowed. A new detachment fault propagates from the culmination, as it becomes more accentuated. This fault in turn also becomes bowed upward. A succession of progressively less bowed detachment faults results (sequence of 1–4). Each new detachment fault bites further into the lower portions of the upper plate, and excises more and more of the stratigraphic section. Attempts to restore the cross-section using the technique of balanced cross-sections will fail, unless the phenomenon of multiple detachment can be properly accounted for. Cross-sections cannot be balanced using only the youngest of the detachment faults. Displacement of a hypothetical dike swarm is shown schematically.

Successive splays of the old master detachment will fire in sequence as illustrated in Fig. 11, where four successive detachment faults are shown above the developing basement culmination. Pre-existing detachment faults, now kinematically inactive, become progressively more warped as the basement dome continues to develop. In some core complexes (e.g. the South Mountains, Reynolds & Lister in review) *there is evidence for a progression of successively less warped detachment faults* as shown. The youngest faults are always those with the least deviation from planarity.

This scenario implies that the generation of multiple detachment faults is an essential element of the history of a major shallow-dipping normal-slip movement zone in an extending orogen.

THE CONSEQUENCES OF MULTIPLE GENERATIONS OF DETACHMENT FAULTS ON THE DEVELOPMENT OF UPPER PLATE STRUCTURE

Multiple generations of detachment faults emanating from the same movement zone at depth fundamentally affect the development of metamorphic core complexes. Of particular importance is the realization that the phenomenon of multiple detachment allows rational explanation of one of the most enigmatic of the structural relations observed in the upper plate of the core complexes, namely cross-sections which cannot be balanced using only the presently visible detachment faults. Since such cross-sections (e.g. as shown in Fig. 12, and the schematic cross-section in Fig. 13) are characteristic of many of the metamorphic core complexes, the phenomenon of multiple generations of detachment is likely to be more widespread than presently recognized, and we argue that it is of considerable importance in determining their evolution.

Effect of excisement on the construction of balanced cross-sections

One of the most important consequences of multiple detachment is the sequence of successive splays from the

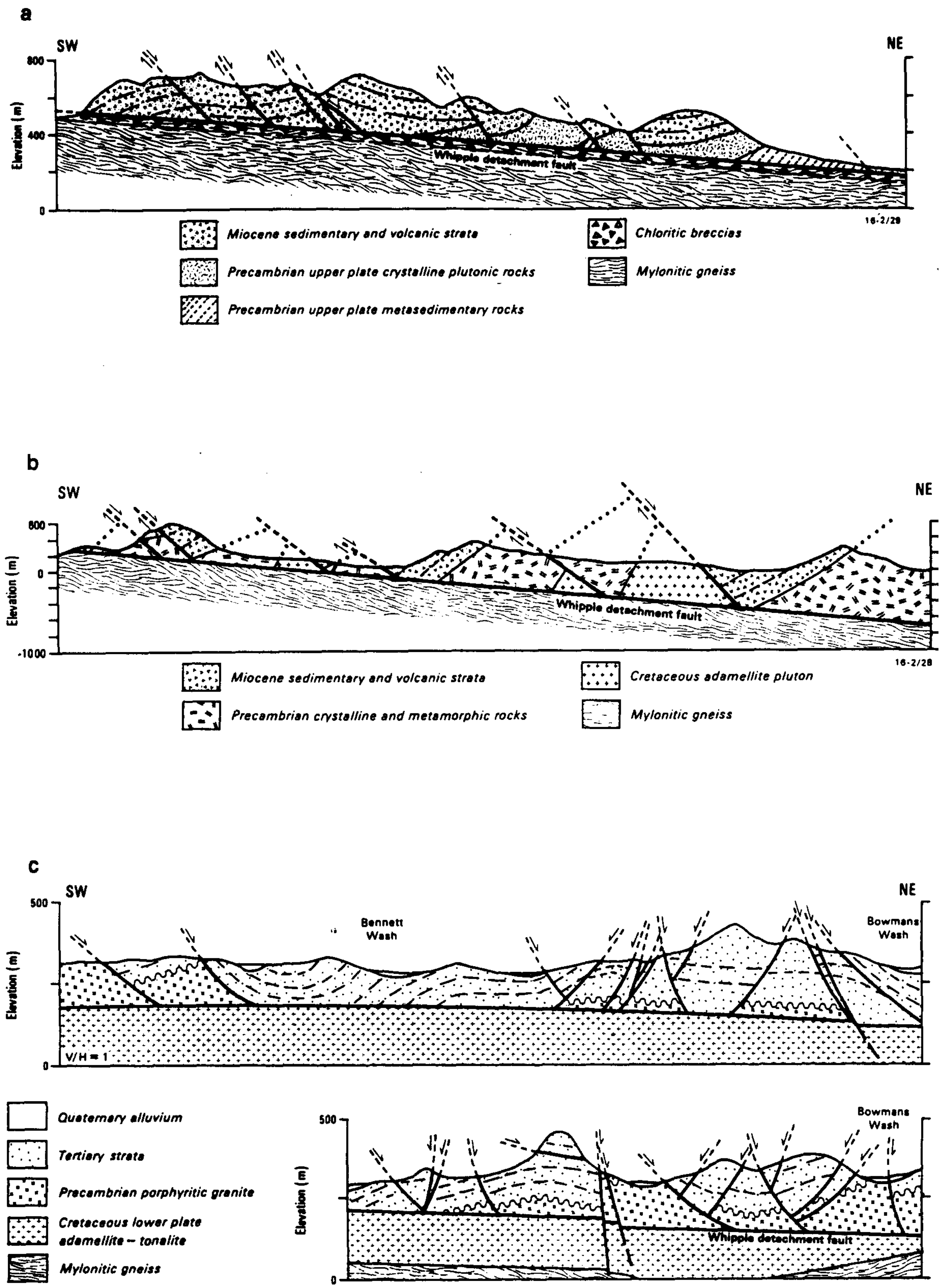

Fig. 12. Three cross-sections illustrating the wide variation in structural geometry of the upper plate rocks to the Whipple detachment fault. Each section shows the abrupt termination of upper plate structures at the detachment fault. The vertical and horizontal scales are identical. Cross-section (a) is through the upper plate of the Whipple detachment fault, in the eastern Whipple Mountains (adapted from Frost, in Anderson & Frost 1981). (b) is from Frost (1980) through the Whipple Wash canyon, eastern Whipple Mountains, where the geometry of upper plate faulting is well exposed. Numerous planar normal faults terminate abruptly at the main Whipple detachment fault. None of these faults cut the detachment. This suggests the present Whipple detachment fault is a relatively young feature. Cross-sections in (c) pass through the upper plate of the Whipple detachment fault, southern flank of the Whipple Mountains (from Thurn 1983). Tertiary strata are broadly folded, and offset by SW- and NE-dipping normal faults. Domino-style faulting cannot be invoked in this area, and Tertiary strata clearly have not been rotated in large tilt blocks and lowered onto the detachment fault. Once again, the cross-sections above the Whipple Fault cannot be balanced using presently visible faults, indicating that the Whipple Fault post-dates upper plate structure in this area, and that the detachment has excised the lower portions of the upper plate. See text for further information.

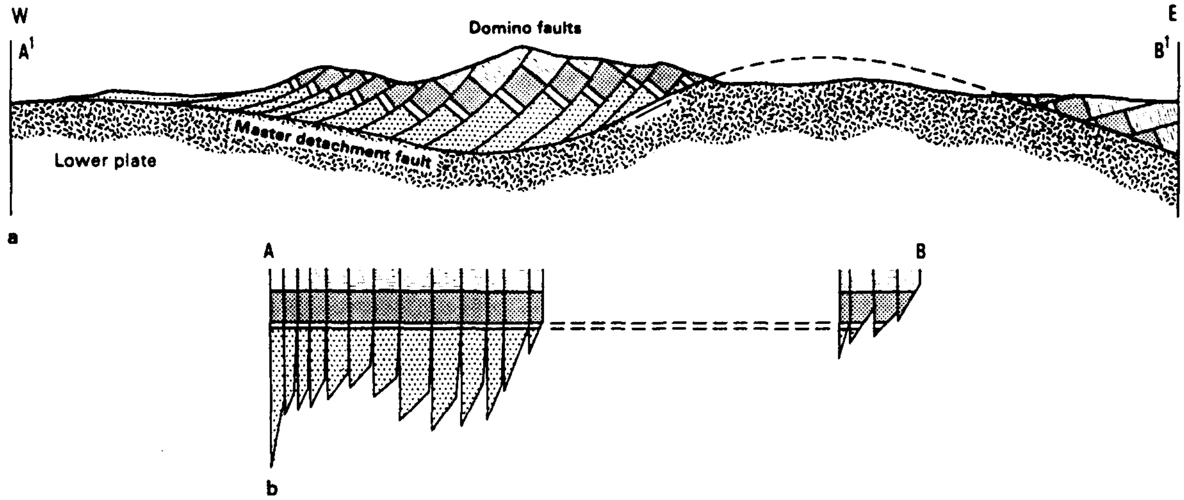

Fig. 13. A (schematic) cross-section produced as the result of multiple listric normal faulting and excisement (a). Restoring this section to the undeformed state (b) shows that segments of the upper plate are missing. Note that the detachment fault roots to the west, not to the east. Detachment faults are often rotated as the result of asymmetric uplift as the result of the formation of basement culminations.

old master detachment fault (Fig. 11). The total accumulated relative displacement is shown by the separation of the hypothetical dyke swarms. Each of the successive detachment faults will accomplish a certain amount of relative translation, as shown by the bisected circles shown in Fig. 11. As each generation of detachment faults bite into the lower portions of the upper plate, they excise more and more of the stratigraphic section. A cross-section of a detachment terrane cannot be balanced using only the presently visible detachments, since, because of the effects of excisement, a significant portion of the section appears to be missing.

The situation is further illustrated in Fig. 13(a), where a parallel array of high-angle normal faults is truncated abruptly at a basal detachment fault. An attempt to reconstruct the section (Fig. 13b) demonstrates that segments of the upper plate are missing. These portions of the (former) upper plate have been excised as the result of multiple detachment, and it is imposssible to balance the cross-sections without further information about the number of detachments that have cut through the section, and where the excised material now resides. The phenomenon of excisement allows explanation of many enigmatic cross-sections of this type, e.g. as described by Anderson (1971), where structural projection of the mapped detachment faults appears to indicate that excisement of upper plate sequences has occurred.

Excisement of listric fault bottoms to produce domino-like fault patterns

One of the strangest structures visible in the upper plates of many of the core complexes is defined by parallel arrays of high-angle normal faults which terminate abruptly at an underlying master detachment (Figs. 12a & b, and 13). Some of these high-angle normal faults have large offsets, and the intervening fault blocks can be strongly rotated. Outcrop is in many cases excellent, and the abrupt truncations of the planar arrays of upper plate faults are clearly visible (see Davis & Lister 1988).

The cross-section in Fig. 12(a) is drawn through the upper plate of the Whipple detachment fault, in the eastern Whipple Mountains, California (adapted from Frost, in Anderson & Frost 1981). Upper plate rocks include SW-dipping Miocene sedimentary and volcanic strata, non-mylonitized largely Precambrian metamorphic and plutonic rocks, and disrupted portions of a sheet-like once-continuous Cretaceous adamellite pluton. Attempts to rotate the fault blocks back to their original configuration (e.g. by realigning the Miocene non-conformity) reveals that large volumes of former upper plate rocks are now missing. Restoration of apparently domino-style rotation along planar faults would produce major space problems along the Whipple Fault. Excisement of the lower portions of the upper plate must have occurred.

The second cross-section (Fig. 12b) is from Frost (1980), and is drawn through the Whipple Wash canyon, in the eastern Whipple Mountains, where the geometry of upper plate faulting is well exposed. Numerous planar normal faults terminate abruptly at the main Whipple detachment fault. None of these faults cut the detachment. This suggests the present Whipple detachment fault is a relatively young feature.

The cross-sections in Fig. 12(c) pass through the upper plate of the Whipple detachment fault, southern flank of the Whipple Mountains (from Thurn 1983). Tertiary strata are broadly folded, and offset by SW- and NE-dipping normal faults. Domino-style faulting cannot be called upon in this area, and Tertiary strata clearly have not been rotated in large tilt blocks and lowered onto the detachment fault. Once again, the cross-sections above the Whipple Fault cannot be balanced using presently visible faults, indicating that the Whipple Fault post-dates upper plate structure in this area, and that the detachment has excised the lower portions of the upper plate. However, in this case, the average rotation of strata in fault blocks above the detachment is zero. Open folds have been simply transected by late-stage faults, and the lower parts of the section have been removed.

Domino-like rotation of fault blocks is an important mechanism for continental extension in the Basin and Range province (Thompson 1960, Wernicke & Burchfiel 1982, Jackson & McKenzie 1983, Gans & Miller 1983, 1984, Miller *et al.* 1983) as well as on passive continental margins (e.g. Christensen 1983). This is true both on the mesoscopic and macroscopic scales. However, many of the so-called 'domino-faults' of the detachment terranes are not what they appear to be at first sight.

As pointed out at the beginning of the paper, two end-member normal fault geometries have been proposed for the brittle processes which result in horizontal extension of the upper plate, one based on arrays of listric normal faults (Anderson 1971, Davis *et al.* 1980), and the other, based on sets of parallel high-angle normal faults separating blocks that rotate domino-style as the crust extends (e.g. Gans & Miller 1983, 1984, Miller *et al.* 1983). Initially faults in the upper plate of the Whipple Mountains were interpreted as listric, soling into the master detachment fault (cf. Frost 1979, Davis *et al.* 1980). Certainly, some faults in the upper plate are listric, and these do flatten into the Whipple Fault. However, these represent a distinct minority of upper-plate faults, and as we will discuss below, they are the youngest generation of structures formed during upper plate extension.

Studies by Frost and his students in Whipple Wash (in the eastern part of the range) where relations of upper plate structures to the Whipple Fault are superbly exposed, demonstrate that most upper plate faults intersect (but do not offset) the Whipple Fault. Moreover, downwards lessening of dip is not generally observed (Frost 1980, 1984, Gross & Hillemeyer 1982).

These prevailing geometric relationships at first sight appear to favour domino-style faulting as the dominant mechanism of extension of the upper plate. However, as pointed out by Gross & Hillemeyer (1982), the geometry of such structures is difficult to explain. Domino-faulting is capable of producing the observed tilts of the fault blocks, but severe space problems should develop at the base of these blocks as these tilts become larger, especially given the size of some of the blocks involved (Fig. 12). In addition it seems impossible to restore these sections to their unfaulted state without leaving gaping holes in the reconstruction (Fig. 13). These volume problems cannot be explained by assuming that chloritic breccias below the detachment fault are derived from upper plate rocks, and scraped off onto the lower plate, as there is clear evidence that this is not the case, both in the field, and from the standpoint of geochemistry (Heidrick & Wilkins 1980).

The lower portions of fault blocks immediately above the detachment fault are often complexly faulted, but there is insufficient complexity to explain geometry as is evident in cross-sections such as those illustrated in Fig. 12 (see also Davis & Lister 1988). In particular we consider the cross-section from Frost (1980) through the Whipple Wash canyon, eastern Whipple Mountains, where the geometry of upper plate faulting is well-exposed. Numerous planar normal faults are shown terminating at the main Whipple detachment fault. Attempts to reconstruct these sections before faulting, e.g. by re-aligning the Miocene non-conformity, reveals that large volumes of former upper plate rocks are now missing. Domino-style rotation along planar faults would produce major space problems along the Whipple Fault. If domino-faulting is to explain this type of structure, we must also ask why the relatively incompetent chloritic breccias in the lower plate have not bulged up into the upper plate to solve these fit problems.

There are two problems with the domino mechanism for extension of the upper plate: (a) as discussed above, there is a space problem at the base of the blocks as they tilt, and this space problem becomes progressively more aggravated as the width of the blocks increases in size; but also (b) although domino-faulting may allow fault blocks to tilt over, abrupt changes in tilt angle cause major fit problems, and therefore *adjacent fault blocks cannot differ substantially in their orientations.* But abrupt changes *do* occur in the orientation of strata across older, steeper, truncated normal faults in the upper plate of the Whipple detachment fault (see Davis & Lister 1988). These geometries are consistent with an original listric character to the intervening normal fault, i.e. the intervening fault is a truncated listric normal fault, not a domino fault. The original shallow-dipping (lower) portions of these faults have been excised by a younger, structurally higher detachment fault. Many of the details in cross-sections such as those illustrated in Fig. 12(c) (after Thurn 1983) can then be explained as the result of multiple detachment. Upper plate structures, truncated by the present Whipple detachment fault, in fact developed earlier with respect to an older, structurally deeper detachment fault. This part of the section must have been excised by subsequent detachment faults, including the present Whipple detachment fault, which have eaten their way progressively upward through the lower portions of the upper plate. At the same time, the present Whipple detachment fault has eaten deepest into the section than any of these previous faults, since it has incised into the mylonitic gneisses of the lower plate.

How do detachment faults eat their way progressively upwards through the lower portions of the upper plate?

Consider how a detachment fault can climb upwards through the lower portions of the upper plate, as the result of progressive excisement of the lower portions of the upper plate as each new detachment fault is initiated. Imagine a listric normal fault as shown in Fig. 14(a), where the active master detachment has bowed upwards until finally, a new master detachment must form. Activity on the old detachment ceases, and relative displacement on the new master fault results in excisement of the lower portion of the upper plate. Excisement of listric fault bottoms (Fig. 14b) leaves domino-like

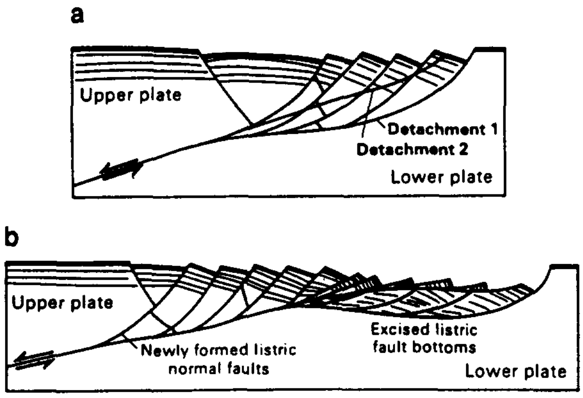

Fig. 14. Multiple detachment leads to excisement of listric fault bottoms. Diagram (a) shows a major splay that has branched from the previously active detachment fault. In (b) this splay has become the master detachment, and excisement of the lower portion of the upper plate has occurred. Previously active normal faults are abruptly terminated at the younger detachment. Younger listric normal faults have formed, associated with the new detachment surface. Multiple detachment thus explains the abruptly truncated, relatively planar, steeper normal faults of the upper plate.

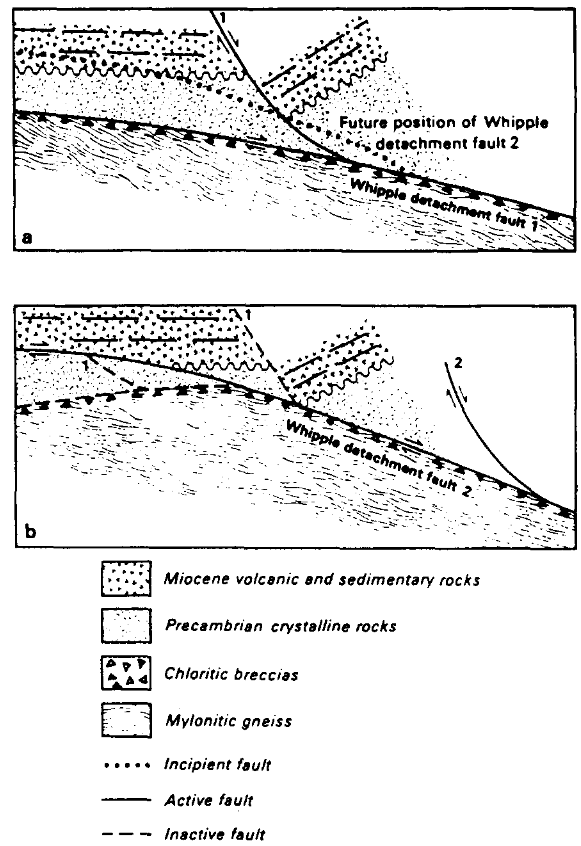

Fig. 15. Schematic representation of the time-evolution of the geometry of the Whipple detachment fault, to explain geological relations illustrated in Fig. 14. Section (a) illustrates inferred geometry of the Whipple Fault during phase 1 of its development. A listric normal fault (1) is associated with detachment fault 1. A splay is about to branch from this fault. Section (b) illustrates a subsequent phase of extensional deformation, where this splay (Whipple detachment fault 2) is now acting as the main detachment fault. This fault is also associated with a listric normal fault (2). However, the only indication that fault (1) in section (b) ever was a listric normal fault is the abrupt change in dip of strata that occurs across the fault.

fault blocks in the upper plate, with arrays of relatively planar high-angle normal faults truncated by the youngest master detachment fault. New listric normal faults sole into this new detachment surface, so some fault blocks undergo at least two periods of rotation. The excisement nappe, which is left structurally higher on the detachment system, contains low-angle more-or-less planar normal faults, which are in fact the structurally high remnants of earlier listric normal fault systems.

Figure 15, a diagrammatic rendering of cross-sections shown in Davis & Lister (1988) illustrates schematically how this may occur in more specific detail. An abrupt change in attitude of the Miocene strata in Whipple Wash occurs as one crosses specific high-angle normal faults. Although any one such fault appears to be merely one of a set of domino-faults, it must in fact be part of a truncated listric normal fault. The abrupt change in attitude of the strata cannot be explained by domino-faulting, since only strata in the hangingwall of the prominent upper plate normal fault exhibit significant rotation. Both hangingwall and footwall blocks would exhibit rotation if domino-style faulting had prevailed. The only explanation is that reverse drag on a listric normal fault has occurred as shown in Fig. 15(a). When the younger detachment fault formed, it truncated the older listric normal faults, and produced the observed structure.

This early listric fault shallowed eastward into an earlier equivalent of the Whipple Fault. In Fig. 15(a), we show the future position of a low-angle, upper plate splay, branching upwards from detachment fault 1, slicing across the upper plate crystalline basement and into the shallow-dipping Tertiary cover. Figure 15(b) illustrates a subsequent phase of extensional deformation, where this splay from the original detachment is now acting as the main detachment fault. Crystalline rocks formerly in the upper plate of the first Whipple detachment fault (1) have been excised by the younger, higher Whipple detachment fault (2) and this leads to truncation of the phase 1 listric normal fault in the upper plate. Some of the former upper plate rocks have now been transferred to a lower plate setting. The upper plate listric fault, active during phase 1, is now kinematically 'dead'. Basement rocks which were upper plate to the phase 1 detachment fault have been excised by the development of the higher splay, and are now transferred to the lower plate of the phase 2 fault. The eastern (once listric) fault of phase 1 extension now appears to be a planar hangingwall fault, with all the attendant geometric problems that such faults present at their abrupt termination with a presumably coeval, underlying detachment fault.

The presently exposed detachment fault can be now recognized to be a younger truncating structure. Once the upper plate normal fault is recognized as an older structure, now dead, the problem of attempting to balance upper plate strata on either side of it vanishes. Instead we are left with the problem of discovering the present location of the excised fault bottoms. Detailed mapping of the complex geology in the upper plate of the Whipple detachment complex has revealed some previously unrecognized detachment surfaces (e.g. Dunn *et al.* 1986), but in general these excised structures have not been recognized in the Whipple Mountains, and therefore they either must lie buried to the west, or they have been eroded from above the higher portions of the Whipple Mountains.

With the transfer of plate interaction from Whipple fault **1** to Whipple fault **2**, lower plate chloritic breccias (phase **1**) are 'switched' (using railroad parlance) to move up beneath the hangingwall of the now-active structurally higher splay (Whipple fault **2**). As chloritic breccias, and deeper level mylonites are shunted and switched along new trajectories, different types of fault products (e.g. gouge and indurated ultracataclasite) may be juxtaposed. Higher, younger, 'Whipple' faults may be too shallow for 'microbreccias' (or ultracataclasites) to develop along them, despite the fact that they, like their earlier phase parents, are underlain by chloritic breccias and deeper non-retrograded mylonitic gneisses. Indeed, some portions of the Whipple Fault do lack the 'microbreccia' ledge so characteristic of other parts of the fault.

Incisement and excisement nappes

If detachment faults initially have irregular geometries, ongoing faulting will remove some of the irregularities. If a splay of the detachment fault bites into the lower plate, *incisement* of the detachment fault into the lower plate is said to occur. If a splay of the detachment fault removes a slice of the lower portion of the upper plate *excisement* is said to have taken place (Fig. 16). Naturally, if slices of rock are transported as allochthons along the movement zone, we will be able to recognize excisement nappes formed during extensional orogeny.

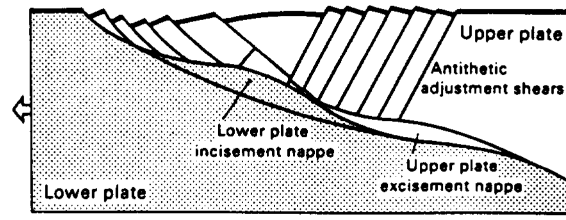

Fig. 16. Splays in the detachment fault lead to the formation of multiple detachment surfaces. Incisement nappes form when the detachment bites into the lower plate, and excisement nappes when the detachment slices off a portion of the lower part of the upper plate. Shaded portion of figure indicates original lower plate.

Complex incisement–excisement geometries are to be expected when large relative displacements take place on a major extensional shear zone of the type we have described. A case for the existence of incisement nappes can be made for the Sacramento Mountains (McClelland 1984). McClelland demonstrated the existence of at least three major detachment faults (Fig. 17a), which define three thin slices of rock above the present master detachment (the Sacramento detachment fault) (see Fig. 17b). The relative age of the detachment faults can be ascertained by examining relations with high-angle normal faults. Useful timing criteria are provided by high-angle normal faults which cut one detachment surface, but are then truncated at a lower detachment (Fig. 17b). The youngest detachment fault is the structurally lowest of the three surfaces, and the oldest is that

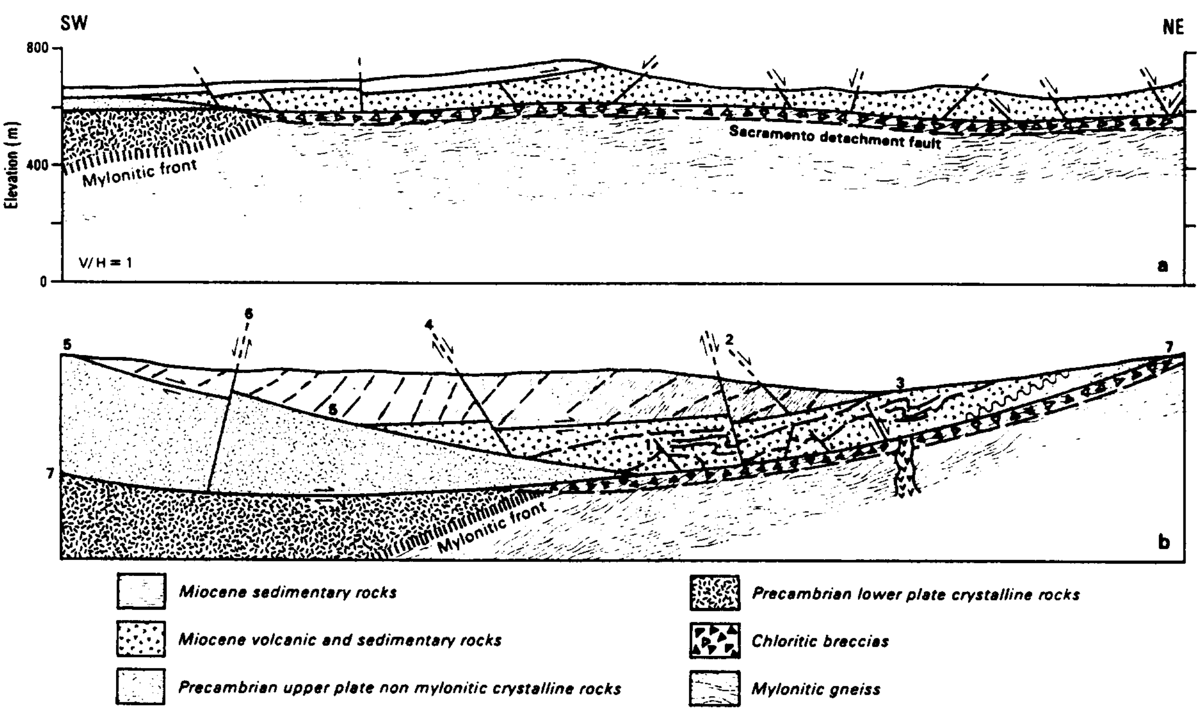

Fig. 17. Thin detachment slices in the upper plate of the southern Sacramento Mountains detachment fault (a), from McClelland (1984). Schematic cross-section (b) illustrates geological and geochronologic relations in this complexly deformed terrane. Three generations of detachment faults exist. The relative ages of high-angle and low-angle faults are indicated by numbers 1–7.

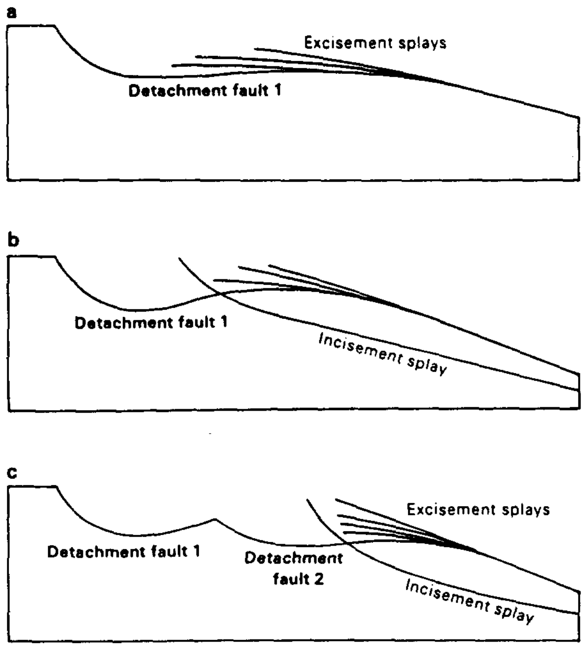

Fig. 18. Development of incisement-excisement structures as the lower plate bows upwards. Excisement faults splay from the currently active master detachment fault (a). Incisement of the detachment fault into the lower plate then follows, and new excisement faults splay off the developing culmination (b). In this way, as the result of successive incisement–excisement sequences, relatively deep levels of the lower plate can be exposed.

which is structurally highest. This relation in itself suggests that progressive incisement of detachment faults into the lower plate took place. However, relatively young Miocene sediments dip steeply into the structurally highest detachment, and McClelland pointed to the familiar difficulty of balancing the cross-section. This led Davis (in Lister *et al.* 1984b) to suggest that this evolving detachment fault system has accomplished both excisement of the lower portions of the upper plates, and incisement into the lower plate, through time. A sequence of detachment faults must be involved in the production of these structures (see Davis & Lister 1988).

Figure 18 shows how multiple detachments may first accomplish incisement, and then excisement. As bowing of the lower plate proceeds, excisement splays cut into the upper plate, firing from the currently active (progressively bowing) detachment fault. This progressive excisement of the lower portions of the upper plate allows the active detachment fault to rise through the section. However, incisement into the lower plate can also occur, and a new detachment system can form which bites deeper into the lower plate. The resulting incisement nappe will have its lower portions removed as the new detachment begins to bow upwards and excisement splays develop as shown. Davis & Lister (1988) show a more complex sequence of faults accomplishing both excisement and incisement. Such a sequence can produce the geometry observed in the Sacramento Mountains (McClelland 1984).

In summary, there appears to be two different modes in which a detachment fault can operate. Excisement splays from the master detachment fault result in removal of the lower portions of the upper plate, and incisement splays bite into the lower plate as it bows upward towards the surface. These splays may subsequently become the active master detachment fault.

THE NATURE OF THE WHIPPLE DETACHMENT FAULT

Multiple low-angle detachment faults have been recognized in most of the southern ranges of the Northern Colorado River region, some in upper plate, and some in lower plate positions. Interpretations vary widely as to whether such detachment faults all developed with shallow dips, or whether some (certainly not all) represent initially steep normal faults that have been rotated into shallow orientations during the extension process. Complex relationships exist between multiple generations of extensional faults that now dip both gently and steeply. Detailed study of these zones will eventually lead to more precise formulation of the processes of excisement and incisement involved in the evolution of major extensional shear zones. However, it is possible, on the basis of present knowledge, to make certain specific statements about one of the best known detachment faults in the southern Colorado River region, namely the Whipple Fault.

This fault, with an areal extent in excess of 10,000 km^2 can be shown to be a primary feature formed during the extensional process. It cuts into middle Miocene strata, and therefore does not represent a re-activated Mesozoic thrust, as has been postulated for some other detachment faults in the U.S. Cordillera (e.g. as for the Sevier desert detachment as proposed by Royse, in McDonald 1976; see also Allmendinger *et al.* 1983).

The present Whipple detachment fault locally truncates sub-horizontal Miocene strata, with the intersection angle not exceeding 10–15°. Hence the fault cannot represent a formerly steep normal fault which has been rotated into shallow attitudes by ongoing extension. It formed with a dip of between 10–15° in its upper levels.

The presently visible Whipple detachment fault had to have formed at less than 2–3 km depth in the central Whipple Mountains, since it truncates sub-horizontal Miocene strata there, and this part of the stratigraphic section is less than 2–3 km thick. Therefore the presently visible Whipple detachment fault is not a structure which formed at 8–12 km depth, onto which Tertiary strata have been lowered by the rotation of large tilt blocks. This is not to say that the presently visible detachment fault does not penetrate to great depths, nor does it suggest that the rocks uplifted in the footwall have not been uplifted from these depths or deeper (cf. Howard *et al.* 1982a). But this observation does provide a firm constraint on the depth of formation of that portion of the Whipple detachment fault presently visible. Successive detachment faults have migrated upwards into the lower plate as the result of progressive excisement of its lower portions. The presently visible fault formed at shallow depths, and is the youngest of this sequence.

The shallow depth of formation for the Whipple detachment fault (less than 2–3 km in the area of Whipple Wash) is additional evidence suggesting that detachment faults do not represent an ancient brittle–ductile transition, since it is unlikely that old crystalline gneisses could have been ductile at such levels. Moreover, the detachment fault formed after the mylonites in the lower plate had become kinematically inactive, at a time when the lower plate was deforming brittlely. This can be determined, because the Whipple detachment fault cuts structures in the lower plate formed as the result of brittle deformation, for example the chloritic breccia and superposed normal faults. Hence the detachment fault, when it was active, did not separate a brittle upper plate from a ductile lower plate. Ductile deformation in the presently exposed lower plate occurred at some time prior to the youngest period of detachment faulting.

We propose that the present Whipple detachment fault may be merely the last member of an evolving system of detachment faults that sliced through the fractured upper crust at the termination of a major extensional shear zone. The surface mapped as the Whipple detachment fault is probably not everywhere of the same age, and the present Whipple detachment fault may represent an amalgamation of several generations of splays from an earlier Whipple detachment fault system. This hypothesis is supported by the fact that the fault products associated with the Whipple detachment system are variable from place to place. At some localities microbreccia is absent, and unindurated fault gouge can be found. This suggests that different segments of the fault represent detachments of different generations. Considerable excisement of the lower portions of the upper plate may have occurred during this process of multiple detachment.

The last point which should be made is that this complex system of detachments has evolved with apparent rapidity, considering that an intraplate process is involved. The Chambers Well dyke swarm in the Whipple Mountains (Davis *et al.* 1982) is almost certainly the lower plate equivalent of the Mohave Mountains dyke swarm to the northeast described by Nakata (1982) and Howard *et al.* (1982b). If so, at least 40 km of relative displacement has occurred as the result of detachment faulting between the two ranges, between approximately 16–19 Ma, based on published and unpublished geochronological determinations (J. Wright personal communication 1984, Wright *et al.* 1986). Geochronologic data indicating rapid rise of the active footwall from mid-crustal to near surface levels between 20 and 18 Ma (Davis & Lister 1988) suggest that most of the 40 km of translation occurred during the early part of the 19–14 Ma interval in which the core complex formed (*ca* 17 to 18–19 Ma). Horizontal velocities on the fault of 0.8 to 2–3 cm per year, or more, are thus indicated.

DISCUSSION

The preceding part of the paper has set the background information against which we have assessed various models for the formation of metamorphic core complexes. Obviously there is a considerable amount of information that needs to be assessed, and we must apologise to the reader working his or her way through it all. We have reached two main conclusions.

One of these conclusions is that the available data set precludes the hypothesis that large detachment faults such as those observed in the Whipple Mountains can be explained by the rotation of gigantic tilt blocks. The metamorphic grade variation in the lower plate is quite insufficient to allow such a hypothesis. Moreover, in the upper plate, we have shown a number of cross-sections where the detachment fault truncates strata for which the enveloping surface remains sub-horizontal over 1–4 km, precluding the hypothesis that the detachment fault was once considerably more steeply dipping.

The other conclusion is that during the evolution of a core complex, multiple generations of detachment faults splayed from some master fault, or controlling movement zone at depth. The last active detachment fault is the youngest feature active during the evolution of the core complex. Successive generations of detachment faults progressively excise the lower portions of the upper plate, so that they eat their way progressively upwards through the overlying sedimentary sequences.

How then can we proceed to explain the apparent paradox posed by the evidence that detachment faults are shallow-dipping normal-slip faults, of large areal extent, formed as *primary* structures during continental extension? Let us explore the hypothesis that shallow-dipping structures form at depth which act as master faults, controlling the development of successive generations of faults (see Fig. 11). If we *can* form shallow-dipping faults at depth, it is conceivable that such faults fired from a successively re-activated master fault at depth, eat progressively into the headwall, leading progressively to the development of a low-angle normal fault with large areal extent. Such a detachment fault would have the correct characteristics: (a) the lower plate would be relatively unfractured; (b) different areal segments of the fault would be active at different times; and (c) the upper plate would be intensely fractured by normal faults related to several generations of detachment faults.

The formation of flat detachment-related shear zones in the continental crust during continental extension

To attempt an explanation for the origin of a possible master fault at depth, we return to consider the mechanical significance of the continental stress guide. We defined the continental stress guide as the diffusely bounded layer of rock at and around the depth at which the transition from brittle to ductile behaviour usually takes place. It is logical that the structures which cut the strongest region of the crust are those which have the greatest influence on subsequent tectonic events, since such failures are fundamental weaknesses which will always be re-activated by suitably oriented stress regimes, and hence will remain active the longest. Hence we surmized that brittle failure of the continental stress guide generates structures of fundamental importance to failure patterns in the upper crust, and that fault patterns in overlying sedimentary overburden are controlled by these basement structures.

The continental stress guide must be of considerable mechanical significance in terms of the behaviour of the crust during orogeny, and it is hence instructive to contemplate its behaviour during extension. In the upper part of the continental stress guide, rocks are dominantly brittle, and any attempt to extend the stress guide will result in faulting. In the lower part of the continental stress guide (where rocks are usually dominantly ductile), brittle failure can still occur, as already discussed: for example if a major seismic event occurs on a structure such as the Wasatch Front of the Basin and Range province, it will cut though the stress guide into the usually ductile zone underneath. Such a major seismic event will therefore provide a fundamental weakness, which will continue to be re-activated if extension continues.

Even if seismic ruptures do not cut all the way through the stress guide, this is the level at which crustal deformation invariably leads to the formation of ductile shear zones in preference to distributed deformation. Structural studies of terrains uplifted from such depths continue to emphasize the importance of such shear zones in their tectonic history. The structural observations we have in the metamorphic core complexes also serve to indicate the importance of ductile shear zones during crustal deformation at these levels. We therefore argue that *any* attempt to extend the continental stress guide will result in the formation of a through-going fault and/or a shear zone. Because of the formation of through-going faults and/or shear zones, a continuing extension of the continental stress guide will result in systematic transfer of relative displacements across the stress guide, which must be accommodated by ductile deformation. Strain compatibility arguments demand that such shear zones form with shallow-dipping orientations.

If, for whatever reason, this relative movement continues, detachment will be accomplished by the formation of shallow-dipping shear zones beneath the stress guides, for example as illustrated in Fig. 19(a). Such behaviour is the normal mechanical response to the existence of anisotropy, here expressed as the result of depth variation of the load-bearing capacity of rock. If the viscosity of rock in the shear zone is too great, such a decoupling shear zone will not attain great lateral extent. Perhaps under these circumstances arrays of steeply-dipping deeply-biting normal faults are formed, as shown in Fig. 4.

The conditions for the formation of such a laterally extensive decoupling shear zone as illustrated in Figs. 19 and 20(a) may simply relate to the ability of the ductilely

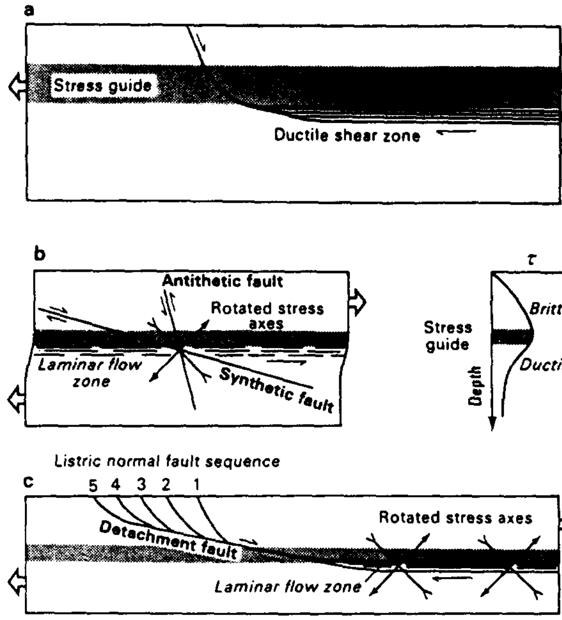

Fig. 19. (a) Extension of the stress guide defined by the brittle–ductile transition results in the formation of a through-going fault. Continued extension results in a sub-horizontal shear zone allowing detachment of the middle to lower continental crust at some depth below the brittle–ductile transition. This sets the stress axes over a wide area into inclined attitudes (ideally 45° to the horizontal). (b) The Coulomb–Mohr solutions for the synthetic failure plane favour the formation and propagation of a low-angle normal fault. (c) This acts as a master fault at depth, from which splay successive listric normal faults (1–5) which extend its area by progressively eating into the footwall of the previously formed fault.

deforming rock in the shear zone to undergo a process termed strain-softening. Possible causes for such rheological softening have been discussed earlier. Of particular importance may be the role of water, fluxing through the shear zone, allowing retrogressive metamorphic reactions, and enhanced dynamic recovery and recystallization. Large volumes of water may be provided by dehydration reactions as granites crystallize. Up to 10% by volume of water may be released, so that a moderately sized batholith can provide considerable volumes of water. Many granites appear to have risen to about the level of the detachment-related shear zones. Continental extension in some circumstances may thus lead to the formation of a shallow-dipping shear zone at some unspecified depth beneath the brittle–ductile transition (Fig. 7), which may act as a zone of decoupling (Fig. 19a).

This zone of decoupling potentially could provide the control which leads to successive detachment faults splaying upwards from the same movement zone at depth. Certainly, if strain softening continued to take place, the locus of deformation in such a shear zone would become exceedingly narrow, and it could then spawn several generations of detachment faults.

There is one other possibility. In any ductile shear zone, the axes of principal stress are rotated into inclined orientations. In an ideal situation (e.g. a horizontal flow plane, and progressive simple shear of a uniform isotropic medium), it can readily be demonstrated that σ_1 will rotate until it dips at 45° over the entire zone of

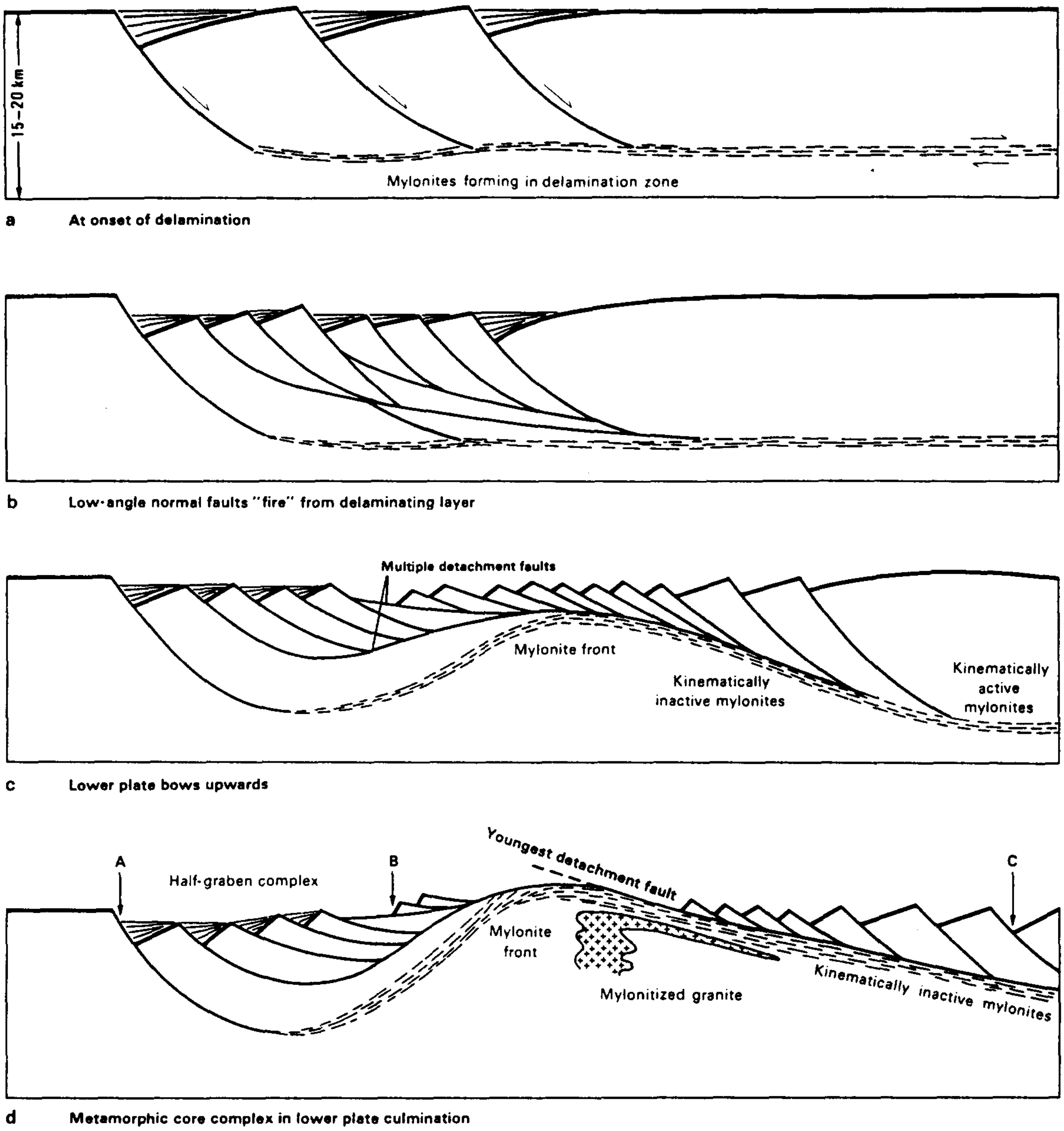

Fig. 20. Model of the development of a metamorphic core complex assuming (a) an initially sub-horizontal ductile shear zone at depth, decoupling the middle to lower crust beneath a steeply-dipping array of deeply-biting normal faults in the upper plate. (b) Low-angle normal faults are spawned from this zone, and the geometry of upper plate extension becomes increasingly complex. The detachment faults splaying from the basal shear zone act as master faults, controlling the generation of successive faults. (c) As the result of unloading, and as the result of the isostatic effects of granite intrusion at depth, the lower plate bows upward, with multiple detachment faults splaying from the developing culmination. The older faults are more bowed. (d) The metamorphic core complex is exposed underneath relatively young detachment faults, with faults A and B related to earlier stages of this evolutionary process. The mylonitic front is related to an upwarped, once sub-horizontal, ductile shear zone.

flowing rock. This can be proven using elemental concepts of continuum mechanics, relating the stress tensor to the rate of deformation tensor (e.g. Malvern 1973). This rotation of the stress field will take place instantaneously over the entire volume and areal extent of the decoupling shear zone (Fig. 19b).

Any fault which attempts to subsequently form in this region will *initially* be governed by this stress field. The Coulomb–Mohr criterion predicts that synthetic faults that emanate from the detaching zone will form with dips of 15–25°, if σ_1 is at 45° to the horizontal (Fig. 19b). The attitude (or the origin) of the structure that initially faulted through the continental stress guide is unimportant to these arguments, since its role is merely to enable the creation of a flat shear zone. What is significant is the *rotation of the stress field* that immediately results once the decoupling process gets underway. The orientation of this stress field favours the nucleation, and propagation, of low-angle normal faults.

We propose that low-angle normal faults which nucleate in the shear zone below the continental stress guide act as *master faults* which control the subsequent evolution of the extensional geometry of flat (detachment) faults. Structures which cut the strongest region of the crust (i.e. the region around the brittle–ductile transition) are those which have the greatest influence on subsequent events, since these are fundamental weaknesses which will always be re-activated by suitably oriented stress regimes. Such faults may propagate upwards from the controlling shallowly dipping deeper level shear zone.

A low-angle normal fault which propagates upwards from the continental stress guide towards the surface will gradually steepen, since the overall attitude of σ_1 in an extending lithosphere can be assumed to be vertical. Rather than imagining that a normal fault achieves listric geometry because a steep fault shallows downwards, we suggest the prerequisite is a shallowly inclined structure at depth, and that this structure steepens as it propagates upwards. *Such a shallow-dipping master fault at depth can control the generation of a large-area, low-angle normal fault by firing in sequence successive listric normal faults which progressively extend the area occupied by the shallow-dipping part of the fault* (Fig. 19c). Each successive newly formed detachment fault bites into the headwall of the previously formed listric fault, and consequently keeps longer to the attitude of the controlling master fault at depth, before it also begins to curve upwards to meet the surface. In this way a low-angle normal fault which acts as a master fault at depth can gradually expand its own area, especially in the presence of lithostatically pressured pore fluids which migrate up the detachment system (Reynolds & Lister 1987). This mechanism also implies that, although the lower plate is bounded upwards by a continuous, areally extensive fault, not all of this fault was actually active at one and the same instant.

We imply from this that we think the key element allowing the formation of a detachment fault to be the creation of a shallow-dipping master fault at depth, and that it is the propagation of multiple generations of low-angle faults from this master fault that leads to detachment faults of large areal extent as we see them exposed today.

Two modes of continental extension?

How to resolve the paradox posed by modern seismological observations, which seemingly contradict field observations in ancient extended terranes? Steep arrays of deeply-biting normal faults exist in modern actively extending terranes, and there is no seismological evidence for concurrently active detachment faults. Steep arrays of deeply biting normal faults, spaced at intervals of 30–40 km as in the Basin and Range, can coexist with gently dipping detachment faults, as long as these faults are not longer than 30–40 km in the direction of relative movement. If these steep normal faults were more closely spaced, they would have cut the detachment zones and been rendered inactive. Therefore, steep closely-spaced arrays of deeply-biting normal faults apparently did not exist at the time that the detachment faults were active.

One possible resolution of this question may be that there may be two fundamentally different modes of continental extension, and one mode of extension may be the precursor of the other. Let us suppose that *mode* I extension involves sets of steeply dipping planar normal faults, as described by Eyidogan & Jackson (1982), Jackson & McKenzie (1983) and Nábelek & Eyidogan (in press), which may cut down as deep as 15–16 km, in a large magnitude seismic event. These faults cut into rocks which are normally below the normal brittle–ductile transition. Suppose the high-angle normal faults connect at depth with a shallow-dipping ductile shear zone. This shear zone would allow relaxation of deviatoric stresses imposed at the fault terminations by periodic seismic events, and it would satisfy strain compatibility conditions imposed by the requirement that the crust undergo horizontal extension. Continued extension results in the initiation of a flat ductile shear zone in the crust at some depth below the stress guide defined by the 'normal' brittle–ductile transition. Strain softening in this shear zone will localize subsequent movements, and coalescence of adjacent shear zones will eventually result in the formation of regionally extensive mylonites (Fig. 20a).

As time goes on, it becomes more and more unlikely that this mode of continental extension will continue, as it becomes increasingly difficult to rotate the large tilt blocks in the upper crust. This could be for purely geometrical reasons, as deviation from the ideal Mohr–Coulomb angle increases. Alternatively, in fitting with what we now know to be the rapidity of the detachment mode of extension, in comparison to the rate of extension normally operating, perhaps a magmatic episode takes place which provides large volumes of fluid, and thus triggers the detachment or decoupling mode.

Let us assume that the *mode* I mechanism operates until 30–40% extension has been achieved, at which stage a switch in the mode of continental extension begins to take place. We suggest that at this time, low-angle normal faults begin to fire and to splay upwards from the detachment shear zone (Fig. 20b). Upward propagation of these faults leads to the formation of areally extensive detachment faults. This marks the onset of *mode* II continental extension.

Mode II extension essentially involves the development of basement culminations associated with regional development of multiple generations of detachment faults. The original basal shear zone, formed in the earliest stages of *mode* I extension, is warped upwards beneath bowed up detachment faults (Fig. 20c), from which splay successive generations of detachment faults as the basement culmination evolves (Fig. 11). Eventually the basement culmination is exposed to form a metamorphic core complex, surrounded by an apron of intensely faulted upper crustal rocks (Fig. 20d). The detachment faults by this time may have actually incised into the mylonitic fabrics formed during the earlier stages of this structural evolution, as shown.

The development of the 'mylonite front'

This model predicts a particular geometry (Fig. 20d). Starting at the headwall fault, one first encounters a

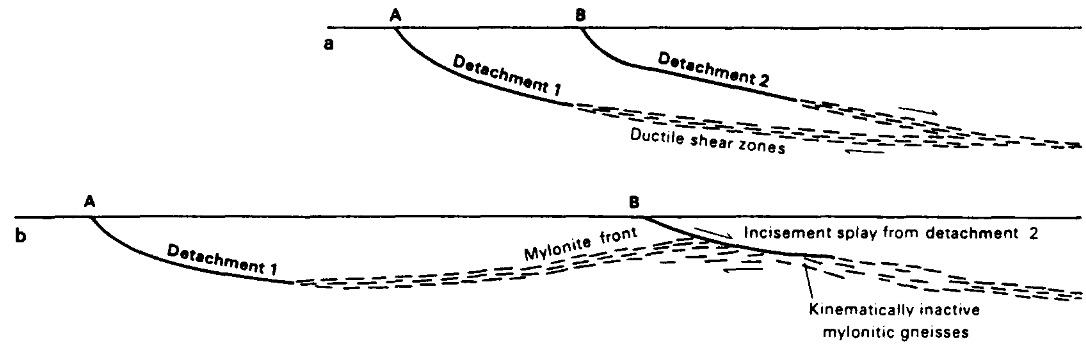

Fig. 21. Development of a mylonite front in the footwall of a younger detachment fault. The younger detachment fault transects mylonitic foliation. The mylonite front marks the location where the older mylonitic fabric in the exposed core complex rolls over, and diverges from the younger, capturing detachment fault.

basin defined by half-graben, and emergent rotated tilt blocks. Structural geometry of upper plate faulting becomes increasingly more complex, as the effects of multiple generations detachment faults, and multiple episodes of tilt block rotation, become increasingly obvious. The basement culmination which defines the metamorphic core complex is then encountered. This is defined by a bowed up detachment fault. This started life as a shallowly dipping fault, perhaps as steeply dipping as 20–30°, and progressively domed as the basement culmination developed. On the backside of the core complex, this fault cuts through uptilted basement which once lay in the stress guide. The detachment fault is back-rotated through the horizontal as the result of doming. The palaeogeotherm increases as we progress further along the cross-section. We encounter mylonitic rocks first at the 'mylonite front' (see Davis 1988), where the once shallow-dipping shear zone has been warped up to the surface. This rolls over into mylonites which progressively increase in strain intensity as we pass over the top of the culmination, onto the frontside of the metamorphic core complex. The detachment fault transects mylonitic foliation.

Interactions of adjacent independent detachment faults may also influence the development of the basement culminations that define the metamorphic core complexes. Consider adjacent continuously dipping movement zones, passing with increasing depth from a brittle detachment fault to a ductile shear zone (Fig. 21a). The second detachment system 'captures' the mylonites associated with the first detachment system, and transports them upwards in its footwall. The 'older' mylonites are back-rotated as the lower plate bows upward to form the broad culmination typical of the metamorphic core complexes, and they are overprinted by younger mylonites related to the second detachment system, before all ductile fabrics are transected by brittle detachment faulting. This leads to the exposure of a 'mylonite front' as shown in Fig. 21(b), and explains the basic structural relations observed in the Whipple Mountains (Davis 1986a,b, 1988, in press, Davis & Lister 1988).

CONCLUSIONS

The concept of a master detachment fault, lying below an extending upper plate containing steeper normal faults, has dramatically changed ideas about possible modes of continental extension. We think that major continental extension leads to the middle and lower crust being dragged out from beneath the fracturing and extending upper crust, and that detachment faults are the upper crustal manifestations of the movement zones responsible. Mylonitic gneisses formed at depth in major shallow-dipping ductile shear zones linked to these detachment faults. Mylonitic detachment terranes (or metamorphic core complexes) result when such deeper level crystalline rocks are drawn to the surface along these movement zones, creating a situation where metamorphic grade diminishes abruptly upwards across the detachment fault.

Models for continental extension solely by pure shear can be rejected for two principal reasons, as follows. Firstly, the *in situ* pure shear model interprets the detachment fault as marking the brittle–ductile transition, yet it can be shown that there is a time lag between brittle detachment faulting and the supposedly synchronous ductile deformation that produced mylonites in the lower plate. Both upper and lower plates were in the brittle field at the time of detachment faulting. In any case, to interpret the detachment faults as representing ancient brittle–ductile transitions is physically unrealistic. Secondly, the model requires coaxial extension of the lower plate, and mesoscopic and microscopic structural analysis demonstrates that this is not the case for at least a dozen metamorphic core complexes or detachment fault complexes in the southwestern Cordillera. Direct and unequivocal evidence for extension of the entire lower plate by bulk pure shear has yet to be produced. The mylonites in the lower plate formed in major shallow-dipping ductile shear zones.

Mylonitic detachment terranes, or metamorphic core complexes, can be explained by the operation of evolving crustal shear zones in an extending orogen. The evolving crustal shear zone model assumes that detachment faults disappear downwards into zones of brecciation, cataclasis, and seismic slip. In the breccia zones, relative displacement accumulates as the result of movement distributed over a broad volume, and is not accomplished by translations on a single discrete fault 'surface', although localized high strain zones in these cataclastic rocks may exist. Movement at deeper levels is accomplished as the result of the operation of (anastomosing) shear zones, and these may broaden with depth so that deformation is more penetrative, and relative movements are more distributed.

The evolving crustal shear zone model envisages continental extension as the result of a combination of detachment faulting, and the effects of the operation of shallow-dipping ductile shear zones (Wernicke 1981a, b, 1983, 1985, Reynolds 1982, 1985, Davis 1983, Davis *et al.* 1983, 1986, Lister & Davis 1983, Lister *et al.* 1984a, b). The detachment faults are merely the upper crustal manifestations of such zones. The model of a throughgoing lithospheric dislocation (Wernicke 1981a, 1983) has many attractive features, but it requires the movement zone to have remarkable persistence. An alternative model is that the lower crust and upper mantle might be subject to pure shear at the terminations of major extensional shear zones. 'Detachment + pure shear' models based on these concepts now resemble early models put forward by Rehrig & Reynolds (1980) and Davis & Hardy (1981).

The evolving shear zone model predicts that: (a) the spatial variation in material behaviour with depth in an evolving shear zone is reflected in time-sequences of behaviour to which particular volumes of rock are subjected as they move upwards through the shear zone; (b) asymmetric isostatic uplift takes place, causing the development of a broad arch or culmination in the lower plate as it bows upwards (e.g. Howard *et al.* 1982b, Spencer 1984); and (c) multiple generations of detachment faults form as older master detachment surfaces become warped and hence unsuited to be the locus of further large relative displacement.

Detachment faults formed at the beginning of the extension process, do not remain active throughout the entire geological history of core complex formation. We show that the present day detachment faults are relatively young features, representing the last of a succession of detachment faults that sliced through the upper crust at the terminations of shallow-dipping crustal shear zones.

The apparent paradox of large-area low-angle normal faults forming in an extensional regime can be explained as the result of the formation of a sub-horizontal ductile shear zone in the continental crust below the stress guide defined by the brittle–ductile transition. This basal shear zone sets up a stress regime mechanically suitable for the nucleation and propagation of low-angle normal faults. The basal shear zone forms during *mode* **I** continental extension, when arrays of steeply-dipping deeply-biting normal faults accomplish extension of the upper crust, and bulk pure shear takes place in the lower crust and upper mantle. The basal shear zone ductilely relaxes stresses built up at the terminations of these normal faults, and runs horizontally to meet strain compatibility requirements. *Mode* **II** continental extension results when brittle detachment faults fire from this basal zone of ductile detachment, so that one half of the extending terrane is then slowly pulled from underneath the other.

Splaying of the master detachment may lead to excisement and incisement. Incisement occurs when the detachment fault bites into the lower plate, and evidence for incisement has been documented in the Sacramento Mountains (McClelland 1984), and in the South Mountains (Reynolds & Lister in review). In addition it can be inferred that the main Whipple detachment fault has accomplished considerable incisement, because it transects mylonitic foliation in its lower plate.

Excisement occurs when younger generations of detachment faults splay from a bowing master detachment fault, slicing into the lower portions of the upper plate. As the lower plate is dragged out from underneath the fracturing and extending upper plate, it is warped upwards into a large arch or culmination. This bowing of the master detachment fault makes it progressively more difficult to continue its operation, and eventually splays of the master detachment must result. Each new splay in turn has the potential to become the master detachment fault. If this occurs, lower plate rocks are 'switched' or 'shunted' to follow a new trajectory, and juxtaposed against upper plate rocks much higher in the stratigraphic section. The lower portions of the upper plate are progressively excised by successive detachment faults, which as a result climb to higher and higher structural levels in the upper plate. Because multiple detachment leads to the excisement of considerable portions of the upper plate, cross-sections can be difficult or impossible to balance on the basis of limited surface and sub-surface information. Crustal reconstructions are possible only if a way is found to restore the missing section.

The multiple detachment model presented is capable of explaining many of the complexities observed in the metamorphic core complexes of the southern Colorado River region of the western United States. For example, in the Whipple Mountains, although the presently observed Whipple detachment fault probably connects at depth to a ductile shear zone, this cannot be the same shear zone that produced the somewhat older mylonitic gneisses presently exposed beneath the detachment fault (Davis 1986a, b). The present detachment fault system has incised into lower plate mylonitic gneisses, slicing through a shear zone that was kinematically dead at the time brittle faulting took place. Note however, that geochronological data (Wright *et al.* 1986) indicate that the time elapsed between the last stages of mylonitization and the formation of the present Whipple detachment fault was less than 5–6 Ma, and no significant changes in the bulk kinematics of deformation appear to have taken place in this time frame.

Most of the fault block rotation in the Whipple Mountains appears to have been caused by listric normal faulting. Domino-like rotations of fault blocks cannot explain large changes in dip of originally planar upper plate strata across individual faults. Listric normal faults allow strata to be sub-horizontal in one block and steeply-dipping in the next (e.g. in the central Whipple Mountains). The arrays of more-or-less planar high-angle normal faults which terminate against the present master detachment faults need not be interpreted as domino faults, since they can be better explained as listric normal faults whose shallow-dipping bottoms have been excised. We suggest that excisement of listric fault bottoms as the result of multiple detachment is a common phenomenon during the evolution of detachment terranes.

The fault presently mapped as the Whipple detachment fault appears to be only the latest surface (or, perhaps, a composite of late generation surfaces) that sliced through the fractured upper plate, accomplishing considerable excisement in the process. This fault is a primary feature formed during the extensional process. It does not represent a re-activated thrust. It does not represent a former high-angle fault which has been rotated into shallow attitudes by ongoing extension. It propagated to near surface levels with a dip of between 10–15°. Hence it cannot represent an ancient brittle-ductile transition in the earth's crust. Moreover, the detachment fault formed after the mylonites in the lower plate had become kinematically inactive, at a time when the lower plate was deforming brittlely. This complex system of detachments evolved with considerable rapidity, and appears to have accomplished a horizontal translation in excess of 40 km within a probable time frame of less than 2 Ma duration.

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