Intracrustal detachment within zones of continental deformation

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ABSTRACT

Geologic mapping of active to recently active geologic structures in Panamint Valley (western United States) and in the Haiyuan region and northern Tibetan plateau (China) suggests detachment in the middle and lower crust on a scale of tens of kilometres to at least several hundred kilometres. Detachment occurs similarly in predominantly extensional (Panamint Valley) and in predominantly compressional (China) environments. It involves structures with displacements of more than 10 km and displacement rates of more than 3 mm/yr, perhaps more than 10 mm/yr. The steeply dipping strike-slip faults present in all three areas (Hunter Mountain fault, Haiyuan fault, and Altyn Tagh fault zone) terminate in zones of extension or compression, and geometric relations indicate that all structures (including strike-slip faults) are thin-skinned and restricted to the upper crust. In Panamint Valley and in the Haiyuan region deformation within these systems can be reconstructed in three dimensions. Displacement on the strike-slip faults is absorbed by extension or compression occurring at the termination of the faults, so strike-slip displacement is roughly equal to and in the same direction as shortening or extension. We propose that left slip on the Altyn Tagh fault zone in northern Tibet is similarly absorbed by shortening southeast of the fault zone within the Qaidam basin and the Nan Shan.

INTRODUCTION

Regions of intracontinental deformation are characterized by broad zones of deformation. Within these zones the upper crust is broken into fragments that move relative to one another and are internally deformed. This style of crustal fragmentation and the marked spatial and temporal variability of deformation along fragment boundaries contrast markedly with the simple behavior of oceanic lithosphere, which is described so well by classic plate-tectonics concepts. Evidence from rock mechanics (e.g., Brace and Kohlstedt, 1980) and seismicity (e.g., Chen and Molnar, 1983) suggests that the different behavior of oceanic and continental lithosphere may be partly explained by different strength profiles. Between about 10 and 40 km depth, the oceanic lithosphere consists of uppermost mantle material and the continental lithosphere consists of continental crust. At these depths, mantle material is thought to remain relatively strong up to temperatures of about 500 to 600 °C, whereas the continental crust is thought to yield by ductile flow at much lower temperatures. The presence of a weak zone in the middle to lower continental crust suggests that the upper continental crust can be detached from the uppermost mantle in areas with elevated geothermal gradients or thick crust. This image of a weak zone of detachment in the lower continental crust invites the obvious question of how the deformation of the upper crust and the underlying uppermost mantle are linked. Before that question can be answered satisfactorily, we must document the magnitudes and rates of displacements within the upper crust, the presence of detachment within the crust, and the kinematic histories of upper crustal fragments.

CRUSTAL EXTENSION: BASIN AND RANGE PROVINCE

Most of the ranges of the Basin and Range province in the western United States appear to be composed of separate crustal fragments isolated by active faults and fault-bounded basins. From our mapping in the Death Valley region we infer that most of these fragments are probably detached from the underlying uppermost mantle. This can be illustrated by examining the evolution and structure of the north-trending Panamint and Saline valleys (Fig. 1), which formed contemporaneously during extension that began about 3–4 Ma and continues at present (Burchfiel et al., 1987; Sternlof, 1988). Geometric and kinematic relations among the faults in the Panamint Valley/Saline Valley area indicate that the two valleys are pull-apart basins connected by the right-slip N60°W striking Hunter Mountain fault zone (Fig. 1) (Burchfiel et al., 1987; M.I.T. Field Geophysics Course and Biehler, 1987).

The geometry of faulting throughout this area is consistent with northwest-southeast–directed extension. Active faults along the east and west side of northern Panamint Valley strike between north and N30°W, and active faults in the valley show both normal and right-slip components. Normal faults in Saline Valley generally strike N20°–25°E and continue northward through the Saline Range. Most of the Saline Range is topographically lower than the surrounding mountain ranges and forms part of the northern segment of the pull-apart structure.

Dextral displacement of 8–10 km has been documented on the Hunter Mountain fault zone (Burchfiel et al., 1987). Almost pure strike-slip displacement is indicated by geomorphic surfaces in unextended parts of the Darwin Plateau and Hunter Mountain, which are at the same elevation on both sides of the fault zone. Because the Hunter Mountain fault zone does not extend beyond the limits of Panamint and Saline valleys, right slip on the Hunter Mountain fault appears to be absorbed entirely by extension in

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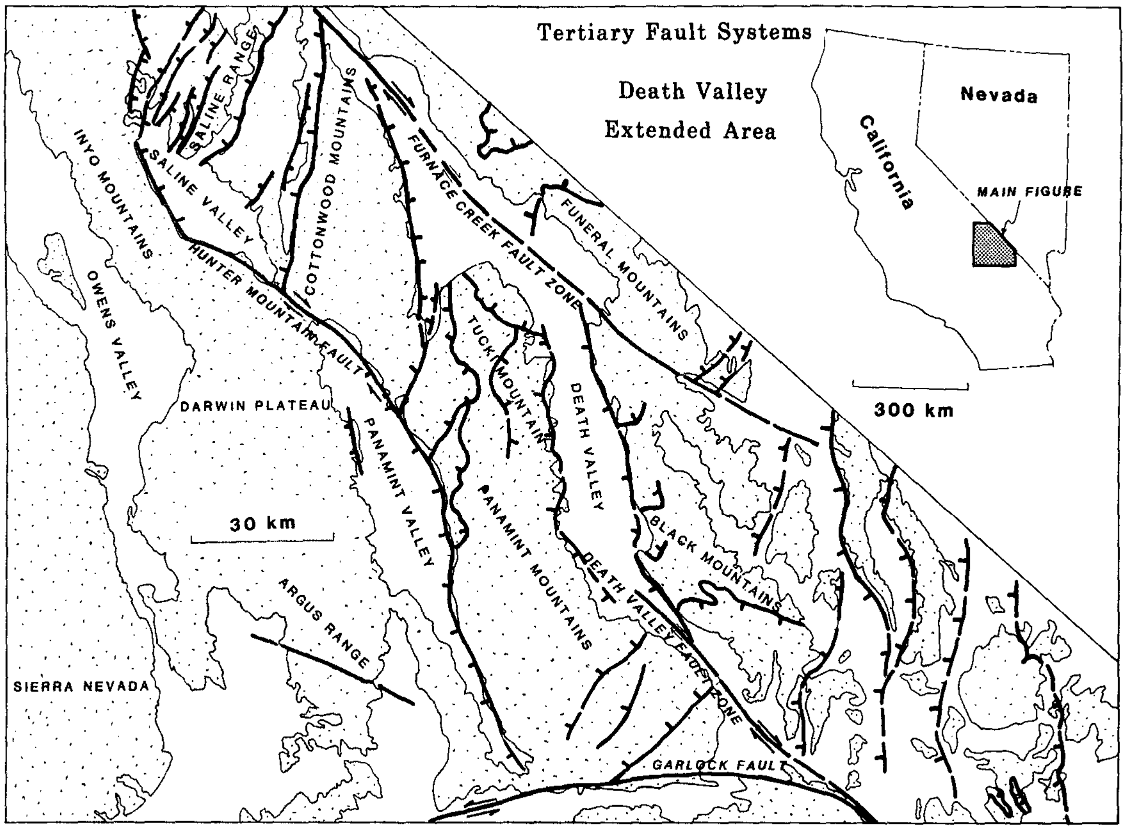


Figure 1. Generalized map of Tertiary fault systems in Death Valley extended area showing location of features mentioned in text.

the valleys. Sternlof's (1988) palinspastic reconstruction across the Saline Range and ranges to the east yields about 8–10 km of extension in the northern pull-apart structure. Geophysical studies of Panamint Valley show a very shallow depth to pre-Tertiary basement and the apparent absence of the strongly magnetized volcanic rock that abounds on the sides of the valley. These data suggest extension of Panamint Valley by 6 to 9 km (M.I.T. Geophysics Field Camp and Biehler, 1987). Thus, it appears that the geometry of this paired pull-apart system can be reconstructed in three dimensions, even though structures beneath northern Panamint Valley cannot be observed directly.

The narrow (12–15 km) widths of the basins and the large amount of extension in Panamint Valley and Saline Valley prohibit a geometry in which range-bounding faults pass steeply through the crust into the mantle beneath the basins. The palinspastic restoration of the Saline Range by Sternlof (1988) indicates that the normal faults in this area are detached at a shallow crustal level. Palinspastic restoration of northern Panamint Valley cannot be made from surface geology because the valley is covered by alluvium, but offset of piercing points on the Hunter Mountain fault zone constrains the geometry of a cross section through northern Panamint Valley (Burchfiel et al., 1987). The cross section requires that a west-dipping, low-angle (5°–15°) normal fault with 8–10 km displacement underlies the valley. A similar conclusion was reached by the M.I.T. 1985 Field Geophysics Course and Biehler (1987) because of the shallow depth to basement inferred from geophysical data.

Because the faults beneath Saline and Panamint valleys appear to be detached at shallow crustal levels, and because the Hunter Mountain fault zone merges east and west with these normal fault systems, we infer that the Hunter Mountain fault zone merges at depth with the gently west dipping normal fault that bounds Panamint Valley and with the shallow detachment surface inferred by Sternlof (1988) to underlie Saline Valley. If the crustal fragments adjacent to the Hunter Mountain fault are detached within the crust, then their relative displacements may not reflect directly the kinematics of the lower crust and upper mantle.

All the Cenozoic extensional structures in the Death Valley region may be similarly detached within the crust. For example, the Garlock fault of the Death Valley region separates an area of late Cenozoic extension to the north from a region to the south that did not extend in late Cenozoic time. Extension north of the Garlock fault occurs partly on low-angle normal faults, and the structural relations between the normal faults and the Garlock fault are similar to those in the Saline Valley area (Davis and Burchfiel, 1973). The direct linking of strike-slip (transfer) and normal faults in this area suggests that all these structures are detached within the crust, and that the Garlock fault is an upper crustal feature that merges with a subhorizontal zone of detachment within the crust. This interpretation is supported by seismic reflection studies which show that the Garlock fault does not offset mid-crustal reflectors (Cheadle et al., 1986; Lemizski and Brown, 1988). A similar zone of detachment between the upper and lower crust in the southern Death Valley region is also suggested by seismic reflection studies which indicate that shallow crustal faults can be traced to depths of about 15 km where they merge or are truncated by a broad zone of subhorizontal reflectors (Serpa et al., 1984).

CRUSTAL SHORTENING: WESTERN CHINA

In the Haiyuan area of north-central China, concurrent slip has occurred on a system of strike-slip faults and thrust faults that marks the northeastern corner of the Tibetan plateau (Fig. 2). Both the strike-slip and thrust faults have changed orientation through time, requiring a complicated history of displacement between crustal fragments. The geometry of the fault system and the rapidity with which rates and directions of displacement have changed along it strongly suggest that upper crustal fragments in this area are decoupled from the deeper crust and mantle.

Detailed mapping shows that 11–15 km of late Pliocene(?)–Quaternary left slip has occurred on the N60°W-striking Haiyuan strike-slip fault zone. Left slip on the Haiyuan fault has been absorbed by shortening within the north-trending Liupan Shan, Madong Shan, and Xiaoguo Shan ranges at the southeast end of the

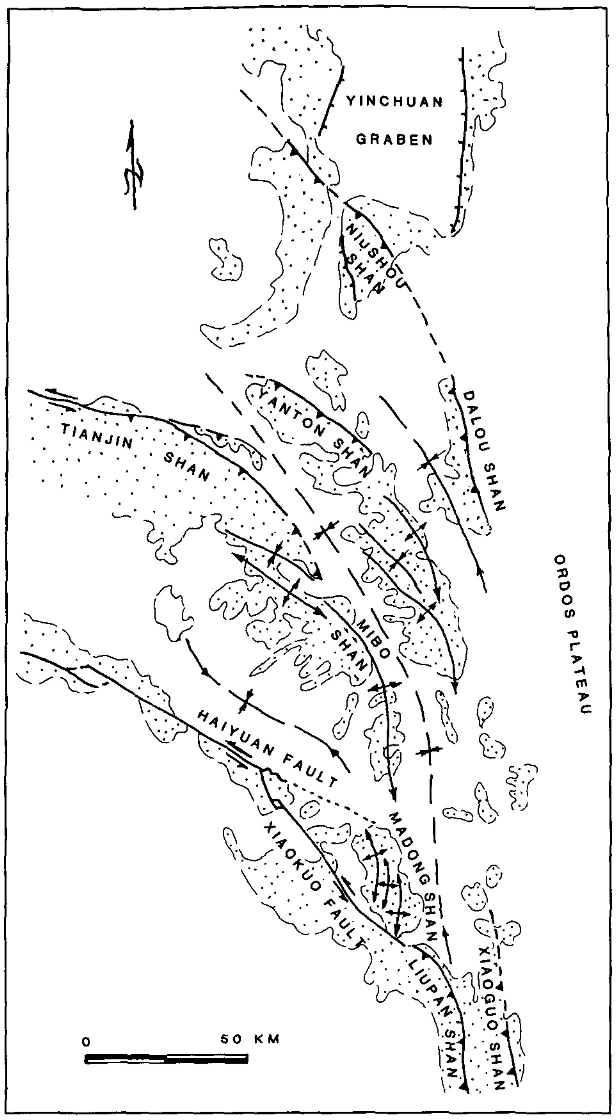


Figure 2. Generalized structural map of southern Ningxia Hui area, China, showing major features mentioned in text. Location of area is along northeastern margin of Tibetan plateau (see H [Haiyuan] and SNA [southern Ningxia Hui area] in Fig. 4).

fault (B. C. Burchfiel et al., in prep.; Zhang et al., in prep.; Fig. 2). Within this period, deformation can be divided into three stages (Fig. 3). During stage I, in late Pliocene or earliest Pleistocene time, crustal shortening occurred on northwest-trending thrust faults and folds that span a region at least 10 km northeast and southwest of the Haiyuan fault and absorbed about 1–2 km of roughly northeast-southwest shortening (B. C. Burchfiel et al., in prep.; Zhang et al., in prep.).

Stage II began after late Pliocene or early Pleistocene time when the left-slip Haiyuan fault cut and displaced these folds and other older structures by 8–15 km. The Haiyuan fault does not appear to reach east of the Xiaoguo Shan (Figs. 2 and 3), and balanced cross sections across the Xiaoguo Shan, Madong Shan, and Liupan Shan reveal a minimum of 12–15 km of crustal shortening in a direction parallel to the trend of the Haiyuan strike-slip fault (Zhang et al., in prep.). The northwest-southeast–directed crustal shortening that occurred in the Liupan Shan, Madong Shan, and Xiaoguo Shan during stage II was nearly perpendicular to the northeast-southwest crustal shortening of stage I. Similarly, convergence between crustal fragments on either side of the fault zone (southern Ningxia and Ordos blocks) must have changed from roughly northeast-southwest to roughly northwest-southeast when the Haiyuan fault became a major structure.

Stage III began at about 200 ka, when slip ceased on the eastern end of the Haiyuan fault and began on the N45°W-trending Xiaokuo fault (Fig. 3). Since that time, 1–1.5 km of left slip has occurred on the currently active Xiaokuo fault (Zhang et al., in prep.). The difference in strike between the Haiyuan and Xiaokuo

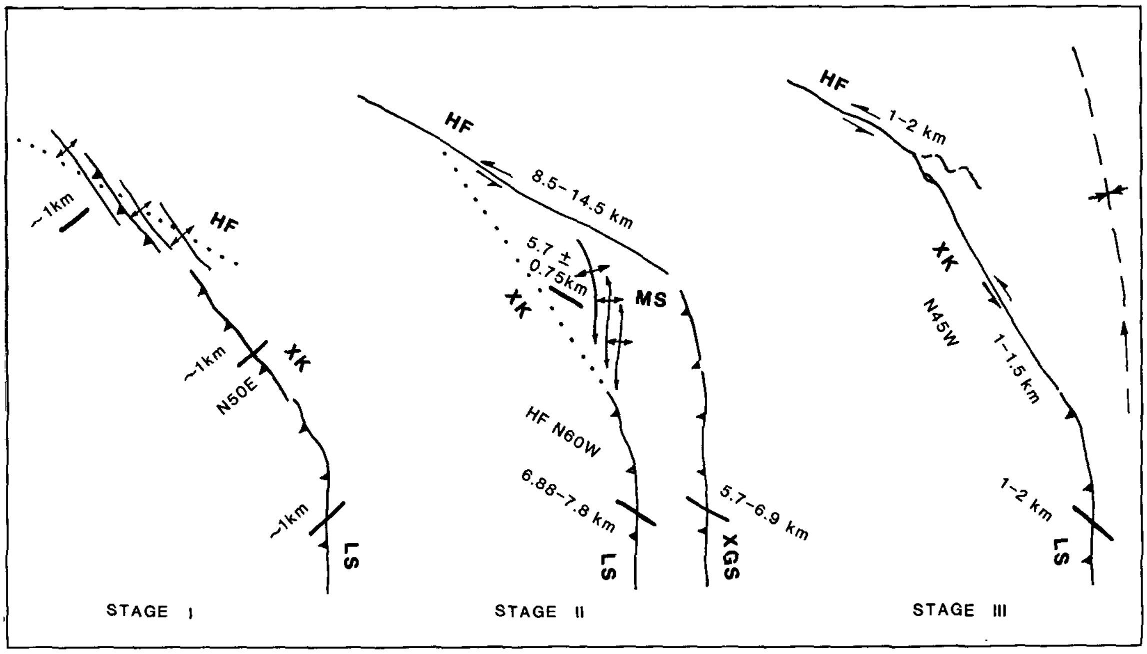


Figure 3. Schematic diagram showing three stages of evolution of structures in Haiyuan-Liupan Shan area of southern Ningxia Hui region. Location of structures is in southern part of Figure 2 and in Figure 4. Dotted line in first two stages indicates location of faults active in next stage. Short heavy line indicates approximate direction of shortening during that stage. Amount of shortening determined from field data is indicated for every major structure during that stage. Stage I—late Pliocene; Stage II—early Quaternary to about 200 ka; Stage III—about 200 ka to present. HF = Haiyuan fault; XK = Xiaokuo fault; LS = Liupan Shan; MS = Madong Shan; XGS = Xiaoguo Shan.

faults requires a component of shortening that is reflected by folding of the inactive part of the Haiyuan fault zone and by the formation of a broad north-plunging syncline east of the Xiaokuo fault (Fig. 3).

Figure 3 shows that within the Haiyuan-Liupan Shan area the direction of shortening has changed twice, by about 30° to 90°, since 2 Ma. Deformation during stages II and III can be reconstructed in three dimensions, strike-slip motion on the Haiyuan and Xiaokuo faults being absorbed by shortening on thrust faults within the Liupan Shan, Madong Shan, and Xiaoguo Shan. Because shortening in these ranges must be parallel to the strike of the Haiyuan fault (stage II) or the Xiaokuo fault (stage III), none of the shortening on these folds and faults seems to have taken place at right angles to the structures.

The geometry of the folds and thrust faults in the Madong Shan, Liupan Shan, and Xiaoguo Shan indicate that these structures are thin-skinned and are underlain by a detachment surface located about 5 to 6 km below the surface, apparently within the crystalline basement (Zhang et al., in prep.). The Haiyuan fault zone must merge with this detachment surface at depth because (1) the left-slip Haiyuan fault zone forms a boundary between a zone of modest crustal shortening to the north and a zone with more than 10 km of northeast-southwest crustal shortening to the south, (2) all structures formed contemporaneously, and (3) shortening in the Madong Shan, Liupan Shan, and Xiaoguo Shan accounts for almost all of the displacement on the Haiyuan fault. The rapidity with which the rates and directions of motion have changed between crustal fragments on either side of the fault system also suggests that these fragments are not directly attached to a large plate or to thick lithosphere below.

Other evidence for detachment of the Haiyuan strike-slip fault comes from the area northeast of the Haiyuan fault zone, where northwest-trending zones of folds and thrust faults (Tianjin Shan, Mibo Shan, Yanton Shan, Dalou Shan, and Niushou Shan) are similar to the stage I structures of the Haiyuan area (Fig. 2). These structures began to form at the same time as the stage I structures in the Haiyuan area, but deformation of these structures appears to have continued until the present. The geometry of these folds and faults indicates that they formed within a northeast-vergent, thin-skinned fold and thrust belt above a southwest-dipping detachment surface. We infer that this detachment surface continues beneath the Haiyuan strike-slip fault and merges with the detachment surface below the Liupan Shan, Madong Shan, and Xiaoguo Shan. However, the convergence rate across these northern folded zones has averaged only about 1–2 mm/yr, in contrast to the 5–10 mm/yr rate of slip on the Haiyuan fault and rate of convergence across the Liupan Shan, Madong Shan, and Xiaoguo Shan (Zhang et al., in prep.).

The geometric relations of the structures in the southern Ningxia Hui Autonomous Region thus suggest that all the folds, faults, and strike-slip faults are detached within the crust. This implies that the convergence between southwest Ningxia and the Ordos platform at shallow crustal levels may not directly reflect the relative motions or sense of deformation within the crust and mantle below the level of detachment. For example, the thin-skinned fold and thrust belt of southern Ningxia exists adjacent to and appears to override active north-trending extensional structures of the Yinchuan graben (Fig. 4). We infer that these extensional structures may continue beneath the thrust belt, so that crustal extension may occur below the thrust belt, separated from it by a southwest-dipping zone of intracrustal detachment. Thus, the southwestern link between extensional structures that surround the Ordos block on three sides may lie below the thin-skinned fold and thrust belt of southern Ningxia (Fig. 4).

IMPLICATIONS FOR THE STRUCTURE OF THE TIBETAN PLATEAU

Structural relations between the Haiyuan strike-slip fault and thrust faults along the northeastern corner of the Tibetan plateau may represent only one example of a more general relation between strike-slip faults and thrust faults within a larger part of the Tibetan plateau (Fig. 4). In particular, we suggest that left slip on the Altyn Tagh fault zone is related to and absorbed by crustal shortening within the Nan Shan, the Qaidam basin, and other convergent structures south of the Altyn Tagh fault zone, and that all these structures are detached within the crust.

The major Tertiary structures of the Tibetan plateau include east-west– to west-northwest–trending Cenozoic folds and thrust faults (Chang et al., 1986; Burke and Lucas, 1985; Molnar et al., 1987; Wang, 1985). Some of these structures are known to be active (Bally et al., 1986). These belts of Cenozoic folds and thrust faults terminate to the west and northwest against the southeast side of the left-slip Altyn Tagh fault zone. Geologic and tectonic maps of China indicate that the Altyn Tagh fault zone ends northeastward in the western Nan Shan (e.g., Ma, 1986; Wang, 1985). Thus, the surficial relations between the Altyn Tagh strike-slip fault zone and the Cenozoic folds and thrust faults of north-central Tibet appear to be similar to those between strike-slip and thrust faults in the Haiyuan area. Therefore, we propose that left slip on the Altyn Tagh fault zone is being trans-

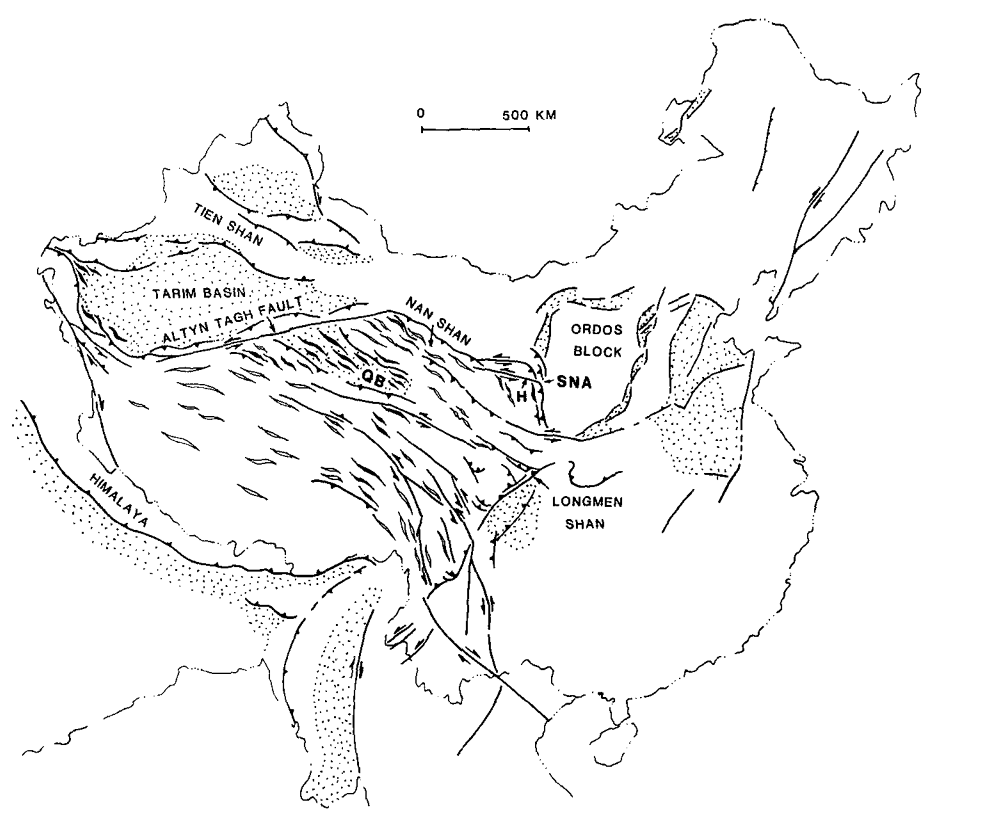
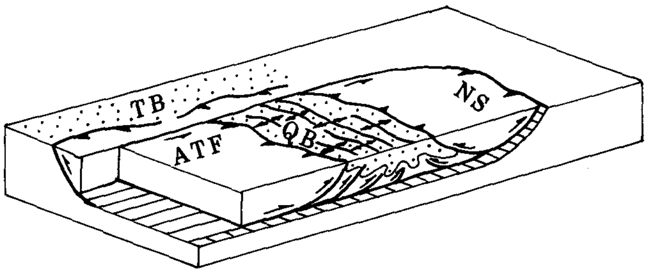


Figure 4. Generalized tectonic map of western China showing structures and features mentioned in text. Dotted areas are Neogene sedimentary basins. Lenses indicate fold trends on Tibetan plateau. Black = known Neogene folds. Open lenses indicate Cenozoic folds or trends of elongate Cenozoic basins that are probably controlled by folding. QB = Qaidam Basin; H = Haiyuan; SNA = southern Ningxia Hui area.

Figure 5. Schematic diagram illustrating nature of upper crustal detachment of structures in area of Qaidam Basin (QB), Altyn Tagh fault (ATF), Nan Shan (NS), and Tarim basin (TB). Dotted areas are Cenozoic sedimentary basins; lined area is zone of intracrustal detachment.



ferred into and absorbed by northeast-southwest shortening within the Qaidam basin and the Nan Shan. This interpretation is supported by fault-plane solutions from earthquakes in this part of Tibet (Molnar and Lyon-Caen, 1989). (Some of the shortening in the Nan Shan is probably also transferred onto the Haiyuan fault.)

If this interpretation is correct, then displacement on the Altyn Tagh fault zone must decrease progressively toward the northeast as its left slip is transferred into crustal shortening along the active folds and thrust faults south of the Altyn Tagh fault zone. This decrease in displacement toward the northeast has also been suggested by Peltzer (1987) and by P. Tapponnier (1987, personal commun.). The rate of displacement and the total amount of displacement along the Altyn Tagh fault are equal to the net rate of shortening and the total amount of shortening that have occurred on the folds and thrust faults that strike into the Altyn Tagh fault from the southeast.

Structural data indicate that the folds and thrust faults in the Qaidam basin and the Nan Shan can be reasonably interpreted as structures formed within a thin-skinned thrust belt and lying above an intracrustal detachment zone (Bally et al., 1986). Along the southern margin of the Tarim basin, Cenozoic and active north-vergent folds and thrust faults of the Altyn range can be similarly interpreted as a thin-skinned thrust belt above a zone of detachment that dips south beneath the Altyn Tagh fault zone. Therefore we infer that the Altyn Tagh fault zone is itself detached at crustal levels and that it merges at depth with a subhorizontal zone (or zones) of detachment that underlies the Altyn range, the Nan Shan, and the Qaidam basin (Fig. 5). Cenozoic shortening also includes the Tien Shan farther to the north; these structures may be similarly detached at depth.

DISCUSSION

Three examples of normal, thrust, and strike-slip faults in extensional and convergent settings support the interpretation that many of the structures observed at the surface within zones of intracontinental deformation may be detached above subhorizontal zones of detachment within the continental crust. Detachment appears to occur on a scale of tens to hundreds of kilometres, and crustal fragments above the zone of detachment move at rates of several millimetres to perhaps more than 10 mm/yr and change direction on a time scale of less than 1 m.y. The extent of detachment between the upper crust and the mantle is uncertain.

Within the context of classic plate tectonics, displacements observed at the surface are assumed to correspond to motion within the uppermost mantle over even modest length scales, perhaps greater than about 100 km. In contrast, we have presented evidence that within broad zones of continental deformation, upper crustal fragments are detached from the upper mantle over horizontal distances up to several hundred kilometres, and we infer that at this scale crustal motions may not be strongly coupled to the motion of the underlying mantle. It is not clear at what minimum length scale crustal motions in continental deformation zones accurately represent the motion within the underlying mantle; e.g., are these motions correlative on a scale of hundreds of kilometres to 1000 km? Or are motions of crustal fragments representative of mantle motions only on the largest scale of entire intracontinental deformation zones, i.e., scales of more than 1000 km in Tibet and the Basin and Range province? The answer to this question is important in that it has implications for the spatial and temporal variability of mantle flow. Clearly, it is important to extend studies such as those presented in this paper to larger scales, but this can only be accomplished by conducting many more local quantitative field studies and by integrating local deformation histories into a regional picture.

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