Possible origin and significance of extension-parallel drainages in Arizona's metamorphic core complexes

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ABSTRACT

The corrugated form of the Harcuvar, South Mountains, and Catalina metamorphic core complexes in Arizona reflects the shape of the middle Tertiary extensional detachment fault that projects over each complex. Corrugation axes are approximately parallel to the fault-displacement direction and to the footwall mylonitic lineation. The core complexes are locally incised by enigmatic, linear drainages that parallel corrugation axes and the inferred extension direction and are especially conspicuous on the crests of antiformal corrugations. These drainages have been attributed to erosional incision on a freshly denuded, planar, inclined fault ramp followed by folding that elevated and preserved some drainages on the crests of rising antiforms. According to this hypothesis, corrugations were produced by folding after subaerial exposure of detachment-fault footwalls. An alternative hypothesis, proposed here, is as follows. In a setting where preexisting drainages cross an active normal fault, each fault-slip event will cut each drainage into two segments separated by a freshly denuded fault ramp. The upper and lower drainage segments will remain hydraulically linked after each fault-slip event if the drainage in the hanging-wall block is incised, even if the stream is on the flank of an antiformal corrugation and there is a large component of strike-slip fault movement. Maintenance of hydraulic linkage during sequential fault-slip events will guide the lengthening stream down the fault ramp as the ramp is uncovered, and stream incision will form a progressively lengthening, extension-parallel, linear drainage segment. This mechanism for linear drainage genesis is compatible with corrugations as original irregularities of the detachment fault, and does not require folding after early to middle Miocene footwall exhumation. This is desirable because many drainages are incised into nonmylonitic crystalline footwall rocks that were probably not folded under low-temperature, surface conditions. An alternative hypothesis, that drainages were localized by small fault grooves as footwalls were uncovered, is not supported by analysis of a down-plunge fault projection for the southern Rincon Mountains that shows a linear drainage aligned with the crest of a small antiformal groove on the detachment fault, but this process could have been effective elsewhere. Lineation-parallel drainages now plunge gently southwestward on the southwest ends of antiformal corrugations in the South and Buckskin Mountains, but these drainages must have originally plunged northeastward if they formed by either of the two alternative processes proposed here. Footwall exhumation and incision by northeast-flowing streams was apparently followed by core-complex arching and drainage reversal.

Keywords: detachment faults, drainage patterns, extension tectonics, geomorphology, metamorphic core complexes, normal faults.

INTRODUCTION

Cordilleran metamorphic core complexes are mountain-sized masses of rock that have been uplifted from mid-crustal depths by ascent beneath large-displacement, gently to moderately dipping normal faults known as detachment faults. These faults place shallow-level crustal rocks, often including synextensional sedimentary and volcanic rocks, on exhumed footwall rocks that are commonly mylonitic (e.g., Davis and Lister, 1988). Mylonitization has been attributed to crystal-plastic shearing downdip from one or more detachment faults, with mylonitic lineations recording the direction of divergence between semirigid crustal blocks (Wernicke, 1981; Davis, 1983; Davis et al., 1986), or shearing between strong upper crust and flowing plastic deep crust (Wernicke, 1992). Hanging-wall rocks typically have been removed from atop the footwall in metamorphic core complexes of Arizona and southeastern California (Fig. 1) and the corrugated form of the footwall block is clearly revealed by resistant crystalline rocks that have been stripped of fault-related breccias (Pain, 1985). Arid climatic conditions have helped preserve corrugations, which were first uncovered in early to middle Miocene time (Spencer and Reynolds, 1989b; Dickinson, 1991; Fitzgerald et al., 1994; Miller and John, 1999). Corrugation amplitudes are generally measured in hundreds of meters to kilometers and wavelengths in kilometers to tens of kilometers. None of the numerous theories for the origin of the corrugations, as folds (Frost, 1981; Spencer, 1982; Yin, 1991), as original grooves (Spencer, 1985; John, 1987; Davis and Lister, 1988), or as a combination of original and molded grooves (Spencer and Reynolds, 1991; Spencer, 1999), has received wide acceptance (e.g., Livaccari et al., 1995). Because of parallelism between corrugation axes and extension direction, however, all these theories relate corrugation genesis to extension.

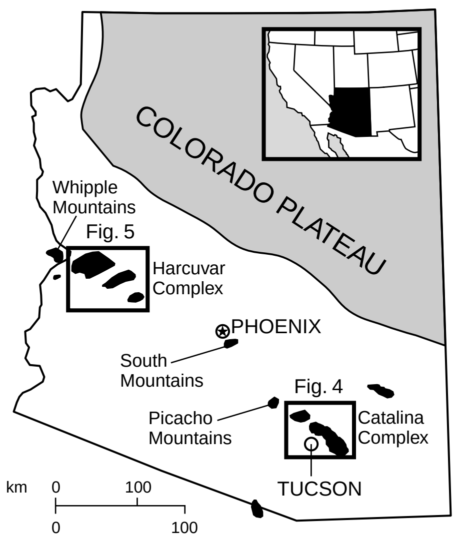

Figure 1. Location map for metamorphic core complexes (black) in Arizona.

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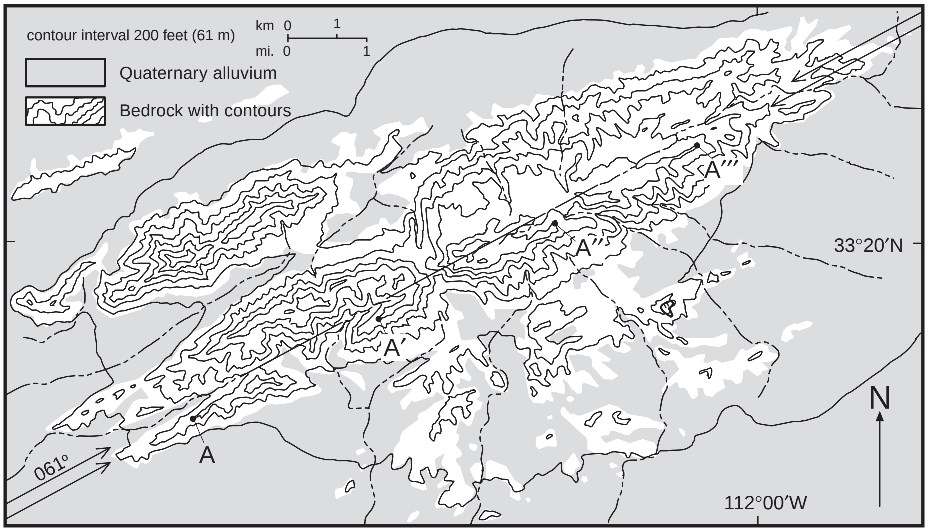

Figure 2. Topography and drainages of the South Mountains, central Arizona. Note small klippe in southeastern part of range. Paired arrows at opposite ends of range are aligned with linear topographic features, as follows: points A, A′, A″, and A‴ are along aligned ridge-crest segments. Parallel line segments to north of aligned ridges connect aligned drainages (geology from Reynolds, 1985).

Many metamorphic core complexes in the arid southwestern United States are incised by drainages that parallel corrugation axes and mylonitic lineation. These drainages were first recognized by Pain (1985), who attributed them to stream erosion on planar fault ramps that dipped in the extension direction, followed by folding with fold axes parallel to extension direction and to drainages. This interpretation is supported by evidence that lineation-parallel drainages have been locally captured by the more numerous and possibly younger drainages that run down the flanks of the corrugations (Pain, 1985). Furthermore, the arid climate in the Mojave-Sonoran desert region and the highly resistant character of the mylonitic rocks that host many of the drainages add plausibility to the inference that drainage patterns have been preserved since establishment 12–20 Ma.

Pain's (1985) envisioned process of corrugation-parallel drainage incision requires fault ramps to have dipped consistently in the extension direction. However, exposed metamorphic core complexes include lateral ramps and lateral terminations with detachment-fault dips that are not consistently in the extension direction and, in some cases, are nearly perpendicular to it. All across the south face of the Santa Catalina Mountains north of Tucson, Arizona, for example, mylonitic lineation is highly oblique to the range front and to the dip of the detachment fault at the foot of the range. Pain's model also requires that folding to produce corrugations must affect footwall rocks after subaerial exposure and drainage incision, at which point footwall rocks are fairly strong and cold. Core complex rocks, typically granitoids and quartzofeldspathic gneisses, would likely exhibit other manifestations of horizontal shortening, especially reverse faults, if folded under such conditions. No such manifestations, however, have been identified. Furthermore, most antiformal corrugations are mylonitic only at one end. The other, nonmylonitic end of each antiform was too cool at the time of detachment faulting to undergo mylonitization and so was part of the strong upper crust even before detachment faulting began. Paleomagnetic data from the South Mountains near Phoenix, Arizona, reveal no evidence of folding and indicate that, if the corrugation that defines the basic form of the range is an antiformal fold, then folding occurred under high-temperature conditions before acquisition of remanant magnetization (Livaccari et al., 1995).

In this article I first outline the distribution and geometry of corrugation-parallel drainages in the South Mountains, Catalina, and Harcuvar metamorphic core complexes in Arizona. Two alternative hypothesis for the origin of corrugation-parallel drainages are then presented that, unlike Pain's hypothesis, are consistent with exhumation of the corrugations as previously formed features that emerged from beneath corrugated detachment faults. Analysis of a down-plunge, cross-section view of the detachment fault in the Rincon Mountains east of Tucson suggests that one proposed mechanism for drainage incision was not effective. An implication of either of the proposed alternative drainage-incision mechanisms is that some extension-parallel drainages have been tilted so that drainage direction was reversed due to lateral migration of the locus of core-complex arching. Drainage reversal by this mechanism supports the concept of a rolling hinge or migrating monoclinal flexure in the wake of core complex exhumation (Wernicke and Axen, 1988; Buck, 1988; Hamilton, 1988), but requires enough uplift of the monocline to produce an asymmetric antiform (e.g., Howard et al., 1982; Spencer, 1984).

ARIZONA'S METAMORPHIC CORE COMPLEXES

South Mountains Metamorphic Core Complex

The South Mountains metamorphic core complex south of Phoenix, Arizona, is elongate in an east-northeast direction and has a grooved or fluted morphology parallel to the long axis of the range (Fig. 2). The eastern half of the range consists of early Miocene granite and granodiorite, whereas the western half consists of Early Proterozoic granite and gneiss (Reynolds, 1985; Reynolds et al., 1986). The eastern half of the range is overprinted by a gently dipping mylonitic foliation that approximately mimics the gently east-plunging antiformal morphology of the range. Mylonitic lineation parallels the antiform axis and asymmetric petrofabrics indicate top-to-the-east shearing during mylonitization (Reynolds and Lister, 1990). Rocks in the western third of the range are nonmylonitic. Abundant north-northwest–striking Miocene dikes in the central part of the range strike perpendicular to mylonitic lineation. Some dikes were intruded during mylonitization and were affected by the plastic deformation, but most are younger. Chloritic alteration and associated brecciation are common at high structural levels in the eastern half of the range. A small klippe overlies a detachment fault on the southeast flank of the range (Reynolds, 1985). Mylonitization occurred between 24 and 19 Ma (Reynolds et al., 1986). The complex cooled through the apatite fission-track annealing temperature (~110 °C) at 17–18 Ma (Fitzgerald et al., 1994) and was probably uncovered immediately after this time.

In general, the South Mountains are a single antiformal ridge surrounded by late Cenozoic basin sediments. The basic form of the range is inferred to reflect the form of an upward-bounding detachment fault, which in turn is inferred from the distribution of carapace-forming, footwall mylonitic fabric and chloritic breccia, and one small klippe, all in the eastern half of the range (Reynolds, 1985). This single antiformal ridge is approximately the same size as antiformal corrugations in other metamorphic core complexes in

Arizona and presumably has the same origin. In detail, the range is characterized by numerous linear ridge crests, ridge flanks, isolated ridges, canyons, and drainages that parallel the trend of the large antiform axis. Two linear features are especially long and straight: The upper reaches of four small drainages are aligned along an 061° trend that is parallel to a nearby alignment of at least four ridge segments (Fig. 2). The relationship of the smaller linear features to the form of the fault is not known. Mylonitic lineation in the South Mountains trends 060° (average of 339 measurements from Reynolds, 1985), parallel to the trend of the antiform that defines the basic morphology of the range as well as to the numerous smaller linear features (Fig. 2). The strong parallelism of the many elongate geomorphic features, all parallel to mylonitic lineation, cannot have been produced by preferential erosion along structural or lithological weaknesses associated with mylonitic lineation because the western third of the range is not mylonitic, but has a geomorphic grain that is at least as well developed as in areas underlain by mylonitic rocks. The north-northwest–striking dike swarm in the central part of the range, and a parallel dominant fracture set, had significant influence on range geomorphology (e.g., Reynolds, 1985, Fig. 5), but the physical processes responsible for the lineation-parallel drainages and ridges overwhelmed geomorphic influences from these structural and lithologic features.

Alternatives to the generally accepted origin of the South Mountains as an uncovered antiformal corrugation of a detachment fault include postdetachment folding of a planar surface to produce a doubly plunging antiformal fold, and uplift as a horst or tilt block bounded by east-northeast–striking normal faults. With these alternatives, streams would be expected to flow almost entirely to the northwest and southeast, down the flanks of the range, with only minor drainages flowing toward the ends of the range. To evaluate the statistical significance of lineation-parallel drainages, and these alternatives for antiform genesis, streams within bedrock that were marked by a blue line on U.S. Geological Survey (USGS) 1:24 000 scale topographic maps were divided into 250-m-long segments and the trend of each segment was measured. A histogram of measurements reveals four evenly spaced peaks, two that correspond to drainages that flow toward the flanks of the range, and two that represent drainages that flow toward the ends (Fig. 3). Such large peaks, or any peaks at all, for drainages toward the northeast and southwest ends of the range would not be expected for a horst, tilt block, or doubly plunging antiformal fold. A doubly plunging antiformal fold would be expected to produce a radial to bimodal drainage pattern that is biased toward the flanks of the antiform. The four histogram troughs shown in Figure 3A, separating the four peaks, represent excluded drainage directions that are inconsistent with a doubly plunging antiformal fold model.

Catalina Metamorphic Core Complex

The Catalina metamorphic core complex near Tucson in southeastern Arizona consists, from southeast to northwest, of the Rincon, Santa Catalina, Tortolita, and Picacho Mountains (Figs. 1 and 4). The ranges are composed of a great variety of nonmylonitic rock types on their northeast flanks and primarily of mylonitic granitic and gneissic rocks on their southwest flanks (Drewes, 1974, 1977; Keith et al., 1980; Davis, 1980; Banks, 1980; Dickinson, 1991; Force, 1997). Mylonitic fabrics overprint Tertiary to Proterozoic granitoids and gneissic rocks of probable Proterozoic protolith age. Mylonitic foliation generally dips southward to westward toward the foot of the ranges and, in the Santa Catalina and Rincon Mountains, beneath the trace of the Santa Catalina detachment fault. Dominantly top-to-the-southwest shearing during exhumation of the complex is indicated by asymmetric mylonitic petrofabrics, offset markers, fold vergence, and the gross asymmetry of the mylonitic fabrics across the range (Davis, 1983; Wust, 1986; Spencer and Reynolds, 1989a; Reynolds and Lister, 1990; Naruk and Bykerk-Kauffman, 1990; Dickinson, 1991; Force, 1997). Embayments and promontories on the southern flank of the Santa Catalina Mountains and the western flank of the Rincon Mountains reflect the corrugated form of the detachment fault and roughly concordant mylonitic foliation. Tilted, hanging-wall conglomerates contain locally abundant mylonitic debris at high stratigraphic levels and indicate that subaerial exposure and erosion of the footwall occurred during detachment faulting (Pashley, 1966; Dickinson, 1991, 1999). The mylonitic rocks cooled through K-Ar biotite and muscovite closure temperatures and apatite and zircon fission-track annealing temperatures between about 26 and 19 Ma (Livingston et al., 1967; Marvin et al., 1973, 1978; Creasey et al., 1977; Marvin and Cole, 1978).

Tanque Verde Ridge in the Rincon Mountains, which is the largest corrugation in the Catalina core complex, is incised by a drainage that runs conspicuously down the crest of the western part of the ridge without dropping off down the steeper ridge flanks (Fig. 4A; Pain, 1985). The upper part of the drainage and two flanking ridge crests trend 245° to 250°, essentially parallel to the 250° ± 10° (1σ) trend of mylonitic lineation (116 lineations measured by protractor from the map of Drewes, 1977). In the lower part of the canyon and farther down the nose of the plunging arch, the sharp ridge crest and canyon both trend 236°, slightly discordant to the 250° trend of mylonitic lineation (Drewes, 1977; Davis, 1980; Fig. 4A in Davis).

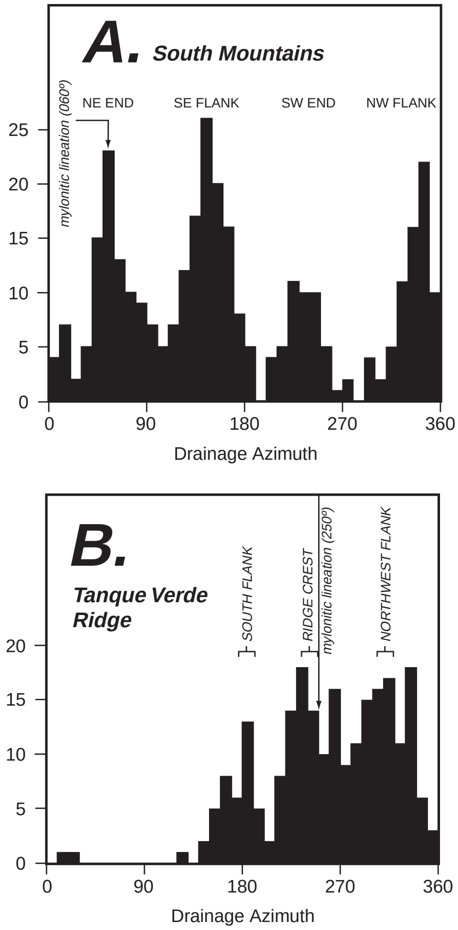

Figure 3. Histograms of drainage trends for (A) the South Mountains and (B) western Tanque Verde Ridge in the Rincon Mountains. Only drainages on bedrock marked by a blue line on U.S. Geological Survey (USGS) 1:24 000 scale topographic maps were used (from Lone Butte, Guadalupe, Laveen, and Tanque Verde Peak USGS 7½′ quadrangle maps). Each drainage was marked at fixed intervals (250 m for the South Mountains, 500 m for Tanque Verde Ridge), and the trend of each line defined by two sequential points, traveling downstream, was measured (332 measurements from the South Mountains, 230 measurements from Tanque Verde Ridge). The histograms thus are statistical representations of drainage orientation in each area.

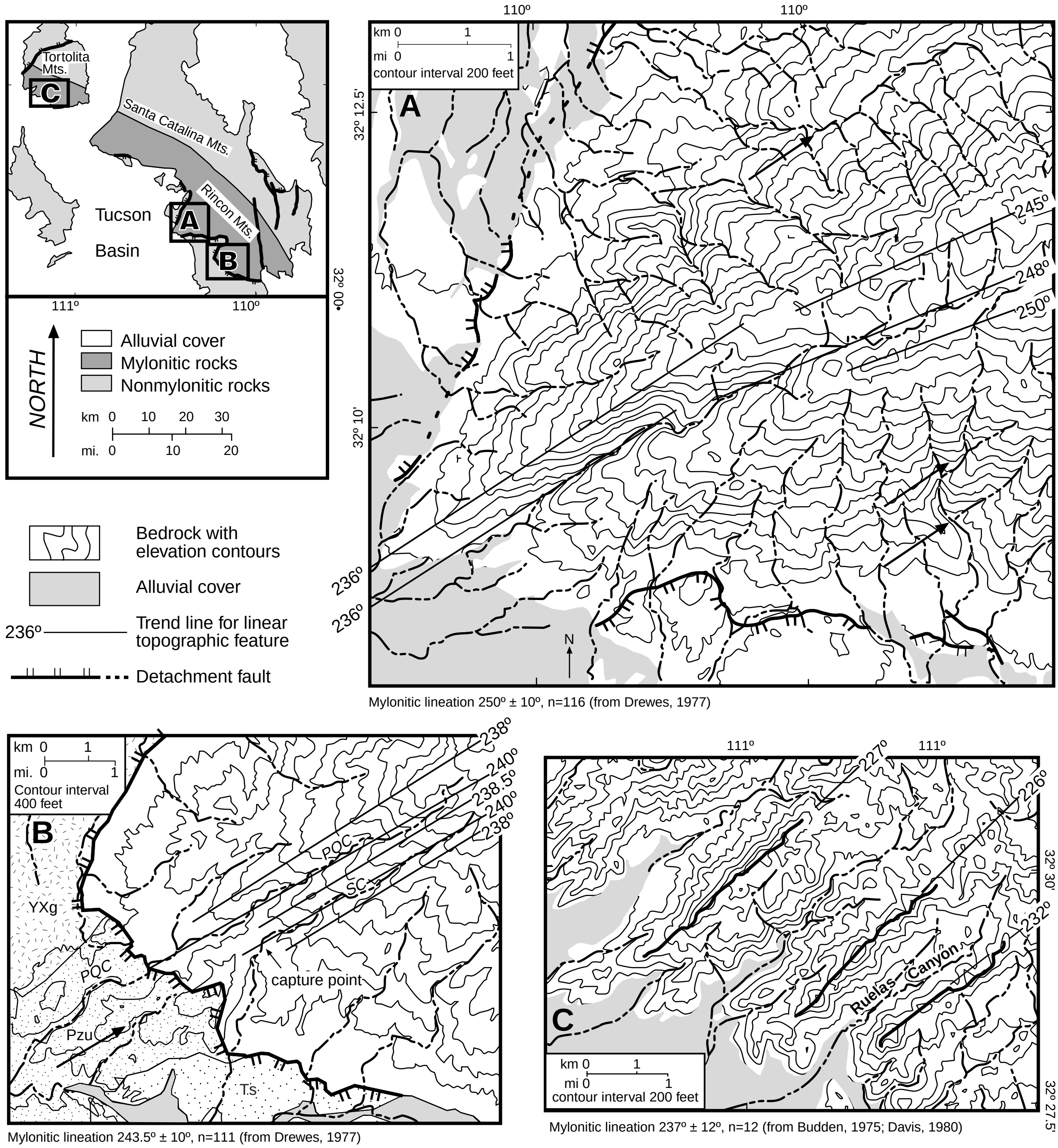

Figure 4. Topographic contour maps for selected areas in the Catalina metamorphic core complex. Straight lines with indicated trend are aligned with linear topographic features. (A) Tanque Verde Ridge. Arrows point to drainages that are on the flanks of the Tanque Verde antiform but are aligned with its axis. (B) Posta Quemada antiform. PQC—Posta Quemada Canyon; SC—Shaw Canyon; YXg— Proterozoic granitic rock; Pzu—Paleozoic sedimentary rocks, mostly calcareous; Ts— Tertiary sedimentary rocks. Arrow points to small canyon in the hanging wall of the Santa Catalina detachment fault that may have been continuous with Shaw Canyon and guided its incision into the footwall of the detachment fault as it was tectonically uncovered. The original Shaw Canyon drainage is interpreted to have been broken when the upper reach (what is now upper Shaw Canyon) was captured by a south-flowing drainage at the indicated capture point. (C) Southwestern Tortolita Mountains. Bold, irregular lines mark ridge-crest drainage divides. 200 ft = 61 m; 400 ft = 122 m.

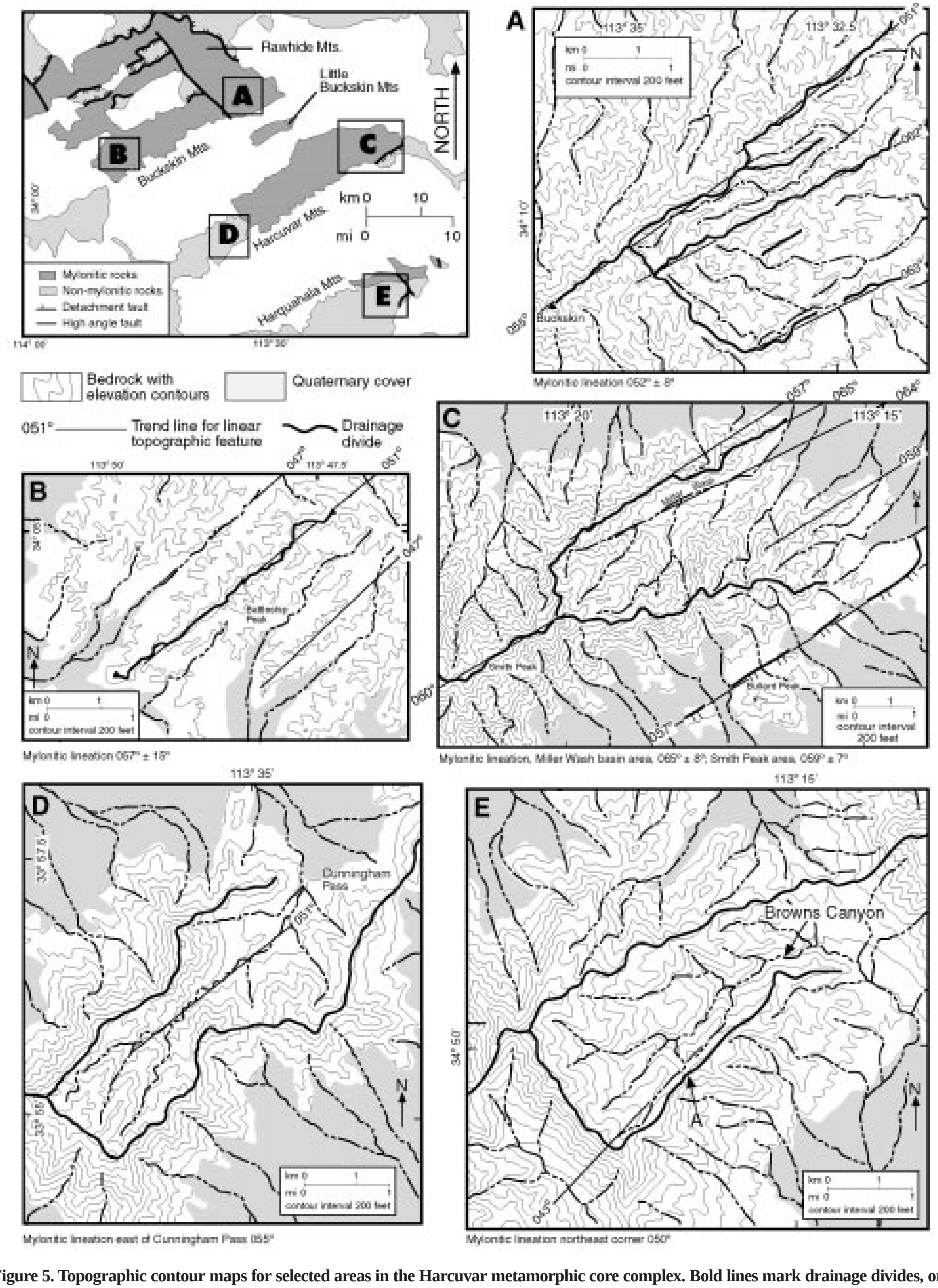

Figure 5. Topographic contour maps for selected areas in the Harcuvar metamorphic core complex. Bold lines mark drainage divides, or, near Bullard Peak in C, the Bullard detachment fault (with double ticks). Straight lines with indicated trend are aligned with linear topographic features. 200 ft = 61 m.

The lower end of the canyon is underlain by weakly fractured, resistant leucogranite that contains no obvious drainage-controlling fractures. In general, the western part of the antiform (area of Fig. 4A) has steep, smooth flanks and a crest that varies from fairly flat at higher elevations to fairly sharp at lower elevations. A bimodal stream-flow pattern, with flow directed down the flanks of the ridge, would be expected. However, a histogram of drainage orientations in the western part of Tanque Verde Ridge shows two peaks for drainage off of the flanks of the ridge, and a third peak for drainage down the nose of the ridge and subparallel to mylonitic lineation (Fig. 3B).

In the southern Rincon and Tortolita Mountains of the Catalina core complex, corrugations are not sufficiently well defined to derive well constrained antiform-axis orientations, and linear drainage trends can only be closely compared to each other, to the general slope direction of each range front, and to mylonitic lineation. Linear drainages in these areas are superimposed on rocks that do not contain lithologic features such as dikes that were likely to have controlled drainage orientation, and possible controlling structures such as a well developed set of planar fractures have not been identified. Two linear drainages and three flanking ridge crests in the southern Rincon Mountains, all with virtually identical trends, are within 6° of the average 243.5° trend of local mylonitic lineation (Fig. 4B). These drainages are incised into the nose of the Posta Quemada antiform, but the broad, rounded shape of the plunging antiform does not make these drainages look conspicuously anomalous and it is not clear that they do not simply plunge down the regional slope. However, strong parallelism among drainages, ridges, and mylonitic lineation is suggestive of tectonic control of drainage orientation, as is similarity of all these features to other antiforms where drainages trend conspicuously along antiform crests. In the southern Tortolita Mountains, drainages and intervening ridge crests are conspicuously linear and parallel, trend within 15° of local mylonitic lineation, and are oblique to the more southerly general slope of the range front (Fig. 4C).

Harcuvar Metamorphic Core Complex

Five parallel antiforms that make up the backbone of the Rawhide, Buckskin, Little Buckskin, and Harcuvar Mountains define a corrugated surface with crest-to-crest wavelengths of 8–12 km and crest-to-trough amplitudes of 200–2000 m (Fig. 5). The Harquahala Mountains make up a sixth antiform with an axis 25 km southeast of the axis of the Harcuvar antiform (Fig. 5). Footwall rocks in all of these ranges consist almost entirely of granitoids and amphibolite-grade gneiss (Rehrig and Reynolds, 1980; Shackelford, 1989; Drewes et al., 1990; Reynolds and Spencer, 1993; Richard et al., 1994; Bryant, 1995). These rocks are overprinted by a gently to moderately dipping mylonitic fabric exposed for as much as 40 km along corrugation axes (Spencer and Reynolds, 1991). Top-to-the-northeast displacement of the hanging wall is indicated by several features, including asymmetric mylonitic petrofabrics (Reynolds and Lister, 1990; Scott, 1995), regional northeast dip of the upward bounding detachment-fault system (Rehrig and Reynolds, 1980; Richard et al., 1990; Spencer and Reynolds, 1990, 1991), displaced rock units (Reynolds and Spencer, 1985), and northeastward decrease in radiometric cooling ages (Richard et al., 1990; Foster et al., 1993; Scott et al., 1998). Tilted hanging-wall rocks in the Buckskin and Rawhide Mountains include abundant mylonitic debris shed from the footwall that was denuded by detachment faulting (Spencer and Reynolds, 1989b). Extension began at about 26 Ma and continued until about 12 Ma (Richard et al., 1990; Bryant et al., 1991; Foster et al., 1993; Spencer et al., 1995; Scott et al., 1998). Subaerial exposure of the mylonitic rocks occurred late during this period of extension (Spencer and Reynolds, 1989b).

Numerous small canyons and ridge crests approximately parallel corrugation axes and mylonitic lineations. Conspicuously linear ridges and canyons in mylonitic rocks at three locations in the Buckskin and Harcuvar Mountains are within 12° of the trend of local mylonitic lineation (Fig. 5, A, B, and C). Linear geomorphic features are also present in nonmylonitic rocks adjacent to areas of mylonitization. In the western Harcuvar Mountains a deep canyon is incised parallel to the long axis of the range (Fig. 5D). The head of this canyon is a moderate to low-relief area surrounded on three sides by long, steep slopes. Granitic rocks in this area are fractured in various directions, and do not contain a single, well developed, northeast-striking fracture set that would have influenced drainage incision to produce the range-parallel drainages. A similar moderate- to low-relief area in upper Browns Canyon in the eastern Harquahala Mountains includes two linear drainage segments that parallel the adjacent northeast-trending southern edge of the low-relief area (Fig. 5E). The leucocratic Browns Canyon granite is only weakly fractured, and some of the drainages in upper Browns Canyon are cut on broad, low-relief swales of resistant, weakly fractured leucogranite.

In general, linear, corrugation-parallel drainages developed in both mylonitic (Fig. 5, A, B, and C) and nonmylonitic (Fig. 5, D and E) rocks and in some areas follow more gently sloping ridge-crest paths instead of descending down steep range flanks. These drainage paths do not appear to have been controlled by fractures or lithologic contrasts. The corrugation-parallel drainages within high-elevation, low-relief areas appear to be relicts of an older drainage system that is being degraded by headward erosion and stream capture from steep, range-flank drainages. For example, one stream capture seems likely in the geologic near future on the southeast flank of the Browns Canyon drainage in the Harquahala Mountains (A in Fig. 5E). Statistical analysis of drainages was not undertaken but probably would be complicated because drainage patterns have also been influenced by tilting associated with young range-crossing high-angle faults in the Harquahala and Harcuvar Mountains. Furthermore, corrugation-parallel drainages on the ends of the southern corrugation in the Buckskin Mountains could be largely oriented down the regional slope, as with the southern Rincon Mountains. Drainage patterns in the areas shown in Figure 5, A–E, are so similar to those in the South Mountains and at Tanque Verde Ridge, however, that it seems likely that all the drainages have a similar origin.

DISCUSSION

Lineation-parallel drainages incised into Arizona's corrugated metamorphic core complexes were first identified and described by Pain (1985), who proposed a two-stage model for their origin, as follows: (1) initial drainage incision when the denuded footwalls were planar slopes, followed by (2) folding of footwalls so that some drainages were carried upward on the crests of rising antiforms. This proposed origin is problematic for at least three reasons: (1) it would require folding of cold crystalline rocks, in this case at the Earth's surface, without any other structural manifestations of shortening, (2) it is inconsistent with paleomagnetic data from the South Mountains that show no folding after high-temperature acquisition of remanent magnetization (Livaccari et al., 1995), and (3) fold axes in each range would have to be strongly aligned with the dip direction of an older and possibly inactive fault, and with older mylonitic lineation, without any obvious reason for such alignment.

One alternative possibility is that corrugation-parallel fractures in footwall rocks controlled drainage incision. However, to prevent streams from flowing off antiform crests and down steep antiform flanks, a single set of corrugation-parallel fractures would have to exert substantially greater geomorphic control than the total influence of fractures of all other orientations. Such a dominant fracture set has not been identified in any of Arizona's metamorphic core complexes. Some extension-parallel drainages in the

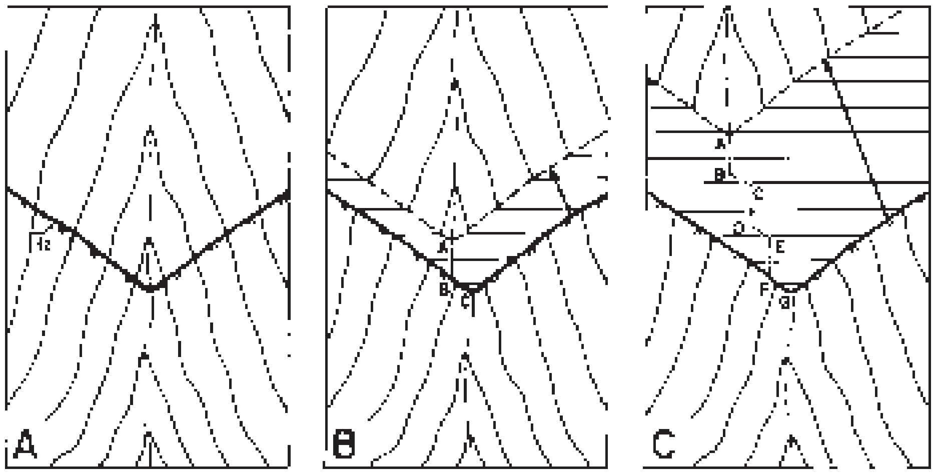

Figure 6. Hypothetical contour map of sequential incision of extension-parallel drainage during detachment faulting. (A) Detachment fault indicated by heavy line with double ticks on hanging-wall block, dips down canyon with a stream in the canyon bottom. Angle α is between map-view trace of fault and topographic contour line on hanging-wall block. (B) A single fault-slip event displaces the footwall block relative to the hanging-wall block by the amount indicated by arrow. Stream flows onto denuded fault ramp at A, crosses it, and reaches fault trace at B. If α is <90°, stream will then flow down fault trace to C, where it reenters the old stream bed. (C) Cumulative offset of three slip events, indicated by arrow, results in detailed irregularity to new stream channel, but net result is formation of an extension-parallel drainage segment extending from point A to point G.

Harquahala and Tanque Verde antiforms are superimposed on remarkably unfractured, gently sloping surfaces of resistant, beautifully exposed leucogranite. In other areas, such as the western Harcuvar Mountains, steep fractures strike in diverse directions and do not seem to have caused preferential weathering in any particular direction except locally.

A more viable possibility is that small, concave-upward grooves in detachment-fault surfaces, with amplitudes of tens of meters and wavelengths of hundreds of meters, localized initial erosional incision on the freshly denuded footwall. Detachment-fault grooves at this scale are not obvious in the maps of many detachment faults, but they exist in a few areas, such as at the Copper Penny Mine in the Buckskin Mountains (Spencer and Reynolds, 1989b), in the southern Rincon Mountains (Drewes, 1977), and below the low-angle Mohave Wash normal fault in the Chemehuevi Mountains of California (John, 1987). High-resolution, three-dimensional mapping of detachment faults using global positioning system receivers might determine that such grooves are more common than is apparent from existing maps and are therefore more likely to have localized lineation-parallel drainages.

Another viable scenario relies on typical normal-fault-related topography where the footwall block is elevated relative to the hanging-wall block, and the hanging-wall block receives water flowing off the footwall block. Consider the case where the footwall of a detachment fault forms a gently plunging antiformal ridge with incised drainages that are directed radially outward from the nose of the antiform and that cross the detachment fault around the periphery of the antiform. After a slip event on the detachment fault, water flowing down an incised footwall drainage empties onto the smooth fault surface of the freshly denuded footwall, crosses the detachment-fault trace, and then continues within the same hanging-wall canyon. If a stream crosses the detachment fault at any point other than at the crest of the antiform, it will flow down the fault-dip line and then be deflected slightly and run along the fault trace for a distance equal to the strike-slip component of offset of the previous slip event. Surface-hydraulic connection between individual footwall and hanging-wall drainages is maintained following each fault-slip event, and each new fault-slip event lengthens extension-parallel drainage segments, even on the flanks of an antiform where stream incision may occur along a path highly oblique to regional slope (Fig. 6). Furthermore, incision into the fault ramp should be rapid because of the poor resistance of typical footwall fault breccias and underlying chloritic breccias. This mechanism of stream-incision control is not applicable where hanging-wall canyons are absent and aggrading alluvial fans form the trailing end of the hanging-wall block, but would be applicable where fans heads, or bedrock, are incised. Most important, this mechanism will generally produce extension-parallel drainages regardless of initial stream orientation or regional slope.

It is possible to assess the relative significance of these two viable mechanisms of drainage control in the southern Rincon Mountains. Two linear drainages incised in footwall rocks near the crest of the Posta Quemada antiform approximately parallel mylonitic lineation and inferred fault-slip direction (Fig. 4B). A down-plunge

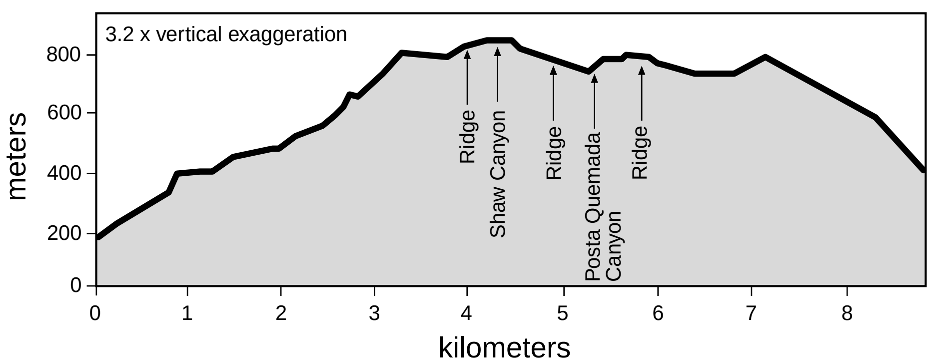

Figure 7. Down-plunge view (plunge 10°, azimuth 240°) of the Santa Catalina detachment fault, Posta Quemada antiform, Rincon Mountains (see Davis and Hardy, 1981, for an expanded down-plunge view). The down-plunge projection of two straight, lineation-parallel canyons and three straight, parallel ridges are shown here, and these features are located in Figure 4B. Shaw Canyon projects down plunge into the structurally highest point on the fault surface and so was not guided during initial incision by a concave-upward groove in the fault ramp. More likely, its incision was guided by the process shown in Figure 6.

view of the Santa Catalina detachment fault, looking down lineation plunge as well as inferred fault-slip direction, reveals considerable fault irregularity (Fig. 7). Posta Quemada Canyon is aligned with a small, concave-upward fault groove, but is also aligned with a canyon in the hanging-wall block, so it satisfies both hypotheses and is not a good test of either. The other canyon, Shaw Canyon, is aligned with a convex-upward groove that is the structurally highest point of the detachment fault in the down-plunge view, and is aligned with a canyon in the hanging-wall block that may have been connected to Shaw Canyon when the detachment fault was active (Fig. 4B). If these drainages were linked during detachment faulting, then this single drainage must have been broken when what is now Shaw Canyon was captured by another stream flowing down the south flank of the antiform (capture point indicated in Fig. 4B). Localization of Shaw Canyon to the crest of a ridge-like groove in the detachment fault and alignment with a hanging-wall canyon supports the hypothesis that maintenance of surface hydraulic connection between footwall and hanging-wall drainages caused streams to be incised parallel to fault-slip direction regardless of fault-surface irregularities. This process could have been responsible for the numerous extension-parallel drainages in Arizona's metamorphic core complexes.

In both the western South Mountains and the Battleship Peak area of the southwestern Buckskin Mountains, streams flow southwestward down extension-parallel drainages (Figs. 2 and 5B), which is exactly opposite to the initial flow direction according to the two viable hypotheses outlined here. This is especially clear in the South Mountains where southwestward-flowing stream segments on the southwestern end of the range align with northeastward flowing stream segments at the northeastern end (drainages aligned along indicated 061° trend in Fig. 2). These divergent flow directions are consistent, however, with drainage-incision localization by both small detachment grooves and maintenance of surface hydraulic connections during fault slip. In either case, the newly exhumed and incised footwalls were apparently tilted so that the northeastward drainage direction was reversed, and reversal occurred as the stream beds were carried over the crest of the broadly arched metamorphic core complexes as if on a conveyer belt. This supports the concept of a migrating monoclinal flexure, or rolling hinge, during laterally progressing denudation and footwall uplift and flexure (Wernicke and Axen, 1988; Spencer and Reynolds, 1991; Axen and Bartley, 1997), but requires enough uplift and flexure of the monocline to produce an asymmetric antiform (e.g., Spencer, 1984). Barbed drainages indicative of drainage reversal are not obvious, possibly because of erosional degradation over the past 12 to 20 m.y., but might be identified by quantitative landform analysis.

CONCLUSIONS

Extension-parallel linear drainages have been an enigmatic feature of Arizona's metamorphic core complexes. Unlike Pain's (1985) hypothesis for their origin, the two mechanisms proposed here are consistent with exhumation of detachment-fault footwalls from below a corrugated detachment fault and do not require subsequent subaerial folding parallel to extension direction. In one of these mechanisms, streams were guided by small, displacement-parallel grooves in the fault surface as it was uncovered. In the other, surface hydraulic connection was maintained between stream segments cut and separated by detachment-fault movement. Both processes could have produced progressively lengthening, extension-parallel drainages. Maintenance of surface hydraulic connection between stream segments is favored by analysis of a down-plunge fault projection in the Rincon Mountains, but the other mechanism could have been effective for other drainages. In either case, drainages are inferred to have retained their basic form for ~12–20 m.y. since initial incision.

If either of these proposed mechanisms substantially controlled drainage incision during detachment faulting, then linear drainages should be effective indicators of extension direction. This is significant because, in many core complexes, the hanging wall is buried, corrugations are poorly defined, and there are no other features that indicate extension direction except mylonitic lineation. It is significant that linear drainages and parallel corrugation axes both may be discordant to mylonitic lineation trend (e.g., Fig. 4A). If drainage-incision mechanisms proposed here are correct, and corrugations are original or molded grooves with axes parallel to detachment-fault slip direction, then discordance with mylonitic lineation is evidence that mylonitization in these areas was caused by deep-crustal plastic flow not strictly linked to shearing downdip from a detachment fault (Wernicke, 1992, Fig. 9; Spencer, 1999). Thus, further analysis of drainage patterns, corrugation trends, and mylonitic lineations may provide new insights into deep-crustal processes in extensional tectonic environments.

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