Evidence for large-scale transport on the Bullard detachment fault, west-central Arizona

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ABSTRACT

The Bullard detachment fault is a gently to steeply dipping normal fault that flanks the Harcuvar and Harquahala mountains of the Basin and Range province in west-central Arizona. The stratigraphy of upper-plate Miocene conglomerates and the regional distribution of upper- and lower-plate pre-Tertiary units indicate that upper-plate rocks were displaced about 50 km to the northeast with respect to the lower plate during middle to late Tertiary time. Normal slip of this magnitude on the regionally northeast-dipping Bullard fault indicates that deep-seated Tertiary-Cretaceous(?) mylonitic gneisses and Mesozoic thrust faults of the lower plate were drawn out from beneath Precambrian rocks along the margin of the Transition Zone of central Arizona during middle to late Tertiary crustal extension. The Transition Zone was, therefore, affected by deep-seated tectonism in both Mesozoic and Tertiary time.

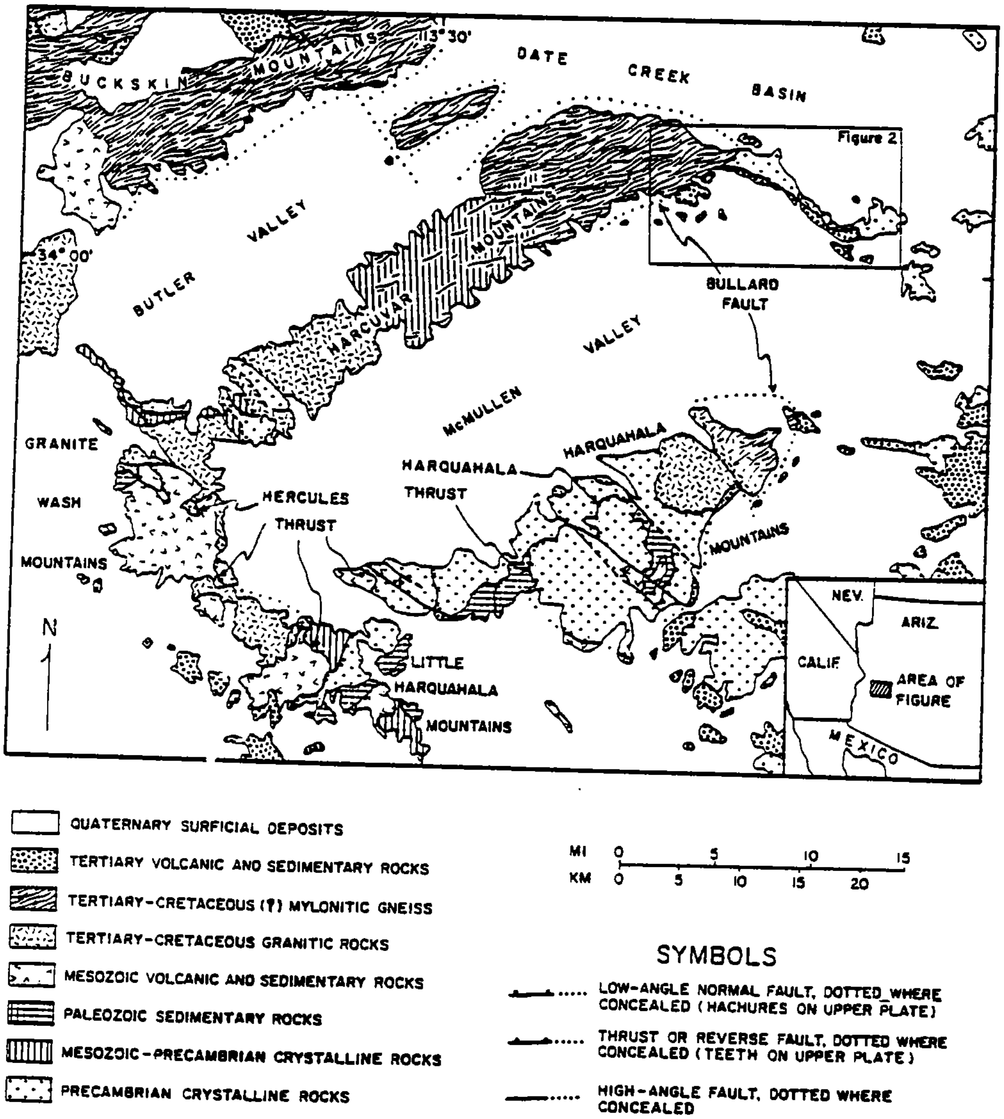

Figure 1. Simplified geologic map of McMullen Valley area. Sources of data include Rehrig and Reynolds (1980), Reynolds (1982), Reynolds and Spencer (1984), and unpublished mapping by S. J. Reynolds, S. M. Richard, and J. E. Spencer.

INTRODUCTION

Current models for the origin of detachment faults[1] associated with metamorphic core complexes can be divided into two groups: those that envision the faults as surfaces of major transport (Wernicke, 1981; G. H. Davis, 1983; G. A. Davis et al., 1983; Reynolds, 1985), and those that consider the fault surface to be an exhumed brittle-ductile transition that has only minor displacement (Rehrig and Reynolds, 1980; Miller et al., 1983). In this paper, we present evidence that the Bullard detachment fault of west-central Arizona accommodated about 50 km of normal slip during middle to late Tertiary crustal extension.

The Bullard detachment fault is a low- to high-angle fault that flanks the northeast ends of the Harcuvar and Harquahala mountains of west-central Arizona (Fig. 1; Rehrig and Reynolds, 1980; Reynolds, 1982). The fault separates upper and lower plates that have undergone dramatically different metamorphic, structural, and thermal histories. Rocks below the fault generally consist of plutonic and high-grade metamorphic rocks that have been complexly overprinted by Mesozoic and Cenozoic metamorphism and ductile deformation. In contrast, upper-plate rocks include highly tilted and faulted middle Tertiary volcanic and sedimentary rocks and Proterozoic metamorphic and granitic rocks that have generally escaped significant Mesozoic and Cenozoic metamor-

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[1] The term "detachment fault" is used by us and, in our view, by many other geologists to describe a low-angle normal fault that formed at a low angle, has significant displacement, and is of subregional extent.

GEOLOGY, v. 13, p. 353–356, May 1985

phism and ductile deformation. Lower-plate mylonitic rocks have yielded K-Ar biotite ages of 25 and 17 Ma (Shafiqullah et al., 1980; Rehrig, 1982), whereas upper-plate, Cretaceous(?) granite yielded a Late Cretaceous K-Ar biotite age (J. Kirkwood, 1977, oral commun.), which indicates that the upper and lower plates of the Bullard fault had contrasting thermal histories prior to mid-Miocene time. Although regionally the fault has a gentle northeast dip, it dips 50°-70° to the southeast in the eastern Harcuvar Mountains because of original irregularities of the fault surface (megagrooves) or warping during or after faulting.

GEOLOGY OF LOWER-PLATE ROCKS

Rocks below the Bullard fault in the Harcuvar Mountains include Precambrian crystalline rocks and Upper Cretaceous to lower Tertiary granitic rocks (Rehrig and Reynolds, 1980). The Harquahala Mountains also contain extensive exposures of these rock types but are further complicated by south- and southwest-vergent thrusts that place Precambrian crystalline rocks over Precambrian, Paleozoic, and Mesozoic rocks (Reynolds et al., 1980; S. M. Richard et al., mapping in progress). Rocks in both ranges have been widely overprinted by a Cretaceous regional metamorphic fabric and, in the eastern part of the ranges, by a Tertiary(?) mylonitic fabric formed by top-to-the-northeast shear. Foliation in the mylonitic rocks generally dips moderately to gently off the flanks of the range and defines broad, east-northeast-trending antiforms.

The Little Harquahala and Granite Wash mountains contain Mesozoic clastic and volcanic rocks that have been overridden along the Hercules and subsidiary thrusts by a variety of Precambrian, Paleozoic, and Mesozoic rocks (Fig. 1; Reynolds et al., 1980, 1983). Lower-plate Mesozoic rocks are only slightly cleaved and metamorphosed away from the southwest-vergent Hercules thrust but have been converted into schists immediately below the thrust, especially in the Granite Wash Mountains. The thrust sheets and thrust-related metamorphic fabrics have been intruded by large plutons of Upper Cretaceous granodiorite and granite.

GEOLOGY OF UPPER-PLATE ROCKS

Upper-plate rocks in the Harcuvar Mountains include Precambrian crystalline rocks with original Precambrian fabric that has been locally overprinted by a southwest- to southeast-dipping, mylonitic foliation of unknown age and significance (Fig. 2; Reynolds and Spencer, 1984). The Precambrian rocks have been intruded by Cretaceous(?) and lower Tertiary(?) granites and are depositionally overlain by a southwest- to south-dipping sequence of middle Tertiary volcanic and sedimentary rocks. The basal Tertiary unit, an arkosic conglomerate, is overlain by trachytic ash-flow tuffs that yielded a 24 Ma K-Ar biotite age (Brooks, 1984) and a 17 Ma K-Ar whole-rock age (Scarborough and Wilt, 1979). The tuffs are overlain by a 600-m-thick sequence of coarse conglomerate and sedimentary breccia that contains, from bottom to top, the following clast types: (1) well-rounded clasts of reddish quartzite exotic to the region;
(2) angular to subangular clasts of p
granite and Mesozoic clastic rocks, a
lenses of sedimentary breccia and gr
abreccia; and (3) angular to subangu
large as 1 m in diameter of Mesozoi
stone, conglomerate, and mudstone,
which are unmetamorphosed and un
a few clasts contain a weakly develo
age. The top of the conglomerate co
minor amounts of Mesozoic volcanic
is overlain by andesite flows, one of
yielded a 16 Ma K-Ar whole-rock ag
borough and Wilt, 1979)..

DIRECTION AND MAGNITU OF TRANSPORT ON THE BULLARD FAULT

Significant normal slip on the Bulla
suggested by contrasting lithologies ar
tural styles across the fault. The fault
rocks representative of different middl
crustal levels; it places upper-plate, hi
middle Tertiary volcanic and sedimen
over lower-plate, deeper-level granitic
mylonitic gneisses that have yielded m
Tertiary cooling ages.

For several well-documented detac
faults, tilted upper-plate units strike pe
lar to the line of transport and dip in a
tion opposite, or antithetic, to the dire
transport (Davis et al., 1980). If this ge
ization is true for the Bullard fault, the
southwest dip of upper-plate units refle
thetic rotation during northeast transpo
upper plate relative to the lower plate.
tematic change in attitude of upper-pla
Tertiary units along Aguila Ridge (Fig.

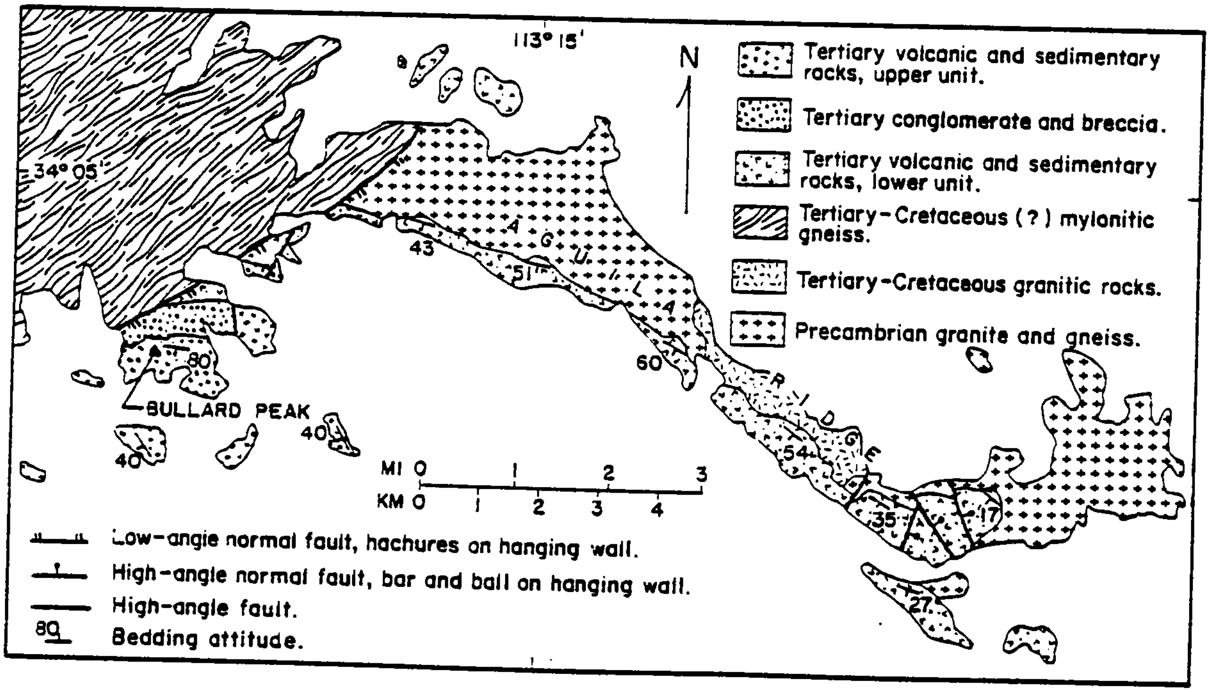

Figure 2. Simplifiec
logic map of Aguila
Ridge, Bullard Pea
and easternmost H
cuvar Mountains. A
without pattern are
ternary surficial de
See Figure 1 for loc
of map area.

interpreted as a large-scale drag structure, also indicates northeast transport of the upper plate (Reynolds, 1982). In addition, relative northeastward displacement of the upper plate is supported by correlation of the Bullard fault with the Whipple-Buckskin-Rawhide detachment fault, which, on the basis of various types of evidence, also displaced upper-plate rocks to the northeast relative to the lower plate (Shackelford, 1980; Davis et al., 1980).

Further evidence of major displacement is contained in the upper-plate sequence of conglomerate and sedimentary breccia. Granitic megabreccia in the conglomerate is composed of porphyritic granite that is lithologically most similar to granites that occur above the Hercules thrust in the Little Harquahala and western Harquahala mountains (Fig. 1), but that is completely dissimilar to any granites we have mapped in the Harcuvar or eastern Harquahala mountains. Correlation of the granite in the megabreccia with granite in the Little Harquahala Mountains is supported by Rb-Sr isotopic analyses that are prohibitive of a Precambrian age and suggestive of a Jurassic age for both granites (P. E. Damon and M. Shafiqullah, 1985, written commun.). Conglomerate that overlies the megabreccia contains large, angular to subangular clasts of unmetamorphosed Mesozoic clastic rocks that are not present in either the Harcuvar or the Harquahala mountains. Regional mapping has revealed that unmetamorphosed Mesozoic clastic rocks are present only in the Little Harquahala Mountains, western Granite Wash Mountains, and ranges farther to the west. Correlative Mesozoic sedimentary rocks occur in windows beneath regional thrust sheets in the western and southern Harquahala Mountains, but they have been strongly metamorphosed. Likewise, clasts of unmetamorphosed Mesozoic volcanic rocks, which are abundant near the top of the Miocene conglomerate, have no source in the Harcuvar or eastern Harquahala mountains, but could have been derived from Mesozoic volcanic rocks that underlie Mesozoic sedimentary rocks in the Little Harquahala Mountains. The angular to subangular nature and large size of the clasts argue against significant sedimentary transport of the clasts prior to deposition. Mesozoic clastic rocks in the Granite Wash and Little Harquahala mountains contain less chert grains and mudstone than some clasts in the Miocene conglomerate, but they nevertheless represent the nearest exposed source of relatively unmetamorphosed Mesozoic rocks.

The strongest evidence for large-scale transport is that the clast stratigraphy of the conglomerate appears to be the inverse of the structural and stratigraphic stacking of the Little Harquahala and Granite Wash mountains. The stratigraphic succession in the Miocene conglomerate from granitic megabreccia to overlying Mesozoic-clast conglomerate suggests that granite overlay Mesozoic sedimentary rocks in the source area. The presence of granite over Mesozoic sedimentary rocks would be unusual in most geologic settings but is precisely what is observed in the Little Harquahala and Granite Wash mountains where Mesozoic sedimentary and volcanic rocks have been overridden by granitic rocks along the Mesozoic Hercules thrust. The upward increase in abundance of clasts of Mesozoic volcanic rocks in the Miocene conglomerate is interpreted as the result of progressive erosional, and possibly tectonic, unroofing of volcanic rocks that underlie Mesozoic sedimentary rocks of the Little Harquahala and Granite Wash mountains.

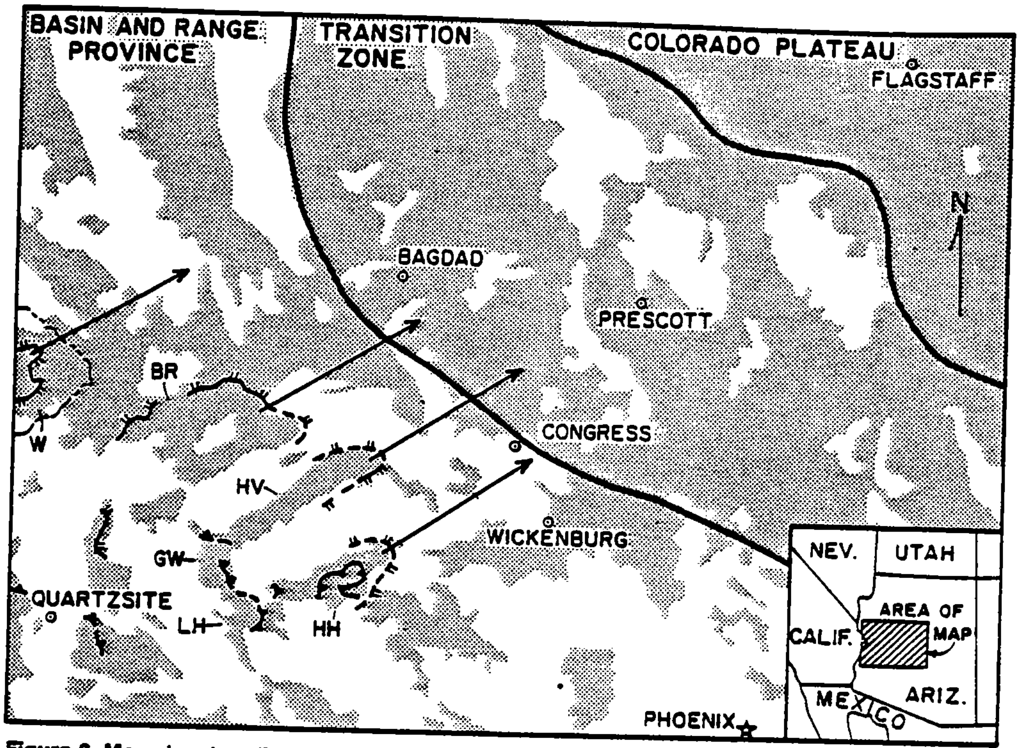

Figure 3. Map showing distribution of pre-Quaternary bedrock exposures (stippled) and major physiographic provinces in part of western and central Arizona and adjacent California. Major faults are shown with same symbols as in Figure 1. Arrows indicate estimated minimum 50-km translation of lower-plate rocks necessary to restore to pre–mid-Tertiary position. Capital letters indicate position of Whipple (W), Buckskin-Rawhide (BR), Harcuvar (HV), Granite Wash (GW), Little Harquahala (LH), and Harquahala (HH) mountains.

We interpret the present-day 50-km distance between the conglomerate and the possible source rocks to be the approximate amount of transport on the Bullard detachment fault. The closest lithologic match to the clasts of Mesozoic rocks actually occurs in Mesozoic sections in the southern Plomosa Mountains, the next range west of the Granite Wash Mountains, but we do not, at present, infer that the fault has 100 km of transport. It is unlikely that Mesozoic sedimentary rocks were originally part of the highest thrust sheet in the Harquahala Mountains, because the thrust sheet and its inferred offset equivalents above the Bullard fault are composed entirely of Precambrian and Mesozoic crystalline rocks; Mesozoic and Paleozoic sedimentary rocks are nowhere observed in the upper plate of the Bullard fault.

Distension of upper-plate rocks results in progressively greater relative displacement on the detachment fault in the direction of upper-plate transport. Displacement on the Bullard fault, therefore, probably increases to 60 or 70 km beneath distended upper-plate rocks identified in the subsurface northeast of the Harcuvar Mountains (Otton, 1981, 1982).

IMPLICATIONS

Our data indicate that detachment faults on the flanks of core complexes do have significant amounts of transport and were not formed as a result of in situ crustal stretching of the lower plate. The restriction of penetrative mylonitic fabrics to the eastern Harcuvar and Harquahala mountains (Fig. 1) indicates that in situ ductile distension of the lower plate, if it occurred, could not have caused more than about 15 km displacement of the upper plate relative to the lower plate. We therefore conclude that most, if not all, of the northeast displacement of upper-plate rocks relative to lower-plate rocks occurred by translation above the Bullard detachment fault.

Geologic mapping and regional geologic relationships indicate that the Bullard fault does not surface to the northeast, but instead projects at depth beneath the edge of the Transition Zone and toward the Colorado Plateau (Rehrig and Reynolds, 1980; Lucchitta and Suneson, 1981; Otton, 1982; proprietary seismic reflection data). If the fault has 50 km of transport and a corresponding original minimum down-dip extent of 50 km, then deeper segments of the fault were almost certainly within the ductile regime, even if the fault had a very gentle original dip. Lower-plate mylonitic rocks formed by top-to-the-northeast shear in the easternmost Harcuvar and Harquahala mountains would probably have been within the ductile regime at the inception of faulting and therefore probably represent initial ductile deformation related to movement on the Bullard fault. An original northeast dip of the fault zone is further supported by the restriction of middle Tertiary cooling ages to the easternmost, and therefore structurally deepest, lower-plate rocks. Our data thus reinforce those models that interpret mylonitic fabrics in core complexes as a ductile, deeper seated manifestation of low-angle normal faulting (G. H. Davis, 1983; G. A. Davis et al., 1983; Reynolds, 1985). We interpret lower-plate rocks exposed in the eastern Harcuvar and Harquahala mountains as having been at a depth of 10 to 20 km prior to Tertiary extension, which, combined with the 50 km estimate of transport, requires an original dip on the Bullard fault of about 10° to 20°.

Restoring 50 km of movement on the Bullard fault and correlative Whipple-Buckskin-Rawhide fault places the most northeasterly exposed lower-plate rocks beneath the cities of Bagdad, Congress, and Wickenburg, near the edge of the Transition Zone (Fig. 3). This implies that the Harcuvar core complex, with its Mesozoic plutons, metamorphic fabrics, and thrust faults, was drawn out from under the Transition Zone, a region dominated in outcrop by Precambrian rocks considered by most geologists to have escaped significant Mesozoic tectonism. Restoring Mesozoic thrust sheets of the Harquahala Mountains to a position under the edge of the Transition Zone opens the possibility that a variety of rock types now exposed in the Basin and Range province were underthrust beneath the present-day Transition Zone in the Mesozoic, only to be exhumed by detachment faulting during middle to late Tertiary crustal extension. Thrust-induced crustal thickening in the Mesozoic could have accentuated the Mogollon Highlands of Harshbarger et al. (1957), a Late Triassic to Eocene uplift that is inferred to have occupied parts of the present-day Transition Zone.

REFERENCES CITED

Brooks, W.E., 1984, Volcanic stratigraphy of part of the McLendon volcano, Anderson Mine area, Yavapai County, Arizona: U.S. Geological Survey Open-File Report 84-350, 42 p.

Davis, G.A., Anderson, J.L., Frost, E.G., and Shackelford, T.J., 1980, Mylonitization and detachment faulting in the Whipple-Buckskin-Rawhide Mountains terrane, southeastern California and western Arizona, *in* Crittenden, M.D., Jr., Coney, P.J., and Davis, G.H., eds., Cordilleran metamorphic core complexes: Geological Society of America Memoir 153, p. 79–129.

Davis, G.A., Lister, G.S., and Reynolds, S.J., 1983, Interpretation of Cordilleran core complexes as evolving crustal shear zones in an extending orogen: Geological Society of America Abstracts with Programs, v. 15, p. 311.

Davis, G.H., 1983, Shear-zone model for the origin of metamorphic core complexes: Geology, v. 11, p. 342–347.

Harshbarger, J.W., Repenning, C.A., and Irwin, J.H., 1957, Stratigraphy of the uppermost Triassic and the Jurassic rocks of the Navajo country (Colorado Plateau): U.S. Geological Survey Professional Paper 291, 74 p.

Lucchitta, Ivo, and Suneson, Neal, 1981, Comment on "Tertiary tectonic denudation of a Mesozoic–early Tertiary gneiss complex, Rawhide Mountains, Arizona": Geology, v. 9, p. 50–51.

Miller, E.L., Gans, P.B., and Garing, John, 1983, The Snake Range Decollement: An exhumed mid-Tertiary ductile-brittle transition: Tectonics, v. 2, p. 239–263.

Otton, J.K., 1981, Structural geology of the Date Creek Basin area, west-central Arizona, *in* Howard, K.A., Carr, M.D., and Miller, D.M., eds., Tectonic framework of the Mohave and Sonoran Deserts, California and Arizona: U.S. Geological Survey Open-File Report 81-503, p. 82–85.

——1982, Tertiary extensional tectonics and associated volcanism in west-central Arizona, *in* Frost, E.G., and Martin, D.L., eds., Mesozoic-Cenozoic tectonic evolution of the Colorado River region: San Diego, California, Cordilleran Publishers, p. 143–157.

Rehrig, W.A., 1982, Metamorphic core complexes of the southwestern United States—An updated analysis, *in* Frost, E.G., and Martin, D.L., eds., Mesozoic-Cenozoic tectonic evolution of the Colorado River region: San Diego, California, Cordilleran Publishers, p. 555–559.

Rehrig, W.A., and Reynolds, S.J., 1980, Geologic and geochronologic reconnaissance of a northwest-trending zone of metamorphic core complexes in southern and western Arizona, *in* Crittenden, M.D., Jr., Coney, P.J., and Davis, G.H., eds., Cordilleran metamorphic core complexes: Geological Society of America Memoir 153, p. 131–157.

Reynolds, S.J., 1982, Multiple deformation in the Harcuvar and Harquahala Mountains, west-central Arizona, *in* Frost, E.G., and Martin, D.L., eds., Mesozoic-Cenozoic tectonic evolution of the Colorado River region: San Diego, California, Cordilleran Publishers, p. 137–142.

——1985, Geology and geochronology of the Sout Mountains, central Arizona: Arizona Bureau o Geology and Mineral Technology Bulletin 195 (in press).

Reynolds, S.J., and Spencer, J.E., 1984, Geologic map of the Aguila Ridge–Bullard Peak area, eastern Harcuvar Mountains, west-central Arizona: Arizona Bureau of Geology and Mineral Technology Open-File Report 84-4, scale 1:24,000.

Reynolds, S.J., Keith, S.B., and Coney, P.J., 1980, Stacked overthrusts of Precambrian crystalline basement and inverted Paleozoic sections emplaced over Mesozoic strata, west-central Arizona: Arizona Geological Society Digest, v. 12, p. 45–51.

Reynolds, S.J., Spencer, J.E., and Richard, S.M., 1983, A field guide to the northwestern Granit Wash Mountains, west-central Arizona: Arizon Bureau of Geology and Mineral Technology Open-File Report 83-23, 9 p.

Scarborough, Robert, and Wilt, J.C., 1979, A study of uranium favorability of Cenozoic sedimentar rocks, Basin and Range Province, Arizona—Part I. General geology and chronology of pre-late Miocene Cenozoic sedimentary rocks: Arizona Bureau of Geology and Mineral Technology Open-File Report 79-1, 101 p.

Shackelford, T.J., 1980, Tertiary tectonic denudatio of a Mesozoic–early Tertiary(?) gneiss complex, Rawhide Mountains, western Arizona: Geology v. 8, p. 190–194.

Shafiqullah, Muhammed, Damon, P.E., Lynch, D.J., Reynolds, S.J., Rehrig, W.A., and Raymond, R.H., 1980, K-Ar geochronology and geologic history of southwestern Arizona and adjacent areas: Arizona Geological Society Digest, v. 12, p. 201–260.

Wernicke, Brian, 1981, Low-angle faults in the Basin and Range Province: Nappe tectonics in an extending orogen: Nature, v. 291, p. 645–648.

ACKNOWLEDGMENTS

We thank Greg Davis, Gordon Lister, Wes Peirce, and Bill Dickinson for helpful discussions, and Steve Richard for providing an unpublished map of the Harquahala Mountains.

Manuscript received October 31, 1984
Revised manuscript received February 7, 1985
Manuscript accepted February 20, 1985

Reviewer's comment

An excellent paper! I wish I'd written it!

Greg Davi