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SOME ASPECTS OF THE MIDDLE TERTIARY TECTONICS OF ARIZONA AND SOUTHEASTERN CALIFORNIA

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Introduction

The middle Tertiary tectonic evolution of the Basin and Range Province of Arizona and the Southwest was dominated by large-magnitude crustal extension and locally voluminous silicic magmatism. Major crustal thinning resulted from crustal extension, which occurred, at least at upper-crustal levels, by movement on large-displacement low-angle normal faults (detachment faults). Modification of the landscape was extreme, with formation of various volcanic eruptive centers, including calderas, and numerous sedimentary basins above tilting normal-fault blocks. The distribution and form of major extensional structures was influenced by structures inherited from older periods of deformation. In this paper, we review the middle Tertiary tectonic evolution of Arizona, and give special attention to west-central Arizona and adjacent southeastern California, an area that has undergone extreme extension and in which a number of important geologic relationships are clearly discernable. In addition, a better understanding of tectonic processes in the Basin and Range Province allows insight into the tectonic evolution of the Transition Zone of Arizona.

The Basin and Range Province of Arizona and the Southwest was the site of two episodes of Cenozoic extension that can be distinguished on the basis of age, direction, and style of extension, and age and chemistry of associated magmatism (Lipman et al., 1972; Shaffiqullah et al., 1980; Zoback et al., 1981). The first episode of extension occurred during Oligocene to mid-Miocene time and resulted in formation of detachment faults, low-angle ductile shear zones (metamorphic core complexes), and regional domains of tilted fault blocks. Middle Tertiary volcanic and sedimentary rocks, and older rocks, were typically tilted to moderate to steep dips by movement on listric or planar normal faults that merge downward with, or are truncated by, an underlying, gently dipping detachment fault or a system of multiple, gently dipping normal faults. Volcanic rocks erupted during this period of extension are primarily ash-flow tuffs and flows of silicic to intermediate composition, and have ^{87}Sr/^{86}Sr initial ratios greater than 0.7055. At about 13-15 Ma detachment faults became inactive and high-angle normal faults became the dominant, active extensional structures. High-angle normal faulting was accompanied by dominantly basaltic volcanism with ^{87}Sr/^{86}Sr initial ratios of less than 0.7055. Elongate sedimentary basins and flanking ranges and range-bounding faults formed during this later, "Basin and Range" episode of extension. The mid-Tertiary episode of extension was characterized by large-magnitude crustal extension and crustal thinning, with extension occurring primarily in a ENE-WSW direction. The younger Basin and Range episode resulted in much less extension and crustal thinning, and was directed in an E-W to ESE-WNW direction. The focus of this paper is the mid-Tertiary, pre-15-Ma period of extensional tectonism.

Extensional faulting and mylonites

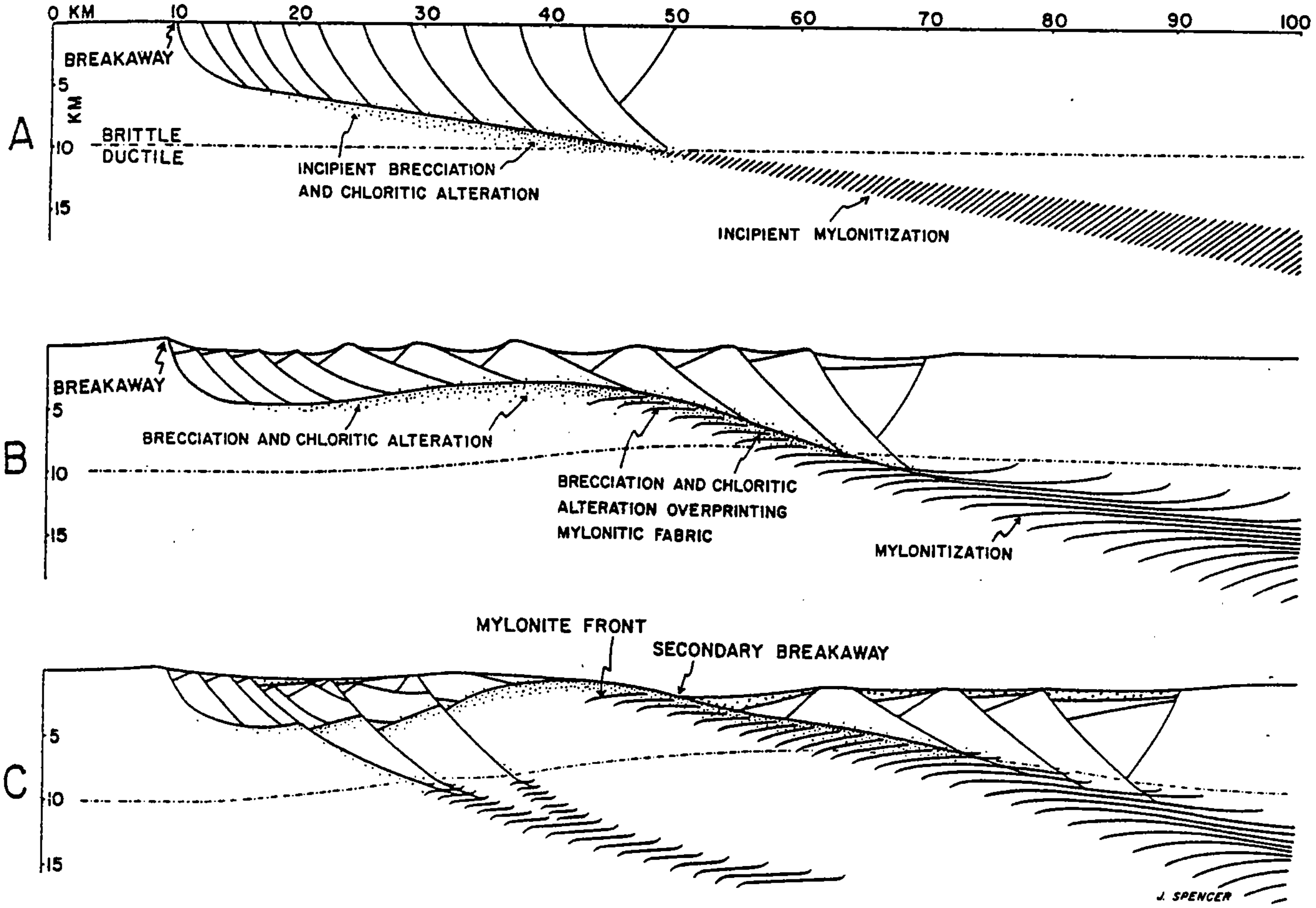
Detachment faults are subregional fault zones that originally formed with a low dip and that have accommodated normal slip of several kilometers to tens of kilometers (Wernicke, 1981; Reynolds and Spencer, 1985a). Large amounts of normal slip on some detachment faults exhumed mid-crustal crystalline rocks that contain gently dipping mylonitic fabrics whose overall sense of shear is parallel to, and in the same sense as, transport on the associated detachment fault (Fig. 1; Reynolds, 1985; Davis et al., 1986). These core-complex mylonites were formed by noncoaxial laminar flow along deeper segments of the detachment zone that were originally below the ductile-brittle transition.

Arizona can be subdivided into regional tilt-block domains in which middle Tertiary rocks dip consistently in one direction (Fig. 2). The dip direction in any tilt-block domain is generally toward the breakaway of the detachment fault that underlies the tilt-block domain, indicating that normal faults in the upper plate of a detachment fault are generally synthetic, rather than antithetic, with respect to the detachment fault.

Detachment faulting exposed different levels of the pre-middle Tertiary crust. Rocks that were at mid-crustal levels prior to faulting are exposed in core complexes that contain thick (>1km) zones of penetrative mylonitic fabric, whereas ductile deformation at shallower crustal levels is represented by thin (<100m) zones of less penetrative mylonitic fabrics that are confined to middle Tertiary plutons and their wall rocks. In these latter areas, emplacement of synkinematic middle Tertiary plutons locally raised geothermal gradients and permitted mylonitization to occur at levels that would otherwise have been above the brittle-ductile transition (Reynolds, 1985). Various levels of middle Tertiary crust are also exposed by wholesale rotation of large fault blocks (e.g. Howard et al., 1982).

Originally deep-seated crystalline rocks that were variably mylonitized during mid-Tertiary extension were exhumed by detachment faulting, underwent isostatic uplift, and are now exposed in archlike or

Core Complex



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

mal structural culminations called metamorphic core mplexes. Arching about a subhorizontal axis perpenicular to the direction of extension resulted from me combination of reverse drag above deeper listric rmal faults or detachment faults, and laterally rying isostatic rebound due to laterally varying ctonic denudation (Fig. 1; Spencer, 1984). Some tamorphic core complexes contain a record of defortion and metamorphism that occurred during pre-mid-rtiary compressional deformation.

West-central Arizona and southeastern California

Strongly mylonitic crystalline rocks are exposed a WNW-ESE-trending belt that includes lower-plate cks of the Whipple, Buckskin, Rawhide, Harcuvar, and rquahala (WBRHH) Mountains of western Arizona and utheastern California (Fig. 3). The subhorizontal lonitic fabric with an ENE-trending lineation in ese ranges is interpreted as a product of shearing ong the down-dip projection of a regional detachment ult during the early part of its movement history eynolds and Spencer, 1985a, b; Davis et al., 1986). uth-vergent thrust faults of the east-west-trending ria fold and thrust belt (Reynolds et al., this volume), located 10-70 km south of the Tertiary mylonites (Fig. 3), project northward beneath the WBRHH area. Restoration of 50 km of ENE-WSW displacement on the regional detachment fault in the WBRHH area places lower-plate rocks under the edge of the Transition Zone in central Arizona (Reynolds and Spencer, 1985a). Thus, the Tertiary mylonites, and the east-west-trending zone of Mesozoic crustal thickening within and north of the Maria fold and thrust belt, formed partly within what is now the Transition Zone.

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The spatial coincidence of the east-west-trending belt of Mesozoic crustal thickening with the Tertiary mylonitic rocks of the WBRHH area suggests that a genetic relationship exists between the two. In addition, the north-south-trending belt of uplifted, arched, lower-plate crystalline rocks north of, and including, the Whipple Mountains, abruptly swings eastward at the Whipple Mountains (domain C in Fig. 3). This abrupt change in trend of the belt of uplifted and arched crystalline rocks at about the area of the inferred east-west-trending Mesozoic crustal welt further suggests a genetic relationship between the two. Finally, domain C (Fig. 3) ends abruptly at the south side of the Harquahala Mountains, which are approximately coincident with part of the inferred southern margin of the Maria fold and thrust belt.

We infer that the primary cause of mid-Tertiary crustal extension was a substantial reduction in the ENE-WSW-directed compressional stress associated with the convergent plate boundary along the continental margin of western North America. Changes in plate interactions related to changing dip of the subducted slab and to the rate of absolute westward movement of North America presumably led to this stress reduction (Coney and Reynolds, 1977; Coney, 1978; Dickinson, 1979). However, the distribution and locus of exten-

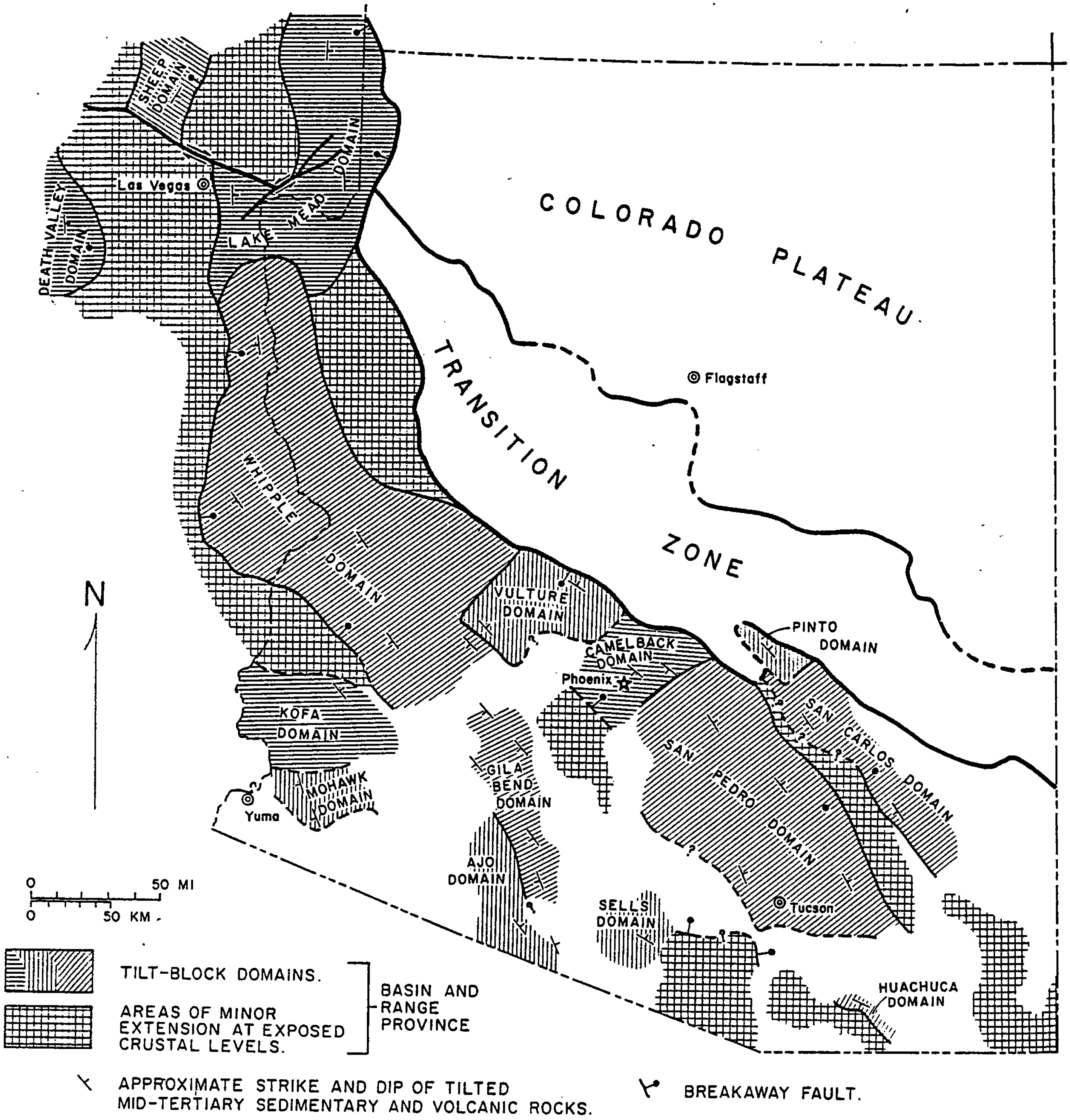

Figure 2. Map of tilt-block domains in the Basin and Range Province of Arizona and adjacent areas.

sion within western North America could have been determined in part by local factors such as crustal strength and thickness. A significant driving force for extension could come from the release of potential energy stored in overthickened crust of the Sevier-Laramide orogenic belt. Both the excess elevation of a mountain range and the depressed Moho associated with a crustal welt represent stored potential energy that could be released during crustal extension (Dalmayrac and Molnar, 1981; Coney and Harms, 1984). In addition, erosion of a mountain range and removal of its mass will not result in eventual elimination of the underlying, downward-projecting Moho bulge or "root" if the flexural rigidity of the lithosphere is large and the Moho root is held down by the stiff lithosphere. Such a situation would produce flexural stresses in the crust that might promote formation, and determine the location and geometry, of major detachment faults (Spencer, 1982, 1985). Greater extension in areas of greater intitial crustal thickness, due to greater available potential energy, would lead to flattening of the Moho.

Rigid lithosphere!

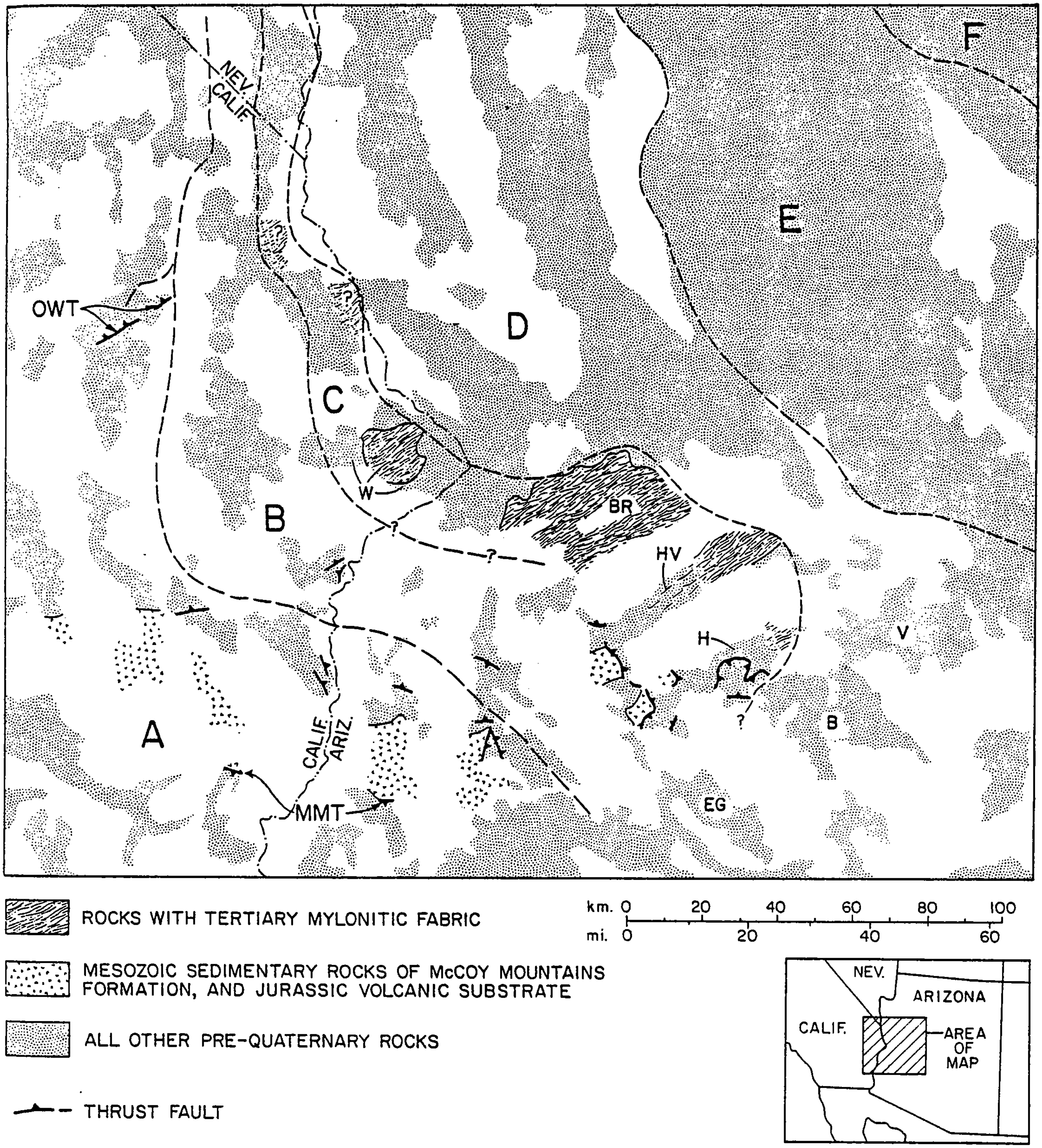

Figure 3. Highly simplified tectonic map of west-central Arizona and adjacent parts of southeastern California. OWT=Old Woman thrust, MMT=Mule Mountains thrust, all other thrust faults shown are part of the Maria fold and thrust belt. Mid-Tertiary tectonic domains are: (A) area of only minor extensional faulting at exposed upper-crustal levels, (B) synformal keel of distended rocks above detachment faults of the Whipple tilt-block domain, (C) belt of arched, uplifted, lower-plate crystalline rocks, including Tertiary mylonites, (D) wedge-shaped (in cross section) upper plate of tilted fault blocks above detachment faults of the Whipple tilt-block domain, (E) Transition Zone, and (F) Colorado Plateau. W=Whipple Mountains, BR=Buckskin-Rawhide Mountains, HV=Harcuvar Mountains, H=Harquahala Mountains, B=Bighorn Mountains, EG=Eagletail Mountains, V=Vulture Mountains.

The great width of the belt of uplifted mylonitic rocks in the WBRHH area is possibly the result of greater displacement on the overlying detachment fault than elsewhere along the belt. Greater displacement and extension would be required to flatten out a preexisting crustal welt. We thus infer that the extensive exposures of mylonitic rocks in the WBRHH area resulted from unusually large-magnitude displacement on the overlying detachment fault that was driven, in part, by isostatic forces inherited from the east-west-trending Mesozoic crustal welt associated with the Maria fold and thrust belt. Large displacement in the WBRHH area thus flattened out the Moho, and produced one of the largest exposures of Tertiary mylonite in the Cordilleran orogen. We emphasize that individual Mesozoic thrust faults were not generally reactivated by detachment faults, and the association of detachment faults with areas of older crustal shortening is only a general one.

Lateral changes in the distribution of extension was also a major factor in determining whether lower-plate rocks were uplifted to surficial levels (Spencer, 1984). For example, extension within an ENE-trending cross section through the Eagletail-Bighorn-Vulture Mountains (Fig. 3) was probably similar in magnitude to extension along a parallel line through the Harquahala or Harcuvar Mountains, yet the distribution of extension and style of extensional faulting as represented by surficial exposures was substantially different. Isostatic readjustment of a Moho root propelled the lower plate to the Earth's surface in the WBRHH area, whereas lack of a Moho root resulted in a broader distribution of extension in the Eagletail-Bighorn-Vulture area, and isostatic uplift was nowhere sufficient to bring lower-plate rocks to the Earth's surface.

Tectonic relationships between the Basin and Range Province and the Transition Zone

It is not possible at present to identify individual thrust faults that project beneath the Transition Zone over much of its length, but pre-mid-Tertiary uplift and northeastward tilting of rocks within the Transition Zone was almost certainly a product, in part, of crustal thickening under its southwestern margin. Southwestward tilting of rocks in the Transition Zone in the mid-Tertiary occurred in response to normal displacement on detachment faults that project beneath the southwestern margin of the Transition Zone and associated tectonic removal of lower-crustal material beneath the southwestern margin of the Transition Zone (Wernicke, 1985), a process we term "deflation". Deflation is inferred to be responsible for the present southwest dip of the erosion surface at the base of early to middle Tertiary conglomerates in the Fort Apache region, which were originally shed northeastward onto the Transition Zone above an inferred northeast-sloping surface.

Mineralization associated with detachment faults

The WBRHH area also contains numerous specular hematite-chrysocolla-malachite deposits along and adjacent to the regional detachment fault that have yielded substantial copper and some precious metals (Wilkins and Heidrick, 1982; Spencer and Welty, 1986). These deposits formed during detachment faulting and are not generally associated with igneous rocks. We infer that mineralization was the product of hydrothermal circulation, along and above the detachment fault, that was driven by heat from rapidly uplifted, lower-plate rocks. Extensive crushing and brecciation along the fault increased permeability and provided an enormous surface area for hydrothermal fluids to leach metallic elements, although the source of metals is not well constrained. The WBRHH area is unusual in its large number and wide distribution of detachment-fault-related mineral deposits. We suggest that unusually vigorous hydrothermal circulation, leading to mineralization, was the product of an unusually hot lower plate at shallow crustal levels, which in turn requires very rapid faulting and uplift (several km/m.y.), initially high geothermal gradients, and large amounts of total uplift (greater than 10 or 15 km; Spencer and Welty, 1986).

Relationship of extension to magmatism

The main pulse of middle Tertiary felsic to mafic magmatism is time transgressive from east to west (Coney and Reynolds, 1977), but existing data are not sufficient to clearly demonstrate a state-wide, time-transgressive character for either the initiation or termination of detachment faulting and crustal extension. Extension and detachment faulting began in some areas before significant magmatism, which suggests that magmatism and the associated elevation of geotherms are not necessary preconditions for the initiation of detachment faults. Some of the increases in geothermal gradients in middle Tertiary time were a consequence, not a cause, of detachment faulting.

Magnitude of extension

Magnitudes of middle Tertiary extension of 50 to 100 percent are indicated by cross-sectional reconstructions of distended areas and by evidence for total tectonic denudation of mid-crustal, core-complex tectonites during detachment faulting. This estimate is supported by comparisons of present crustal thickness (25km) of the Basin and Range Province with those that must have existed prior to extension in order to account for early Tertiary drainages that flowed onto the Colorado Plateau (present crustal thickness 40 km) from the presently topographically lower Basin and Range Province (Peirce et al., 1979; Wernicke 1985; Reynolds and Spencer, 1985b).

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