Preliminary Reconstruction of Miocene extension in the Basin and Range of Arizona and Adjacent Areas

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INTRODUCTION

Large-scale continental extension significantly rearranged the distribution of pre-Tertiary rocks in southern and western Arizona during Miocene time [Spencer and Reynolds, 1989a]. Topography resulting from this extension event has been modified by subsequent less intense extension, and together these events are responsible for the physiographic division of the state into a three provinces: Colorado Plateau, Transition zone and Basin and Range. Rocks on the Colorado Plateau have been relatively unaffected by Phanerozoic deformation. The Transition zone has been affected by relatively weak Laramide deformation, and mildly to moderately affected by late Cenozoic normal faulting and basin and range topographic development. Basins are relatively shallow and little tilting accompanied the extension. The Basin and Range province has been affected by intense deformation during several episodes in Mesozoic time and large-scale extension, commonly accompanied by steep tilting of rocks, mostly during early to middle Miocene time. This project represents an initial attempt to produce a palinspastic map representing the distribution of rocks in early Oligocene time before extension. This map is intended to help analyze Laramide deformation and possible controls on the distribution of Laramide porphyry copper deposits.

PROCEDURE

The reconstruction was produced in three steps. First, a generalized geologic map was prepared at a scale of 1:500,000. This map provided a compilation of the basic data necessary for the reconstruction, including the location of major detachment faults, the average dip of tilted Tertiary strata in extended terranes, and the distribution of pre-extensional structures and rock units to appear on the reconstructed map. The major sources of data for this compilation were the Geologic Map of Arizona [Reynolds, 1988], the New Mexico Highway Geologic map [New Mexico Geological Society, 1982], Carta Geologica, Tijuana [Direccion General de Geografia del Territorio Nacional, 1980], Geologic Map of the Silver City Quadrangle [Drewes et al., 1985] and Spencer and Reynolds [1989]. Information from these compilations was supplemented by inspection of sources used to produce them, and with data from a variety of other publications. The base map used was reconstructed to remove the effects of late Miocene deformation in southwestern Arizona following Richard [1993].

Next, the compiled data was used to define structural domains for the reconstruction (Figure 1). Three types of domains were defined (Figure 2): (1) unextended upper-crustal domains; (2) internally unextended domains of denuded mid-crustal rocks that form the footwall of major detachment faults (core complexes); (3) relatively uniformly extended upper crustal domains characterized by similar strike and average dip of Tertiary strata (as determined by eyeball averaging of available data). In many cases the domain boundaries are mapped faults, but commonly the type 3 domains are separated by diffuse zones of deformation across which the strike of tilted blocks or the degree of tilting changes.

Finally, the extension was reconstructed using two approaches. The most reliable method used cumulative slip estimates based on matching geologic features and reconstructing cross sections along transects across the extended terrane. Only two such complete transects were available: the Las Vegas area at the northwest end of the reconstructed region, and west-central Arizona in the central part of the reconstructed region. In some other cases, geologically based estimates of extension across segments of the extended terrane were used to constrain smaller regions (see more detailed discussion below). The other reconstruction technique was used in type 3 domains for which geologic estimates of extension were not available. In these cases, the average dip of Tertiary strata was estimated, faults were assumed to have been originally vertical (this provides a minimum estimate of extension) and the extension direction was assumed to be perpendicular to the strike of Tertiary strata. The equations of Thompson [1960] can then be solved to determine that the reconstructed width l_0 of a uniformly extended domain of present width l is simply: $l_0 = l \cos(\delta)$ where δ is the average dip of bedding. These domains were simply contracted by a factor of $\cos(\delta)$ perpendicular to the average strike of tilted Tertiary strata (i.e. the present width was multiplied by $\cos(\delta)$).

RECONSTRUCTION

The northwestern part of the region was reconstructed first because of the relatively better control afforded by data from the Las Vegas area and west-central Arizona. As discussed by Wernicke et al. [1988] the Spring Mountains and Las Vegas-Arrow Canyon Ranges form an unextended domain, offset by right slip on the Las Vegas shear zone. This domain continues southward into California probably as far as the New York Mountains. A northwest-trending fault near the Nevada-California State Line (State Line fault) offsets the domain in a fashion similar to the Las Vegas shear zone. Generally accepted geologic constraints on reconstruction of the Spring Mountains block relative to the Colorado Plateau include (only recent references for the interpretations are cited):

- Frenchman Mountain reconstructs to a position near the northern part of the Gold Butte Block [Bohannon, 1984; Rowland et al, 1990].
- The Las Vegas shear zone has up to 48 km of right slip [Wernicke et al., 1988]; however, a significant part of this displacement might be Mesozoic in age because only Paleozoic rocks are involved [Royse, 1983].
- Cumulative extension between the Colorado Plateau and the Spring Mountains block north of the Las Vegas shear zone is estimated to be 54±10 km [Axen et al, 1990].
- Geochemical similarities dictate that volcanic rocks in the McCulloch Mountains probably erupted above the Nelson and Boulder City plutons, and volcanic rocks in the River Mountains erupted above the Wilson Ridge pluton [Weber and Smith, 1987]. These rocks were erupted before the onset of major extension.
- The Hamblin Bay strand of the Lake Mead fault system offsets parts of the Hamblin-Cleopatra volcano by 20 km in a left-lateral sense [Bohannon, 1984].

I have estimated slip on the Las Vegas shear zone by assuming that it is a transfer fault linking extension south of the fault in the Lake Mead area with extension north of the fault in the Indian Springs area [Guth, 1990]. Reconstruction of a cross section across Indian Springs Quadrangle [Guth, 1990, Figure 7] yields an estimate of 26 km of WNW extension in terrane north of the Las Vegas Valley shear zone. This value is interpreted to represent the Tertiary slip on this structure; Mesozoic oroclinal bending is inferred to account for the rest of the offset across Las Vegas valley [Royse, 1983].

The total displacement of the southern Spring Mountains from Grand Wash cliffs is thus interpreted to be 81.5 km to 085°. This figure is the sum of the following vectors: (1) 26 km to 290° estimated on the Las Vegas shear zone; (2) 54 km to 255°, extension between the Colorado Plateau and rocks in the footwall of the Sheep Range detachment north of the Las Vegas Shear zone (Mormon Mountains transect) [Axen et al, 1990; Wernicke et al., 1988]; (3) 5±10 km to 245° to account for possible rotation within the Spring Mountains block as discussed by Wernicke et al. [1988]. South of the State Line fault, another 10 km of NW displacement of the Clark Mountains is added to this total [Burchfiel et al., 1982]. My total displacement estimate is within the best fit error region for the reconstruction of Wernicke et al. [1988], and is consistent with the Rowland et al. [1990] reconstruction of Frenchman Mountain. Reconstructing the Spring Mountains block via the Mormon Mountains transect and Las Vegas Shear zone avoids uncertainties in the original configuration of Frenchman Mountain relative to the River Mountains or Spring Mountains, for which the data are equivocal or absent.

Spencer and Reynolds [1991] provide a thorough review of available geologic evidence to sum extension along transects across the extended terrane between the transition zone near Bagdad and the Maria belt in the area of Quartzsite. They estimated a total of 86±13 km of extension. I have used their extension estimates to reconstruct this region.

Reconstruction of cross sections along a transect from the Hieroglyphic Mountains to the Big Horn Mountains [Richard et al., 1988] results in an estimate of 41 to 43 km of extension along this transect. Distinctive Jurassic(?) plutonic rocks crop out in adjacent parts of the southernmost Harcuvar domain (Figure 2) and northern Eagletail domain (southwest of Vulture domain in Figure 2), dictating that little slip has occurred between these domains. This provides the only link across the diffuse transfer zone that bounds the south side of the Maria belt unextended block (Figure 2), continues eastward to separate the Harcuvar and Vulture domains.

Tertiary rocks were deposited directly on Proterozoic rocks in central Arizona, or on as yet poorly understood Mesozoic metamorphic terranes in southwestern Arizona. Stratigraphic markers for estimating slip are thus absent. Three significant normal fault systems are recognized. The Chocolate Mountains fault is interpreted to link with the Baker Peaks detachment [Pridmore, 1983]. Because Orocopia schist in the footwall of this fault is absent or sparse in sedimentary rocks deposited before or during the major extension event, I interpret that this fault has small enough slip that the schist was not exhumed by fault movement. A normal fault bounding Jurassic(?) meta-igneous rocks in the Cemetary Ridge area is inferred to link with a recently mapped detachment fault bounding the Tertiary(?) Columbus Wash pluton in the Gila Bend Mountains [Gilbert et al., 1992; Gilbert and Spencer, 1992; Gilbert and Skotnicki, 1993]. Because of the apparently shallow level of intrusion of this pluton, this fault is not believed to have more than a few km of slip. The most significant extensional structure in central Arizona is the White Tank-South Mountains detachment fault [Spencer and Reynolds, 1989a], but because of the absence of exposed upper plate rocks, the slip on this fault is not known.

Flat lying volcanic rocks of 18-20 Ma age cover much of the region around Ajo in the south central part of the state. Older (20-23 Ma?) volcanic rocks at Ajo [Hagstrum et al., 1987], in the northern Sauceda Mountains, and in the Kofa and Gila Bend Mountains and poorly dated sandstone in the Comobabi Mountains are moderately to steeply tilted, and strike more westerly than tilted Tertiary strata in other parts of the state. Based on this scant data a large region of more NNE-SSW extension was defined in the south central part of the state. The N-S stretching lineations in the Coyote Mountains [Davis, 1980], and evidence for northward displacement of the upper plate of the San Xavier fault in the eastern Sierrita Mountains have been interpreted to reflect a similar extension direction at the eastern edge of this domain, above a north-dipping detachment fault that underlies the Sierrita Mountains and terminates in a transfer zone along the NW side of the Santa Rita Mountains. Total slip on this fault is not constrained.

The south-dipping detachment fault in the Pozo Verde Mountains [Haxel and Goodwin, 1990] at the Mexican border near Sasabe has been interpreted as the northernmost exposure of a fault system along the southwest side of a belt of metamorphic rocks exposed between the Pozo Verde Mountains and the Magdalena Complex [Nourse, 1989] in Sonora, Mexico. Based on strain data and cross section reconstructions, Nourse [1989] estimated 50-100% NE-SW extension across a corridor presently 50 km wide (17 to 25 km of extension). The relationship between this fault system and the Coyote-Sierrita fault system, with a more northerly extension direction, is uncertain, but the two faults have been linked by a mostly hypothetical fault zone on the west side of the Baboquivari Mountains.

Dickinson [1991] interpreted a minimum of 27.5 km top-to-the-southwest extension across the southeastern part of the Catalina detachment fault to align the western limit of Proterozoic Rincon Valley granodiorite in the hanging wall and footwall. He interpreted that displacement on the detachment faults bounding the Catalina core complex are 20 to 30 km, decreasing to the northwest.

The reconstruction of fault slips as summarized above and extension within type 3 domains based on the average tilt of strata resulted in some compatibility problems in the initial reconstruction which were resolved by rotating some domains by 5-10° clockwise or counterclockwise about a vertical axis. This regional rotation is required as a mechanism to transfer extension from one extending domain to another, allowing large systems of normal faults to lose slip along strike as other en echelon systems gain slip. The rotations used are indicated on Figure 2.

DISCUSSION OF MAP

The reconstructed base map was produced from a digitized version of the Arizona geologic map [Reynolds, 1988; Reynolds and Richard, 1993], with generalized additions from sources summarized in the procedure section. Within Arizona, rock units included in the generalized map are summarized in Table 1.

Table 1. Rock units included in generalized units

Rock Unit	Units from Reynolds[1988] included	Other units included
Cretaceous volcanic rocks	Kv	Cretaceous volcanic rocks near La Caridad in Mexico, and some TKa in New Mexico [Drewes et al, 1985].
Laramide intrusions	TKg	Cretaceous plutonic rocks in the southern Clark, New York and Homer Mountains of California [Spencer and Reynolds, 1989a] TKd and TKg in New Mexico [Drewes et al, 1985] and porphyry at Cananea
Laramide two mica granitoids	TKgm	
Jurassic Plutonic rocks	Jg	
pre-Laramide Mesozoic supracrustal rocks	Jv, Jsv, KJs,	

Paleozoic sedimentary rocks	Pz, MzPz in extended terrane, MC along edge of Colorado Plateau and in Transition zone. Note that many rocks shown as MC, PP and P in SE Arizona are not shown	All Paleozoic rocks in the Spring Mountains block
Proterozoic rocks	Xm, Xg, YXg, Yg. Note that Xms, Xmv, Xq and Apache Group are not shown	Precambrian rocks in southern Nevada and in the New York Mountains and Homer Mountain, California.
Orocopia Schist	Mzo	

The outline of the restored position of outcrops in the footwall of the Buckskin-Bullard detachment fault is shown. Rocks in the footwall of other major detachment faults (White Tank, South, Catalina and Rincon Mountains) are not shown. The present version of the map is also missing rock units in the Sierra Estrella, Dos Cabeza and Pinaleño Mountains due to technical problems.

PROBLEMS

Slip estimate is minimum

The assumption made that fault-bedding intersections are 90°, i.e. the original dip of the faults was 90°, is clearly not valid in some areas. Based on available geologic maps, it appears most likely that the assumption is valid in the northern Colorado River corridor (Black and El Dorado Mountains [Anderson, 1977, 1978], and possibly in the Vulture domain [Grubensky, 1989]). It is unlikely that this assumption is valid in the Ray-Globe area [Peterson, 1962; Creasy et al., 1983] and San Pedro valley (see maps in Dickinson [1991]). If the original dip of the faults was 60°, the present 30-60° average dip of Tertiary strata requires significantly more extension.

Pinaleño Mountains not extended

In the present version of the reconstruction, less than 5 km of extension have been reconstructed across the Pinaleño Mountains. Naruk [1987] estimated a minimum of 6-9 km slip based on strain in Tertiary mylonitic rocks of the footwall. The actual extension accommodated on these faults is almost certainly greater. In order to allow for this extension, some additional vertical axis rotation of rocks, or greater extension accommodated by normal faults is necessary in the Globe area. Steep dip of Apache Group rocks and basal Tertiary sediments in this area, and likelihood that the original dip of faults in the Ray-Globe area makes greater extension likely in this area.

Timing and direction of extension in the northern part of the belt

The more easterly extension in the northern part of the Colorado River corridor is interpreted to result from the superposition of a right slip component resolved onto the Las Vegas shear zone and State Line fault and NE-SW extension observed in the Mormon Mountains transect north of the Las Vegas shear zone and in the Chemehuevi Mountains to the south. Extension in this strip migrated continuously from south to north, with major tilting of strata occurring in the Whipple-Chemehuevi Mountains area between about 19 and 17 Ma, and between 14.3 and 12 Ma in the northern part of the Colorado River Corridor [Faulds et al., 1994]. Displacement on the Las Vegas shear zone was apparently coeval with extension in the northern Colorado corridor. This reconstruction proposes some 36 km of right slip on the combined Las Vegas shear zone and State line fault. These faults are not recognized southeast of the Cerbat-Aquarius Mountains block; the proposed slip must be accommodated in some fashion. Possibilities include about 20° clockwise rotation of the Maria Belt; slip on unrecognized northwest-trending right slip faults, or NW-SE extension of 30-40% in the region between Interstate-40 and the Maria belt. Because of the absence of evidence for NW-SE extension, the third possibility is considered least likely. Northwest-trending faults with right oblique slip cut the Buckskin detachment fault system [Spencer and Reynolds, 1989b (Figure 2); Richard et al., 1990 (Table 2)] , and may be part of a set of post ~18 Ma faults accommodating some of this slip. Some clockwise rotation is also possible.

Laramide ore deposits

Laramide porphyry copper systems and associated vein deposits typically formed in shallow sub-volcanic to volcanic settings, at depths of less than about 5 km in the latest Cretaceous to early Tertiary crust [Titley, 1982]. Over much of southwestern Arizona, these upper-crustal rocks were removed by early Tertiary erosion, and exposed late Cretaceous rocks include mesozonal plutons with early Tertiary cooling ages and supracrustal rocks metamorphosed to greenschist facies or higher [Reynolds et al., 1988]. Rocks exposed in the footwall of major detachment faults (i.e. metamorphic core complexes), which have been translated several tens of kilometers southwestward relative to their hanging wall rocks during early Miocene extension, include rocks that were at mid-crustal depths before they were tectonically denuded [Reynolds et al., 1988; Anderson, 1988]. Thus, the metamorphic core complexes are composed of rocks that were well below the active mineralizing systems in Laramide time.

Porphyry copper deposits in Arizona are located in regions that were not deeply eroded in early Tertiary time or tectonically denuded in middle Tertiary time. In the terminology of Figure 2, the type two domains are thus unlikely to host porphyry copper deposits. Many of the deposits occur in type three domains, which have undergone extension by movement on complex arrays of normal faults. Normal faults in such domains typically have total displacemnt of less that about 5 km. Reconstruction of mineralized intrusive systems that have been broken up by such arrays of faults provides a means to locate exploration targets.

A map reconstruction of an extended terrane provides the means to estimate the displacement on faults or the magnitude of extension in adjacent areas, based on the requirement that material continuity be matained. If one strip across the extended terrane can be reconstructed with confidence, this places strong constraints on how adjacent strips can be reconstructed, especially if along strike ties can be established. For example, in this reconstruction, the fact that reconstructions of the Las Vegas and west-central Arizona transects yielded similar magnitudes of extension dictated that extension in the intervening region (Black and El Dorado Mountains area) be similar. Such logic, applied to more detailed reconstructions in the vicinity of extended mineralized systems (e. g. Sierrita, Ray, Miami-Inspiration) would assist in the location of possible unexposed segments of those systems.

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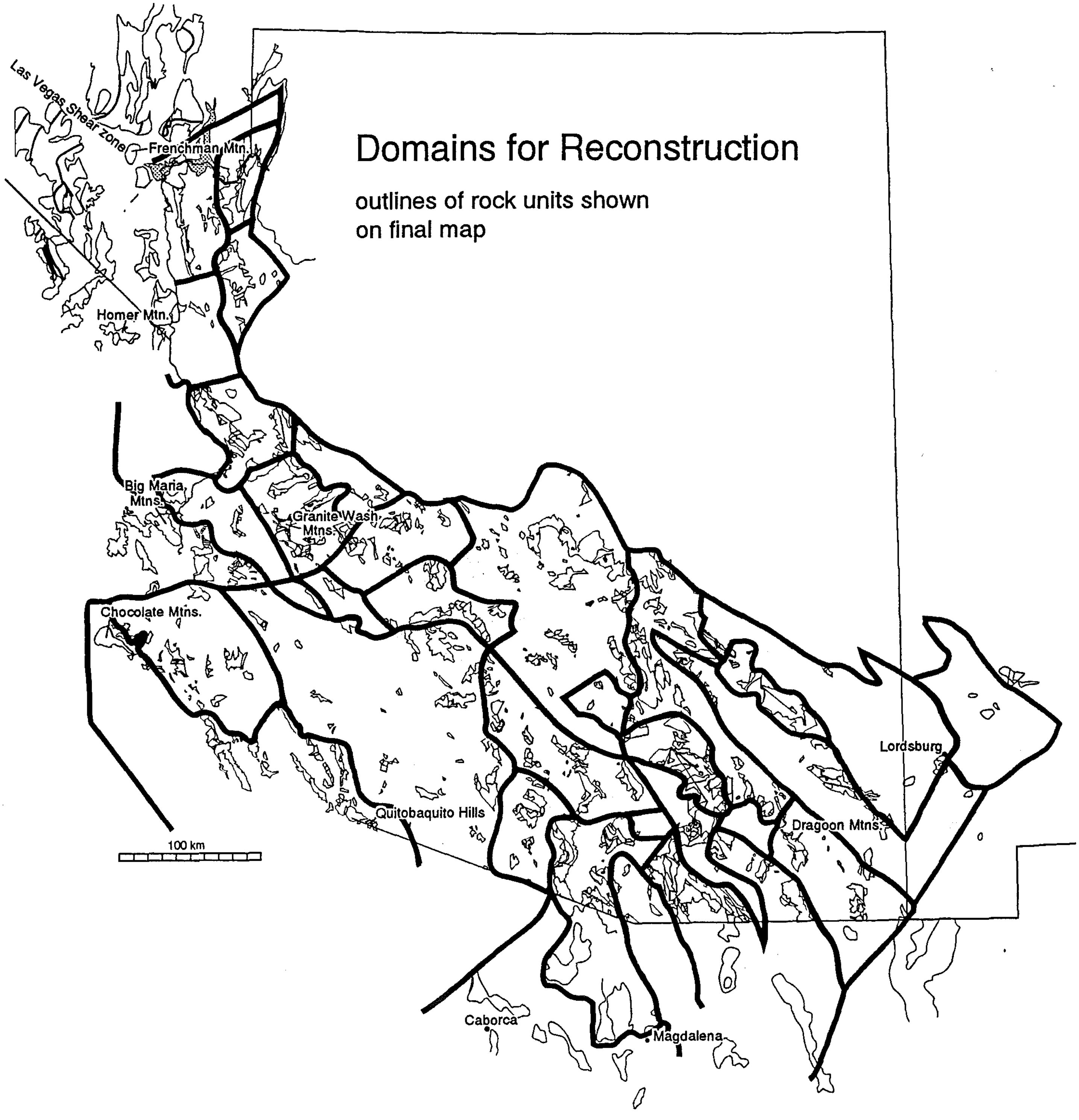

Figure 1. Outlines for the domains used in the reconstruction on a base map that includes the outlines of the rock units shown on the final reconstruction. The borders of the state of Arizona are shown for reference (except in parts of SW Arizona in which late Miocene deformation has been reconstructed).

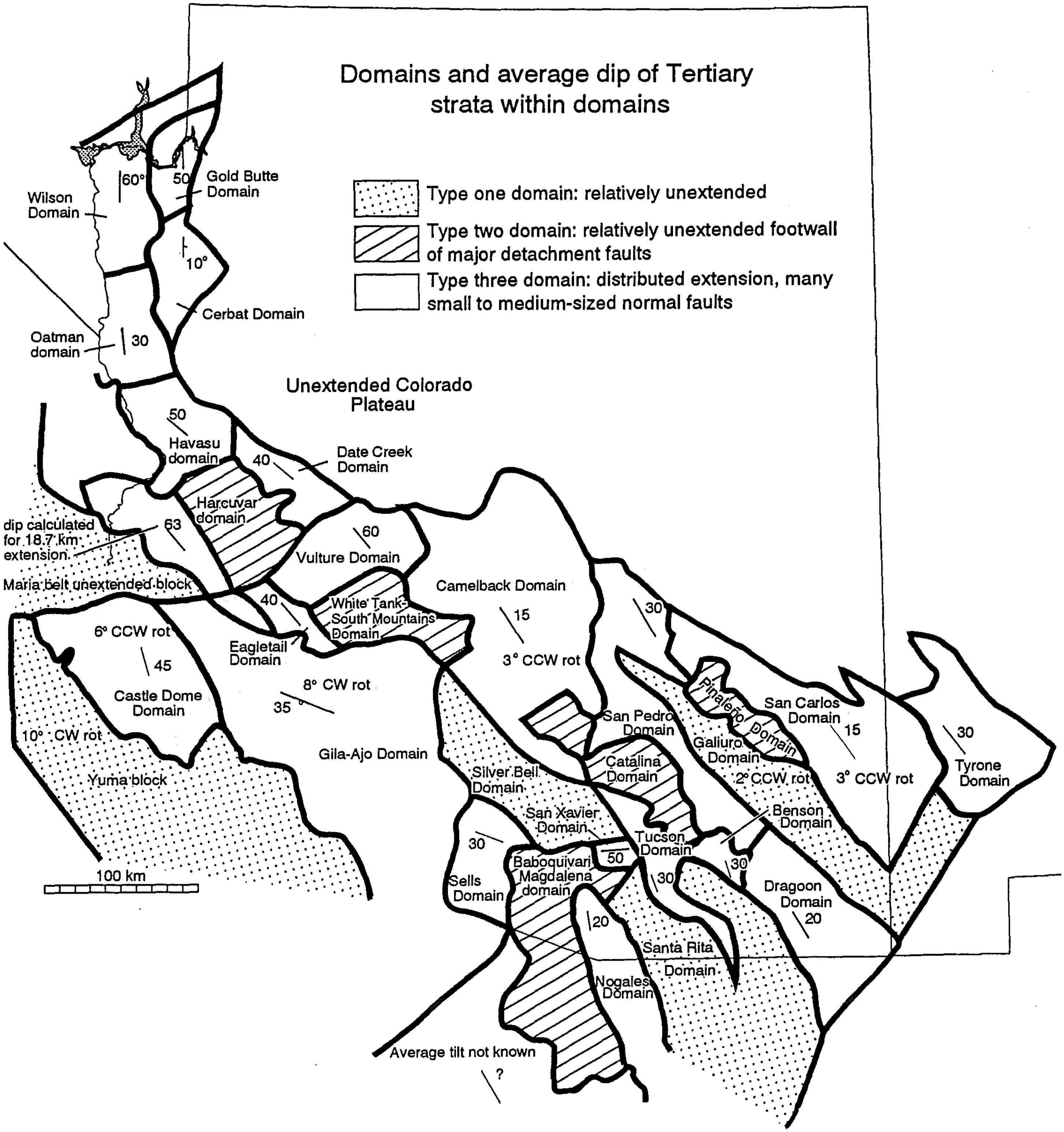

Figure 2. Names of domains used in text, along with average dip of type three domains used in reconstruction, and amount of rotation reconstructed in some domains.