New Mexico Geological Society

Downloaded from: https://nmgs.nmt.edu/publications/guidebooks/51



Inversion of Late Jurassic-Early Cretaceous extensional faults of the Bisbee Basin, southeastern Arizona and southwestern New Mexico

Timothy F. Lawton

2000, pp. 95-102. https://doi.org/10.56577/FFC-51.95

in:

Southwest Passage: A trip through the Phanerozoic, Lawton, T. F.; McMillan, N. J.; McLemore, V. T.; [eds.], New Mexico Geological Society 51 st Annual Fall Field Conference Guidebook, 282 p. https://doi.org/10.56577/FFC-51

This is one of many related papers that were included in the 2000 NMGS Fall Field Conference Guidebook.

Annual NMGS Fall Field Conference Guidebooks

Every fall since 1950, the New Mexico Geological Society (NMGS) has held an annual Fall Field Conference that explores some region of New Mexico (or surrounding states). Always well attended, these conferences provide a guidebook to participants. Besides detailed road logs, the guidebooks contain many well written, edited, and peer-reviewed geoscience papers. These books have set the national standard for geologic guidebooks and are an essential geologic reference for anyone working in or around New Mexico.

Free Downloads

NMGS has decided to make peer-reviewed papers from our Fall Field Conference guidebooks available for free download. This is in keeping with our mission of promoting interest, research, and cooperation regarding geology in New Mexico. However, guidebook sales represent a significant proportion of our operating budget. Therefore, only *research papers* are available for download. *Road logs*, *mini-papers*, and other selected content are available only in print for recent guidebooks.

Copyright Information

Publications of the New Mexico Geological Society, printed and electronic, are protected by the copyright laws of the United States. No material from the NMGS website, or printed and electronic publications, may be reprinted or redistributed without NMGS permission. Contact us for permission to reprint portions of any of our publications.

One printed copy of any materials from the NMGS website or our print and electronic publications may be made for individual use without our permission. Teachers and students may make unlimited copies for educational use. Any other use of these materials requires explicit permission.

This page is intentionally left blank to maintain order of facing pages.

INVERSION OF LATE JURASSIC–EARLY CRETACEOUS EXTENSIONAL FAULTS OF THE BISBEE BASIN, SOUTHEASTERN ARIZONA AND SOUTHWESTERN NEW MEXICO

TIMOTHY F. LAWTON
Department of Geological Sciences, New Mexico State University, Las Cruces, NM 88003, tlawton@nmsu.edu.

Abstract—Laramide shortening in the southwestern United States inverted Late Jurassic–Early Cretaceous extensional faults. Evidence for inversion includes: (1) up-dip and along-strike changes from normal to reverse stratigraphic offset on individual faults; (2) abrupt changes in thickness of Lower Cretaceous strata at Laramide reverse and oblique-slip faults; (3) abrupt changes in the Mesozoic subcrop across reverse faults, with Paleozoic strata more deeply eroded on hanging walls than footwalls; (4) fault-zone horses of basement or strata older than adjacent rocks in either hanging wall or footwall; (5) intermontane Laramide basins positioned at abrupt transitions in thickness of the Jurassic–Cretaceous section, usually flanking thick uplifted successions and overlying thin footwall successions. Pre-Laramide extensional faulting formed the Late Jurassic–Early Cretaceous Bisbee basin, part of a rift-basin assemblage extending from southern California to the Gulf of Mexico. Jurassic–Lower Cretaceous sections are as much as 4700 m thick in the proposed axis of the Bisbee basin, but thin away from the axis in a stepwise fashion across northwest-trending, basement-involved faults. In the Late Jurassic and Early Cretaceous, these structures were steep normal faults that bounded half-graben basins. In the latest Cretaceous, the same structures were reverse and oblique-slip faults that accommodated shortening oblique to the structural trend established during the Jurassic. Documented examples of inversion structures are restricted to faults within the former Bisbee rift basin; Laramide structures north of the Burro uplift, although basement-involved, do not demonstrably reactivate older faults.

INTRODUCTION

Several models have been proposed to explain the origin of Laramide structural patterns in the southwestern United States. No consensus yet exists for the origin of Laramide structures, and perhaps the only point of agreement is that they are the result of crustal shortening that began late in the Cretaceous. Models for Laramide structures fall into three basic categories. A thin-skinned model, involving ramp and flat thrust-fault geometries, has been invoked on the basis of rare, yet conspicuous exposures interpreted as flat faults (Corbitt and Woodward, 1973; Drewes, 1980, 1988, 1991). A strike-slip model has been proposed by other workers who describe steep, basement-involved faults and rotation of strike trends about sub-vertical axes adjacent to the faults (e.g., Brown and Clemons, 1983; Seager, 1983). A thick-skinned model emphasizing reverse faults that cut basement has also been proposed for Laramide structures in Arizona and New Mexico (Davis, 1979; Seager and Mack, 1986). Combining aspects of the thin-skinned and thick-skinned models, Drewes (1980) suggested that Laramide shortening was accommodated by steep reverse faults that soled into a regionally extensive detachment in the middle crust.

This paper proposes an alternative hypothesis, that most or even all Laramide faults represent inversion structures. They are reactivated faults that were previously Jurassic–Cretaceous normal faults active during the formation of the extensional Bisbee basin. The inversion model combines features of thick-skinned models with concepts of basement-fault reactivation. The idea that Laramide faults had a prior history is not new (e.g., Thorman and Drewes, 1980; Drewes, 1991); Davis (1979) and Bilodeau (1984) suggested that many Laramide structures represent reactivated, older Mesozoic normal faults. Yet criteria for recognition of reactivation have not been advanced. Laramide faults of the Southwest have recently been interpreted as inversion structures (Lawton, 1996; Bayona, 1998; Bayona and Lawton, this volume), largely based on the types of observations that are summarized here. The purpose of this paper is to establish and illustrate criteria for fault inversion that demonstrate that most Laramide faults of southwestern New Mexico and southeastern Arizona can be regarded as reactivated normal faults. Acceptance of this tenet suggests that Laramide structural trends are poor indicators of the Laramide stress field and that they better reflect the distribution of older extensional structures. The maps presented here are the result of compilation of data from sources cited in the text; the cross-sections are based on both new geologic mapping and reinterpretation of published geology as noted in the figure captions.

MODELS OF INVERSION STRUCTURES AND SYNTECTONIC DEPOSITS

Inversion tectonics involves reversal of older displacement on a fault or fault system (Williams et al., 1989). When applied to reactivation of a former normal fault, it potentially involves uplift of an extensional basin, or basin inversion (Fig. 1a, b; Bally, 1984). The orthogonal inversion model (Fig. 1a, b), modified from Williams et al. (1989), involves two temporally separate phases of approximately coaxial extension and contraction. An initial extensional phase creates a hanging-wall half-graben or graben that is thrust over its own footwall during a subsequent contractile phase. Stratigraphic separation on a partially inverted fault changes from normal offset down the dip of the fault plane to up-dip reverse offset at a position on the fault known as the null point (Fig. 1b). Local thin-skinned thrusting of the distal, thin part of the extensional basin may take place to accommodate shortening (Hayward and Graham, 1989). Syntectonic basins of the contractile phase are small intermontane or broken-foreland basins presumably formed by load-induced flexure. Thick extensional deposits of the footwall are offset geographically from synorogenic contractional deposits, which lie on thin extensional-phase deposits adjacent to the uplifted hanging wall. Strata equivalent to the syn-extensional deposits of the hanging wall may be absent from the footwall. A near-orthogonal orientation of the older extensional fault surface to subsequent compressive stress does not typically result in fault reactivation (Sibson, 1995; Bayona and Lawton, this volume).

Reactivation of basement-involved faults in a strike-slip setting (Fig. 1c, d), in which the shortening direction is oblique to the initial extension direction, is probably a more common phenomenon. This tectonic setting may result in transpression and uplift of the hanging wall (Fig. 1c), as in conventional inversion, or of the footwall (Fig. 1d). Syntectonic basins resulting from hanging-wall uplift may form as pull-apart basins at steps in the basement fault system or by flexure at releasing or restraining bends. Older extensional basins and younger wrench basins are offset geographically. In the case of footwall uplift, syntectonic deposits may be lacking, or if formed at steps in the fault system, may partly overlap thick extensional basin deposits. Both oblique and orthogonal reactivation mechanisms may result in emplacement along the fault zone of basement blocks, or horses, that are torn from the footwall and transported up-dip (Fig. 1a, c, d). The resulting blocks can be older than either footwall or hanging-wall strata at a particular level of exposure.

Orthogonal-inversion model. Modified after Williams et al. (1989). Standard inversion with approximately coaxial extensional and contractional phases. Stratigraphic units: (1) Basement; (2.) Pre-extensional deposits; (3) Synextensional deposits; (4) Post-extensional deposits; (5) Syn-shortening deposits. Extensional and contractional basins offset; contractional synorogenic deposits overlie thin or absent extensional basin deposits.

Oblique-inversion models. Faults reactivated by shortening direction oblique to intial extension direction, resulting in transpression or transtension. Syntectonic basins resulting from hanging-wall uplift may form as pull-apart basins at steps in the fault system or at releasing or restraining bends. Extensional and contractional basins are offset geographically. Syntectonic deposits may be lacking in cases involving uplift of the extensional footwall. Both oblique-inversion and orthogonal-inversion mechanisms may result in fault-zone horses of rock older than rocks in either footwall or hanging wall at comparable structural level.

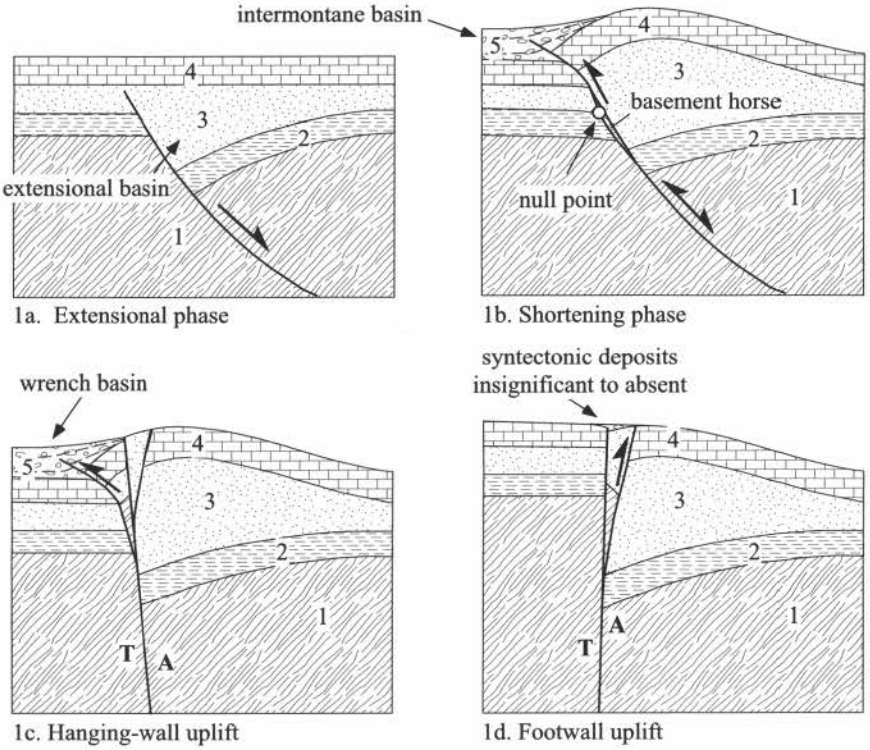


FIGURE 1. Models for basin and fault inversion, showing hypothetical locations of synorogenic deposits of shortening phase.

STRATIGRAPHIC RECORD OF LARAMIDE INVERSION

The inversion model proposed here for the southwestern Laramide province consists of two episodes of crustal deformation, both of which are well recorded by the regional stratigraphy. An initial episode of crustal extension from Late Jurassic to Early Cretaceous time formed the Bisbee basin, represented by strata of the Bisbee Group (Fig. 2; Mack et al., 1986; Dickinson et al., 1989). Onset of extensional faulting is indicated by an Upper Jurassic marine and volcanic succession recognized in the U.S. only in the Chiricahua Mountains of southeastern Arizona (Lawton and Olmstead, 1995; Olmstead, 1998) and Little Hatchet Mountains of southwestern New Mexico (Lawton and Harrigan, 1998). The succession at both localities consists of approximately 1 km of shallow marine, prodeltaic and deltaic strata overlain by 200 m of mantle-derived mafic volcanic flows. In the Little Hatchet Mountains, marine conglomerate and calclitharenite record unroofing of the Paleozoic stratigraphic section north of the extensional basin; overlying mafic volcanics grade up-section to approximately 3500 m of Neocomian–Albian marine strata and red beds. In the Chiricahua Mountains, the Jurassic section is thrust over Cretaceous red beds (Lawton and Olmstead, 1995). The Cretaceous section in the Chiricahua Mountains is more than 2400 m thick (Epis, 1952), for a total composite Bisbee Group thickness of about 3500 m. The Glance Conglomerate, derived from Precambrian through Permian rocks, is syn-extensional in southeastern Arizona (Bilodeau, 1979, 1982) and is in part equivalent with the Jurassic section of the Chiricahua Mountains. The Cretaceous part of the Bisbee Group in both Arizona and New Mexico consists of interbedded shallow-marine and nonmarine rocks (Mack et al., 1986; Dickinson et al., 1989; Klute, 1991).

The second episode of crustal deformation, a shortening event generally known as the Laramide orogeny, is widely recorded by continental deposits of local basins (Fig. 3). Adjacent to the axis of the former Bisbee basin, such as in the Chiricahua and Little Hatchet mountains, these strata range in age from Campanian to early Tertiary (Fig. 2). They include the Fort Crittenden Formation of Arizona, the Cabullona Group of northern Sonora, and the Ringbone Formation of New Mexico. The Cretaceous strata are locally overlain by calc-alkaline intermediate volcanic rocks whose ages are not adequately known in the region. The Hidalgo Formation, a succession of andesite flows and breccias that conformably overlies the Ringbone Formation, is 71 Ma near its base (Lawton et al., 1993; Young et al., this volume), and is probably restricted to the Maastrichtian, based on stratigraphic relations in the Little Hatchet Mountains. Near the flanks of the Bisbee basin, synorogenic Laramide strata appear to be restricted to the Tertiary. These strata include the Lobo Formation, whose age is poorly known, but generally accepted as Eocene (Fig. 2; Seager and Mack, 1986; Clemons and Mack, 1988), and the Love Ranch Formation, which is also probably Eocene (Seager et al., 1997). Both the Lobo and Love Ranch formations contain clasts derived from the Cretaceous andesites. The equivalent Bobcat Hill Formation of the Peloncillo Mountains is Eocene in its upper part (Lucas, 1992) and is overlain by folded andesite with a 44-Ma fission-track age (Bayona and Lawton, this volume). Similarly, the Paleocene–Eocene Skunk Ranch Formation contains an andesite breccia and was folded prior to overlap by volcanic rocks of the upper Eocene Rubio Peak Formation (Fig. 2; Hodgson, 1991, this volume). The presence of lake facies, extreme variability in sandstone and conglomerate composition, and local fluvial dispersal directions parallel to structural strike demonstrate that Laramide strata were derived from adjacent uplifts and occupied structurally separate basins, rather than a larger basin that encompassed the foreland region (Hayes, 1987; Inman, 1987; Basabilvazo, 1991, this volume; Wilson, 1991; Mann, 1995; Bayona, 1998; Bayona and Lawton, this volume).

STRUCTURAL RECORD OF LARAMIDE INVERSION

Laramide faults are conspicuous features of most of the ranges from the Huachuca Mountains of southeastern Arizona eastward to the Rio Grande (area of Fig. 3b). Many exposures are of steep, basement-involved structures that probably have an appreciable component of strike-slip offset (Seager, 1983; Seager and Mack, 1986; Brown and Clemons, 1983; Clemons, 1983, 1985). Other faults have moderate dips (e.g., Seager and Mack, 1990). The sense of strike-slip offset in the region has been interpreted as both right-lateral (Seager, 1983; Clemons, 1983, 1985; Seager and Mack, 1986) and left-lateral (Drewes, 1982; 1991; Hodgson, 1991). Obliquity of footwall fold axes to adjacent reverse faults in the Little Hatchet, Peloncillo and Chiricahua

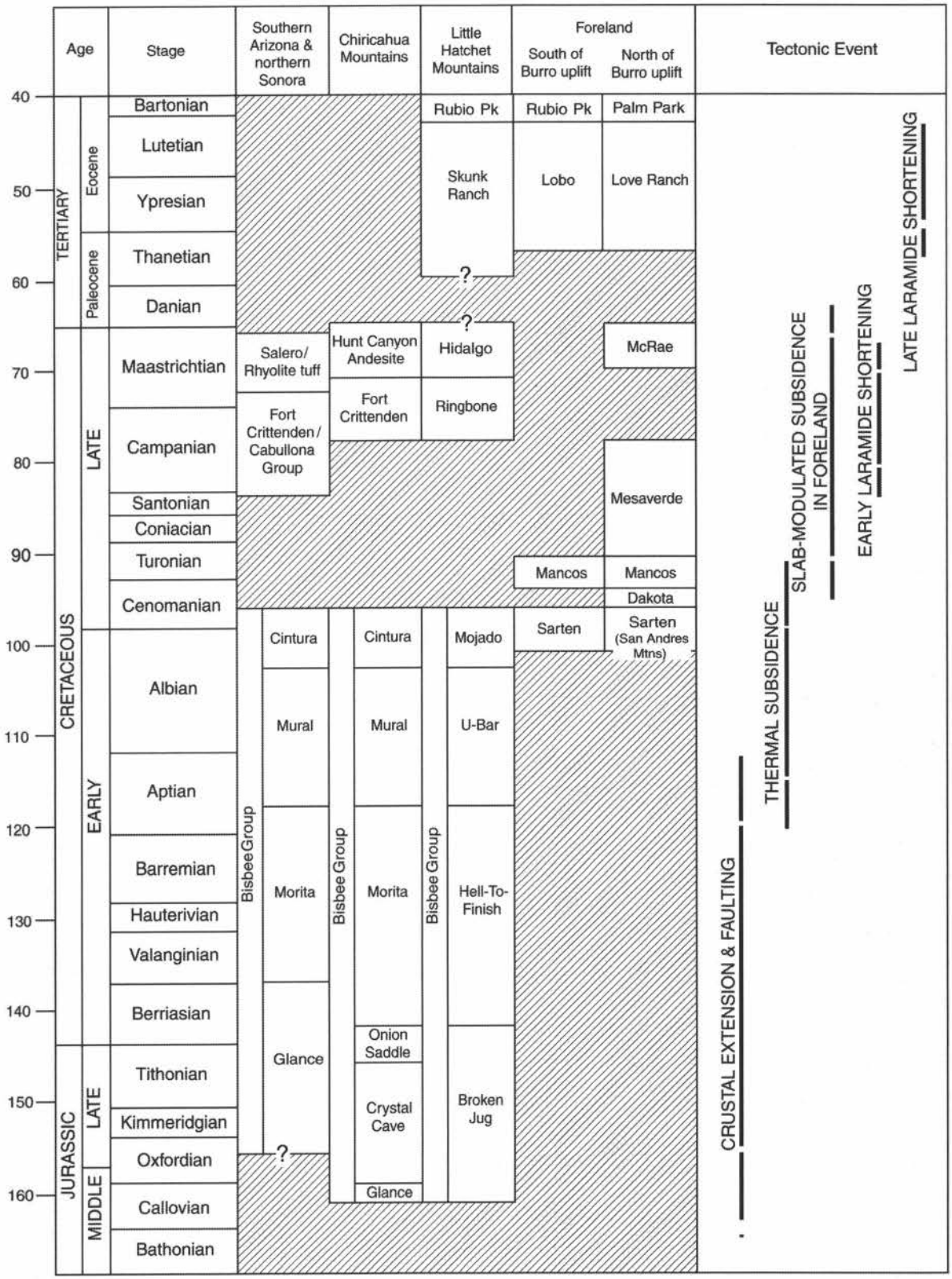


FIGURE 2. Stratigraphic age and correlation of Bisbee Group and Laramide strata of selected localities in southeastern Arizona and southwestern New Mexico. Columns on right are interpreted mechanisms of tectonic subsidence and deformation. Sources: Mack et al. (1986); Dickinson et al. (1989); Lawton et al. (1993); Lawton and Olmstead (1995); Lawton and Harrigan (1998); Lucas and Estep (1998).

Mountains provides evidence for left-lateral displacement (Hodgson, 1991, this volume; Lawton and Olmstead, 1995; Bayona, 1998; Bayona and Lawton, this volume). Therefore, most major, northwest-trending Laramide faults of the region are here interpreted to have had a component of left-lateral slip.

Laramide structures in Arizona and New Mexico have several characteristics that combine to suggest that they are reactivated extensional structures. These characteristics include: (1) greater erosional truncation

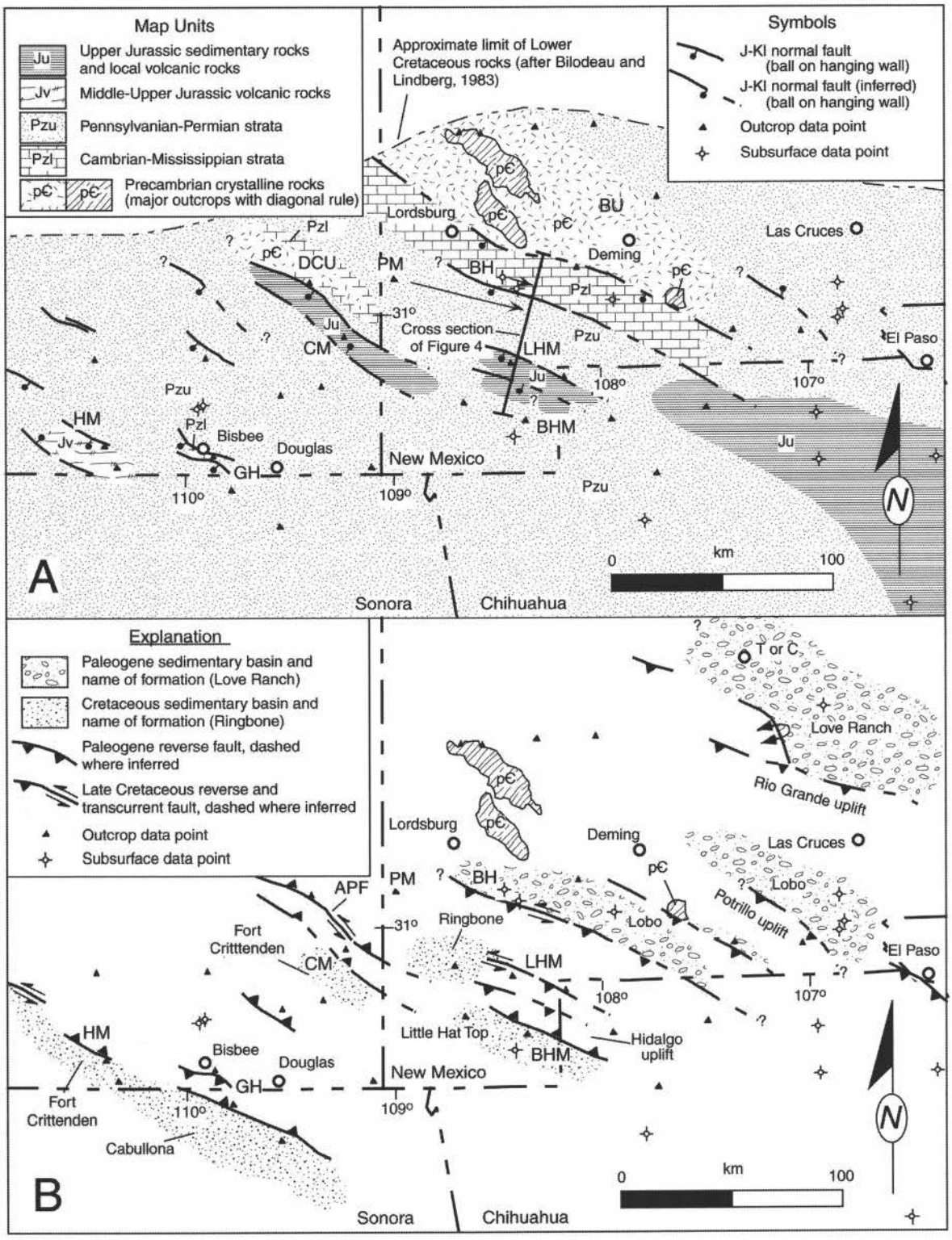


FIGURE 3. Location of study area in southeastern Arizona, southwestern New Mexico and northern Mexico. **A**, Lower Cretaceous subcrop map and locations of inferred major extensional faults of Late Jurassic–Early Cretaceous age. **B**, Distribution of Laramide strata and major faults. Location abbreviations: APF, Apache Pass fault zone; BU, Burro uplift, CM, Chiricahua Mountains; DCU, Dos Cabezas uplift; BH, Brockman Hills; BHM, Big Hatchet Mountains; GH, Gold Hill fault; HM, Huachuca Mountains; LHM, Little Hatchet Mountains; PM; Peloncillo Mountains. Laramide Burro uplift of Seager and Mack (1986) is here termed Potrillo uplift to avoid confusion with the Early Cretaceous Burro uplift. Line of section of Figure 4 indicated; data projected from Brockman Hills and Peloncillo Mountains as shown by arrows.

of pre-extensional stratigraphy in the footwalls of individual faults than in the hanging walls, with more strata preserved beneath the pre-Mesozoic unconformity on the hanging-wall blocks of reverse faults; (2) abrupt changes in thickness of the Jurassic and Lower Cretaceous section at Laramide faults; (3) changes from normal to reverse stratigraphic offset in an up-dip direction on individual faults; (4) presence in fault zones of blocks older than rocks in either the hanging wall or footwall at that structural level; (5) along-strike changes from normal to

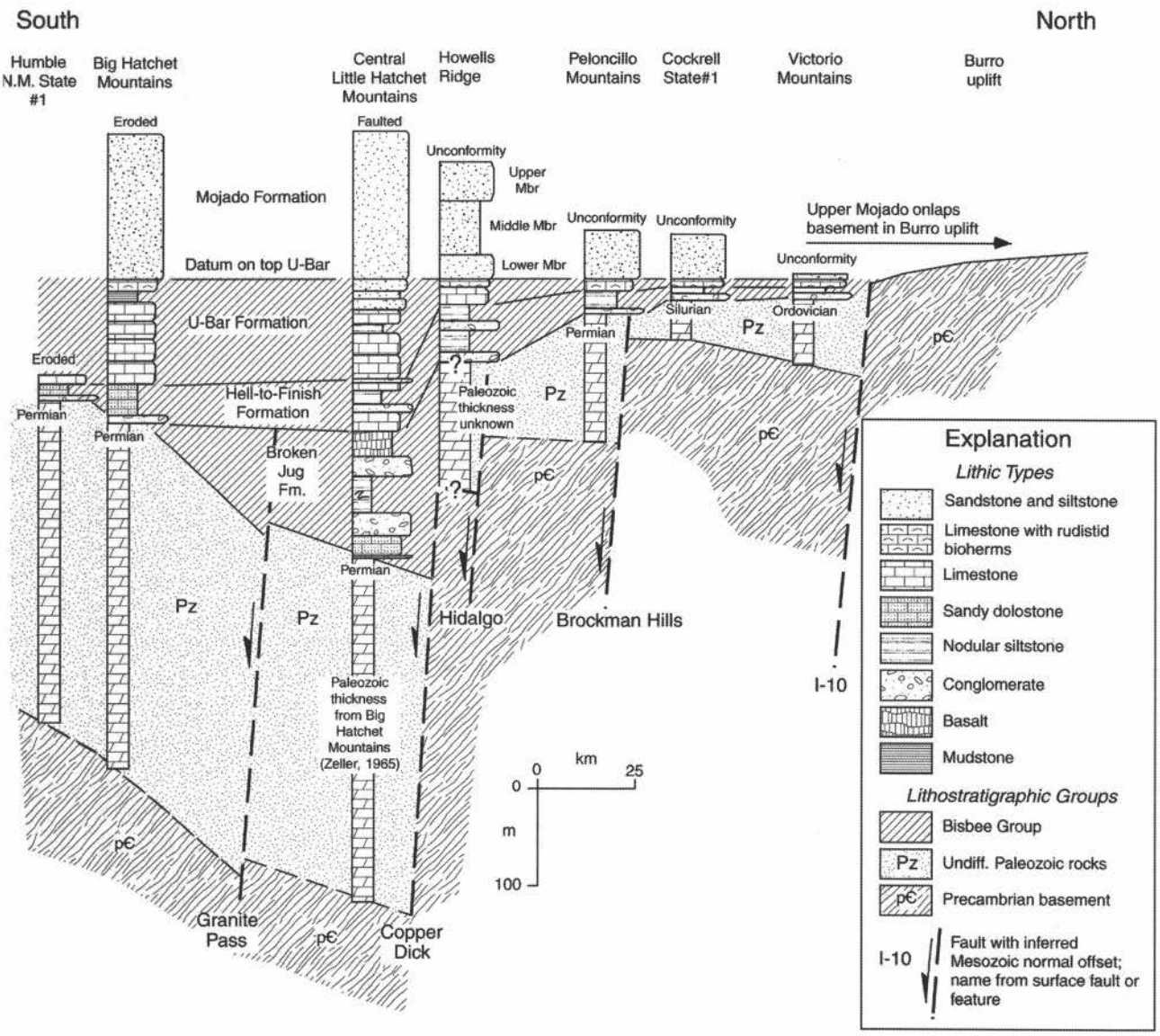


FIGURE 4. North–south restoration of Bisbee basin (at end of U-Bar deposition) from Big Hatchet Mountains to Burro uplift. Location of cross-section is shown in Figure 3. Paleozoic period names indicate Mesozoic subcrop at each location. Stratigraphic sections for Peloncillo Mountains and Cockrell State #1 well near Brockman Hills are projected from WNW as indicated in Figure 3. Thickness of Paleozoic section in Little Hatchet Mountains is from measured sections of Paleozoic strata in the Big Hatchet Mountains (Zeller, 1965)

reverse offset on some structures.

In most cases, extensional hanging-wall blocks were uplifted along Laramide structures and retained their identity as hanging-wall blocks (Fig. 1). An apparent exception, the Dos Cabezas uplift (Fig. 3a), was high during Jurassic extension as shown by basement detritus in Upper Jurassic sandstones (Olmstead, 1992). The footwall remained high when it was subsequently thrust southwest over Jurassic strata. Although Drewes (1982) interpreted thrusting of Paleozoic and Mesozoic strata northeast over Precambrian basement, mapped fault dips and sense of overturning of strata beneath the fault indicate southwest-vergent thrusting of Precambrian over the Phanerozoic section. Clasts and sandy detritus from this uplift are present in the Fort Crittenden Formation in the southern Chiricahua Mountains (Mann, 1995). In the case of the Dos Cabezas uplift, the Jurassic footwall became the Laramide hanging wall, probably as a result of left-lateral transpression (footwall uplift model of Figure 1d).

Truncation of pre-extensional stratigraphy is recorded as abrupt changes in the ages of units that lie unconformably beneath the Lower Cretaceous section. The Lower Cretaceous subcrop pattern records increasing truncation of strata northeastward from the region of the Big and Little Hatchet Mountains toward the Burro uplift in New Mexico (Fig. 3a). Changes in the amount of pre-Early Cretaceous erosion takes place at faults with Laramide reverse or oblique displacement. Important structures with demonstrated or inferred steps in the age of the youngest pre-extensional subcrop include the Gold Hill fault south of Bisbee, Arizona, the Apache Pass fault zone south of the Dos Cabezas uplift, the Copper Dick fault in the Little Hatchet Mountains, and the Brockman Hills fault (Fig. 3a, b). Other faults are inferred from distribution of Jurassic strata in the Chiricahua Mountains and in the Little Hatchet Mountains.

Jurassic–Lower Cretaceous structural trends generally strike northwest–southeast. The two Jurassic basins identified in Arizona and New Mexico appear to form an en echelon pattern (Fig. 3a). Jurassic corals have been reported from northern Chihuahua south of Deming, New Mexico (Reyeros de Castillo, 1974), but continuity of rocks in New Mexico with the Jurassic in Chihuahua has not yet been demonstrated. Correlative ages and Tethyan ammonites found in both the Chiricahua Mountains (Lawton and Olmstead, 1995) and the Chihuahua trough suggest a marine connection to the southeast.

Abrupt changes in thickness of the Jurassic and Cretaceous section

take place at Laramide structures that are interpreted as having earlier normal offset. These changes cause the syn-extensional section of the Bisbee basin to thin northward from the Big Hatchet Mountains to the Burro uplift (Fig. 4). The presence of Jurassic strata beneath Upper Cretaceous rocks south of the steep Copper Dick fault in the Little Hatchet Mountains indicates depth to basement was greater there than to the north, where Jurassic rocks are absent. Evidence regarding the position of the rift axis in the Big Hatchet Mountains is somewhat ambiguous: Cretaceous rocks overlie Permian strata in the southern part of the range, but the Mesozoic section thickens rapidly northward from the Humble State #1 well (Fig. 4). Jurassic strata may have once been present above the very thick and complete Paleozoic section in the northern part of the Big Hatchet Mountains. If so, they probably occupied a half-graben with a northern flank at what is now the Granite Pass fault (Fig. 4). Farther north, Lower Cretaceous strata are thin and rest on lower Paleozoic strata north of the Brockman Hills fault, but on upper Paleozoic strata south of the fault. Cenomanian strata of the Bisbee Group onlap Precambrian rocks of the Burro uplift and ultimately pinch out to the north.

Individual structures best display the detailed characteristics of inverted normal faults. Perhaps the most instructive example is the Gold Hill fault, exposed in the southern Mule Mountains south of Bisbee, Arizona (Figs. 3b, 5). This fault has features that demonstrate a Late Jurassic–Early Cretaceous extensional history and a post-Early Cretaceous, presumably Laramide, shortening history. Syndepositional extension is demonstrated by thickening of the Glance Conglomerate to the south across the fault (Bilodeau, 1979). The Glance Conglomerate consists of a lower limestone-clast petrofacies and upper schist-clast petrofacies that resulted from unroofing of the Paleozoic section to basement during deposition of the Glance Conglomerate (Bilodeau, 1979). The limestone-clast petrofacies is about 200 m thick on the footwall of the fault zone and 1800–2300 m thick on the hanging wall. Although the fault dominantly displays normal separation of units, other features of the fault zone indicate that reverse offset took place on the fault after the Early Cretaceous. These features include: (1) a footwall syncline in strata of the Bisbee Group beneath the fault; (2) horses of Paleozoic rocks in the fault zone that override younger strata of the footwall, creating local older-over-younger relationships; (3) erosion of the footwall Paleozoic section to a greater stratigraphic depth than the Paleozoic of the hanging wall prior to onlap by the Glance, resulting in an abrupt change in Lower Cretaceous subcrop across the fault. Along the strike of the fault, Pennsylvanian strata are thrust over Lower Cretaceous rocks. The exposed relationships indicate that the Gold Hill normal fault was not fully inverted during shortening. Reverse stratigraphic offset is present on the fault above the Lower Cretaceous unconformity, whereas offset is normal below the unconformity. The change in stratigraphic separation along the dip of the fault plane demonstrates the dual history of the fault.

A Laramide reverse fault with Early Cretaceous normal offset is also present in the Brockman Hills of southwestern New Mexico (Fig. 6). The Brockman Hills fault, drilled in 1985 on seismic data by Marshall Young Oil Company, has features to indicate that the main fault zone is an extensional structure of Late Jurassic or Early Cretaceous age subsequently reactivated by Laramide shortening. Important features include: (1) an abrupt change in the Lower Cretaceous subcrop at the fault, with Permian rocks present on the hanging wall and Silurian rocks on the footwall; (2) Paleozoic strata thrust over Eocene(?) synorogenic clastics of the Lobo Formation in the Klondike basin (Lawton and Clemons, 1992); (3) folding of hanging-wall and footwall strata indicated by the dipmeter log. The Brockman Hills fault zone is therefore a Paleogene structure, part of the Laramide broken foreland that formed on the northeastern flank of the former Bisbee basin.

DISCUSSION

The inversion-tectonic model for Late Cretaceous–Paleogene deformation in the Southwest predicts that most Laramide faults dip more steeply than 60° and penetrate basement. It also predicts that changes in Lower Cretaceous stratal thicknesses should take place across Laramide faults. A north–south cross-section of the Little Hatchet Mountains drawn using this model (Fig. 7) reveals some important characteristics of the deep structure. Subsurface information is scant from the range, but surface locations of structures such as the Copper Dick and Hidalgo faults are coincident with abrupt changes in thickness of both the Mesozoic and Paleozoic section at depth. The cross-section also indicates that, except near the south end of the range, basement was returned to a nearly regional level by inversion, whereas at the end of extension in the mid-Cretaceous, there was significant structural relief on basement (Fig. 4). The Granite Pass fault that emplaces basement over Paleozoic strata (Zeller, 1970), with a minimum of 4600 m of reverse stratigraphic offset, takes on particular significance to the possible geometry of the Bisbee basin. If the Granite Pass fault is a reactivated normal fault, then it probably formed the northern boundary of a Mesozoic half-graben prior to inversion (Fig. 4).

The inversion model is similar to the thick-skinned model of

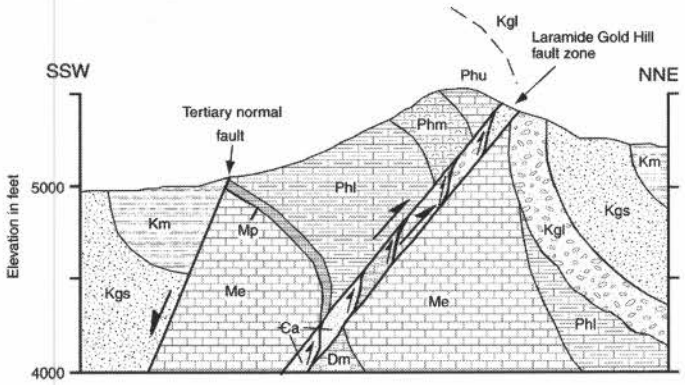


FIGURE 5. Geologic cross-section across Gold Hill fault, south of Bisbee, Arizona (Fig. 3). Although main hanging-wall block has normal offset in Paleozoic with respect to the footwall block, offset is reverse above sub-Cretaceous unconformity. Also displayed is deeper erosion of Paleozoic strata beneath Cretaceous unconformity of footwall as compared to hanging wall, and footwall syncline developed in Cretaceous strata. Explanation: Ca, Abrigo Formation; Dm, Martin Formation; Me, Escabrosa Limestone; Mp, Paradise Formation; Ph, Horquilla Limestone, divided into lower, middle and upper parts in hanging wall; Kgl and Kgs, limestone-clast petrofacies and schist-clast petrofacies, respectively, of Glance Conglomerate (after Bilodeau, 1979); Km, Morita Formation. Geology by T. F. Lawton, unpublished mapping, 1988.

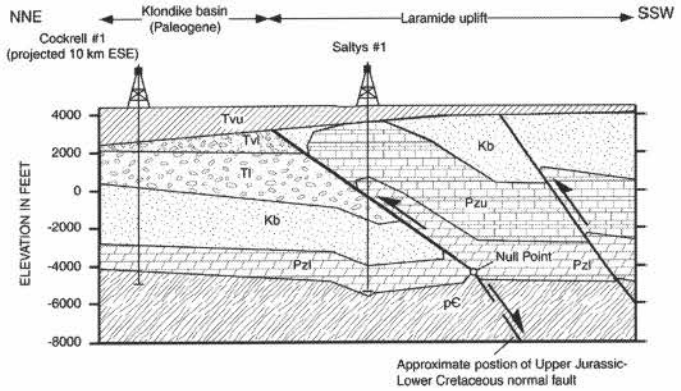


FIGURE 6. Brockman Hills structure, southeast of Lordsburg, New Mexico (Fig. 2). Devonian through Permian strata that are present beneath the Lower Cretaceous section are absent from the footwall, and Lower Cretaceous strata are thin on the footwall. Eocene Lobo Formation was deposited in Klondike intermontane basin adjacent to active structure (Lawton and Clemons, 1992). Syn-shortening deposits are geographically offset from the thick pre-extensional (Paleozoic) strata and from the thicker Lower Cretaceous section, as in the models of Figure 1. Explanation: pC, Precambrian crystalline rocks; Pzl, Cambrian through Silurian strata; Pzu, Devonian through Permian strata; Kb, Cretaceous Bisbee Group; Tl, Lobo Formation; Tvl, volcanic rocks of probable Eocene age; Tvu, volcanic rocks of Oligocene age.

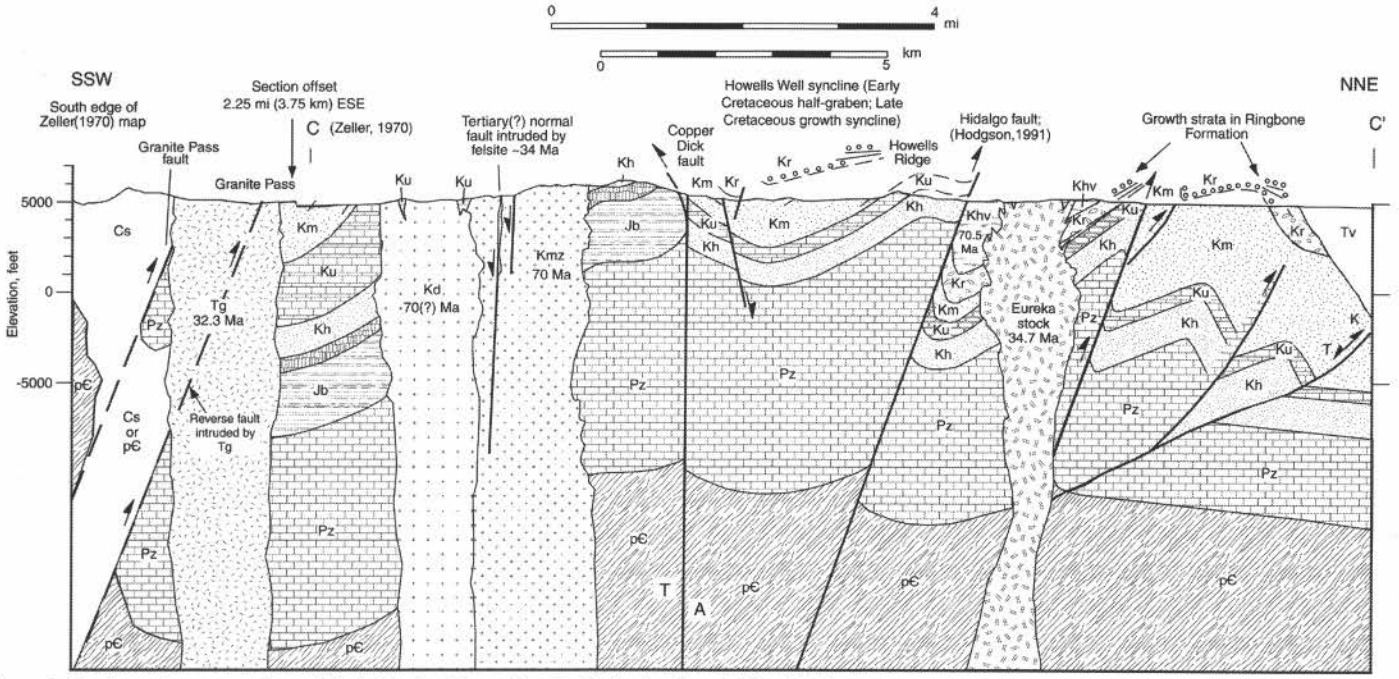


Figure 7. North–south cross-section of Little Hatchet Mountains. Geologic data from Zeller (1970), Lawton and Harrigan, (1998), Channell et al. (this volume), and Young et al. (this volume). Explanation: pC, Precambrian rocks; Cs, Cambrian syenite; Pz, undifferentiated Paleozoic strata; Jb, Broken Jug Formation, including basalt flows differentiated at top; Kh, Hell-to-Finish Formation; Ku, U-Bar Formation; Km, Mojado Formation; Kr, Ringbone Formation; Kd, diorite pluton; Kmz, monzonite pluton co-genetic with diorite; Khv, Hidalgo Formation; Tg, Tertiary granite; Tv, Oligocene ash-flow tuff.

Laramide deformation (Seager, 1983; Seager and Mack, 1986), but it does differ in its prediction that thick Paleozoic and Mesozoic sections might have once overlain basement blocks near the rift axis. This prediction in turn suggests that the amount of Laramide uplift south of the present Colorado Plateau may have been as significant as that along its western flank, where topography is inferred to have attained Altiplano-like heights (McQuarrie and Chase, 2000). At a given rate of surface denudation, shortening on steeply dipping faults has the potential to generate surface uplift more rapidly than is the case in thin-skinned settings. It is therefore possible that the southwestern Laramide province was a high-standing topographic region in the early Tertiary.

The inversion model also implies that locations and orientations of Laramide faults are closely linked to positions of older basement structures formed during subsidence of the Bisbee basin. Laramide structures may thus be poor indicators of the early Tertiary stress field, but they offer promise in prospecting for older faults and predicting important changes in subsurface stratal geometries. Beyond the extent of the Bisbee basin, where reactivation of older faults may be less important as a controlling factor of Laramide trends (e.g., Seager et al., 1997), Laramide faults may better indicate the Late Cretaceous–Paleogene stress field.

ACKNOWLEDGMENTS

Research support was provided in part by the New Mexico Bureau of Mines and Mineral Resources and NSF Grant EAR-9304759. Russ Clemons and Greg Mack introduced me to the geology of southwestern New Mexico. Reviews by Jeffrey Amato and William Seager improved the figures and text.

REFERENCES

Bally, A. W., 1984, Tectogenese et sismique reflection: Bulletin de la Société Géologique de France, v. 26, p. 279–286.

Basabilvazo, G. T., 1991, Stratigraphy, depositional environments, and sediment dispersal pathways of the Upper Cretaceous Ringbone Formation in the Little Hatchet Mountains of southwestern New Mexico [M.S. thesis]: Las Cruces, New Mexico State University, 158 p.

Bayona, G., 1998, Stratigraphic relationships of Cretaceous and Paleogene deposits, and their tectonic implications; central Peloncillo Mountains, Hidalgo County, New Mexico [M.S. thesis]: Las Cruces, New Mexico State University, 151 p.

Bilodeau, W. L., 1979, Early Cretaceous tectonics and deposition of the Glance Conglomerate, southeastern Arizona [Ph.D. dissertation]: Stanford, California, Stanford University, 145 p.

Bilodeau, W. L., 1982, Tectonic models for Early Cretaceous rifting in southeastern Arizona: Geology, v. 10, p. 46–470.

Bilodeau, W. L., 1984, Laramide sedimentation and tectonics in S.E. Arizona and S.W. New Mexico—reactivation of pre-Laramide basement structures: Geological Society of America, Abstracts with programs, v. 16, no. 6, p. 445.

Bilodeau, W. L. and Lindberg, F. A., 1983, Early Cretaceous tectonics and sedimentation in southern Arizona, southwestern New Mexico, and northern Sonora, Mexico; *in* Reynolds, M. W. and Dolly, E. D., eds., Mesozoic paleogeography of west-central United States: Society of Economic Paleontologists and Mineralogists, Rocky Mountain Section, Denver, Colorado, p. 173–188.

Brown, G. A. and Clemons, R. A., 1983, Florida Mountains section of southwest New Mexico overthrust belt—a reevaluation: New Mexico Geology, v. 5, p. 26–29.

Clemons, R. E., 1983, Geology of Gym Peak quadrangle, Luna County, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Geologic Map 58, scale 1:24,000.

Clemons, R. E., 1985, Geology of South Peak quadrangle, Luna County, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Geologic Map 59, scale 1:24,000.

Clemons, R. E. and Mack, G. H., 1988, Geology of southwestern New Mexico: New Mexico Geological Society, Guidebook 39, p. 45–57.

Corbitt, L. L. and Woodward, L. A., 1973, Tectonic framework of Cordilleran foldbelt in southwestern New Mexico: American Association of Petroleum Geologists Bulletin, v. 57, p. 2207–2216.

Davis, G. H., 1979, Laramide folding and faulting in southeastern Arizona: American Journal of Science, v. 279, p. 543–569.

Dickinson, W. R., Fiorillo, A. R., Hall, S. L., Monreal, R., Potochnik, A. R. and Swift, P. N., 1989, Cretaceous strata of southern Arizona; *in* Jenney, J. P. and Reynolds, S. J., eds., Geologic evolution of Arizona: Arizona Geological Society Digest, v. 17, p. 447–462.

Drewes, H., 1980, Tectonic map of southeast Arizona: U.S. Geological Survey, Miscellaneous Investigations Map I-1109, scale 1:125,000.

Drewes, H., 1982, Geologic map and sections of the Cochise Head quadrangle and adjacent areas, southeastern Arizona, U.S. Geological Survey, Miscellaneous Investigations Map I-1312, scale 1:24,000.

Drewes, H., 1988, Development of the foreland zone and adjacent terranes of the Cordilleran orogenic belt near the U.S.-Mexican border: Geological Society of

America, Memoir 171, p. 447–463.
Drewes, H., 1991, Description and development of the Cordilleran orogenic belt in the southwestern United States and northern Mexico: U.S. Geological Survey, Professional Paper 1512, 92 p.
Epis, R. C., 1952, Geology of the Pedregosa Mountains, Cochise County, Arizona [Ph.D. dissertation]: Berkeley, University of California, 255 p.
Hayes, M. J., 1987, Depositional history of Upper Cretaceous Fort Crittenden Formation in southeastern Arizona; *in* Dickinson, W. R. and Klute, M. A., eds., Mesozoic rocks of southern Arizona and adjacent areas: Arizona Geological Society Digest, v. 18, p. 315–325.
Hayward, A. B. and Graham, R. H., 1989, Some geometrical characteristics of inversion; *in* Cooper, M. A. and Williams, G. D., eds., Inversion tectonics: Geological Society, Special Publication 44, p. 17–39.
Hodgson, S. A., 1991, Geology and tectonics of the northern Little Hatchet Mountains, Grant and Hidalgo counties, southwestern New Mexico [M.S. thesis]: Las Cruces, New Mexico State University, 117 p.
Inman, K. F., 1987, Depositional environments and sandstone petrography of Cretaceous sedimentary rocks, Adobe Canyon, Santa Rita Mountains, southeastern Arizona; *in* Dickinson, W. R. and Klute, M. A., eds., Mesozoic rocks of southern Arizona and adjacent areas: Arizona Geological Society Digest, v. 18, p. 301–314.
Klute, M. A., 1991, Sedimentology, sandstone petrofacies, and tectonic setting of the late Mesozoic Bisbee basin, southeastern Arizona [Ph.D. dissertation]: Tucson, University of Arizona, 268 p.
Lawton, T. F., 1996, Laramide inversion of Late Jurassic–Early Cretaceous extensional faults, SE Arizona and SW New Mexico: Geological Society of America, Abstracts with programs, v. 28, no. 6, p. 509–510.
Lawton, T. F. and Clemons, R. C., 1992, Klondike basin-late Laramide depocenter in southern New Mexico: New Mexico Geology, v. 14, p. 1–7.
Lawton, T. F. and Harrigan, P. J., 1998, Broken Jug Formation-redefinition of lower part of Bisbee Group, Little Hatchet Mountains, Hidalgo County, New Mexico: New Mexico Geology, v. 20, p. 69–77.
Lawton, T. F. and Olmstead, G. A., 1995, Stratigraphy and structure of the lower part of the Bisbee Group, northeastern Chiricahua Mountains, Arizona: Geological Society of America, Special Paper 301, p. 21–39.
Lawton, T. F., Basabilvazo, G. T., Hodgson, S. A., Wilson, D. A., Mack, G. H., McIntosh, W. C., Lucas, S. G. and Kietzke, K. K., 1993, Laramide stratigraphy of the Little Hatchet Mountains, southwestern New Mexico: New Mexico Geology, v. 15, p. 9–18.
Lucas, S. G., 1992, Eocene mammal from the Bobcat Hill Conglomerate, Peloncillo Mountains, southwestern New Mexico: New Mexico Geology, v. 14, p. 9–12.
Lucas, S. G. and Estep, J. W., 1998, Lithostratigraphy and biostratigraphy of the Lower-middle Cretaceous Bisbee Group, southwestern New Mexico, USA; *in* Lucas, S. G., Kirkland, J. I. and Estep, J. W., eds., Lower and middle Cretaceous terrestrial ecosystems: Albuquerque, New Mexico Museaum of Natural History and Science, Bulletin 14, p. 39–55.
Mack, G. H., Kolins, W. B. and Galemore, J. A., 1986, Lower Cretaceous stratigraphy, depositional environments, and sediment dispersal in southwestern New Mexico: American Journal of Science, v. 286, p. 309–331.
Mann, J. D., 1995, Stratigraphy, petrology, and depositional environments of the Upper Cretaceous Rucker Formation, southeastern Arizona [M.S. thesis]: Las Cruces, New Mexico State University, 114 p.
McQuarrie, N. and Chase, C. G., 2000, Raising the Colorado Plateau: Geology, v. 28, p. 91–94.
Olmstead, G.A., 1992, Depositional environments, lithofacies, and petrology of Lower Cretaceous (lower to middle Albian) and Tertiary (Rupelian) strata within the northeastern Chiricahua Mountains, southeastern Arizona [M.S. thesis]: Las Cruces, New Mexico State University, 101 p.
Olmstead, G. A., 1998, A palynological analysis of Upper Jurassic dinoflagellate cysts from the Chihuahua trough and Bisbee basin, northern Mexico and southeastern Arizona [Ph.D. dissertation]: El Paso, The University of Texas, 211 p.
Reyeros de Castillo, M. M., 1974, Corales del jurásico superior de Chihuahua: Universidad Nacional Autónoma de México, Instituto de Geología, Paleontología Mexicana, Número 40, p. 7–43.
Seager, W.R., 1983, Laramide wrench faults, basement-cored uplifts, and complementary basins in southern New Mexico: New Mexico Geology, v. 5, p. 69–76.
Seager, W. R. and Mack, G. H., 1986, Laramide paleotectonics of southern New Mexico: American Association of Petroleum Geologists, Memoir 41, p. 669–685.
Seager, W. R. and Mack, G. H., 1990, Eagle Nest-Granite Hill area, Luna County, New Mexico—a new look at some old rocks: New Mexico Geology, v. 12, p. 1–7.
Seager, W. R., Mack, G. H. and Lawton, T. F., 1997, Structural kinematics and depositional history of a Laramide uplift-basin pair in southern New Mexico—implications for development of intraforeland basins: Geological Society of American Bulletin, v. 109, p. 1389–1401.
Sibson, R., 1995, Selective fault reactivation during basin inversion: potential for fluid redistribution through fault-valve action; *in* Buchanan, J. and Buchanan, P., eds., Basin inversion: Geological Society, Special Publication 88, p. 3–19.
Thorman, C. T. and Drewes, H., 1980, Geologic map of the Victorio Mountains, Luna County, southwestern New Mexico: U.S. Geological Survey, Map MF-1175, scale 1:24,000.
Williams, G. D., Powell, C. M. and Cooper, M. A., 1989, Geometry and kinematics of inversion tectonics; *in* Cooper, M. A. and Williams, G. D., eds., Inversion tectonics: Geological Society, Special Publication 14, p. 3–15.
Wilson, D. A., 1991, Depositional environments, provenance, and age of the Skunk Ranch Formation, Little Hatchet Mountains, southwestern New Mexico [M.S. thesis]: Las Cruces, New Mexico State University, 87 p.
Zeller, R. A., Jr., 1965, Stratigraphy of the Big Hatchet Mountains area, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Memoir 16, 128 p.
Zeller, R. A., Jr., 1970, Geology of Little Hatchet Mountains, Hidalgo and Grant Counties, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Bulletin 96, 26 p.