Geology of the Solitario, Trans-Pecos Texas (Geological Society of America Special Paper 250): Discussion and reply

Discussion

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INTRODUCTION

The Solitario, a mid-Tertiary laccolithic dome in Trans-Pecos Texas, is a fascinating geologic feature that combines a complex history of laccolithic uplift and caldera collapse. Doming has exposed a complete section of Lower Cretaceous rocks as well as the southwesternmost segment of the Ouachita foldbelt in the United States (Henry and others, 1991). An accurate geologic map, thorough description of the geology, and well-substantiated interpretation are necessary to demonstrate these features. Unfortunately, GSA Special Paper 250 (Corry and others, 1990) provided none of these. Problems with Special Paper 250 fall into three categories: (1) inadequate description of the geology, (2) demonstrable errors in the geologic map and cross section, and (3) unsubstantiated and commonly contradictory interpretations of the geology and evolution. We provide a few examples of each and suggest that interested geologists examine the map while considering this discussion.

INADEQUATE DESCRIPTION

The complex geology of the Solitario requires thorough description, integrating map, cross sections, and text. Only the stratigraphic descriptions of the Paleozoic and Cretaceous rocks are complete and were extracted from Herrin's (1958) dissertation. The map should show abundant strikes and dips and should be accompanied by several cross sections, because the geometry of the rocks is critical to understanding the multiple episodes of deformation in the Solitario. Not only are the map and cross section inaccurate, but only one section is provided. Even if this section were accurate, it would depict at most only a few aspects of the dome. Sections to illustrate the dome and caldera more thoroughly and to illustrate structures in the Paleozoic rocks are needed.

Corry and others make several unsubstantiated claims about mechanisms and geometry of doming. The text mostly discusses their model of doming but provides little description of the geometry of the dome to evaluate the model. The map has few strike and dip measurements, particularly in the Cretaceous rim, and many of them are photointerpretations with no dip value. For example, only one measured strike and dip is shown in the rim within 1 km of the line of cross section.

DEMONSTRABLE ERRORS IN THE MAP AND CROSS SECTION

Geologic Map

Inspection of the geologic map reveals numerous errors. The map routinely violates the "rule of v's." As is evident on the cover photo and shown by a few strikes and dips on the map, Cretaceous rocks forming the rim of the Solitario dip 15° to 55° radially outward. In numerous locations, however, the map pattern depicts these rocks as inward dipping. Notable examples are the Shutup Conglomerate on hill 4822 1 km south of the Lefthand Shutup, and the Telephone Canyon Formation around hill 5001 near the eastern border; both cases would require overturned beds. Contacts between the Maravillas, Caballos, and Tesnus Formations in the canyon southwest of hill 4825 in the Righthand Shutup Folded Area dip 40° to 50° to the south. The map pattern indicates an abrupt reversal of dip to the north that does not exist. Mapped contacts between Cretaceous Santa Elena, Del Rio, Buda, and Boquillas, and Tertiary Chisos Formations in the southwestern part of the map either strike straight across areas of significant relief or "v" upstream. The former indicates vertical beds; the latter indicates that beds dip either to the northeast or to the

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southwest but less steeply than topography. In fact, they dip between 20° and 55° southwest.

Numerous faults have the opposite offset from what is shown on the map. For example, the odd, rectangular fault system of the "collapsed block" in the Lower Shutup is portrayed as displacing Del Carmen Limestone *down against the younger* Santa Elena Limestone. Along another fault in the western rim south of the Righthand Shutup Folded Area, Paleozoic Tesnus Formation is shown downfaulted against Cretaceous Yucca Formation and sills within the Yucca. A west-northwest–striking fault in the northwest rim, bounding another "collapsed block," is a third example. Again, older units are down against younger units. Cretaceous rocks in the rim have undergone only outward tilting during doming; they were largely flat lying before doming, and so relationships depicted in each of these examples are impossible. Furthermore, the rectangular fault systems and right-angle bends in faults of the first two examples appear extremely unlikely.

Errors are also common in portrayal of the complexly folded Paleozoic rocks. Depicted relations around Eagle Mountain in the southeastern part of the Solitario are especially intriguing. On the north side of Eagle Mountain, the Caballos Novaculite is shown as pinching out, leaving Tesnus and Maravillas Formations in direct stratigraphic contact, a relationship found nowhere else in Trans-Pecos Texas. On the southwest side, a wedge of Caballos Novaculite continues straight across a fault, apparently without displacement, although the fault offsets all other units.

Cross Section

The single cross section also embodies numerous errors. Possibly the most critical are shown by the interpreted circumferential and radial hinges; the existence and geometry of these are integral parts of the authors' model of doming. First, the hinges as depicted create irresolvable space problems. This is most apparent for the northwesternmost hinge. Attempting to "unhinge" the beds across this structure requires either a void at the top or overlap at the bottom. Second, the first and third hinges from the southeast end of the section apparently had no effect on the rocks, which are neither displaced nor rotated. Third, several hinges shown on the cross section are not shown on the map. Although the authors stated that hinge locations are uncertain, they apparently considered them sufficiently located to depict on the cross section but not on the map. Fourth, the cross section depicts the second (radial) hinge from the northwestern end as being down on the south, whereas the map depicts it down on the north. Finally, although the cross section shows circumferential hinges uniformly dipping inward, the one hinge depicted in the text (Fig. 41) appears to dip outward.

The depiction of the Collapsed Central Block is particularly misleading. This central graben was noted by all previous workers (Powers, 1921; Sellards and others, 1933; Lonsdale, 1940; Wilson, 1954; Herrin, 1958). Corry and others, however, limited it to the northern part and claimed that it is circular (see their Figs. 6 and 40 and discussion on page 84). They show a "probable caldera" at the south end, which they apparently consider unrelated. In fact, the entire 6 × 2 km graben, not simply the southern end, is a caldera that was probably produced by a combination of extension during doming and pyroclastic eruption of the underlying laccolith (Henry and others, 1991). Corry and others had not recognized the existence of a caldera in the Solitario until we pointed it out during field review in 1988, even though Lonsdale had suggested "cauldron-like subsidence" in 1940. Ash-flow tuff ponded within the caldera, although most of their "Needle Peak Tuff" consists of collapse breccia derived from the caldera walls.

Their cross section also shows Paleozoic and Cretaceous rocks at the north end of the caldera truncated across the top of the laccolithic magma body. Because these simply subsided into the magma chamber during caldera collapse, they must continue in the subsurface to its southern end, below the words "probable caldera" on their cross section.

A final example from the cross section involves the Solitario thrust north of the collapsed central block. The authors show an overturned anticline in the underlying plate continuing into the air *across* the thrust, as if the thrust were not there. Additionally, the cross section in this area depicts an anticlinal axis southeast of the thrust and Marathon Formation cropping out adjacent to the thrust. Neither appears on the map, which shows Dagger Flat Sandstone adjacent to the thrust. Attitudes within 100 m of the thrust show beds steeply overturned to the northwest, which would be the southeastern limb of the anticline. In fact, the map shows no evidence of this anticline, and we doubt that it exists.

Field Relations

Other errors in the geologic map and section require field inspection for complete assessment. Nevertheless, we point out several of the greatest here. The large area of Buda Limestone outcrop at the southern border is really Santa Elena Limestone. The Buda Limestone and Del Rio Clay continue as narrow bands south through hill 3390; therefore, the Santa Elena–Del Rio–Buda contacts are mislocated by ~2 km. The depicted contacts also "v" the wrong way.

Corry and others show Del Carmen Limestone to be the youngest Cretaceous unit within the Collapsed Central Block; however, the overlying Sue Peaks Formation, Santa Elena Limestone, Del Rio Clay, Buda Limestone, and Boquillas Formation are also present. Indeed, Santa Elena Limestone makes up most of the Cretaceous outcrop within the block.

Caballos Novaculite is shown cropping out within the core of the southern continuation of the Tres Papalotes syncline. In fact, Tesnus Formation crops out there; Caballos dives beneath the land surface from both limbs.

For an area of such structural complexity, thorough discussion of the structures is needed. The only extensive structural discussion, however, concerns a Quaternary landslide, the Shelter thrust, for which the map pattern does not correspond to the text figures. Although the map indicates relative ages of faults, no basis for the age assignments is given, and the text provides almost no description of the faults. For example, a northwest-striking fault that forms the southwestern boundary of the Northern Folded Area is shown as a late Paleozoic fault where it cuts Paleozoic rocks and as an Eocene fault where it cuts Cretaceous and Tertiary rocks.

Because of doming by the laccolith, the structure of Paleozoic rocks can be viewed radially by the down-structure viewing method. In the Righthand Shutup Folded Area, the Maravillas-Caballos couplet can then be seen to display a broad, open syncline overthrust by a folded sequence of the same beds. As depicted by Corry and others, the Righthand Shutup Folded Area consists of three parallel synclines without intervening anticlines or other structures. Fort Peña Formation is shown in the central syncline (actually an anticline), although no such outcrop exists.

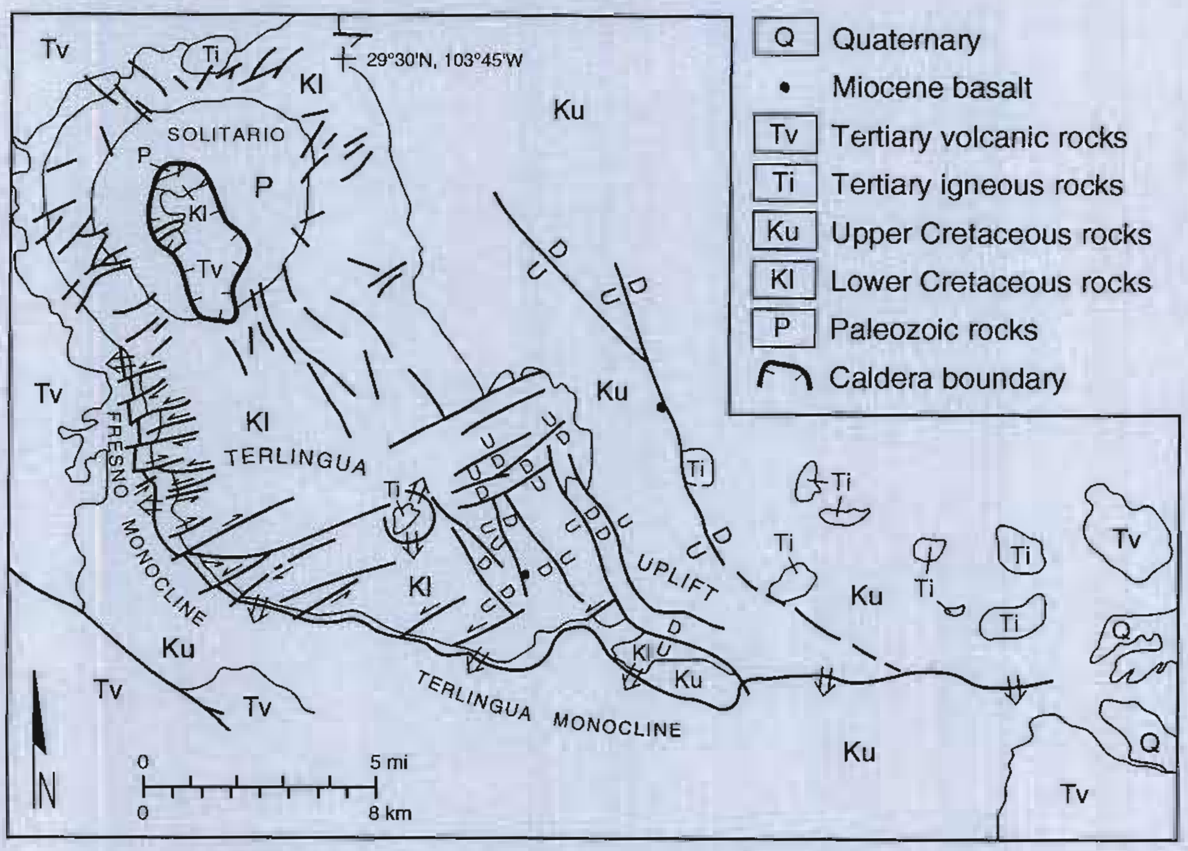

Figure 1. Simplified geologic map of the Solitario and Terlingua uplift.

The Northern Folded Area exhibits a similar structure, although the hanging wall has been broken into several imbricate slices. The structures along the east side, south from Tres Papalotes, resemble the imbricate structures exposed along the southern edge of the Dagger Flat anticlinorium in the Marathon Basin (King, 1937; Muehlberger and others, 1984). Thus, we interpret the entire Solitario Paleozoic outcrop area to be the southwestern counterpart of the Dagger Flat anticlinorium and the adjacent edge of the imbricate structures of the Southern Domain (Muehlberger and Tauvers, 1989).

Finally, the igneous geology of the Solitario is grossly oversimplified. Corry and others depict the "rim sill" as a single, continuous body. Instead, the "rim sill" consists of three major petrographic types (porphyritic rhyolite, aphyric rhyolite, and porphyritic trachyte) emplaced at many stratigraphic horizons in the Lower Cretaceous rocks. The Needle Peak Tuff as mapped is mostly nontuffaceous caldera-collapse debris deposits. Ash-flow tuff related to caldera collapse crops out at the southern end of the block, below debris deposits, and occurs as clasts within them.

UNSUBSTANTIATED INTERPRETATION

Geometry and Mechanism of Doming

The Solitario is a laccolithic dome, a point recognized by the earliest workers (Powers, 1921; Lonsdale, 1940). The geometry and mechanism of doming by rigid-block rotation along circumferential and radial hinges proposed by Corry and others, however, are not substantiated by field data. By their model, hinges separate blocks of constant strike and dip. Although never clearly stated, it is implied that blocks undergo little if any internal deformation. Specifically, they are not folded. These relationships should be best illustrated by the Cretaceous rocks of the rim, which were mostly flat lying before doming.

Our mapping (C. D. Henry and W. R. Muehlberger, unpub. data) shows substantially different relations. First, as noted above, the mapped hinges as depicted by Corry and others have impossible geometric problems. Second, as mapped by us, "radial" faults in the rim related to doming largely do not match the location or style of deformation of the radial hinges mapped by Corry and others. The faults mapped by us strike dominantly east-northeast and northwest, regardless of their location around the Solitario rim (Figs. 1 and 2; Henry and others, 1991). Thus, many are oblique to the rim. The east-northeast faults are probably Laramide strike-slip faults reactivated during doming; such faults are common south of the Solitario along the Terlingua uplift (Figs. 1 and 2; Erdlac, 1990). Finally, although a few radial and circumferential hinges are present, their geometry and abundance are not at all similar to those shown by the authors. Attitudes in the Cretaceous rocks mostly change gradually around and across the rim. Circumferential hinges of the Solitario are much like those recognized in laccoliths of the Henry Mountains, Utah (Jackson and Pollard, 1988); that is, they are folds in which attitude changes smoothly across fold axes, not abruptly across zones of rigid-block rotation as interpreted by Corry and others. This fold geometry suggests that the abundant marl beds within the Cretaceous

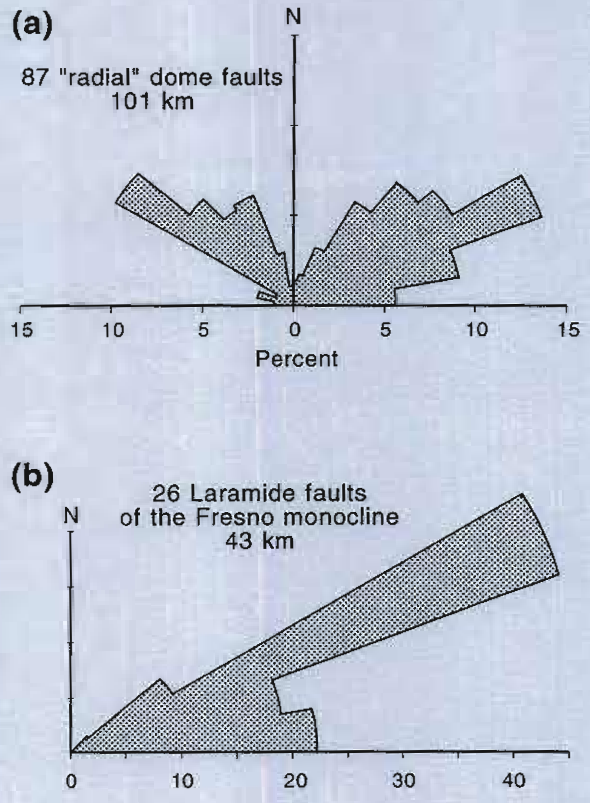

Figure 2. Rose diagram of orientation and length of faults: (a) in the rim of the Solitario; (b) in the Fresno monocline.

section allowed bedding-plane slip. The authors implied (p. 84) that their model is similar to that of Jackson and Pollard; in fact, the two are markedly different.

The authors interpreted a flat roof to the laccolith/dome. Although a nearly flat roof is possible, the evidence they cite for it does not exist. The authors claimed (p. 83) that the lowermost Cretaceous rocks flatten abruptly inward, from about 40° to 10°, adjacent to the Righthand Shutup Folded Area along a circumferential hinge (the missing hinge zone of the cross section). Our thorough field examination showed that Cretaceous rocks at this location maintain steep dips. Furthermore, in a discussion of Ouachita structures (pages 73–74 and their Fig. 33), the authors cited and used the calculations of Bagstad (1981). They failed to mention, however, that Bagstad assumed that the steep dips of the rim continue inward nearly to the central collapsed block. It is not clear that Corry and others recognize this contradiction. The authors make many subsidiary interpretations regarding the laccolith's volume and depth of emplacement based upon an assumed flat roof. Because the basic assumption is suspect, all of these interpretations are suspect. We conclude that their map depicts a geological model, not necessarily what is there.

Geophysical Interpretation

Interpretation of the geophysical maps perpetuates some of the problems in interpretation of Solitario geometry. First, two positive anomalies shown on the gravity map (their Pl. 2) are based on insufficient data. One in the south-central part of the map is based on a single data point; the nearest adjacent point is more than 10 km away. The southern margin of the broad positive anomaly (−110 mGal solid contour) at the south end of the Terlingua uplift on Plate 2 is defined largely on the basis of one point. The authors associate this anomaly with mercury mineralization in the Terlingua district and speculate on extension of the district on the basis of the anomaly. The poor definition of the anomaly makes this speculation inappropriate.

The most important conclusions that the authors make from the gravity data are that the Solitario lacks an identifiable gravity anomaly and that this lack indicates that the intrusion that caused doming has no density contrast with its host rocks (p. 61). Yet each of their profiles on Plate 2 shows a distinct positive anomaly over the Solitario. The amplitude (>6 mGal) and wavelength (>12 km) are those expected from the laccolith by the authors' own calculations. They argued further that measured densities of Paleozoic and Cretaceous rocks are indistinguishable from those of igneous rocks that they interpret to be the exposed top of the laccolith. Measurements of the latter, however, are almost entirely on a shallow and hydrothermally altered intrusion that must be well above the laccolith. Measured densities of this rock range from 2,000 to 2,800 kg/m^3. We conclude that emplacement of the laccolith at the level of zero density contrast is possible but not demonstrated by their data.

Similarly, the authors stated that the positive magnetic anomalies shown in Plate 4 are unrelated to the Solitario laccolith (p. 66); they attributed the anomalies to younger, buried mafic intrusions. As with the gravity data, they supported this interpretation with data on magnetic susceptibility of igneous rocks within the Solitario (Table 17). Hydrothermal alteration, however, destroyed most mafic minerals in the exposed igneous rocks; application of these data to the buried laccolith is doubtful. We suggest that the magnetic data correlate well with the known geology of the Solitario and are best interpreted as reflecting the laccolith. The low-level aeromagnetic map shows a high outside but clearly outlining the Collapsed Central Block (that is, the caldera). The caldera is a magnetic low, except at the south end where a high overlies exposed ash-flow tuff, the eruptive product of the laccolith. These relationships are consistent with a magnetic high above the remaining thick part of the laccolith outside the caldera and a relative low within the caldera where the underlying laccolith must be thinner by the amount of subsidence.

Early Erosion of the Solitario

Corry and others asserted that the dome eroded nearly to its present level almost immediately after formation, that the present-day surface mimics that formed in the Eocene, and that the eroded material was transported outward through a few narrow canyons (shutups) that are almost identical to those that exist today (p. 13 and 97). They made these assertions apparently because they did not recognize the caldera or understand its significance. They thought that deposition of "Needle Peak Tuff" on Paleozoic rocks within the dome required removal by erosion of most of the interior of the dome, including much of the Paleozoic section. In fact, the debris deposits that actually make up "Needle Peak Tuff" were deposited within the caldera or against its eroded wall. This erosion was clearly *into* the caldera.

Of course, erosion of the dome and outward transport of debris did begin as soon as it was uplifted. Although not recognized by Corry and others, conglomerates interbedded with Tertiary volcanic rocks outside the dome record this erosion. For example, an ~50-m-thick section of conglomerate immediately west of the Solitario contains clasts as much as 1.5 m in diameter, indicating a nearby source. Clasts near the base consist exclusively of igneous rocks, mostly lavas that partly covered the Solitario before doming. Upward, clasts of Cretaceous rocks appear and become progressively more abundant. At the top of the conglomerate, clasts are more than 90% Cretaceous rock. Yet no Paleozoic clasts are present. This pattern indicates progressive unroofing of the Solitario; lavas that covered the Solitario were stripped initially, followed by the Cretaceous section. Erosion during this period, however, did not uncover the Paleozoic rocks.

Terlingua Uplift

The Terlingua uplift, an area of uplifted Lower Cretaceous Santa Elena Limestone, lies southeast of, and continuous with, the Solitario (Fig. 1). Corry and others attributed the uplift to doming that postdates the Solitario. They based their interpretation predominantly on incorrect depiction of uplift geometry and an incomprehensible discussion of its time of origin. In contrast, our work and that of Erdlac (1990) demonstrated that the Terlingua uplift resulted from Laramide shortening; that doming of the Solitario postdates, and is superposed upon, the uplift; and that abundant evidence of Laramide shortening preceding doming is present within the Solitario.

The Terlingua uplift is bounded on the south and west by the steep (south to southwest dips up to 75°) Terlingua and Fresno monoclines (Fig. 1). Cretaceous rocks are flat lying on top of the uplift and dip gently northeast off its northeast flank; however, there is no clearcut northeastern margin. Although they provide no map view, the authors interpret an eastern end of the Terlingua monocline ~15 km southeast of the Solitario; this would define a parallelogram-shaped uplift of 15 by 12 km. In fact, the monocline is clearly traceable eastward another 18 km where it disappears beneath Quaternary deposits on the west side of Big Bend National Park (Fig. 1). The true dimensions of ~30 km by 12 km indicate a large, elongate body consistent with formation by horizontal shortening.

Faults and stylolites provide more definitive evidence of a Laramide origin. Two sets of nearly orthogonal faults, east-northeast and northwest, are present across the uplift (Fig. 1). Corry and others, assuming that all faults were normal and contemporaneous, evidently thought that the two sets required laccolithic uplift. Only the northwest faults, however, are predominantly normal; bedding offset and slickenlines show that most of the east-northeast faults are strike-slip. Measurement of several hundred stylolites across the uplift indicates a maximum principal stress ($\sigma 1$) oriented N61°E, indistinguishable from that of Laramide folding elsewhere in the Big Bend region and throughout the southwestern United States (Erdlac, 1990). Stylolites indicate that $\sigma 1$ curved to about N38°E across the Terlingua monocline, that is, into a position more nearly perpendicular to it. Both the east-northeast strike-slip faults and tectonic stylolites require horizontal shortening. The curvature of stress trajectories into the monocline indicates influence by the monocline on stylolite formation and thus their mutual formation during Laramide tectonism.

Northwest faults generally terminate against east-northeast faults, which suggests that the former are younger. Distinctive Miocene alkali basalts, related to Basin and Range extension, are present along two northwest faults within the uplift (Fig. 1). Thus the northwest faults were active and probably formed during Basin and Range extension long after Laramide folding, formation of the Terlingua uplift, and formation of the east-northeast faults.

The Solitario is superposed on the northwestern end of the Terlingua uplift. The Fresno monocline strikes into, and merges with, the southwestern limb of the Solitario (Fig. 1), which is evident on the cover photograph of Special Paper 250. The southwestern limb is steeper (up to 55°) than all other sides (maximum about 40°). The "radial" fault system consists of two dominant trends, east-northeast and northwest (Figs. 1 and 2). East-northeast faults are commonly oblique to the dome and display bedding-parallel slickenlines, which is inconsistent with their forming in homogeneous rocks purely as a result of extension during doming. We attribute these features to superposition of doming upon the Laramide monocline. The monocline faces southwestward and was cut by east-northeast strike-slip faults during Laramide folding. Many such faults were reactivated during doming. Tectonic stylolites, *en echelon* fractures, and conjugate shears, displaying both simple and pure shear, are common in Lower Cretaceous rocks in the rim of the Solitario. When tilting of the rim is removed, these features indicate N60°E shortening.

Corry and others argued that the Terlingua uplift formed after the Solitario (p. 91–95). We find this argument to be contradictory and nearly incomprehensible. They also stated (p. 76) that the Solitario rests on a block that was "uplifted, rotated, and deformed in broad, low-amplitude folds during the Laramide orogeny." This statement alone seems to contradict their arguments against Laramide origin. They further stated, however, that "the Solitario dome is located on or near the crest of one of those folds," citing Baker (1934). They failed to mention that this broad anticline, which they stated is of Laramide origin, is the Terlingua uplift.

CONCLUSIONS

Parts of Special Paper 250 are valuable, such as those on geochemistry and geochronology by McDowell and on economic geology by Phillips. The dissertation map and study of Herrin (1958) were excellent, particularly given the lack of concepts in caldera evolution and of an accurate topographic base at the time. Herrin's stratigraphic data for the Paleozoic and Cretaceous sections are the most informative parts of the text. Unfortunately, major modifications of the map and report by Corry have been nearly uniformly in the wrong direction. Our disagreement is largely with the interpretations of the first author.

Clearly, some points that we make are matters of interpretation that can be evaluated only in the field. Our own work is published only in abstract at this time, although our detailed mapping is complete and being prepared for publication. Meanwhile, we make a standing offer to all geologists to visit the Solitario with us and to examine the geology.

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Reply

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INADEQUATE DESCRIPT ION

We have been accumulating geologic, geophysical, geochronologic, and geochemical data in the Solitario over nearly three decades, and the data from our work are presented in 18 tables, 48 figures, 8 appendices, and 4 maps, as well as 97 pages of text. Where data were available, we presented maps and figures at different map scales and time periods, or in the case of the magnetic data, at different flight elevations. The effects of three orogenies and two extensional events are documented. Sample locations are described and given in appendices. Known fossils are tabulated and localities plotted. Various hypotheses are examined and methods described in detail.

In addition to complete stratigraphic descriptions of seven Paleozoic and nine Cretaceous formations, the Tertiary Buck Hill Group includes six formations. We mapped 14 rock types in the Solitario Igneous Suite, and the map scale does not readily lend itself to more detail. A total of 45 rock units are shown in Plate 1. A casual comparison of Herrin's (1957) dissertation and Special Paper 250 will reveal substantial differences in the Paleozoic and Cretaceous stratigraphy presented as our ideas evolved.

Available information, including drilling, the thin plate of Paleozoic rocks at the base of the collapsed central block (Pl. 1), and abundant dike swarms, indicates that the Paleozoic section found in the central basin is only a thin veneer (<500 m thick) over the roof of the laccolith. The structural basis for our estimate is shown in Figure 38 (p. 82). Due to the northeast strike of the Ouachita deformation, cross sections showing the Paleozoic rocks are best done perpendicular to that direction. Inasmuch as the dome is radially symmetric, it is sufficient to show one cross section through the center in a northwest-southeast direction to present the dome in the detail we have data to support.

Mechanisms and geometry of laccolithic domes are discussed at length in Corry (1988), and additional elaborate discussion was not believed to be necessary in Special Paper 250.

Despite the volume of data presented in Special Paper 250, we readily acknowledge that a great deal of work remains to be done, and that in many cases we had to either simplify or present a reconnaissance of many of the problems encountered due to resource and time limitations.

DEMONSTRABLE ERRORS IN THE MAP AND CROSS SECTION

Geologic Map

Herrin did his mapping in the early 1950s, using a plane table to map the Paleozoic rocks in the central basin, and a small-scale black and white air photo to map the Cretaceous rim (Herrin, 1957). I did most of my field mapping in the summer of 1971, using ~1:30,000 black-and-white air photos. Not until the spring of 1972 did a preliminary 1:24,000 topographic map become available on which the map presented in Corry (1972) was based. Phillips did most of his field mapping in late 1971 and early 1972 on the central igneous complex, and the end result, combined with a great deal of additional work by AMAX geologists, was shown in Figure 14 (p. 41). Low-level color air photos at an approximate scale of 1:6,000 covering the central basin and parts of the rim were made available in 1977, and these were extensively used in preparing the geologic map (Pl. 2). A small area of folded Paleozoic rocks in the eastern central basin was remapped in the field during 1985 by Herrin. The mapping of the Buck Hill Group in and to the west of Fresno Canyon is based largely on McKnight (1970). For the errors and mistakes resulting from this process, and no doubt there are many, we plead *mea culpa*.

Without attempting to defend the V direction at every stream crossing on the map, often where we did not know the dip of the beds, I nonetheless have major disagreements with the Discussion of Henry and others. Many of the errors claimed by Henry and others in the present Discussion are new to us, and all of the authors included in their Discussion were reviewers of the map. That poses an interesting question in ethics as to whether these errors should have been pointed out during the review; and whether a table of errata might now serve science better.

Henry and others were not remiss as reviewers concerning the faulting associated with the collapsed block in the Lower Shutup. Checking back shows that the map sent them for review has the older Del Carmen Limestone *up* against younger Santa Elena Limestone, as it should be. Between the review and final drafting of the map, however, the U and D symbols for these faults were reversed. Similarly, in the Righthand Shutup folded area, the center of the three synclines (the one cut by FL-16) was mapped as an anticline plunging

20°SW, but it was drafted as a syncline with no plunge angle. The Fort Peña Formation also should have been drafted in this area with dashed contacts. No doubt other drafting errors can be found.

Henry and others comment that the Cretaceous rocks in the rim have "undergone only outward tilting during doming" is patently false and is contradicted by their own statements in their section on Geometry and Mechanism of Doming where they recognize "considerable bedding plane slip." In addition, as we pointed out on p. 86, the blocks have also been translated outboard as well as rotated. Note also that at this point they say the Cretaceous rocks were "largely flat lying before doming," another internal contradiction they make, because later in their discussion of the Terlingua Uplift, they want the more steeply dipping beds on the southwestern flank to be folded as part of the Terlingua uplift prior to the intrusion of the laccolith during Laramide deformation.

Cross Section

If one attempts to "unhinge" the beds across the Solitario, the kinematics of how the blocks were rotated, translated, and internally deformed must first be understood. I will confess that such an understanding is presently beyond me, although pulling the roof rocks apart over the dome could be expected to create voids at the top of the hinges. I can demonstrate from field evidence that the blocks of massive Cretaceous limestone forming the rim of the Solitario were rotated, translated, and slipped along bedding planes (predominantly in the marly beds) from their original flat-lying position. The changes in strike (radial hinge) as well as dip (circumferential hinge) across the hinge zones on the surface are particularly evident in the low-level color and infrared false-color airphotos. Although I think that it is safe to assume that the hinges are much more complicated than those drawn in the cross section, without more detail as to the kinematics of the deformation, there are not adequate data to support a more complex representation.

The limitations on the cross section are the location of the hinge zones at the surface, and the stratigraphic thickness of the individual Cretaceous formations, because we found no evidence for significant thinning or thickening of units except for the relatively thin marly units, primarily the Telephone Canyon and Sue Peaks Formations. Inasmuch as there is no evidence that the Cretaceous rocks were deeply buried beneath a Tertiary overburden at the time of intrusion, the limestone would have been in a brittle deformation regime. Individual blocks would therefore undergo little or no ductile deformation, and massive beds, such as Del Carmen and Santa Elena limestones, must have reached their present positions by some combination of rotation and translation. Within these constraints, the cross section of the Cretaceous rim is our best fit to the available data.

Herrin and I have been debating the possibility of a caldera in the southern part of the central basin for a good many years. Corry (1976, p. 155) discussed the evolution of laccoliths into calderas. An AMAX geologist pointed out the ignimbrite in the Needle Peak Tuff at Indian Caves (Fig. 19, p. 48) to me in the late 1970s. I reviewed Henry and others (1989) work in the Christmas Mountains with considerable discussion and correspondence about the formation of laccocalderas and the Solitario.

The central intrusive complex (Fig. 14, p. 41) is intimately associated with the collapse of the central block, although they exclude it (their Fig. 1) from their caldera. On p. 84, we pointed out that "*the eastern boundary fault of the central block (Plate 1) cuts the syenite-monzonite porphyry stock and the rhyolite breccia, but not the granite porphyry*." Elsewhere, we show that both the syenite-monzonite and rhyolite breccia are early components of the Solitario laccolith that intruded prior to the collapse of the central block. These relations were interpreted to mean the granite porphyry was squeezed up on the eastern flank by foundering of the central block into underlying magma. Although only a minimum age of 35.6 ± 1.4 Ma (Table 14) is available for the granite porphyry, its intrusion, and the collapse of the central block, are clearly late-stage developments in the emplacement of the Solitario laccolith that began 37.5 ± 0.8 Ma (Table 14). As Henry and others insist that the collapse of the central block is related to caldera formation, then, by inference, caldera formation must also be a late-stage development.

There are discrepancies with the sketch they present as their Figure 1. They depict their caldera (mainly Tv on their sketch) completely surrounded by a ring fault. We found no evidence that the ring fracture on the western side of our probable caldera extended to the collapsed central block (see our Pl. 1). Secondly, if the ring fault does continue around the east side of the caldera, it is presently covered by Needle Peak Tuff and is not mappable from surface exposures as they suggest. Third, faulting associated with the caldera extends considerably farther into the southern rim than they show.

Henry and others claim that the Paleozoic and Cretaceous rocks should be shown continuing in the subsurface across the area we label "Probable Caldera" in the cross section. We do not have, and they do not offer, data to support such an interpretation.

The overturned anticline dashed in above Dagger Flat Sandstone on the cross section was an attempt to show how the Ouachita facies, particularly the Cambrian Dagger Flat Sandstone, may have been folded *prior* to the thrusting. If our interpretation is correct, then the Marathon Formation must underlie the Solitario thrust fault as shown. The later thrust faulting deformed and locally refolded beds in proximity to the thrust plane and makes the interpretation difficult from surface exposures. Interpretations other than the one shown are possible, of course, but we think that this interpretation is the simplest. Unfortunately, during final drafting, the thrust plane of the Solitario thrust fault was not extended to the Dagger Flat Sandstone contact, implying, from the cross section, that Om should be exposed on the surface north of the thrust fault. The color choice also obscures the relationship in the cross section, because both the fault and Om are very similar shades of blue.

Field Relations

Buda Limestone usually stands out on the air photos as a distinctive white rock and was mapped as such on the southern margin of the quadrangle. Examination of the cover photo will show the color change in the drainage, evident as the light-colored triangular block to the right of the Lower Shutup, compared to the generally much darker Santa Elena Limestone. Henry and others claim that they find Santa Elena Limestone in that locality, but they present no evidence. The mistake here is not that the rock type is wrong or that the V's are in the wrong direction, but that *both* groups missed the boundary faults on what is apparently another collapsed block. On re-examination of the air photos, the northern (left side of the block in the cover photo) boundary fault to this block is particularly obvious, once recognized, but the boundary faults on both flanks can be discerned on the cover photo.

Henry and others claim that Santa Elena Limestone makes up most of the Cretaceous outcrop within the collapsed central block. Evidence, which they do not provide, for their statement should include identification of characteristic fossils or rock types such as the marker bed of interbedded chert and sandy limestone found 64 to 76 m above the base of the Santa Elena Limestone. Similar evidence is required for the presence of Sue Peaks Formation. If it is to be accepted that Santa Elena Limestone is the dominant rock type at the nearly flat-lying southern end of the collapsed central block, then the massive (209-m-thick), resistant Del Carmen Limestone we mapped there must be accounted for, because stratigraphic succession requires it.

The structural complexity of the area was described by presentations of the regional setting at three time periods in Figures 27 to 30. Discussions of the three orogenies, Llanorian, Ouachita, and Laramide, known to have affected the area are included. Five hypotheses for the origin of the Solitario dome are considered in the light of available data. A structural analysis of the dome and the related Terlingua Anticline is included. From field relations we have *attempted* a relative age assignment for the faults, and the basis for our age assignments is given in the legend on the map. Where we could not determine from field relations whether the doming reactivated older faults, however, we have identified the fault with its original time period only.

As to "grossly oversimplified" igneous geology, we made the deliberate decision to base our mapping on units that have outcrops of sufficient extent to be mappable at a scale of 1:24,000 except in the central igneous complex shown in Figure 14 (p. 41). We mapped the rim sill rhyolite separately only because of its structural significance in the history of the dome. We clearly noted on p. 42 that the rim sill is "*petrographically indistinguishable from many other rhyolite outcrops in the central basin*." Separation of even the rim sill rhyolite into separate cooling units and petrographic types is clearly beyond the scope of our study and largely unresolvable at the available map scale. The diversity of the Needle Peak Tuff was noted on p. 46, and it was pointed out that the "*present study is basically a reconnaissance*." Secondly, we limited our mapping of the Solitario igneous suite to units that were distinguishable in the field, and we gave field descriptions with supplemental petrographic descriptions. As a third criteria, we included igneous rocks that we considered critical in attempting to unravel the history of the dome.

UNSUBSTANTIATED INTERPRETATION

Geometry and Mechanism of Doming

Although we agree that the Solitario is a laccolith, it is not so clear that Henry and others believe that. They maintain that the caldera eruption removed the Cretaceous roof rock, and the entire collapsed central block was part of the caldera system. Their discussion supports the contention of McAnulty (1976) that the Solitario is, instead, a caldera. We rejected that hypothesis for reasons stated on p. 79–80, and we reaffirmed Powers (1921) hypothesis that the Solitario is, indeed, a laccolith.

The formation of hinges, as mapped in the Solitario, has been demonstrated in experimental and theoretical models, and a circumferential hinge is visible in cross section in the nearby Wax Factory laccolith in Fresno Canyon (Corry, 1988, Figs. 41 through 44, and Pl. VI). The change in strike across a radial hinge zone in the Lower Shutup is dramatically evident on the cover photo and in Figure 44 (p. 90). Change in strike across radial hinge zones is also evident in the Cretaceous rim rocks shown in Figure 11 (p. 29). We stated on p. 84 that the *field* evidence is the roof of the Solitario dome deformed by a "*series of rigid body rotations **and translations*** [emphasis added] *of discrete blocks*." The term *rigid body* implies no internal deformation.

Henry and others state that instead of rigid body rotations and translations, they find evidence for folding in "which attitude changes smoothly across fold axes, not abruptly across zones of rigid-block rotation" and claim that attitudes "in the Cretaceous rocks mostly change gradually around and across the rim." That does not jibe with our observations, the cover photo, or Figures 11 and 44. The change in strike across the Lower Shutup is 50°. Across the Lefthand Shutup, the strike changes 30°. Around the unnamed shutup near Three Windows, the strike changes 45°. Within the space of about 100 m, changes in dip of 20° or more can be observed as shown in Figure 42. Within the space of the few meters shown in Figure 43, the dip changes by ~20° to 25° with obvious cataclastic deformation typically associated with *brittle* beds being bent.

Furthermore, their model would require ductile deformation of massive limestone beds at depths generally <1 km. The field evidence is that the Yucca, Glen Rose, Del Carmen, or Santa Elena limestones were *not* ductile at the time of deformation. For ductile roof deformation, they must also account for the fact that the rocks extended above the laccolith during roof deformation. That extension tended to relieve the body forces, with the net result that the rocks were even more brittle. I have demonstrated theoretically (Corry, 1988) that true tension, that is, tensile stresses that exceed the body forces, exists in the roofs of deforming laccoliths to depths of at least 200 m. Thus, ductile deformation of the massive limestones in the roof of the Solitario, required by their model, is mechanically improbable and unsupported by field or laboratory evidence.

Because the hinge zones form in extension, if not true tension, they are zones of weakness due to cataclastic deformation within the hinges, and are thus easily eroded. The major radial hinge zones are therefore now the shutups draining the central basin.

They present a sketch (their Fig. 1) in which they outline faults that strike "dominantly east-northeast and northwest, regardless of their location around the Solitario rim." It is not clear to me what the relation, if any, of these faults is to the hinge zones being discussed. They also do not define what they are mapping as faults. With the exception of normal faults, faults are only defined for rocks in compression, whereas the roof of the Solitario obviously deformed by extension.

If an elastic plate is loaded by a flat, lubricated body, such as an intruding sill, there is a strong tendency for it to simply punch through the overburden (Corry, 1988). Such laccoliths are approximately cylindrical, with a shear zone forming a fault at the periphery. That is not what happened to the roof of the Solitario, however, despite the fact that the massive limestone closely approximated a flat elastic plate, and the rim sill rhyolite must have been the equivalent of a lubricated punch at the time of intrusion. Instead, as Henry and others confirm, the beds in the rim of the Solitario are bent outward by the intrusion. In examining such problems theoretically and in the field (Corry, 1988), I inferred that for Christmas-tree laccoliths the ductile, or plastic, zones forming above each separate sill would merge before the surface was affected by the intrusion. Thus, ductile deformation in an otherwise brittle regime would be possible, and I have been able to model this process theoretically (Corry, 1988, Pl. VI). On p. 81, the evidence that the Solitario must be a Christmas-tree laccolith is presented. The interpretative cross sections shown by Jackson and Pollard (1988, their Fig. 10) show clearly the multiple sills associated with Christmas-tree laccoliths and the ductile deformation of the sedimentary beds associated with these sills. *At the levels of sill intrusion* beneath the Cretaceous section, the same ductile deformation occurred in the Solitario. Although plastic zones develop in the vicinity of the sills in the model, *above* the shallowest sill the overburden remains elastic, or brittle. Clearly the rim sill rhyolite was the top of the Christmas tree in the Solitario, and thus the *brittle* roof rocks were deformed by a ductile dome growing beneath them and pushing them up and out of the way, as illustrated in the cross section in Plate 1. Variations in the final dip of blocks within the roof of 20° to 30°, or more, around the periphery of the laccolith might reasonably be expected of this process, and I see no need to invoke earlier Laramide deformation to account for the steeper dips on the southwestern flank, as Henry and others do. This is the same model as shown by Jackson and Pollard (1988), except the level of erosion is deeper in the Henry Mountains, and ductile deformation associated with the sills on the flanks is better exposed there.

We pointed out on p. 83 that it was Powers (1921) who first suggested a flat roof for the dome. I found one outcrop of Shutup Conglomerate that continued far enough into the central basin to directly support Powers' (1921) contention. Henry and others state that the evidence does not exist because they could not find the same outcrop. Most people who have worked in the field have had difficulty locating features described by previous workers. With or without that strike and dip, however, the roof of the Solitario was almost certainly relatively flat, in common with most of the laccoliths in the world, and they state several times that the roof rocks were flat lying before doming. Additionally, in Figure 38 we calculate the dip of the roof rock independently on the other side of the central basin and come up with 8°. Given the evidence for a relatively flat roof, our interpretations of volume and depth are as good as we have data to support.

The acknowledgments in Bagstad's (1981) thesis show that I worked fairly closely with him and was reasonably familiar with his work. I see no contradiction in using his subarea map (adapted as Fig. 33), and giving him credit for his work, because I think he did a fine job.

Geophysical Interpretation

In examining the −100 mGal anomaly at the southern end of the Terlingua uplift in Plate 2, the single point anomaly questioned by Henry and others was taken by the same investigator who made a number of other gravity measurements in the area. We could find no reason to suspect that the datum is bad. Inasmuch as it is a single point anomaly, we followed the common convention of dashing the contour lines around it. The anomaly is also supported by data farther to the south, off the margin of Plate 2, contoured independently and shown in Figure 23. As a large amount of the work in the Solitario was associated with economic geology, one of the objectives of our survey was to point out possible mineralized areas, and we would have been remiss if we had not done so.

In defining any gravity anomaly, the *regional* field must first be defined, because any anomaly is *always* calculated with reference to that field. Within the limits of the available data, we have graphically represented our chosen regional field in Plate 2. Our choice of regional field is consistent with the smooth regional field shown in Figure 23 (p. 62) in the vicinity of the Solitario. After the regional field is removed, there is no evidence for the >6-mGal gravity anomaly Henry and others claim in their discussion. For further evidence of the absence of a gravity anomaly, compare the contour closures around the +8-mGal anomaly at the southern end of the Terlingua uplift in both Plate 2 and Figure 23 with the lack of closures around the Solitario.

Most of the density determinations were made on core from holes 739-5 (to 733 m) and PN-3 (to 154 m). Although hydrothermal alteration affects parts of the core, most of it, particularly in the bottom of hole 739-5, was relatively unaltered, as indicated by small standard deviations of the measurements shown in Table 16 (p. 63). Thus, I stand by the interpretation that the Solitario laccolith has no discernible density contrast with the surrounding country rock.

Henry and others also question our interpretation of the positive magnetic anomalies shown in Plate 4. Hydrothermal alteration creates magnetic mineralization as often as it destroys it, but again Henry and others present no data to support their statements. In Table 17 (p. 66), the granite porphyry at depths >330 m in hole 739-5 has no measurable magnetic susceptibility, in common with most of the granitic rocks in the Solitario. Near surface syenite porphyry showed weak susceptibility in a few core samples and may account for the small magnetic high over the central intrusive complex, but not enough to cause the large anomaly found in Plate 3. I find it difficult to reconcile their description with Plate 4. They claim that the caldera is a magnetic low. In their caldera, however, they include our collapsed central block that is largely thick, nonmagnetic sedimentary rock. They recognize only one magnetic high at the south end that I agree is associated with Needle Peak Tuff, which was found to have some magnetic susceptibility (Table 17). They ignore, however, the dipole anomaly at Three Springs, which is probably the result of a late-stage intrusive pipe, and the relationship between the olivine syenite intrusions that have high magnetic susceptibility (Table 17) and are clearly younger than the laccolith or caldera (Table 14). They then claim that these "relationships are consistent with a magnetic high above the . . . laccolith outside the caldera and a relative low within the caldera where the underlying laccolith must be thinner by the amount of subsidence." I do not find any evidence in the low-level aeromagnetic or structural data to support that supposition. They also ignore aliasing effects, discussed on p. 65, in their interpretation. Of all the rhyolite samples, only one from Needle Peak showed significant susceptibility (Table 17). Aliasing is evident in Plate 4 around Needle Peak, and it reduces the magnetic anomaly to a nose in the contours off the west side of the monopole high in the caldera.

Neither the high-level (Pl. 3) nor low-level magnetic (Pl. 4) maps show a positive anomaly on the southern flank or the negative anomaly on the northern flank of the laccolith to be expected from a shallow, floored intrusion containing significant magnetic minerals at this latitude. The same observations hold for the regional survey (Fig. 24, p. 65).

In contrast, all of the more mafic, younger (Tables 14 and 15, p. 55 and p. 57) rocks have significant magnetic susceptibility (Table 17), and I see no basis in the *ad verecundiam* arguments of Henry and others to change our interpretation.

Early Erosion of the Solitario

Our interpretation that the dome was eroded to almost its present level very quickly (<1 m.y.) after doming is based on the observation that patches of Needle Peak Tuff can be found scattered throughout the central basin overlying Paleozoic rocks outside the probable caldera and on the eroded Cretaceous rim. The deposition of the tuff on Paleozoic rocks requires the removal of the Cretaceous roof rocks first.

On p. 8, and restated on p. 30, we pointed out that the central basin, particularly the northern part, is very close to the original Wichita paleoplain, and that at least the crests of the ridges are very near the original paleoplain surface. Thus, very little erosion of the Paleozoic rocks would have been required to expose the dome to its present level in the Eocene, or earliest Oligocene, epochs, and it is therefore unlikely that clasts of Paleozoic rocks would be abundant in debris aprons off the dome, and then only in the very top of such aprons. A relevant question is whether Henry and others have convincing evidence that the top of the apron they examined is intact and has not been removed by the extensive recent, or prior, erosion evident in Fresno Canyon. If not, then their argument that "erosion during this period did not uncover the Paleozoic rocks," based on the debris apron, is mere speculation. In addition, the shutups on the western flank of the dome drain very little of the central basin even today and, thus, have never transported much in the way of Paleozoic clasts from the central basin.

On p. 84, we pointed out that collapse of the original crestal graben block involved loss of support to the south, and "*the reason for loss of support was either erosion of the roof or eruption and subsequent collapse of a small caldera, or both*." On the same page, we also pointed out that collapse of the central block "*postdates initial deposition of Needle Peak Tuff, because Santa Elena Limestone blocks, apparently from the crest of the central block, slid out over the tuff during or after collapse*." As noted above, the timing of the collapse of the central block is limited by the minimum age of the granite porphyry, but it postdates the intrusion of the syenite-monzonite porphyry and the rhyolite breccia because the boundary fault of the central block cuts those units. The collapse of the central block thus occurred well after the formation of the dome. Near the blocks of Santa Elena Limestone that overlie the tuff, a latite dike cuts Needle Peak Tuff, and the K-Ar age of that dike is 37.8 ± 3.5 Ma. These relations limit the formation of the basal units of the tuff to within about 1 m.y. after formation of the dome. One million years is certainly sufficient time to have eroded the severely fractured roof off the dome prior to the eruption of the caldera.

I have no difficulty with the hypothesis that the basal units of the Needle Peak Tuff were deposited within the caldera, but the scattered patches of Needle Peak Tuff outside the caldera *must* have been deposited *after* the central basin was exposed. I have seen no evidence, nor do Henry and others present any, to suggest that erosion was *into* the caldera as they contend. Drainage into the caldera would suggest ponding; indeed they claim that in their discussion. I have not seen any beds that suggest lake deposits in the tuff, nor do they point out any. Clearly, streams were flowing (Fig. 17, p. 47) in the central basin during early deposition of the tuff, and that strongly suggests an exterior drainage from the central basin through an existing shutup.

Terlingua Uplift

Three orogenies involving shortening have affected the Solitario area, followed by two extensional events. The most subtle orogeny to affect the area is the Laramide.

Weak deformation striking approximately northwest, that might be of Laramide origin, was found by Bagstad (1981) to be primarily in rocks older than Tesnus, and he concluded that these folds preceded the Ouachita orogeny.

Baker (1934) originally pointed out that the Solitario lay near the crest of a broad, low-amplitude fold which extends 25 to 30 km north of the Solitario and as far south as the town of Terlingua (Herrin, 1957, p. 134) and is *probably* of Laramide origin. Henry and others, but most especially Erdlac (1990), want to carry the argument further and account for the forced folds found in the Terlingua uplift by Laramide contraction. They also claim that they have now found abundant evidence of Laramide deformation within the Solitario. Unfortunately, the only data they provide is a crude sketch and a rose diagram of some selected faults. They then argue *post hoc ergo propter hoc* that because Erdlac (1990) obtains a σ_1 of N60°E for stylolites in the Terlingua uplift, which corresponds to measurements of σ_1 associated with Laramide deformation elsewhere, that all of the observed deformation in the Terlingua uplift is the result of Laramide contraction. We know from elementary statistics that correlation does *not* imply causation. Furthermore, Yates and Thompson (1959, p. 48) concluded that extension by faulting across (transverse to) the Terlingua structure is about equal to crustal shortening by folding on the flanks, and that is inconsistent with Laramide shortening.

Even though Henry and others provide descriptions of the relative ages of the faults they map, their argument lacks an age determination that places the deformation responsible for the Terlingua uplift within the time frame of the Laramide orogeny. The available age relations clearly do *not* support their argument, as pointed out in the accompanying Discussion of Erdlac's (1990) paper.

CONCLUSIONS

It is reassuring to find that our work has not disappeared into obscurity but has, instead, stirred up considerable controversy.

Most people who have worked in the field recognize that the perfect geological map has yet to be drawn. In an area as complex as the Solitario, additional field work will turn up new relations and find errors in any previous work. That is a process by which science advances.

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