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Richard M. Chamberlin and Orin J. Anderson

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THE LARAMIDE ZUNI UPLIFT, SOUTHEASTERN COLORADO PLATEAU: A MICROCOSM OF EURASIAN-STYLE INDENTATION-EXTRUSION TECTONICS?

RICHARD M. CHAMBERLIN and ORIN J. ANDERSON
New Mexico Bureau of Mines and Mineral Resources, Socorro, New Mexico 87801

Abstract—Published accounts of Eurasian tectonics and indentation-extrusion experiments on plasticine support the concept that India has acted as a rigid indenter and driven 2000 km into "plastic" Eurasia thereby causing: (1) vertical extrusion of the Himalayas immediately in front of the indenter, (2) cradling and northward translation of the unstable wedge-shaped Tibetan Plateau in front of the Himalayan uplift, now accreted to the indenter and (3) lateral extrusion of Indochina, followed by China, eastward off the right face the Tibetan wedge, which now forms a streamlined secondary face accreted to the Indian indenter. The NW-trending Zuni uplift (60 × 100 km) lies within the Colorado Plateau, adjacent to the N face of a NNE-trending gravity high, which extends from El Morro, NM to the plateau margin near Morenci, AZ, about 250 km to the SSW. Limited evidence indicates that the El Morro gravity high represents a Precambrian mafic igneous belt (rift?); and that it was truncated by a NW-trending strike-slip shear zone during the late Paleozoic Ouachita–ancestral Rocky Mountain orogeny. We hypothesize that during the late Laramide (Eocene), the El Morro gravity high acted as a rigid crustal beam (indenter); it was detached at a mid-crustal ductile zone and driven northward by horizontal stresses generated at the edge of the plateau. The N face of the El Morro indenter functioned as a large hydraulic ram; it created hydrostatic pressures in excess of the lithostatic pressures, and thereby caused about 2400 m of vertical extrusion and uplift centered about the Mt. Sedgwick block complex—the Precambrian core of the Zuni uplift. High-angle reverse faults that bound this core complex appear to grade laterally into left- and right-lateral strike-slip faults toward the corners of the main block. Extruded blocks preferentially slipped left (NW) across the indenter face, locally pulling apart and creating a cup in the N face of the uplift. Inward compression, caused by the cup, created the wedge-shaped Bluewater Lake block, now spearheading the streamlined indenter. The sinuous Nutria monocline was then formed at the leading edge of tapered blocks, uplifted and extruded to the west off the spearhead. At the same time, en echelon (left stepping) monoclines of the Grants-Fernandez system formed in front of NNE-extruded blocks on the right flank of the spearhead. Late-stage strike-slip faults outlined the contracted flanks of the indenter as it weakened by strain heating(?). Near Fence Lake, along the west flank of the El Morro gravity high, as much as 5 km of left-lateral slip is inferred on a concealed fault that juxtaposes marine against nonmarine Cretaceous strata. We suggest these traits may qualify the Zuni uplift as a microcosm of Eurasian indentation-extrusion tectonics.

INTRODUCTION

The December 1982 issue of Geology shows on its cover a simple indentation experiment done on unilaterally confined blocks of plasticine (Tapponnier et al., 1982). The experiment suggests that India has acted as a rigid die (indenter) and penetrated deep into a plastic body (Asia). Complex rigid-plastic deformation in front of the indenter (dominated by pure shear) quickly becomes asymmetric and large strike-slip faults form to allow lateral extrusion of tapered blocks toward the unconfined face. Only eyewitnesses to the experiment are sure that the extruded bock mimicking Indochina formed first and that the South China representative formed second.

Mechanical engineers who have studied the indentation of rigid-plastic materials are convinced that it is primarily the shape of the indenter face and the boundary conditions of the plastic material that determine the final geometry of deformation. To our knowledge, this paper is the first to apply basic concepts of indentation-extrusion tectonics, as derived from ongoing continental collision in Eurasia, to the thick-skinned (cratonic mode) Laramide orogenic belt.

We present here a *working hypothesis* concerning the mechanism of uplift, geometry of major structural domains and kinematic relationship of structural blocks within and around the Laramide Zuni uplift. The hypothesis is based on a comparison of the geometric characteristics of indentation-extrusion tectonics—as we understand them from the literature—to a schematic tectonic map of the Zuni uplift (presented later). The tectonic map was compiled from published geologic maps and our own limited observations concerning sense of slip in fault zones on the NE flank of the uplift (see road logs for Day 1, Stop 5 and Day 2, Stop 2, this guidebook). Our hypothesis was developed late in the publication schedule of this guidebook; therefore, the road logs do not describe the local structure in terms of indentation-extrusion tectonics. However, we believe the local structural relationships observed at the stops are generally compatible with our hypothesis.

Evidence that supports an indentation-extrusion origin for the Zuni uplift is mostly circumstantial. It is the overall geometric similarity of distinct structural domains in the Zuni uplift, to those described in Eurasia, that gives us sufficient confidence to present this hypothesis for the scrutiny of others. In the structural analysis of fault-block mountain ranges, it is the accurate determination of sense of slip, on contemporaneously formed faults outlining the blocks, which provides the key to understanding.

Geologic concepts concerning the origin of Laramide uplifts have evolved into two apparently incompatible schools of thought—uplift by horizontal compression vs. uplift by vertical forces—the latter generally related to some form of isostatic imbalance. We suggest that the concepts of high hydrostatic pressure and *vertical extrusion* immediately in front of an indenter, followed by lateral extrusion adjacent to the mushrooming secondary face of an indenter—all driven by horizontal compression—may help unite these contrary schools of thought.

REGIONAL SETTING OF THE ZUNI UPLIFT

The Laramide Zuni uplift (Fig. 1) is located in the southeastern quadrant of the Colorado Plateau, about 250 km from its southern margin. The NW-trending Zuni uplift measures about 60 × 100 km; its total structural relief is about 2400 m (Kelley, 1967; Hackman and Olson, 1977).

The Zuni uplift lies at the north end of a 25–30 mgal, residual gravity high (Hildebrand et al., 1982), which trends NNE from near Morenci, AZ to El Morro, NM. Ander and Huestis (1982) previously interpreted the northern half of the Morenci–El Morro gravity high—their Chimney Hill gravity high—as a shallow mafic intrusion possibly emplaced sometime before Laramide deformation. They recognized that this gravity high exerted a strong control on the Chain of Craters vent zone (Maxwell, 1982), which parallels the east flank of the high.

More recently, Sumner (1985, p. 169–171) interpreted a strong mag-

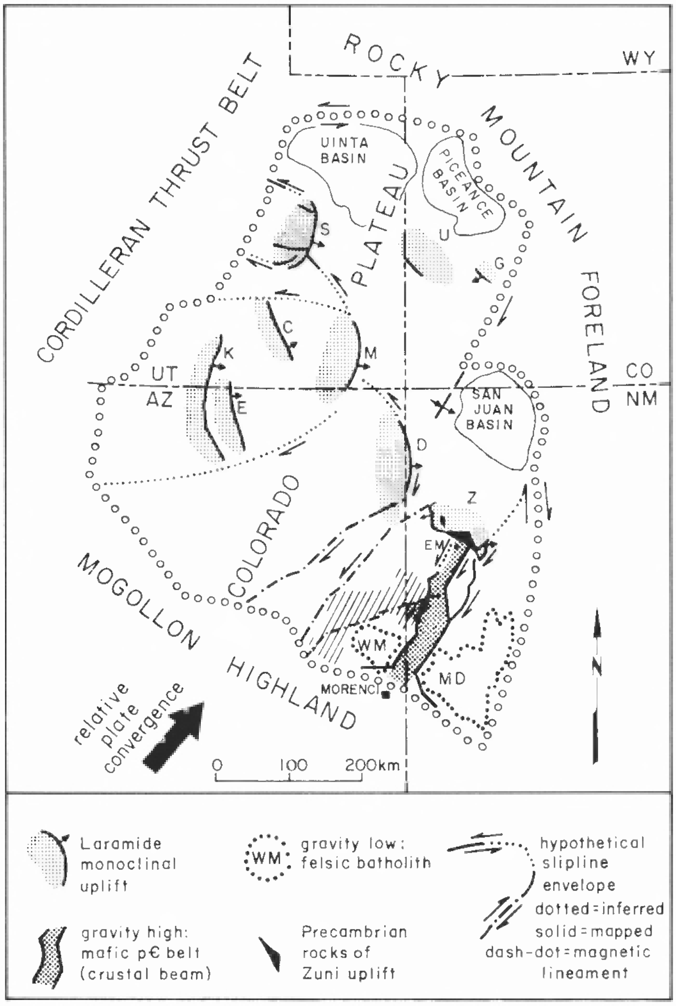

FIGURE 1. Map showing regional setting of the Zuni uplift (Z) and other Laramide monoclinal uplifts within the Colorado Plateau; S = San Rafael, C = Circle Cliffs, M = Monument, K = Kaibab, E = Echo Cliffs, U = Uncompahgre, G = Gunnison and D = Defiance. The gravity high between Morenci and El Morro (EM), and the gravity lows under the White Mountains (WM) and Mogollon-Datil (MD) volcanic fields are from Hildebrand et al. (1982). Magnetic lineaments and a large magnetic high, greater than 600 gammas (lined area, adjacent to WM), are from Bond and Zeitz (1987). The geometries of hypothetical sliplines (lines of maximum shear stress, i.e., faults; Tapponnier and Molnar, 1976) are drawn with the assumption that salients and recesses along the flanks of the Colorado Plateau caused horizontal stresses to be focused into various parts of the plateau. Base map, plus direction of relative plate convergence for late Laramide time, compressional highlands and deep Laramide basins are from Chapin and Cather (1981, fig. 1). Additional modifications are from Hunt (1956, fig. 37), King and Beikman (1974) and Chamberlin (unpublished reconnaissance mapping, Catron County, NM). See text for discussion.

netic high (greater than 600 gammas) in the area west and north of the White Mountains (lined area adjacent to WM, Fig. 1) as an "ancient buried intrusive paleorift." Sumner also states:

> The body is interpreted to extend at least 10 km into the earth's crust and appears to have a magnetite content of about 1 percent more than the surrounding rock. . . . The anomalous feature appears to crop out near its southwest corner, a few kilometers northeast of Globe, Arizona, where the material is mapped geologically as Precambrian diabase. . . . From the geometry and lithology of this huge magnetic intrusive body, it is probably an ancient tectonic rift and spreading center.

The regional magnetic map of Bond and Zeitz (1987) shows that Sumner's magnetic high extends into New Mexico, and is apparently contiguous with the southern end of the Chimney Hill gravity high of Ander and Huestis (1982). Where it passes between the middle Tertiary batholithic gravity lows of the White Mountains and Mogollon-Datil volcanic fields, the southern half of the Morenci–El Morro gravity high is reduced in intensity, but not in amplitude. This attentuation may be why Ander and Huestis did not recognize the southern half of the El Morro gravity high. The El Morro gravity high is almost entirely outlined by late Cenozoic normal faults, generally correlative with the Morenci-Reserve fault zone of Ratté (1989). It was our observation that the axis of the El Morro gravity high correlated with a Precambrian gneissic gabbro on the south flank of the Zuni Mountains (Goddard, 1966) and the NNE-trend of the high, which led us to the conclusion that the Morenci–El Morro gravity high—and Sumner's (1985) magnetic high—are the expression of a Precambrian mafic belt (Fig. 1).

The concepts of indentation-extrusion tectonics imply that it is variation in the strength (yield stress) of large blocks of the continent that control the complex patterns of deformation, and not so much the direction of applied stress. There are several extrinsic and intrinsic variables that control the yield strength of blocks of rock. We suggest the El Morro gravity high is an intrinsically rigid crustal block because of a higher mafic mineral content, such as olivine (see Goetz and Brace, 1972; Morgan and Golombek, 1984).

We hypothesize that the El Morro gravity high (EMGH) has acted as a rigid crustal beam, and efficiently transmitted horizontal compressional stresses from the Laramide Mogollon highlands to its northern face near El Morro. We further suggest that the EMGH acted as a large hydraulic ram that pressured a mid-crustal ductile zone (Morgan and Golombek, 1984). High hydrostatic pressures at the north face of the EMGH then presumably formed the Zuni uplift by both vertical and lateral extrusion.

How was the north face of the El Morro indenter (EMGH) formed? We suggest that the EMGH was sheared off by a NW-striking strike-slip shear zone during the Ouachita–ancestral Rocky Mountains orogeny—a continental collision event (Kluth and Coney, 1981; Dickinson, 1981). Isopach maps of the Pennsylvanian system (McKee and Crosby, 1975) show that all but the SE tip of the Zuni uplift was a Pennsylvanian highland, commonly referred to as the Zuni-Defiance platform. The east flank of this Pennsylvanian highland also parallels the El Morro gravity high south into the Quemado-Pietown area. A possible southern continuation is obscured by the Mogollon-Datil volcanic field. Except for the Monument Arch, all of the monoclinal uplifts of the Colorado Plateau closely or partially mimic trends in the Pennsylvanian sedimentary section (McKee and Crosby, op. cit.). We speculate that it was the ancestral Rocky Mountain orogeny and related strike-slip faults that sheared the Colorado Plateau off the North American craton.

Chapin (1983, fig. 8) shows the entire Colorado Plateau translated about 100 km northward into the Wyoming province, thus acting as the driving force for a commensurate amount of crustal shortening and right slip along the east margin of the plateau. Chapin and Cather (1981) describe the Colorado Plateau as a bulwark crowded against the craton. If the entire Colorado Plateau is viewed as an indenter, detached at the base of the lithospheric mantle, with the geometry in Figure 1, it is possible to see why the deep San Juan, Piceance and Uinta basins are present where they are—adjacent to the leading N edge of an indenter. As suggested by this diagram (Fig. 1) and the above discussion, we believe that the entire Laramide Rocky Mountains should be re-evaluated with the concepts of indentation-extrusion tectonics.

Post-Laramide extension and basaltic volcanism has evidently been guided into the Zuni area by the deep-seated zone of Laramide shear that formed along the right flank of the EMGH, which is now marked by the Chain of Craters vent zone (Maxwell, 1982). The *Laramide* Chain of Craters shear zone was apparently refracted to the NE during formation of the Zuni uplift, this refracted shear zone is expressed by the Mount Taylor volcanic trend. Collectively, these right stepping volcanic zones of late Cenozoic age have been assigned to the Jemez lineament (Aldrich et al., 1983; Aldrich and Laughlin, 1984). Relatively minor extension has reactivated NE-trending Laramide strike-slip faults in the Grants area as dip-slip normal faults with as much as 60 m of stratigraphic separation (see road log, Day 2, Stop 1, this guidebook).

There are many fine articles on Laramide tectonics and the geophysics of the Colorado Plateau that provided our basic understanding. Hinze and Braile (1988) and references therein present geophysical evidence supporting the concept of the Colorado Plateau as a rigid cratonic block. Classic descriptions of monoclines by Kelley (1955) and their patterns (Kelley and Clinton, 1960; Davis, 1978), with constraints on their origins (Woodward, 1976), all provide helpful "food for thought." Lowell and Gries (1983) provide a wealth of information on Laramide tectonics. In an exceptionally perceptive and enlightening description of the continental crust, Burchfiel (1983, p. 132) presents a map of worldwide belts. This map shows the Colorado Plateau and part of the Wyoming basins as blocks of Proterozoic and Archean rock, respectively, floating in the Cordilleran orogenic belt—immediately offshore from cratonic counterparts of the same age. This enlightened global perspective obviously implies remobilization and shearing of the craton in the Rocky Mountain foreland.

SOME GEOMETRIC AND KINEMATIC ASPECTS OF INDENTATION-EXTRUSION TECTONICS

The following qualitative summary of block geometries and the kinematics of indentation-extrusion tectonics is based on Figure 2, tempered by descriptions of real continental collision tectonics in the Mediterranean and Eurasia. In our summary we draw heavily from articles by McKenzie (1972), Molnar and Tapponnier (1975, 1981), Tapponnier and Molnar (1976) and Tapponnier et al. (1982). For more comprehensive and quantitative discussions of extrusion tectonics, the reader may want to review these articles.

Examination of fault plane solutions and distribution of seismicity allowed McKenzie (1972, fig. 2) to map aseismic (rigid) Arabia driving north into the Caucasus and wedging apart seismic (plastic) blocks of Turkey and Iran. Traditional application of a "regional stress field" analysis could not explain the complex motions. Says McKenzie (op. cit., p. 176), "It is therefore simpler at present to neglect the stress field, which must be exceedingly complicated, and account for the features produced by major deformation directly in terms of plate motions." Consideration of the major domains of deformation shown on Figure 2 should account for some of these complicated and shifting stresses.

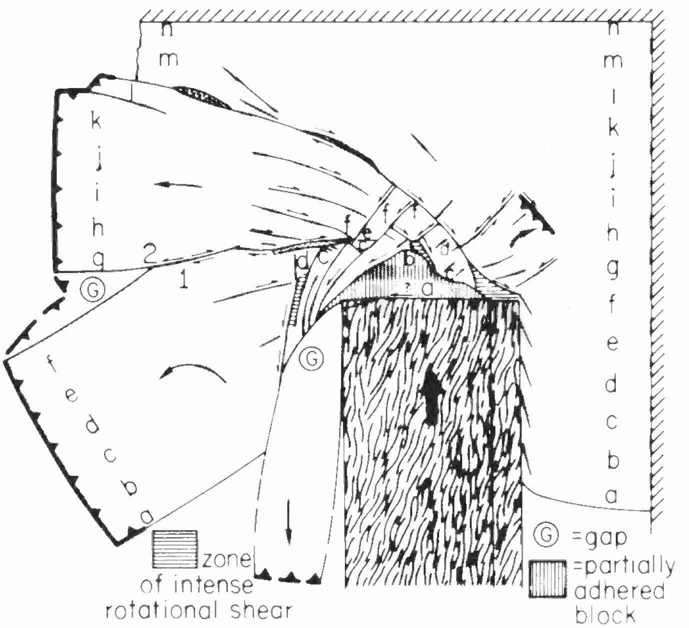

FIGURE 2. Line drawing showing mirror image of indentation experiment on unilaterally confined blocks of plasticine (Tapponnier et al., 1982; used with permission of author). Experiment was originally used to suggest that India has acted as a rigid die and penetrated 2000 km into "plastic" Eurasia, thereby producing large arcuate strike-slip faults and causing extrusion of Indochina, and then China, across the Pacific oceanic plate. Mirror image provides an orientation of asymmetry more likely to fit the Laramide Colorado Plateau, where the *relatively* unconfined domain lay to the left (e.g., Cordilleran thrust belt). Modifications include foliation pattern added to rigid die, vertical lines to identify partially adhered (accreted) block, bold arrows showing sense of motion and rotation for large extruded blocks, small arrows showing sense of lateral slip, horizontal lines in zones of intense shear and flattening (at corners of indenter), thrust symbols at strongly convergent leading edge of extruded blocks and letters to correlate light-colored layers in area of strong deformation. Encircled "G" represents open space, or gaps, in experiment that would not occur in the crust. We infer an additional extruded block could occupy the gap on left side of experiment. Hachured lines define transtensional zones near tail of extruded blocks and at releasing bends on flanks of extruded blocks. See text for additional description.

We recognize five geometrically distinct structural domains on Figure 2. They are: (1) the indenter, (2) partially adhered (accreted) triangular wedges immediately in front of the indenter, (3) large blocks extruded to the left (rotating counterclockwise) with broad leading edges that are convergent and tapering tails that are transtensional, (4) a small, strongly rotational block above the confined right corner of the block that is attempting to get out of the way (extrude to the right) by rotating clockwise with the "flow" and (5) relatively undeformed plasticine on the periphery of these domains. We infer that the small rotational block (number 4 above) will have one leading face that is distinctly transpressional (i.e., marked by a reverse fault or monocline) and another leading face that is transtensional (i.e., marked by a subtle strike-slip fault).

Triangular accreted wedges (partially adhered block, Fig. 2) in front of the indenter are locally deforming by pure shear with conjugate, strike-slip faults. An early wedge (vertical lines, Fig. 2) is temporally related to the first large extruded block (layers "a–f") and the second wedge (smallest "f" near apex of wedge, Fig. 2) is related to extrusion of the second large block (layers "g–l"). The accreted wedge is obviously unstable with time, and constant shifting of blocks here is important in the lateral extrusion mechanism. Note also that the strongest shearing (flattening) of the plastic occurs where it must "flow" around the corners of the indenter. Since the sliplines (faults) are lines of maximum shear stress, they curve away from their point of origin. In the direction of propagation, lines of right slip curve left, and lines of left slip curve to the right.

"Plastic" yielding of rock occurs when the maximum shear stress (maximum stress minus minimum stress, divided by 2) reaches the yield stress, for a given set of variables (Tapponnier and Molnar, 1976). Minor elastic deformation prior to plastic yielding is ignored, and the rocks are described as "rigid" below the yield stress and "plastic" above the yield stress. Variables that control the yield stress, or strength of rocks, are temperature, composition, strain rate, anisotropy, configuration of applied stress and the combination of configuration of applied stress with different orientations of anisotropic (i.e., foliated) rocks.

With the foliation pattern shown on the indenter in Figure 2, we suggest that some rigid crustal blocks may have strength properties similar to a deck of cards. A deck of cards is flexible when pushed on from the side, yet rigid when pushed on at the end, and furthermore it is able to slip parallel to card faces (foliation) in the direction of relative rigidity. This "card deck" model might apply to the San Rafael uplift and late-stage development of the Zuni uplift. Under any set of conditions, mafic rocks (e.g., olivine-rich) are generally stronger than their felsic counterparts (Morgan and Golombek, 1984). Thus, the mafic rocks of the El Morro gravity high did not require variations in the geothermal regime to give it rigidity. However, the best known rigid indenter blocks, India and Arabia, can be succinctly described as "old-cold" cratonic blocks with a thick mantle lithosphere, making them the most rigid (McKenzie, 1972; Molnar and Tapponnier, 1981).

Tapponnier and Molnar (1976) emphasize that the geometry of rigid-plastic deformation in front of an indenter is strongly controlled by the indenter's shape. Flat-faced indenters form mushroom-shaped envelopes of deformation about twice as wide as the face of the indenter. Wedge-shaped indenters split the rock into two envelopes that are extruded laterally as they slide along the face of the indenter.

All other variables aside, it is well established that rocks are weakest in a tensional stress field and strongest when in a triaxial compressional field. Consider the small rhombohedral block containing the smallest letter "f" near the apex of the accreted wedge in Figure 2. Compressional stress (foward pressure) is being transmitted by temporarily stable blocks below it, into both the lower left and lower right flank of the block, thereby placing it under triaxial compression (there is a lid on the experiment). This block is now stronger than the plasticine ahead of it. Thus, the cradled block temporarily acts as a secondary wedge-shaped indenter face and splits into the plasticine in front of it. A concave-faced indenter would immediately form a relatively rigid cradled wedge in front of it. We suggest that the Tibetan plateau is acting as an unstable cradled wedge in front of the concave Himalayan uplift, which itself acts as a secondary (accreted) "pusher" face for India.

Evidently a rigid crustal or lithospheric block (indenter), when pushed ahead, acts as a hydraulic ram at its leading face. At mid-crustal or at deeper levels, a zone of ductile rocks (see Morgan and Golombek, 1984) is pressured by the indenter face to create high hydrostatic pressures which can overcome the force of gravity, thereby lifting the overlying column of rock immediately in front of the indenter (e.g., Himalayas and western Iran). Simpson et al. (1986, p. 8360) interpret strong gravity highs over Laramide uplifts in Wyoming and weaker highs on the Colorado Plateau as logically explained by uplift of dense lower crustal rocks. Thus, we suggest that as uplift progresses relatively mafic lower crustal rocks are raised, and the gravitational potential of the blocks increases until the point when the weight of the blocks balances the hydrostatic pressure. Presumably, it is this hydrostatic balance that seems to weld (accrete) uplifted blocks to the face of the

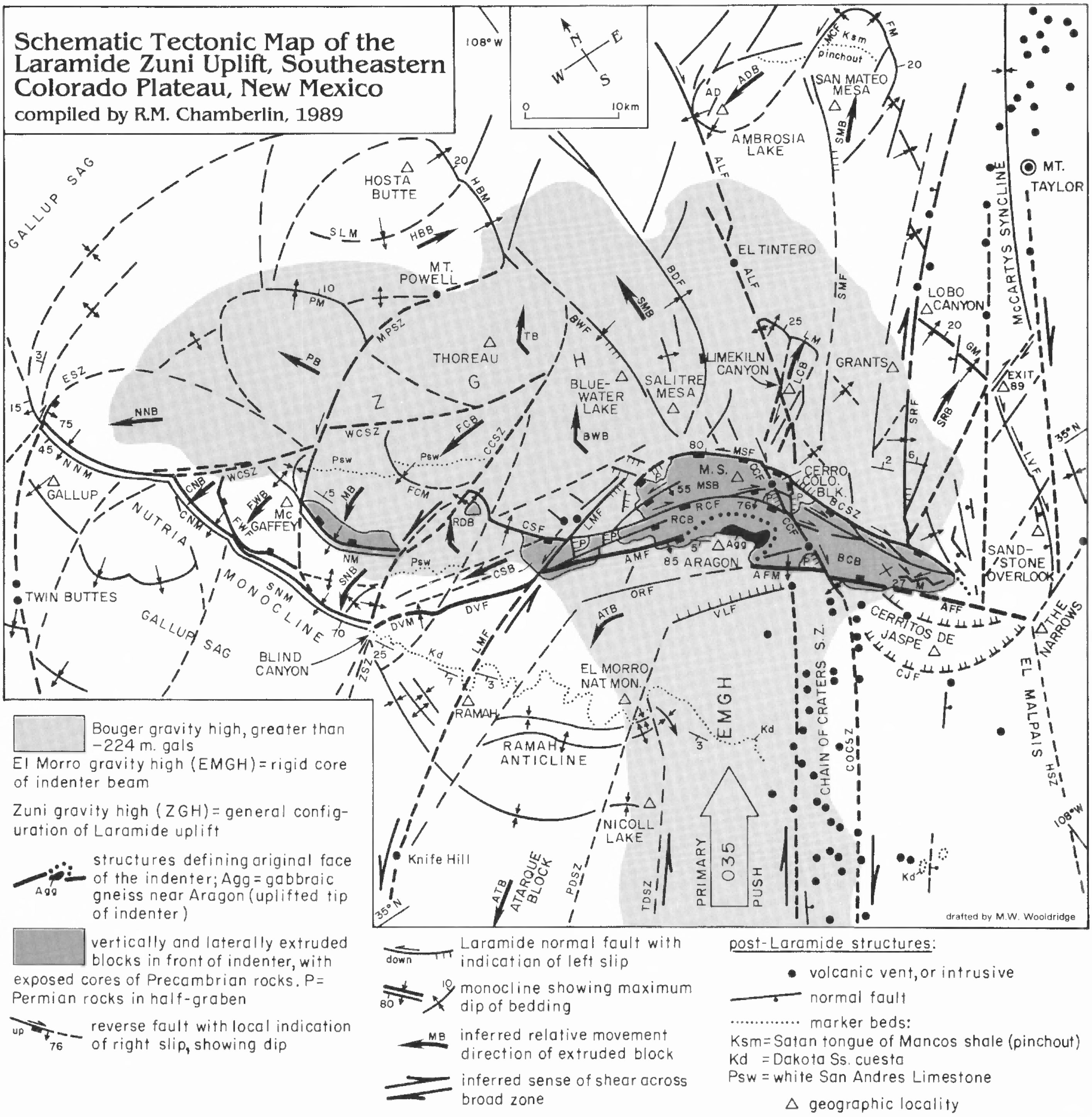

FIGURE 3. Schematic tectonic map of the Zuni uplift. Compiled from Keller and Cordell (1983); Goddard (1966); Santos (1966); Kelley (1967); Hackman and Olson (1977); Maxwell (1986); and Skylab photo (Fig. 4). Mount Sedgwick (MS), elevation 2821 m, is the topographically and structurally highest point on the uplift. See Table 1 for names and interpretation of structures; 27M = Section 27 fluorspar mine (Goddard, 1966).

indenter. As the indenter moves forward more hydrostatic pressure is created, and the uplift grows until the increasing gravitational potential, lithostatic stress, exceeds lateral confining pressures. At this point, strike-slip faults become dominant, and blocks are laterally extruded off the wedge formed in front of the uplifted and accreted blocks. We believe this progression from uplift, to lateral shifts in the uplift (unstable wedge), to formation of a cup, to development of a cradled wedge, and finally lateral extrusion of blocks can all be observed in the structural domains of the Zuni uplift.

STRUCTURAL DOMAINS OF THE ZUNI UPLIFT

Assumptions and methods

Our untested hypothesis for the origin and evolution of the Zuni uplift is presented here in the form of a schematic tectonic map (Fig. 3). The basic scheme was to outline major structural blocks in order to better understand the architecture of the uplift. The structures we portray with solid lines are shown on the published maps cited in the caption. Bolder lines signify the relatively important structures. Dashed lines represent inferred shear zones (labels on Fig. 3, ending with "SZ"), which are generally not shown on the published maps. Many of these inferred shear zones are apparent as distinct or delicate lineaments on high-resolution (unscreened) prints of the Skylab photograph reproduced in Figure 4, which unfortunately must be published as a halftone. For this compilation we assumed that terminations or shifts in trend of monoclines, and folds, occur in the proximity of basement shear zones. Post-Laramide volcanic vents and intrusive necks (middle Tertiary to Quaternary) were also helpful in delineating deep-seated shear zones. We see only very minor indications of post-Laramide normal faulting to

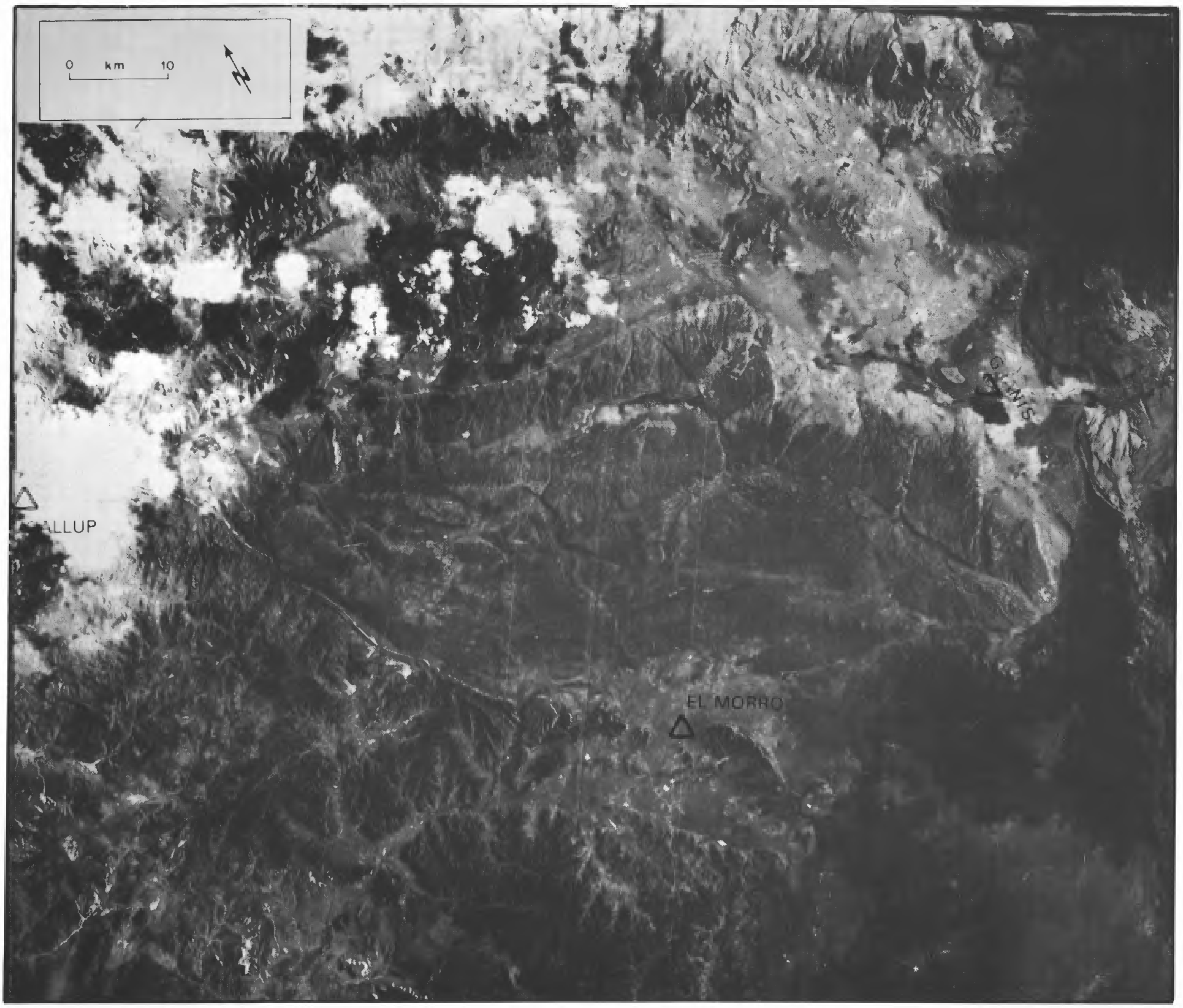

FIGURE 4. Composite photograph of the Zuni uplift from Skylab 3 (NASA/JSC SL3, 85-014 and 85-015, September 1973). Precambrian core of uplift is outlined by outward dipping cuestas of Permian Glorieta Sandstone. Note the hackly, broken appearance of Precambrian rocks along north flank of large blocks on right (Mount Sedgwick, MSB, and Bonita Canyon, BCB, blocks; Fig. 3, Table 1). In contrast, Precambrian exposures in blocks on left have the smooth look of an exhumed late Paleozoic erosion surface (Smith et al., 1959). Gently south-dipping sandstone cuestas at El Morro mark the subtle back of the indenter. Left of center, the sandstone cuestas abruptly narrow into hogbacks of the Nutria monocline where they cross the left flank and corner of the El Morro indenter, which is defined by the WNW-striking Dan's Valley fault (DVF, Fig. 3). About 10 km west of Grants, the broad nose and south-tapering flanks of the uplifted and northward extruded Limekiln Canyon block (LCB, right half of block on Fig. 3) are well defined by alluvium and linear drainages, respectively. Other, more subtle lineaments that are visible on high resolution (unscreened) prints of this scene, have been used to locate probable sliplines around blocks as mapped in Figure 3. These Skylab photos were graciously provided by Amy Budge at the Technology Applications Center of UNM.

the west of the Chain of Craters shear zone (COCSZ, Fig. 3) or to the west of the San Rafael fault (SRF, Fig. 3). From here on, acronyms used to label structures on Figure 3 will be cited without reference to that figure or to their description on Table 1. Table 1 summarizes our basic interpretation of all the major structures and other selected structures shown in Figure 3. The names of previously mapped structures are mostly from Kelley (1967). Names of shear zones and other structures identified here are mostly from nearby geographic features shown on the U.S. Geological Survey 30′ × 60′ quadrangles that cover this region. Sources of other names are cited in Table 1.

Edwin Goddard's (1966) classically detailed geologic map of the Zuni Mountains fluorspar district, centered about Mt. Sedgwick, provides the critical structural details for the core of our tectonic map and the heart of our hypothesis. We salute his genuine looking map and champion his interpretation of the Laramide structural control and Lar-

TABLE 1. Tabular outline of major and selected minor structures related to the Zuni uplift; grouped by spatial and functional domains and approximate order of formation. Each structure is listed by map symbol (Fig. 3), then followed by the name and basic interpretation. Letter(s) at end of symbol identify general class of structure; B = block, M = monocline, D = dome, F = fault, and SZ = shear zone. Indicated direction of vergence is equivalent to inferred direction of lateral extrusion. Structures listed with map symbol underlined are named herein; other structures were named by Kelley (1967) or by reference cited.

I. Indenter: El Morro indenter complex

EMGH: El Morro gravity high—rigid core of indenter, Precambrian rift(?);
Agg: gabbroic gneiss near Aragon— exposed tip of indenter (Goddard, 1966);

A. Indenter Face:

AFM: Agua Fria monocline—pre-Laramide shear zone, truncated EMGH, Laramide reverse fault;
AFF: Agua Fria fault—offset equivalent of AFM;
AMF: Agua Media fault—like AFM, left reverse fault;
DVF: Dan's Valley fault—offset equivalent of AMF;
DVM: Dan's Valley monocline—like DVF, left reverse fault;

B. Indenter Flanks:

HSZ: Hickman shear zone—early right flank, right-lateral shear zone postulated by Maxwell (1986); named by Wengerd (1959);
ZSZ: Zuni shear zone—early left flank, mapped near Zuni Pueblo (Hackman and Olson, 1977), terminates Atarque monocline;
COCSZ: Chain of Craters shear zone—anastomosing right-lateral shear zone, major magma conduit in late Cenozoic, late-stage continuation (CCF) displaces indenter face about 1 km in right lateral sense (Maxwell, 1982 and 1986);
LMF: Lookout Mountain fault—late-stage left-slip fault, offsets AMF-DVF, magma conduit for Knife Hill and Lookout Mountain;
PDSZ: Pinitos Draw shear zone—left slip fault, terminates Galestina monocline (Anderson, 1987);
TDSZ: Terrero Draw shear zone—left-slip fault, terminates Atarque monocline;

C. Anterior Tensional Zone:

CDF: Cerritos de Jaspe fault—major normal fault formed by primary uplift pulling away from detached sedimentary section, repeats Permian rocks (Maxwell, 1986), covered by basalt;

D. Late-stage Indenter:

VLF: Valle Largo fault—transtensional left-slip fault presumably related to late-stage strain heating(?) and softening of the indenter tip at depth, thereby causing westerly extrusion behind the original indenter face;
ORF: Oso Ridge fault—transpressional right-slip fault similar to VLF;
ATB: Atarque block—late-stage SW vergent block related to softening of indenter tip, leading edge of block formed Atarque monocline (Anderson, 1987);

TABLE 1, continued

II. Primary Uplift and Accreted Wedge: Mt. Sedgwick–Bluewater complex

A. Primary Uplift:

RCB: Redondo Canyon block—vertically extruded block, gradational(?) to Agg;
RCF: Redondo Canyon fault—high-angle reverse fault, like AFM, but NE vergent;
MSB: Mt. Sedgwick block—like RCB, may be secondary to RCB;
MSF: Mt. Sedgwick fault—like RCF, 1 km reverse slip, some left slip indicated;
BCB: Bonita Canyon block—composite lateral equivalent of RCB plus MSB;
BCSZ: Bonita Canyon shear zone—minimum of 300 m of right slip indicated (Goddard, 1966);
CCB: Cerro Colorado block—transtensional horst block formed by push from right corner of RCB;
CCF: Cerro Colorado fault—late-stage right-slip fault, 1 km offset of AFM-AFF, magma conduit, connects with COCSZ and ALF;

B. Primary Lateral Extrusions:

CSB: Camp Seven Canyon block—extruded west along indenter face, separated from MSB + RCB by tensional (necked) zone;
CSF: Camp Seven Canyon fault—high-angle reverse fault and monocline;
RDB: Rincon dome block—sharp corner on left flank of primary uplift, extruded west with CSB, NNE vergent;

C. Accreted Wedge and Early Fault:

BWB: Bluewater Lake block—initially slipped westerly into tensional gap between MSB and CSB-RDB combination; cradled block then became second-order NNE vergent wedge forming domain boundary between westerly and northeasterly extruded blocks, inward compression yields additional strength;
BWF: Bluewater fault—transtensional to transpressional right-slip fault, looks like faulted monocline;
LVF: Las Ventanas fault—minor right-slip fault defining early NE periphery of the Zuni uplift, reactivated by Late Cenozoic extension (this report);

III. Second-Order Extrusions:

A. Westerly Extrusions:

CNB: Central Nutria block
SNB: South Nutria block
MB: McGaffey block
FCB: Foster Canyon block
} sequentially extruded to WSW to form imbricate set, central and south segments of Nutria monocline (Kelley, 1967) represent leading edge of block, collectively referred to as McGaffey complex;
CCSZ: Cottonwood Canyon shear zone—left-slip shear zone on south flank of McGaffey complex, truncates white facies of San Andres Limestone (Psw, Fig. 3);
WCSZ: Whitewater Canyon shear zone—inferred zone of complex right- and left-lateral shear, poorly defined in Chinle Fm;

B. Northeasterly Extrusions:

SRB: San Rafael block—leading edge bound by NE vergent Grants monocline (GM), tail of extrusion near Gallo Peak mapped by Maxwell (1986);
SRF: San Rafael fault—complex right-lateral reverse fault, some rotational scissors component, and local transtension at tail of SRB;
LCB: Limekiln Canyon block—small composite extrusion formed by refraction of right-lateral shear across the north face of the Cerro Colorado block;
ALF: Ambrosia Lake fault—right-lateral shear zone, refracted continuation of Cerro Colorado fault, magma conduit for El Tintero, controlled or triggered formation of Ambrosia Lake dome block;
SMB: Salitre Mesa block—anticlinal horst-like block, distinct convergence of bounding faults at tail;

TABLE 1, continued

BDF: Big Draw fault—reverse fault with right-slip component, bounds right side of SMB;
TB: Thoreau block—slipped west with McGaffey block complex, then became cradled between BWB and third order Pinedale block (PB);

IV. Third-Order Extrusions:

NNB: North Nutria block—youngest of deep seated extruded blocks, NW vergent;
NNM: North Nutria monocline—youngest segment of Nutria monocline, left-lateral reverse fault in basement;
ESZ: Ebon shear zone—high-angle reverse fault with right and left shear evident at leading corner where it cuts Torrivio Member of Gallup Sandstone (this report);
PB: Pinedale block—NNW vergent block;
PM: Pinedale monocline—right-lateral reverse fault in basement;
MPSZ: Mount Powell shear zone—truncates Pinedale monocline, McGaffey monocline, and forms pusher face that produced late stage Fort Wingate block (FWB), superimposed on CNB and SNB, magma conduit for Mt. Powell;
FWB: Fort Wingate block—third-order, west vergent block, deforms Nutria monocline into central and south segments;
FWF: Fort Wingate fault—west vergent reverse fault, may be shallow seated thrust, Stinking Springs thrust of Edmonds (1961);

V. Late-Stage Structures:

HBB: Hosta Butte block—east vergent, slightly cradled block, may be detached from basement;
HBM: Hosta Butte monocline—may be thin-skinned thrust fault;
SLM: Smith Lake monocline—may be expression of thin-skinned tear fault;
SMB: San Mateo Mesa block—may be thin-skinned gravity-slide block, NE vergent;
FM: Fernandez monocline—sharp bend and segmented character suggests thin-skinned thrust below;
MCF: Mulatto Canyon fault—left-slip fault, pinchout of Satan Tongue of Mancos Shale offset more than 1 km, Santos (1966);
ADB: Ambrosia Lake dome—west vergent(?) block, complexly faulted (Kelley, 1967), site of major uranium orebodies in Westwater Canyon Member of Morrison Fm; unusually discontinuous pattern of Westwater channel sands on isolith map of Galloway (1980, fig. 1) is consistent with right slip on Ambrosia Lake fault, and a complex of conjugate strike-slip faults.

amide ancestry for the Zuni fluorspar deposits. Goddard's map clearly shows that the Cerro Colorado fault (CCF), although locally covered by basalt, is a distinct right-slip fault (with 10° plunge of slickensides) and several right-lateral offsets of fault block corners. His portrayal of "breccia-reef quartz veins" at releasing bends, in many of the major reverse faults, provides a critical sense of lateral shear component for these Laramide structures. Hydraulic implosion breccias, presumably equivalent to Goddard's breccia veins, are now recognized as common features at releasing bends in strike-slip fault systems (Sylvester, 1988, p. 1691). Offset of dikes and other steeply dipping contacts in the Precambrian rocks, as mapped by Goddard, were also used to interpret local sense of lateral shear. Our own observations of right-slip on the Las Ventanas fault (LVF) and other faults on the NE periphery of the uplift are based on the criteria of Angelier et al. (1985). En-echelon small fractures that splay into the fault zone from the main fault surface, at angles (15–20°) appropriate for Riedel shears, were the most useful criteria of Angelier et al.

In the Cerro Colorado area (Fig. 3), small N-trending half grabens that contain inliers of Permian rocks have been identified by the typical aspect of normal faults—hanging-wall strata dipping gently into the structurally higher block. High-angle reverse faults are identified from dip observations of Goddard (1966) and a common association with abrupt monoclinal warping of adjacent strata.

For a basic description of the Zuni uplift and a discussion of its possible origins see Kelley and Clinton (1960, p. 45–48). We note with esteem that Kelley could *not* accept the notion of a simple regional stress field as a cause for the Zuni uplift. The age of the Zuni uplift is loosely constrained. Regional data of Chapin and Cather (1983) imply that it is a late Laramide uplift of Eocene age.

Gravity domains

Our interpretation of gravity patterns within the area of Figure 3 is based on two simplifying assumptions that seem to work. We assume that: (1) adjacent to or "off" the uplift the patterns are essentially of pre-Laramide ancestry, and (2) within or "on" the uplift the patterns represent a combination of locally distinct Laramide blocks superimposed on pre-Laramide structural trends. As previously stated, the exposure of a gneissic gabbro near Aragon (Agg), which lies along the axis of the El Morro gravity high (EMGH), is a primary line of evidence for its interpretation as a Precambrian mafic belt, capable of acting as a rigid indenter.

We have chosen the –224 mgal contour from Keller and Cordell's (1983) Bouguer gravity map as a reasonable approximation for the shoulders of the gravity high, since it generally follows an inflection in the contour pattern between the clearly defined axis of the high and adjacent gravity lows. Jenkins and Keller (this guidebook) present Bouguer and residual gravity maps that include the Zuni uplift. Their maps show the detailed patterns that we describe here. Our hypothesis concurs with their interpretation of the regional trends. Truly interested readers may want to make an overlay to compare the gravity maps from either of these sources to Figure 3 (scale 1:625,000).

All gravity measurements in the Colorado Plateau and western Cordillera are relatively low on a continental scale and recorded as negative numbers. Thus, the axis of the EMGH lies within –224 mgals and is flanked by gravity lows with axial values as low as –240 mgals (the low is a numerically larger number, but negative in sign). The EMGH appears to widen sharply as it crosses onto the Precambrian-cored (darker shaded, Fig. 3) blocks that mark the NW-trending axis of the Zuni uplift gravity high (ZGH). This same mushrooming pattern of the gravity contours would also be evident if values between –218 to –230 mgals were chosen to define the EMGH. We therefore think this pattern is significant and generally defines the north face of the El Morro indenter. On the color-contoured, residual gravity map of Hildebrand et al. (1982), the Zuni uplift gravity high (ZGH) appears as a glowing orb which seems to emanate from the tip of the El Morro gravity high (EMGH). This perspective was one of the early observations that suggested to us an indentation-extrusion origin for the Zuni uplift.

The –224 mgal contour around the ZGH is distinctly arbitrary and only provides a general configuration of the Zuni uplift. Actually, the –224 mgal contour does not close on the north side of the Pinedale block (PB), and it is projected across a vague low between the core of the ZGH and another high in the Gallup sag to the NW. The approximated –224 mgal contour was chosen because of its continuity with the EMGH and because it seems appropriate to show at least one contour of equal gravitational potential about the uplift. As stated previously, the large hydrostatic pressures that are created at the face of the indenter near its base (mid crust), are intermittently balanced by the increasing gravitational potential of rocks uplifted around the high pressure zone. At –208 mgals, Mount Sedgwick is the high point of the uplift. Steep gravity gradients are associated with the Mt. Sedgwick block (MSB) and support the estimate of 1 km of throw on the Mt. Sedgwick fault (MSF) and about 300 m on the Agua Fria monocline (AFM) (Hackman and Olson, 1977, sheet 2). The total estimated structural relief on the uplift—from Mt. Sedgwick to the northwest termination of the Nutria monocline—is estimated to be 2400 m (Hackman and Olson). The largest gravity gradient parallels the Nutria monocline, with undulations in the gravity pattern appropriately paralleling undulations in the monocline. The steep gravity gradient parallel to the Nutria monocline merges with a slightly smaller gradient which parallels the Dan's Valley reverse fault. The Dan's Valley fault (DVF) exhibits about 60 m of vertical component, down toward the crest of the uplift—in the wrong sense to satisfy the gravity trend. We suggest that the Dan's Valley gravity trend primarily reflects lateral (westward) slip of the Camp Seven (CSB) and Rincon Dome (RDB) blocks along the north face of the indenter.

Gravity stations are widely separated in the western part of the uplift (Keller and Cordell, 1983). However, the two main westerly extruded blocks shown on Figure 3, the McGaffey block (MB) complex and the north Nutria block (NNB), do exhibit a weak gravity high along their crest lines and appropriate trends in the gravity potential. The northern apex of the Bluewater Lake block (BWB) is associated with an almost closed 1–2 mgal gravity low, roughly symmetrical about the point of the wedge. We think this supports our interpretation that the Bluewater block formed the apex of an accreted wedge which was depressed as it split and forced apart blocks being extruded to the left and right. The Grants monocline (GM, Fig. 3) system is associated with a moderate gradient toward Mt. Taylor. The Fernandez monocline (FM) has no clear gravity expression.

In summary, the gravity field about the Zuni uplift appears to support the concept of an indentation-extrusion origin. The Mt. Sedgwick block (MSB) was distinctly uplifted, apparently bringing relatively dense mid-crustal rocks closer to the surface. The McGaffey (MB) and North Nutria blocks (NNB) were apparently uplifted and extruded westerly, parallel to local gravity highs, to form the Nutria monocline.

Comparison with the extrusion experiment

We believe that the tectonic map of the Zuni uplift (Fig. 3) exhibits several similarities (and some differences) in geometry to the plasticine extrusion experiment shown in Figure 2. The most obvious difference is that the large blocks extruded to the left in Figure 3 formed a reasonably straight line of strong convergence as expressed by the Nutria monocline. The totally unconstrained faces of extruded blocks in the experiment (Fig. 2) do not line up and are at a much higher angle to the face of the indenter. We suggest that in the real world of the Zuni Mountains, the extruded blocks moved to and then along the same zone of weakness. Presumably this zone of weakness represents a pre-Laramide shear zone that truncated the EMGH. As much as 2 km of apparent right lateral offset of a steep contact between gneissic granite and metarhyolite was mapped by Goddard (1966) along the Redondo Canyon fault (RCF). We think this sense of shear and amount of offset is locally inappropriate for Laramide deformation. Therefore, we believe the Redondo Canyon fault was part of a major pre-Laramide shear zone. The existence of a pre-Laramide shear zone would explain the general alignment of blocks along the Nutria monocline with the strongly uplifted blocks at Mt. Sedgwick.

The Bonita Canyon shear zone (BCSZ) is suggested as an analog of the zone of intense right lateral shear near the right corner of the indenter in the experiment (Fig. 2). Fault and vein relationships at the section 27 fluorspar mine (27 M, Fig. 3; Goddard, 1966) locally indicate a zone of pure shear in front of the indenter. The Bluewater Lake block (BWB) apparently forms the apex of an accreted wedge, similar to the "partially adhered block" of Figure 2. It is the abrupt change in sense of vergence between the McGaffey block (MB) complex and the Mt. Sedgwick block (MSB) complex (along the Cottonwood Canyon shear zone, CCSZ) that originally convinced us that extrusion tectonics could be applied to the Zuni uplift. The Cottonwood Canyon shear zone (CCSZ) would be a classic example of compartmental deformation, as defined by Brown (1984). The general sequence of development of fault blocks that make up the Zuni uplift is summarized in Table 1. Thus, this table summarizes the evolution of the Zuni uplift as we presently understand it.

EVIDENCE OF STRIKE-SLIP FAULTING

Several areas on the tectonic map imply the existence of significant strike-slip motions on faults in the region. We suspect that the largest amount of strike-slip has occurred on the Chain of Craters shear zone (COCSZ) and a refracted continuation of this zone expressed by the Mount Taylor volcanic trend (Fig. 3), but can offer no proof. The Cottonwood Canyon shear zone (CCSZ) appears to truncate a local, white-colored facies in the basal San Andres Formation (Psw, Fig. 3; cf. Fig. 4). We interpret the Mulatto Canyon fault (MCF), and adjacent geometric constraints mapped for the pinchout of the Satan Tongue of the Cretaceous Mancos Shale (Santos, 1966), as evidence for over 1 km of local left-slip on this fault. Galloway's (1980, fig. 1) sandstone isolith map of the Westwater Canyon fan system (Morrison Formation) shows a seemingly inappropriate amount of discontinuity and changes in trend adjacent to the Ambrosia Lake fault (ALF). We suggest right-lateral shear on the Ambrosia Lake fault in conjunction with unrecognized conjugate strike-slip faults could have formed this discontinuous pattern. Both Kelley and Clinton (1960, fig. 2) and Maxwell (1986) recognized that the fault designated here as the Cerro Colorado fault (CCF) shows evidence of right-lateral shear.

Mapping by Anderson (1987) in the Atarque–Fence Lake area provides control on the landward pinchout of the Pescado Tongue of the Cretaceous Mancos Shale. This northwest-trending pinchout projects to the Atarque area on the north side of Jaralosa Draw, a basalt-filled paleovalley. Along the strike of the projection, south of the basalt, lie exposures of the nonmarine Moreno Hill Formation. These field relationships imply from 1 to 5 km of left lateral offset across a hidden fault related to the left flank of the El Morro gravity high (EMGH).

We have observed numerous crushed zones and near vertical shears with subhorizontal slickensides in upper Cretaceous sandstones along the east flank of the Zuni uplift. Many of these are unmapped (Fig. 5),

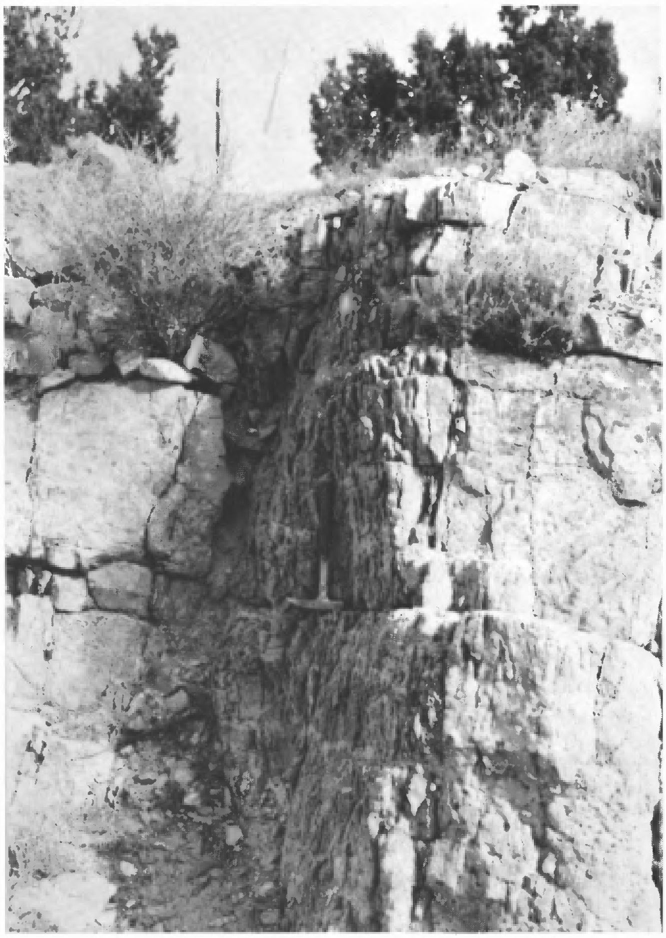

FIGURE 5. Well exposed, but unmapped, zone of dextral shear cutting Dakota Sandstone in old railroad grade cut adjacent to the Rio San Jose ($\mathrm{SW}^{1}/_{4}$ sec. 10, T10N, R9W). Site is on Grants monocline near its southern terminus, bedding dips 18° to ENE (to right and away from view point). Note total rupture (10-cm-thick gouge) on left side of zone. Faintly preserved slickensides plunge 40° to NNE, subparallel to strike of anastomosing shears visible on right. Sense of shear, after bedding is rotated to horizontal, is dextral, with minor normal component. This is one of four similar shears exposed across a zone 20 m wide. This shear zone may represent the continuation of the Las Ventanas right-slip fault, which presumably formed prior to inclination of the Grants monocline. This site is known to local residents as Mitote' (B. McBride, oral commun., 1989). Hammer is 30 cm long.

and some are only now being documented (see Day 1 and Day 2 road logs, this guidebook). We believe that strike-slip faults, some with several kilometers of offset, do cut across the Colorado Plateau. We suggest that one must look in the right places, with an open mind, and collect detailed data in order to document strike-slip faults.

A TEST OF THE HYPOTHESIS

Prior to the development of our indentation-extrusion hypothesis, we had collected observations on slip directions of conjugate microthrusts from three sites on the northeastern periphery of the Zuni uplift. The general character of these microthrusts at a fourth site is shown in Figure 6. At all three sites—(1) Lobo Canyon, (2) Exit 89 and (3) Sandstone Overlook—the microthrusts were observed in basal sandstones of the Dakota. The locations of these sites are plotted on Figure 3; they are 13 to 15 km apart. We interpret the slickensides on the microthrusts as Laramide structures formed parallel to the local maximum horizontal compressive stress during the formation of the Zuni uplift.

The data are summarized in a stereographic plot shown as Figure 7. Examination of the data supports the following conclusions: (1) the conjugate sets are essentially symmetrical about bedding, (2) they have been rotated with bedding to their present orientation, (3) site means are distinctly different, (4) site standard deviations (variability) increase toward the south and (5) comparison with the map (Fig. 3) implies they radiate from near the face of the proposed indenter. When plotted on a map, the mean stress orientation lines intersect (with a small triangle of error) at a point about 5 km SSW of Aragon (Fig. 3). The Sandstone Overlook is distinctly off to the right of the El Morro indenter, whereas the Lobo Canyon site is well out in front of the indenter. Thus, the greater variability at the Sandstone Overlook may reflect some northward movement of the indenter face as the microthrusts formed. Alternatively, these microthrust observations might be interpreted as a product of late-stage gravity sliding off the uplift. But this latter possibility would not be consistent with our observation that there are no microthrusts, only tension fractures in the Dakota Sandstone at the Narrows (Fig. 3). Appropriately, the Narrows area lies behind the El Morro indenter in an anterior zone of tension (Table 1).

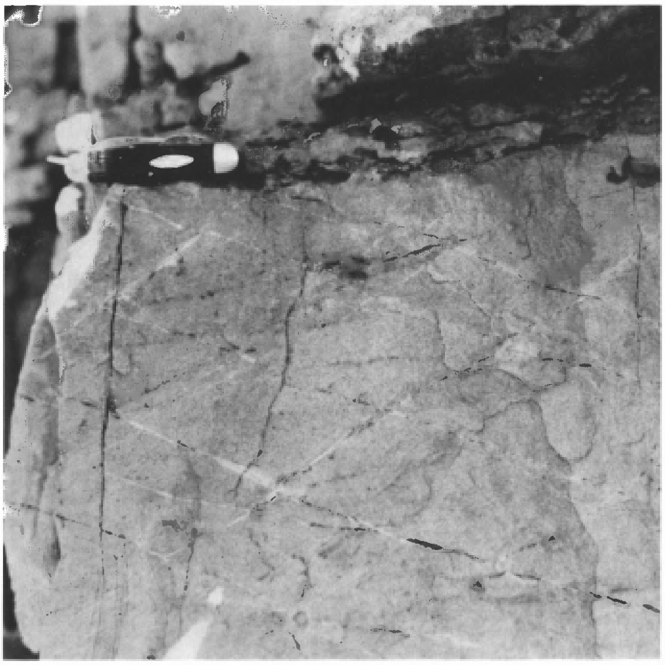

FIGURE 6. Looking north at cross-section view of conjugate microthrusts (white lines and dark linear vugs) in late Cretaceous Paguate Sandstone about 1.5 km north of Las Ventanas windmill (SW¼ sec. 21, T9N, R9W). Note low angle of intersection to bedding (parallel to knife). Right-dipping fractures preferentially offset left-dipping fractures with hanging wall up. Knife is 9 cm long.

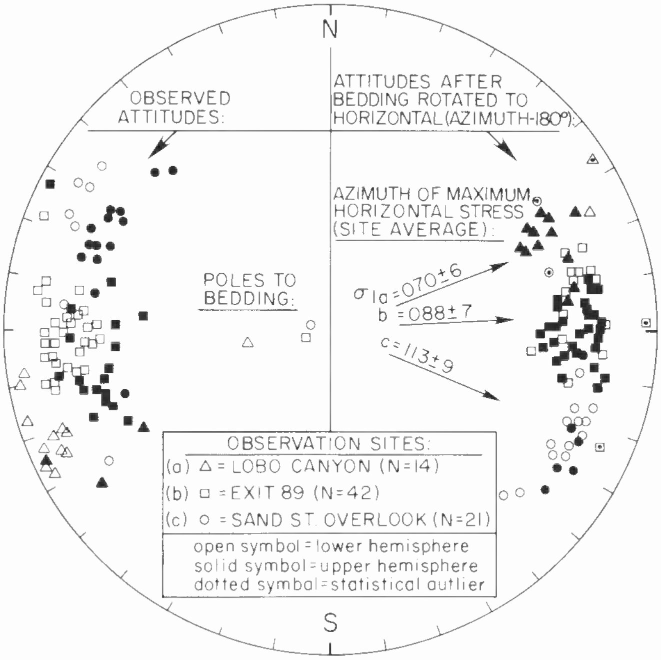

FIGURE 7. Stereographic plot of slickenside orientations found on microthrust faults at three sites along the northeast flank of the Zuni uplift. Site locations are shown on Figure 3. Reoriented attitudes, with site bedding horizontal, are arbitrarily plotted to their inverse azimuth (reoriented azimuth-180°); so they do not plot on top of the original observations. Site means and standard deviations were calculated with outlier data omitted.

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