DAVID BLOOM Bloom

COLLAPSE OF ROCKY MOUNTAIN BASEMENT UPLIFTS

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ABSTRACT

Several Rocky Mountain uplifts have collapsed, usually back down the root-zone of the thrust that raised the uplift because isostatic stresses were concentrated there. In the buckled slabs, basement is juxtaposed next to deep sedimentary fills and probably more basic subcrust is juxtaposed next to the granitic upper crust at their bases. Uplifts have "anti-roots" and strong positive gravity anomalies with slabs held up by strength rather than buoyancy, making them susceptible to collapse. The Rio Grande rift trends along the crests of older uplifts. Collapse may have been accentuated by Neogene uplift that removed softer basin fills. This substitution of "air for rock" should have increased gravity stressing.

Some of the largest gravity faults on the foreland, including the Sangre de Cristo Range-San Luis Basin boundary fault and possibly the Teton fault, each with structural relief that may exceed 20,000 ft, are caused by this mechanism. Their large size may be because a significant increment of displacement above the isostatic equilibrium position is added to the buoyancy mechanism that drives these faults.

The north side of the Brown's Park graben in the eastern Uintas bears this root-zone control relationship to the Uinta thrust, increasing in distance from the thrust trace as stratigraphic throw and amount of overhang of the thrust increases. A plunging section of the South Granite Mountains fault system in the area of Ferris Mountain provides a down-plunge cross section in which the collapse fault can be seen to join and "back down" the root zone of the thrust that raised the uplift. In all of these cases the outer thrust lip "hung up" and is left standing higher than the once-higher core of the uplift. Distance between the two types of faults provides a rough estimate of the amount of overhang of the older thrust over sediments of the basin block.

Collapse has taken place during the Laramide compressive episode by "isostatic thrust reversal" in which the basin and uplift rim thrust back over the uplift core as isostatic stresses cause failure. This decreases the size and stressing of each. The low-angle footwall under the Wind River Range gave support and prevented major collapse. Models show these relations.

Several lesser but logical types of gravity failure are present including sag of thrust overhangs and failure of oversteepened range fronts and dip slopes.

INTRODUCTION

The purposes of this paper are: 1- document collapse of uplifts in the Rocky Mountain foreland, 2- explain the collapse, and 3- use that collapse to gain as much information as possible about buried geometries and mechanical attributes of the structures involved. To do this effectively, it is necessary to: 1- describe the geometry of the earlier compressive deformation and 2- discuss "first causes" during collapse.

In the Rocky Mountains in the United States, a superposition of earlier compressive and later extensional structural styles have resulted in abnormally deformed cratonal basement for several hundred kilometers inward from the most external thin-skinned thrusting. This foreland breakup is an exception to the rule, since the Canadian Rockies and most other orogenic belts are thin-skinned in their external parts and the basement in front is isostatically depressed and essentially unbroken (Bally and others, 1966).

SUMMARY OF EARLIER COMPRESSIONAL STRUCTURES

The older structural style is the Laramide (Late Cretaceous-middle Eocene) compressive breakup of the foreland which dominated the deformation in Wyoming, southern Montana, western Colorado, much of New Mexico, and parts of Utah, Arizona, and Idaho (Fig. 1). The reader should refer to Blackstone, 1963; Love and others, 1963; Prucha and others, 1965; Sales, 1968; Stone, 1969; Tweto, 1975; and Stearns, 1978, for broad-scope summaries from a variety of perspectives. A genetically similar Permo-Pennsylvanian ancestral Rockies deformation (Mallory, 1958; Kluth and Coney, 1981) was concentrated in the southern part of the area (Fig. 2).

Both the Laramide and Permo-Pennsylvanian episodes caused up to 40,000 ft of structural relief on "stubby", often arcuate basement-cored uplifts with diverse trends and generally asymmetric cross sections (Blackstone, 1963; Sales, 1968; Stearns, 1978). Equally impressive intervening basins of similar diversity of trend and asymmetry developed (Berg, 1962; Keefer, 1970; Love and others, 1963).

Bounding structures between uplift and basin have been subject to diverse interpretations, even though this is a mature exploration province and they are spectacularly, if only partially, exposed. This may be because there is as much diversity in the people who study them as there is in structures themselves. While some workers favor one configuration and apply it to all structures, my own prejudice is that a spectrum of frontal geometry exists ranging from high-angle normal through low-angle thrust, but probably with high-angle thrust dominating and a modest (2-10%) of regional shortening. Low-angle normal faults are scarce except in gravity detachments. The high-angle normal faults that formed during the older compressive episode are like crestal grabens on compressive anticlines. They are a logical part of, but do not characterize the structure; yet, because they are high and well exposed, they receive an abnormal amount of attention.

While some geologists (Bell, 1955; Smith, 1965; Sales, 1968; Stone, 1969; Thomas, 1971) have emphasized the role of wrench faulting, horizontal offset appears to have been modest and just enough to accommodate the shortening on the thrusts with which they are linked. Their horizontal component is almost always quantitatively overshadowed by the vertical component, as for example the north flank of the Uinta Mountains, where the

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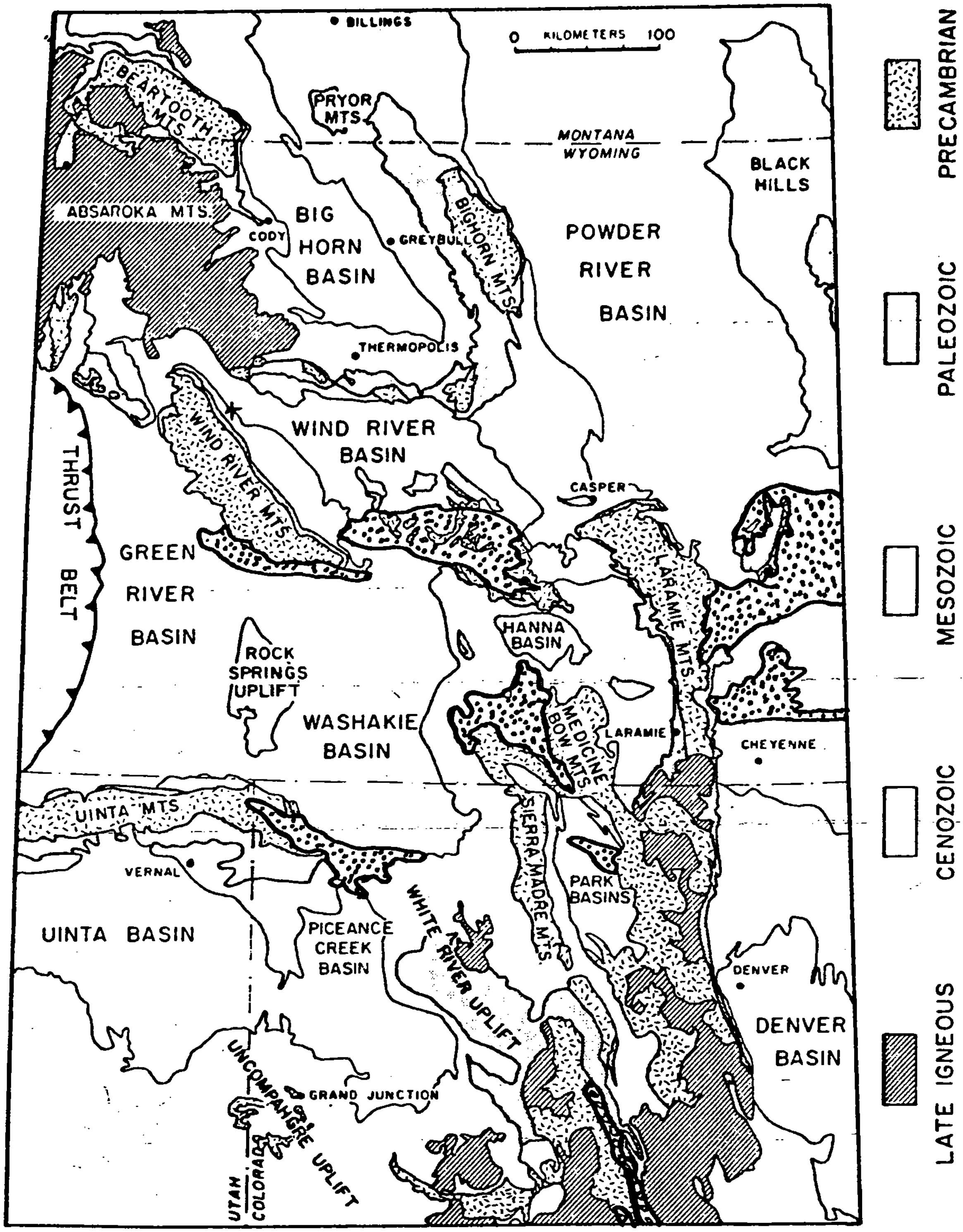


Figure 1. Generalized index map of the northern and central Rocky Mountain foreland modified from Stearns (1978). Miocene fills (heavy stipple), strongly controlled by collapse, have been added from King and Beikman (1974).

strike-slip equals four-tenths of the dip slip (Hansen, 1965). A general lack of piercing points makes the existence of wrench faults difficult to document.

The presence of thrust overhangs of the basement over adjacent basin sediments is well known, with penetrations catalogued by Gries (1983). The largest appears to be on the southwest flank of the Wind River Range (Berg, 1962; Berg and Romberg, 1966; Smithson and others, 1978; Brewer and others, 1980) where in excess of 12 mi of overhang seems established both by reflection seismic and gravity data, and the outer edge has been penetrated by the drill several times (Gries, 1983).

Most well penetrations have been near the outer edge of the potential overhang and seismic evidence usually deteriorates toward the uplift. Consequently, it would be helpful to augment drill and geophysical evidence with field examples. There is evidence for six miles of thrust overhang in a plunging area of the South Granite Mountains uplift (Sales, 1971). The important geometric fact was established there that a major collapse fault

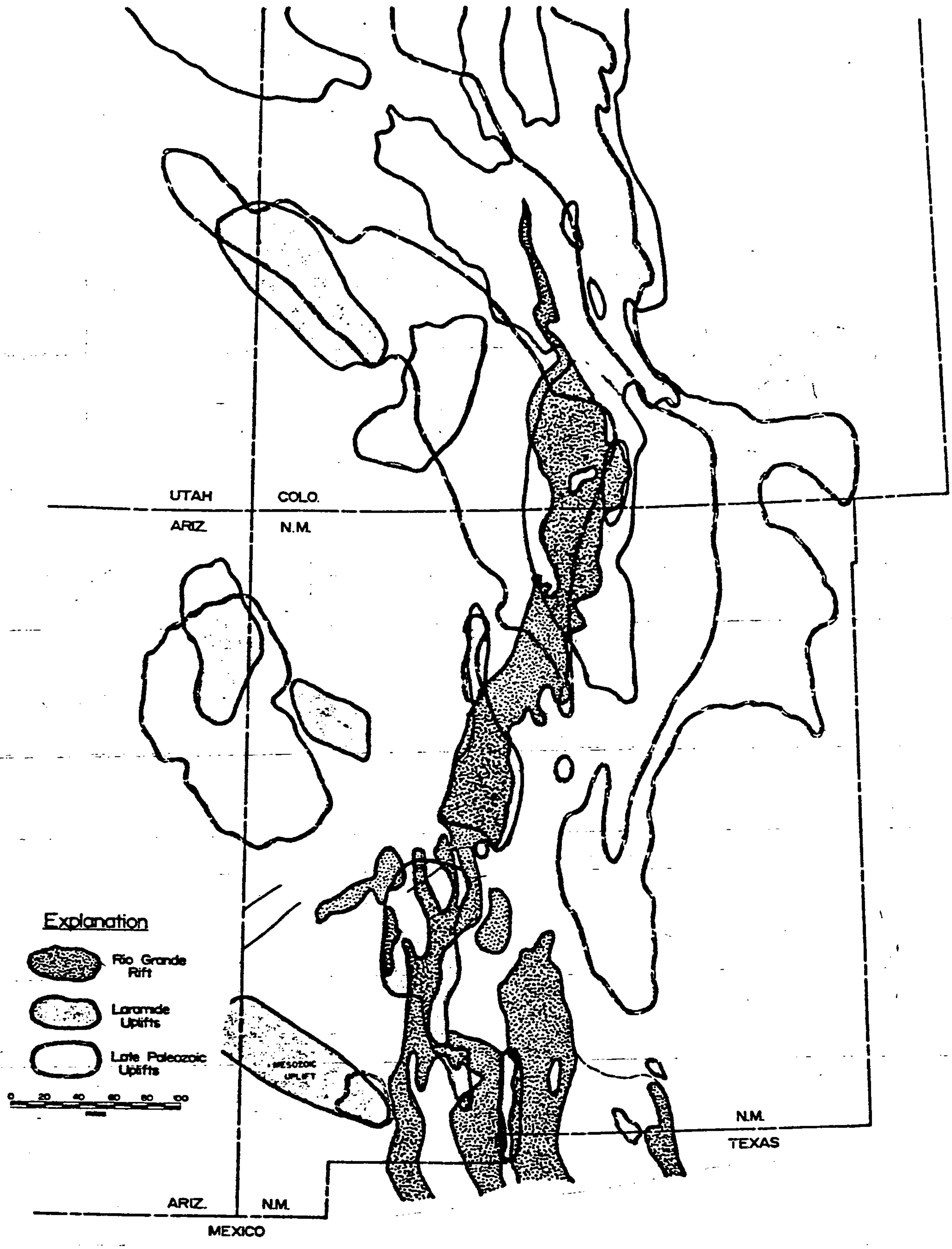


Figure 2. Outline map of the Rocky Mountain foreland in Colorado and New Mexico modified from Chapin and Seager (1975) showing overprinting of the younger Rio Grande rift structures on Laramide and late Paleozoic ancestral Rockies uplifts.

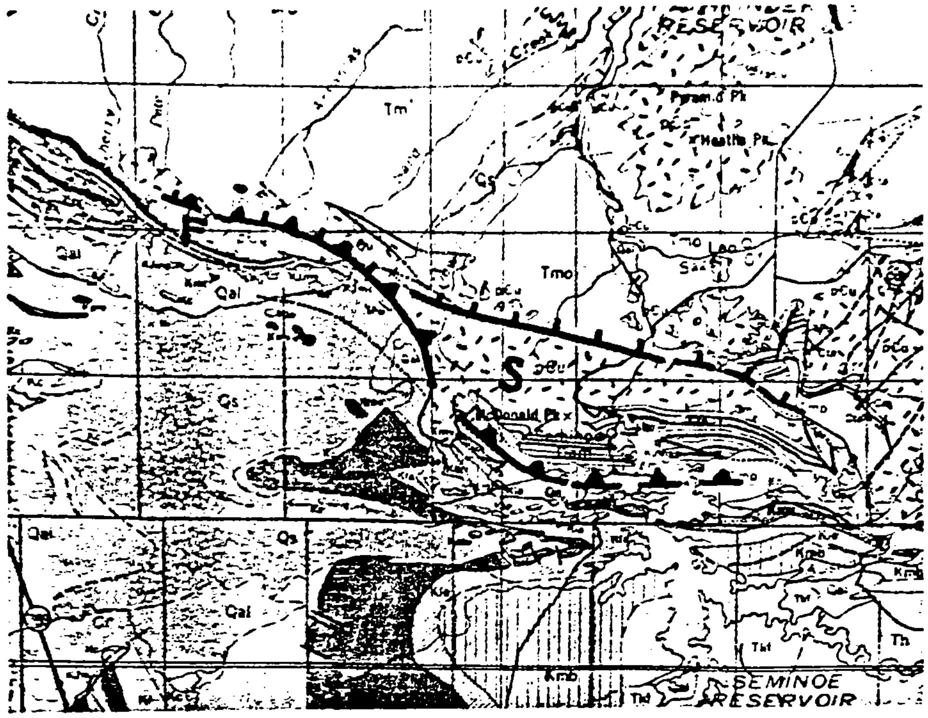


Figure 3. A part of the state geologic map of Wyoming (Love and others, 1955) showing the eastward-plunging south flank of the Granite Mountains uplift. Laramide thrust (sawtoothed) raised the uplift relative to the basin and later normal fault (hachured) collapsed the range core relative to the high-standing south rim at Ferris Mountain (F) and Seminoe Mountains (S). At its west (rootward) end the thrust is interpreted to have both earlier thrust and later collapse movement. Cretaceous Mesaverde (Kmv) forced into a syncline and anticline by the southward push of the thrust. All of these relations can be seen by viewing the map down-plunge at a low angle from the west. Square grid is townships for scale.

converges in an up-plunge direction with the older thrust that caused the uplift, and joins it (Fig. 3). This is equivalent to the collapse fault "backing-down-the-root-zone" of the thrust in cross section (Fig. 4), as first suggested by Sales (1968) stressed-slab experiments (Fig. 5). These stressed slabs seem to be substantiated by the gravity characteristics established by Berg and Romberg (1966) and Malahoff and Moberly (1968) and are shown graphically on the new regional gravity maps of the United States (Hildenbrand, 1982), which suggest that the uplifts have "anti-roots" rather than "roots" and are held up by beam strength rather than isostasy.

The geometry of the Granite Mountains lends itself to a surface technique for estimation of overhang of an unexposed large thrust; the eastern Uinta and Sangre de Cristo uplift margins are used as additional examples. The down-structure reconstruction at Ferris Mountain demonstrates that there can be closed structures generated under the overhangs because a logical case can be made that West Ferris Mountain anticline was formed under such an overhang which has since been eroded. In a similar manner, one possible interpretation suggests that Clay Basin anticline was formed under the Uinta thrust, the lip of which has been eroded back due to cross-arching by the Rock Springs uplift.

REGIONAL STRESSES (FIRST CAUSES)

The conceptual framework within which one views the detailed structural relations tends to prejudice even the more factual of those relations. Therefore, it is judicious to set down the basic rationale of how the regional mechanism is perceived, even though this is obviously the most speculative part of a paper. This is the reasoning for first presenting the broad speculations, next the more detailed principles that seem to logically follow, and last, the specific examples.

I detailed in 1968 the lines of evidence that Wyoming deformation is fundamentally compressive, driven by plate interaction at the Pacific margin, and is an integrated mechanical system. In short, a subducted plate crumbled the foreland, even though this was an unusual response in terms of the normal way that forelands react. Many have suggested and since refined this theme (Lipman and others, 1971; Lowell, 1974; Burchfiel and Davis, 1975; Coney, 1976; and Dickinson and Snyder, 1978). All of these suggest that shallow subduction caused greater than usual foreland deformation. We may have an actualistic analog under South America, where a presently active low-angle slab (Barazangi and Isacks, 1976) seems to be causing active breakup of a type not unlike that of the Rocky Mountain foreland (Richard Allmendinger, personal communication, 1982).

I also pointed out that: 1- a near duplication in map view of the uplift-basin distribution could be achieved by a simple and logical stress sytem compatible with plate tectonics, and 2- the same model could create a diversity of cross-sectional variations that roughly mimicked the surface and subsurface geology. Stone (1969) independently interpreted a very similar regional stress orientation and mapped all of the foreland faults within this regional scheme. At least three workers (Hamilton, 1981; Chapin and Cather, 1981) have suggested refinements of this basic map-view stress system while retaining its essential precept — a crowding of the area of the craton caught between the more coherent Colorado Plateau block and the buttress of

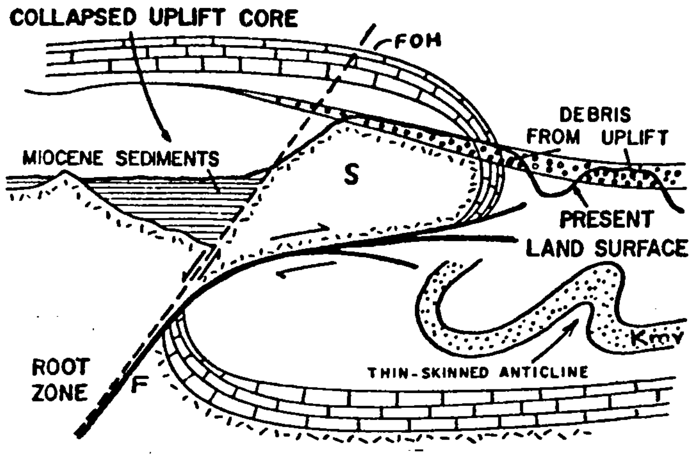


Figure 4. North-south cross section through south margin of the Seminoe Mountains, based on the down-plunge view of the previous map, showing collapsed core. Because of plunge, Ferris Mountain (F), Seminoe Mountains (S), and the Freezeout Hills (FOH) occur at successively higher positions in the cross section. Kmv = Cretaceous Mesaverde.

the craton. These workers have added needed refinements to an obviously broad-brush first pass.

It would be inaccurate to give the impression that everyone agreed with this general solution of horizontal compression. An equally represented school of verticalists have pointed out the apparent preponderance of high-angle faults and near vertical motions. They interpreted lower angle faults as the exception or as confined to high structural levels where large boundary faults have lost lateral support and collapsed basinward. They envisioned that most low-angle faults steepen downward in the tradition of Prucha and others (1965), and considered the foreland to be composed of vertical block uplifts. This point of view is well represented in Memoir 151 published by the Geological Society of America. Interestingly, workers of the vertical persuasion have a variety of opinions toward first causes. Some are apparently non-plate tectonic (Gilluly, 1963; Prucha and others, 1965). Others, such as Stearns (1978), suggested that the evidence is not available for a unique solution, that there may be space problems involved in a regional solution of horizontal compression, but that it is nevertheless attractive. Still others (Eardley, 1963; Berg, 1981, Matthews, personal communication, 1978) preferred a passive role for the crust and an active hydraulic-jacking from below by the plastic supporting stratum or deep intrusives, though Matthews apparently viewed this as having taken place within the plate tectonic framework.

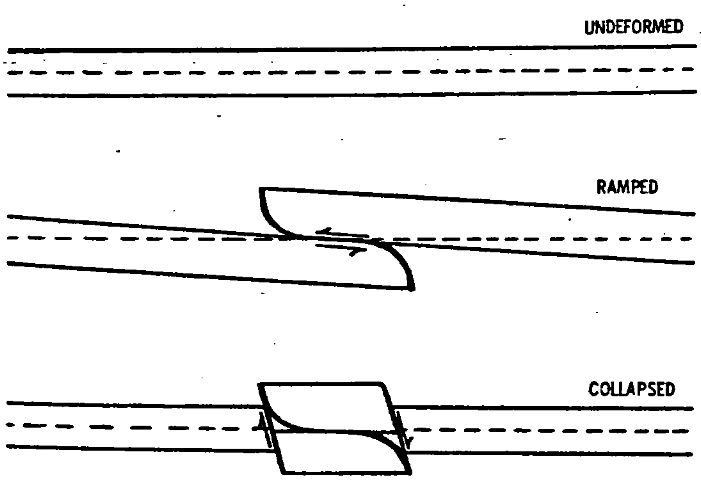


Figure 5. Basic configurations of stressed crustal slabs in the Rocky Mountain foreland. Modified from Sales (1968).

FAULT ATTITUDES

Some workers, most notably Blackstone (1980, and many earlier publications), Brown(1982), and Baltz (1972), have a strong preference for thrust fault interpretation. Others (Lowell, 1974; Ray Price and Frank Royse — informal personal discussions) have postulated that these thrusts might flatten or become listric at depth. It is interesting that the latter three workers have strong backgrounds in thin-skinned tectonics. At the other extreme, verticalists have argued that the dips of most faults at deep structural levels are near vertical (Fig. 6), as in the experiments by Sanford (1959); they also tend to envision a vertical first cause. I believe that high-angle thrusts dominate, but that a diversity of fault dips are possible in a horizontally compressed (end-loaded) stress field, with the crust as the actively buckled unit and the plastic substratum having the role of passive cushion. Several lines of reasoning make this seem logical:

1- As was pointed out by myself (1968) and Stone (1969) only those boundary structures that trend northwest-southeast are perpendicular to the regional principal horizontal compressive stress and are likely to be pure thrusts that reflect a full component of the shortening. This, combined with its western position near the source of the stress, is the basic reason that the Wind River thrust has the greatest overhang and the lowest angle, most planar trace through the crust, as expressed on the Wind River COCORP reflection seismic line (Brewer and others, 1980). The only other candidates for this full component of compression are the west side of the Casper arch and possibly some of the westward-facing thrusts on the west side of the Front Range in Colorado, such as the Elk Mountain thrust,

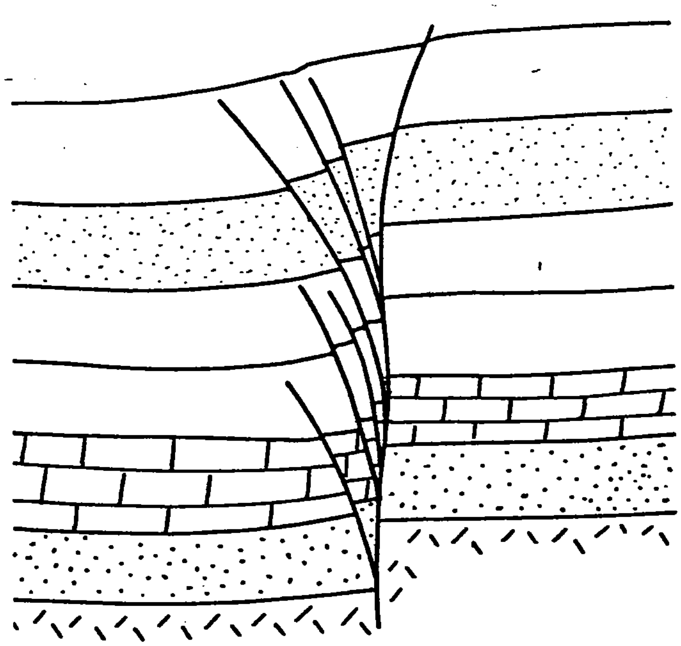


Figure 6. Cross section based on the Sanford (1959) model experiment in which isotropic dry sand with powdered markers is subjected to a vertical step offset at its base. The general sequence of fault initiation is lowest and most basinward first, highest and most upliftward last.

the eastern Sangre de Cristo fault (Tweto, 1975), and possibly the northeastern corner of the Beartooths and the Piney Creek segment of the east side of the Big Horn uplift. All of these latter structures are farther inboard (or eastward) from the source of the push or too far south toward the pole of rotation (Hamilton, 1981), and therefore, should not have as much displacement as the Wind River thrust. All other trends of frontal structures, especially the west-northwest trends (Owl Creeks, South Granite Mountains, and north side of the Beartooths, as well as the thrust on the northeastern corner of the Uinta range) are in a primary left-lateral shear relationship to the eastward-directed principal horizontal stress, as expressed clearly by Sales (1968) and Stone (1969). Even though the latter structures have closure components causing them to overhang, they are basically a hybrid between vertical strike-slip and thrust faults, and should be expected to have steeper root zones than the more northwest-trending structures. This is probably the dominant reason that west-northwest trends of structure show both more collapse (the core of the Granite Mountains and the graben of the Brown's Park) and more complex development of secondary structures (crest of the Owl Creeks) than do the northwest trends. Both Chapin and Cather (1981) and Gries (1983a) have suggested that directions of stress may have changed during the Laramide orogeny.

2- In the stress situation of loading from one side Hafner (1951), the trajectories of the principal horizontal stress (σ_1) are turned downward (Fig. 7). One conjugate shear to this stress trajectory is a rather flat fault that would be equivalent to a fault that is very nearly parallel to the basement surface near the continental margin. The other is a downward steepening fault that takes a more direct route through the simulated crust. The low-dip shear is ideally oriented to move into layered (bedding) surfaces and become the sole thrust in the thin-skinned environment, but would be inappropriate in the thick-skinned environment because it would have to traverse inordinately far through less-layered basement. The steeper shear cuts efficiently across basement, but is unlikely to occur in the thin-skinned setting because it intersects bedding, which is the greatest direction of weakness, at a steep angle and would also have to continue into the basement at a high angle. Throughgoing crustal shears do not have this limitation because they bottom against a plastic substratum rather than against a rigid basement (Fig. 5).

3- The models (used in my 1968 paper and since) have ample high-angle as well as low-angle thrusts, and many that steepen downward. The prime requirements to produce this diversity are: 1- the presence of an effectively bottomless plastic substratum, and 2- a compressive couple or rotational shear giving ample chance for hybrid faults. Because of this constraint, while the shallow subducted slab is the most plausible mode for transferring stress into the foreland, it cannot be so shallow that it prevents intervention of a plastic stratum between it and the base of the elastically buckled crust. Indeed, the compressing cratonward flow of this plastic substratum in front of a slab with prograde motion is the most logical mode of stress transmission — if there was compressive flow in the substratum, the crust on top could not help but buckle (Fig. 8). This would largely eliminate the argument by Gilluly (1972) that stresses cannot be transmitted far inward from a plate margin. Also, with the general acceptance of the Molnar and Tapponnier (1975) synthesis of the Himalayan-Baikal orogeny, the distances in the Rocky Mountain foreland are conservative in comparison.

4- Structurally and topographically high-level structures, the ones best displayed and studied, should have steeper dips and higher percentages of steep dips than those representing

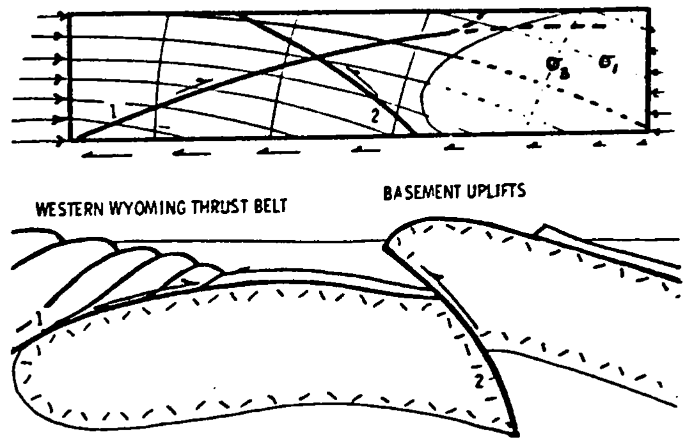


Figure 7. **Diagram comparing theoretical analysis of Hafner (1951) with a generalized cross section through the western Wyoming thrust salient, Green River basin, and Wind River uplift. The upper diagram shows stress trajectories caused by end-loading (σ 1 and σ 3) and the ensuing conjugate fault orientations (1 and 2). The flatter shear (1) is efficient in the thin-skinned setting because its orientation is nearly parallel to the basement surface and superjacent sediment layers dipping at low angles into the geosyncline to the west, and because it steps over, rather than through, unbedded basement. The steeper fault (2) is more efficient in the thick-skinned environment because it cuts at a moderately high angle through statistically isotropic basement and will be preferred as long as the crust sits on a fluid substratum rather than on a hard decollement so that the vertical component can be absorbed.**

deeper structural levels. This is the class of high structures that are conceptually in an extensional environment above the surface of no strain on the shoulders and crests of these huge anticlinal structures. I would classify most of the "horns" and high tilt blocks (Milnar Mountain, Horn area of the Bighorns, Elk Mountain, Rattlesnake Mountain, and the Pryor Mountains) in this category. I do not believe that these high level structures must all be thrusts in order to maintain that the regional stress was horizontal — again, crestal grabens are expected in compressively buckled folds. Though this paper does not attempt to resolve the dispute over the reverse, vertical, or normal attitude of these high-level faults, I would point out that they, by themselves, are not good structures on which to base arguments for first cause.

GRAVITY-INDUCED WHOLE-CRUST STRESSES

Gravity stresses develop as parts of the crust are forced out of equilibrium during buckling. They provide a strong control for later collapse. A very pronounced mechanism of tectonic control exists in the region shared by the classic Laramide foreland basement deformation and the more recent Rio Grande rifting. There is a great deal of post-Laramide extensional faulting throughout much of the Wyoming-Colorado foreland, well outside the boundaries of the physiographically defined Rio Grande rift (see, for example, Denson and Botinelly, 1949; Love, 1970; Epis and Chapin, 1975; Izett, 1975; Taylor, 1975; Tweto, 1979).

Wyoming uplifts, unlike classic fold mountain belts, have antiroots rather than roots and are held up by strength rather than buoyancy (Sales, 1968; Malahoff and Moberly, 1968). The evidence for this is the large positive gravity anomalies over uplifts (Fig. 9). As demonstrated in figure 5, the crust in the Wyoming province has been deformed into a combination of flexed and overlapping slabs bounded by a combination of monoclinal

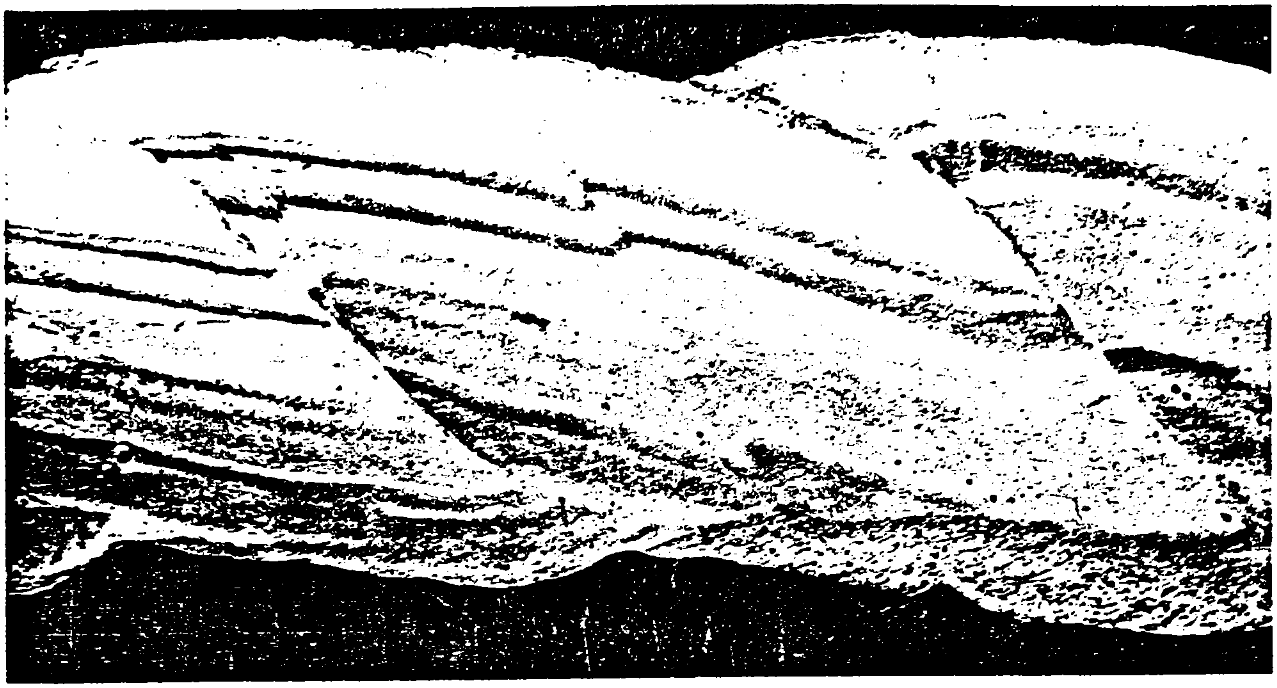


Figure 8. Model that seems to closely simulate geometry across the more severely compressed Green River basin-Wind River uplift-Wind River Basin-Owl Creek uplift area. In both nature and the model, vergence (steep asymmetry) is toward the source of the push. Faulting is in basically isotropic plaster resting on more fluid barite drilling mud. Push is from a piston on the left which serves to both end load the plaster layer and create a tectonic slope on the more fluid barite layer. The latter may dominate in transmitting stress to the other end of the model which is about 2.5 ft long. Thickness of the plaster layer with "false" black and white "stratigraphy" is about three inches. Barite was removed prior to photographing. Photo shows a few of several imbrications that progressed from left to right or outward from the source of the push. Model done by Bob Coskey.

flexure, upthrust, and overthrust boundaries involving modest crustal shortening compared with the thin-skinned thrusting to the west. Because the evidence for thrust overhang and regional plate tectonic causes has been increasing, concepts of pure block uplift and drape have become less attractive.

The role of gravity during buckling is straightforward. If the crust were located between plastic layers of its own density, there would be no gravity anomalies or stresses. The greater the density differential at the interfaces, the greater the stress. Since there is a density differential between the crust and subcrust and between the crust and air, gravity anomalies are created when the crust moves vertically. Young sediments act like a plastic layer because they are less competent and because geomorphic processes minimize relief by eroding highs and depositing in lows. Therefore, the effective density differential at the top of the crust may be about Δ .5 (2.7-2.2 gm/cc), but is highly rate and relief dependent.

The crust resists these anomalies with its strength. If slabs collapse during compression or later extension, these "frozen in" anomalies will be reduced (Fig. 5). This is the basic reason for the strong tendency of Rio Grande rift basins to be positioned over Laramide uplifts (Fig. 2).

The substitution of "air for rock" (by differential removal of less dense basin fills) during Plio-Pleistocene rejuvenation should have increased the positive anomaly over uplifts and contributed to collapse.

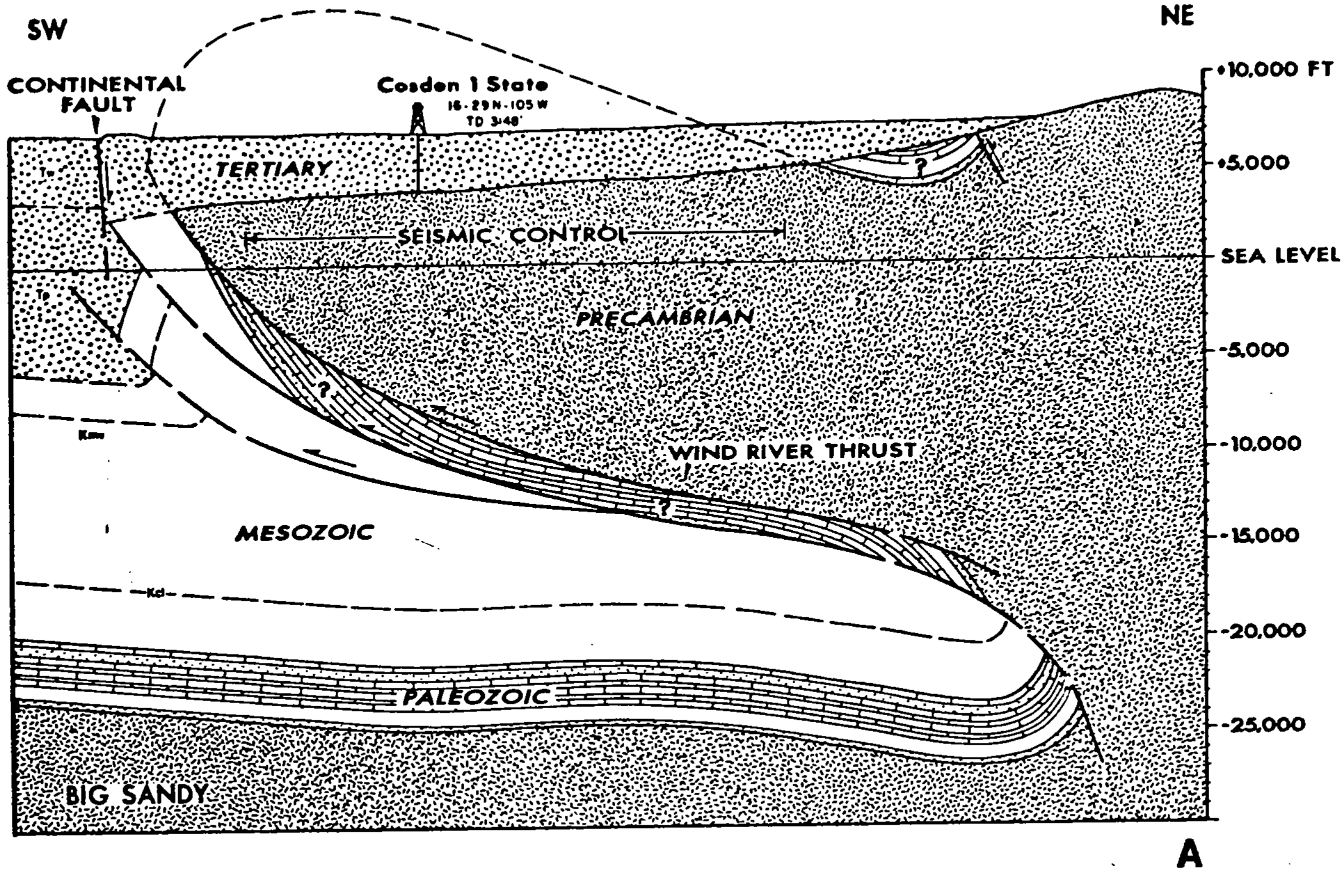
A SPECIAL CASE — COLLAPSE BACK DOWN UPTHRUST ROOT ZONES

Most of the uplifts and basins of the Wyoming province are markedly asymmetrical, the classic examples being the Green River basin-Wind River uplift, Wind River Basin-Owl Creek uplift pairs. These tilted and ramped slabs have a variety of stress along them, as shown in the stylized profiles of figure 5. Asymmetrical gravity highs are present over the uplifts as are lows over the basins, much as Berg and Romberg (1966) measured on the Wind River Range. These anomalies pass from positive to negative, where dip slopes pass through the neutral elevation. This happens again at the frontal structure, where the crust is effectively, though not necessarily geometrically, doubled. That doubling may be anything from a simple monoclinal flexure through a nearly vertical upthrust to a low-angle basement thrust, such as the Wind River thrust. The zone with the greatest susceptibility for collapse exists at either limit of the effectively doubled crust. It appears that more uplift cores collapse downward than do basins relax, though this may be partly an exposure problem. One set is highly exposed, the other deeply buried under basin fills and absorbed in incompetent strata.

Three of the larger uplifts of the Wyoming province, the Granite Mountain uplift (Love, 1970), the eastern Uinta uplift (Hansen, 1965), and the Laramide San Luis uplift (Tweto, 1979), have suffered major collapse. The "down-to-the uplift" faults, which effected collapse, parallel and are inward from the surface trace of the Laramide thrusts upon which the uplift was raised. This is because collapse took place down the root zone of the earlier thrust. Each example shows a slightly different aspect of the collapse mechanism and is discussed in more detail.

South Granite Mountains Collapse

The Sand Pass-Bradley Peak area of the South Granite Mountains uplift (Sales, 1971) can be analyzed by down-structure viewing (Mackin, 1950) which clearly reveals: 1- about six miles of overhang of basement core over sediments on the southward-directed basement thrust, and 2- a down-to-the-uplift collapse



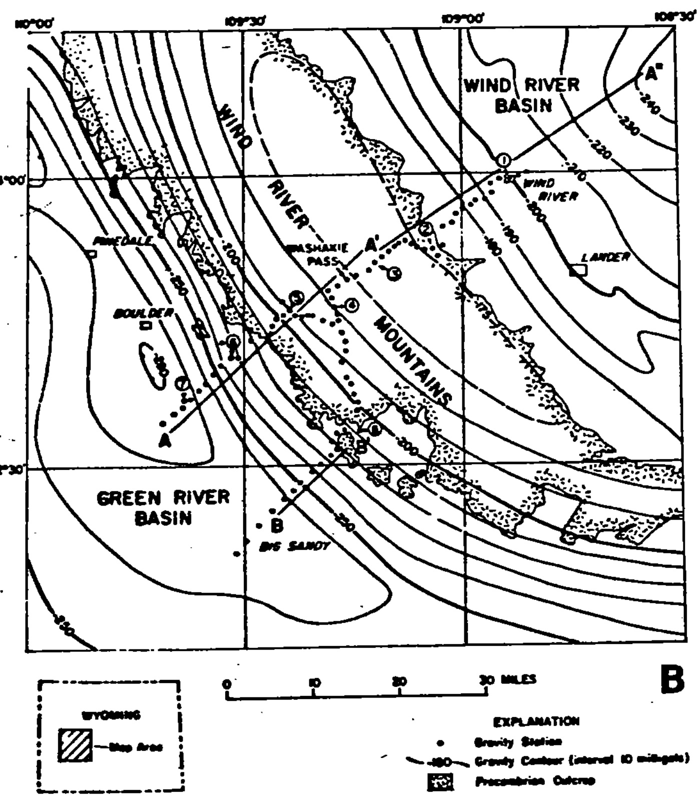


Figure 9. Cross section of the southwestern flank of the Wind River Range (A) after Berg (1962) and Berg and Romberg (1966) showing the general configuration of the southwest flank of the uplift and (B) the gravity gradient associated with it. This gravity configuration is the basis for considering the deformation as stressed crustal slabs rather than isostatically compensated "rooted" uplifts.

fault (the Pathfinder fault of the South Granite Mountains fault system) back down the root zone of the thrust, bypassing its shallow lip (Fig. 4). Because of the plunge view and erosive beveling, the later gravity fault is seen to approach and link up with the root zone of the thrust at Sand Pass (Fig. 3). This general geometry, though perhaps not its mechanical implications, was recognized earlier by Knight (1951), and is evident from his structure map of the area reproduced here as figure 10.

In addition to the relation between the thrust and normal fault, three features are noteworthy: 1- the overturned and sheared-out limb of the fold-thrust (Fig. 11), which has been penetrated in several wells on other structures (Gries, 1983) and which has been interpreted from seismic in the area of the Wind River thrust (Berg, 1962), is definitely, if only intermittently, exposed along the curving thrust trace; 2- the apparent thin-skinned Obrien Springs anticline (T.24N., R.86W.) formed by a push from the south-moving fold-thrust (Figs. 4 and 10); and 3- West Ferris anticline probably formed under the lip of the thrust prior to its erosion, and is an excellent exposed analog for exploration targets under still intact thrust overhangs.

Eastern Uinta Collapse

Once this general collapse relationship, reasoned first from simple gravity models (Sales, 1968) and then mapped in the South Granite Mountains (Sales, 1971), was realized, more areas seemed to fall into the pattern. A good case can be made that the Brown's Park graben in the eastern Uinta Mountains (Hansen, 1965; Izett, 1975) has collapsed on the younger Mountain Home fault back down the root zone of the earlier south-dipping Uinta thrust fault (Fig. 12). There is a proportional increase in stratigraphic throw, in width of the fault's crush zone, and in distance between its surface trace and the down-to-the-uplift Mountain Home fault to the south of it. This suggests that

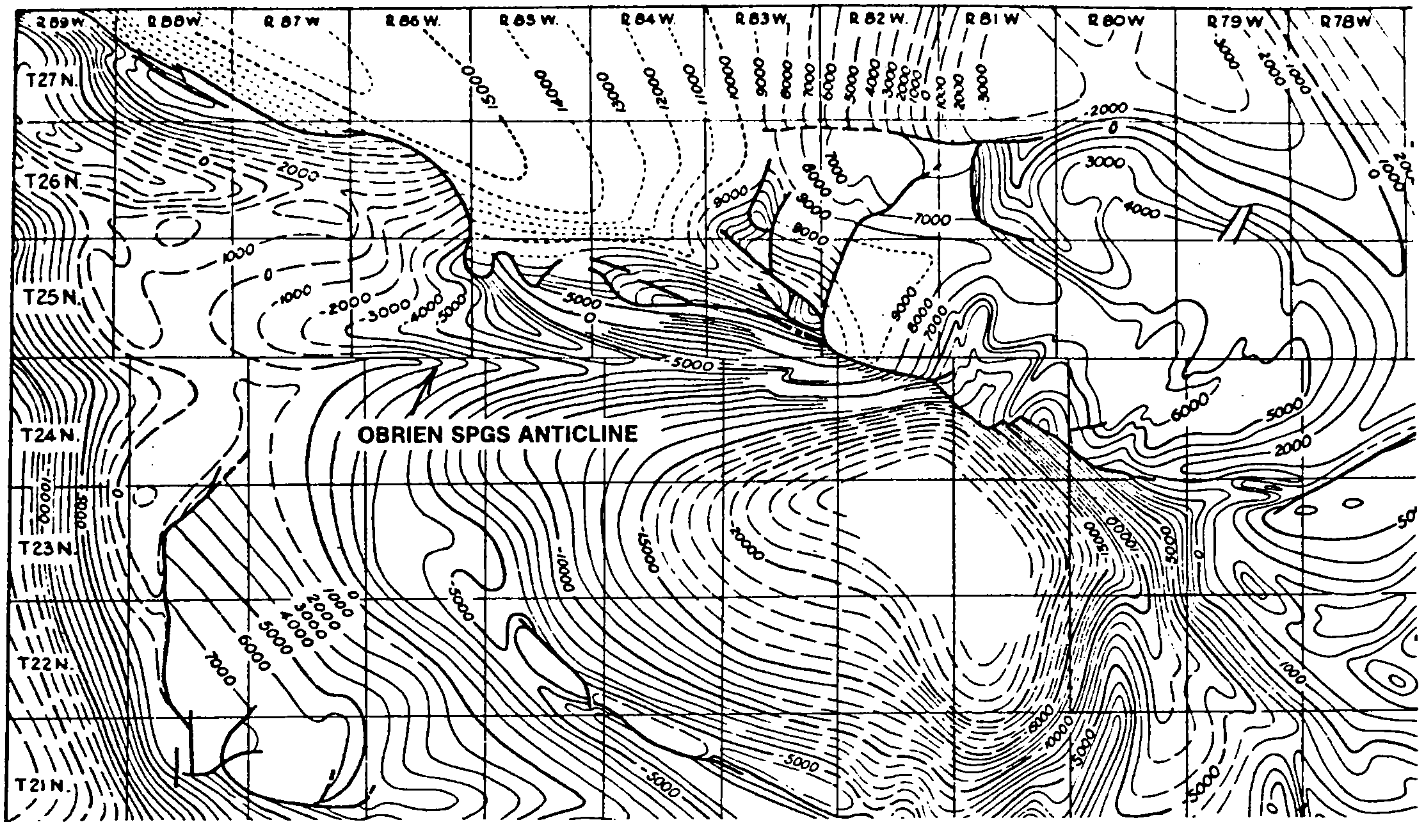


Figure 10. Structure map of the Hanna basin and the southern part of the Granite Mountains uplift after Knight (1951). The South Granite Mountains thrust plunges into the ground in T. 26 N., R. 86 W. Area of dashed contours in the northwestern part of the map shows Knight's interpretation of the presumed pre-collapse configuration of the range core. The West Ferris Mountain structure in the southern half of T. 27 N., R. 87 W. represents a very large "oilfield-sized" structure that should have been generated under the thrust lip when that lip was restored to its pre-erosional extent. Area centered on T. 25 N., R. 80 W. is the Freezeout Hills which represents the uncollapsed "bulb" on the plunging east end of the uplift.

thrust overhang increases with throw and that the collapse fault is logically spaced behind it to accommodate the eastward increase in throw (Fig. 12). Further, that spacing decreases logically where these structures are cross cut by the south-plunging axis of the Rock Springs uplift, giving the impression both that the thrust lip has been eroded back as a result of the cross arching and that the Clay Basin structure may have formed well under the thrust prior to this cross arching. West of Brown's Park where throw on the Uinta thrust has lessened so that collapse would no longer be necessary, normal faults are replaced by sigmoidally flexed anticlines which suggest that a slight left-lateral component in the root zone of that thrust system (Hansen, 1965) was also active at the surface.

Sangre de Cristo — San Luis Basin

One of the largest normal faults in the Rocky Mountain province, the Sangre de Cristo fault, may have had both its position and offset controlled by the collapse mechanism. The Sangre de Cristo Range is the most linear and uniformly wide uplift in the Colorado foreland (Fig. 13). It contrasts strongly with other, broader uplifts. Like the South Granite Mountains of Wyoming, the Sangre de Cristo uplift has different boundary structures on its two sides (Tweto, 1975). The older and geomorphically much less distinct late Laramide upthrust structure dominates and controls the east side of the Sangre de Cristo Range, while the younger and much sharper scarp on the west side is late Tertiary and still tectonically active. This same geometry can be duplicated mechanically in plaster over barite models that are first squeezed together and then pulled apart (Fig. 14).

Prior to the late Tertiary, the Sangre de Cristo Range was not a topographic or structural entity, but represented merely the east flank of the much broader Laramide San Luis uplift. The core of that uplift has since been downdropped to form the late Tertiary San Luis Basin, which is shown in the upper right portion of the photograph in figure 13. At a still earlier stage, sedimentological evidence (Tweto, 1979) suggests that the core was up-arched prior to the development of sharp uplift and thrusting on its east flank as the present Sangre de Cristo Range. This suggests the history presented in figure 15. This geometry and its causative mechanics appear to be similar in principle to that of the South Granite Mountains structure, with three differences: 1- the San Luis uplift collapse structure is several times larger than the Granite Mountains collapse structure (20,000 + vs. ± 3,000 ft throw); 2- the timing is slightly different with the San Luis uplift collapse still taking place, though there is some evidence for Eocene to Miocene collapse for most of the San Luis Basin (Chapin and Cather, 1981; Robbie Gries, personal communication, 1983), while the Granite Mountains uplift collapse was dominantly a Miocene feature; and 3- owing to lack of plunge and resultant erosive beveling, the root zone of the Sangre de Cristo-San Luis structure remains completely buried and must be inferred by the previously presented line of reasoning (Fig. 16).

The Case for Teton Fault Control

The case for collapse might also be made for the Teton fault in northwest Wyoming, though the geometry in map view is not as clear as previous examples (Fig. 17). Here, the type of stress and collapse described for the Sangre de Cristo uplift appears

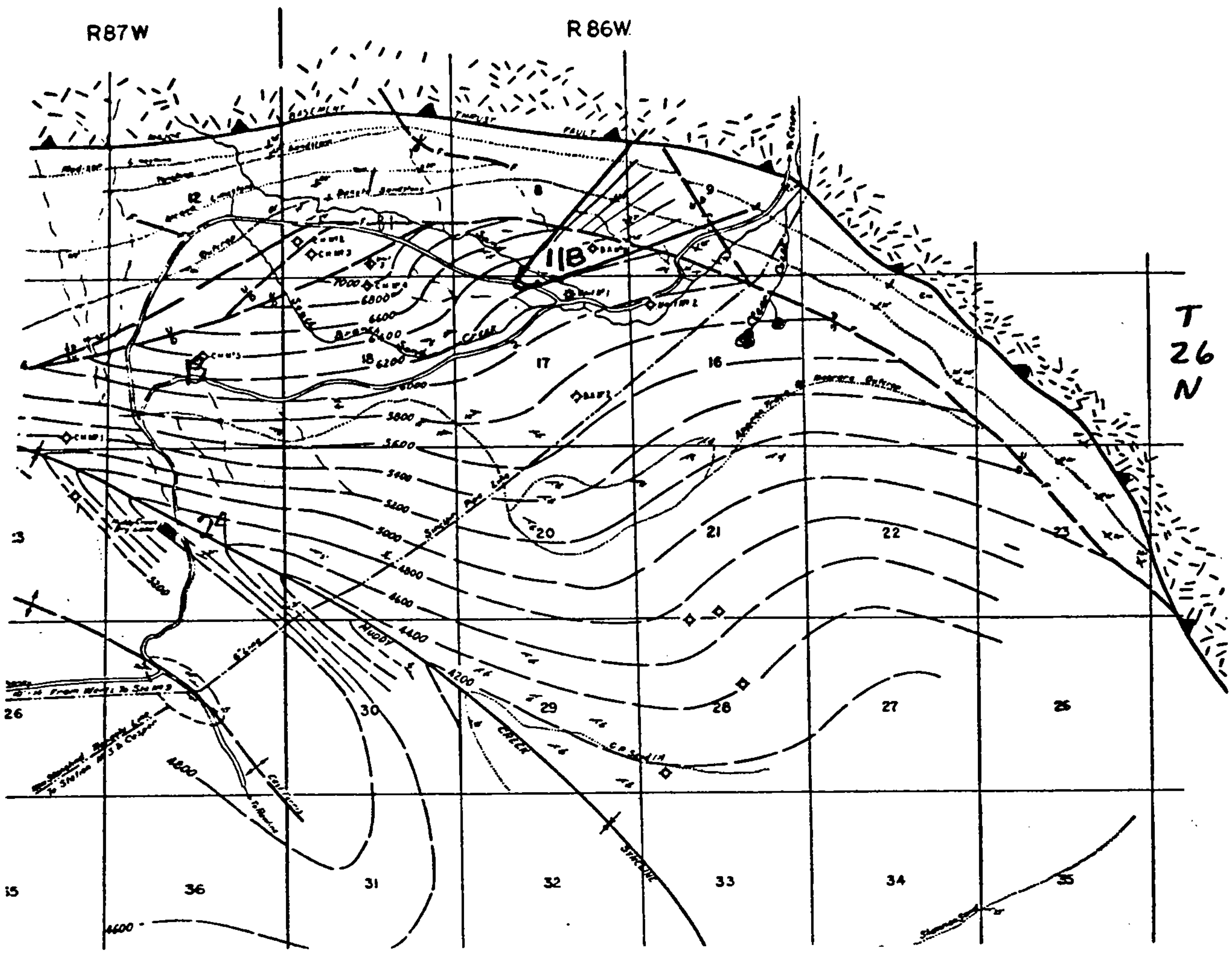


Figure 11. (A) Detailed map of the area where the South Granite Mountains fold-thrust plunges into the ground (from Veronda, 1951). Note predominance of overturned dips in the area adjacent to basement and compare with Wind River cross section (Fig. 9A).

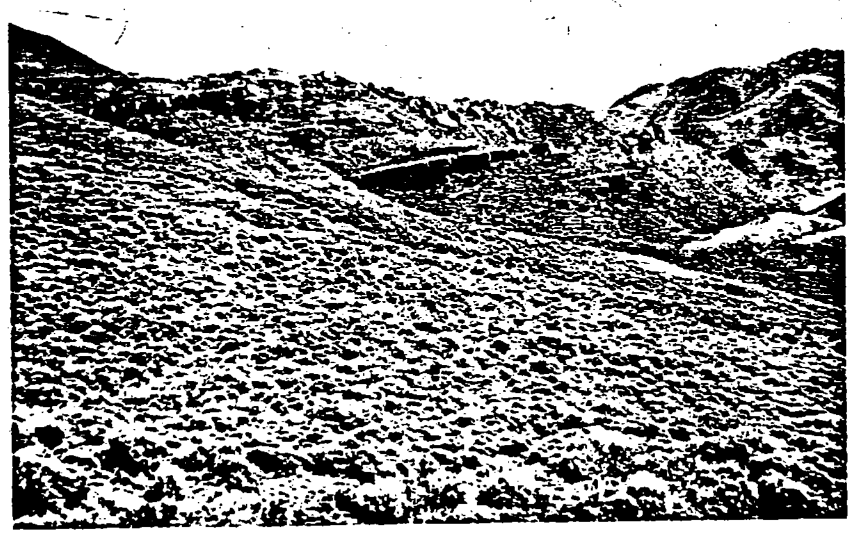


Figure 11. (B) Exposure of the overturned limb of the thrust indicated by the "photo V" on Figure 11A. Jurassic Nugget at base of slope, Triassic Alcova cliff former in mid-slope and Mississippian Madison on skyline, all overturned and dipping about 30°N.

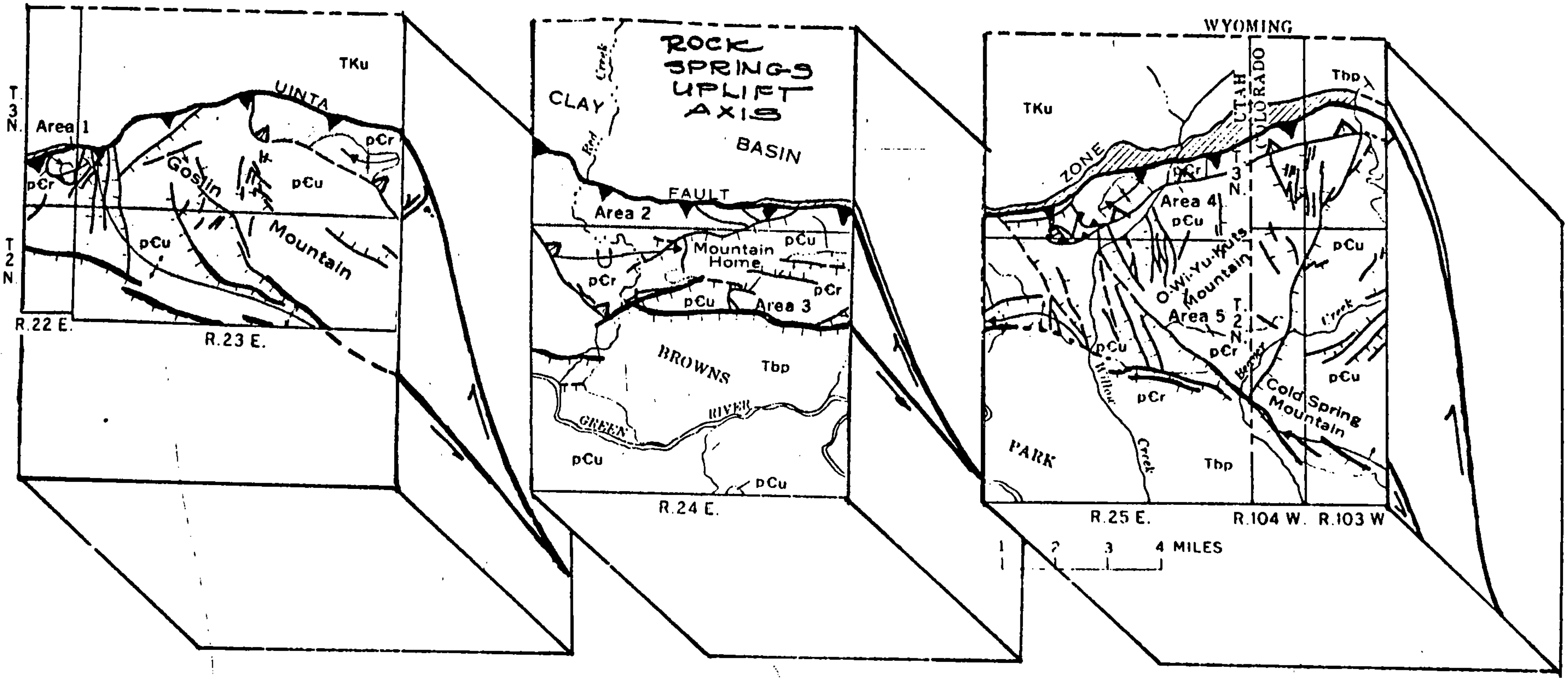


Figure 12. Reconstruction of the relation between the Uinta thrust and the Brown's Park collapse zone. Map from Hansen, 1965.

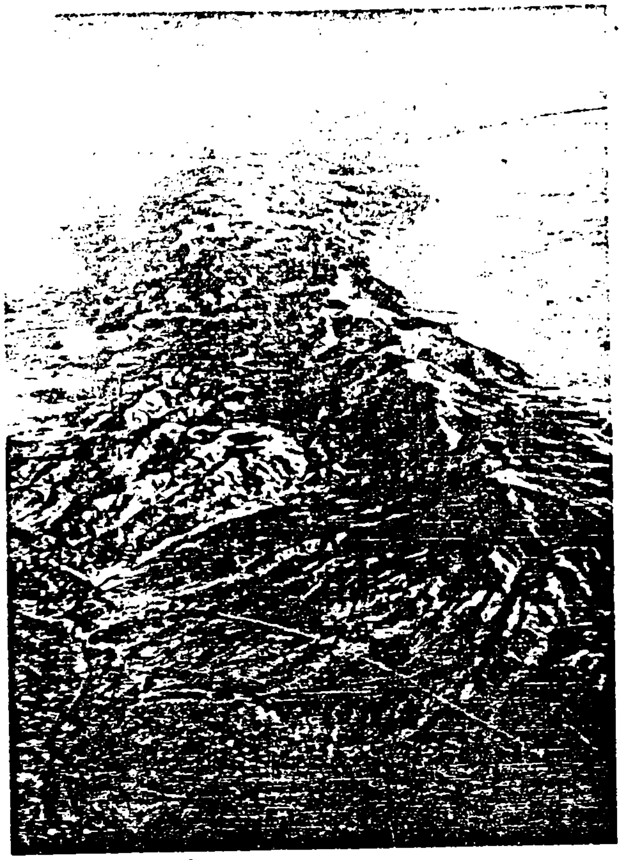
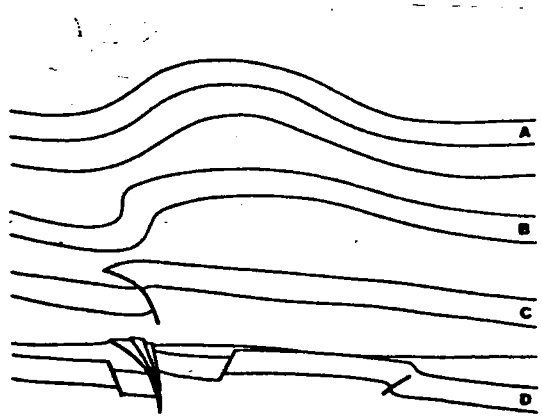


Figure 13. Southward view of the central Sangre de Cristo Range with the Neogene San Luis rift basin on the west (right) and the Laramide Wet Mountains-Huerfano Park compressive basins on the east (left). Notice the extreme uniformity of range width and the sharp geomorphic contrast between the two sides of the range. Peaks reach 14,000 ft and valley levels are about 7,500 ft.

Figure 14. "Push-pull" model of plaster over more fluid barite in which the younger normal fault (hachured) was controlled by and "backed down" the root zone of the older thrust fault (saw-toothed) leaving the thrust lip "hung up" between.



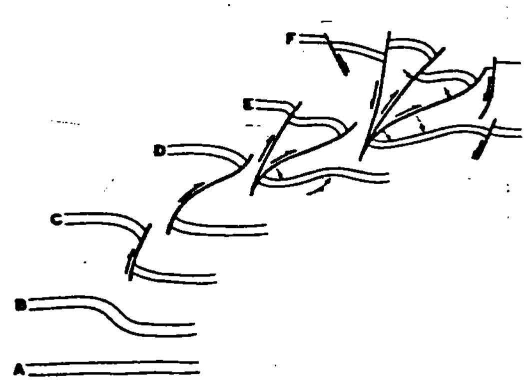


Figure 15. Summary evolution of foreland uplifts (left) and frontal structures (right) from Sales (1968).

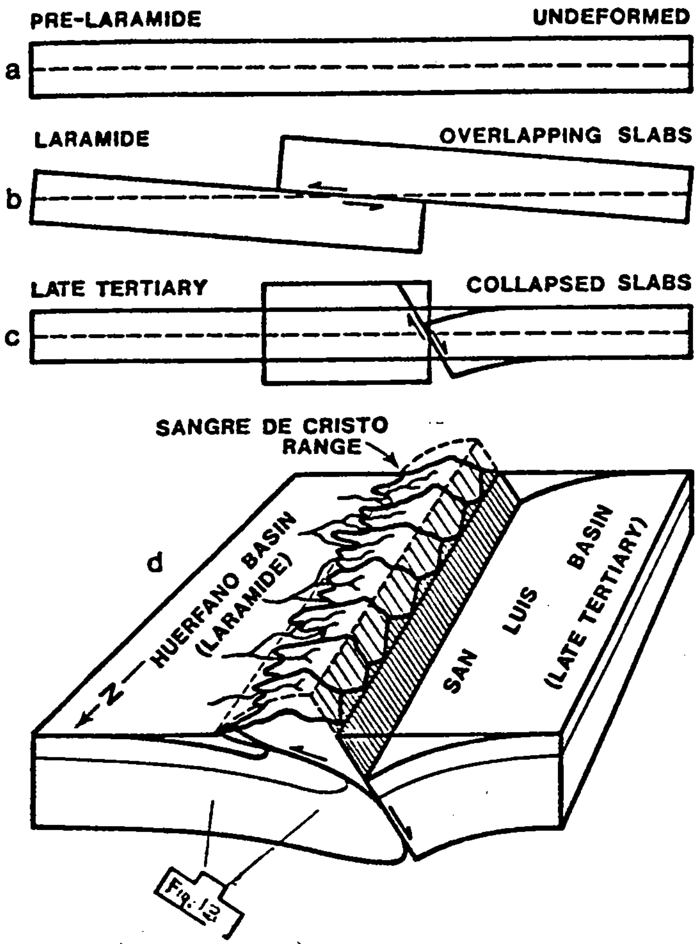


Figure 16. **Perspective diagram of the interpreted relation between the Laramide thrust and Neogene normal fault that have blocked out the central Sangre de Cristo uplift. The control of the normal fault by the thrust root zone had resulted in the abnormally uniform width of the range. Initiation of the younger normal fault from a point above isostatic equilibrium resulted in abnormally large size of the range. Prior to the collapse of the San Luis Basin the Sangre de Cristo Range was merely the flank of the broader and earlier San Luis uplift which shed sediments across it.**

to have developed in relation to the buried, northerly trend of the western part of the Laramide Cache Creek thrust. The western "prow" of the Gros Ventre uplift, bounded by the Cache Creek thrust, was forced up and over the adjacent basin block during the Laramide orogeny, much as the prow of an icebreaker is forced up and over the ice that it is trying to break. During later basin and range relaxation, the "prow" broke off, tilted westward, and raised as the Teton Range, buoyed up by the Cache Creek footwall block. Loss of the "prow" caused the slab to sag "amidship" to form Jackson Hole, with offset that approaches or exceeds 25,000 ft (J.D. Love, personal communication, 1979).

Other Examples

While we tend to notice and emphasize the very large and spectacular structures, there appear to be many smaller rifted structures that have been considerably influenced in their position by gravity-related stresses created during an earlier basement upthrust episode. A similar geometry seems to exist along the Williams Range thrust in Colorado (Howard, 1966) and along the Rock Creek normal fault west of the Arlington thrust in the eastern Medicine Bow Mountains of Wyoming (Houston, 1968).

Farther south along the Rio Grande rift, the western Manzano uplift rift fault (Kelley, 1979) is controlled by the root zone of the eastern Manzano Laramide boundary fault root zone, and control of the eastern Franklin Mountains boundary fault by the root zone of the western Franklin Mountains (Harbour, 1972) seems likely.

REVERSAL OF MOVEMENT ON THE MAIN THRUST

With this strong tendency for uplifts to collapse back down thrust root zones, some reversal of movement would be expected of even the higher structural levels of these master thrusts. This phenomenon has been well documented for the Uinta thrust (Hansen, 1965) and is about 1700 ft or 1/20 of the suggested 34,000 ft maximum throw on the thrust.

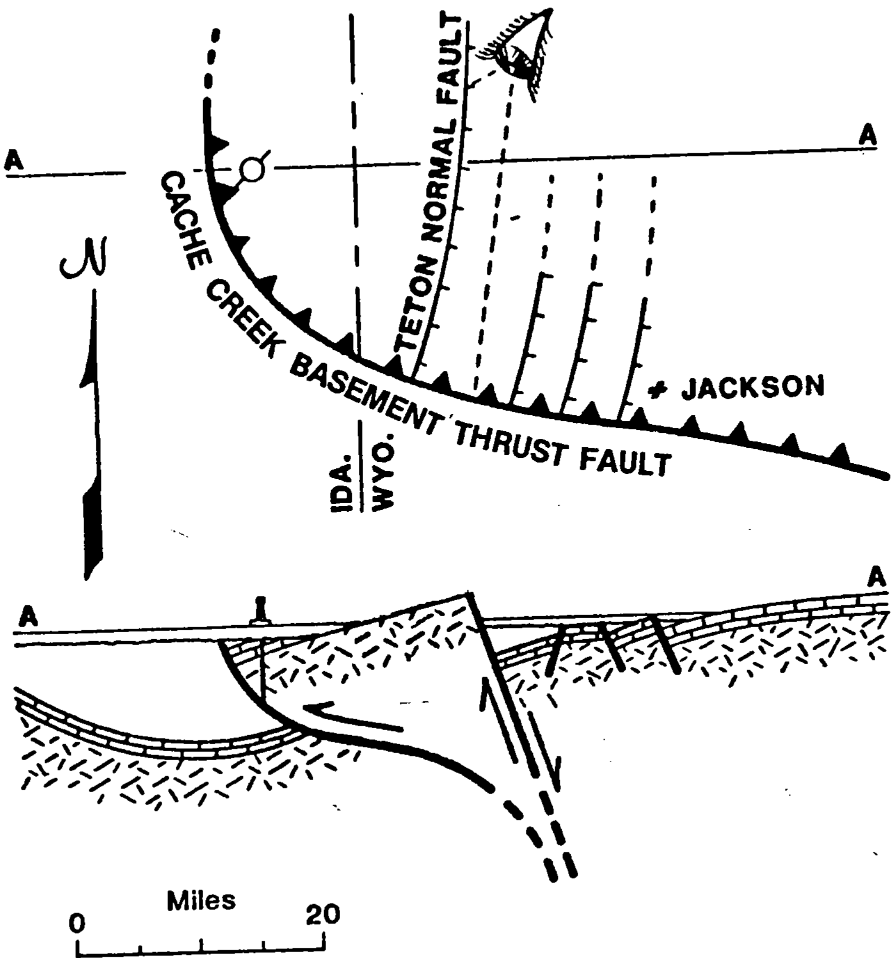
COLLAPSE DURING COMPRESSION

The collapse features described so far have been Neogene in age and related to the Rio Grande rift, or dominantly Miocene in the Granite and Uinta mountains. In principle, collapse, defined as gravity-induced failure of slabs, may take place during the compressive episode any time the beam strength of the slab is exceeded. One class of structures in the foreland — the "horns" that have developed in the margins of the uplifts (e.g., Milner Mountain north of Boulder, Colorado, the "horn" at the east end of the Tensleep fault on the east side of the Big Horn Mountains, and Rattlesnake Mountain on the west side of the Big Horn Basin) may be examples of collapse during compressive deformation. While most of them have a strong en echelon character, their basic configuration is down-to-the-uplift. Thus, they are antithetic and decreased the structural relief of the uplift while it formed. As Couples and Stearns (1978) have suggested, this fault lies neatly into the Hafner theoretical fault set predicted for a sinusoidally flexed slab. It is unfortunate, however, that a "vertical first cause" connotation has come to be associated with this fine diagram and approach, since the potential fault sets have nearly the same diversity and configuration when end-loaded on a plastic substratum as when driven vertically from below.

In one sense, the thrust faults themselves can be thought of as collapse structures in that they can serve to keep gravity stresses and broader wavelength structural relief at lower levels than that structural relief could otherwise attain. This is especially true of those thrusts that reverse the throw on previously developed frontal structures, for which I used the term "isostatic thrust reversal" (Sales, 1968). If ramping into an overlapping slab configuration continually increases gravity stress to the failure point, thrusting of the basin block back over the uplift block by "isostatic thrust reversal" will reduce this imbalance, as is sometimes seen in models (Fig. 18).

WHY THE WIND RIVER RANGE DID NOT COLLAPSE

An apparent anomaly is why the Wind River uplift, largest of the uplifts and with the largest thrust overhang on its southwest side, did not collapse. With the availability of the COCORP deep line, this is logically explained. The continuous low-angle thrust under that range provides a ramp which buoys the central uplifted part of the range more effectively than the steeper root zones of the hybrid frontal structures, such as the south flank of the Granite Mounains which have undergone severe collapse. In terms of our nautical analogy, the Granite Mountains were like a boat whose prow had been pulled up on the end of a dock — a very stressed condition. By contrast, the Wind River uplift is like a boat that has been pulled up on a sloping loading ramp



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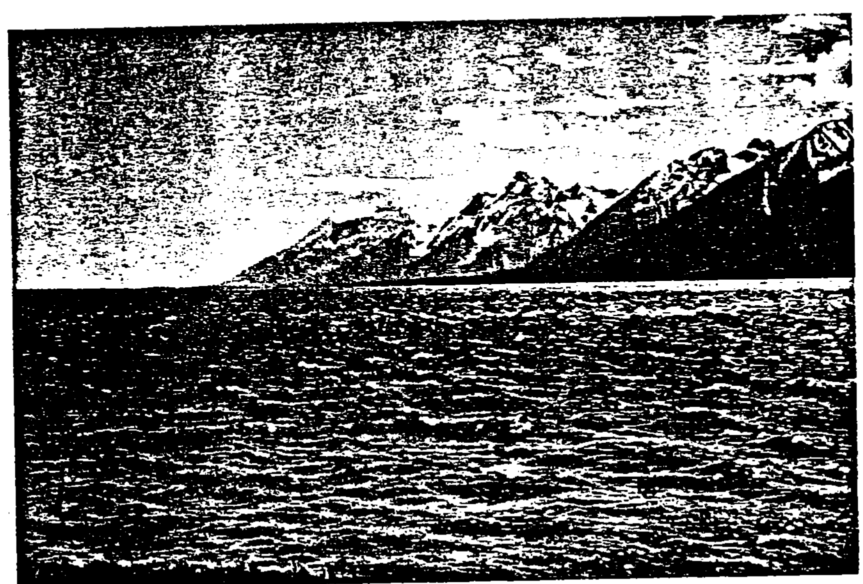

B

Figure 17. (A) Simplified map and cross section suggesting a relation between the older Cache Creek thrust and the younger Teton normal fault. Under this interpretation the Teton block is another "hung up thrust lip" similar to the central Sangre de Cristo uplift and the Seminoe Mountains.
(B) View of the Teton fault scarp from the approximate position shown in the map (A).

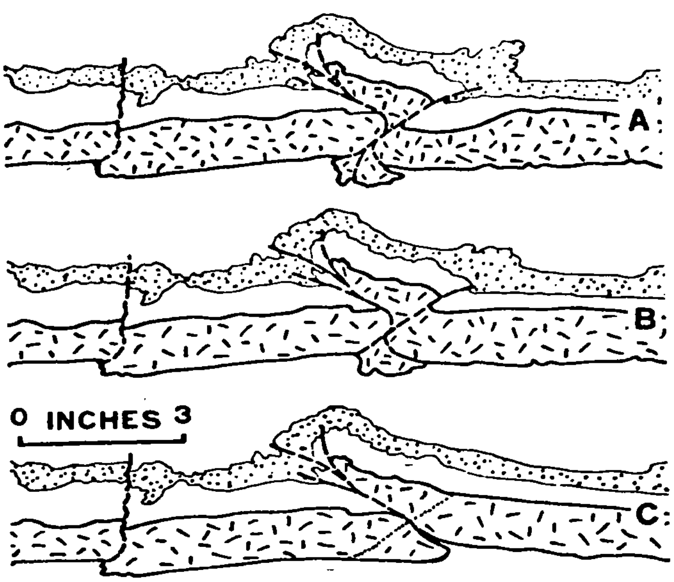

Figure 18. The principle of "isostatic thrust reversal" as reconstructed from a three layer plaster model sitting on a barite subcrust (cross section A). Reconstruction suggests that the central structure in the diagram grew out of an overlapping slab configuration (cross section C) when the gravity stressing forced the slabs to collapse during compression. Therefore, even though the younger of the two faults is a thrust, it is still a collapse feature in that it was positioned by gravity stresses, driving the basin block back over the uplift block toward the isostatic equilibrium configuration. This may explain formation of North Park and South Park basins along the western crest of the early Front Range uplift and behind the "hung up thrust lip" of the Park, Gore, and Mosquito ranges. Progression is from C to B to A.

or beach, and as a result, has its midsection much better supported (Fig. 8).

DID THE UPLIFT AND BASIN SLABS CONTINUALLY DECREASE IN SIZE WITH CONTINUED STRESS?

If the crustal slabs can only resist a finite maximum gravity-induced stress and that stress continues as closure develops, it seems logical that the slabs should continue to break up and decrease in size as orogeny developed. Thus, the whole Rocky Mountain geosyncline of Late Cretaceous age (Gilluly, 1963) may represent the initial mega down-buckle in this end-loaded environment and perhaps the Moxa arch (Blackstone, 1963) and related early westerly swells represented the outermost positive buckle. While amplitudes were very low, this great single fold set would be viable; but since strength is inversely proportional to size, it would have to rapidly break up. Next, a subregional set of very large folds may have formed, the Uinta-White River-San Luis-southern Sangre de Cristo uplifts being one; the Rampart Range-Front Range-Snowy Range-Medicine Bow uplifts being a second; and the Wind River-Granite Laramide uplifts, having a more graceful outline and fewer kinks, being a third. At a later stage (conceptually if not temporally), changes in range trend, thrust overhang, and range collapse should become more severe, both along single frontal structures and for uplifts as a whole (Fig. 15). The overlap-collapse zone of two of these large uplifts may be seen today as the Sangre de Cristo "hung-up thrust-lip" for the southernmost megafold and the Gore-Mesquito and perhaps West Range thrust lip for the west-facing Front Range uplift (Fig. 19).

UNCOLLAPSED HIGHS AT THE ENDS OF RANGE MEGA-UPLIFT

It stands to reason that if stressing increases as buckling progresses until gravity induced failure develops, that same situation should pertain geographically between the plunge of the uplift and the fully developed central section. In other words, we should expect the plunge of uplifts not to have experienced enough stress to collapse, even if the central area had. An example seems to be the east plunge of the Granite Mountains uplift where the Freezeout Hills are separated from the collapsed main core of the Granite Mountains uplift by a series of northeast-trending cross faults in the Bennett Mountains northeast of Seminoe Reservoir (Figs. 10 and 20).

Similar reasoning may explain in part the southern end of the Sangre de Cristo uplift and the Sawatch uplift as the remnant southern and northern culminations, respectively, of the earlier San Luis uplift. There is some possibility that the Pikes Peak area and the north-plunging Medicine Bow-Snowy Range uplifts are the southern and northern culminations, respectively, of the large earlier stage mega-Front Range uplift.

BASINWARD COLLAPSE OF UPLIFTS

The foregoing sections described "thick-skin" collapse in that the faults logically penetrate to the plastic substratum. In this section, however, the more surficial basinward collapse of uplift margins is discussed. The collapse of thrust lips takes place both vertically and horizontally and decreases the steepness of the flank. Extensional collapse of a thrust lip toward the adjacent basin has been documented by Fanshawe (1939) and Wise (1963) for the Boysen Dam area of the south flank of the Owl Creek uplift (Fig. 21). An additional component of this collapse has taken place as gravity glide sheets from higher parts of the uplift. A single basin-facing normal fault, the Boysen fault, separates the rear of the extending thrust lip from the more coherent mountain block behind.

Couples and Stearns (1978) have suggested this same relationship as a dominant feature in crestal areas of the Wind River uplift. They cited the low altitude and relief to the southwest of the range crest, and suggested that a somewhat downward-steepening thrust root was roughly delineated by a basin-facing fault zone. While extension and breakup on the largest of the frontal structures could be expected, there are two problems with this interpretation: 1- The high level pedimentation episode suggested by Love and others (1963) gives an equally plausible cause for a subsummit-level surface, especially since it is developed on most of the other large uplifts and developed on dip slopes and other areas where basinward extension does not seem to have occurred; 2- The COCORP line with its planar thrust trace through the crust is evidence against a downward curving root zone that would be most compatible with this mechanism.

A second type of collapse, the vertical sagging of overhanging thrust lips onto the underlying basin sediments, seems best displayed along the Continental fault (Berg, 1962) that rims the southwest flank of the Wind River thrust. It should logically lose throw with depth, as it seems to. However, the "basin rebound fault" would logically lie nearly under it, and being thick-skinned, should gain throw with depth. It may be hard to distinguish between these two types.

A third style of basinward collapse is well displayed at Five Springs on the west side of the Bighorn Mountains (Fig. 22) and could be paraphrased as "book-shelf" collapse in which a series of down-to-the-uplift normal faults, that may or may not penetrate basement, allow the oversteepened panel on the range front to sag basinward much as books sag toward the free end

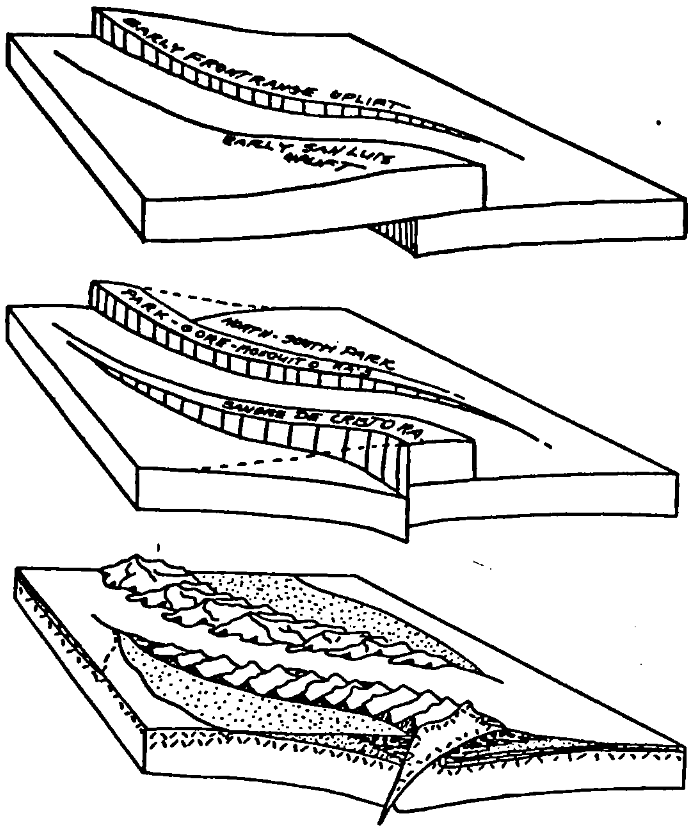

Figure 19. Sequential and stylized block diagrams of the Colorado Rockies suggesting that they evolved from two simple opposed overlapping en echelon slabs. The northerly early Front Range slab collapsed during compression to explain the Laramide age basin fill of North and South Park basins. The southern San Luis uplift collapsed during Neogene incursion of the Rio Grande rift from the south.

of a book shelf. It seems plausible that the "horns" are a deep-seated variation of this mechanism.

Another feature common to several thrust lips might be termed a "thrust lip back thrust". It is represented by the Bender and Goslin faults on the lip of the larger Uinta thrust (Fig. 12), Oil Mountain on the lip of the Casper arch thrust, and Big Sheep Mountain anticline on the lip of the deep Bighorn Basin structure to the west. A thrust lip back thrust might be a "horn" as well.

IMPLICATIONS FOR HYDROCARBON PROSPECTING

This analysis has several implications in prospecting for hydrocarbons:

1- It provides a rationale for explanation and a geometric means of assessing the amount of overhang on boundary faults in the foreland province;

2- It gives possible field-visible examples of oilfield-sized structures that appear to have been generated under these thrust-lips and have since been exposed by erosion;

3- It explains a possible mechanism for control of the position and configuration of younger collapse structures that may be used to assess the geometry of the older compressional structures;

4- It provides possible rationale for timing differences in the province.

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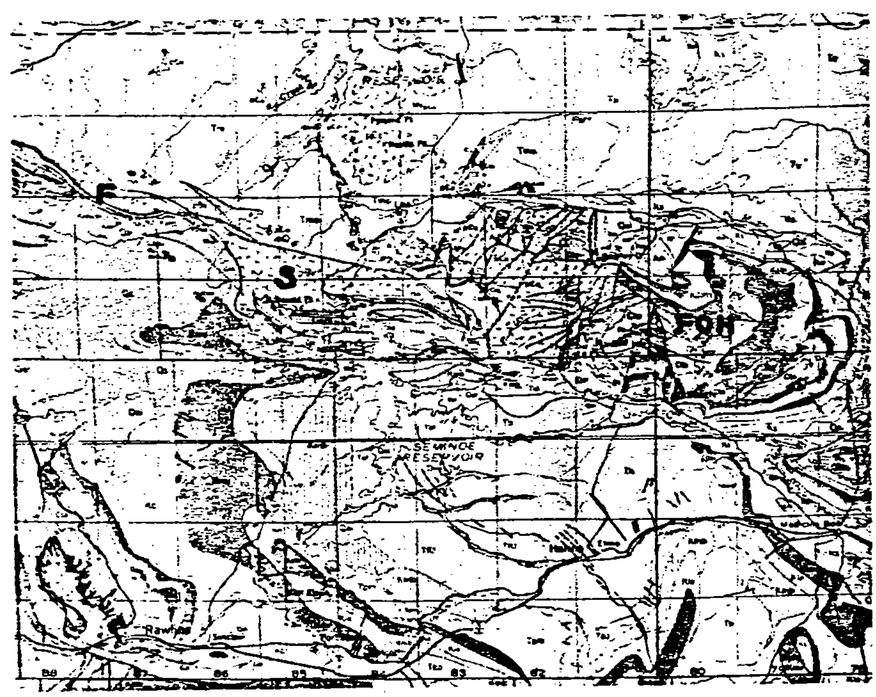

Figure 20. Geologic map of the eastward-plunging termination of the Granite Mountains uplift showing the Freezeout Hills (FOH) as the uncollapsed "bulb" on the end of the uplift. These terminations resist collapse because they represent smaller and therefore stronger arches than the central parts of the uplifts. F = Ferris Mountains, S = Seminoe Mountains. Map from Love and others, 1955.

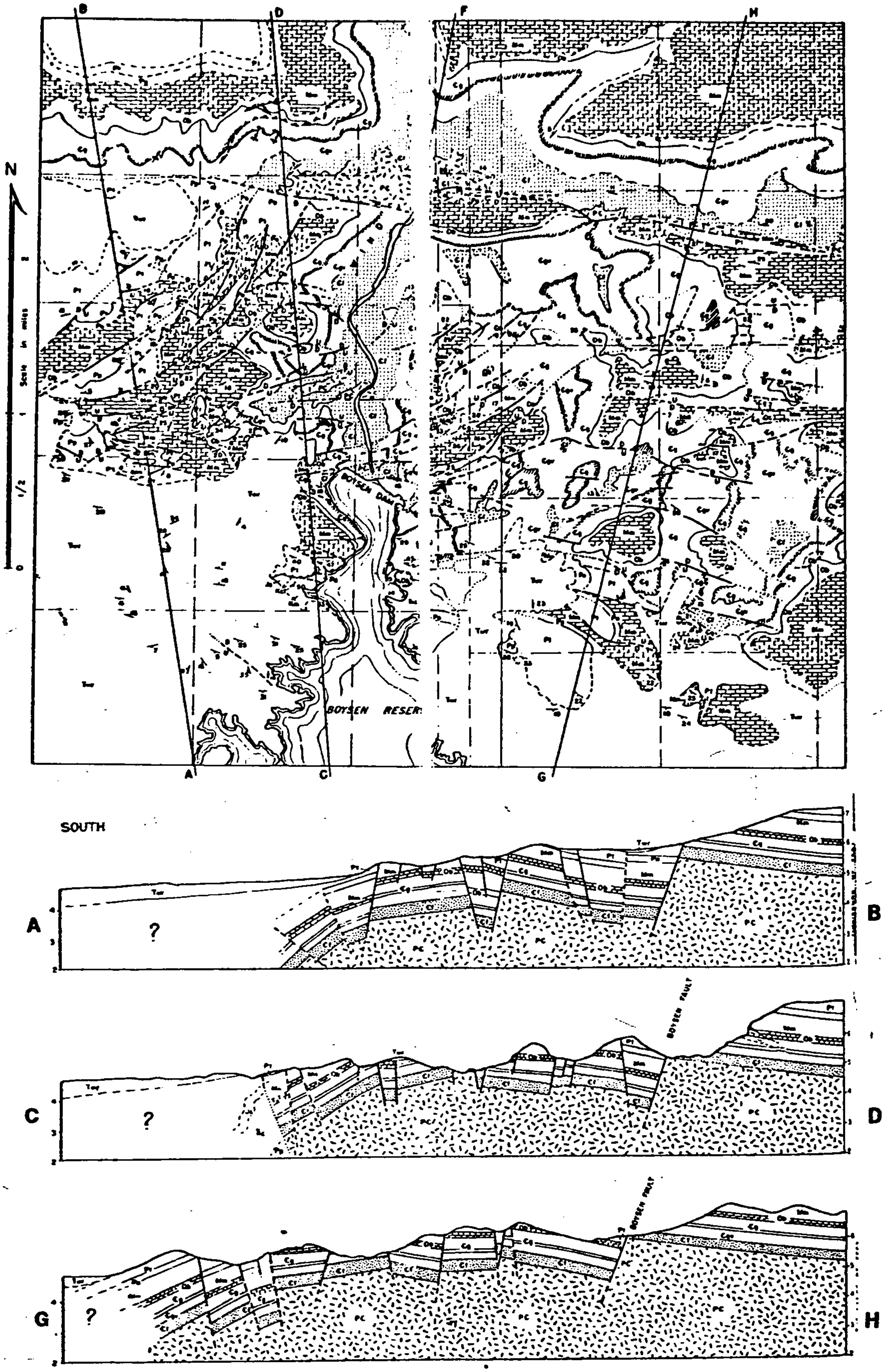

Figure 21. Summary diagram of the central Boysen Dam segment of the southern Owl Creek uplift showing one of the best developed and exposed examples of basinward collapse of a thrust lip. The two main modes are normal fault breakup and extension and gravity sliding. The large Boysen normal fault separates the southward collapsing thrust lip from the more coherent core of the range.

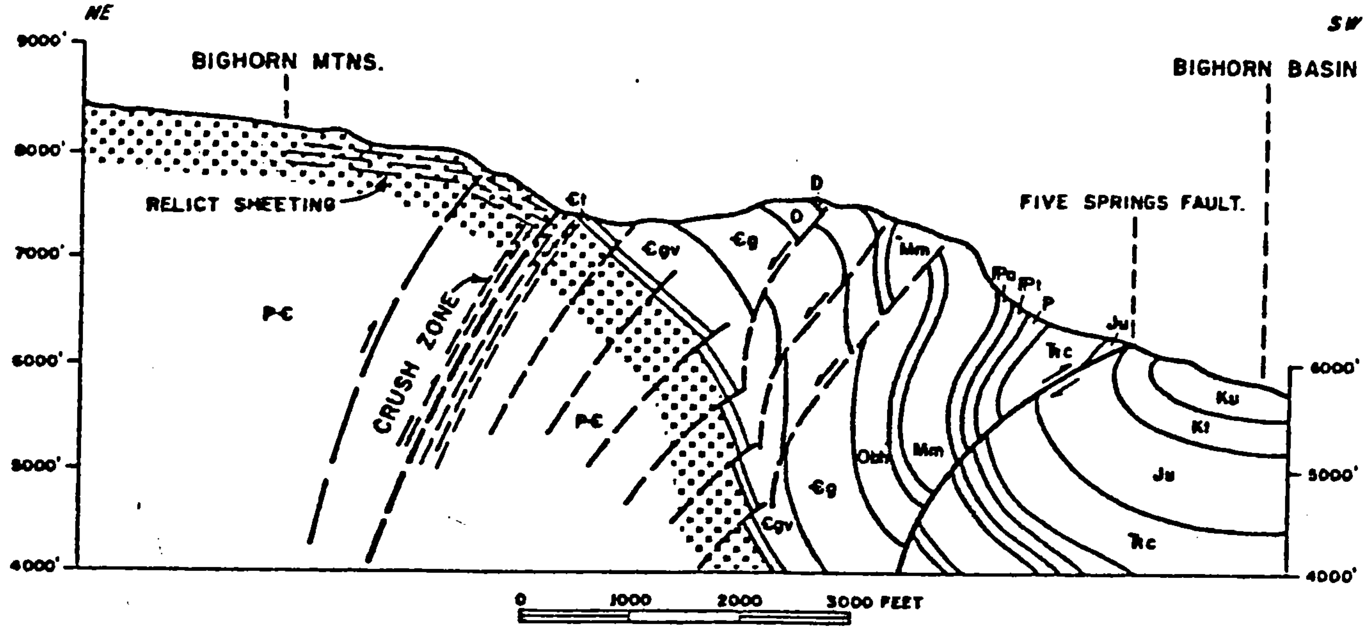

Figure 22. Cross section of the west flank of the Bighorn uplift at Five Springs showing "book shelf" collapse of oversteepened monocline toward basin. The Five Springs thrust is a subsidiary compression feature at the base of this dip panel. After Osterwald, 1961.

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