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Low-Angle (Denudation) Faults, Hinterland of the Sevier Orogenic Belt, Eastern Nevada and Western Utah

ABSTRACT

Low-angle faults that place younger strata on older are the distinctive structural feature of the hinterland of the Sevier orogenic belt in Nevada. Although shown on many maps as Mesozoic thrust faults, these low-angle faults may in many places be extension, denudation, and gravitational gliding features of Tertiary age. The complexity of later Tertiary deformation caused by crustal extension in the hinterland has not been sufficiently emphasized.

Several contrasting interpretations of the relation between hinterland and Sevier belt structures exist. Whitebread, Hose, Roberts, and Crittenden advocate gravitational gliding models that differ in detail, but in general they correlate extension in the hinterland with thrusting toward the foreland during the Cretaceous. Misch, Nelson, Fritz, Miller, and Woodward assign a Mesozoic age to the low-angle faults which they relate to a regional décollement. The frontal breakout of this décollement is proposed by them to be west of, and older than, the thrust faults of the Sevier belt or perhaps equivalent in age to them. Other geologists (Armstrong, Burchfiel, Davis, and Fleck) argue for a compressional origin for the Sevier belt that involves considerable crustal shortening. To them the low-angle hinterland faults are unrelated to Sevier belt thrusting. Geometric and chronologic problems are created by the first two interpretations, making the third interpretation most attractive.

INTRODUCTION, GENERAL SETTING

The Basin and Range province is characterized by tilted fault blocks bounded by normal faults of post-Eocene age (Nolan, 1943; Mackin, 1960; Hamilton and Meyers, 1966) that trend generally north-south. The blocks expose deformed Paleozoic strata that display a variety of structural styles but most distinctive in the eastern Great Basin are low-angle faults that juxtapose younger rocks on older (Misch, 1960). These faults, which will often be referred to in this paper as denudation faults (because strata originally overlying the footwall have been removed tectonically), have been interpreted in various ways. Their origin and significance is today a topic of dispute and disagreement. I believe that the models linking denudation faults with thrust faults of Cretaceous age that lie to the east in the Sevier orogenic belt are unlikely and that the denudation faults are predominantly of Tertiary age and related to Basin and Range faulting. This involves reinterpretation by me of certain structures, but does not mean that I disagree with the distribution of rock units as shown on any maps. The central focus will be on structures of east-central Nevada where denudation faults are abundant and many areas are well mapped. The most useful large-scale geologic maps for the eastern Great Basin are the western half of the state geologic map of Utah (1:250,000) (Stokes, 1963; Hintze, 1963) and the county maps of Nevada (1:250,000 and approximately, 1:125,000-preliminary form) (Longwell and others, 1965; Tschanz and Pampeyan, 1970; Hose and Blake, 1970; Kleinhampl and Ziony, 1967).

Some of the topics discussed in this paper were touched upon in my papers on the Sevier orogenic belt (Armstrong, 1968a, 1968b). Those papers should be consulted for premonitions, elaboration, or clarification of ideas, and more thorough documentation of facts cited.

The eastern Great Basin (Fig. 1) is underlain by Paleozoic strata of the Cordilleran miogeo-

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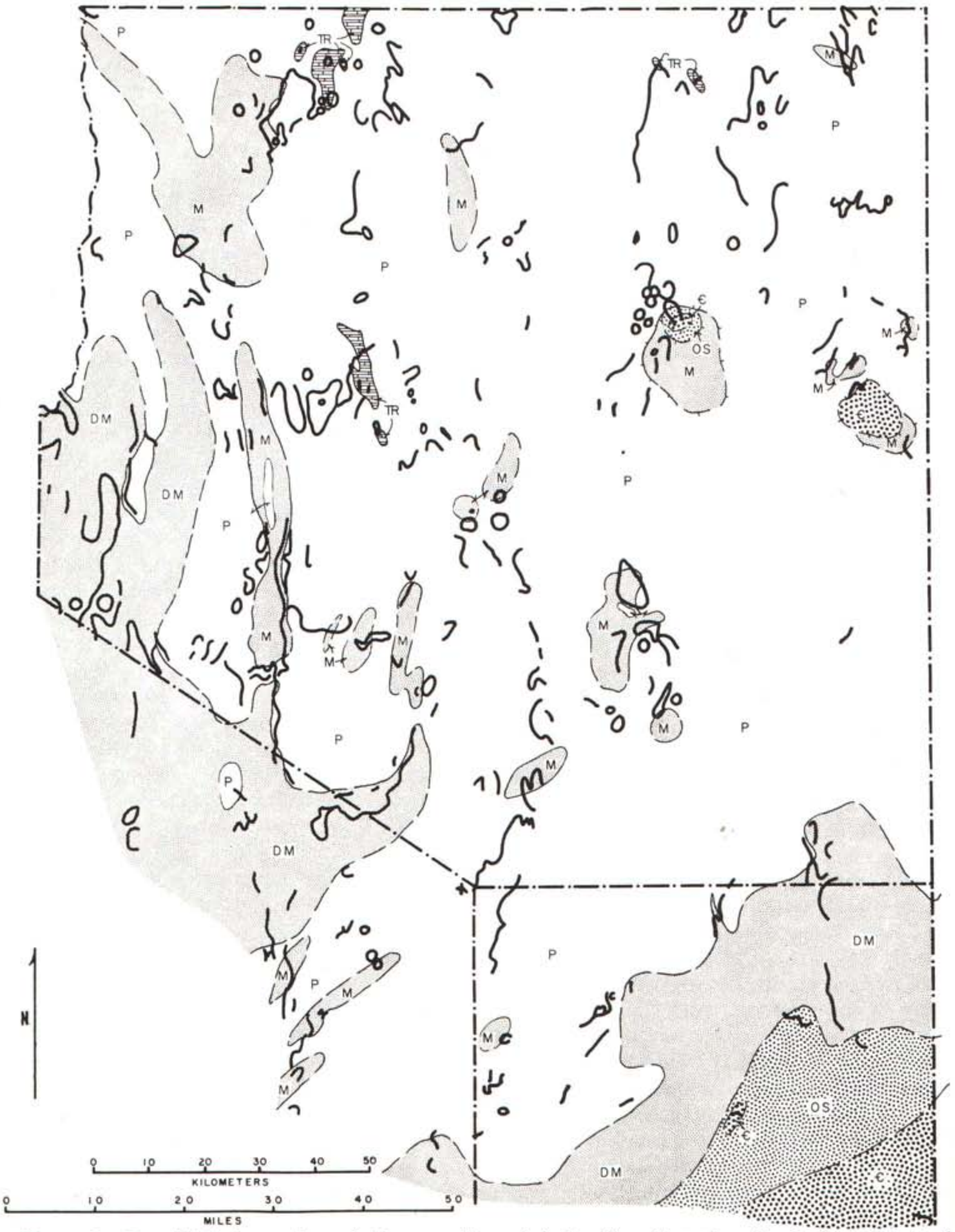


Figure 3. Pre-mid-Tertiary paleogeologic map of White Pine and portions of Nye and Lincoln Counties, eastern Nevada. Heavy lines indicate distribution of significant contacts as shown on the county maps (Hose and Blake, 1970; Kleinhampl and Ziony, 1967; Tschanz and Pampeyan, 1970). Contacts for the paleogeology are shown by a light line. Geologic systems indicated by letter symbols are: €, Cambrian; OS Ordovician and Silurian; D, Devonian; M, Mississippian; P, Pennsylvanian and Permian; TR, Triassic. The paleogeology shows that by the end of the Mesozoic, the area was characterized by broad gentle folds, and faults of small stratigraphic displacement. At the surface, upper Paleozoic strata were extensive. Only two exceptional areas where lower Paleozoic carbonate rocks have been reported to underlie Oligocene volcanic strata in White Pine County are evident. The surface of this region was not broken by any major through-going thrust faults of comparable magnitude to those in the Sevier belt, which lies only a few miles to the east and southeast, nor was it broken by structures expressing tens of miles of extension as the present-day geology of the region does.

ence of exposed older Precambrian rocks is disputable, although such ancient rocks probably underlie most of the region at depth. The contact between metamorphosed and unmetamorphosed strata in Nevada and Utah is usually a fault that developed during or after the waning stages of regional metamorphism (Misch, 1960; Misch and Hazzard, 1962; Nelson, 1969; Misch, 1971). Commonly it juxtaposes younger rocks over older.

PRE-TERTIARY HINTERLAND STRUCTURES

Evidence sufficient to date any orogenic structures as pre-Tertiary is rare in the hinterland. A conformable sequence of Eocambrian through Lower Jurassic strata indicates that virtually all tectonic complexity in the region developed at some time during the last 200 m.y., but it is only at those few places where Late Jurassic–Early Cretaceous or mid-Cretaceous plutons crosscut deformed rocks that a significant refinement in dating is possible. In Elko County, plutons at least 150 m.y. old crosscut complex imbricate thrust faults in the H-D range (Riva, 1970), deformed and metamorphosed strata in the Ruby Mountains (Kistler and Willden, 1969) and deformed miogeosynclinal strata at Whitehorse Mountain (Adair and Stringham, 1957). A slightly younger pluton cuts deformed strata in Dolly Varden area (Snow, 1964). In White Pine County, metamorphism and deformation in the Snake Range precedes 120 m.y. and may predate 165 m.y. (Armstrong and Hansen, 1966; Lee and others, 1970). At Ely, faulting of upper Paleozoic strata, including younger-on-older style faults, predates plutons that have been accurately dated as 109 m.y. (Bauer and others, 1966; McDowell and Kulp, 1967).

Mesozoic thrusting, much of it older than the Sevier belt in Nevada and Utah is also recognized in the Inyo and Clark Mountain regions of California (Stevens, 1969; Olson, 1970; Burchfiel and others, 1970; Burchfiel and Davis, 1971). Thrust faults in the Nevada test site (Barnes and Poole, 1968; Hinrichs, 1968) and farther north in western Lincoln County and in northern Nye County (Tschanz and Pampeyan, 1970; Dodge, 1970) may be equally as old.

The amount of displacement on various Mesozoic thrust faults in the hinterland can only be estimated in rare cases where contrasting facies of units such as Mississippian clastic rocks, derived from the Antler orogenic belt, are juxtaposed (Brew, 1971; Thorman, 1970).

One Mesozoic structure that is widespread, and perhaps universal in the Grant–White Pine, Egan and Shell Creek Ranges is localization of bedding-plane faults along Mississippian shale. Rocks below this fault zone are usually relatively unfaulted. The Pennsylvanian and younger strata in the hanging wall are severely broken by high-angle faults that do not extend below the detachment zone, as shown particularly well in the southern Egan Range. Structures of this zone are locally imbricate (for example, the Becky Peak thrust fault of the northern Schell Creek Range described by Dechert, 1967); in some places, such as the White Pine Range (Drewes and others, 1970) Tertiary volcanic rocks postdate movement along such faults within the Mississippian strata, but in some areas, the Tertiary rocks are as broken as the underlying upper Paleozoic strata. A reasonable interpretation is that weak zones, such as the Mississippian shale, were sites of considerable movement at one or more times during the Mesozoic. These same zones of weakness were reactivated during the Tertiary. At any given place, the movement at different times may have been in different directions (generally eastward movement of upper plates being probable during the Mesozoic; down-dip movement likely during the Tertiary); structural confusion is an obvious consequence.

Cretaceous sedimentary rocks at a few localities in the hinterland unconformably overlie older rocks but do not provide evidence for dating specific structural features. The pre-Tertiary unconformity (as shown by the paleogeologic maps of Armstrong, 1968b; Fig. 3) truncates many broad folds, some of considerable length and magnitude and a few faults; most of these faults have stratigraphic displacements of less than one geologic system. Mapping of the Schell Creek and Snake Range areas by Dechert (1967) and Nelson (1966) shows Tertiary volcanic rocks overlying Cambrian rocks. This is in contrast to the Mississippian or younger strata that usually underlie the Tertiary in the hinterland. These relations could be disregarded, or argued to be due to unrecognized structures of Tertiary age, but they may indicate pre-Tertiary periods of denudation in the region, a possibility I would prefer to leave open, particularly in the light

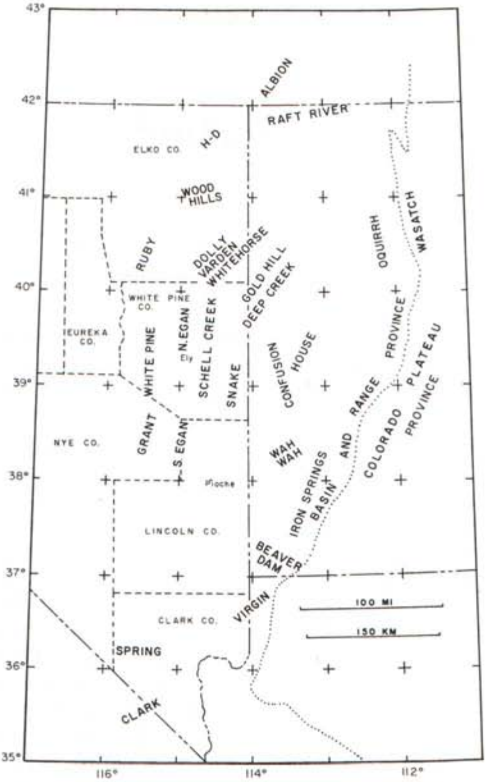


Figure 1. **Geographic names of selected topographic and geographic features in the eastern Great Basin of Nevada and Utah.**

syncline. The zone of transition between miogeosyncline and platform, the Wasatch zone, is the locus of the Sevier orogenic belt. In this zone, approximately 100 mi wide, the strata of the miogeosyncline were thrust over platform strata during the Cretaceous. Here, Tertiary normal faults bound fault blocks that contain older-over-younger listric thrust faults and related folds which conform to the rules of structural style established in the Wyoming, Montana, and Canadian Rocky Mountains (Rubey and Hubbert, 1959; Armstrong and Oriel, 1965; Mudge, 1970; Price and Mountjoy, 1970; Dahlstrom, 1970). At least 40 mi of tectonic contraction is expressed by these Mesozoic compressional structures of the Sevier belt.

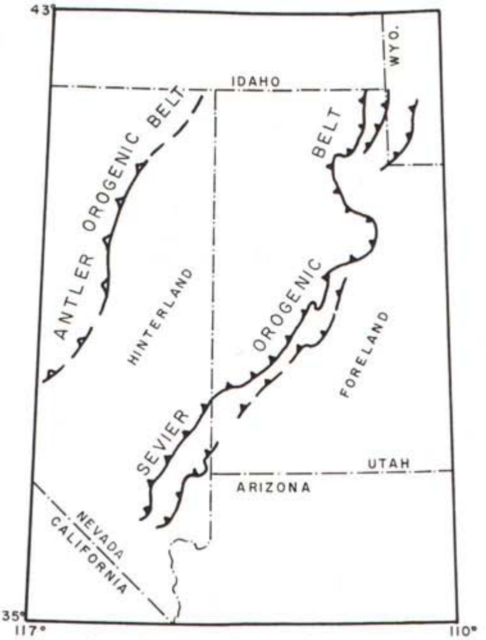


Figure 2. **Tectonic index map for the eastern Great Basin.**

The hinterland of the Sevier belt (Fig. 2) has a complex tectonic history and is the site of many extant problems, including, but not restricted to, the denudation faults discussed in detail in this paper. Between the Sevier orogenic belt and the frazzled eastern edges of the Antler orogenic belt in central Nevada (Roberts and others, 1958) is a zone 100 to 150 mi wide of heterogeneous structural style. The structure of individual mountain ranges in the hinterland of the Sevier orogenic belt may be relatively simple homoclines or broad folds, broken only by steep normal faults. Many ranges display low-angle faults placing younger rocks on older and older on younger, but the former predominate. A few ranges (Snake, Southern Deep Creek, Grant, Ruby, and Raft River ranges and the Wood Hills are spectacular examples) expose metamorphosed and tightly folded lower Paleozoic and Eocambrian strata with metamorphic fabrics produced by synkinematic penetrative deformation during the Mesozoic (Misch, 1960; Misch and Hazzard, 1962; Nelson, 1966; Bick, 1966; Cebull, 1970; Howard, 1966, 1971; Thorman, 1970; Armstrong and Hansen, 1966; Compton, 1969). Older Precambrian basement rocks recrystallized and remobilized during metamorphism of geosynclinal strata, are exposed only in the Raft River–Albion Ranges in northwestern Utah–southern Idaho and in California (Armstrong and Hills, 1967; Lanphere and others, 1964). Elsewhere in the hinterland, the presof the uncertain age of many denudation-type structures and the complex tectonic history of the region.

Although we can be certain that some metamorphism of geosynclinal strata occurred in the Ruby Mountain and Snake Range areas before the Cretaceous, it is possible that elsewhere, presumably at deeper structural levels or in hot spots, that deep-seated flow of rocks occurred much more recently. Indeed some flow and the consequent development of flaser gneisses seem to have taken place within the Tertiary in the Raft River–Albion Range areas (R. R. Compton, R. E. Zartman, and Armstrong, work in progress). Any crustal shortening model for the Sevier orogenic belt necessarily requires flow or faulting at depth in the hinterland—deformation that must be synchronous with the eastward thrusting of miogeosynclinal strata in the Wasatch zone.

GLIDE BLOCKS IN THE SEVIER OROGENIC BELT

Gravity slides of Late Cretaceous(?) and Tertiary age have been recognized at several localities within the Sevier belt. Typically these displaced blocks lie with low-angle contacts on older strata but some lie on rocks as young as Tertiary. The rocks are usually intensely brecciated near tectonic contacts; the entire upper plate may be shattered, but some plates are not. Underlying rocks are deformed only in a thin zone close to the tectonc contact. An example of the scale and style of these glide blocks is shown in Figure 4, taken from Seager's (1970) study of the Virgin Mountains. Farther south, glide blocks in the Spring Mountains have been described by Secor (1963a, 1963b) and in the Clark Mountains by Burchfiel and Davis (1971). In the Pioche district north of the Virgin Mountains, several glide structures override Tertiary sedimentary and volcanic rocks (Armstrong, 1964; Gemmill, 1968); to the northeast, similar structures are reported in the Beaver Dam Mountains (Cook, 1960; Jones, 1963) and Iron Springs district (Mackin, 1960) in Utah.

An example of a fault that was cited as a thrust fault (Baker, 1964), but which I think is a large glide structure is the Big Baldy fault of the southern Wasatch Mountains. As illustrated on Figure 5, a simple interpretation

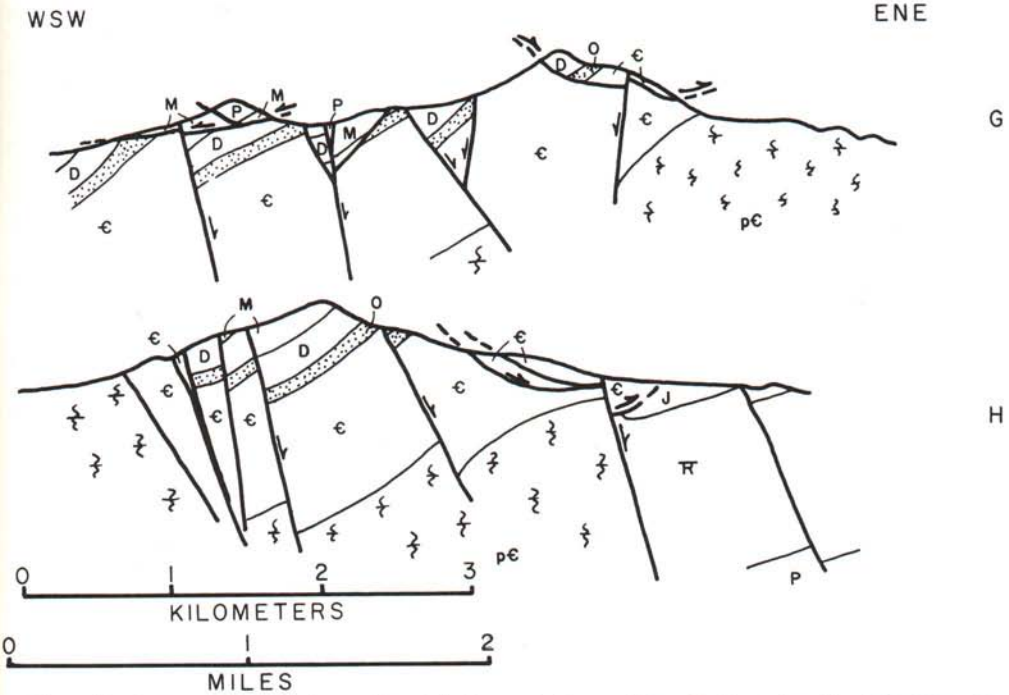


Figure 4. Cross sections of the northern Virgin Mountains (Seager, 1970) showing gravity glide structures. Geologic systems indicated by letter symbols are: pЄ, Precambrian; Є, Cambrian; O, Ordovician; D, Devonian; M, Mississippian; P, Pennsylvanian and Permian; R̄, Triassic; J, Jurassic.

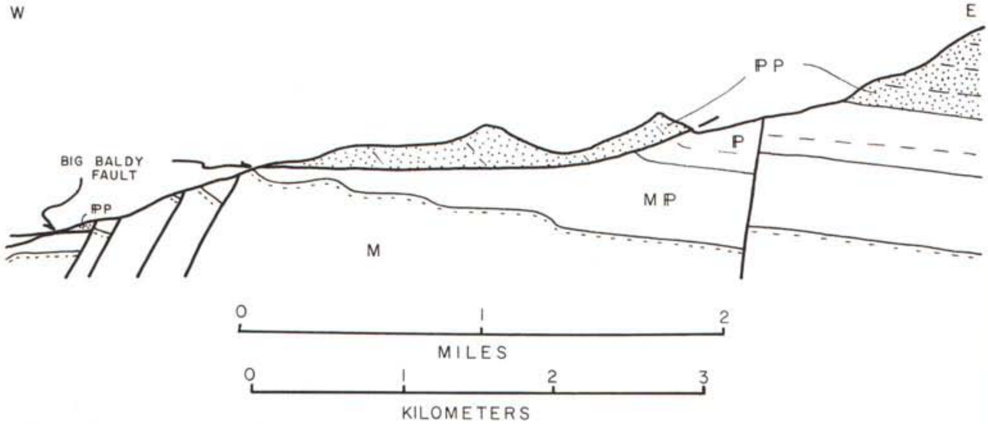


Figure 5. Cross section of the Big Baldy fault of the southern Wasatch Mountains (Baker, 1964). This appears to be a normal fault that bounds a simple glide block rather than a thrust fault. Geologic systems indicated by letter symbols are: M, Mississippian; ℙ, Pennsylvanian; P, Permian.

of the Big Baldy block is that it moved down and to the west and was rotated as it slid along a curved fault surface. Faulting along the Wasatch front would have provided the original free surface that permitted failure; later faulting along the front displaced the glide surface slightly. An alternate proposal, that it is a thrust fault, requires a complex ad hoc explanation in which a thrust fault rises stratigraphically, descends, and rises again, resulting in a stratigraphic displacement much less than total displacement and the observed younger-on-older relation. Such gymnastics are unnecessary, and certainly not needed to explain the structures known to occur west of the Wasatch fault in this area. I have chosen the Big Baldy fault for reinterpretation because I think it illustrates the potential for conflicting interpretations that is widespread in the structurally more complex hinterland.

The examples cited demonstrate that gliding, often provably related to relief developed as a consequence of later Tertiary faulting, is a phenomenon of common occurrence within the miogeosynclinal strata of the eastern Great Basin. It is reasonable to expect similar structures within the hinterland and surprising that such an explanation has not been considered for all the structures of similar style and scale known to occur there.

DENUDATION STRUCTURES OF THE HINTERLAND

Robert Scott used the term "denudation fault" for the widespread tectonic contacts that place younger on older rocks (Moores and others, 1968; Drewes and others, 1970), and I think this is a useful term with minimal genetic connotations attached. It is concordant with the thinking of most workers concerned with the hinterland (tectonic removal of hanging-wall strata) regardless of how they think these faults are related to the big picture. Peter Misch and his students prefer to use the term décollement (shearing off) for many of the same features and believe in a compressional origin for most of these faults, although Misch (1960) admits that Tertiary gravitational gliding is important locally, as around Sacramento Pass in the Snake Range. Where younger rocks are observed lying on older, the simplest geometric model for the development of such a structure involves extension—as along high- or low-angle normal faults (Dahlstrom, 1970). This is illustrated in Figure 6. An important concept, popular in the Canadian Cordillera and I think useful in the Great Basin, is the listric normal fault—one that alternately cuts across and parallels stratification. Such faults, as illustrated on Figure 6, result in juxtaposition of younger-on-older rocks as occur on many of the low-angle faults of the Sevier hinterland. If strata are upright and not tightly folded, the only possible geometric explanations for compressional faulting of older rocks on younger are: (1) low-angle faults that decapitate folds (this mechanism produces at most only 50 percent younger-on-older contacts, usually less); (2) imbrication of already imbricate rocks by a second generation of

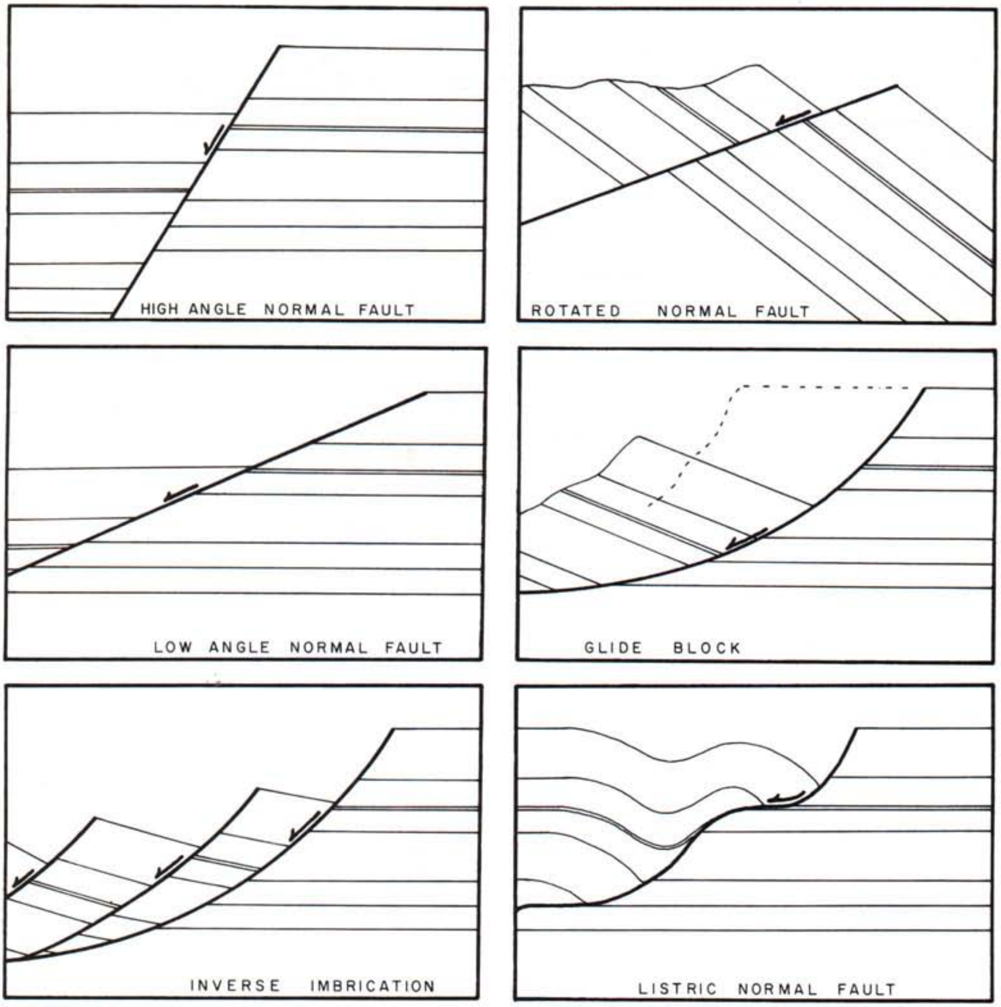


Figure 6. Ideal geometries of extension and denudation faults that place younger rocks on older. Many younger-on-older faults of the hinterland of the Sevier orogenic belt can be interpreted as conforming to these simple models or to more complex permutations and combinations.

thrusts steeper, relative to bedding, than the first generation (this likewise produces many more older-on-younger contacts than vice versa); and (3) by erosion thrusting or thrusting along an unconformity, which can proceed with completely flexible geometry, depending on the landscape or unconformity being overridden. None of these geometric mechanisms seems to be applicable to the hinterland structures. Geometric logic is a necessary prerequisite to any acceptable model for structural evolution.

A recent great increase in the acceptance of gravitational gliding and extensional mechanisms to explain denudation faults of the hinterland is evident. As long ago as 1945, Longwell described low-angle faults in Clark County, Nevada, but the idea did not become popular until the late 1960s. Hunt and Mabey (1966) interpreted the structure of the Panamint Range as shown on Figure 7 as a deeply exposed normal fault, an inverse-imbricate denudation structure. Wright and Troxel (1969) interpreted the Amargosa chaos as drag below normal faults that flatten at depth, inverse imbricate listric normal faults in the jargon of this paper. Fleck (1970a) suggested that the chaos may be megaslides (large-scale versions of

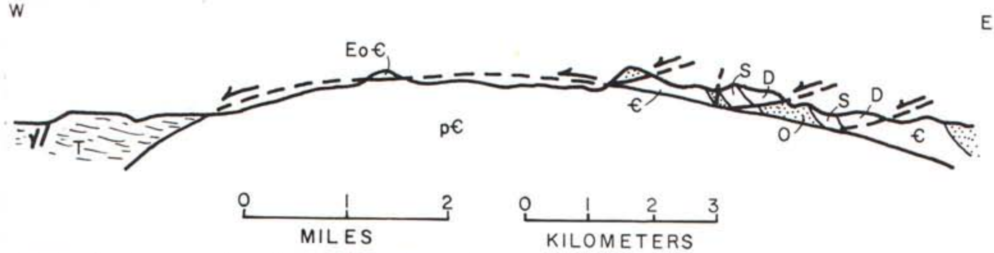


Figure 7. Cross section of the Tucki Mountain fenster (Hunt and Mabey, 1966), an example of an inverse-imbricate denudation structure of Tertiary age in the Death Valley region.

the Tin Mountain landslide described by Burchfiel, 1966). There is general agreement that these structures are Tertiary, as they postdate and involve Tertiary rocks. Once popular and widely quoted compressional-thrust explanations for these same features are falling out of favor. Hunt and Mabey (1966) cite the reason for their interpretation: extreme attenuation of units, maintenance of stratigraphic order within the fault mosaic, abundance of small normal faults which show a tendency to merge with the master fault, and absence of imbrication and folding. These aspects are precisely those of many of the low-angle fault complexes of east-central Nevada.

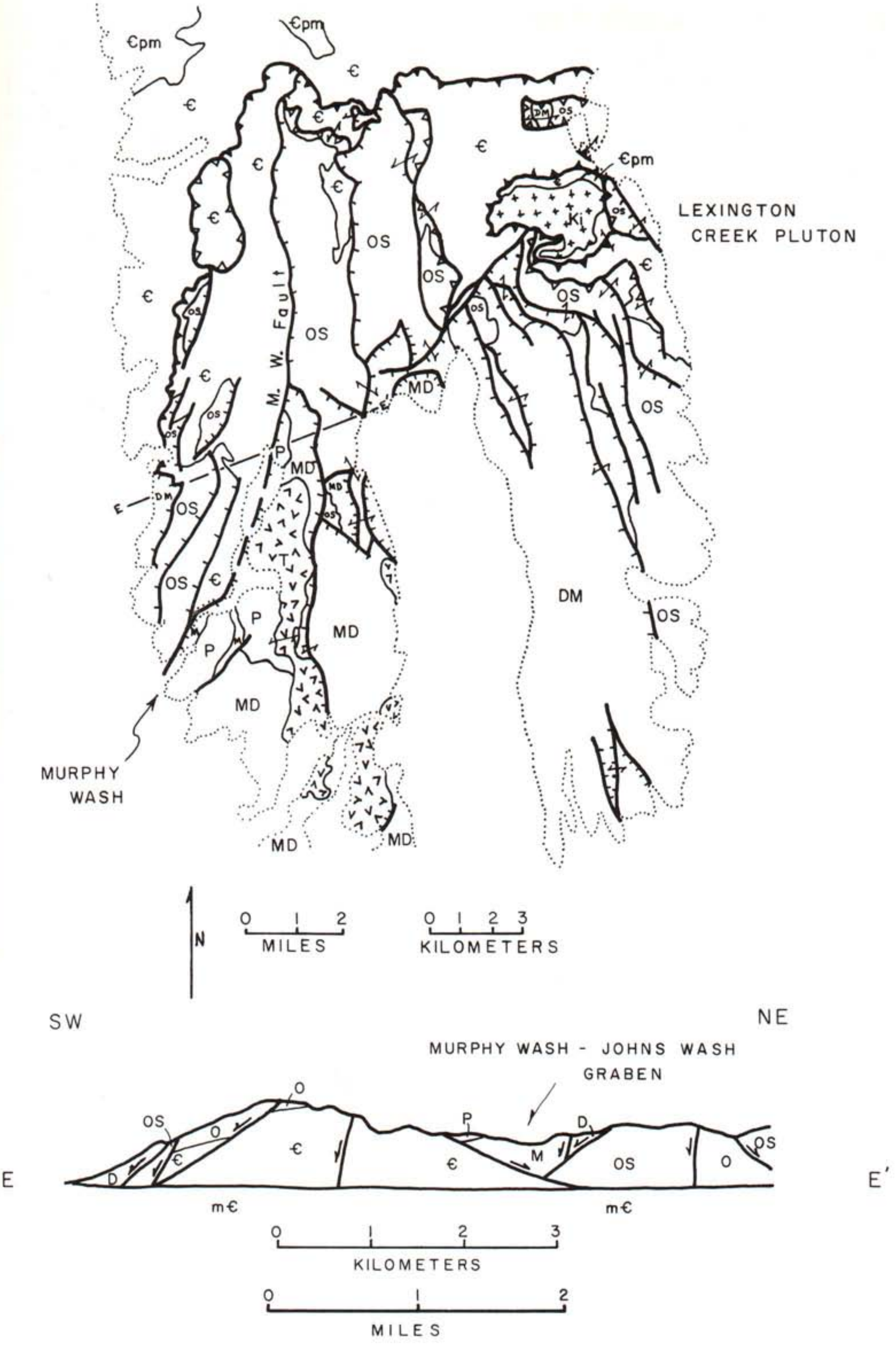
Extension and gravitational gliding explanations for low-angle faults in east-central Nevada were suspected by Young (1960) and strongly advocated by Drewes (1964, 1965, 1967), Moores (1968), Moores and others (1968), Drewes and others (1970), Whitebread (1968), Hose and Danés (1968), and Hose and Blake (1969), but the age and significance of the extension is not agreed upon. In order to discuss the interpretations of various authors and to develop my own ideas, it is useful to discuss specific examples going from east to west across east-central Nevada.

Snake Range

First, and perhaps most important of all, is the Snake Range. This area inspired Misch's (1960) idea of a décollement thrust fault separating complexly sliced upper plate rocks (Cambrian and younger) from a relatively intact autochthon of Cambrian and older strata that had been metamorphosed during the Mesozoic (prior to emplacement of massive granites in the vicinity of Wheeler Peak). Misch (1960) and Nelson (1966, 1969) describe the décollement in great detail and on indirect evidence (unconformities below Cretaceous strata that lie more than 100 mi away from the Snake Range) conclude that it is of Mesozoic, pre-Laramide age. I believe that evidence for dating the faults may be found in the southern Snake Range area shown on Figure 8, recently mapped by Whitebread (1969) and Hose and Blake (1970) and studied by Lee and others (1970).

As can be seen on Figure 8A, normal faults that displace Oligocene volcanic rocks (dated 29.7 m.y. by Armstrong, 1970) can be traced northward where they are observed to merge with the basal décollement. This suggests to me that the décollement itself may be of Tertiary age, at least in part. Further evidence of a young age for the décollement is the dating studies of Lee and others (1971) that showed total argon loss from cataclastic rocks, produced during movement on the décollement, less than 20 m.y. ago. These authors interpreted this to mean that the most recent movement along the décollement, which cuts the Mesozoic granites, is of Tertiary age. I agree wholeheartedly.

Figure 8. Geologic map of the southernmost part of the Snake Range (Whitebread, 1969; Hose and Blake, 1970) and a cross section (E-E′ of Whitebread, 1969) that includes the Murphy Wash–Johns Wash Graben. The numerous faults above the Snake Range décollement merge or truncate against it implying that they are synchronous or older. The fact that some of these faults displace Tertiary volcanic strata suggests a Tertiary age for the décollement. Geologic units indicated by letter symbols are: Ꞓpm, Cambrian Prospect Mountain quartzite; Ꞓ, Cambrian carbonate rocks and shale; OS, Ordovician and Silurian; DM, Devonian and Mississippian; P, Pennsylvanian; Ki, Mesozoic intrusive rocks; T, mid-Tertiary volcanic rocks. Dotted lines are contacts of bedrock with Quaternary cover. Faults are annotated: hachures for high-angle faults (ticks on upper, downdropped plate) and teeth on upper plate of low-angle faults. These same conventions apply to all the maps in this paper.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Deep Creek Mountains and Gold Hill

North of the Snake Range, at the southwestern end of the Deep Creek Mountains, Nelson (1966, 1969) mapped a structurally complex area of upper Paleozoic rocks. The inverse imbrication and brecciation associated with deformation suggest a shallow extensional genesis for his structures. A critical factor in unraveling this area will be a detailed study of Tertiary volcanic stratigraphy and structure, but such studies are still incomplete (work in progress by M. C. Blake and R. K. Hose). If the volcanic structure is complex, it will be necessary to attribute at least some of the low-angle faults mapped by Nelson to the Tertiary. A principle that must be observed in the study of such areas where both Tertiary volcanic and older rocks are present was emphasized by Mackin (1960): *Tertiary strata, including layered volcanic rocks are the guides to the amount of later Tertiary deformation that has taken place.* This younger deformation must be subtracted before a reasonable interpretation of Mesozoic structure is possible. Casualness on this point has contributed much confusion to the literature concerning the eastern Great Basin.

Just north of the Deep Creek Mountains, at Gold Hill, Nolan (1935) first recognized the complex tectonic history of the hinterland. At a time when the geology of the surrounding region was largely unknown, he recognized several periods of compression and extension that he could demonstrate were pre-Eocene in age. In addition, he described complex younger-on-older fault relations and high-angle block faulting of post-Eocene age. Such a chronology fits well with the regional history as known even today, the only qualification being that the post-Eocene younger-on-older faults are more likely extension-denudation-gliding structures than the result of regional compression during later Tertiary time.

Schell Creek Range

The next range to the west is the Schell Creek Range. Dechert (1967), Young (1960), and Drewes (1967) are the principal contributors to knowledge of the geology there. Drewes recognized the complexity of the tectonic history of the area and carefully qualified the interpretations he gave his structures. He was one of the first workers in the region to show large Tertiary glide blocks containing Tertiary strata and recognize that Mesozoic

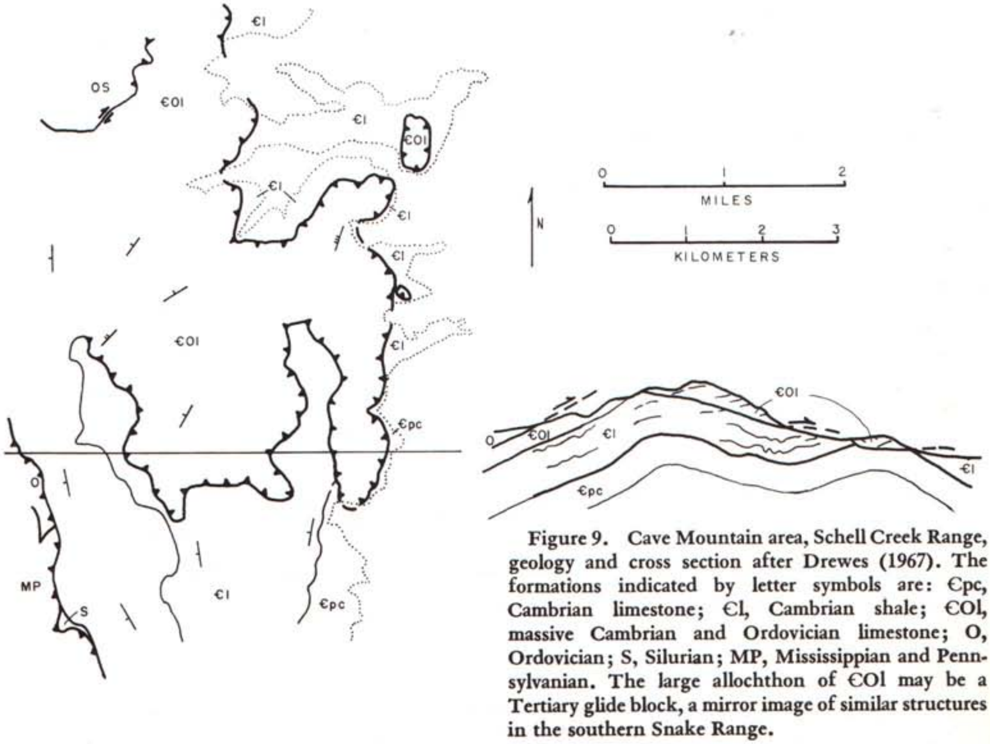

Figure 9. Cave Mountain area, Schell Creek Range, geology and cross section after Drewes (1967). The formations indicated by letter symbols are: Єpc, Cambrian limestone; Єl, Cambrian shale; ЄOl, massive Cambrian and Ordovician limestone; O, Ordovician; S, Silurian; MP, Mississippian and Pennsylvanian. The large allochthon of ЄOl may be a Tertiary glide block, a mirror image of similar structures in the southern Snake Range.

faults may have been sites of Tertiary movement. I go only a bit further than he in interpreting faults in his area as Tertiary. In the Cave Mountain area (Fig. 9), a denudation fault has been mapped. The fault begins at a normal stratigraphic contact between massive upper Cambrian and Ordovician limestone (ꞒOl) and underlying shale (Ꞓl) (known to be prone to slumping and landsliding) and, as followed eastward, shows increasing stratigraphic discordance so that eventually the limestone (ꞒOl) overlies middle Cambrian limestone (Ꞓpc). The strata designated ꞒOl are upright and dip steeply into the fault. The geometric relations are precisely correct for an extensional-gravitational, perhaps mega-landslide, origin for this structure. It is most easy to imagine this happening during the Tertiary, during or after uplift of the range. A mirror-image symmetrical structure involving the same stratigraphic units occurs southwest of Wheeler Peak in the southern Snake Range on the opposite side of Spring Valley. This "twin" of the Cave Mountain structure, visible on Figure 8 (Whitebread, 1969), is part of the southern Snake Range décollement for which a Tertiary origin by extension has already been discussed.

Farther south in the area mapped by Drewes in the vicinity of Connors Pass, I would extend the hypothesis of a Tertiary age to the "Schell Creek Range thrust." Figure 10 shows Drewes'

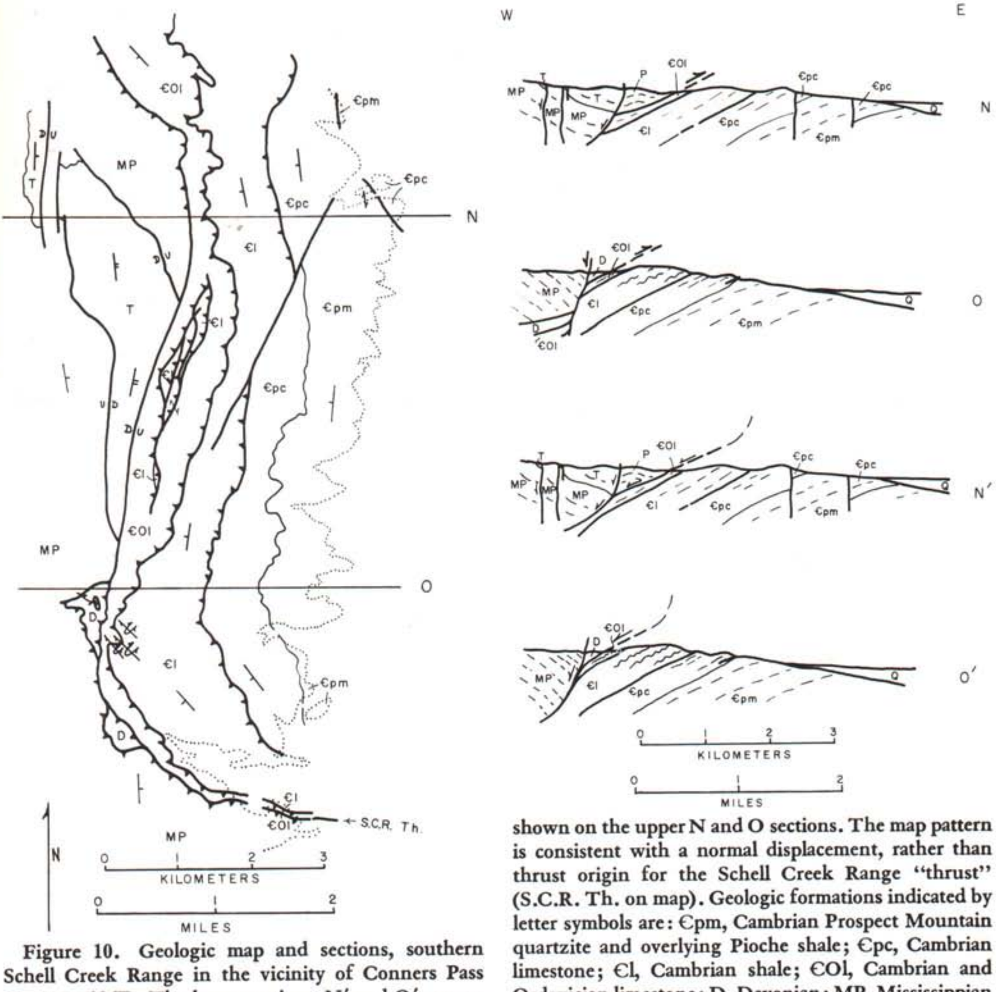

Figure 10. Geologic map and sections, southern Schell Creek Range in the vicinity of Conners Pass (Drewes, 1967). The lower sections, N′ and O′, are an alternate interpretation to the published structure, shown on the upper N and O sections. The map pattern is consistent with a normal displacement, rather than thrust origin for the Schell Creek Range "thrust" (S.C.R. Th. on map). Geologic formations indicated by letter symbols are: Ꞓpm, Cambrian Prospect Mountain quartzite and overlying Pioche shale; Ꞓpc, Cambrian limestone; Ꞓl, Cambrian shale; ꞒOl, Cambrian and Ordovician limestone; D, Devonian; MP, Mississippian through Permian; T, Tertiary.

map and sections and my interpretation. The map pattern is actually more consistent with a Tertiary age for the Schell Creek "thrust" because a large area of Tertiary rocks is down faulted against the ЄOl limestone between sections N and O. The published map suggests that the Schell Creek Range thrust fault is cut by the younger normal fault that forms the southeast boundary of the east dipping Tertiary strata. The problem, as I see it, is that this Tertiary normal fault has the same trend, direction of stratigraphic displacement, and magnitude of displacement as the fault called the Schell Creek Range thrust fault in areas to the north and south. The minimum displacement of the normal fault is one-half mile, yet it dies out on the map within a few hundred feet under a small patch of alluvium just south of its projected intersection with cross section N (Fig. 10). This is a geometric impossibility—a fault displacement cannot change along strike by more than the distance along strike (the

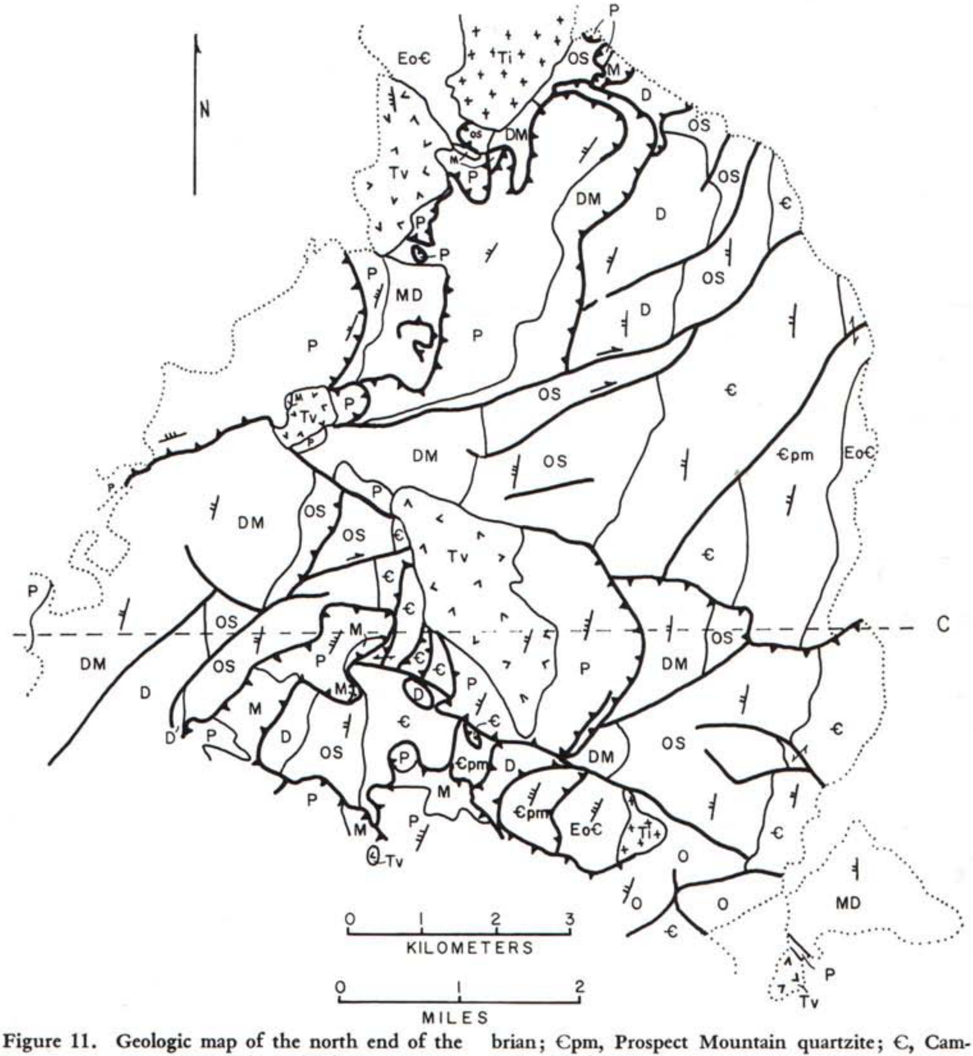

Figure 11. Geologic map of the north end of the Egan Range (Fritz, 1968). The published interpretation is shown even though it must be incorrect, as no structure is shown to explain the westward dip of the Tertiary volcanic rocks crossed by section C-C. Geologic systems indicated by letter symbols are: EoЄ, Eocambrian; Єpm, Prospect Mountain quartzite; Є, Cambrian shale and carbonate; OS, Ordovician and Silurian; D, Devonian; M, Mississippian; P, Pennsylvanian and Permian; Tv, Tertiary volcanic rocks; Ti, Tertiary intrusive rocks.

maximum would be along a fault with scissors movement—displacement away from the hinge point would be equal to the distance from the hinge times the rotation on the hinge in radians—this would seldom approach a 1:1 relation). Continuing on the other side of the same patch of alluvium with the same trend and sense of stratigraphic displacement is the Schell Creek Range thrust fault. To me, the simplest interpretation is that the "thrust" and the Tertiary normal fault are one and the same feature—structures due to extension and resulting in denudation of the half-dome east of Connors Pass. Most of the structure in this area can be viewed as Tertiary denudation rather than the effects of Mesozoic compression or extension. Indeed, several striking drag folds observed near Connors Pass (Fig. 10) indicate down-dip movement, the fault zone between the limestone (ЄOl) and shale (Єl) itself being deformed by these folds. Drewes (1967) commented on this evidence in his report but felt that, in general, fold attitudes gave ambiguous results for direction of displacement along faults in the area. He felt the evidence slightly favored eastward movement, but he made the uncertainties involved in his determination explicit.

Egan Range

An area where the structural significance of Tertiary volcanic rocks (Mackin, 1960) has been ignored is the northern Egan Range. Figure 11 shows the geology of part of the area mapped by Fritz (1960, 1968). The published map shows many faults, and on cross section C-C they appear as nearly horizontal "thrusts" to which a Mesozoic age is assigned in the descriptive text (Fritz, 1960). The steeply dipping Tertiary volcanic strata intersected by cross section C-C *are not* related to any structure capable of producing their steep dip in the Tertiary! In fact, they dip westward toward a steeply east-dipping contact mapped as a normal stratigraphic overlap. Insight into the true nature of the structure is gained by rotating the volcanic rocks back to horizontal (as they must have been approximately 35 m.y. ago). This has been achieved on Figure 12 by simply rotating Fritz's section C-C. The Mesozoic "thrusts" immediately become normal faults (consonant with the direction and magnitude of the stratigraphic displacements along them) that postdate, and thus displace the volcanic rocks. The western contact of the volcanic rocks must, of course, be itself a fault. The only normal stratigraphic contact is with the underlying Pennsylvanian strata—with only a small angular discordance being evident. The structure here is rather similar to the Panamint Range structure of Hunt and Mabey (1966). In the Egan Range, we have normal faults rotated to a near horizontal present-day attitude by tilting of the range—tilting proven by the attitude of the volcanic strata.

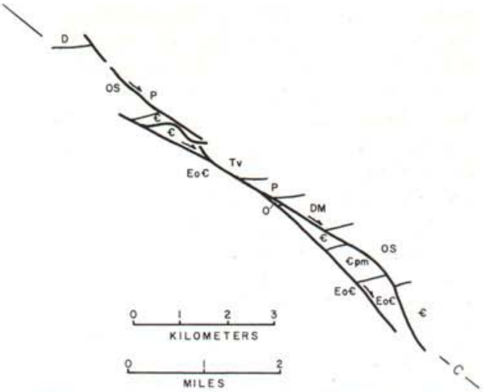

Figure 12. Cross section C-C of Fritz (1968) rotated so as to bring the Tertiary volcanic rocks to a horizontal position. The true nature of many of the "thrust" faults shown on Fritz's map is revealed—they are normal faults rotated to a near horizontal attitude during later Tertiary time.

The patch of volcanic rocks near the north end of the area shown on the map likewise seems to me to violate the principle discussed by Mackin (1960); a major fault between the volcanic rocks and the Eocambrian strata to the north is required. Such an interpretation is in agreement with the work of Adair (1961, and 1963, personal commun.) but denied by R. K. Hose (1971, personal commun.). The contact in dispute is quite steeply dipping but not well enough exposed to be uniquely identified as depositional or tectonic. I would connect the volcanic-Eocambrian contact with a major later Tertiary fault that forms the contact of the Cherry Creek pluton with Paleozoic rocks south of it (Adair, 1961). This Tertiary normal fault would include, in part, a younger-on-older "thrust" that Misch identified as part of his Mesozoic regional décollement. There need be no such structure here at all.

This reinterpretation of parts of Fritz's map does not mean to imply that his entire structural complex is a Tertiary feature. There are many faults, including imbricate thrust faults that cannot be reasonably interpreted as anything but pre-Tertiary structures. The point to make is that the Mesozoic thrust interpretation has been carried too far, and the Tertiary structures have been considerably underrated.

Another example of proliferation of Mesozoic thrust faults in violation of Mackin's principle occurs farther south, in the southern Egan Range, in an area mapped by Brokaw and Shawe (1965; Fig. 13).

On the published map and section, a younger-on-older thrust fault is shown along the west side of the eastward-tilted Egan Range fault block. Slightly farther west, a normal fault of negligible stratigraphic displacement is shown. The Tertiary strata lying on the east side of the range, dipping eastward, are the same units as those lying nearly horizontally west of the range and west of the two faults mentioned above. These two areas were part of an originally extensive horizontal and continuous blanket of Tertiary strata. The displacement *proven* by present attitude of the Tertiary strata amounts to thousands of feet of warping or faulting. There is no structure on the map, as published, to account for this displacement. However, the orientation of the "thrust" and amount of stratigraphic throw along it are exactly as needed to explain the Tertiary deformation. My solution to this dilemma is that the Mesozoic "thrust" is a low-angle normal fault of later Tertiary age—the low angle being in part a consequence of eastward tilting of the southern Egan Range.

Grant–White Pine Ranges

Moores and others (1968) emphasized the importance of gravitationally driven Tertiary gliding and denudation structures in the northern Grant and southern White Pine Ranges.

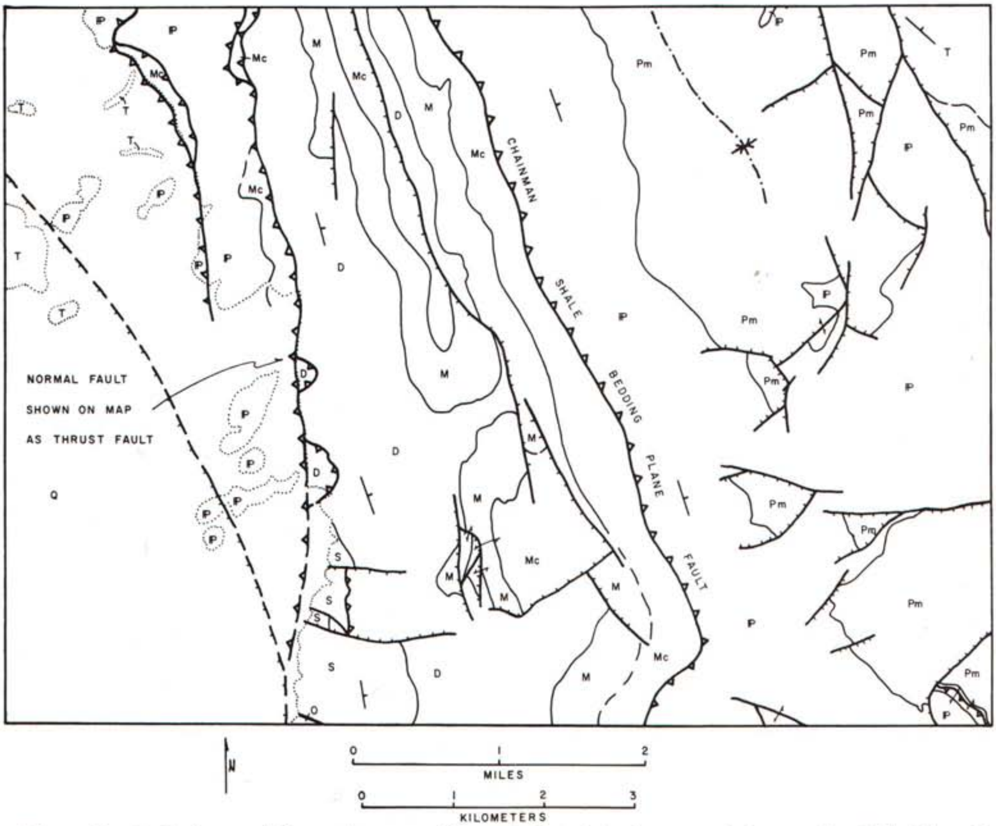

Figure 13. Geologic map of the northern part of the Ely 3 SW. quadrangle (Brokaw and Shawe, 1965), Egan Range, just southwest of Ely, Nevada. The thrust fault shown along the west side of the range must be the Tertiary normal fault required to explain the uplift and eastward tilting of the range. Geologic systems indicated by letter symbols are: O, Ordovician; S, Silurian; D, Devonian; M, Mississippian, mostly limestone; Mc, Mississippian shale; P, Pennsylvanian; Pm, Permian; T, mid-Tertiary sedimentary and volcanic rocks.

They could not fail to be impressed by large masses of Paleozoic strata enclosed within, and overlying, Tertiary volcanic and sedimentary rocks in their area. Yet in the same ranges, at deeper levels, structures of pre-Tertiary age are present. Cebull (1970) has described the spectacular effects of regional metamorphism, large-scale recumbent folding, and imbrication that occur around Troy, south of the area mapped by Moores and others (1968). Some of the structural complications described by Cebull may be of Tertiary age; denudation faults related to range uplift would be so similar in appearance as to be indistinguishable from some of Cebull's thrusts, but a Mesozoic age seems reasonable for most.

To the north of the area mapped by Moores and others (1968), in the White Pine District, the published map of Humphrey (1960) shows Mesozoic thrust faults as well as several faults which can be interpreted as Tertiary denudation features, one in particular being the Lampson "thrust" as shown on Figure 14. The striking feature of this "thrust" is that it dies out completely near the north edge of the figure where it is joined by a wrench fault, the Eberhardt fault. Geometric logic suggests that the increasing stratigraphic displacement southward is an expression of increasing normal displacement along a fault hinged at its northern end. But this is the reverse of the published interpretation! The Tsv strata that abut against the Lampson fault scarp provide further suggestion, following Mackin's principle, that displacement along the fault is normal rather than reverse. To me, the map pattern suggests that the upper plate on which the Tertiary strata lie has moved downward and westward, at the same time rotating clockwise about 10°. The slice of Silurian[1] rock thrust on nearly overturned Devonian strata near the south side of the area shown on Figure 14 remains to be explained. This structure is presumably the reason a thrust origin for the Lampson fault was initially inferred. These structural complications at depth suggest to me that the normal fault has merged with, and followed a Mesozoic thrust plane that existed below a décollement in the Mwp shale before Tertiary faulting began. This suggestion allows a reconciliation of the evidence for normal and reverse movements along the same fault. The map pattern around Mount Hamilton, also on Humphrey's (1960) map, likewise contains suggestions of possible reinterpretation of Mesozoic thrust faults as composite structures involving reverse *and* normal displacements of various times along the same faults. Unfortunately, these structures are not datable and thus could be Mesozoic or Tertiary. It is impressive, however, that two illustrations (his Figs. 12 and 13) in Humphrey's (1960) report show drag suggesting down-dip movement

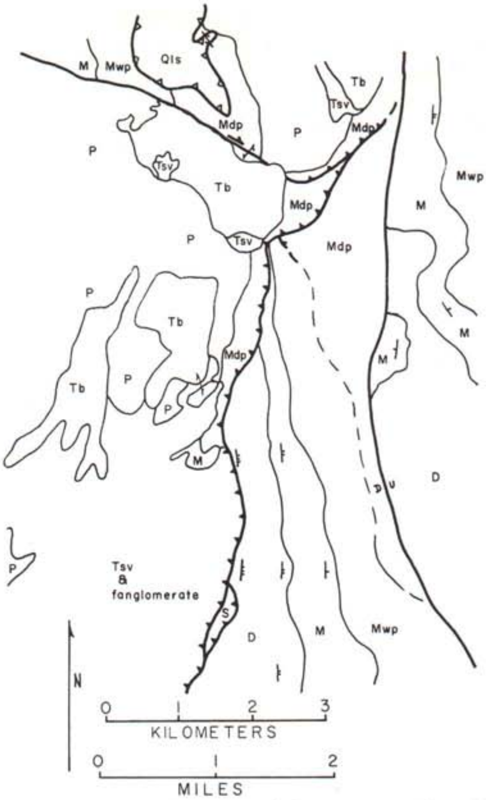

Figure 14. Geologic map of the Lampson "thrust" White Pine district (Humphrey, 1960). Stratigraphic displacement on the "thrust" increases southward, suggesting normal, rather than thrust movement, but some features observed toward the south (imbrication, near-overturning of Devonian strata) suggest thrusting. This may be reconciled by proposing that a Tertiary normal fault intersects and joins at moderate depth a Mesozoic listric thrust. This would be an example of reversal of movement along a given fault surface during two stages of deformation, a normal expectation in a region with complex tectonic history.

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[1] R. K. Hose (Hose and Blake, 1970, and 1971, personal commun.) reports that this is probably Devonian Simonson Dolomite, and so the structure may not be as complex as indicated by Humphrey (1960).

along a fault mapped as a thrust fault (Monte Cristo fault with up-dip movement, but younger-on-older stratigraphic displacements). Similar complexity is probably applicable to many other hinterland structures. Re-use of Mesozoic faults during Tertiary deformation was an important conclusion of Drewes (1964, 1967), and has been well documented in the Canadian Rockies (Dahlstrom, 1970; Bally and others, 1966).

Ruby Mountains

In the Ruby Mountains, Willden and others (1967) and Willden and Kistler (1969) discovered a klippe of brecciated Devonian rocks overlying an Oligocene granitic pluton, itself slightly brecciated near the tectonic contact. They invoked a period of compressional thrusting during the Tertiary and related it to K-Ar dates on crystalline rocks north of the klippe that reach a minimum of 21 m.y. along the west side of the range, the side where the klippe lies. The evidence could as well be interpreted, as in the Snake Range, to indicate tectonic denudation of the range during Tertiary time. The westward decrease in K-Ar dates may even be a clue to the direction of movement of the cover and the rate it was pulled (or slid) off the Ruby Range into the valley on the west side. The klippe of Devonian rocks would be merely a remnant of the block that moved off, resulting in rapid cooling of rocks that had up to that time remained too hot to retain argon. To interject a period of regional compression during the later half of Tertiary time unnecessarily complicates the tectonic history; it can only be accomplished by a rather involved manipulation of known examples of datable displacements of Tertiary strata that are convincing evidence of extension which occurred throughout the region after the effusion of Tertiary volcanic rocks began, approximately 40 m.y. ago.

GLIDING VERSUS PUSHING IN THE SEVIER OROGENIC BELT—HOW DOES THE HINTERLAND FIT THE BIG PICTURE?

Several authors (Whitebread, 1968; Roberts, 1968; Roberts and others, 1965; Hose and Danés, 1968; Hose and Blake, 1969) have suggested that the denudation (attenuation of Hose and Danés) structures of the hinterland are genetically linked with thrusting in the Seviér orogenic belt. They invoke a gravitational gliding mechanism whereby denudation (attenuation) in the hinterland is synchronous with thrusting along the Wasatch zone; extension in the hinterland must match compression in the Wasatch zone if crustal shortening has not occurred. Gravitational gliding mechanisms have also been invoked as explanations for other sectors of the Cordilleran fold and thrust belt (Scholten, 1968; Crosby, 1968, 1969; Mudge, 1970). It should be emphasized that the scale of the glide structures advocated to explain the Sevier belt and its lateral continuation is at least an order of magnitude larger than the scale of glide blocks related to local uplifts during Tertiary [and Mesozoic(?)] time. Large-scale gliding involves movement of sheets of sedimentary strata that are at most 5 mi thick and more than 100 mi in width over distances of 40 to 100 mi. Opposition to large-scale gliding has been expressed, however, by other geologists who advocate crustal shortening as a genetic explanation for the fold and thrust belt (Armstrong, 1968b; Burchfiel and Davis, 1968; Fleck, 1970b). For the Canadian Cordillera, Price (1969) and Price and Mountjoy (1970, 1971) propose an attractive model of crustal thickening in the hinterland and consequent lateral flow of supra-crustal material to produce the fold and thrust belt. This model involves crustal shortening of a magnitude similar to, if not identical with, the compression expressed in the fold and thrust belt (more than 100 mi in southern Canada), and although it is referred to as a gravitational mechanism (gravity being a very important part of the driving force), it significantly differs from the mechanism proposed by the gliders. The thrust faults are projected westward, at depth, into deep zones of intracrustal flow. Plates move uphill (but down lithostatic gradients), so that an eastward slope of the movement planes is not required at any time. Such a mechanism does not require that the rear of the moving plates be a zone of extension at the earth's surface so that a region of extension and denudation in the hinterland is not necessary—if lacking it is not a detriment for the model. If present, such a zone of extension can have an explanation independent of the genesis of the fold and thrust belt; there is no necessity that events in zones of extension and compression be synchronous and displacements in the two belts of comparable magnitude.

Armstrong (1968b), Burchfiel and Davis

(1968), and Fleck (1970b), do not consider the denudation structures of the hinterland of the Sevier belt to be directly related to the genesis of the fold and thrust belt. A different model created by Misch (1960; Misch and Hazzard, 1962) and supported by his students (*including* Fritz, 1960; Woodward, 1964; Miller, 1966; Nelson, 1966, 1969) proposes a link between hinterland and Wasatch-zone structures that has to be discussed separately as it does not represent a combination of any of the "glide" or "push" models already outlined. Misch envisages the younger-over-older faults of the hinterland as décollements between a relatively rigid "basement" (deep seated geosynclinal strata that have been subject to Mesozoic synkinematic regional metamorphism prior to thrusting) and a severly tèctonized cover that was being pushed[2] eastward relative to the "basement" at some time late in the Mesozoic but *prior* to the "Laramide" deformation in the Sevier orogenic belt (Misch, 1960, 1971). Another zone of thrusting, lying geographically between the Sevier belt and the hinterland, but now buried by Tertiary valley fill, is proposed by Misch. This hidden thrust zone is the one Misch relates to the hinterland structures. He does not recognize hinterland structures of "Laramide" age that would correspond with Sevier orogenic belt structures in age and be linked with them in genesis. Moreover, Misch believes the denudation faults to be of compressional origin, not structures resulting from extension.

Misch believed the décollement faults he described were Mesozoic, because he felt that the deformation style was in contrast with the style of faults that displace Tertiary volcanic rocks, but this might be simply a change in style with depth along the same fault. Some of the faults upon which our disagreement focuses were buried at depths of at least 5 mi, if the paleogeologic map and sections are at all correct, so that we both agree that the slicing, mylonitization, and retrogression observed in lower Paleozoic rocks was not a surficial phenomenon, but rather one that took place at lithostatic pressures of several kilobars. The intense brecciation noted by Nelson (1966, 1969) where low-angle faults displace upper Paleozoic rocks is exactly the style of deformation associated with Tertiary glide blocks in the Mojave Desert region (Burchfiel, 1966; Burchfiel and Davis, 1971).

Obviously a diversity of opinion exists as to genesis and significance of hinterland and Wasatch-zone structures. My own preference has been, admittedly, for pushing rather than gliding as an origin for the Cretaceous Sevier orogenic belt and, as outlined in this paper, for denudation and gliding, much of it Tertiary, on a local scale to explain the hinterland structures. I think it worthwhile to outline all the reasons that I think make the large-scale gravitational gliding model untenable, and why I differ with Misch on interpretation although we have no disagreement on geologic observations or tectonic sequence in the hinterland. Some objections are geometric, others chronologic. Arguments about mechanism are, for the most part unsatisfactory and inconclusive, as they require knowledge we do not have on the large-scale behavior of rocks. I prefer to analyze what has happened, geometrically and chronologically, rather than to try to answer abstract questions of how it happened (mechanism and driving force). I am willing to grant anyone a process regardless that it may conflict with intuition or an evolving body of theory, if it can be proved to have happened.

Gliding models require a net downhill slope between area of uplift, source of moving plate, and area of imbrication of the plate. Mudge (1970) imagines an uplift of 60,000 ft in western Montana to propel his moving plate, yet there is neither stratigraphic evidence within the area of uplift for such extremely elevated mountains (needless to speculate on the paleoclimatic consequences of such mountains that exceed the highest point in the Himalaya Mountains by a factor or two), nor is there evidence on either side that requires such an uplift. In fact, this supposed source area is known to have been the site of basins accumulating sediments at moderate elevations (a few thousand feet at most) by the later part of Eocene time (Price, 1962, 1971). In the eastern Great Basin, it is difficult to find evidence of great uplift during later Mesozoic time. What we do know is that the entire region was near sea level up to the Jurassic. A few localities within the region contain fluviatile and lacustrine sediments of approximately middle Cretaceous age (this should be near the time of maximum uplift) which have yielded

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[2] Misch (1960, p. 41) describes the process as "westward underthrusting" of a non-yielding foreland. He does not consider attenuation in the hinterland to be significant (Roberts and others, 1965).

paleobotanical remains indicative of relatively low elevations (Easton, 1954), not alpine highlands. Over much of the hinterland, the earliest datable Tertiary deposits, Eocene lakebeds containing faunas that indicate relatively modest elevations (Winfrey, 1960), overlie upper Paleozoic strata (*compare* paleogeologic map of Armstrong, 1968 and Fig. 3). The fact that these upper Paleozoic strata are preserved over much of the hinterland strongly suggests that the area never lay more than a few thousand feet above sea level. Only an average of a few thousand feet of strata have been eroded from the geosynclinal pile of the hinterland, and this could have taken place at low elevations during the 100 m.y. of available geologic time. Had there been high mountains in the hinterland, one would expect some evidence of them. As it is, they are needed to support the gliding theory—but are not independently documentable. The available facts support a history during which the hinterland is only moderately uplifted. The Sevier fold and thrust belt that lay to the east was the principal source of clastic material that filled the Rocky Mountain geosyncline.

The estimates of cumulative thrust and fold displacements in the Sevier orogenic belt range from a precisely documented figure of more than 175 mi in southern Canada to conservative estimates of 40 to 60 mi in Utah and southern Nevada. Extension of comparable magnitude is simply not present in the hinterland. This is a bold assertion, but a defensible one. The width of the hinterland belt does not usually exceed 150 mi. In order to preserve a geometrically *necessary* equality between extension and compression would require 30 to 100 percent extension of the hinterland during the Mesozoic. Nothing of this magnitude has been shown by existing maps. The pre-Tertiary paleogeology (Fig. 3) of the region is relatively simple, consistent with only a few extension faults having a cumulative displacement of no more than a few miles. An aggregate of a few miles of pre-Tertiary extension is the most that the hinterland geology allows—insufficient by an order of magnitude to be an inverse expression of the Sevier orogenic belt. The extension needed is of greater magnitude, in the hinterland zone itself, than that extension known to be responsible for the Tertiary structure of the Great Basin! There is simply not such a basin-and-range structure evident in the pre-Tertiary geology, yet without it the glide model is untenable.

Comparison of Mudge's (1970) cross sections and map of his "source area" reveal a similar geometric inconsistency that makes his glide model unsatisfactory (Price, 1971). There is no extension structure in his "source area" that approaches the magnitude of the compression that he, himself, documents in thrusts and folds along the eastern margin of his supposed glide block. Individual stratigraphic units in the Belt Series can be followed across his hinterland. The maximum gaps shown on his map would allow (but don't even require) about 10 mi of extension. He needs more than 30 mi of extension to claim that his model satisfies the most elementary geometric rules of conservation of volume and area (Dahlstrom, 1969).

Further geometric difficulties of the glide hypothesis are the seemingly discontinuous nature of suitable denudation structures. The glide model or Misch's pushing model require continuity of a movement surface over the entire hinterland, yet a suitable fault or fault zone is difficult to follow from range to range and seemingly lacking in many places. For example, contrast the northern Egan Range (denudation-décollement structures reported by Woodward, 1964, and Fritz, 1960, 1968) with the southern Egan Range (continuous lower Paleozoic sections reported by Kellogg, 1960, 1964; and Playford, 1961) or the Snake Range (denudation-décollement structures reported by Misch, 1960; Nelson, 1966; and Hose and Blake, 1970) with the northern Deep Creek Mountains (continuous lower Paleozoic section reported by Bick, 1966; and Nolan, 1935). Either the denudation-décollement structures are discontinuous (negating the glide or décollement thrust hypothesis) or they jump up and down stratigraphically to levels not observed in presently exposed rocks (an *ad hoc* excuse to retain the tenability of the glide-décollement hypotheses). This is very much in contrast to the zone of compression where major faults parallel individual stratigraphic horizons for hundreds of miles.

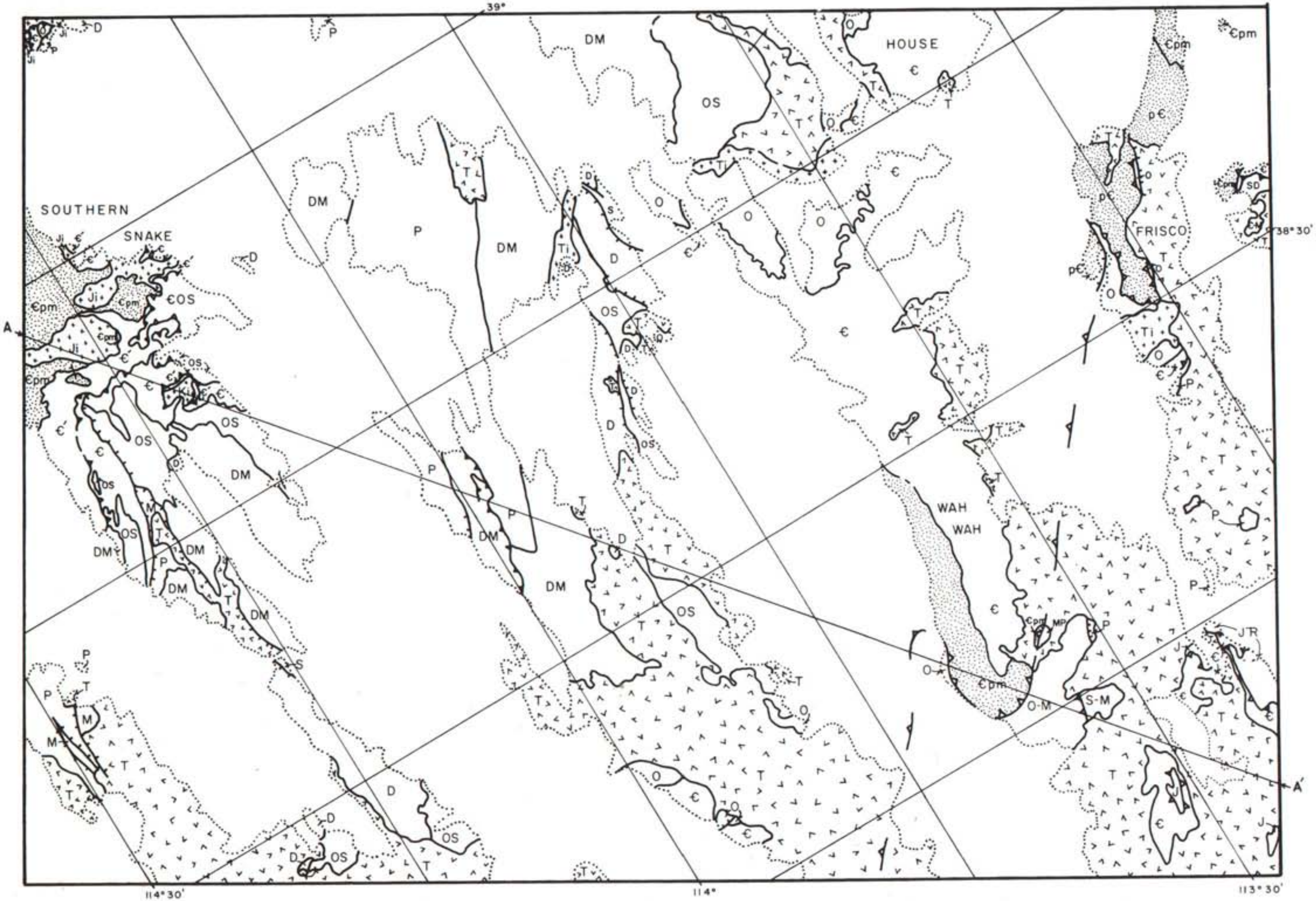
An even more devastating argument against the models that correlate hinterland denudation-décollement structures with the fold and thrust belt is their provincialism. Most participants in this debate would agree that the same genetic model must apply throughout the length of the fold and thrust belt (no one has proposed that all three models are correct but apply in different areas that lie on strike with one another). The denudation-décollement structures that are the focal point of this paper exist only in the Basin and Range province. Comparable or correlative features are not recognized elsewhere in the North American Cordillera. The inspiration and support for a glide-décollement model is lacking entirely from some sectors of the Cordillera. My own inclination is to seek a Basin and Range–related explanation for these structures confined to the Basin and Range province. A plausible genetic connection between extension and compression structures cannot be taken seriously when it proves inapplicable elsewhere along the same structural belt.

Further geometric difficulties posed by the glide-décollement models can be shown by trying to draw a cross section from the southern Snake Range through the Wah Wah Range to the Colorado Plateau platform (Fig. 15) (between sections C and D of Armstrong, 1968). The "autochthon" (according to the gliders) of the Snake Range lies only about 60 mi from the Wah Wah thrust trace where Eocambrian and lower Cambrian quartzites overlie imbricate Paleozoic carbonate strata. Before Tertiary regional extension, the two areas were probably even closer. If the shortening in the Wah Wah area is on the order of 50 mi as is suggested for areas along strike (the stratigraphic displacements in the Wah Wah area exceed 5 mi—and this is for faults essentially parallel to bedding planes where now observed so that actual displacements much be much larger) then that entire upper plate east of the Snake Range must be allochthonous. This would *require* a source area *west* of the Snake Range (and not on top of it). This, in turn, creates insurmountable stratigraphic problems. The nature of the Cambrian quartzite and overlying carbonate strata of the Wah Wah allochthon requires that they come from the east of the Snake Range "autochthonous sections. Wah Wah Cambrian is transitional between Snake Range and platform sections in paleogeographic setting and sedimentary facies (Robison and Bentley, 1958; Robison, 1960; Palmer, 1960). Wah Wah Lower Cambrian is not the least bit affected by regional metamorphism whereas the Lower Cambrian of, and west of, the Snake Range is distinctly metamorphosed (chlorite grade) and we have already agreed that the metamorphism is regional, and prior to the Cretaceous in the Snake Range and vicinity (Misch, 1960; Misch and Hazzard, 1962; Armstrong and Hansen, 1966; Lee and others, 1970). The unsuitability of the glide model is shown by these purely geometric arguments. The fact that the same Cambrian formations occur in both upper and lower plates in the Snake Range is further evidence that displacements involved are small. The Eocambrian rocks of the Snake Range that underlie the "décollement" are fully as allochthonous as the Wah Wah upper plate. The "décollement" structures are younger and an order of magnitude smaller in displacement than the Sevier Belt thrust faults. Alternate interpretations that have been proposed to date are in conflict with the facts shown on geologic maps!

Finally, I reject the glide-décollement models on chronological grounds. I have attempted to show that few, if any, of the hinterland denudation structures are synchronous with deformation in the Sevier orogenic belt. Some can be shown to be definitely older; many, including type examples of denudation-décollement structures are *provably* Tertiary in age and most *may* be, although this proposition is debatable because the age of many faults simply cannot be established.

CONCLUSIONS

Roberts and others (1965), Roberts (1968), Hose and Danés (1968), Whitebread (1968), and Hose and Blake (1969) conceive of a broadly arched-up hinterland within which denudation and attenuation occurred as Paleozoic strata glided down an eastward gradient toward the Sevier belt, a zone of compression tectonics during the Cretaceous. I have attempted to show that the age and magnitude of displacement of denudation faults in the hinterland are unsuitable for tectonic correlation with thrusting in the Sevier belt, that the two processes may be unrelated. My objections to Misch's model are that the predominantly young age and lack of continuity of the décollement structures make it unnecessary, and indeed impossible, to relate them to a deformed belt that has never been observed, or to the Sevier belt structures. We both agree that the décollement structures are of deep-seated origin involving retrograde metamorphism and cataclastic deformation of rocks that had been affected by regional metamorphism at some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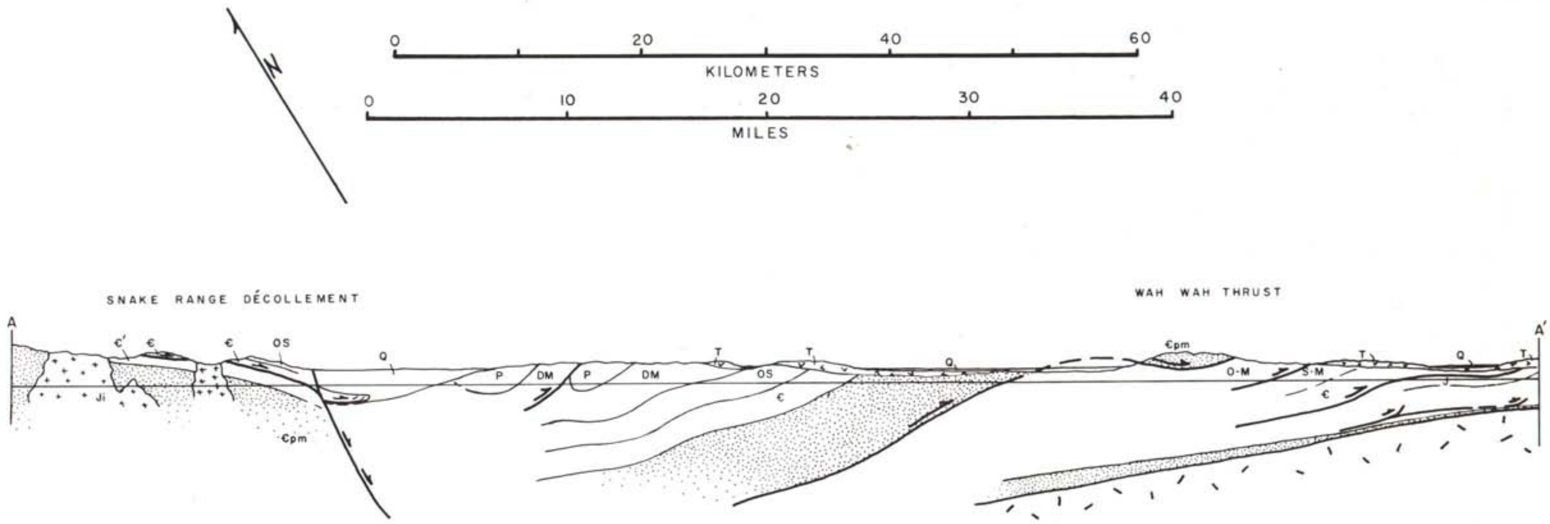

Figure 15. Geologic map and section for the region including the Snake Range, site of denudation-décollement structures of the hinterland, and the Wah Wah Range, a part of the Sevier orogenic belt zone of imbricate thrusts. This area of closest approach of the two types of structure clearly demonstrates the difficulties of genetically relating the two types of structures. The Snake Range is not a logical or adequate source for the Wah Wah allochthon and a connection between the thrust and décollement faults does not seem likely. The interpretation offered is that the Snake Range is as allochthonous as the Wah Wah upper plate, the décollement structures being much smaller and related to Tertiary extension and denudation in the Snake Range area. Letter symbols for geologic units are: p€ and €pm, Eocambrian and lower Cambrian basal clastic sequence; €′, Cambrian of Snake Range "autochthon"; €, Cambrian; O, Ordovician; S, Silurian; D, Devonian; M, Mississippian; P, Pennsylvanian and Permian; Ji and Ki, Mesozoic intrusive rocks; Ti, Tertiary intrusive rocks; T, mid-Tertiary volcanic strata.

earlier time (at least as early as the Jurassic in some areas), but we disagree in that I concur with the advocates of gliding in attributing them to extension, while he argues for a compressional genesis.

Figure 16 contains three cross sections of the crust of the western United States illustrating a possible tectonic history for the past 200 m.y. The sections have been constructed so as to preserve length and area, allowing for some removal of strata by erosion, but preserving the amount of crystalline crust. Until the middle of the Jurassic, the Cordilleran geosyncline remained close to sea level, as illustrated on section C. The crustal thickness chosen is that typical of areas of low elevation or shallow seas today (James and Steinhart, 1966). By this time, considerable tectonic complexity existed in areas to the west of east-central Nevada as a consequence of Paleozoic and Triassic orogenies.

During the remainder of the Mesozoic and until about 50 m.y. ago, the region of the miogeosyncline was subject to one or more protracted periods of orogeny. A metamorphic infrastructure formed as high-temperature isotherms rose and engulfed deep geosynclinal strata. Regional compression led to thickening of the mobile, deforming crust, principally in the zones of high-grade metamorphism and, as a consequence of thickening, resultant isostatic uplift, and regional compression, the suprastructure pushed up over the edges of the stable craton, creating a foredeep immediately east of a fold and thrust belt (Sevier orogeny; section B). Clastic sediments largely derived from the fold and thrust belt accumulated in the foredeep. At the end of the Cretaceous the platform itself broke up into basins and uplifted blocks (Laramide orogeny) (Sales, 1968).

About 40 m.y. ago, volcanism spread into the Great Basin from the north, and distension of the crust began. During the last 20 m.y., distension has widened the area east of the Antler belt to near its early Jurassic width (section A). An anomalously low-density upper mantle keeps the region today at higher elevation than would seem normal for its observed crustal thickness (Prodehl, 1970). At the surface, the distension is expressed by tilted fault blocks. Internally these blocks are cut by faults of various ages. Faults formed at depth during

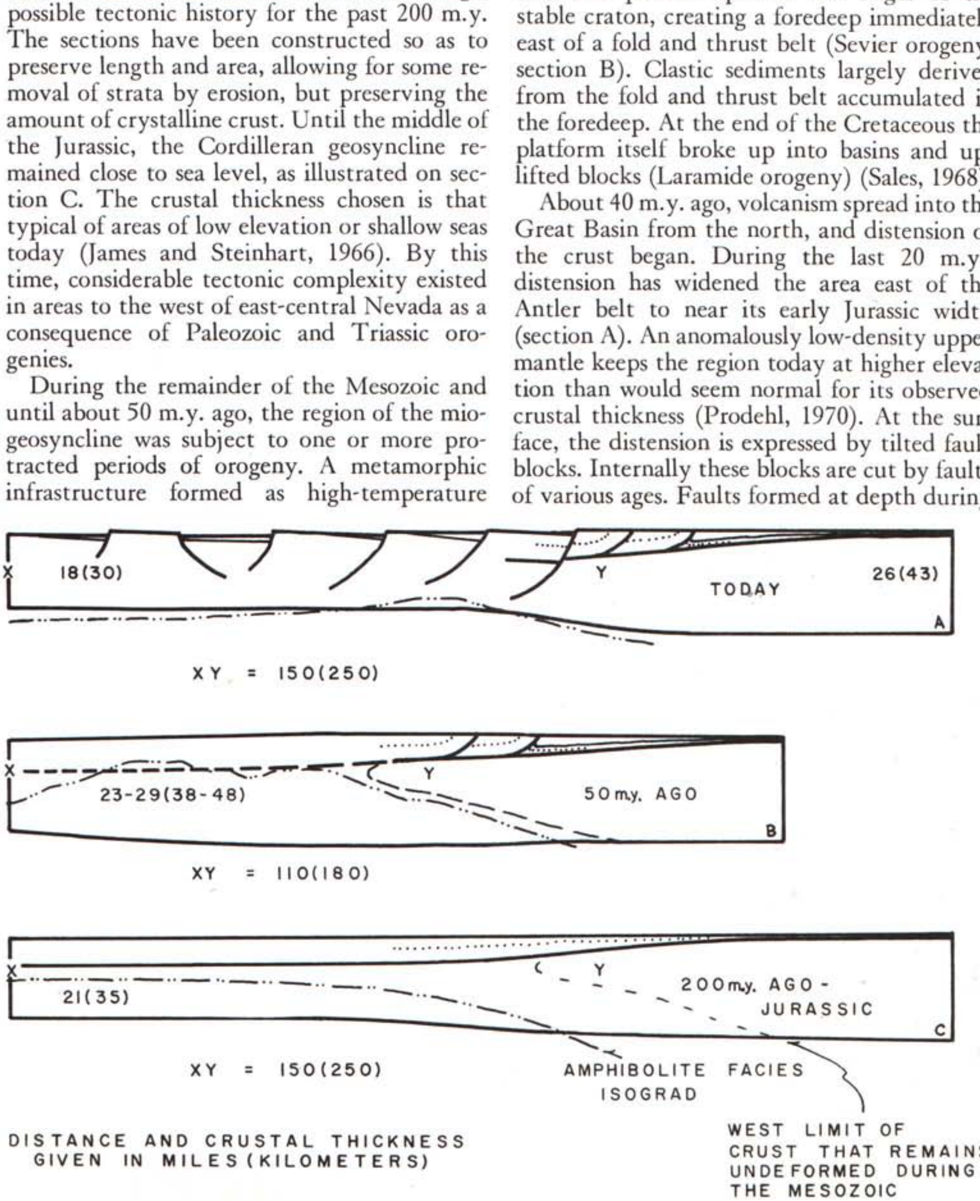

Figure 16. Crustal cross sections of the region between Eureka, Nevada, and the Colorado Plateau, showing changes in crustal thickness and width during Mesozoic and Tertiary deformation of the region. The profiles conserve area, except for some removal of supracrustal rocks by erosion between sections C and B.

earlier stages of extension and denudation are cut by higher angle faults formed during later stages. The most recent large normal faults bound the present ranges.

The hinterland is thus a polyorogenic region of heterogeneous structural style. Unconformities and cross-cutting granitic bodies of pre-Tertiary age prove that regional metamorphism of deep parts of the miogeosyncline and folding and faulting of shallower strata occurred during the Mesozoic over the entire region, but there is no evidence for extensive stretching in the hinterland prior to 40 m.y. ago. Regional extension during later Tertiary time is largely responsible for the observed high- and low-angle normal faulting, vertical and rotational movement of blocks, arching of uplifted blocks, and tectonic denudation on a variety of scales—up to several miles of displacement. Low-angle faults of this period tend to follow incompetent strata and pre-existing low-angle faults, thus complicating and mimicking the Mesozoic structures. Although it is difficult to date many low-angle faults, it is likely that many, once considered to be Mesozoic, are actually Tertiary. Several examples of low-angle faults, mapped as thrust faults, that may be interpreted as Tertiary denudation structures, have been described. The fact that many low-angle faults in the hinterland cannot be logically considered as anything but Mesozoic should not detract from the conclusion that extension of the hinterland is predominantly a late Tertiary phenomenon. Thus the extension cannot be genetically linked with thrusting in the Sevier orogenic belt.

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