DAVID BLOOM

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STRUCTURAL DISCORDANCE BETWEEN NEOGENE DETACHMENTS AND FRONTAL SEVIER THRUSTS, CENTRAL MORMON MOUNTAINS, SOUTHERN NEVADA

Brian Wernicke

Department of Geological Sciences,
Harvard University, Cambridge,
Massachusetts

J. Douglas Walker and Mark S. Beaufait

Department of Earth, Atmospheric and
Planetary Sciences, Massachusetts
Institute of Technology, Cambridge,
Massachusetts

Abstract. Detailed geologic mapping in the Mormon Mountains of southern Nevada provides significant insight into processes of extensional tectonics developed within older compressional orogens. A newly discovered, WSW-directed low-angle normal fault, the Mormon Peak detachment, juxtaposes the highest levels of the frontal most part of the east-vergent, Mesozoic Sevier thrust belt with autochthonous crystalline basement. Palinspastic analysis suggests that the detachment initially dipped 20-25° to the west and cut discordantly across thrust faults. Nearly complete lateral removal of the hanging wall from the area has exposed a 5 km thick longitudinal cross-section through the thrust belt in the footwall, while highly attenuated remnants of the hanging wall (nowhere more than a few hundred meters thick) structurally veneer the range. The present arched configuration of the detachment resulted in part from progressive "domino-style" rotation of a few degrees while it was active, but is largely due to rotation on younger, structurally lower, basement-penetrating normal faults that initiated at high-angle.

The geometry and kinematics of normal faulting in the Mormon Mountains suggest that pre-existing thrust planes are not required for the initiation of low-angle normal faults, and even where closely overlapped by extensional tectonism, need not function as a primary control of detachment geometry. Caution must thus be exercised in interpreting low-angle normal faults of uncertain tectonic heritage such as those seen in the COCORP west-central Utah and BIRP's MOIST deep-reflection profiles. Although thrust fault reactivation has reasonably been shown to be the origin of a very few low-angle normal faults, our results indicate that it may not be as fundamental a component of orogenic architecture as it is now widely perceived to be. We conclude that while in many instances thrust fault reactivation may be both a plausible and attractive hypothesis, it may never be assumed.

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INTRODUCTION

In Bally et al.'s [1966] classic account of the Cordilleran foreland fold and thrust belt in Canada, evidence was presented suggesting that a period of extension, characterized by west-dipping, listric normal faults, followed eastward thrusting and apparently reactivated the older thrust faults. "Backslippage" on thrust faults has been documented by seismic reflection profiling throughout

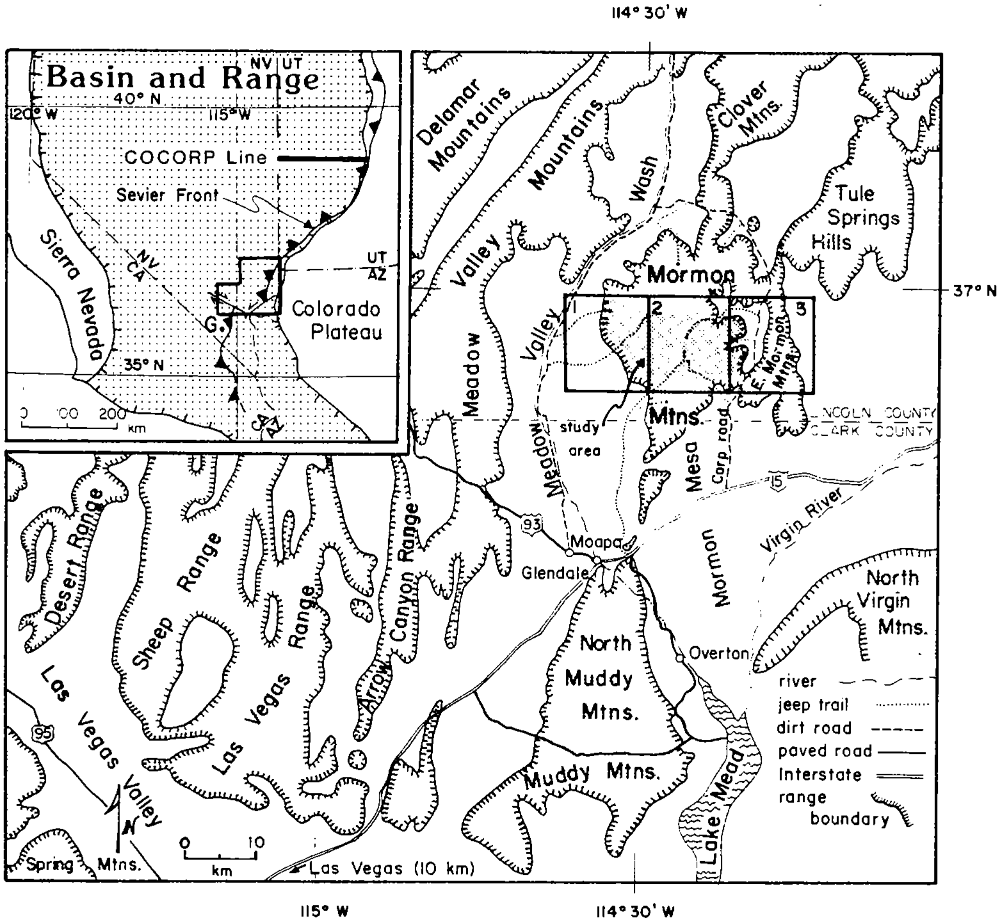


Fig. 1a. Index map showing access roads and location of study area with respect to major tectonic features and adjacent mountain ranges. 1, Rox NE quadrangle; 2, Moapa Peak NW quadrangle; 3, Davidson Peak quadrangle.

parts of the thrust belt not severely overprinted by extensional tectonics [e.g., Royse et al., 1975; Royse, 1983]. The normal faults commonly have up to several kilometers of displacement, and form basins in which older strata are antithetically rotated into the fault surface, with older strata dipping more steeply than younger. In some parts of the Cordilleran thrust belt (particularly the Nevada-Utah sector or Sevier orogenic belt, and its hinterland to the west), a group of enigmatic terrains are characterized by large-scale younger-over-older faulting much more complex than the indisputably "backslipped" portions of the thrust belt in Canada and Wyoming. In these terrains the concept of thrust fault reactivation has been widely applied to faults which lack prima facie evidence of an earlier compressional phase of movement [e.g., McDonald, 1976; Keith, 1982; Drewes, 1967, 1981].

The Mormon Mountains, located along the eastern margin of the Basin and Range physiographic province (Figure 1a), is a well-exposed example of low-angle normal faults superimposed upon thin-skinned compressional structures. Here, structures associated with the Sevier orogeny are distinguishable from the extensional faults because of their classical fold-thrust belt geometry and their detailed characterization in relatively undisturbed ranges along strike of the Sevier belt to the south [Burchfiel at al., 1974, 1982; Davis, 1973; Bohannon, 1981, 1983a, b; Carr, 1983; Axen, 1984]. Thus, this terrain offers an unusual opportunity to examine the influence of

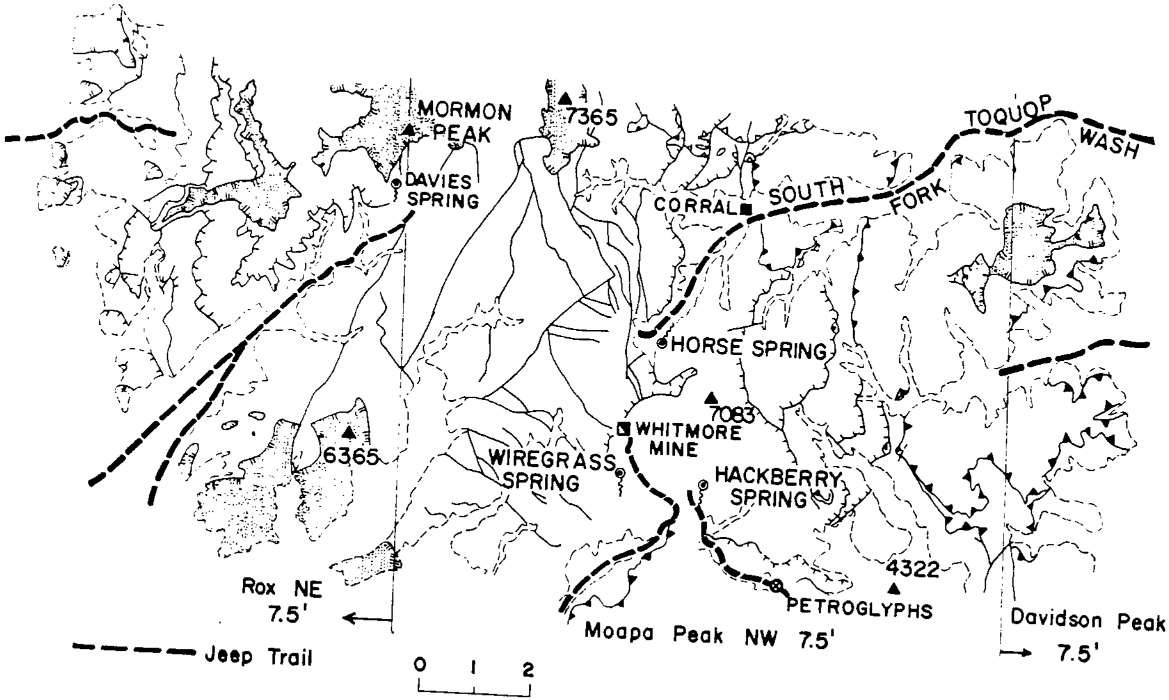


Fig. 1b. Localities referred to in text, superimposed on contacts from Figure 3. Mormon Peak allochthon is shaded.

preexisting compressional structures on large-magnitude extensional tectonics, as well as an opportunity to gain new insights into the extensional structures themselves.

This report summarizes the results of detailed mapping from the 1979, 1980 and 1981 field seasons, which covered the central part of the Mormon Mountains (Figures 1a, 1b). The results of this study have major implications for the interpretation of the many orogenic belts which have undergone a period of compression followed by extension. In particular, the process of reactivation of thin-skinned thrust faults appears to be of lesser importance than the formation of new low-angle normal faults in accommodating crustal extension. Our documentation of this process bears heavily on the interpretation of deep reflection profiling in "collapsed" thin-skinned thrust belts. It appears that low-angle normal faults mapped or detected seismically within older thrust belts may not be tacitly assumed to be reactivated thrusts. Further, since low-angle normal faults can break on new planes discordant to thrusts, then they should have no trouble forming in the absence of any preexisting anistropy.

Previous Studies

Apart from the brief mentions of the Mormon Mountains by Spurr [1903] and Longwell [1926], C. M. Tschanz [1959; Tschanz and Pampeyan, 1970] was the first to describe the geology of the map area (Figure 1a). He mapped the area during the late 1950's and early 1960's in reconnaissance as part of a report on the geology and mineral deposits of Lincoln County, in which he outlined the basic distribution of rock types. However, due to a lack of detailed stratigraphic information, limited field time, and exceptional structural complexity, he was not able to identify the major structural features of the area discussed in this report. Olmore [1971] described and mapped the structure of the East Mormon Mountains and a portion of the Tule Springs Hills. He interpreted the geology of the East Mormon Mountains in terms of large-scale, east-directed thrust faulting locally modified by "backslipping"; however, most of the faults he mapped as

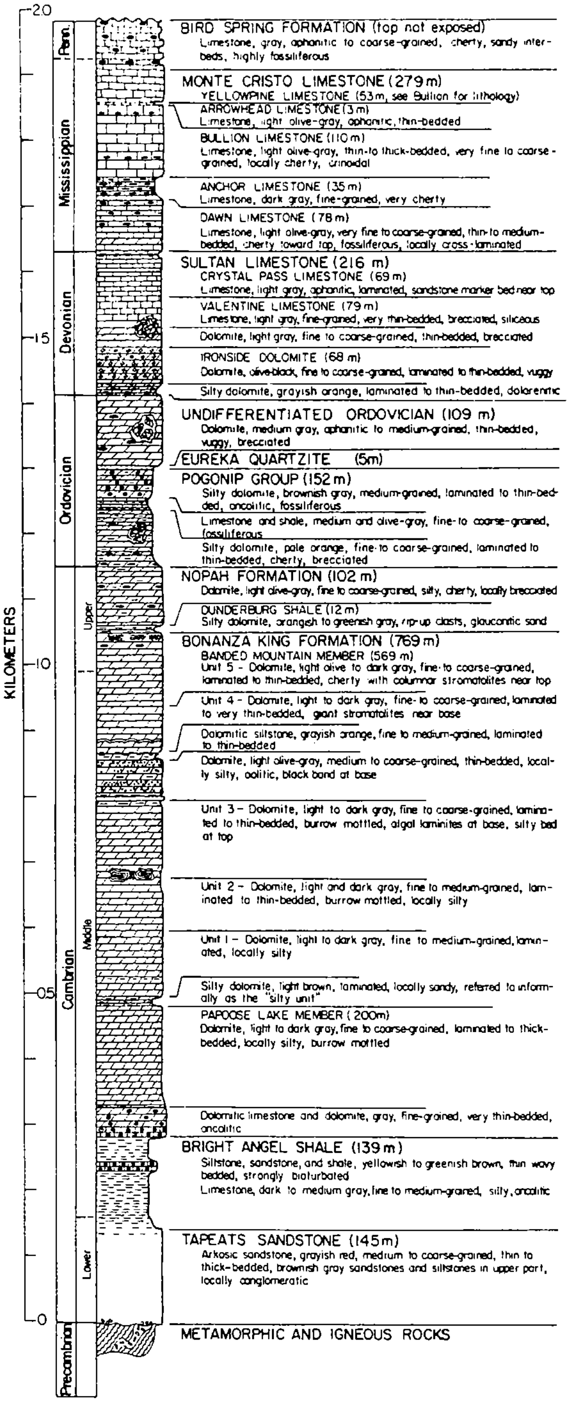


Fig. 2. Stratigraphic column, central Mormon Mountains.

thrusts are unrelated to the Sevier orogeny. Structures in the Tule Springs Hills not thought to have experienced "backslippage" by Olmore have been severely modified by Tertiary extensional deformation. Olmore's interpretations, similar to those of many workers who tried to view low-angle normal faults in terms of compressional thrusting, predated major breakthroughs in the understanding of extensional tectonics in the Basin and Range made during the 1970's [for example, Anderson, 1971; Wright and Troxel, 1973; Proffett, 1977]. Nonetheless, his mapping has provided important information for interpreting the area considered in this report. Longwell mapped the southern portion of the Mormon Mountains in reconnaissance for the 1:250,000 geologic map of Clark County [Longwell et al., 1965], and published several reports on the geology of the Muddy Mountains and North Muddy Mountains [Longwell, 1921, 1926, 1949, 1962]. Ekren et al., [1977] mapped part of the northernmost Mormon Mountains as part of a reconnaissance study of Tertiary rocks in Lincoln County.

STRATIGRAPHY

The stratigraphy of the central part of the Mormon Mountains consists of an approximately 2000 m thick Cambrian through Pennsylvanian sequence of shallow marine rocks transitional between the thick miogeoclinal sediments to the west and the thin veneer of cratonal sediments characteristic of the Grand Canyon region to the east. This sequence nonconformably overlies Proterozoic crystalline rocks and is in turn overlain unconformably by Quaternary alluvial and landslide deposits (Figure 2 and Plate 1). The Paleozoic strata can be divided into three major sequences: a 284 m thick lower terrigenous sequence, a 1205 m thick middle dolomite sequence, and 511-m-thick upper limestone sequence. The lower terrigenous sequence consists of the Tapeats Sandstone and Bright Angel Shale (Lower to Middle Cambrian), the middle dolomite sequence is composed of the Bonanza King Formation, Nopah Formation, Pogonip Group, Ely Springs Dolomite, and the Ironside Dolomite Member of the Sultan Limestone (Middle Cambrian through Late Devonian), and the upper limestone sequence consists of the Valentine and Crystal Pass Limestone Members of the Sultan Limestone, the Monte Cristo Limestone, and the lower part of the Bird Spring Formation (Late Devonian through Pennsylvanian). The lower terrigenous sequence contains several thin carbonate units within the

Bright Angel Shale, and the dolomite and limestone sequences are intercalated with several sandstone, siltstone and shale units.

Thicknesses of stratigraphic units given above and in Figure 2 were determined by Jacob's staff measurement in the easternmost part of the map area and in the East Mormon Mountains. Pronounced thickening of the lower part of the miogeoclinal section occurs within autochthonous rocks (below the basal Sevier allochthon or Mormon thrust plate, Figure 3) across the area. Using cross section thicknesses, it is estimated that Cambrian strata are about 50% thicker in the western Mormon Mountains than in the East Mormon Mountains, giving a total east-to-west thickening of roughly 400 m.

STRUCTURAL GEOLOGY

Four major structural levels produced by compressional and extensional faulting of the miogeoclinal package are separated by, from bottom to top, floor faults of duplexes below the Mormon thrust, the Mormon thrust, and the Mormon Peak detachment. These levels will be referred to here, from bottom to top, as the autochthon, parautochthon, Mormon thrust plate, and the Mormon Peak allochthon (Figure 3). The parautochthon and Mormon thrust plate were emplaced over the autochthon by east-directed thrusting during the Mesozoic Sevier orogeny. In Miocene time, both the autochthon and thrust stack were dismembered by a system of west-dipping, low-angle normal faults, the largest of which is the Mormon Peak detachment. Normal faulting caused varying amounts of eastward tilting of rock units in the map area; in the footwall of the Mormon Peak detachment, structurally lower rocks (autochthon and Precambrian basement) lie to the west of structurally higher rocks (parautochthon and Mormon thrust plate).

Mormon Thrust System

The Mormon thrust system, exposed in the eastern half of the map area (Plate 1 and Figure 3), is composed of the Mormon thust plate, containing the Banded Mountain Member of the Bonanza King Formation and the Nopah Formation, and structurally lower duplexes which contain every formation from the Nopah Formation to the Yellowpine Limestone Member of the Monte Cristo Limestone. The geometry of the Mormon thrust system indicates that it was formed by east-directed, ramp-decollement style thrusting. The thrust faults are either bedding-parallel or cut up-section to the east (Plates 1 and 2). Figure 4 depicts the geometry of the thrust system by showing, in map view, the lithologies immediately below the sole of the thrust system. This map indicates that the base of the thrust system overrides Mississippian rocks in western areas of exposure, and ramps up across Pennsylvanian rocks to the east. Enigmatically, the decollement localized in the most isotropic units in that part of the section: the footwall decollement over much of the Mormon Mountains occurs in the Bullion and Yellowpine Limestones, both massive, coarse grained, poorly bedded units, rather than in the well bedded, finer-grained limestones immediately above and below (Sultan Limestone and Bird Spring Formation, Figure 2). Even more enigmatic is that the hanging wall of the Mormon thrust detached everywhere in strong dolomites of the Banded Mountain Member of the Bonanza King Formation, largely in units 2 and 3, rather than in weaker shales and limestones in the Bright Angel Shale only a few hundred meters below. A similar geometry of decollement thrusting exists to the south in the Spring Mountains [Burchfiel et al., 1982; Willemin et al., 1981], where the major thrusts are detached just a few hundred meters above the Bright Angel Shale in strong Bonanza King dolomites. These observations, combined with Bohannon's [1983 a, b] mapping in the Muddy Mountains, define a 200 km-long segment of the Cordilleran foreland fold and thrust belt in which the major frontal decollement ignored presumably weak layers in the sedimentary wedge and broke the "hard way" (Figure 5).

The parautochthonous duplexes beneath the Mormon thrust dip northeastward and are folded by northwest-trending, northeast-vergent overturned folds, suggesting transport to the northeast (Fig. 6). Parautochthonous slices were probably derived from a ramp between the Cambrian and Mississippian decollement portions of the thrust system, because bedding in the slices generally intersects the bounding faults at high angle. The general northwest strike of strata in the slices suggests that the ramp from which they were derived may also have had a

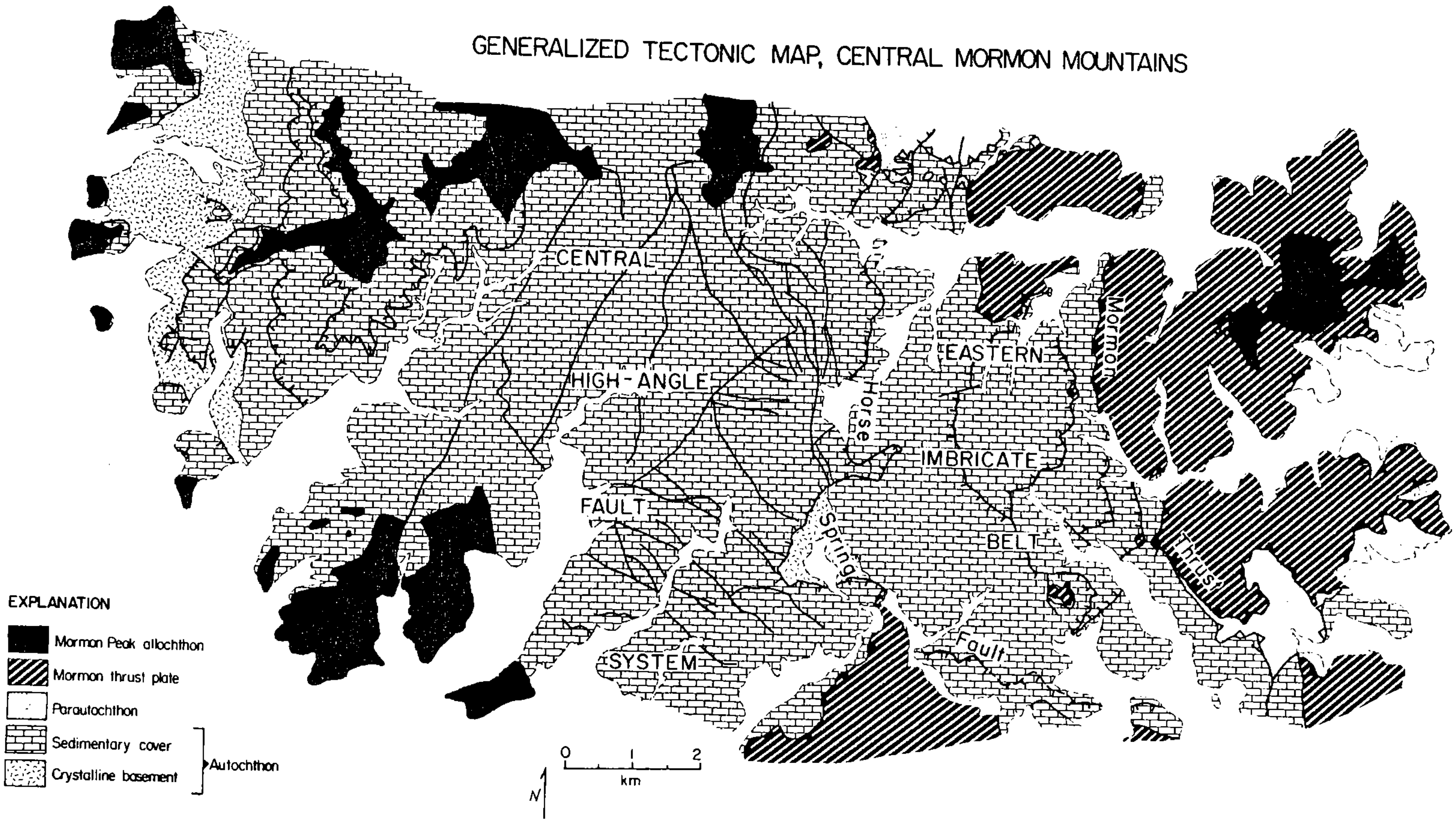


Fig. 3. Major structural units of the central Mormon Mountains.

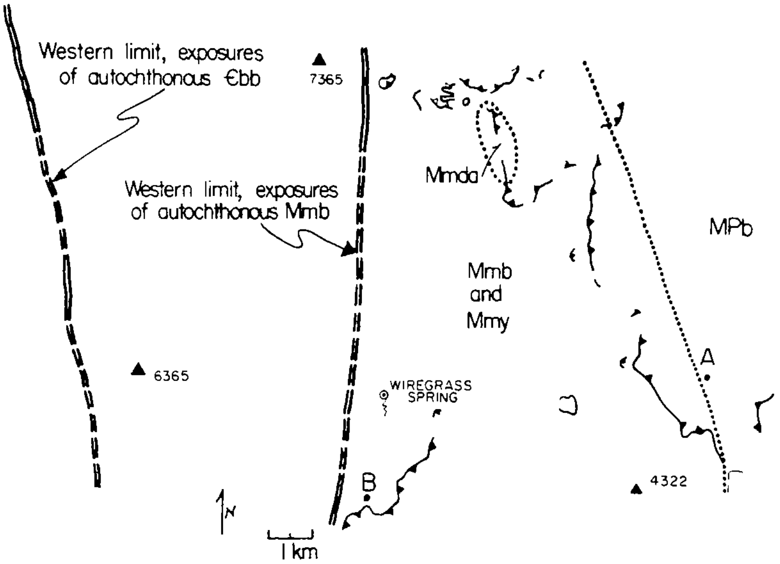


Fig. 4. Map showing footwall geology of the Mormon thrust system. Barbed line shows map trace of the base of the thrust system from Plate 1.

northwesterly strike. In addition, the ramp east of the Mississippian decollement portion of the thrust system may also strike northwest because the footwall pinchout of the Bird Spring Formation strikes northwest (Fig. 4). Ramps certainly need not strike perpendicular to transport direction, but the consistency of the northwest orientation with the northeast vergent folds in the parautochthon and northeast dip of parautochthonous slices suggests a rather simple initial geometry of breakage, with duplexes derived from a Cambrian-Mississippian ramp subsequently emplaced against the next ramp to the east. Although these geometries are most simply interpreted as the result of northeast-directed thrusting, they are not restrictive evidence for such a transport direction. Any transport direction deduced for the Mormon thrust system does not take into account any possible rotations of the entire system about a vertical axis during Tertiary deformation.

No systematic pattern of folding was observed in the Mormon thrust plate. Both southeast- and northeast-overturned folds are present, along with both northeast- and northwest-striking, open to tight upright folds, with no apparent preferred orientation of axes.

Folds in the autochthon were observed at one locality (Figure 4, location B). Here, recumbent folds directly beneath the Mormon thrust are overturned to the southeast (Plate 1), suggesting that the Mormon thrust system may have had a period of southeast transport. A thrust fault between two parautochthonous slices (location A, Figure 4; Plate 1) has been folded and is overturned to the north. This indicates that folding of slices, and therefore at least part of the movement on the Mormon thrust, followed imbrication of these two parautochthonous slices.

The location of the ramp between the Cambrian and Mississippian decollement portions of the Mormon thrust is unknown. The source terrain (original underpinnings) of the Mormon thrust plate must lie west of the westernmost autochthonous outcrops of its oldest stratigraphic units (Banded Mountain dolomites, Figure 4), but the upper segment of the ramp may have overlapped these exposures. The easternmost possible position of the top of the ramp corresponds to the western limit of exposures of autochthonous Monte Cristo Limestone, which corresponds to the westernmost outcrops of the Mormon thrust itself (Figure 4). Perhaps the ramp lay over the western part of the mapped area, because older-over-younger imbrications within the Bonanza King Formation there are common, particularly in the area west of Davies Spring (Figures 1b, Plate 1).

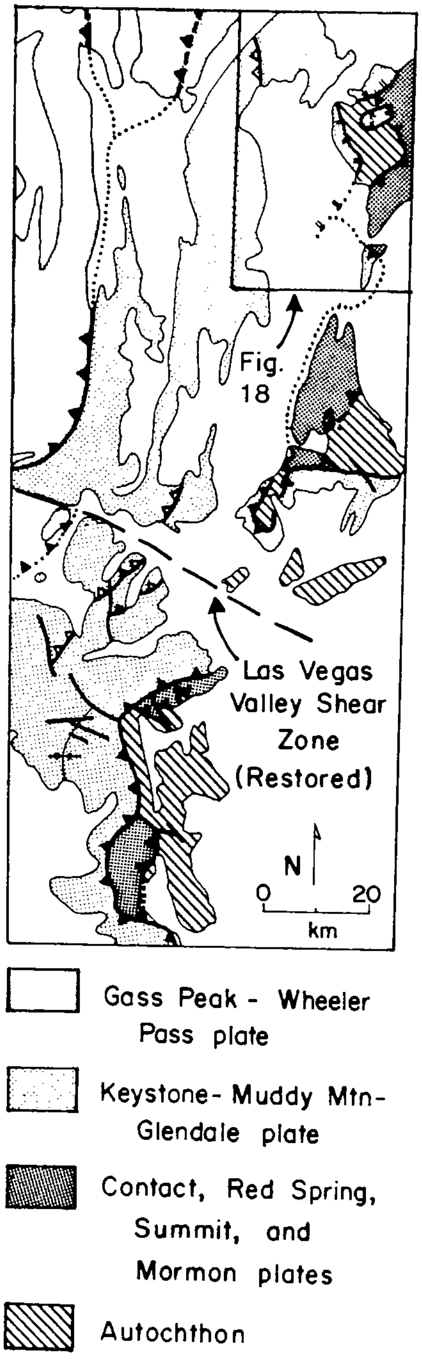


Fig. 5. Major thrust plates of the Sevier orogenic belt in southern Nevada. The two lowest thrusts consistently detach in dolomites from the Cambrian Bonanza King Formation. Between the Keystone-Muddy Mountain and Gass Peak-Wheeler Pass thrusts is a broad, regional synclinorium consisting of miogeoclinal rocks which have been folded and faulted on small thrusts.

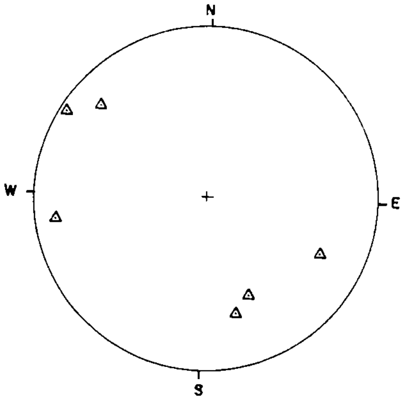


Fig. 6. Axes of macroscopic, flexural-slip folds in parautochthonous slices suggesting northeastward transport.

The presence of these slices may indicate proximity to the ramp. However, these imbrications are also intimately associated with younger-over-older, west-directed normal faults beneath the Mormon Peak detachment. Thus, the older-over-younger relationships may simply be a consequence of juxtaposing pieces of higher thrust allochthons onto the autochthon by normal faulting and be unrelated to the original position of the Cambrian-Mississippian ramp.

No data within the map area yield information as to the precise timing of thrust faulting. Regional constraints suggest a mid-Jurassic to Late Cretaceous age for compressional deformation [Armstrong, 1968; Carr, 1980; Burchfiel and Davis, 1971, 1981]. The total amount of shortening represented by the Mormon thrust system is at least 30 km, based on reconnaissance outside the area of Plate 1 [Wernicke, 1982; Wernicke et al., 1984].

Eastern Imbricate Normal Fault Belt

A group of west-dipping, rotated low-angle normal faults and associated high angle faults that disrupt the thrust terrane is present in the eastern part of the map area (Plate 1, Figure 3). The largest of these, the Horse Spring fault (Plates 1 and 2; Figure 3) has approximately 3 km of offset near Whitmore Mine (Plate 2, D-D'), but almost completely dies out only 6 km to the north. Along section A-A' (Plate 2), the Horse Spring fault may be represented by a series of normal faults which cut autochthonous Devonian and Mississippian rocks and basal slivers of the Mormon thrust system, but cumulative extension along these faults is only about 200 m.

An interesting kinematic problem of the Horse Spring fault is the difference in tilt between the hanging wall and footwall in its central area of exposure, as seen in section D-D' (Plate 2). As noted in Wernicke and Burchfiel (1982) planar normal faults cannot cause differential tilt between hanging wall and footwall unless the blocks deform internally in some way. Concave upward listric faults, because they are curved, force differential rotation and tilt the hanging wall more steeply than the footwall. Since footwall strata are inclined 20-30 degrees more steeply than hanging wall strata, and no evidence was found for significant internal deformation of the fault blocks (except within ca. 100 m of the fault plane), neither the planar nor concave upward listric models are adequate. Palinspastic restoration of section D-D' elucidates the basic problem (Figure 7): the fault cuts through the footwall section much more quickly than the hanging wall section, suggesting that the two were not initially in direct contact. Apparently a wedge of material once lay between the two. The reconstruction in Figure 7 was done so as to minimize the volume of this wedge by restoring the hanging wall to its easternmost possible position. The simplest kinematic scheme to account for ths missing wedge is to have it squeezed out to the west from between the hanging wall and footwall. The geometry of the faults bounding the wedge derived from this reconstruction indicates that the upper one was an east-directed thrust fault emplacing older rocks over younger. The lower, more steeply dipping fault, in conjunction with the Horse Spring fault, forms a downward steepening normal fault zone, which serves to accommodate differential tilt between the hanging wall and footwall. Undeformed regions are separated from imbricate normal fault systems by concave upward listric fault zones if the blocks dip toward them [Wernicke and Burchfiel, 1982], and it is suggested here that concave downward fault systems may serve as boundaries if the blocks dip away from the undeformed region, as appears to be the case here.

Drag folding directly beneath the Horse Spring fault is well developed where the fault crosses the Bright Angel Shale-Bonanza King Formation contact, along a segment between Horse Spring and Hackberry Spring. Here the footwall rocks are folded over to the west. Numerous bedding plane faults within the limestone unit of the Papoose Lake Member are apparently folded over, and slices of basal Papoose Lake are discordantly faulted across the Bright Angel Shale (sections F-F' and B-B', Plate 2).

The Horse Spring fault dips west to northwest to the north of Wiregrass Spring, but abruptly changes to a southwest dip of about 30° in its southern exposures. In its southeasternmost exposures, the fault becomes difficult to define, and is represented on Plate 1 as a vastly oversimplified zone of faults near hill 4322. Chaos structure [Noble, 1941] is spectacularly developed along the southeastern segments of the fault, particularly in a canyon 0.5 km due north of the petroglyphs (Figure 1b), where several hundred meters of section are omitted across a complex fault zone (see Wernicke and Burchfiel [1982], and Wright and Troxel [1973], for an explanation of the genesis of chaos).

In general, the southern portion of the eastern imbricate belt is much more complex than the relatively simple tilted-block geometry of the northern portions. Near bedding-parallel faults are far more abundant, and brecciation is so intense that in most instances it took considerable effort to find an outcrop suitable for taking an attitude. As complicated as Plate 1 is in this area, it barely begins to document the complexity of deformation.

Faults structurally beneath the Horse Spring fault generally do not display differential tilt between hanging wall and footwall, and are thus believed to be of planar rotational-type as described in Wernicke and Burchfiel [1982]. The total extension of the eastern imbricate belt along section D-D' (Plate 2) is approximately 3 km. The total extension along F-F' (Plate 2) is a similar amount, since a reconstruction of the section should not allow overlap of the Mormon thrust. It is noteworthy that such a small amount of extension can cause such an extreme amount of deformation.

The direction of extension in the eastern imbricate belt cannot be determined with precision, but two lines of evidence suggest that it is approximately east-northeast. The first

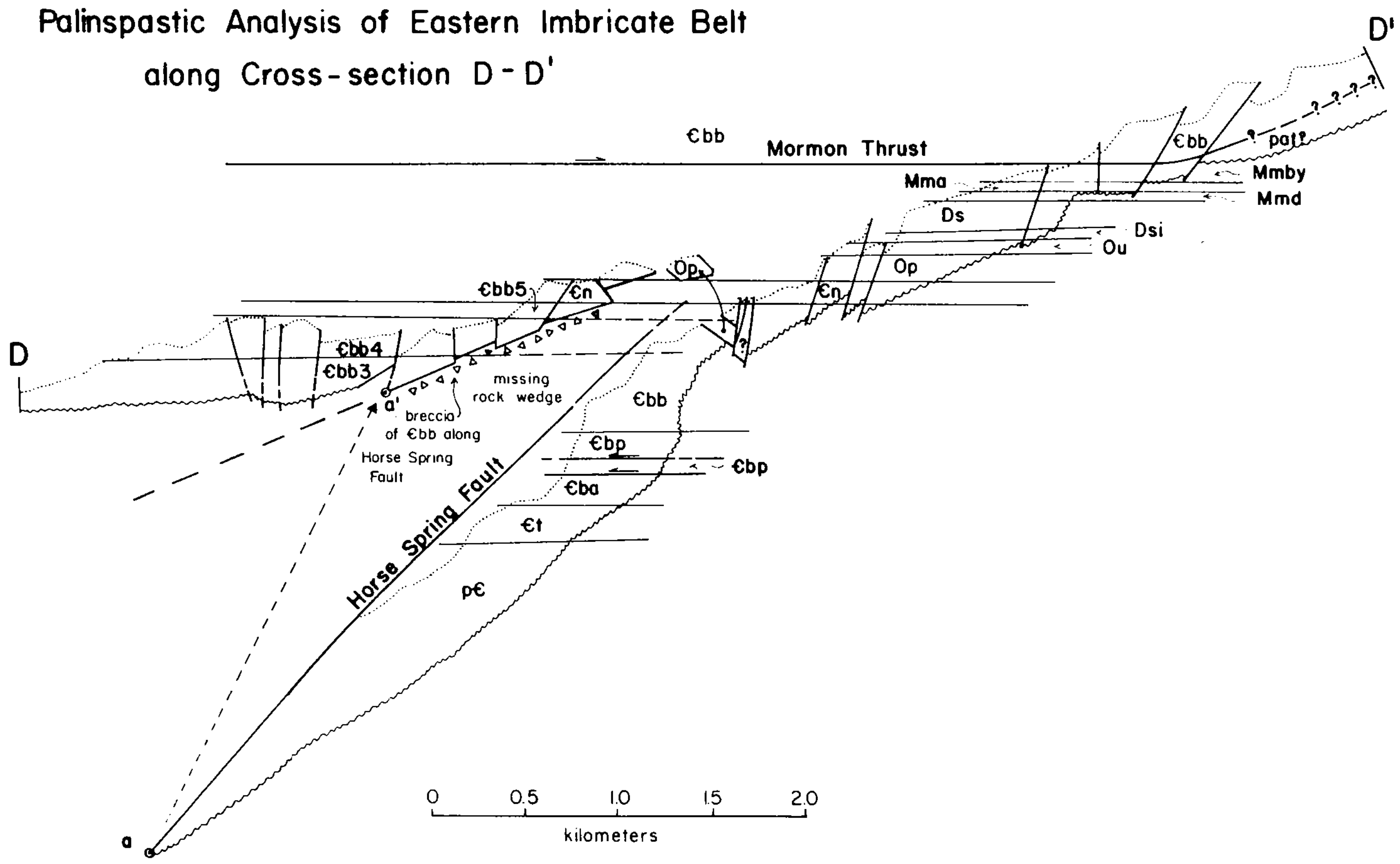


Fig. 7. Reconstruction showing space problem that exists between hanging wall and footwall of the Horse Spring fault. p€, Precambrian basement; €t, Tapeats sandstone; €ba, Bright Angel Shale; €bp, Papoose Lake Member, Bonanza King Fm.; €bb, Banded Mountain Member, Bonanza King Fm.; €n, Nopah Fm.; Op, Pogonip Group; Ou, Ely Springs Dolomite; Dsi, Ironside Dolomite Member, Sultan Limestone; Ds, Sultan Limestone; Mmd, Dawn Limestone; Mma, Anchor Limestone; Mmb, Bullion Limestone; pat, parautochthon.

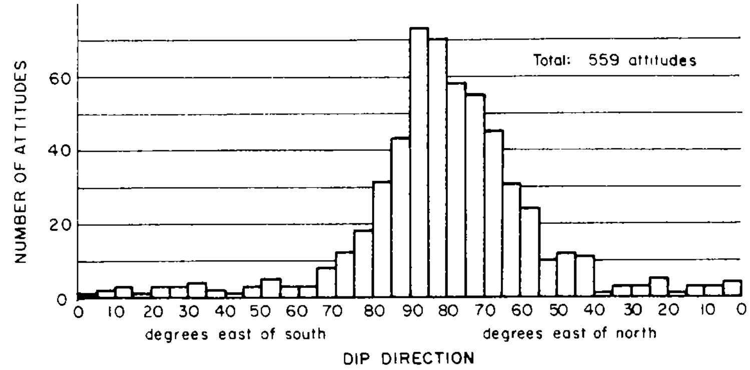


Fig. 8. Tilt direction histogram of eastern imbricate belt suggesting an extension direction of N80W±20°.

is the sense of rotation of autochthonous Paleozoic rocks. In areas where slickenside striae are abundant within simple imbricate normal fault terranes, their trend tends to parallel the dip direction of rotated strata [e.g., Anderson, 1971; Davis et al., 1980; Davis and Hardy, 1981]. Thus, assuming that the autochthonous Paleozoic section was roughly horizontal or gently inclined to the west prior to imbricate normal faulting (see below), the extension direction may be inferred from their sense of tilt. Tilt directions of autochthonous sedimentary rocks (Figure 8) suggest an extension direction of approximately N80°E. The second, in accord with the first result, is derived from two intersecting fault planes which do not offset each other, located 1.7 km ENE of peak 7083 (just north of section D-D', Plate 2). Regardless of the chronology of movement on these two faults, this geometry is only possible if the slip-line of at least one of the faults is parallel to their line of intersection. The orientation of both fault planes is well constrained, and their line of intersection trends S82°W and plunges 25° (Figure 9), in crude agreement with the extension direction based on the average dip direction of rotated strata.

As discussed in Wernicke et al. [1984], an east-directed subhorizontal normal fault exposed in the Tule Springs Hills and East Mormon Mountains may underlie the Mormon Mountains at shallow depth and may function as a basal detachment for the eastern imbricate belt. The eastern imbricate belt and inferred basal detachment involve autochthonous crystalline basement (Plate 1), and thus their formation was not influenced by the Mormon thrust, despite their close structural proximity. These facts are an exception to the notion that low-angle normal faults developed within older compressional thrust belts are reactivated thrust faults because the thrusts are presumably planes of weakness. The eastern imbricate belt and its basal detachment developed discordantly across the older structural grain, suggesting that (1) preexisting planes of weakness are not required for the initiation of thin-skinned normal fault systems, and (2) preexisting structural features such as thrust faults do not always influence their localization. The relationships observed here suggest that the fracture of crystalline basement and its autochthonous cover along relatively high-angle planes was easier than reactivating an old, very low-angle decollement thrust. This is not surprising in view of the likelihood that the least principal stress was nearly parallel to the geoid during extensional tectonism.

As will be discussed in more detail below, two faults in the eastern imbricate belt cut the Mormon Peak detachment and rotate it eastward (Plate 1).

Central High-Angle Fault System

In the central, structurally simplest part of the map area, a system of high-angle faults are present in the autochthon structurally above the Horse Spring fault but below the Mormon Peak detachment (Plate 1). The faults are of small normal displacement (10-100 m), and generally dip between 50° and 70°. Some of the faults change orientation along strike. Collectively, they account for very little extensional strain.

The faults may be divided into two sets: a north-northeast-striking set and a northwest-striking set (Figure 10). The apparent sense of throw on the north-northeast striking set is consistently down to the west-northwest, and on the northwest striking set, generally down to the southwest.

Assuming average strikes of N49°W and N23°E (Figure 11) and a dip of 60° for the two fault sets in the more organized part of the system (most of the scatter, particularly in the northwest striking set, are from faults in the northeastern part of the area adjacent to the Horse Spring fault), the faults plot on a stereogram as a near-perfect conjugate shear system, with a least principal stress axis oriented at N76°E35°, trending nearly parallel to the principal elongation direction inferred for the eastern imbricate normal fault system. Unfortunately, the actual slip direction on these faults is unknown due to lack of offset linear features and slickenside striae, so it is not possible to rigorously support this interpretation. Another, albeit more complex interpretation, would be to consider slip on the faults as purely downdip and to call attention to the fact that the two sets occur largely in separate spatial domains: a northwest-striking set to the north and the north-northeast-striking set to the south. In this case, two separate principal elongation (and presumably, least principal stress) directions could be inferred, oriented perpendicular to the strike of each fault set, and perhaps a third corresponding to the domain of north-northwest striking faults adjacent to the northern part of the Horse Spring fault (Plate 1).

The fact that one of the faults cuts the Mormon Peak detachment at one end and is truncated by it at the other strongly suggests that the high-angle faults were active during the final stages of displacement on the Mormon Peak detachment (Plate 1; fault A, Figure 10). None of the high-angle faults can be shown to postdate final movement on the Horse Spring fault.

Mormon Peak Detachment

The structurally highest tectonic unit in the map area is the Mormon Peak allochthon, marked at its base by a conspicuous topographic ledge formed by the Mormon Peak detachment. The detachment surface forms a smoothly contoured dome (Figure 12) which mantles the domal topography of the range. Shown on Fig. 12 is a set of topographic contours which serve to constrain the projection of the detachment east of peak 6365 (it must project above ridges consisting of lower plate strata). The structural relief on the dome is about 1 km over the width of the map area.

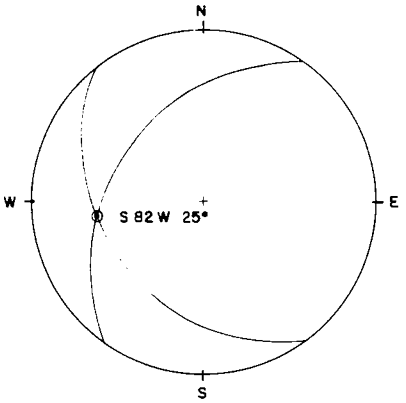


Fig. 9. Intersection of nonoffsetting faults, eastern imbricate belt.

Beneath the detachment, a similar broad domal structure is expressed by the orientation of autochthonous (relative to the Mormon thrust system) Paleozoic strata. Figure 13a shows the strike and dip direction of attitudes taken in the domal structure, omitting the central high-angle fault system and formational contacts. Figure 13b shows a structure contour map on the base of the Tapeats Sandstone in the same area drawn by extrapolating to its stratigraphic depth at each of the points shown. Contouring was done without attempt to extrapolate faults of the central high angle fault system to depth. Although Figures 15a and 15b have approximately the same form, they differ in that the contour on the Tapeats has an eastward elongate domal crest while the structural form indicated from attitudes shows a localized crest. The localized crest in Figure 13a is coincident with the western part of the elongate crest in the Tapeats, and the easten part of the elongate crest is the locus of maximum relative uplift due to northeast- and northwest-striking faults of the central high-angle fault system.

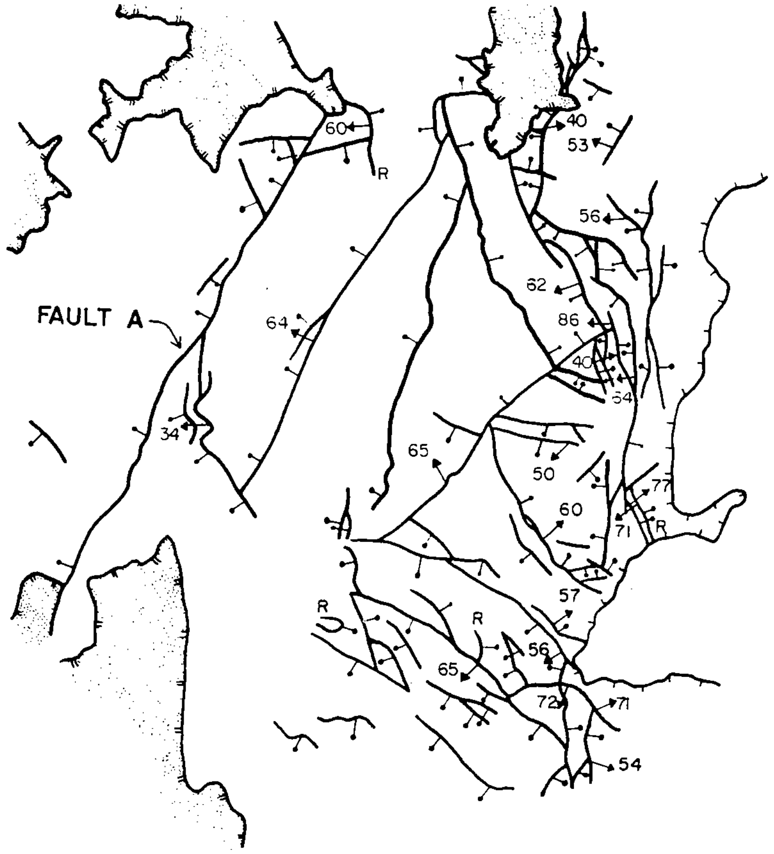


Fig. 10. Summary diagram, central high-angle fault system. Bar and ball on downthrown block. Reverse faults marked with an R. Mormon Peak allochthon is stippled.

The difference in form of the two diagrams may thus be attributed to the high-angle faulting. Since the locus of uplift of the central high-angle fault system does not coincide with the center of the well defined dome in bedding attitudes it seems unlikely that the two structures formed synchronously.

An important problem is the relationship between the domal structure expressed in the autochtonous Paleozoic section and the domal form of the detachment surface. Inspection of Figures 12 and 13 suggests that the two structural forms are certainly not perfectly coincident, the detachment appearing to be much smoother and having less total relief. Figure 14 shows two cross sections comparing the form of the lower plate strata and the detachment, and it is clear, at least in cross section A-A', that if the curvature of the detachment were removed, a pronounced warping of the autochthonous Paleozoic would remain. Although there is no a priori reason to assume that the detachment was initially planar, the crude coincidence (on the scale of the range) of folding of the lower plate about an east-west axis with the detachment fault arch suggests that the two may be an expression of the same process. It is clear that a substantial degree of folding of the Paleozoic section predated at least late movement on the detachment. If the folding of the lower plate accompanied the early history of movement on the detachment there must have been enough movement thereafter to smooth out the form of the detachment by truncation and removal of the early-domed surface. Alternatively, folding of lower plate strata may be related to Mesozoic deformational events, in which case its spatial association with the domed detachment is merely coincidental. We

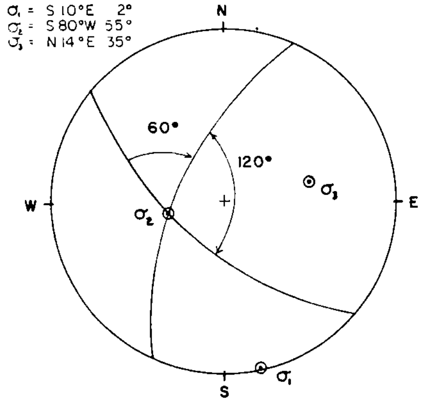


Fig. 11. Possible orientations of principal stress axes during development of the central high-angle fault system.

favor the former hypothesis, on the basis of similar relations in a number of Tertiary detachment terrains in the southern Basin and Range province. In these terrains, axes of folds in lower plate mylonitic foliation are remarkably coincident with domes in the detachments, although lower plate structures are in detail clearly discordant to the faults [e.g., Davis et al., 1980; Rehrig and Reynolds, 1980].

Since it has been shown that (1) the central high-angle fault system was active during the final stage of emplacement of the Mormon Peak allochthon; (2) the doming of lower plate strata significantly predates these stages; and inferred that (3) doming of lower plate strata and the development of the central high-angle fault system are diachronous, it follows that doming largely preceded development of the central high-angle fault system. Both early doming and later high-angle faulting are here interpreted to be synchronous with movement on the Mormon Peak detachment. If the doming of miogeoclinal strata in the lower plate accompanied early movement on the detachment, it seems likely that the present domed configuration of the detachment is a consequence of continued folding, rather than an initially curviplanar surface of breakage.

The detachment cuts downsection toward

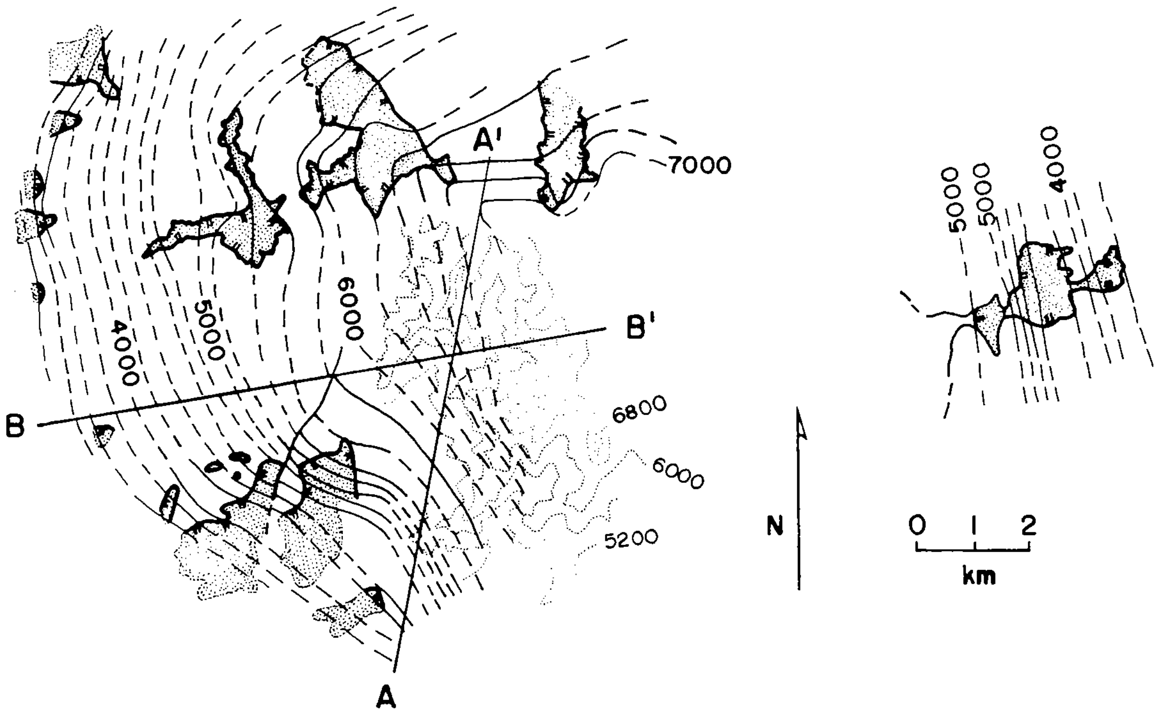


Fig. 12. Contour map of the Mormon Peak detachment (in feet), dashed where not well constrained. Mormon Peak allochthon is stippled. Topography which constrains positions of contours is dotted. Section lines correspond to those on Figure 15.

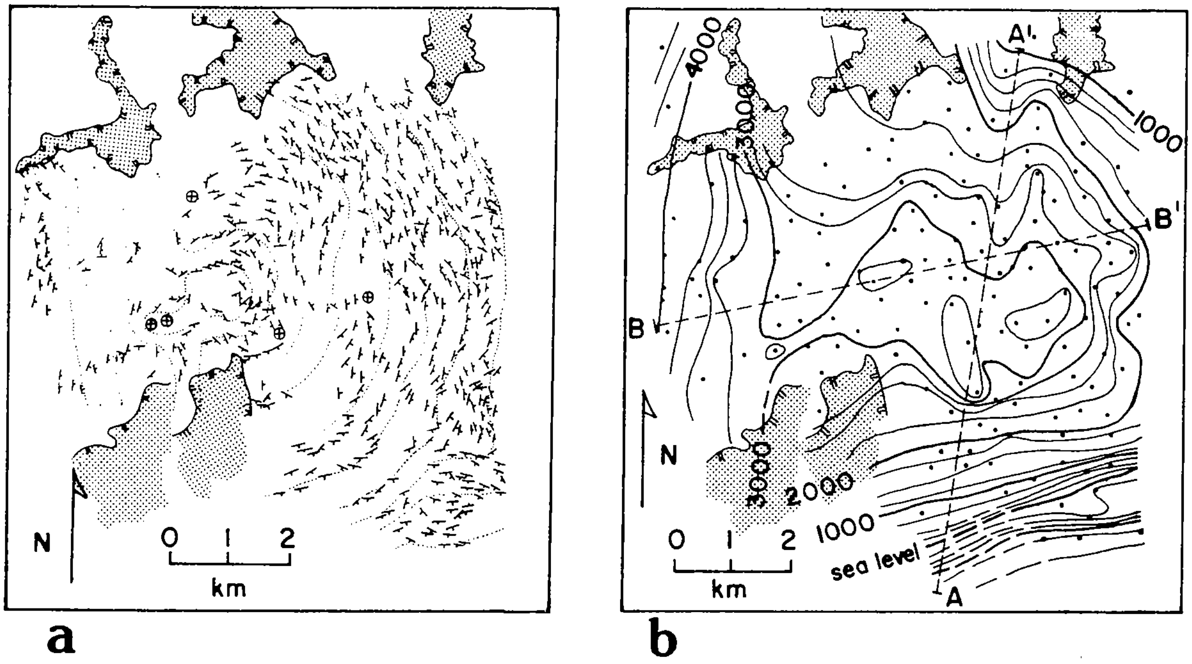


Fig 13. a) Attitude symbols delineating a domal structure in the autochthon.
b) Structure contour on the Tapeats Sandstone datum (feet above sea level). Points show locations where elevation of datum was calculated. Mormon Peak allochthon is stippled.

the west in the footwall. The easternmost klippe in the map area rests upon the Mormon thrust plate only a few hundred meters above the thrust, and the next klippe to the west upon autochthonous Devonian and Mississippian rocks. The remainder of the klippen to the west cut gradually downward through the autochthon, until the westernmost exposed klippen rest upon Precambrian basement (Plates 1 and 2, Figure 3).

An important aspect of the thrusted terrain is that it provides a reasonably accurate means by which to measure the amount of tilting due to the Miocene extensional event. Cross-sections and reflection seismic profiles of thrust belts which have not been disrupted by later events typically show that the autochthonous sedimentary package and bedding-parallel portions of the basal thrust fault are very gently inclined (typically between 3 and 8 degrees) away from the foreland [e.g., Bally et al., 1966; Royse et al., 1975; Cook et al., 1979; Price, 1981; Jordan et al., 1983]. To place constraints on the rotation due to extension, and hence the initial dip of the Mormon Peak detachment, it must be assumed that the preextension structural configuration of the Mormon Mountains was typical of that of the frontalmost segments of undisrupted thin-skinned fold-thrust belts. The absence of any significant structures in the autochthon related to compressional deformation, and the simple ramp-decollement geometry of the Mormon thrust system suggest that this is the case. In addition, where postdetachment domino-style faulting has affected the autochthonous sedimentary package and Mississippian decollement segment of the Mormon thrust in the eastern imbricate belt, faults now dipping 20°-45° eastward and making a high-angle (near 90°) with bedding palinspastically restore such that either bedding was initially horizontal (e.g., Figure 17) or dipping to the east. A large westward preextension dip of these strata would require the imbricate normal faults to have rotated from an initial west dip through the vertical to their current dip, an extremely unlikely kinematic scenario. Thus, assuming a horizontal or shallow west dip of the autochthonous strata gives

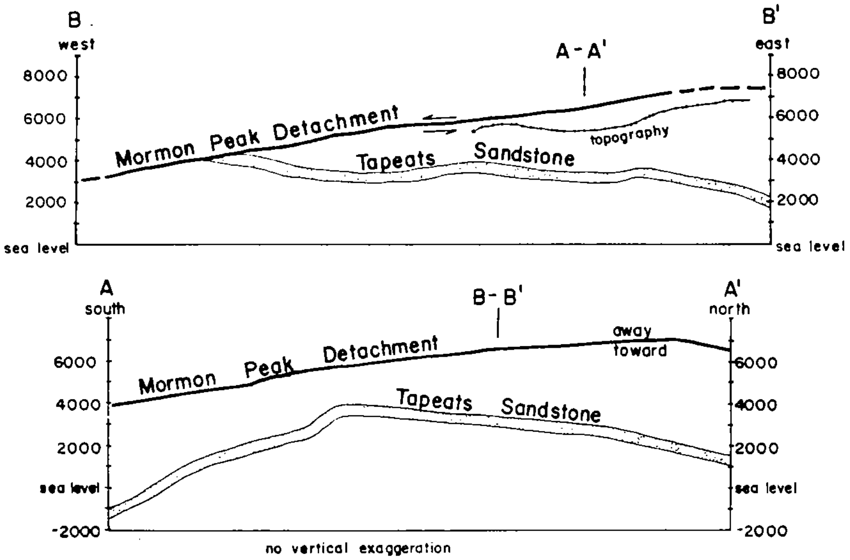


Fig. 14. Cross sections of contour maps in Figures 13b and 12, comparing the structural form of the Mormon Peak detachment and the lower plate dome.

a maximum estimate for the initial dip of the Mormon Peak detachment (Figure 15). (Figure 15a) shows cross section B-B' (Plate 2) with all the major blocks extrapolated down to the base of the Tapeats sandstone. The reconstruction shown in Figure 15b was done so as to restore the Tapeats to a common, planar datum. In doing so, the eastern and western traces of the Mormon Peak detachment restore into remarkable alignment, making an angle with the Tapeats of about 17°. Adding a preextension westward dip of 3°-8° for the Tapeats across the entire area suggests the initial dip of the Mormon Peak detachment was about 20°-25°.

As is common with faults in the eastern imbricate normal fault system, intense brecciation occurs adjacent to the detachment, and in both the upper and lower plates persists for several tens of meters away from it. The breccias are characterized by considerable clast rotation and highly variable grain size and sorting. In contrast, the thrust faults of the Mormon thrust system generally do not have clast-rotated breccias associated with them. Where present, they are volumetrically minor, and usually occur within a few meters (rather than tens of meters) of the faults. These observations are consistent with those of a number of workers in the Basin and Range province who have noted the same difference in degree of fracturing between compressional and extensional faults [e.g., Guth, 1981; Seager, 1970]. In cases where it is ambiguous whether a low-angle fault is a thrust or a low-angle normal fault, the presence of large amounts of clast-rotated breccia favors the latter.

In addition to pervasive brecciation on outcrop scale, the Mormon Peak allochthon is highly internally deformed at map scale, and could be characterized as a tectonic megabreccia. Consistently, near bedding-parallel faults omit stratigraphic section, high-angle faults have normal geometry, and both either tangentially merge with or are truncated by the detachment. Prior to extension, the allochthon was composed of an intact Paleozoic section ranging from Banded Mountain dolomites at the base up to the Mississippian and Pennsylvanian Bird Spring Formation at the top. It has been broken into a series of tilted normal fault blocks. Although the Paleozoic sections within the blocks were probably somewhat deformed during the Sevier orogeny, no evidence was found within any of the blocks to suggest major deformation in the map area before block faulting, although mapping by Tschanz and Pampeyan [1970] in the Meadow Valley Mountains to the west suggests that substantial

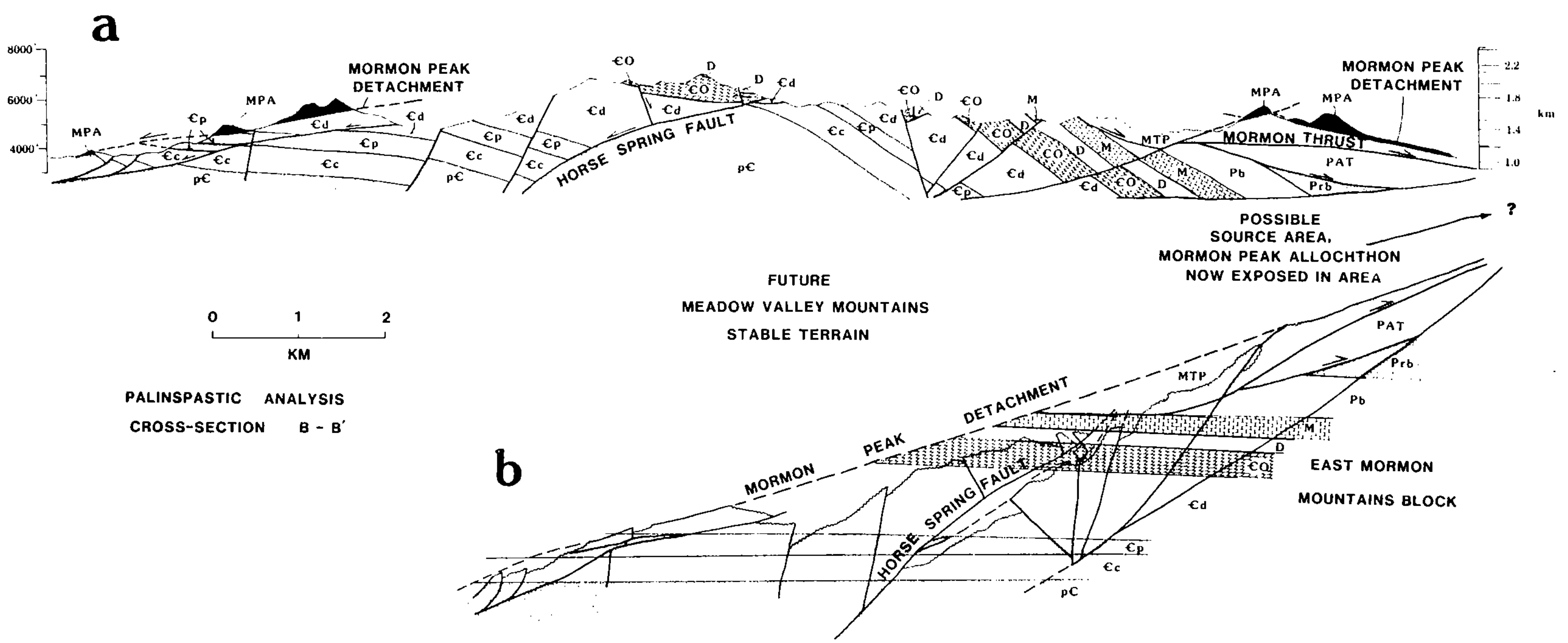


Fig. 15. Cross section B-B' (Figure 3) simplified and extrapolated to the depth of the Tapeats Sandstone. b) Restoration of section in Figure 15a. p€ : Precambrian basement; €c, Cambrian clastics; €p, Papoose Lake Member; €d, Cambrian dolomites; €O, Cambrian-Ordovician; D, Devonian; M, Mississippian; Pb, Bird Spring Fm.; Prb, Permian red beds; PAT, parautochthon; MTP, Mormon thrust plate; MPA, Mormon Peak allochthon.

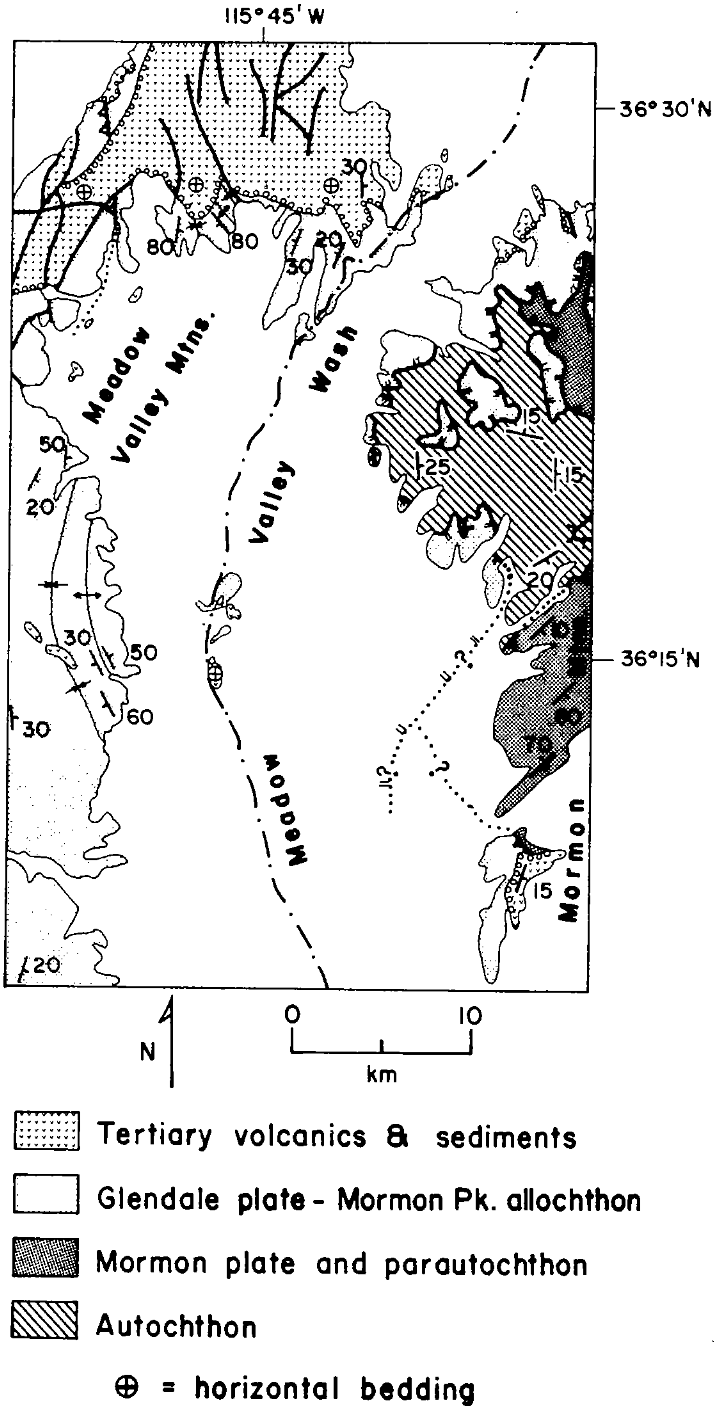


Figure 16. Tectonic map showing the structural relationship between the Mormon Mountains and Meadow Valley Mountains. Geology in part from Tschanz and Pampeyan [1970] and Ekren [1977].

Mesozoic compressional deformation and tilting is present within the Mormon Peak allochthon there (Figure 16). In the Mormon Mountains, the normal faults separating the tilted blocks generally dip in the opposite direction to bedding in the blocks, as would be expected from imbricate normal faulting of a

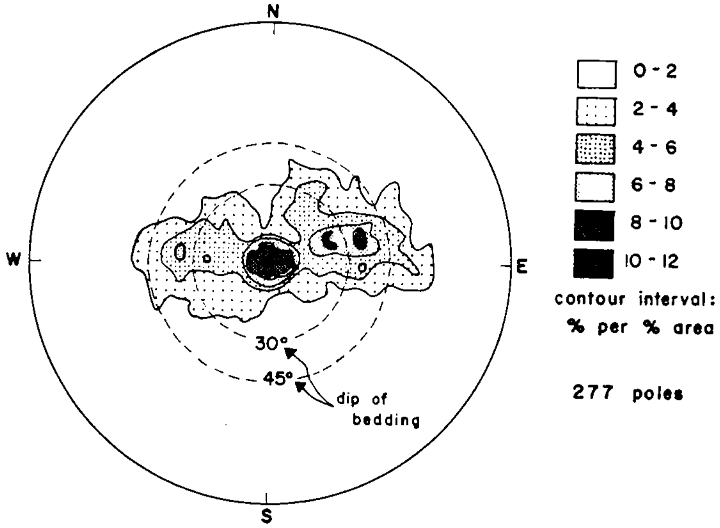


Fig. 17. Equal-area plot showing tilt directions in the Mormon Peak allochthon. Most of the tilts are less than 30°, with over 90% less than 45°.

near-horizontal package of rock where faults rotate to a moderate or low dip from an initial steep dip. In addition, at several localities in the north part of the Mormon Mountains (about 5-10 km north of the northern boundary of the map area), tilted Tertiary ignimbrites rest disconformably or with very slight angular unconformity on the Bird Spring Formation in the Mormon Peak allochthon (work in progress). For these reasons, it appears that the magnitude and direction of tilting of Paleozoic rocks in the Mormon Peak allochthon is largely the result of Tertiary imbricate normal faulting.

The direction of tilt of the blocks (Figure 17) is separable into east- and west-tilted domains. The west-tilted domains show a preferential tilt toward the southwest, while east-tilted domains show no preference between southeast and northeast (most of the southeast tilts occur in blocks near peak 6365).

The boundaries of the tilt domains within the allochthon in the western part of the map area trend roughly east-northeast, parallel to the tilt direction of the blocks. The change in tilt direction across the boundaries does not take place along discrete fault zones, but seems to be accommodated along diffuse zones (Plate 1). Two domain boundaries in the central and eastern part of the map area trend perpendicular, or at least at a high-angle, to tilt direction, and are of "antiformal" type, since the blocks dip away from the boundary [Stewart, 1980]. The basic pattern of tilt-parallel and tilt-perpendicular boundaries observed in the Mormon Peak allochthon is highly analogous to regional tilt patterns observed in the Basin and Range province [Rehrig et al., 1980; Stewart, 1980; Wernicke and Walker, 1982].

The east-northeast extension direction inferred from the tilt direction of upper plate rocks is consistent with that inferred from the eastern imbricate belt and central high-angle fault system. The slightly scattered pattern of tilts observed in Figure 17 might be that expected from imbricate normal faulting acting on a package of randomly (but not steeply) tilted strata.

Since the tilted blocks in the allochthon form a coherent package not affected by thrusting, they must have been derived from a single thrust plate. This requires that Cambrian rocks in the westernmost-exposed klippen of the allochthon have moved at least 8 km, the distance from these klippen to the footwall cutoff of the Mormon thrust. Matching Banded Mountain strata in the Mormon Peak extensional allochthon with Banded Mountain in the Mormon thrust plate connects the Paleozoic section in the allochthon with the Mormon thrust plate. However, regional considerations suggest that these rocks were derived from a higher tectonic element of the Sevier orogen, the Glendale-Muddy Mountain thrust plate.

In common with the Muddy Mountains and Spring Mountains [Bohannon, 1983a, b; Burchfiel et al., 1974, 1982; Axen, 1984], the Mormon Mountains contain two major thrust faults: the Mormon thrust and the higher Glendale thrust. South of the map area, the Mormon thrust plate dips gently southward. About 10 km south of the southernmost klippe of the Mormon Peak allochthon in the map area, Banded Mountain dolomites of the Glendale thrust plate are thrust over the Jurassic Aztec Sandstone and the Cretaceous (?) Overton Conglomerate. These Mesozoic rocks form a contiguous (but structurally disrupted) stratigraphic sequence with Cambrian strata in the Mormon thrust plate to the north [G. J. Axen, personal communication, 1983]. The Mormon thrust is therefore not the highest thrust fault in the frontal part of Sevier orogen at the latitude of the Mormon Mountains.

Reconnaissance mapping by us and by Tschanz and Pampeyan [1970] outside the map area indicates that the Mormon Peak allochthon is structurally continuous with folded late Paleozoic and early Mesozoic strata exposed in the Meadow Valley Mountains (Figure 16). These folded rocks are part of a regionally continuous synclinorium of folds and small thrust faults that occurs in the Keystone-Muddy Mountain-Glendale thrust plate. Therefore, rocks of the Mormon Peak extensional allochthon are part of the Glendale-Muddy Mountain thrust plate and not the Mormon thrust plate.

If two thrust plates are cut out along the detachment, then its structural omission in western areas of exposure could approach 10 km, the thickness of two full miogeoclinal sections thrust above an autochthon comprised of Cambrian through Mississippian rocks. A minimum omission of 4 km is suggested by the reconstruction in Figure 15b, assuming very little post-thrusting westward dip of the Tapeats sandstone and a topographic slope toward the foreland. Both the initial westward dip of the autochthon and eastward dipping topographic slope conspire to increase the estimate of omission, as does any overburden that lay above the easternmost, structurally highest rocks in the footwall of the detachment (Fig. 15b). In addition, since in the map area the youngest strata within the Mormon thrust plate are Upper Cambrian and the oldest strata in the Mormon Peak allochthon are Middle Cambrian, the preextension Glendale thrust in the study area need only have duplicated a small amount (less than several hundred meters) of section. These considerations indicate likely paleodepths of autochthonous basement exposed in the western Mormon Mountains of about 5-8 km.

The age of extensional faulting in the map area is mid- to late-Miocene. Mapping by B. Wernicke et al. (unpublished map, 1984) and by Ekren et al., [1977] in the northern Mormon Mountains indicates that imbricately normal-faulted mid- to late Miocene volcanic rocks are truncated by the Mormon Peak detachment. The highest unit in the volcanic section, which rests disconformably on mid-Miocene ash-flow tuffs, is a basaltic andesite that yielded a whole-rock K-Ar age of 8.5±0.3 Ma [Armstrong, 1970, sample 203I]. Assuming this to be its true age, it follows that the Mormon Peak detachment must have been active at this time, since upper plate normal faults either merge with or are truncated by the detachment. Although the volcanic sections are conformable, lack of angular unconformities does not necessarily indicate that extensional tectonism had not begun prior to eruption of the basaltic andesite. In fact, the Miocene section on the Mormon Peak allochthon in the Meadow Valley Mountains is still flat lying (Figure 16), even though it has been transported at least 8 km to the west-southwest on the Mormon Peak detachment. Thus, no data in the immediate area directly bear on the precise time of onset of extensional tectonism. It is probable that extension in the Mormon Mountains was partly coeval with west-southwest directed extension in the Lake Mead Area, over 60 km to the south of the mapped area, described by Anderson [1971, 1973], Anderson et al., [1972], and Bohannon [1979, 1983a, b]. They have shown on the basis of structural and sedimentologic analysis of synorogenic clastic and volcanic deposits, that the most intense west-southwest directed extension occurred between about 14 and 10 Ma ago.

Unconformably overlying the extended terrane are flat-lying clastic rocks of the Muddy Creek Formation, which fill the modern valleys. The maximum age of these deposits in the vicinity of the Mormon Mountains is unknown, and it is therefore possible that low-angle normal faulting in the Mormon Mountains continued well past 8.5 Ma ago, perhaps into the Pliocene.

DISCUSSION

Both the eastern imbricate fault system with its inferred basal detachment and the Mormon Peak detachment do not appear to be spatially coincident with older Mesozoic thrust faults.

Since the hanging wall detached within Bonanza King dolomites, the characteristic detachment plane for thrust faults in the region, it is possible that the Mormon Peak detachment followed an old thrust plane (Glendale thrust?) along part of its trajectory. However, its penetration into crystalline basement in the westen Mormon Mountains is extremely difficult to reconcile with a reactivated thrust fault geometry. Again, thrust fault geometries both in the Mormon Mountains and throughout southern Nevada demonstrate that basement was not involved in the frontalmost part of the thrust belt. In the region shown in Figure 5, the decollement planes of the two frontal thrusts carry Cambrian dolomites without exception; nowhere are they observed to carry crystalline basement. This observation holds for the frontalmost parts of the vast majority of thin-skinned fold-thrust belts developed within continental margin sedimentary prisms.

The Mormon Mountains have many of the characteristics of a widespread group of terrains which have been termed "metamorphic core complexes" [Davis and Coney, 1979], including a domal range form, a domal, structurally higher-over-lower, low-angle dislocation surface structurally veneering the range, and imbricate normal faulting both above and below the dislocation surface [e.g., Shackelford, 1980]. Unlike the metamorphic core complexes, rocks beneath the dislocation surface in the Mormon Mountains show no indication of ductile deformation or mylonitization. As originally hypothesized by Davis and Coney [1979] and Rehrig and Reynolds [1980], the deformation in the lower plates of the metamorphic core complexes, characteristically consisting of a shallowly dipping mylonitic foliation containing a mineral lineation which trends parallel to the upper plate extension direction, serves as an accommodating mechanism for upper plate extension. However, in some of the core complexes, the mylonitic lineations were shown to predate upper plate imbricate normal faulting by more than 40 Ma [Davis et al., 1980]. In others, the tectonites formed only 5-10 Ma prior to imbricate normal faulting [Rehrig and Reynolds, 1980; Keith et al., 1980]. In either case, the data seem to be incompatible with models which view lower plate ductile strain simply as a synchronous, in situ accommodation of upper plate imbricate normal faulting, a mechanism of crustal extension suggested by many workers prior to the recognition of the significance of metamorphic core complex terrains [e.g., Wright and Troxel, 1973; Proffett, 1977]. There has been considerable debate among workers in the lineated terrains as to whether or not the tectonites are genetically related to upper plate extensional deformation and the basal detachments themselves. Geologists who regard the two events as separated by several tens of millions of years do not consider the two to be necessarily genetically related, while those who interpret them as being separated by only a few million of year favor models in which they are part of the same deformational system. The data presented here indicate that all of the attributes of Mormon Mountains geology in common with metamorphic core complexes described above need not form in close proximity to mylonite tectonites, and provides further documentation for the similar conclusion of Davis et al. [1980] and Shackelford [1980].

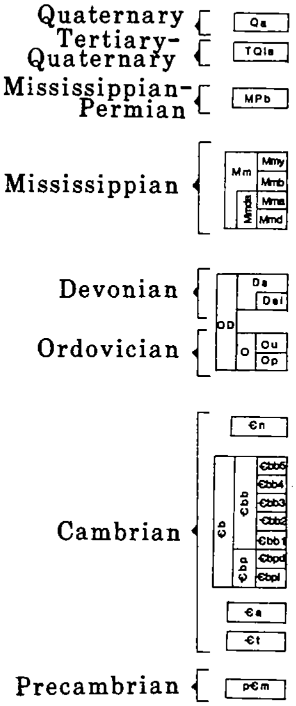
The occurrence of an unmetamorphosed Paleozoic section beneath the Mormon Peak detachment, deformed only by minor normal faulting (central high-angle fault system) during translation of the detachment, conclusively demonstrates that the lower plate was extended at most only a few hundred meters during emplacement of the Mormon Peak allochthon. Thus, lower plate extension cannot be invoked as a driving mechanism for upper plate translation and extension, since the Mormon Peak allochthon has been translated more than 8 km relative to the lower plate. A megalandslide or gravity-slide mechanism for the emplacement of the Mormon Peak allochthon is equally untenable, because there clearly are no "toe" relationships indicative of shortening in ranges to the west. In the Meadow Valley Mountains, there is no indication of any complex mid- to late-Miocene deformation. As mentioned above, throughout the Meadow Valley

GEOLOGIC MAP OF THE CENTRAL PART OF THE MORMON MOUNTAINS, LINCOLN COUNTY, NEVADA

Geology by

Brian P. Wernicke, J. Douglas Walker, and Mark S. Beaufait

MAP UNITS



Qa, Alluvial deposits

TQls, Landslide deposits

ANGULAR UNCONFORMITY

MPb, Bird Spring Formation

Mm Monte Cristo Formation

- Mmy, Yellowpine Member
- Mmb, Bullion Member
- Mma, Anchor Member
- Mmd, Dawn Member
- Mmda, Undifferentiated Dawn and Anchor Members

Ds, Sultan Formation

- Dsi, Ironside Member

OD, Undifferentiated Ordovician through Devonian

O, Ordovician rocks

- Ou, Ely Springs Dolomite
- Op, Pogonip Group

Єn, Nopah Formation

Єb, Bonanza King Formation

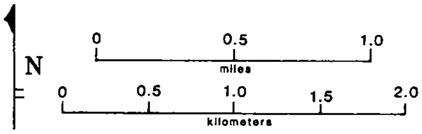
- Єbb, Banded Mountain Member
  - Єbb5, Unit 5
  - Єbb4, Unit 4
  - Єbb3, Unit 3
  - Єbb2, Unit 2
  - Єbb1, Unit 1
- Єbp, Papoose Lake Member
  - Єbpd, Dolomite unit
  - Єbpl, Limestone unit

Єa, Bright Angel Shale

Єt, Tapeats Sandstone

NONCONFORMITY

pЄm, Precambrian metamorphic and igneous rocks



Assisted by S.C. Semken, D.L. Olgaard and J.M. Stock

EXPLANATION OF SYMBOLS

ATTITUDES

40 Strike and dip of bedding
40 Strike and dip of overturned bedding
40 Strike and dip of bedding overturned more than 180
Strike of vertical bedding
Horizontal bedding
Horizontal bedding, upside-down
40 Approximate strike and dip of bedding
Strike and dip of foliation
Strike of vertical foliation
40 Dip direction and dip of fault
40 Dip direction and dip of overturned fault
Approximate dip direction and dip of fault

CONTACTS (DASHED WHERE APPROXIMATELY LOCATED, DOTTED WHERE CONCEALED, QUERIED WHERE INFERRED, TEETH ON UPPER PLATE OF LOW-ANGLE FAULTS)

?— Depositional
High-angle fault
Low-angle normal fault
Thrust fault
Mormon thrust
Low-angle normal faults placing older rocks over younger in western part of map area
Mormon Peak detachment

FOLD AXES (TRACES DASHED WHERE APPROXIMATELY LOCATED)

UPRIGHT:

10 Axial trace and plunge of anticline
10 Axial trace and plunge of syncline

SMALL-SCALE (ARROW ON STEEP LIMB WHEN ASSYMETRIC):

10 Trend and plunge of anticline
10 Trend and plunge of syncline

OVERTURNED AND RECUMBENT:

10 Axial trace and plunge of anticline
10 Axial trace and plunge of syncline

Topography by U.S.Geological Survey

Mountains and in Meadow Valley Wash, mid-Miocene ash-flow tuffs as old as 12.5±0.3 Ma (K-Ar, sanidine, sample 203F, Armstrong [1970] and an underlying undated lacustrine limestone lie in near horizontal depositional contact upon folded and east-vergent thrust faulted Paleozoic and Mesozoic strata [Tschanz and Pampeyan, 1970; Ekren et al., 1977], and thus could not have been significantly deformed as a result of movement on the Mormon Peak detachment (Figure 16). It is thus geometrically required that the detachment continue into the subsurface to the west beneath the Meadow Valley Mountains. Further, the probable 5-8 km paleodepth for western exposures of the detachment seem too large for the detachment to be the sole fault of a large gravity slide.

As proposed in Wernicke [1981], the simplest means to generate the core complex tectonic association [Davis and Coney, 1979] is by large movement on rooted low-angle normal faults. Whether or not mylonitic shear zones are present in the lower plate depends on the local geotherm and the magnitude of displacement on the detachment, which in several studies have been shown to be on the order of at least 30-60 km [Bartley and Wernicke, 1984; Allmendinger et al., 1983; Compton and Todd, 1979; Davis et al., 1982].

The reconstruction in Figure 15b suggests that the Mormon Peak allochthon was wedge shaped. The apparent westward structural simplification of the allochthon is therefore probably due to its increased ability to resist internal fragmentation resulting from frictional resistance on the detachment [Wernicke 1981, Figure 3c]. A similar westward structural simplification exists in the lower plate, with the eastern imbricate belt giving way westward to the structurally simple central high-angle fault terrain. Perhaps this also is the product of a west-thickening, wedge-shaped allochthon above the inferred detachment at depth beneath the eastern imbricate belt. The overall picture of extensional strain is thus envisioned as large-scale, east-over-west simple shear of two imbricate, wedge-shaped slabs which are penetratively extended by rotational imbricate normal faulting [Wernicke and Burchfiel, 1982] concentrated in the thin, eastern portion of the slabs (Figure 18). This is precisely the mechanism of large-scale strain accommodation usually observed in areas which have experienced large-scale compression [e.g., Milnes and Pfiffner, 1980; McClay and Coward, 1981; Price, 1981], except that the slabs are bounded by normal faults instead of thrust faults [Wernicke, 1981].

The most basic kinematic aspect of the extensional system in the Mormon Mountains (and many other areas of large-scale crustal extension) is the duality of detachments (which initiate at low angles of 10°-30°) and rotational imbricate normal faults (which initiate high angles of 60°-90°). In both cases blocks between the faults rotate, but rotation of detachments and undeformed portions of the blocks they bound is at a maximum 20°-30° range, while "domino style" blocks may rotate as much as 70°-80°. In extended areas, the "division of labor" among fault types appears to be that detachments (here defined as normal faults which initiate at low-angle) are the first-order accommodators of crustal pull-apart, while "domino" style and listric normal faults serve to penetratively dilate the shallow portions of the blocks between them. It is in this sense that the term extensional allochthon is applied: they are rock masses whose lower bounds are normal faults which initiate at low angle. As such they are the first-order building blocks of extensional orogens.

The imbricate geometry of extensional allochthons in the Mormon Mountains, and the fact that normal faults of the eastern imbricate belt offset the Mormon Peak detachment illustrate some important aspects of the kinematics of extensional systems. First, it suggests that detachments are not single, regional subhorizontal surfaces which accommodate differing styles of crustal extension (e.g., brittle vs. ductile) but are components of large-scale systems of imbricated extensional allochthons, whose bounding detachments need not merge at any particular level within the crust. Second, these imbricate systems may progressively step downward. Such a chronology may also apply to west-central Utah and the Snake Range areas (Bartley and Wernicke [1984]; Wernicke [1982], see below). Third, folding of the detachments along axes perpendicular to transport occurs as the result of reverse-drag flexing of initially planar, gently dipping surfaces in the hanging wall of rotational imbricate normal faults within

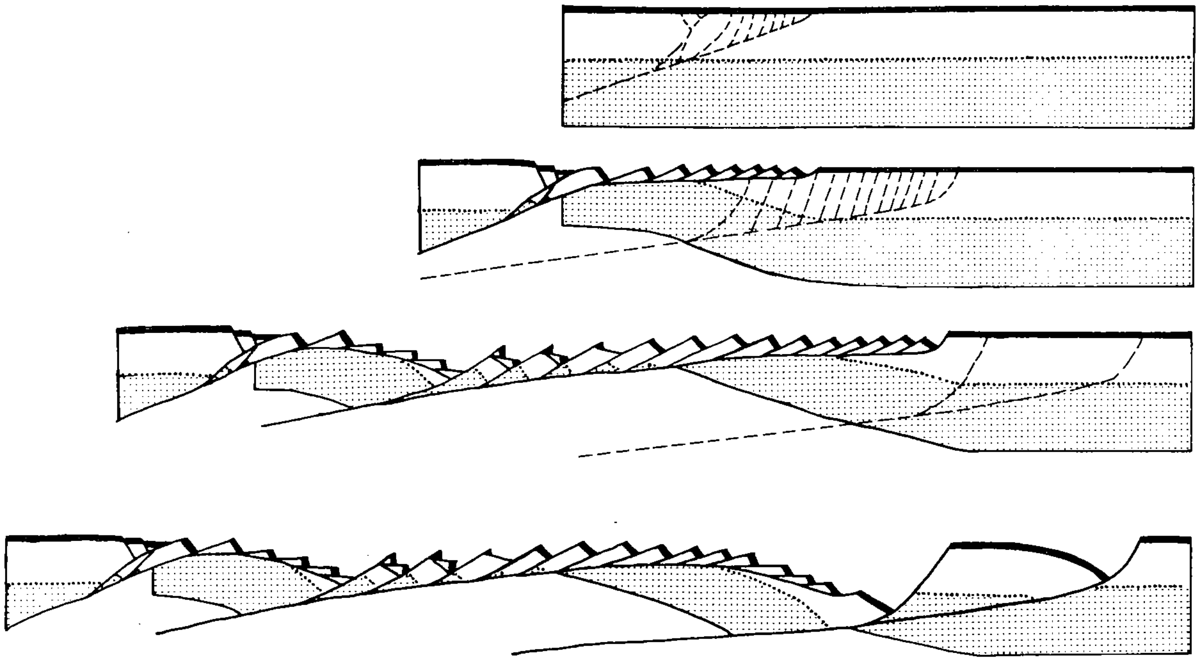


Fig. 18. First-order scheme for the accommodation of upper crustal extensional strain in the Mormon Mountains area. Large, imbricate slabs are sheared past one another on low-angle normal faults while their shallow ends experience relatively penetrative extensional strain by a variety of normal fault types. Movement on structurally lower detachments causes post-displacement faulting and folding of structurally higher ones.

younger, structurally lower extensional allochthons (Figure 18). Folds with axes parallel to transport (flexing of the Mormon Peak detachment and autochthonous Paleozoic strata, section A-A', Figure 14; see also Frost [1981]) are most likely the result of a small component of regional shortening perpendicular to the regional extension direction. The mechanism of transport-perpendicular fold development might be isostatic rebound of the crust beneath inhomogeneously extended extensional allochthons [Wernicke, 1985; Spencer, 1984]. However, at least in the case of the Mormon Peak (this report), northern Snake Range and House Range detachments [Bartley and Wernicke, 1984] and Tucki Mountain fault (K. V. Hodges et al., 1984) reverse drag on younger, structurally lower faults seems to be the mechanism of folding.

STRUCTURAL SUMMARY

Following conformable sedimentation from Early Cambrian through Early Jurassic time in the Mormon Mountains area, large-scale, east-directed, decollement-style thrust faulting disrupted the miogeoclinal wedge during the Late Jurassic (?) through Late Cretaceous Sevier orogeny. The Mormon thrust was active during this time, and moved the Mormon thrust plate to the east, dislocating slabs of Cambrian through Mississippian rocks from a ramp between decollement portions of the thrust, folding them about northwest-trending axes, and accreting them against a structurally higher Mississippian-Triassic footwall ramp. In accord with regional relationships [Burchfiel and Davis, 1971; Carr, 1980; Axen, 1980; Bohannon, 1983a, b], the Glendale plate was subsequently emplaced on top of the Mormon plate.

Following a period of presumed tectonic quiescence from Paleocene through early Miocene (?) time, large-scale, thin-skinned extensional tectonism began to dismember the Sevier orogenic belt in a west-southwest direction, as inferred from several independent kinematic arguments. The major exposed extensional structure, the Mormon Peak detachment, developed obliquely across the major thrust plates of the Sevier orogen rather than reactivating them. It has a minimum displacement of 8 km, and juxtaposes the highest structural levels of the Sevier orogenic belt with Precambrian crystalline basement of the autochthon. Subsequently, an inferred, structurally lower detachment of perhaps equal importance formed beneath the eastern imbricate belt within Precambrian crystalline basement, and thus also did not reactivate a preexisting thrust. The Mormon Peak detachment formed with a dip of approximately 20°-25° to the west, and the initial stages of movement on the fault are interpreted to have been accompanied by folding of the area about ENE-trending axes. Late in its history of movement, as this broad warping continued, the central high-angle fault system became active, further deforming the system, and was locally active following final emplacement of the Mormon Peak allochthon. Based on cross-cutting relationships, the eastern imbricate belt was active after final emplacement of the easternmost klippe of the Mormon Peak allochthon and the last movements on the easternmost faults of the central high-angle fault system. These relationships do not preclude partially synchronous movement on westernmost segments of the Mormon Peak detachment and faults in the eastern imbricate belt, but do suggest that the emplacement of the Mormon Peak allochthon largely predated their development. The current eastward dip of about 20° of the detachment in the easternmost klippe (Plate 1) is the result of rotation by faults in the eastern imbricate belt.

All major elements of the modern topography between the Meadow Valley Mountains and the East Mormon Mountains appear to be linked to the final structural configuration of the extensional allochthons. No evidence was found for a younger episode of widely spaced high-angle normal faults ("Basin and Range" faulting). The total amount of crustal extension accommodated within the mapped area is a minimum of 8-11 km (varying with latitude), but is permissably as great as 20 to 25 km.

IMPLICATIONS FOR DEEP REFLECTION PROFILES OF EXTENDED THRUST BELTS

Deep seismic reflection profiling north of the Mormon Mountains along strike of the Sevier orogenic belt [Allmendinger et al., 1983] and along the Caledonian front in Scotland [Brewer and Smythe, 1984] show that both areas have experienced a period of crustal extension following compression (Figures 19 and 20). Combined with surface geology and drilling results, we believe these reflection profiles are perhaps illustrative of concepts deduced from our mapping.

The reflector geometry of a portion of the COCORP west-central Utah survey is shown in Figure 19a. Although we do not wish to give a detailed interpretation of this reflector geometry here, some aspects of it are remarkably compatible with geometries we have observed. The geometry of the Sevier Desert detachment (lower detachment on Figure 19b) at its shallow end seems to be highly analogous to the Mormon Peak detachment. At point A, it crosses the Pavant thrust at an angle of about 15°-20°, similar to that between the Mormon Peak detachment and Mormon thrust (Figure 15). The arching at B is interpreted here to be related to drag or sympathetic shear beneath the detachment, as observed beneath western portions of the Mormon Peak detachment. The interpretation presented here is not unique. For example, the detachment at point A may reactivate a ramp portion of the thrust, then sole along the old thrust parallel to autochthonous stratigraphy at depth, thereby reactivating a thrust along its entire trajectory. Relationships mapped in the Mormon Mountains simply demonstrate that a nonreactivation interpretation is perfectly viable, and may not be ruled out based on the erroneous assumption that all low-angle normal faults in extended thrust belts follow old thrust planes.

Similar to the Mormon Peak and lower extensional allochthons, the Sevier Desert extensional allochthon exhibits westward structural simplification. East of point C, the reflector geometry and well data [Mitchell, 1979] suggest fragmentation of the upper plate by west-dipping imbricate normal faults, whereas west of C there is no evidence of any major internal extension.

The normal faults at and west of C cut a 4.2 Ma-old basalt flow (or its equivalent stratigraphic horizon) found in the Gulf no. 1 Gronning well (TD 2458 m; Lindsey et al. [1981]), yet farther west, at point D, we interpret the same horizon (which may not contain the basalt at D) to overlap a growth-fault basin formed in the hanging wall of the House Range detachment. The relationships at C and D

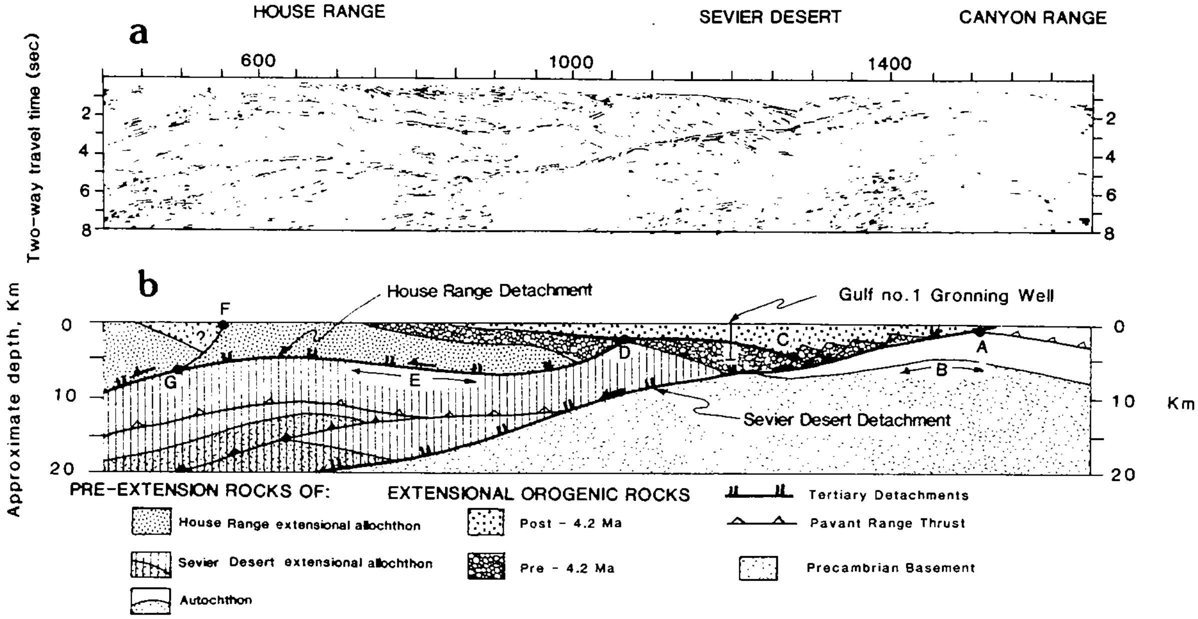


Fig. 19. Interpretation of reflector geometry from COCORP west-central Utah survey. a) Reflector geometry, after Allmendinger et al. [1983]; b) Structural interpretation discussed in text. See Figure 1 for location of profile.

thus suggest that a substantial amount of movement on the Sevier Desert detachment postdates movement on the eastern segment of the House Range detachment. This is extremely significant because the large arch at E developed in the House Range detachment appears to be the result of reverse-drag flexing above the younger, structurally lower detachment (cf. Figures 16 and 20; see also Bartley and Wernicke [1984], Figure 3). Although no attempt was made to depth-correct the seismic data, Allmendinger et al. [1983] have shown that the segment of the House Range detachment along E retains its current easterly dip (though of only a few degrees) once the effect of velocity pull-up in the House Range is taken into account. Restoring the basalt horizon to the horizontal (unflexing the hanging wall of the Sevier Desert detachment) rotates the segment of the House Range detachment along E to the horizontal. Thus, at about 4 Ma before present, movement on the structurally deeper Sevier Desert detachment rotated the House Range detachment through the horizontal, thereby deactivating it. However, to the west, the linear topographic scarp along the west side of the House Range (at point F) and the coalescence of the western boundary fault with the detachment at depth (point G) suggest that its trace west of G may have continued moving into the Quaternary, and could even still be active. The two detachments may thus have moved simultaneously.

None of the available data constrain the time of initiation of the two detachments: either one or the other may have formed first, or they may have initiated synchronously. At any rate, similar to the Mormon Mountains area, deformation induced by movements of structurally lower detachments seems to rotate and deactivate at least parts of higher ones. We suspect this may be the predominant mechanism of along-strike folding of detachments throughout the Basin and Range.

The large-scale geometry of the extending orogen in Utah may be interpreted as the development of low-angle normal faults (detachments) bounding extensional allochthons which fail by imbricate, rotational normal faulting (both listric and planar) at their shallow ends. Although it is difficult to rule out the possibility that the detachments there in all cases reactivate thrusts, processes observed in the Mormon Mountains make plausible

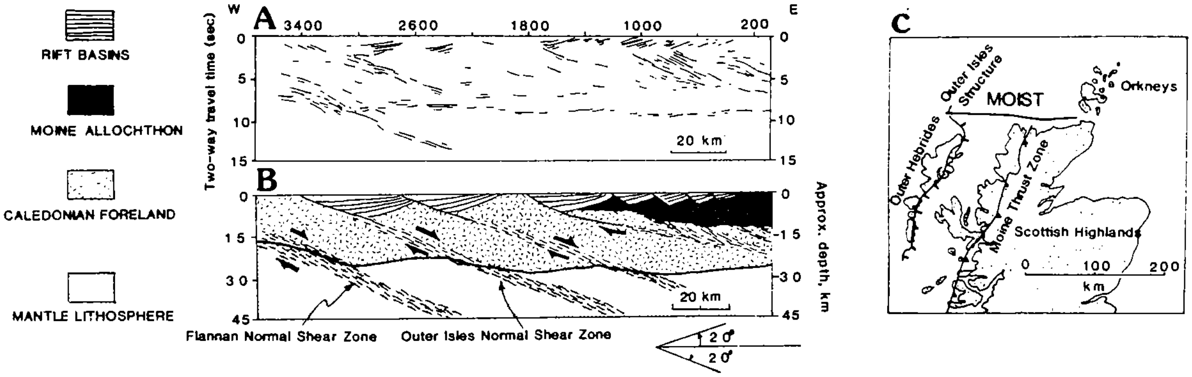


Figure 20. Interpretation of MOIST profile. a) Reflector geometry from Brewer and Smythe [1984]; b) Structural interpretation discussed in text; c) Location map of MOIST profile relative to major on-land structures.

interpretations which include substantial discordance between the two, including the involvement of autochthonous crystalline basement as far east as the Gulf no. 1 Gronning well.

The detachments are interpreted here not to merge at any particular decoupling horizon in the crust. Although the Utah reflection data do not preclude the possibility of a decoupling horizon in the lower crust between differing styles of extension, we have difficulty in seeing how the orogenic stockwerk geometries of crustal extension as envisioned by a number of workers [e.g. Hamilton, 1982; Miller et al., 1983] might apply. We view the "brittle-ductile transition" as simply the gradual change from brittle shear to ductile shear along crustally penetrating normal faults and shear zones, rather than a subhorizontal boundary which exerts profound influence on extensional geometry. At this time, we see no compelling mechanical reasons which preclude our hypothesis.

In fact, the MOIST seismic reflection profile across the Caledonian front in Scotland (Figure 20) [Brewer and Smythe, 1984] provides the most substantive evidence to date that single, low-angle normal shear zones may penetrate not only into the lower crust, but well into the mantle.

We have reproduced Brewer and Smythe's line-drawing interpretation of the MOIST data and present below it an interpretation emphasizing the importance of the Permo-Triassic (?) extensional orogen superimposed upon the Caledonian (Figure 20). It is stressed that no attempt has been made to depth-correct our interpretation, and as such Figure 20 cannot be construed as a true cross-section.

Brewer and Smythe [1984] interpret the reflector geometry primarily in terms of Caledonian thrusts which later experienced back-slippage as normal faults during Permo-Triassic (?) rifting. Based on this interpretation, they conclude that the Caledonian thrusts are more akin to deeply penetrating, Wind River-type structures [Soper and Barber, 1982] than they are to thin-skinned thrusting [McClay and Coward, 1981] apparent beneath the Blue Ridge and Inner Piedmont of the southern Appalachians [Cook et al., 1979].

Although clearly plausible and in many respects attractive, their interpretation hinges quite heavily upon the assumption that normal faults in compression zones always reactivate thrusts. If this is not assumed, there is little need for any of the shallowly inclined reflectors to be old thrust planes, particularly the Outer Isles and Flannan structures. No surface information is available for the Flannan, and the surface exposures of the Outer Isles "thrust" [Sibson, 1977] yield little firm basis for determining its age and its sense and amount of slip. Our interpretation, which is merely one of many that are possible, views the Outer Isles and Flannan structures as deeply rooted normal faults and shear zones which extend the Caledonian foreland lithosphere. We depict the base of the Caledonian orogen to be the Moine thrust zone, discordantly overprinted by deeply rooted normal faults. If the Flannan and

Outer Isles reflectors are indeed virgin normal faults, then the Moine thrust exposed on the surface is the northwest limit of Caledonian orogenesis. This in turn raises the possibility that the on-land exposure of the Outer Isles "thrust" is a late Paleozoic normal shear zone, having no relation whatsoever to early Paleozoic mountain building. In view of the interpretative nature of arguments for a thrust-fault origin of the Outer Isles structure, this hypothesis may be worth considering.

Our interpretation suggests that the crust along the MOIST profile has nearly doubled in width. We note that the normal faults, without depth correction, dip about 15°-20° to the southeast and the steepest observed bedding in the half-grabens is dipping about 15°-20°. Applying a "megadomino" kinematic model to these values suggests 80-100 percent increase in original width of the line, using the relevant equations for tilted-block geometry [see Wernicke and Burchfiel, 1982, Figures 2 and 3]. This estimate is minimum, because possible velocity pull-down from the basinal rocks maximizes both the near surface fault dip and the dip of bedding in the grabens. These pull-downs toward the graben center conspire to minimize the extension estimate. A preextension crustal thickness of 40 to 50 km is indicated.

Fault-bed angles of 30°-40° suggest a similar initial dip for the faults, somewhat steeper than the probable initial dips for the Sevier Desert, House Range and Mormon Peak detachments. The overall pattern of extension bears strong similarity to Davis' [1983] concept of continental rifting, except the initial dips are perhaps somewhat lower than his suggested 45°. Although the Moho reflector is not sharply offset by any of the structures except the Flannan, viewing its reflector geometry (Figure 20) along a low-incidence-angle line of sight reveals two broad upwarps aligned with downdip projections of the Outer Isles and next-higher subparallel structures. We interpret this in terms of broad shearing of the Moho, similar to that accomplished by the more obvious Flannan structure. The shear zone geometry for the Moho proposed here suggests it could be offset as much as 20 km or more along the Outer Isles structure, an amount commensurate with our interpretation of its surface offset. The shear zone model permits large strains without creating a great deal of structural relief. It should be noted that the dip of deeper segments of the Outer Isles structure may be steeper than shown here because of the velocity pull-up effect of deeper crustal rocks. Similar to the Flannan reflectors, then, the shear zone may actually steepen as it crosses the Moho [cf. Wernicke, 1984], perhaps a result of stress refraction near the mechanical interface between weak lower crust and strong mantle. As is the case with the Sevier Desert profile, we see little evidence for an extensional orogenic stockwerk on MOIST, although this possibility cannot be ruled out on the basis of reflector geometry alone. The data suggests to us that single, low-angle normal faults and shear zones penetrate not only deeply into the continental crust, but also into at least the upper 15 km of mantle lithosphere. Indeed, one could scarcely imagine a reflector geometry less indicative of rheological influences on the geometry of fault zones at depth.

We present our interpretations of these profiles neither as the "final word" nor even as necessarily more attractive than others. Our main purpose is to illustrate how concepts of orogenic architecture are most clearly documented by hands-on observation of relationships in the field. Without this kind of information there is little basis for interpreting the deep reflection profiles. In particular, we suspect that the concept of thrust fault reactivation may be far less important a process than the blocking out of extensional allochthons discordantly across the grain of the older compressional ones.

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M. S. Beaufait and J. D. Walker, Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA 02139.

B. Wernicke, Department of Geological Sciences, Harvard University, Cambridge, MA 02138.

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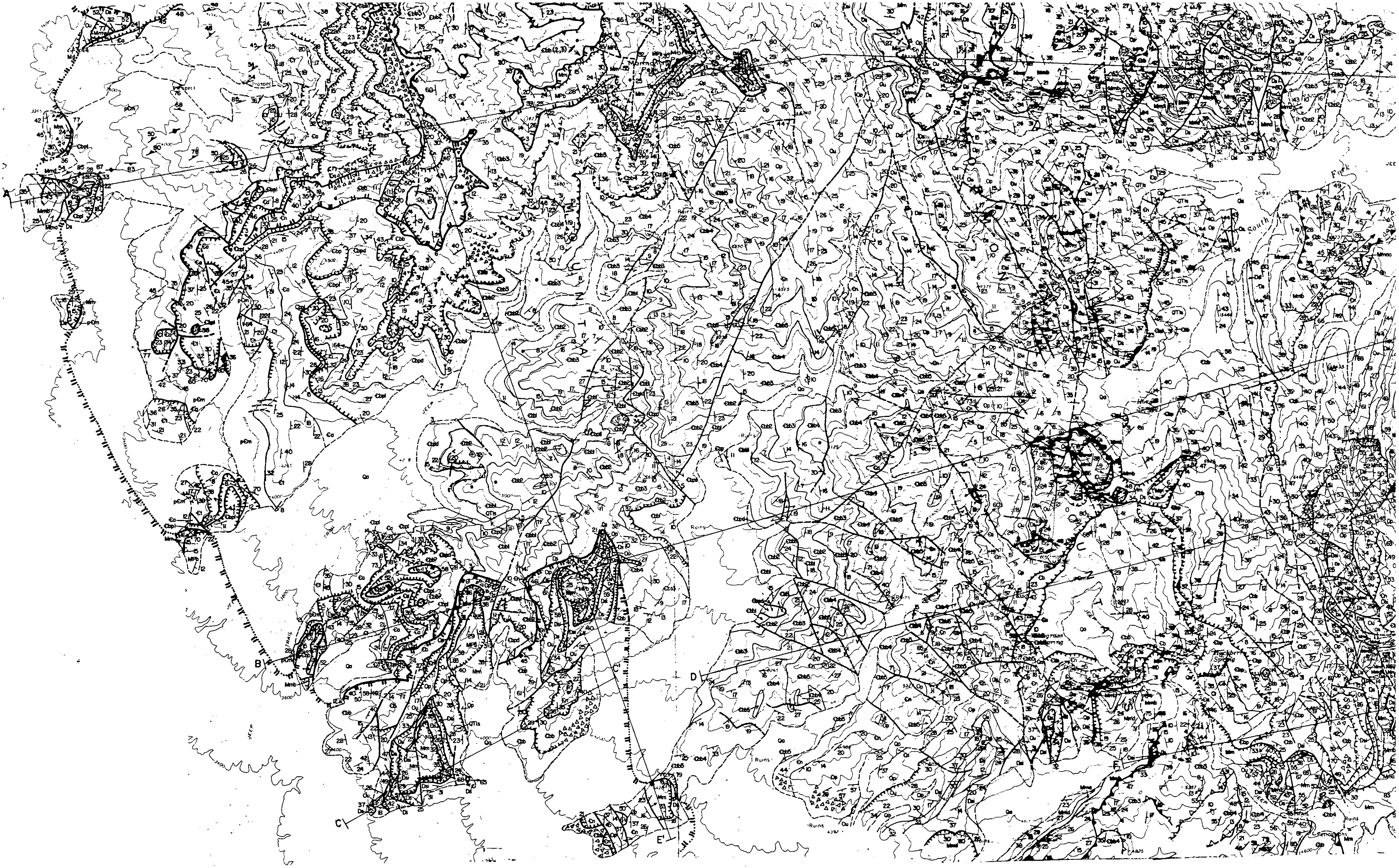
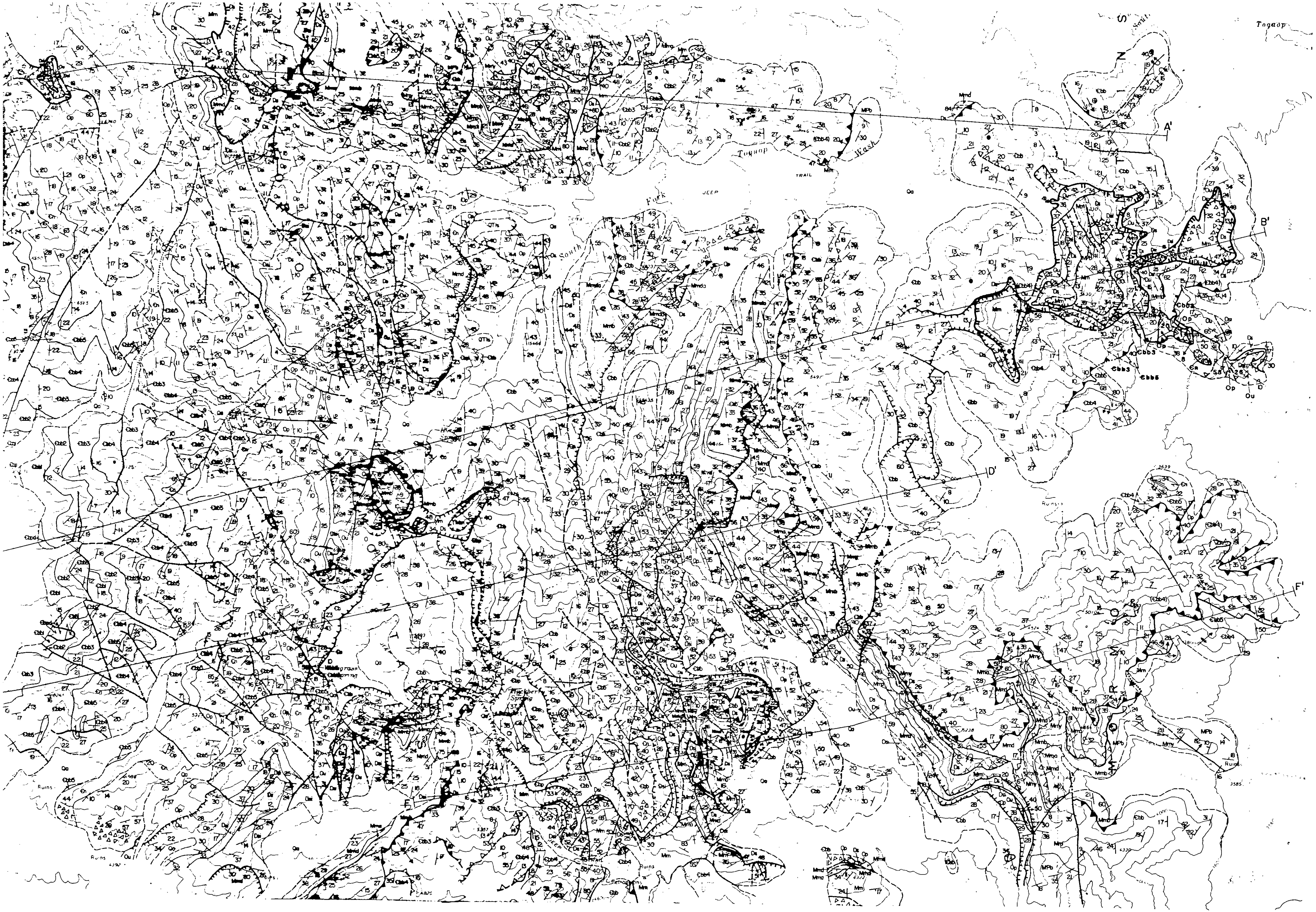


Plate 1. Geologic map of the central Mormon Mountains.


Togaop
A'
B'
D'
F'
F
Toquop Wash
South Fork
JEEP TRAIL
Huckberry Spring
Ruins

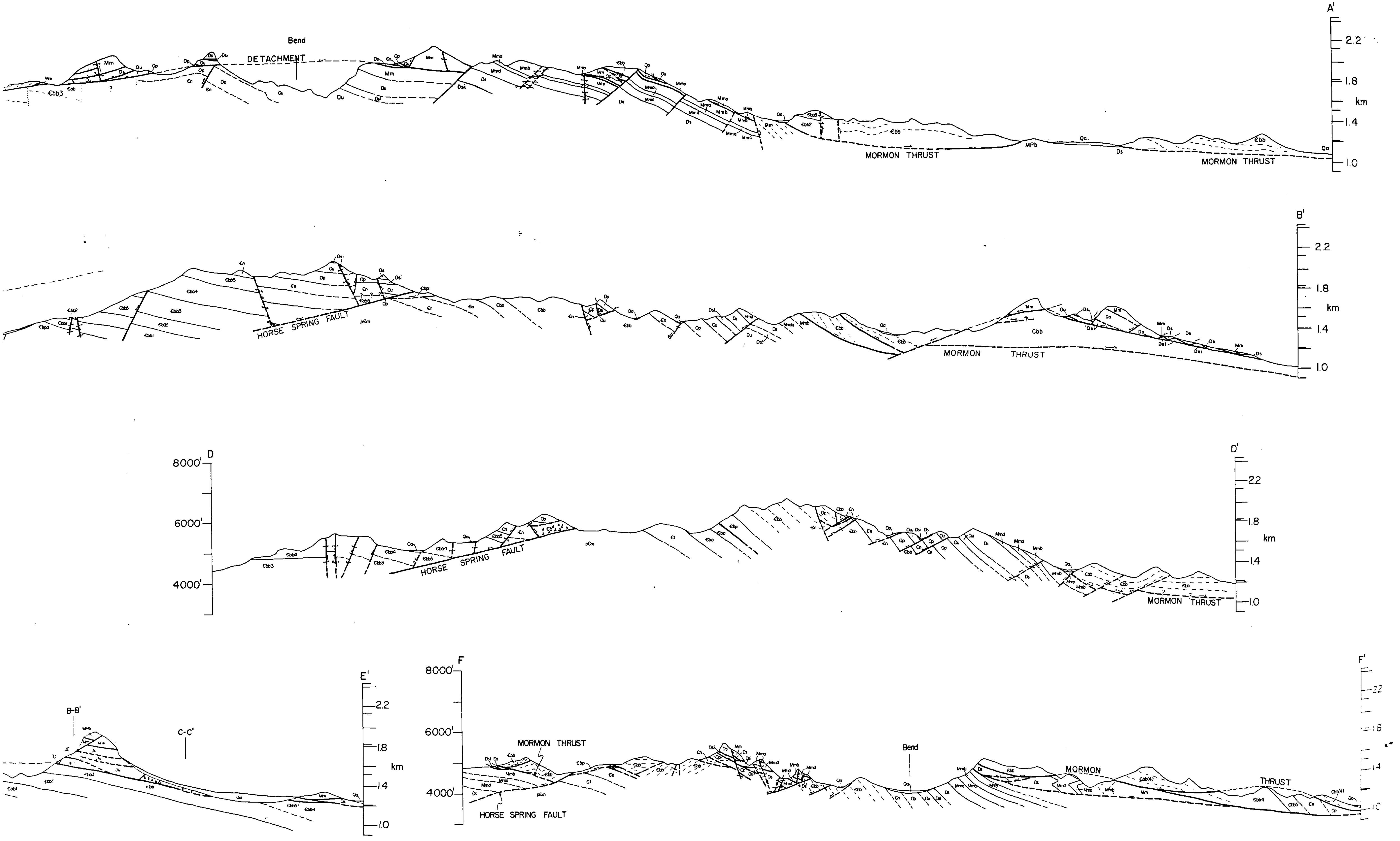
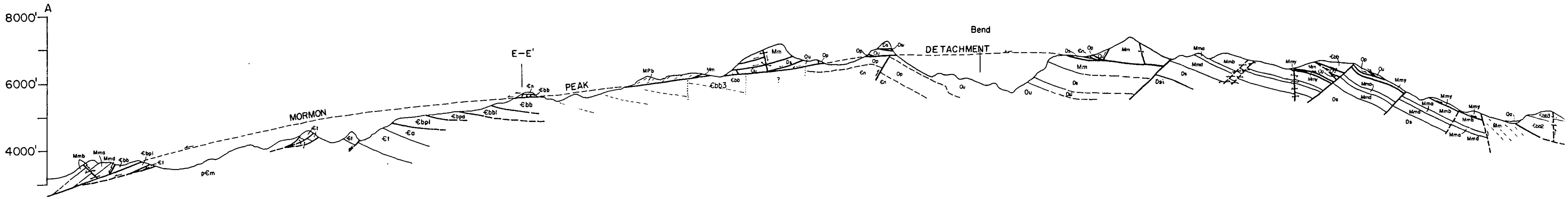
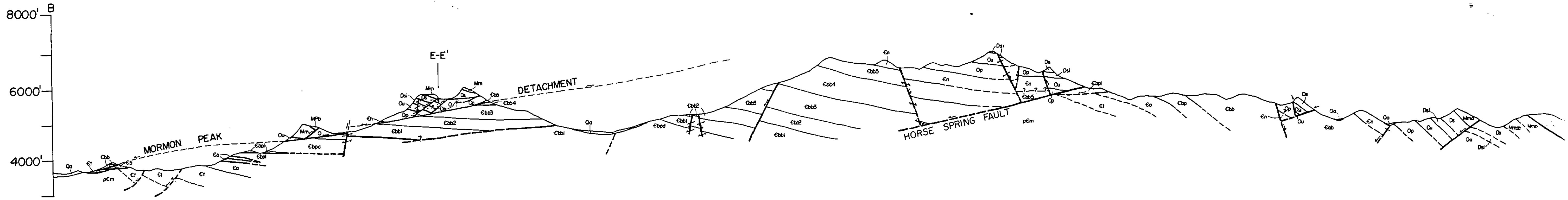
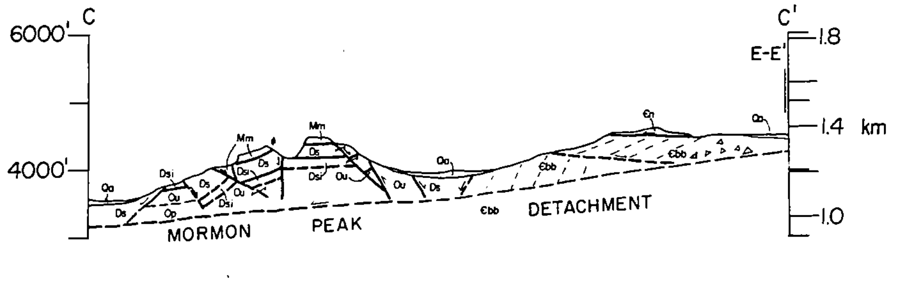


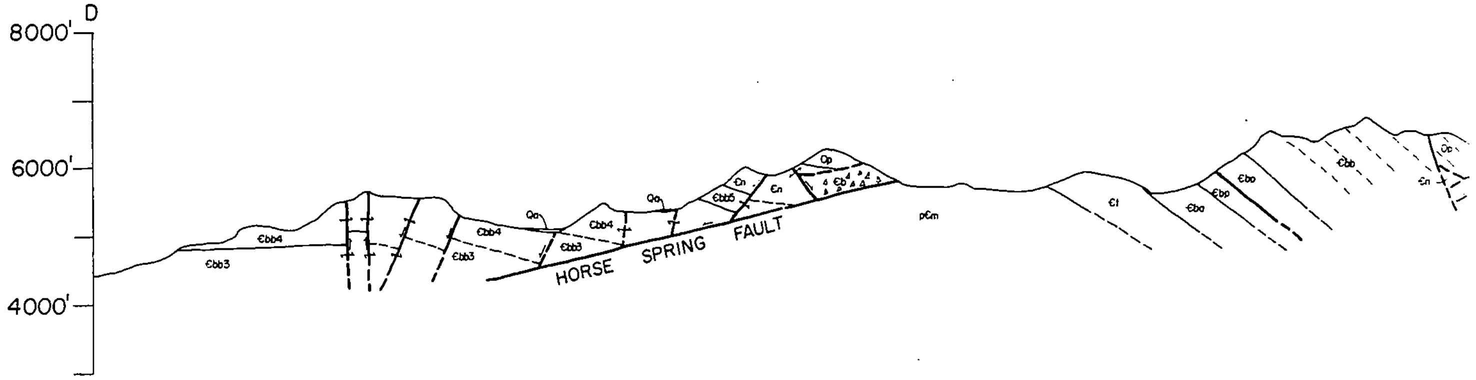
Plate 2. Cross sections, central Mormon Mountains. No vertical exaggeration.

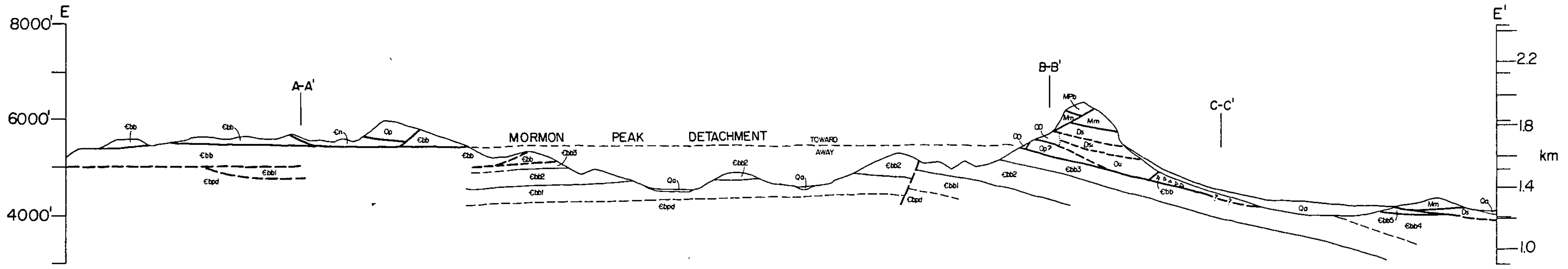
BLOOM

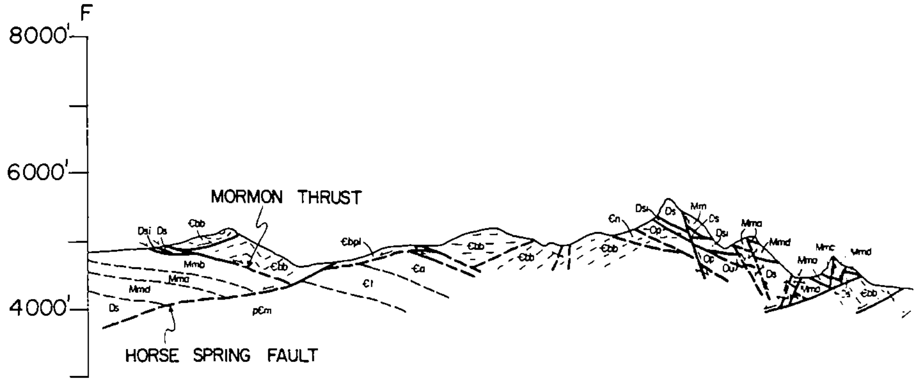

A
8000'
6000'
4000'
E-E'
MORMON
PEAK
DETACHMENT
Bend
Mmb
Mma
Mmd
Ꞓbb
Ꞓbpl
Ꞓt
pꞒm
Ꞓa
Ꞓbpd
Ꞓbbl
Ꞓn
MPb
Mm
Ꞓbb3
Ou
Op
Ds
Dsi
Mmy
Ꞓbb2


B
8000'
6000'
4000'
E-E'
MORMON
PEAK
DETACHMENT
HORSE
SPRING
FAULT
Qa
Ꞓt
Ꞓbb
pꞒm
Ꞓa
Ꞓbpl
Ꞓbpd
MPb
Mm
Ꞓbbl
Ꞓbb2
Ꞓbb3
Ꞓbb4
Ꞓbb5
Ꞓn
Op
Ou
Ds
Dsi
Mmd


C
6000'
4000'
C'
E-E'
1.8
1.4 km
1.0
MORMON
PEAK
DETACHMENT
Qa
Mm
Ds
Dsi
Op
Ou
Ꞓn
Ꞓbb


D
8000'
6000'
4000'
HORSE
SPRING
FAULT
Ꞓbb3
Ꞓbb4
Ꞓbb5
Qa
Ꞓn
Op
pꞒm
Ꞓt
Ꞓa
Ꞓbp


E
8000'
6000'
4000'
E'
2.2
1.8
km
1.4
1.0
A-A'
B-B'
C-C'
MORMON
PEAK
DETACHMENT
TOWARD
AWAY
Ꞓbb
Ꞓbbl
Ꞓbpd
Ꞓn
Op
Ꞓbb2
Ꞓbb3
Qa
MPb
Mm
Ds
Ou
Ꞓbb4
Ꞓbb5


F
8000'
6000'
4000'
MORMON THRUST
HORSE SPRING FAULT
Dsi
Ds
Mmb
Mmd
Ꞓbb
Ꞓbpl
pꞒm
Ꞓt
Ꞓa
Op
Mm
Mma
Mmc