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Mesozoic Evolution
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Mesozoic evolution, hinterland of the Sevier orogenic belt

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ABSTRACT

West of the Mesozoic foreland Sevier orogenic belt in northern Utah and southern Idaho, a regional detachment of inferred mid-Jurassic age occurs in Upper Mississippian shale and can be traced westward to the margin of the coeval magmatic arc, represented by spaced calc-alkalic intrusions. The detachment may be the oldest and structurally highest thrust of the Idaho-Wyoming thrust belt. If so, it bridges the apparent spatial and temporal gap between magmatism and thrusting, thus suggesting a direct genetic link. Thin-skinned deformation is interpreted here to be driven from the heated magmatic arc toward the colder craton by lateral tectonic compression created by lateral volume increase due to intrusion, elevated crustal geotherms, and possible thickening in the arc. The metamorphic complexes occur at the crustal interface between these two thermal-tectonic regimes and may themselves be allochthonous.

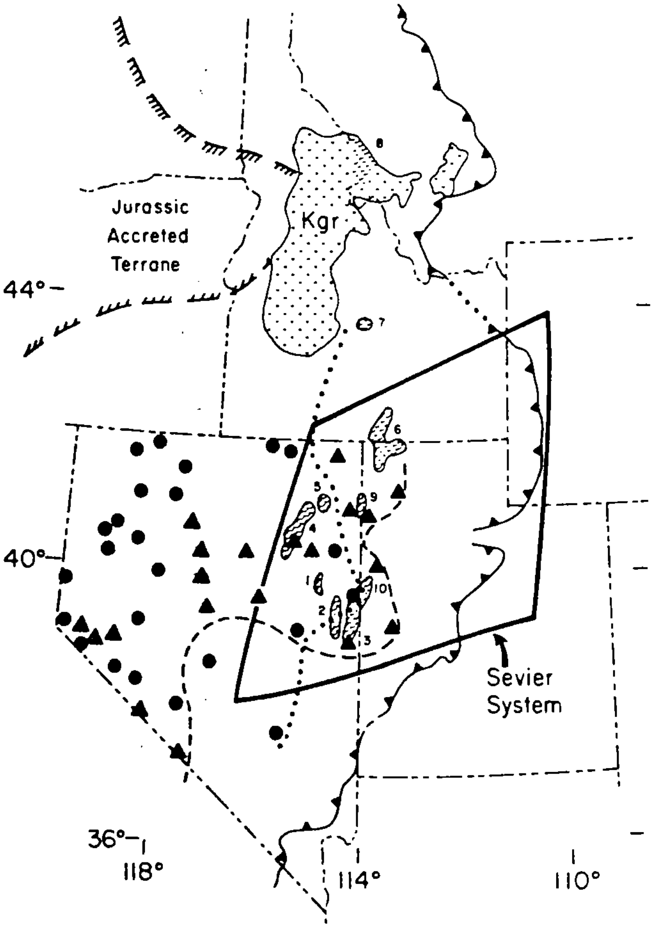

Figure 1. Location and generalized tectonic map. Barbed line = front of foreland thin-skinned thrusting; circles and dotted lines = plutons and eastern limit of magmatism during Cretaceous; triangles and heavy dashed lines = plutons and eastern limit of magmatism during Jurassic; wavy diagonal lines = probable Mesozoic metamorphic terranes in (1) Egan, (2) Schell Creek, (3) Snake, (4) Ruby, (5) Wood Hills, (6) Grouse Creek-Raft River-Albion, (7) Pioneer, (8) Bitterroot lobe, (9) Pilot, and (10) Deep Creek Mountains. Data compiled from Davis and others (1978), Davis and Coney (1979), and sources noted in Figure 2 and text.

INTRODUCTION

Perhaps the most poorly understood part of an entire Cordilleran-type mountain belt is the region between the foreland fold-thrust belt and the magmatic arc, here referred to as the hinterland. Although crustal geometries and timing relations for both the foreland and subduction complex-arc are known generally, a mechanically reasonable tectonic model linking the two remains elusive (reviewed in Armstrong, 1972). The focus of this paper is the hinterland of the Sevier orogenic belt in eastern Nevada, western Utah, and southern Idaho (Fig. 1). The Sevier belt is ideal for study because the timing of deformation is stratigraphically closely bracketed. The foreland thrust belt in Idaho and Wyoming is one of the best dated in the world (Armstrong and Oriel, 1965; Oriel and Armstrong, 1966; Royse and others, 1975), and recent mapping and geochronology to the west have illuminated the structural development of the metamorphic complexes and surrounding rocks of the hinterland and plutonic belt (Armstrong, 1976; Hose and Blake, 1976; Compton and others, 1977; Oriel and Platt, 1979; Miller, 1980; Miller and Hoggatt, 1981; Allmendinger, 1980).

SEVIER OROGENIC SYSTEM

Within the Sevier orogenic belt we recognize four distinct tectonic elements (Fig. 2), reviewed below from east to west.

Idaho-Wyoming-Utah thrust belt. Part of the Cordilleran foreland thrust belt stretching from Alaska to Mexico, the classic Sevier belt (Armstrong, 1968) is characterized by (1) thrusts with west-dipping, listric geometry, soling into a major basal detachment of Archean or Proterozoic age at the western side of the thrust belt (Royse and others, 1975); (2) a minimum of 50% (about 140 km) shortening of supracrustal strata perpendicular to the belt without the development of mylonites or much metamorphism; and (3) younging of major thrust faults from west to east with deformation spanning nearly 100 m.y. from latest Jurassic(?)

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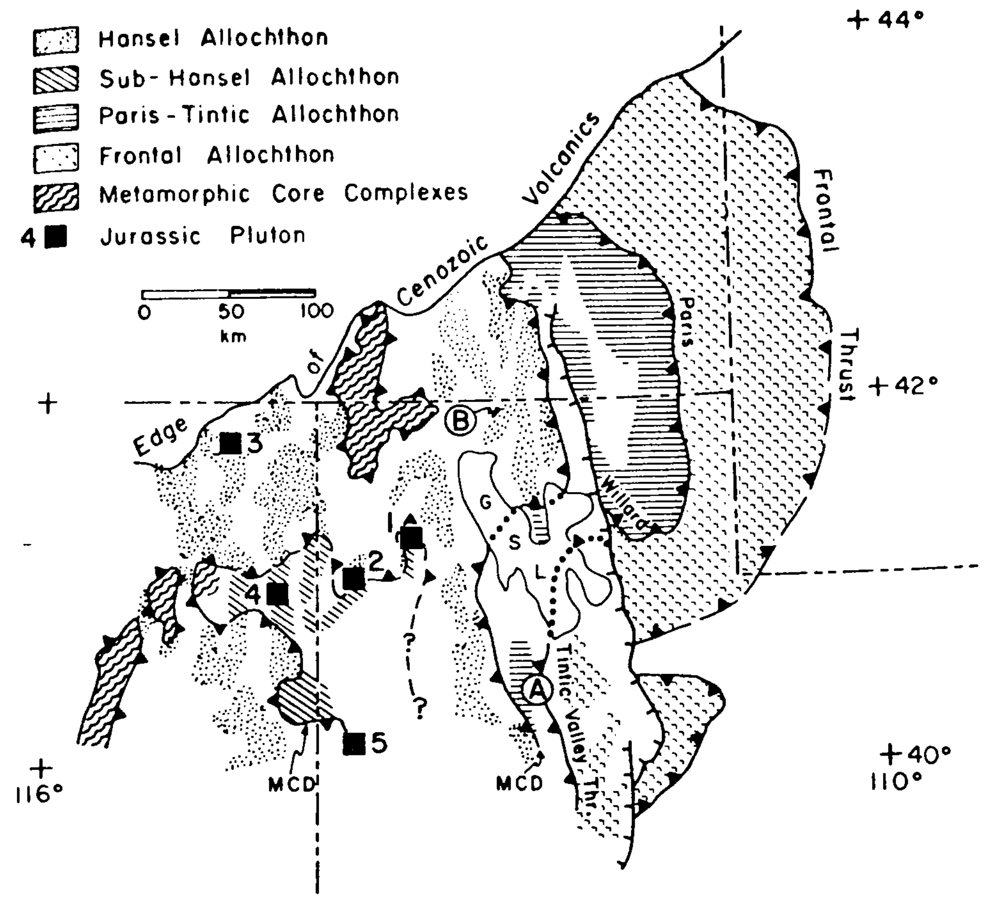

Figure 2. Generalized Mesozoic tectonic map of northern Sevier belt in northern Utah, southern Idaho, and northeastern Nevada. Patterns shown only in present mountain ranges. Hachured line = Wasatch fault. Structural detail not shown around metamorphic complexes (Pilot Mountain not differentiated) or east of Wasatch fault. At A, a folded klippe of Hansel plate is present on east side of Stansbury Mountains. B indicates Hansel and North Hansel Mountains. Ages of Jurassic plutons: (1) 149.6 ± 4.5 m.y. (Carroon, 1977); (2) 140, 170, 192 m.y. (Armstrong and Suppe, 1973; T. McKee, 1980, personal commun.); (3) 154, 160 m.y. (Coats and others, 1965); (4) 130, 154 m.y. (Armstrong and Suppe, 1973); (5) 151 to 153, 132 m.y. (T. McKee, 1980, personal commun.). K-Ar dates recomputed using new decay constants, where appropriate. Map based on Oriel and Platt (1979), Jordan and Douglass (1980), sources cited in text, and unpublished data.

to earliest Eocene (Armstrong and Oriel, 1965; Armstrong, 1968).

Hinterland. The rocks west of the well-known foreland thrust belt in Idaho and Utah are characterized by nonductile deformation and insignificant metamorphism. Rocks in the suprastructure of the metamorphic complexes are here included in the hinterland province. Low-angle faults placing younger rocks over older rocks have been recognized for some time (Misch, 1960; Nelson, 1969; Armstrong, 1972; Hose and Danes, 1973; Compton and others, 1977; Moore and Sorensen, 1978), and attempts to place them in a regional perspective generally fall into two classes: Cenozoic denudation (Armstrong, 1972) or Mesozoic attenuation faults (Hose and Danes, 1973). Both suggest gravity as the principal driving mechanism. Recent work, primarily by the U.S. Geological Survey, indicates that younger-over-older low-angle faults occur at a few specific stratigraphic levels and crop out over a vast region (Oriel and Platt, 1979). Largely on the basis of that work, we suggest that there is a regional decollement in shale of Late Mississippian and earliest Pennsylvanian age, and we discuss below the evidence for Mesozoic compressive deformation involving that decollement.

Mesozoic metamorphic belt. Behind the foreland thrust belt near the west side of the hinterland province lies a linear, probably originally continuous, terrane of greenschist- to amphibolite-facies metamorphic rocks (Fig. 1). The north-trending Mesozoic metamorphic belt coincides with, but is not entirely limited to, the Tertiary metamorphic core complexes recognized by Davis and Coney (1979) where radiometric ages are reset, obscuring the Mesozoic events. However, recent geochronology (Table 1; DeWitt, 1980) confirms that the foreland deformation and earlier phases of hinterland metamorphism were approximately coeval, and possibly genetically related (Misch, 1960; Price and Mountjoy, 1970; Dickinson, 1976).

Magmatic arc. Although the Sierra Nevada and Idaho batholiths are perhaps the most familiar expression of the Cordilleran magmatic arc, Jurassic and Cretaceous calc-alkalic plutons are known throughout Nevada and westernmost Utah (Fig. 1; Armstrong and Suppe, 1973). This plutonic suite was created during eastward subduction of oceanic crust beneath North America, probably starting in the Late Triassic in the southern Sierra Nevada and southern British Columbia and spreading throughout the entire Cordillera by Jurassic time (Davis and others, 1978).

SPATIAL AND GEOCHRONOLOGIC EVIDENCE FOR COEVAL EVOLUTION OF METAMORPHIC COMPLEX AND MAGMATIC ARC

Plutons of Middle to Late Jurassic age (160 to 140 m.y.) extend as far east as western Utah (Figs. 1, 2). This easternmost fringe of the earliest plutonic belt in this part of the Cordillera coincides spatially and temporally with metamorphism and deformation in the metamorphic belt (reviewed in Table 1). The importance of the Jurassic magmatic arc in eastern Nevada and western Utah may be masked because it intruded and was partly derived from thicker continental crust, whereas the western part intruded thinner, denser oceanic crust (Miller and Bradfish, 1980). Therefore, the depths of emplacement may have differed from west to east, creating quite different degrees of exposure after erosion. Also, an equal number of Mesozoic plutons might be expected to occur beneath the Cenozoic grabens of the Basin and Range.

The plutons in western Utah and throughout Nevada suggest elevated crustal geotherms everywhere in and west of the metamorphic complexes during Jurassic time. Thus, the Mesozoic metamorphic complexes exposed in the hinterland of the Sevier orogenic belt and to the north probably represent fragments of an originally continuous, relatively

TABLE 1. SUMMARY OF MESOZOIC METAMORPHIC EVENTS IN SEVIER BELT

Location*	Time of Mesozoic metamorphism and deformation† (B.P.)	References
Albion (6)	162, 157, 130–66 m.y. (K-Ar)	Armstrong (1976), Miller (1980)
Raft River–Grouse Creek (6)	No Mesozoic dates (due to intense Tertiary overprint?), but may be Jurassic by analogy with Albions	Compton and others (1977), Compton and Todd (1979)
Pilot (9)	Pre-91 m.y. (K-Ar on hornblende)	Miller and Hoggatt (1981)
Ruby (4)	160 m.y. (Rb-Sr on pegmatite in migmatite), 82 m.y. (Rb-Sr on postkinematic granite)	Willden and Kistler (1969), Snoke (1980), Howard (1980)
Deep Creek–Kern (10)	Undated, but first phase may be Mesozoic, on basis of analogy with other terranes	Nelson (1969), Armstrong (1972)
Schell Creek (2)	188 m.y. (K-Ar on hornblende)	Hose and Blake (1976)
Snake (1)	Jurassic (160 m.y.) granitoids crosscut folded Paleozoic strata	Lee and others (1970)

*Numbers in parentheses refer to site numbers in Figure 1.

†All localities have undergone at least some degree of overprinting by Cenozoic metamorphism and deformation.

narrow, strongly heated terrane next to the plutonic belt. As such, they occur along the boundary between hot, ductile continental crust intruded by arc plutons and cold continental crust to the east, rather than being the locus of thermal upwelling as suggested by Price and Mountjoy (1970) and Armstrong (1972).

METAMORPHIC COMPLEX–THRUST-FOLD BELT RELATIONS

The Middle to Late Jurassic times of metamorphism and intrusion reported in the metamorphic complexes are generally 10 to 20 m.y. earlier than the earliest foreland thrusting yet recognized. Although loosely dated, the time resolution is better in the Idaho-Wyoming thrust belt than elsewhere (Armstrong and Oriel, 1965; Oriel and Armstrong, 1966; Royse and others, 1975). Below, we focus on the southern Idaho–northern Utah segment of the Sevier orogenic belt.

The critical structural link between metamorphic complex and foreland thrust belt is the as yet incompletely understood hinterland, which, in the northern Utah–southern Idaho segment, falls between the northern Wasatch and Bannock Ranges on the east and the Grouse Creek, Raft River, and Albion Mountains to the west (Fig. 2). There, low-angle faults along which younger rocks overlie older rocks occur in similar stratigraphic position over widespread regions (Oriel and Platt, 1979; Jordan and Douglass, 1980). The upper and most widely exposed of three allochthons recognized by Oriel and Platt (1979) is composed primarily of the Pennsylvanian-Permian Oquirrh Group, with a decollement in the Upper Mississippian and Lower Pennsylvanian Manning Canyon Shale. Oquirrh Group and overlying strata also comprise a major allochthon south of the Idaho-Utah state line (Fig. 2; Moore and Sorensen, 1978; Jordan and Douglass, 1980). The decollement is essentially a bedding-plane thrust that places younger rocks over older rocks, generally without major omission or duplication of section (Oriel and Platt, 1979).

An allochthonous sheet in the suprastructure of the Raft River–Grouse Creek metamorphic complex, also composed of nonmetamorphosed or slightly metamorphosed Oquirrh Group, is bounded at the base by a similar decollement in the Upper Mississippian sequence. Compton and Todd (1979) and Compton and others (1977) considered this fault, which omits a significant part of the sequence, to be the principal decollement in those ranges. Broad regions of east-central Nevada are also underlain by a Mesozoic low-angle fault in Mississippian shale (Armstrong, 1972, p. 1731).

Scattered and widespread exposures of allochthons above the Manning Canyon Shale decollement lying east of the metamorphic complex are here inferred to be part of a single major allochthonous sheet, on the basis of the following similarities in Idaho and Utah: (1) the similar stratigraphic level of the decollement within or near a contact with the Manning Canyon Shale; (2) the general continuity of facies in the Oquirrh Group of the allochthon (Jordan and Douglass, 1980); (3) the absence of recognized local ramps across significant stratigraphic intervals; and (4) a consistent style of deformation, characterized by largely homoclinal sections and, locally, major folds. However, more than 50% of the surface area is covered by Neogene basin deposits, and subsurface data are sparse; the decollement exposed in many ranges may be discontinuous. Moreover, parts of this decollement have probably been reactivated during Cenozoic deformation.

The relations of this inferred regional thrust sheet east of the metamorphic complex to the similar allochthon over the metamorphic complex and the allochthon above Mississippian shales in east-central Nevada remain to be tested. We suggest that they may represent one regionally extensive thrust sheet, here informally designated the Hansel plate (for exposures in the Hansel and North Hansel Mountains, Fig. 2, site B), bounded at its base by the Manning Canyon Shale detachment (MCD in Fig. 2).

The date of translation of this allochthon is constrained only as post–Early Triassic and pre-Pliocene through most of the hinterland. In the metamorphic belt, Compton and Todd (1979) and Compton and others (1977) suggested that most of the 60 km of minimum transport on a decollement in Mississippian shales over the Raft River–Grouse Creek complex occurred before the first metamorphism or during its earliest stages. If that metamorphism began in Jurassic time, as suggested by analogy with the Albion terrane, then emplacement of the plate is probably primarily Jurassic as well. To the west, the Upper Mississippian shale detachment in the HD Range is dated as mid-Jurassic by crosscutting dikes from the Contact pluton (Riva, 1970). Our tentative correlation of the decollement east of the metamorphic belt with these implies that the Hansel plate may have moved about 60 km in the Jurassic. Mapping of asymmetric folds and microstructural fabric analysis east of the metamorphic complex suggest that the rocks in the Hansel plate were deformed and translated from west to east by layer-parallel compression (Allmendinger, 1980).

In view of the more than 60 km of offset above basement in the core complex and 140 km of shortening above basement in the Idaho-Wyoming thrust belt (Royse and others, 1975), a reasonable inference is that all of the sedimentary rocks in the hinterland are allochthonous. Four aspects of the Manning Canyon decollement and Hansel plate are relevant to relations between the foreland thrust belt and hinterland. First, the detachment is stratigraphically higher than exposures of the westernmost foreland thrust and therefore is probably not the western equivalent of any of those thrusts. Second, the Manning Canyon decollement apparently ramped to the surface west of the present location of the northern Wasatch Range (west of the Paris thrust); at Samaria Mountain, Platt (1977) found Permian parts of the Oquirrh Group below what appears to be the Manning Canyon decollement. South of the Great Salt Lake, a ramp or eroded homoclinal fold in the thrust may occur between Stansbury and South Mountain, a short distance west of the buried trace of the Tintic thrust (Fig. 2, site A). Third, the Middle to Late Jurassic time of offset inferred above predates the Paris thrust of latest Jurassic–earliest Cretaceous time (Armstrong and Oriel, 1965). Since the belt is characterized by eastward younging of thrusts during nearly 100 m.y., the Manning Canyon decollement may well represent the oldest and structurally highest thrust in the Sevier orogenic system. Finally and most speculatively, the lower plate of the Manning Canyon decollement (Fig. 2) contains rocks of the same general age and composition as those of the Paris-Tintic plate farther east and may be structurally continuous from foreland to hinterland.

The stratigraphic omissions exhibited by the Manning Canyon decollement in the metamorphic complex remain problematic. There are three alternative explanations. First, the omissions may be due to attenuation faulting over a locus of Mesozoic thermal upwelling, causing the thrust belt to be driven from the metamorphic complexes by gravitational potential (Compton and Todd, 1979; Hose and Danes, 1973). Second, the Hansel allochthon was possibly driven from the west by horizontal compression over the top of an independent, thermally doming metamorphic complex. As a plate moved from west to east over a dome, the stratigraphic position of the decollement descended on the west side of the dome and climbed on the east side, thus remaining nearly horizontal. The third possibility is that the stratigraphic omissions are not Mesozoic but were created during mid-Tertiary reactivation of the older decollement.

We favor some combination of the second and third possibilities, for several reasons. Both to the west (HD Range; Riva, 1970) and east (Allmendinger, 1980) of the metamorphic belt, rocks above the Manning Canyon decollement apparently moved from west to east during Mesozoic time. An F_1 fold culmination in the Raft River–Grouse Creek complex need not indicate a genetic link between doming and thrusting, as suggested by Compton and others (1977) and Compton and Todd (1979), but could have been developed by independent doming during and *after* the regional translation and emplacement of the thrust plate. Finally, cross sections based on seismic-reflection profiles and surface geology in the foreland thrust belt (Royse and others, 1975) suggest that structurally lower thrust faults may cut into crystalline basement at or just west of the northern Wasatch Range. If so, it seems unlikely that the same thrusts would step up stratigraphically, and apparently geometrically, westward in order to root in, or be driven by, the metamorphic complexes. Thus, the metamorphic complexes, as well as Jurassic stocks emplaced at higher structural levels, may also be allochthonous (Fig. 3c).

Our conclusion is that the Hansel plate moved from west to east over the entire region east of the magmatic arc during the Mesozoic. Many parts of the Manning Canyon decollement have almost certainly moved again in various directions during Cenozoic extension, complicating the present structural geometry.

MODEL AND IMPLICATIONS FOR CORDILLERAN-TYPE OROGENS

A major question in the genesis of Cordilleran-type foreland deformation is the relative importance of plate-margin collision-accretion and magmatic-arc thermal processes as driving mechanisms. The Golconda allochthon was probably emplaced at the continental margin west of the Sevier belt prior to any deformation described here (Davis and others, 1978). The closing of a small back-arc basin in western Nevada during mid-Jurassic time involved from 10 to 60 km of shortening (Speed, 1978) and could conceivably have acted as a "triggering" mechanism for foreland deformation. However, this event and subsequent plate-margin accretion west of the Sevier belt (for example, Franciscan and related rocks) were apparently not of sufficient magnitude (on the basis of available data) to account for at least 200 km of foreland shortening. This probably contrasts with the post-Triassic accretionary tectonics to the north in Canada. Alternatively, the close temporal and spatial relations between plutonism over an east-dipping subduction zone, the metamorphic belt, and initial thin-skinned deformation described above suggest that processes in the magmatic arc play an important role in generating foreland deformation, as suggested by Hamilton (1978).

The shallow Hansel plate was probably the first major allochthon to be emplaced in northern Utah and southern Idaho, driven eastward from the mid-Jurassic magmatic arc (Fig. 3). The first regional metamorphism took place synchronously along the eastern margin of the plutonic belt. This metamorphism was a dynamic event due to lateral translation of material away from the arc. Heating of the rocks may have caused doming (Compton and Todd, 1979). After the initial Middle to Late Jurassic stages, the eastern margin of deformation progressed eastward, and decollement levels shifted to deeper horizons, eventually resulting in the well-known foreland thrust-belt sequence. The overall shortening rate in the Idaho-Wyoming part of the belt was about one to two orders of magnitude smaller (0.1 to 0.2 cm/yr; implicit in Fig. 20 of Armstrong and Oriel, 1965) than current plate-motion rates. If subduction was continuous throughout the Cretaceous and early Tertiary, this observation implies that thin-skinned foreland deformation was either intermittently or possibly never directly coupled to the subduction zone.

Unless arc plutons are derived solely from remobilized in situ continental crust, their intrusion requires that the pre-existing

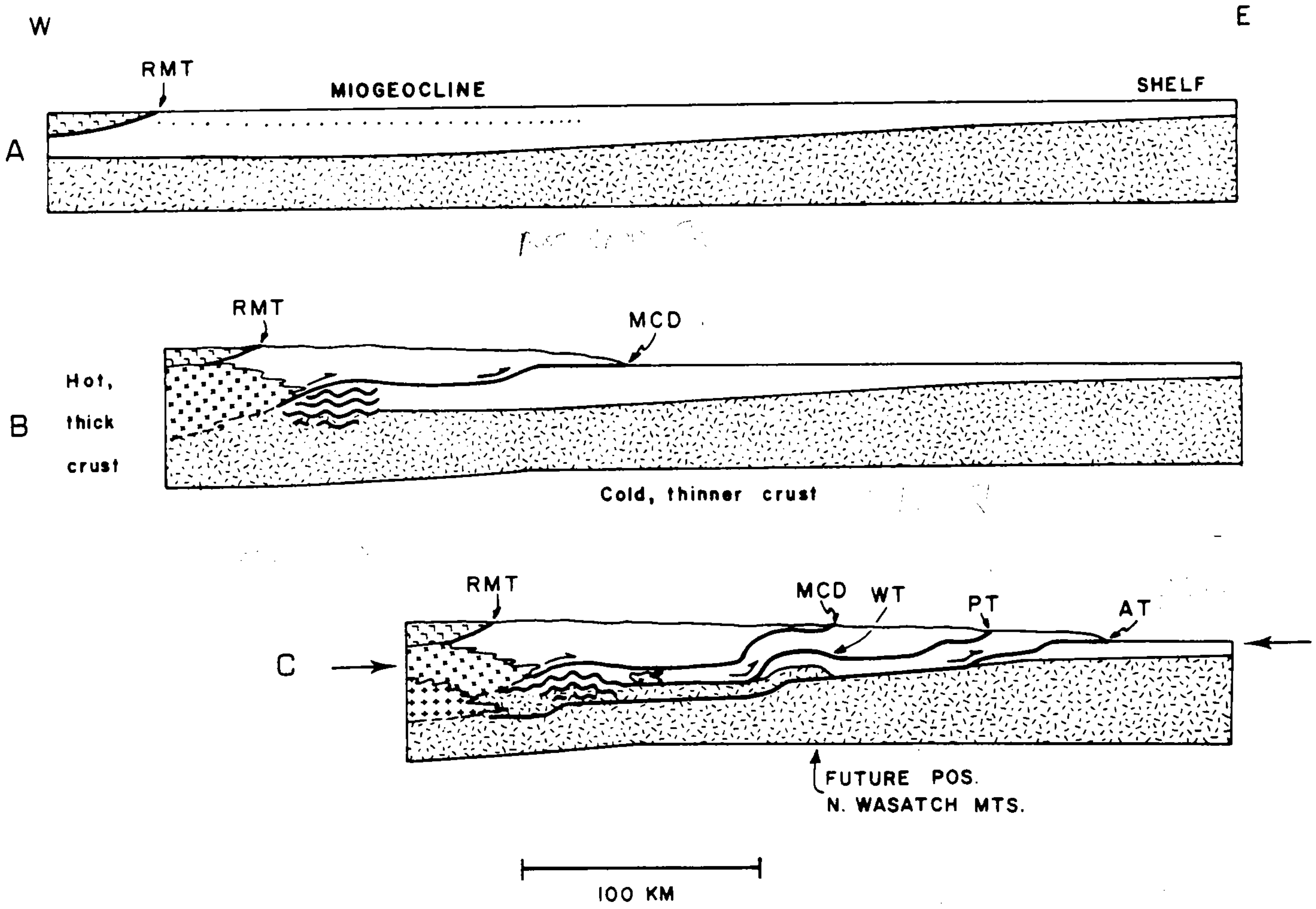

Figure 3. Schematic cross sections showing Mesozoic evolution of northern Sevier belt. Dash pattern indicates continental basement. Approximately 1:1 scale, but exaggerated to show detail. (A) Post-Early Triassic; RMT = Roberts Mountains thrust. Golconda thrust and transition from continental to oceanic crust are located west of cross section. Dotted line = palinspastically reconstructed extent of Manning Canyon Shale and equivalents. (B) Middle-Late Jurassic; heavy wavy lines indicate metamorphic complexes; x pattern indicates plutons (schematic only); MCD = Manning Canyon detachment. (C) Late Cretaceous, after emplacement of Absaroka thrust; PT = Paris thrust, WT = Willard thrust, AT = Absaroka thrust. Arrows at side show approximate present erosional level.

crust increase in volume at the level of emplacement. However, the entire crust in the plutonic belt is not stretched but may be both thickened and lengthened, due to volume increase, heating, and possibly some lateral compression at the plate margin. These effects may combine to produce the lateral tectonic compression at the boundary between hot and cold crust. This compression acts on the back (west) end of the wedge of sediments involved in thin-skinned thrusting over undeformed basement, as in Chapple's (1978) model. The location of foreland deformation over cold basement directly east of the hotter, thicker magmatic arc is not coincidental, and the metamorphic belt occurs at the transition between these two regimes.

If upper-crustal lengthening by intrusion of plutons, suggested for the Andes by Clark and others (1976), was a dominant driving mechanism, then it should approximately balance shortening in the foreland, with the net cross-sectional lengths of upper and lower crust remaining the same. Then, the base level of emplacement of upper-crustal arc batholiths might constitute a type of detachment horizon (Fig. 3). In the western United States, available data on the three-dimensional geometry and intrusion mechanisms of Mesozoic plutons are insufficient to test this hypothesis. The structural geometry of the Sevier foreland thrust belt is similar to thrust belts of collisional orogens (for example, Timor and the Appalachians), because different driving mechanisms produce lateral compressive stress in the sedimentary wedges of both.

The main purpose of this paper is to refocus attention on the Mesozoic history of the hinterland of the Sevier belt. Although there has been a vast increase in data on Tertiary tectonics in the last decade, Misch (1960) and Armstrong (1972) provided the most significant regional contributions concerning Mesozoic deformation in the hinterland. Many important points of this paper—the continuity and age of the Mississippian shale detachment, the structural connection between foreland and hinterland, and timing relations and structural style of Mesozoic deformation in the hinterland—all require further documentation and should at present be regarded with some skepticism. Additional field work and geochronology are needed, and seismic-reflection profiles and drill holes would provide crucial three-dimensional control.

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FORUM

Comment and Reply on 'Mesozoic evolution, hinterland of the Sevier orogenic belt'

COMMENT

Brian Wernicke, *Department of Earth and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139*

Allmendinger and Jordan (1981) have attempted to relate plutonism, metamorphism, and thrusting in the Cordillera by interpreting selected features of the Sevier hinterland. Although the pros and cons of their large-scale speculations have been previously discussed (Burchfiel and Davis, 1975; Hamilton, 1978), the specifics of their Jurassic and Cretaceous scenario behind the thrust belt invite comment.

Allmendinger and Jordan hypothesized that the fault within latest Mississippian (Chester) shales (Manning Canyon shale decollement) is an east-directed thrust fault, of Middle to Late Jurassic age, with at least 60 km offset. They favor the theory that the juxtaposition of the superjacent "Hansel plate" across older Precambrian basement and its thin veneer of metasedimentary cover in the Raft River–Grouse Creek–Albion complex are due to the plate "being driven from the west . . . over the top of an independent, thermally doming metamorphic complex. As a plate moved from west to east over a dome, the stratigraphic position of the decollement descended on the west side of the dome and climbed on the east side, thus remaining nearly horizontal" (Allmendinger and Jordan, 1981, p. 311). They further hypothesized that the initial deformation and coeval medium-grade metamorphism of the cover rocks immediately beneath the Manning Canyon decollement occurred "during and *after* the regional translation . . . of the thrust plate" (italics theirs). Also relevant is their statement, "Many parts of the Manning Canyon decollement . . . moved again in various directions during Cenozoic extension," recognizing that at least part of the present picture was forged by the rather messy (but surficial) process of "denudation," which they alluded to as being localized landsliding on older thrust planes.

Their interpretation requires that metamorphism of the Raft River cover occurred at the same average depth as the Mississippian shale horizon. The maximum depth of this horizon on a regional scale could not have exceeded about 3 to 4 km prior to Mesozoic tectonism, even though to the south in the Oquirrh basin it locally may have reached 10 km. In areas adjacent to the Raft River Mountains, however, the "Hansel plate" may have attained a maximum thickness of about 6 to 8 km, if liberal amounts of internal thickening and a minimum of subaerial erosion are assumed.

Metapelites in the cover terrane structurally only tens to hundreds of metres beneath unmetamorphosed and slightly metamorphosed "Hansel plate" strata are commonly staurolite-kyanite schists (Compton and others, 1977; R. L. Armstrong, unpub.; Thorman, 1970). As indicated in Figure 1 here, these rocks could not have crystallized at less than about 530 °C and 4.5 kb (Turner, 1981; Ganguly, 1972; Holdaway, 1971), corresponding to a depth of about 16 km. Actual geobarometry of staurolite-kyanite schists from hinterland complexes both north and south of the region discussed by Allmendinger and Jordan (Labotka, 1980; Ghent and others, 1979) has yielded pressure values in the 6 to 9.6 kb range, at about 22 to 35 km depth.

The apparent sharp temperature contrast across the Manning Canyon decollement in the metamorphic terranes makes hypotheses of major postdisplacement metamorphism extremely difficult to accept (for example, Misch, 1960). However, the above pressure arguments indicate that at least an 8 km (but probably more like 10 to 20 km) vertical column of rock lay between the "Hansel plate" and the metamorphic cover terrane during Jurassic metamorphism and was subsequently removed. Because rocks provably as young as Late Cambrian (stratigraphic depth 6 to 7 km) contain staurolite-kyanite assemblages (Thorman, 1970), the metamorphic complexes are clearly areas of heating and *depression*, not heating and uplift as stated by Allmendinger and Jordan. Further, the "denudation" of this amount of material from atop the complexes by means of radial gravity sliding triggered by their uplift (Drewes, 1967; Armstrong, 1972; Coney, 1974, 1980) geometrically requires the existence of equally thick stacks of sheets over large areas with many older-over-younger relationships between them, and an increase in metamorphic grade toward the top of the pile. Such stacks are simply not a reality of hinterland geology; thus, invoking variably directed landsliding to significantly ease the pressure discrepancy problem across the Manning Canyon decollement is obviously not the solution.

The main problem with Allmendinger and Jordan's model is that it seems to rather specifically deny both the generation and removal of the petrologically required overburden of the metamorphic terrane.

Any interpretation of hinterland evolution must incorporate (1) Middle to Late Jurassic heating and pronounced tectonic thickening of the miogeocline, prior to any significant foreland shortening [as suggested for the Shuswap complex by Brown (1978) and Simony and others (1980)], (2) a later event [late Eocene(?) to Miocene] that juxtaposed vast tracts of upper-crustal rocks with mid-crustal rocks, and (3) no large-scale surface faulting prior to the deposition of Eocene-Oligocene volcanic and sedimentary rocks, because the base of the Tertiary section consistently rests on unmetamorphosed upper Paleozoic rocks (Armstrong, 1972)—that is, the metamorphic terrane was probably still at considerable depth after all compressional deformation in the foreland

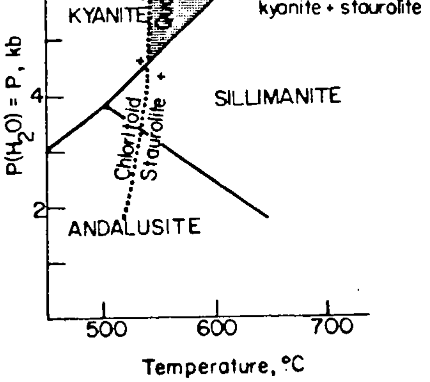

Figure 1. Pressure-temperature stability of staurolite and kyanite, after Turner (1981).

had ceased. A reasonable first-order approximation to hinterland development might be the following.

Phase 1. By Middle Jurassic time, arc-induced heating of the craton sufficiently weakened it to allow compressive yielding (Burchfiel and Davis, 1975) on an east-propagating low-angle fault deep beneath the hinterland, probably within submiogeoclinal basement. Convergence was accommodated in the upper plate by variably directed flexural-slip folding and brittle thrusting such as that in the Confusion Range (Hose, 1977) at shallow levels, *gradually* giving way downward to more ductile modes of shortening at depth, like those in the Wood Hills (Thorman, 1970). During this phase, the basal decollement is "blind"—that is, it does not propagate to the surface—and the mass above it thickens by large-scale pure shear (though lots of simple shear at smaller scales), thus not forming faults with large stratigraphic displacement at the surface (Fig. 2, a and b).

Phase 2: The metamorphic complexes, which were allochthonous from the moment of conception [see Bartley (1981, p. 249–253) for a discussion of data in support of this concept in a collisional setting; compare with Allmendinger and Jordan's (1981) Fig. 3B], ceased deforming at the Jurassic-Cretaceous boundary because the blind decollement broke through to the surface, and thus upper-plate shortening was instead absorbed by thin-skinned foreland thrusting. In this phase, the hinterland is rigid (Fig. 2, c). The concept of initial blind thrusting and penetrative upper-plate thickening followed by an eastward "breakthrough" of thin-skinned thrusting was proposed for the Canadian foreland belt by Thompson (1981), and phases 1 and 2 are an extrapolation of that geometry to the hinterland metamorphic areas. It thus differs from Brown's (1978) model in that penetrative strain occurs only in the upper part of the crust, the lower crust remaining rigid beneath and well to the west of the metamorphic complexes as they form.

Phase 3. East-directed low-angle normal faulting shredded the hinterland during the Tertiary, juxtaposing highly contrasting structural levels on faults with horizontal transport rivaling that of the older thrusts to the east, thinning the hinterland crust by a factor of two (Wernicke, 1981; Fig. 2, d). These low-angle faults are not reactivated thrusts.

The Mesozoic history of the Sevier hinterland thus contrasts with its Canadian counterpart in that phase 2 foreland thrusting was of insufficient magnitude in the former to expose the deep-seated metamorphic terrane (only the Canadian foredeep contains igneous and metamorphic detritus). The Tertiary history of the two differs in that the metamorphic terrane in the south was exhumed by low-angle normal faulting (igneous and metamorphic detritus finally appearing in mid-Tertiary syntectonic basins) while the already-uplifted Canadian complexes remained quiet.

To conclude, where the Manning Canyon decollement currently exists outside the complexes, it is merely a slightly detached bedding-plane fault during phase 1, with possibly as much or more movement during phase 3. Where it exists inside the complexes, it is an enormous low-angle normal fault, having little if anything to do with prior compressional orogenesis. Allmendinger and Jordan's choice to emphasize the Mesozoic history of the Sevier hinterland is certainly justified, but their interpretation of that history neglects the nature and magnitude of later events, contradicts

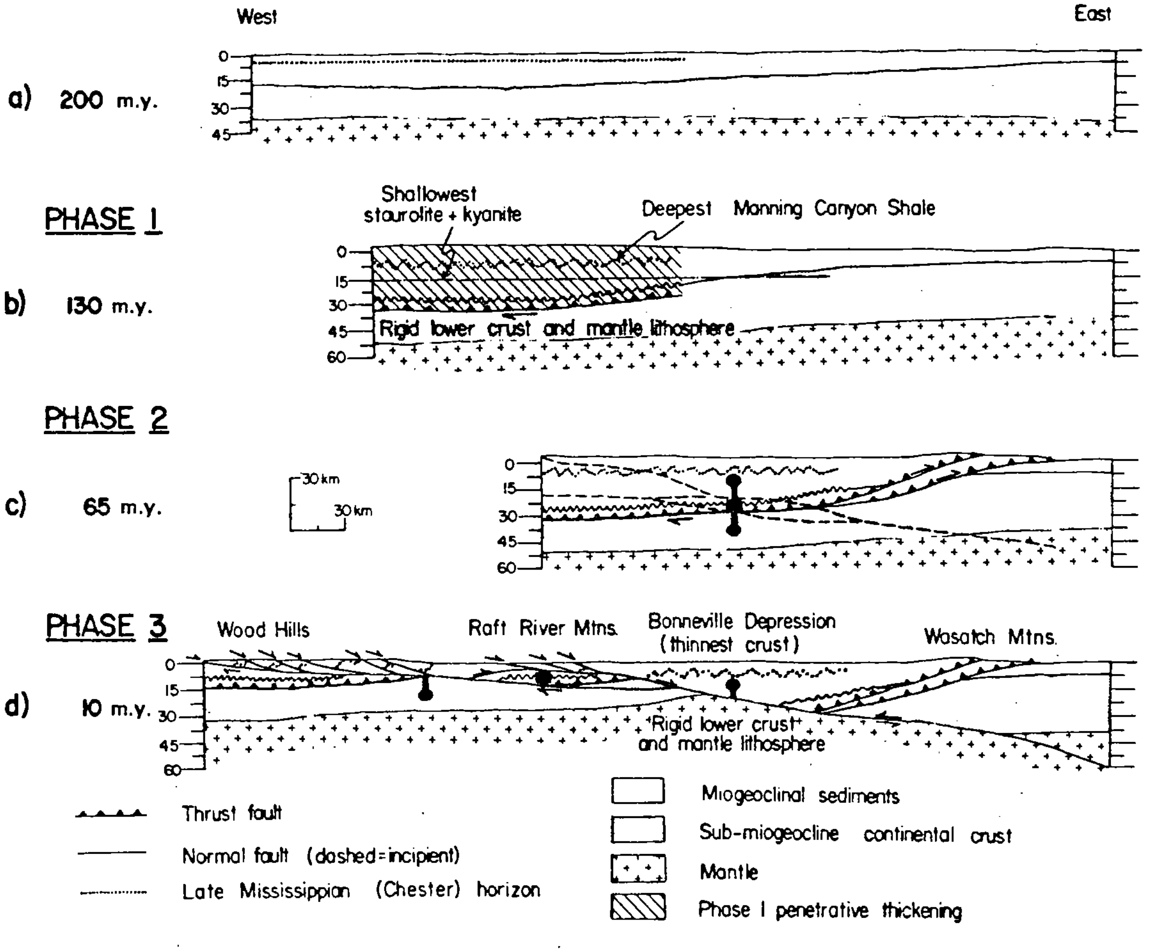

Figure 2. Three-phase development of eastern Great Basin. a: Undisturbed miogeocline. b: At end of phase 1, when penetrative thickening caused depression of miogeoclinal strata. c: At end of phase 2, when considerable shortening and uplift had occurred in foreland, with tectonic stability and only minor erosion in hinterland. d: At end of phase-3 low-angle normal faulting, but prior to formation of basins and ranges, when hinterland crust had been greatly thinned, largely by means of simple shear between rigid blocks. Notice how model requires locus of surficial imbricate normal faulting to be horizontally removed from zone of thinnest crust, accounting for position of Bonneville depression. It also provides explanation for Basin-and-Range-like crust (Smith, 1978) of apparently unextended Wasatch Mountains by removing a wedge of lower crust on same fault zone responsible for upper-crustal thinning.

important petrologic data, and fails to take into account valuable insights gained from studies in the less disrupted and more continuously exposed Canadian terrane.

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REPLY

Teresa E. Jordan, Richard W. Allmendinger, *Department of Geological Sciences, Cornell University, Ithaca, New York 14853*

We had hoped that our paper (Allmendinger and Jordan, 1981) would stimulate discussion of the Mesozoic tectonics of the hinterland region, and Wernicke emphasizes a related point; the problem of differentiating Cenozoic and Mesozoic metamorphism and deformation. However, the partial quotations in Wernicke's Comment misrepresent some of the ideas in our original paper. We did not suggest that the omissions of strata and juxtaposition of facies in the metamorphic complexes are solely the result of thrusting over a thermally doming complex. What Wernicke cites is only one of three alternatives that we presented. Our preferred interpretation was a combination of Cenozoic extensional tectonics *and* the formation of a dome during the Mesozoic. We based this interpretation on the careful work of Compton and Todd (1979), who concluded that the formation of a structural dome accompanied the first (Jurassic?) metamorphism in northwest Utah. Cenozoic extensional tectonics characterized by extensive low-angle faults that omit strata and juxtapose metamorphic facies have been widely documented by numerous researchers in the region (Armstrong, 1972; McDonald, 1976; Compton and others, 1977; Davis and Coney, 1979; papers in Crittenden and others, 1980). We fully recognize, as stated in our paper, the important influence of this Tertiary deformation on the structural geometry of the hinterland region, and we did not state or imply that its effects were limited to localized landsliding. However, because the purpose of the paper was to look beyond the Cenozoic deformation to see what pieces of the Mesozoic puzzle remain, and because of the space limitations of *Geology*, we felt that an in-depth review of the previously well-documented Tertiary deformation was unnecessary.

Our model of deformational sequence and geometry was derived specifically for the northern Utah and southern Idaho segment of the Cordillera. That segment contains the abnormally thick and sharply bounded upper Paleozoic Oquirrh Group and an underlying shale horizon—the Pennsylvanian and Mississippian Manning Canyon and Chainman Formations. It is the character of those two units that may be largely responsible for the observed structural geometries of this part of the hinterland. This unique combination of paleogeographic features does not extend north of the Snake River Plain or south of central Utah (let alone into Canada or southeastern California), nor do we extend our proposed structural geometries into those regions.

The somewhat greater amount of shortening in the Canadian Rockies (105 to 170 km in Canada versus 140 to 150 km in Idaho and Wyoming, based on well-constrained palinspastic reconstructions in each; Price, 1981; Royse and others, 1975) is only one of several significant differences between the two regions that suggest that direct comparisons are overly simplistic. We feel that differences in hinterland structural geometry between British Columbia and Utah, Nevada, and southern Idaho probably reflect variations in the geometry of the pre-Jurassic continental margin of North America, differing histories and geometries of terranes accreted during Mesozoic and Cenozoic time, and differing magmatic character of the two segments of the Cordillera.

The metamorphic assemblages in the metamorphic complexes will certainly provide a serious constraint on both Mesozoic and Tertiary regional tectonics, particularly once we have a better understanding of what can be attributed to Mesozoic versus Tertiary metamorphism. In the Albion Range, R. L. Armstrong (unpub.) has documented a kyanite-staurolite assemblage in rocks of the Raft River and Harrison Summit sequences from an area that yields consistent Cretaceous ages. Compton and others (1977), however, documented kyanite-bearing rocks in the Raft River sequence of the Raft River Range, where metamorphic ages are consistently mid-Tertiary. The regional stratigraphic patterns in northern Utah and southern Idaho suggest that at least 8 km of Ordovician to Triassic strata overlay (during the Mesozoic) rocks bearing the kyanite-staurolite assemblage. Although workers are sharply divided over the possible existence and thickness of strata of late Precambrian to early Paleozoic age between the Raft River Sequence and confirmed Ordovician strata, there is a documented possibility that 3 to 6(?) km of section has been structurally omitted (see, for example, Crittenden, 1979; Miller, 1981; compare with Compton and Todd, 1979; R. L. Armstrong, unpub.). Thus, the range of stratigraphic burial depth of the kyanite-bearing rocks was 8 to 14 km. Clearly, such stratigraphic questions must be resolved before we can understand the full significance of the metamorphic assemblages. Given such uncertainties, it seems premature to base models of depression of the metamorphic complexes region during the Mesozoic solely on the high-pressure metamorphic assemblages, particularly in view of structural evidence suggesting doming (Compton and Todd, 1979).

Thus, our original model of hinterland evolution is entirely consistent with the three points Wernicke cites as fundamental features of hinterland history, although we suggested that the crust thickened west of the metamorphic complexes in the Jurassic, rather than in them as suggested by Wernicke. Since we have inferred that the Manning Canyon decollement ramped to the surface far to the east of the metamorphic complexes, it would have behaved much as a blind, bedding-plane thrust and would have produced no surface faulting in the metamorphic complexes. Cretaceous metamorphism and thrusting have been documented in the Albion Range and Pilot Mountains (Armstrong, 1976, and unpub.; Miller and Hoggatt, 1980), so rather than conclude, as Wernicke does, that "metamorphic complexes . . . ceased deforming at the Jurassic-Cretaceous boundary," we believe that foreland thrusting and hinterland thrusting and metamorphism were contemporaneous during the Cretaceous. Finally, as we originally stated and Wernicke has emphasized, widespread low-angle extensional faulting occurred during the Tertiary. In the case of the Manning Canyon horizon, we believe that this later deformation was localized along an earlier plane of weakness that was a significant bedding-plane thrust during the Mesozoic. Pre-Sevier thrusting could have been localized along the Manning Canyon horizon as well.

In summary, there is a fundamental difference between Wernicke's concepts and ours regarding the Mesozoic evolution of the hinterland region of northern Utah, southern Idaho, and northeastern Nevada. He suggests thickening by large-scale pure shear above a deep-seated decollement beneath the metamorphic complexes during the mid-Jurassic. In contrast, our model suggests that in Mesozoic time, successive basal decollements were created at progressively deeper crustal levels and each new decollement ramped to the surface progressively farther to the east. Thus, in our view, the decollement stepped from the Mississippian in the mid-Jurassic (Manning Canyon decollement) to the Lower Cambrian and upper Proterozoic sequence in earliest Cretaceous time (Paris-Willard thrusts), to within the basement beneath the Farmington complex in the northern Wasatch Mountains and probably beneath the metamorphic complexes in the Late Cretaceous (Absaroka thrust). We feel that our view is consistent with structural and stratigraphic field data and radiometric dating in both the foreland and the hinterland (although data in the latter is admittedly meager). Wernicke has largely ignored local structural field data and timing relations in favor of drawing analogies with distant segments of the Cordillera or even with the collisional Caledonian orogen in Norway. Our approach to understanding foreland and hinterland deformation processes has been to study and contrast the along-strike differences in mountain belts, rather than to try to fit all into a single model.

Note: On page 308 of our paper (Allmendinger and Jordan, 1981), in the second sentence under the topic heading Sevier Orogenic System, point 1 *should* read: "thrusts with west-dipping, listric geometry, *which have been interpreted from seismic data to cut into crystalline basement* of Archean or Proterozoic age at the western edge of the thrust belt. . . ."

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