Extension in the Cretaceous Sevier orogen, North American Cordillera

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ABSTRACT

Recent geologic studies in the western United States Cordillera provide evidence of extensional deformation in Cretaceous time, during development of the Sevier foreland fold and thrust belt. This evidence comes from the region roughly bound on the east by the fold and thrust belt and on the west by the Mesozoic continental arc. We postulate that extension in this "Internal Zone" accommodated gravitational collapse of the evolving Sevier orogen. Major surface-breaking normal faults and extensional basins that characterize other regions of syncompressional gravitational collapse (such as the Himalayan orogen) have not been documented in the Cretaceous record of the Internal Zone. Consequently, if extension was widespread in the Internal Zone, then it had little surface expression. We propose a conceptual model of the Sevier orogen, consistent with geologic constraints and supported by simplistic rheological arguments, in which westward movement of a mid-crustal extensional allochthon was driven by buoyancy stresses in the overthickened Internal Zone. Bound at the top by the master décollement of the Sevier fold and thrust belt and at the bottom by a west-dipping, normal-sense shear zone, this extensional allochthon would have been effectively decoupled from the upper and lower crust and free to accommodate gravitational collapse during continued convergence across the orogen.

INTRODUCTION

Isostatically compensated, tectonically thickened lithosphere in a compressional orogen has a tendency to spread laterally under the influence of gravity (Molnar and Tapponnier, 1978; Dalmayrac and Molnar, 1981; Houseman and others (1981). Whether or not the buoyancy stresses arising from lateral variations in lithospheric thickness are sufficient to produce extensional deformation depends on a number of factors (England and Houseman, 1988). Simply put, the tendency to spread is counterbalanced by the compressional boundary stresses responsible for thickening. The most likely mechanisms that might tilt the balance toward extension are significant increases in the potential energy of the orogen caused by convective removal of the lower part of the thickened lithosphere, or significant reductions in compressional boundary stresses.

The last stage of orogeny in many convergent settings is marked by a transition from compression to extension (Dewey, 1988). For example, a number of workers have suggested that Cenozoic extension in the Basin and Range province of the western United States initiated as a consequence of gravitational collapse of the thickened hinterland of the Mesozoic Sevier orogen (Coney and Harms, 1984; Coney, 1987; Sonder and others, 1987; Wernicke and others, 1987). It is becoming increasingly clear that large-scale extensional structures can also form *during* compression in convergent settings and serve to moderate topographic contrasts during lithospheric thickening (Burchfiel and Royden, 1985). Several lines of evidence suggest that extensional structures were widespread in the Cretaceous "Andean-type" setting of the North American Cordillera. In this paper, we review this evidence, present a working hypothesis regarding the cause and significance of Cretaceous extension, develop a kinematic model of gravitational collapse in the orogen, and suggest ways in which this model may be tested.

THE INTERNAL ZONE OF THE SEVIER OROGEN

Armstrong (1968) defined the Sevier orogeny as the mountain-building event responsible for the development of the North American Cordilleran fold and thrust belt between southern Idaho and southern Nevada. In broad terms, this event spanned the Cretaceous Period (Armstrong, 1968; Heller and others, 1986; Lawton, 1986; Allmendinger, in press). In the southern Idaho–southern Nevada sector, the Sevier orogen consisted of a relatively stable foreland on the east, a central fold and thrust belt, and a hinterland region to the west. Following Armstrong (1972), most workers have placed the western limit of the hinterland at the eastern limit of the Roberts Mountain allochthon, which was emplaced during the Late Devonian–Early Mississippian Antler orogeny (Roberts and others, 1958; Burchfiel and Davis, 1972). The Sevier hinterland is dominated by weakly metamorphosed to unmetamorphosed, Paleozoic to lower Mesozoic strata of the Cordilleran miogeocline overlain by Oligocene and younger volcanic sequences. Precambrian crystalline basement and high-grade metamorphic equivalents of upper Precambrian and Paleozoic strata, intruded by metaluminous to peraluminous granitoid plutons, are exposed sporadically in metamorphic core complexes such as the Ruby Mountains and the Snake Range of east-central Nevada.

Outside of the southern Idaho–southern Nevada sector, the Sevier hinterland is more difficult to define. To the north, both the Roberts Mountain allochthon and the Mesozoic–early Tertiary continental arc (in the form of the Idaho batholith) lie closer to the Sevier thrust belt and partially occupy the same tec-

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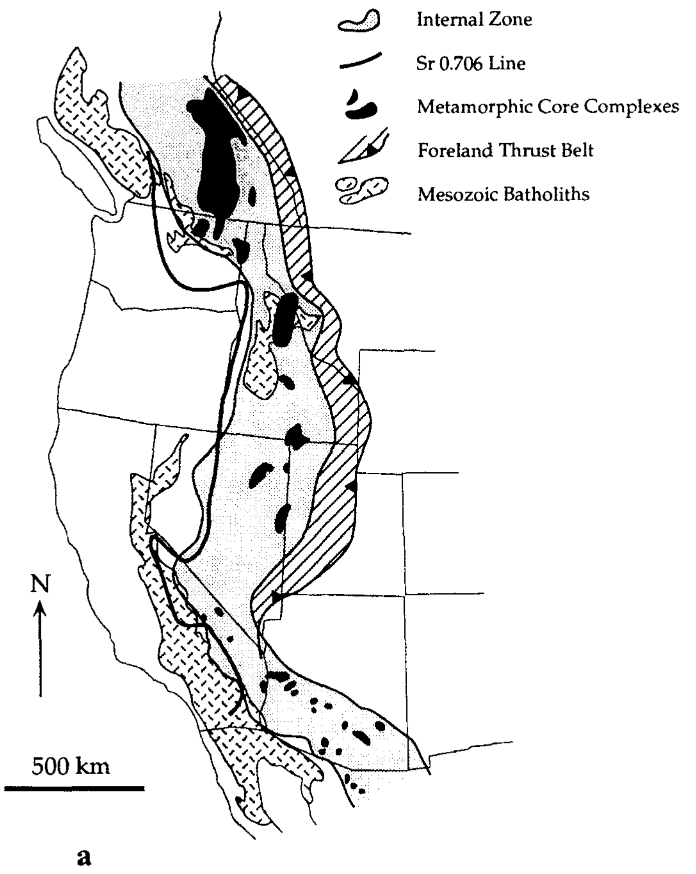

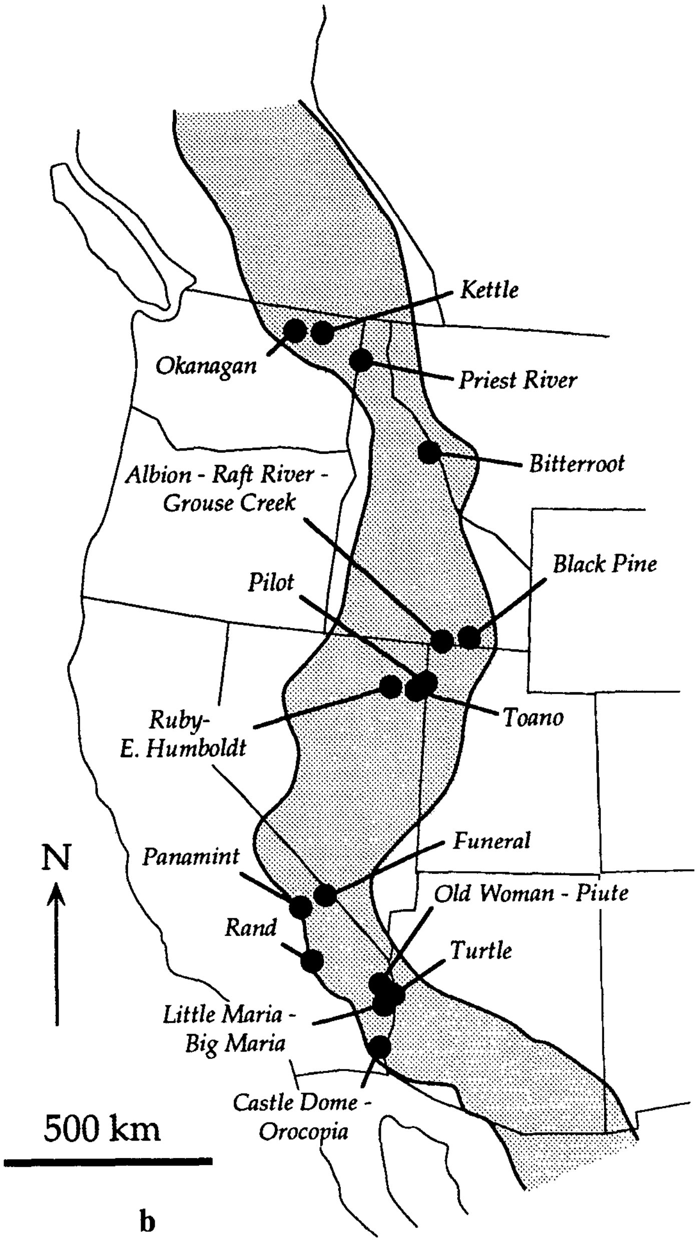

Figure 1. Tectonic setting of the Sevier orogen. a. Distribution of important tectonic features. Shaded area indicates the Internal zone as defined in this paper. b. Locations of areas containing evidence of Cretaceous extension.

tonic position as the hinterland in Nevada. Metamorphic core complexes such as the Pioneer Mountains and the Bitterroot Range of Idaho expose mid-crustal rocks of the Mesozoic–early Tertiary arc in their footwalls (Hyndman, 1980; Dover, 1981; O'Neill and Pavlis, 1988). The Sevier thrust belt mimics the trend of the Mesozoic magmatic arc of western North America where it changes trend, transects the Cordilleran miogeocline, and passes into the craton in southeastern California (Burchfiel and Davis, 1972, 1975). In the Mojave desert region and elsewhere in western Arizona, the deformational style changes dramatically from the typical ramp-flat geometry characteristic of the central sector of the Sevier belt to basement-involved thrusts and recumbent folds more reminiscent of the hinterland (Burchfiel and Davis, 1981; C. F. Miller and others, 1982; Reynolds and others, 1986).

Even though the Sevier hinterland *sensu stricto* is difficult to recognize outside of the southern Idaho–southern Nevada sector, it is possible to define a zone running the length of the southern Canada–western United States Cordillera that encompasses many of the lithotectonic elements characteristic of the hinterland in the eastern Great Basin (Fig. 1a). This "Internal Zone," as we will refer to it, includes all of the Cordilleran metamorphic core complexes (Coney, 1980; Armstrong, 1982) and the belt of Mesozoic-Paleogene peraluminous plutons described by Miller and Bradfish (1980). North of southern Nevada, the Internal Zone trends north-south and is bound on the east by the Sevier thrust belt and on the west by the Mesozoic magmatic arc. The western margin of the zone mimics, but does not precisely correspond to, the westward limit of Precambrian North American basement as inferred from the position of the $^{87}Sr/^{86}Sr_{initial} = 0.706$ contour for Phanerozoic igneous rocks (Fig. 1; Kistler and Peterman, 1973; Armstrong and others, 1977). South of southern Nevada, the Internal Zone changes its trend to northwest-southeast, transecting the Sevier thrust belt as it passes out of the miogeocline. In this region, we define the Internal Zone such that it includes the metamorphic core complexes of southeastern California and Arizona.

Largely due to structural complexities produced by Tertiary extension and the wide distribution of Cenozoic cover sequences, the Internal Zone of the Sevier orogen is poorly understood.

Several of the Cordilleran metamorphic core complexes yield petrologic and geochronologic evidence for *minimum* crustal thicknesses of 25–35 km during Mesozoic time (Hodges, 1988; Snoke and Miller, 1988), and the actual thickness of the Internal Zone probably was closer to 50–60 km (Coney and Harms, 1984; Parrish and others, 1988). Palinspastic reconstructions require that total shortening was substantially greater than 100 km in the Sevier thrust belt (see Allmendinger, in press, for a concise review), but we have few quantitative constraints on the amount of shortening in the Internal Zone. Mesozoic thrust faults with large throw have been documented in some parts of the Internal Zone (for example, the southeastern Canadian Cordillera; Brown and others, 1986), but they are not common. Large fold nappes have been mapped in several of the metamorphic core complexes (Howard, 1966; Thorman, 1970; Snoke and Lush, 1984; Brown and others, 1986), and most of the core complexes display compressional ductile structures (Armstrong, 1982; E. L. Miller and others, 1988; Snoke and Miller, 1988).

There is clear evidence for ductile deformation in some parts of the Internal Zone in the Jurassic Period, and many authors have suggested that most of the Mesozoic deformation in the metamorphic core complexes distinctly predated development of the Sevier thrust belt (for example, Misch, 1960; Armstrong and Hansen, 1966; Armstrong, 1982; Snoke and Miller, 1988). Recently acquired geochronologic data from many of the core complexes, however, confirm the importance of Cretaceous thermal and deformational events at deep levels within the Internal Zone (for example, Brown and others, 1986; Reynolds and others, 1986; Miller and Gans, 1989; Fletcher and Karlstrom, 1990; Hodges and others, 1992). The emerging picture of Sevier orogenesis shows Cretaceous crustal shortening in the upper crust of the foreland, and coeval shortening in the middle and lower crust of the Internal Zone (Read and Brown, 1981; Miller and Gans, 1989).

Except in portions of the southern Canadian Cordillera (Brown and others, 1986), the upper crust in the Internal Zone appears to have been deformed relatively little in late Mesozoic time (Misch, 1960; Armstrong, 1968; Miller and Gans, 1989). In the eastern Great Basin, a blanket of Eocene-Oligocene volcanic and sedimentary rocks unconformably overlies pre-Tertiary units with little angular discordance. Paleogeographic reconstructions of the basal Tertiary unconformity reveal that it was developed mainly on upper Paleozoic strata and that a maximum of 2 or 3 km of structural relief was present in late Mesozoic time prior to Tertiary overlap (Armstrong, 1968; Gans and Miller, 1983).

TABLE 1. EVIDENCE FOR MESOZOIC EXTENSION IN THE INTERNAL ZONE

Area	Summary of evidence	References
Castle Dome–Orocopia region, Arizona-California	High-pressure, oceanic rocks of the Orocopia Schist are exposed in windows through weakly metamorphosed to unmetamorphosed strata in several mountain ranges between the Castle Dome Mtns., Arizona, and the Orocopia Mtns., California. Several window-bounding faults show evidence of major normal displacement in Late Cretaceous to earliest Tertiary time (a, b, c, d, e)	a, Haxel and others, 1985; b, Haxel and others, 1988; c, Jacobson and others, 1988*; d, Richard and Haxel, 1991†; e, Jacobson, 1990*.
Little Maria and Big Maria Mountains, California	Ductile shear zones with low-angle, northeast-directed, normal displacement have been mapped in the Little Maria Mountains (f). Extreme, high-temperature attenuation of strata has been documented in the Big Maria Mountains (g). ^{40}Ar/^{39}Ar and conventional K-Ar cooling ages suggest rapid cooling of the Big Maria and Little Maria metamorphic terrains in Late Cretaceous–early Eocene time (f, h, i)	f, Ballard and Ballard, 1990; g, Hamilton, 1982*; h, Hoisch and others, 1988; i, Ballard, 1990†.
Old Woman and Piute Mountains, California	A large, west-dipping ductile shear zone with normal-sense displacement (western Old Woman Mountains shear zone) dominates the western Old Woman Mountains (j). The shear zone post-dated 73 Ma intrusive rocks, and rapid cooling of the Old Woman–Piute terrain over the 73 Ma to 65 Ma interval implies Late Cretaceous tectonic denudation (j, k, l).	j, Carl and others, 1991*†; k, Foster and others, 1989; l, Foster, 1989.
Turtle Mountains, California	In the west-central Turtle Mountains, an east-dipping mylonitic shear zone (the West Turtle shear zone) shows evidence of amphibolite-facies thrust displacement and greenschist-facies reactivation as a normal fault (m). ^{40}Ar/^{39}Ar thermochronologic data indicate that the central and southern parts of the range had cooled below ~500 K by 90 Ma (n, o). This cooling has been attributed to Early Cretaceous extension (m).	m, Allen and O'Hara, 1991†; n, Allen and others, 1990; o, Foster and others, 1990.
Rand Mountains, California	A southwest-dipping, normal-sense shear zone in the southwestern Rand Mountains juxtaposes hanging-wall, middle-crustal units with footwall, lower-crustal units (p). The shear zone cuts a monzogranite dated at 87 ± 1 Ma using U-Pb zircon (q). Rapid cooling of the footwall over the 75 Ma–70 Ma interval (inferred from^{40}Ar/^{39}Ar data) implies a Late Cretaceous age for the shear zone (r).	p, Postlewaite and Jacobson, 1987*; q, Silver and Nourse, 1986; r, Jacobson, 1990†.
Panamint Mountains metamorphic core complex, California	The Harrisburg fault is the oldest of a composite system of normal faults that frame the Panamint metamorphic core complex(s). Hanging wall to the north-northwest displacement on the detachment at upper-greenschist facies conditions is commonly assumed to have occurred in Tertiary time, but older movement is possible (t). The age of the Harrisburg detachment is bracketed between 101 Ma and 11 Ma by Rb-Sr and ^{40}Ar/^{39}Ar geochronologic data (s, u). Cooling of the Panamint core complex through greenschist-facies temperatures occurred in Late Cretaceous to Eocene time (v).	s, Hodges and others, 1990*; t, Hodges and others, 1987*; u, from L. W. McKenna, unpub. data; v, Labotka and others, 1985.
Funeral Mountains metamorphic core complex, California-Nevada	Low-angle, high-temperature shear zones omit section in the metamorphic core of the Funeral Mountains (w, x). Thermobarometric data and Gibbs' Method modeling of zoned garnets in pelitic rocks indicate nearly isothermal decompression of the core during the late stages of amphibolite-facies metamorphism (y). U-Pb zircon and monazite data for intrusive rocks bracket the age of extensional shear zones in the core between 74 Ma and 70 Ma (x). ^{40}Ar/^{39}Ar cooling ages of metamorphic rocks indicate unroofing of the core in Late Cretaceous–Paleocene time (y, z).	w, Troxel and Wright, 1989*; x, Applegate and others, 1991†; y, Hodges and Walker, 1990†; z, DeWitt and others, 1988.
Ruby Mountains–East Humboldt Range metamorphic core complex, Nevada	Rim thermobarometry and Gibbs' Method modeling of zoned garnets in pelitic rocks from the northeastern East Humboldt Range imply as much as 20 km of tectonic denudation during the late stages of amphibolite-facies metamorphism (aa). ^{40}Ar/^{39}Ar data from the East Humboldt Range (bb) suggest that amphibolite-facies decompression of the metamorphic core occurred in latest Jurassic(?) to middle Cretaceous time (aa).	aa, Hodges and others, 1992*†; bb, Dallmeyer and others, 1986.
Pilot Range, Nevada-Utah	The Pilot Range décollement is a normal fault that places weakly metamorphosed Upper Cambrian–Upper Permian miogeoclinal strata on greenschist- to amphibolite-facies, upper Proterozoic–Ordovician rocks (cc, dd). The décollement is cut by granitic dikes that are probably related to a granodiorite pluton dated at 39 Ma (U-Pb zircon, ee), but the maximum age of the structure is constrained only to be younger than Jurassic. Late Cretaceous–early Paleocene K-Ar muscovite and biotite ages from the footwall may date tectonic denudation by movement on the décollement (dd).	cc, Miller and Lush, 1981*; dd, Snoke and Miller, 1988†; ee, D. M. Miller and others, 1987*.

EVIDENCE FOR MESOZOIC EXTENSION

Recent structural, geochronologic, and petrologic studies in the Internal Zone have produced evidence of Mesozoic extensional deformation in 16 localities (Fig. 1b). Before briefly reviewing these studies, we want to explain our criteria for "evidence."

Most of us can agree that the simplest interpretation of a fault that places younger rocks on older rocks, omitting stratigraphy, is that it is a normal fault. There are, of course, many ways to produce younger-over-older relationships that do not involve normal faulting, but someone wanting to argue for one of these alternatives would find himself saddled with the burden of proof. In interpreting geologic data from the Internal Zone, we have taken the approach that Mesozoic phenomena characteristic of better-

TABLE 1. (*Continued*)

Area	Summary of evidence	References
Toano Range, Nevada	A low-angle detachment separating the unmetamorphosed suprastructure and metamorphic infrastructure of the Toano Range may be part of the Pilot Range décollement (ff). Footwall K-Ar and $^{40}Ar/^{39}Ar$ cooling ages are Late Cretaceous to Paleocene and may be related to an episode of tectonic denudation (gg, hh, ii).	ff, Snoke and Miller, 1988; gg, Lee and others, 1980; hh, Lee and Marvin, 1981; ii, D. M. Miller and others, 1990*†.
Black Pine Mountains, Idaho	An early episode of east-west, bedding-parallel extension accompanied very low-grade (anchizonal) retrograde metamorphism in the Black Pine Mtns. (jj). Whole-rock K-Ar (kk) and $^{40}Ar/^{39}Ar$ (ll) data for slates strongly affected by the retrograde event imply that the early extensional event occurred in late Early Cretaceous to Late Cretaceous time.	jj, Wells and Allmendinger, 1990*†; kk, Smith, 1982*; ll, Wells and others, 1990*†.
Albion–Raft River–Grouse Creek metamorphic core complex, Idaho-Utah	Two distinctive facies of amphibolite-grade metamorphosed strata of late Proterozoic age are juxtaposed across the Basin–Elba fault zone in the Albion Mtns. (kk, ll). The zone includes structural slices of greenschist facies, fossiliferous Carboniferous and unfossiliferous, probable Ordovician strata. This unusual relationship is most easily explained by a scenario in which the Basin–Elba fault zone is a normal-sense shear zone that transects a pre-existing thrust fault. Basin-Elba faulting was accompanied by the widespread development of northwest-trending mineral and stretching lineations in the northern Albion Mountains, by retrograde metamorphism of the hanging wall and footwall near the fault zone, and by prograde, greenschist-facies metamorphism in the zone itself. Ductile extensional structures that are probably of about the same age have also been described in the eastern Raft River Mountains (mm). Retrogressed amphibolite-facies samples collected near the Basin-Elba fault and greenschist-facies rocks from outside the fault zone provide K-Ar and $^{40}Ar/^{39}Ar$ hornblende, muscovite, and biotite ages ranging from 90–68 Ma (nn, oo, pp). These data imply strongly that the Basin-Elba fault developed in Late Cretaceous time. $^{40}Ar/^{39}Ar$ muscovite plateau ages ranging from 82 to 90 Ma suggest a Late Cretaceous age for early extensional structures in the eastern Raft River Mountains (mm).	kk, D. M. Miller and others, 1983*; ll, Hodges and McKenna, 1986; mm, Wells and others, 1990*†; nn, Armstrong and Hills, 1967; oo, Armstrong, 1976; pp, K. V. Hodges and others, unpub. data.
Bitterroot Mountains, Montana-Idaho	Existing geochronologic data indicate that at least some unroofing of the amphibolite-facies core of the Bitterroot Mountains occurred in middle Eocene time (qq, rr). Undeformed, shallow-level plutonic rocks of probable Eocene age, however, intrude the southeastern part of the metamorphic core and studies of metapelitic assemblages in the core have found persistent evidence of decompression during Cretaceous metamorphism (ss, tt, uu).	qq, Chase and others, 1983; rr, Garmezy and Sutter, 1983; ss, Hyndman and others, 1988*†; tt, Hyndman and Alt, 1972; uu, Cheney, 1975.
Priest River metamorphic core complex, Idaho-Washington	A 4-km-thick mylonite zone with top-to-the-east sense of shear dominates the southern part of the Priest River complex and defines the Spokane dome (vv). Although this structure is commonly interpreted as a compressional feature (vv), an extensional origin is equally consistent with geologic constraints (ww). Based on crosscutting relationships between dated intrusive rocks and mylonitic fabrics, mylonitization occurred in Late Cretaceous–early Eocene(?) time (xx, yy).	vv, Rhodes and Hyndman, 1984*; ww, Parrish and others 1988*; xx, Bickford and others, 1985; yy, Rhodes, 1986.
Kettle metamorphic core complex, Washington–British Columbia	An east-dipping, sillimanite-grade mylonite zone is exposed beneath the Kettle River fault, the detachment on the eastern side of the Kettle dome (zz). Kinematic indicators suggest eastward vergence, consistent with normal-sense movement (aaa). The age of the mylonite zone is unknown. Both Mesozoic–early Tertiary contractional and Eocene extensional episodes of movement have been suggested (aaa, bbb). Based on similarities between the Kettle mylonite zone and other east-dipping shear zones on the eastern sides of the Priest River and Okanogan core complexes nearby, we propose that the Kettle mylonites may have been produced during Late Cretaceous extension.	zz, Rhodes and Cheney, 1981; aaa, Rhodes and Hyndman, 1988*; bbb, Parrish and others, 1988*.
Okanogan complex, Washington–British Columbia	An east-dipping mylonitic fabric is developed locally in the core of the Okanogan complex, and an east-dipping, east-directed mylonitic shear zone on the east side of the complex separates the metamorphic infrastructure and allochthonous metasedimentary rocks of pre–Late Triassic age (ccc, ddd, eee). U-Pb geochronologic data for plutonic rocks indicate development of the east-directed mylonites between 85 Ma and 55 Ma (fff).	ccc, Orr, 1985; ddd, Hansen and Goodge, 1988*; eee, Ross, 1981*; fff, Potter and others, 1991.

*Reference contains maps and/or cross sections that may be useful in evaluating evidence for extension.

understood extensional settings (like the Tertiary Basin and Range province) have an extensional origin unless proven otherwise. Thus, if a demonstrably Cretaceous fault or shear zone attenuates or omits stratigraphic section, then we take this as evidence of Cretaceous extension.

Petrologic and geochemical data also may provide indications of crustal thinning. If a fault places low-grade rocks on high-grade rocks, then it can be reasonably interpreted as a normal fault. Moreover, metamorphic pressure-temperature paths characterized by nearly isothermal decompression and time-temperature paths indicative of rapid cooling provide strong evidence of tectonic denudation during extension (England and Jackson, 1987; Ruppel and others, 1988; Hodges and others, 1989).

We hasten to add that we do not consider "evidence" to be synonymous with "proof." Further exmaination of some of the phenomena discussed in this paper may show that they are not related to extension. Our purpose here is not to convince the reader that Mesozoic extension occurred in all of the areas indicated in Figure 1b. Instead we try to demonstrate that the evidence for Cretaceous crustal thinning in the Internal Zone is so widespread that we must consider seriously the implications that Sevier-age extension would have for tectonic models of the North American Cordillera.

Table 1 is a brief review of the evidence for Mesozoic extension in the Internal Zone. Space limitations preclude exhaustive analysis of the data on which this table is based, but a more thorough discussion has been filed in the GSA Data Repository.[1] In addition, asterisks beside specific references in Table 1 indicate sources that contain maps and cross sections that may be useful in evaluating the evidence for Mesozoic extension. Previous workers have proposed significant Mesozoic extension in 12 of the 16 areas discussed, and the pertinent references containing these proposals are marked with a dagger symbol in Table 1.

WORKING HYPOTHESIS: EXTENSION IN THE INTERNAL ZONE

Table 1 demonstrates that the evidence for Cretaceous to early Tertiary extensional deformation in the Internal Zone is compelling in some areas (for example, the Funeral Mountains), and merely suggestive in others (for example, the Okanagan complex). However, we believe that existing data justify the working hypothesis that Internal Zone extension, coeval with shortening in the foreland, was a fundamental aspect of Sevier orogenesis.

We are not the first to recognize the possible importance of Mesozoic extension in the North American Cordillera. Allmendinger and others (1984), for example, reviewed evidence for Cretaceous and Jurassic extension in the eastern Great Basin of the United States and suggested that it may have been related to stretching over the roofs of Mesozoic plutons or gravity spreading. Subsequent papers, many of them referenced in Table 1, have addressed the possibility of localized extension in the convergent Sevier setting, and several causative mechanisms have been proposed. Although stretching associated with plutonic activity may have been important on a local scale, many areas where extension occurred experienced relatively insignificant Cretaceous plutonic activity. It is tempting to revive the classic model of Price and Mountjoy

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[1] This additional information may be secured free of charge by requesting Supplementary Data 9213 from the GSA Documents Secretary.

(1970) in which gravitational spreading of a diapirically rising hinterland drove shortening in the Cordilleran fold and thrust belt, but this scenario is refuted by geologic evidence that shortening in both the foreland and the Internal Zone began well before Late Cretaceous extension (Allmendinger, 1992), and by seismic and geologic evidence that the basal décollement of the foreland fold and thrust belt projects beneath much of the Internal Zone (for example, Armstrong, 1982; Brown and others, 1986; Potter and others, 1986; Allmendinger and others, 1987). Such inconsistencies have prompted several workers (for example, Allmendinger and others, 1984; Wells and Allmendinger, 1990; Allmendinger, in press) to focus on models in which gravitational instabilities produced by crustal thickening lead to extension at upper-crustal levels in the Internal Zone at the same time as contraction at lower-crustal levels. Because the structures produced in such a scenario have been documented extensively in the Himalayas (Burg and others, 1984; Burchfiel and Royden, 1985; Herren, 1987; Hodges and others, 1989; Valdiya, 1989; Burchfiel and others, in press), it is perhaps important to explore further the applicability of a "Himalayan model" to the Sevier orogen.

LIMITATIONS OF A HIMALAYAN MODEL

The metamorphic core of the Himalayan orogen includes metamorphic rocks of predominantly Proterozoic-Cambrian age that have been intruded by Oligo-Miocene leucocratic granites (LeFort, 1975). The structural base of this package is marked by the Main Central Thrust, a north-dipping shear zone that accommodated a minimum of 100 km of southward thrusting in mid-Tertiary time (Pêcher, 1978; Brunel and Kienast, 1986; Hubbard, 1988; Macfarlane, 1990). The contact between the metamorphic core of the orogen and its relatively unmetamorphosed suprastructure is a set of north-dipping normal faults and shear zones collectively referred to as the South Tibetan detachment system (Burchfiel and others, in press). Burchfiel and Royden (1985) suggested that the South Tibetan system moved synchronously with the Main Central Thrust in order to accommodate gravitational collapse of the Himalayan topographic front.

The kinematic model proposed by Burchfiel and Royden (1985) is shown in Figure 2. In Miocene time, the metamorphic core of the Himalayan orogen is thought to have extruded southward relative to higher and lower structural levels toward the foreland of the orogen. As this material proceeded, it was quickly eroded by virtue of high relief at the topographic front; indeed, studies of core samples from the Bengal Fan reveal that material from the metamorphic core was transported rapidly to areas far removed from the front (Copeland and Harrison, 1990). Movement of faults of the South Tibetan detachment system produced significant *local* relief north of the topographic front where these structures breached the Earth's surface, and relatively large extensional basins related to the South Tibetan system have been documented in southern Tibet (Burchfiel and others, in press).

Late Cretaceous geologic characteristics of the Sevier orogen are consistent with some aspects of this model but not with others. The magnitude of sediment accumulation in the Cretaceous foreland basin is consistent with a large topographic gradient at the position of the Cordilleran fold and thrust belt (Jordan, 1981), and thermobarometric data from several metamorphic core complexes constitute evidence for Internal Zone crustal thicknesses well in excess of 35 km (for example, Hodges, 1988; Hodges and Walker, 1990; Hodges and others, 1992). There is, however, little indication that large extensional structures breached the surface in the Internal Zone. Known or inferred Cretaceous extensional structures discussed in Table 1 have associated fabrics indicative of movement at intermediate to deep crustal levels. To our knowledge, there is no documented example of a Cretaceous normal fault in the Internal Zone that cuts rocks exposed at the surface in Sevier time.

Crustal thinning characteristically produces local relief and numerous extensional basins, and it is in this regard that the Sevier orogen deviates most markedly from the Himalayan model. The low-angle, regional unconformity that developed beneath mid-Cenozoic strata in the eastern Great Basin is compelling evidence that large topographic gradients were not present in many parts of the Internal Zone in Cretaceous time (Armstrong, 1968). Upper Cretaceous strata are uncommon in any part of the Internal Zone. Scattered Late Cretaceous basins in some areas have been interpreted as extensional (Vandervoort and Schmitt, 1990), but these seem incapable of accommodating more than a small volume of detritus.

This observation leads to a striking paradox: although thermobarometric data from metamorphic core complexes suggest that as much as 20 km of overburden may have been stripped from rocks at deep crustal levels during Cretaceous extension (for example, Hodges and Walker, 1990), the geologic record reveals no suitable repository for this material. Such material imbalances constitute the most persuasive arguments against a kinematic model in which gravitational collapse of the Sevier orogen was accommodated by widespread extension of the upper crust in the Internal Zone at the same time as contraction in the lower crust. For the collapse hypothesis for the Sevier orogen to survive, it must evolve beyond the simple Himalayan model illustrated in Figure 2.

AN ALTERNATIVE KINEMATIC MODEL

If gravitational collapse was not accomplished through surface-breaking extensional faults, then what alternative mechanisms are possible? Clearly, the structural mode of gravitational collapse of an orogen will be dictated by the rheology of the thickened lithosphere. Imbrication of rocks of different composition during orogenesis undoubtedly will lead to a

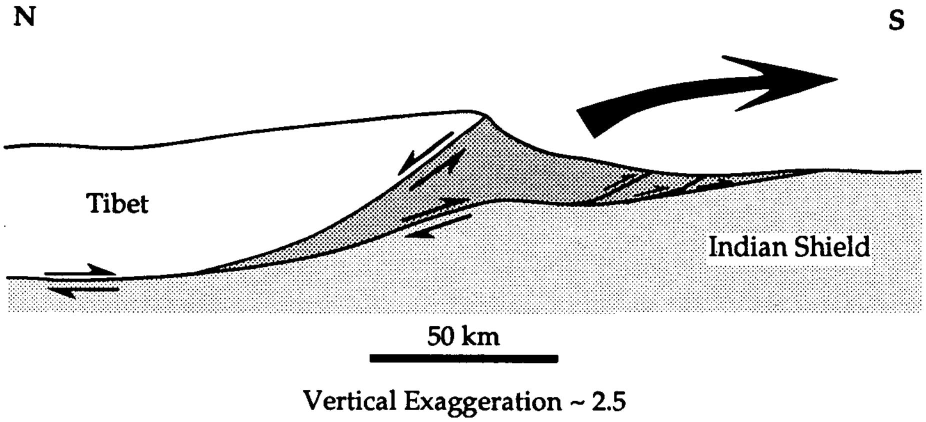

Figure 2. The Himalayan model for gravitational collapse, adapted from Burchfiel and Royden (1985). The more darkly shaded region denotes the allochthon produced by southward expulsion of the metamorphic core of the orogen relative to rocks above and below.

complex rheological stratification of the crust (Ranalli and Murphy, 1987). Weaker zones are likely to act as decoupling horizons in an evolving mountain belt (Dahlstrom, 1970; White and Bretan, 1985). Before asking where such interfaces might have been in the Internal Zone, we must construct a rheological model of the Sevier orogen.

TABLE 2. RHEOLOGICAL PARAMETERS

Material	logA ($MPa^{-n}s^{-1}$)	n	E ($kJmol^{-1}$)	Reference
Marble	33.2	4.2	427	Schmid and others (1980)
"Wet" quartzite	9.1	1.8	167	Hansen and Carter (1982)
"Wet" granite	7.7	1.9	137	Hansen and Carter (1982)
Clinopyroxenite	17.0	2.6	335	Shelton and Tullis (1981)

Note: table after Kirby and Kronenberg, 1987.

Rheological Implications of Basement-Involved Shortening

The existence of structures such as the Monashee décollement in British Columbia (Brown and others, 1986), as well as subsurface information derived from seismic reflection profiles (Allmendinger and others, 1987), constitutes strong evidence that thickening in the Internal Zone was accomplished through basement-involved shortening rather than the upper-crustal imbrication characteristic of foreland fold and thrust belts (Snoke and Miller, 1988; Allmendinger, 1992). Although some material may have been added to the crust in the form of a mantle-derived magmatic component, and despite the certainty of complex shortening geometries, we will base our lithologic model on the simplistic assumption that the Internal Zone can be viewed as a two-tiered stack in which each tier corresponds to a pre-Sevier crustal section (Fig. 3).

The lower tier in this model is meant to represent an intermediate position within the Paleozoic-Mesozoic Cordilleran miogeocline and is essentially the same as that proposed by Patiño Douce and others (1990). The structurally higher section contains no carbonate rocks, is thinner than the lower section, and has a generally more "mafic" composition. This aspect of the model reflects the probability that hanging-wall rocks were thrust eastward from an original position characterized by more distal miogeoclinal units transitional into the eugeocline (Burchfiel and Davis, 1975; Oldow and others, 1989).

For the model, we assume that the thermal structure of the Internal Zone can be described by the steady-state geotherm shown on the left-hand side of Figure 3. This thermal gradient is generally consistent with heat-flow measurements in active tectonic regions (Chapman, 1986) and with thermobarometric data for Cretaceous metamorphic assemblages from the Internal Zone (for example, Hodges and Walker, 1990). We are, of course, aware of the complex thermal structures that naturally arise from tectonic activity (England and Thompson, 1984), but the effect of arbitrarily invoking a significant temperature inversion below the thrust shown in Figure 3 would be to amplify the important rheological characteristics discussed below.

It is commonly assumed that the strength of the lithosphere is governed by frictional sliding of rocks at low temperatures and by steady-state, power-law creep at higher temperatures (Goetze and Evans, 1979). Frictional behavior is taken to be essentially independent of rock type (Byerlee, 1978), but plastic deformation depends on material, temperature, and strain rate as related by the equation:

$$\dot{\epsilon} = A\sigma^n \exp(-Q/RT)$$

where $\dot{\epsilon}$ is strain rate (s^{-1}) (s is the stress difference [MPa]), R is the gas constant ($kJK^{-1}mol^{-1}$), T is temperature (K), and A, n, and Q are material-specific parameters that can be experimentally derived (Kirby and Kronenberg, 1987). Because such experimental data are available for relatively few polymineralic rocks, we have constructed our rheological model based on the assumption that the mechanical properties of the units in our lithologic model can be approximated by the data obtained for rocks such as marble, quartzite, granite, and clinopyroxenite (Table 2). The right-hand side of Figure 3 shows the maximum permissible shear stresses in our lithospheric model as a function of depth, given the assumed temperature structure and a nominal strain rate of $5 \times 10^{-16}s^{-1}$.

Despite the dangers inherent in the construction of simplistic strength versus depth profiles

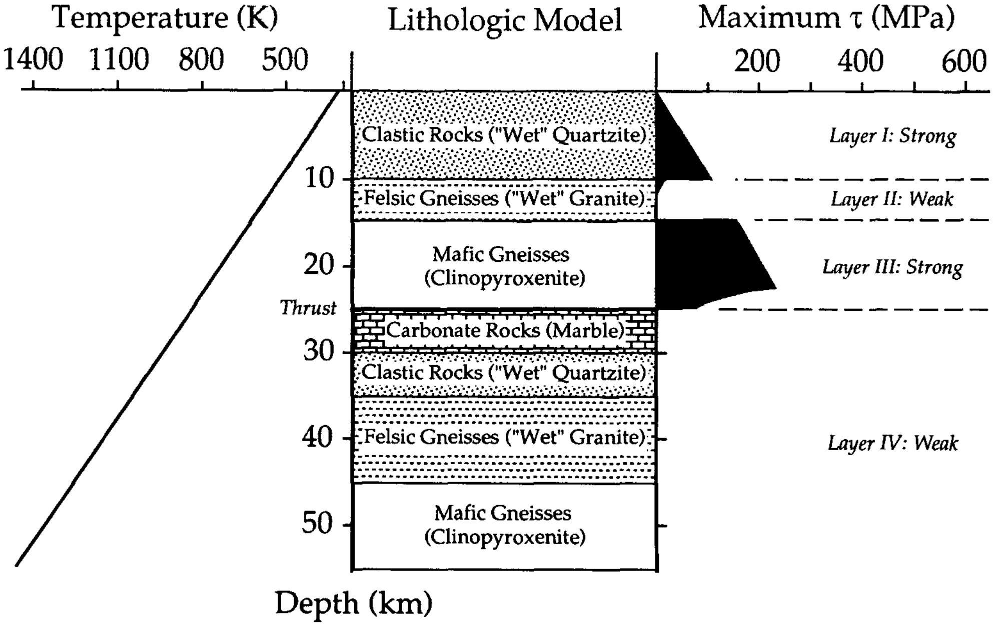

Figure 3. Simplistic geothermal, lithologic, and strength models for the Internal Zone. Filled regions on the plot of maximum shear stress (τ) versus depth indicate accessible levels of shear stress before failure or yield. See text for further explanation.

(Rutter and Brodie, 1991), Figure 3 illustrates an important rheological consequence of "thick-skinned" thrusting in an orogenic hinterland: mafic rocks of the lower crust that are thrust over felsic rocks of the middle and upper crust form high-strength zones at intermediate depths within the orogen (Ranalli and Murphy, 1987). Our rheological model is characterized by a strong, dense, middle crust (Layer III) sandwiched between weaker, upper-crustal rocks of the thrust hanging wall (Layer II) and similarly weak rocks of the thrust footwall (Layer IV). Note that the apparent weakness of the upper portion of the thrust footwall is an artifact of the assumed geothermal gradient; a temperature inversion beneath the thrust would expand the thickness of Layer III at the expense of Layer IV.

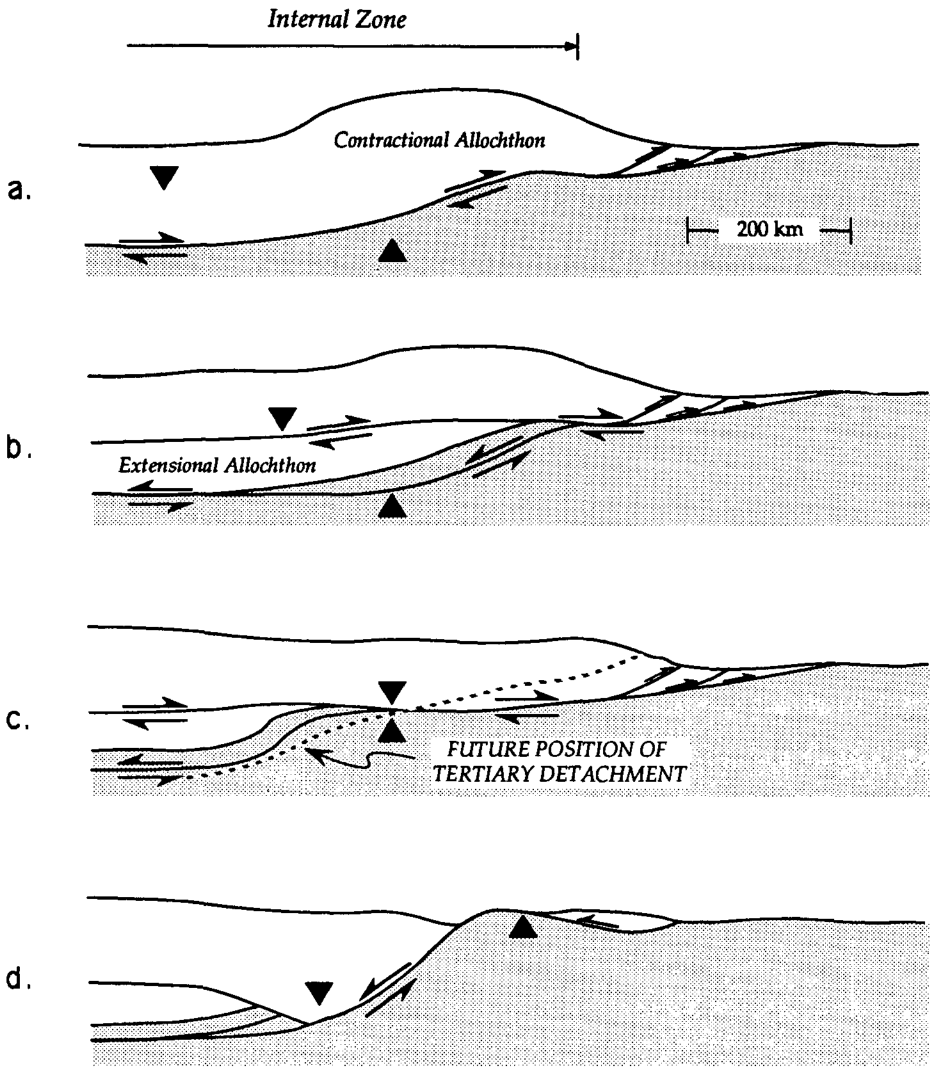

Figure 4. Kinematic model for gravitational collapse of the Internal zone and denudation of lower-crustal rocks, not drawn to scale. The shaded area designates the North American craton. Filled triangles are markers illustrating changes in relative crustal position of two crustal horizons. Arrows indicate relative movement on active faults. Faults that are not active do not have movement indicators. a. Generation of thickened crust and topographic gradients in Jurassic-Cretaceous time. b. Initiation of mid-crustal extensional allochthon in Cretaceous time. c. Cretaceous movement of extensional allochthon causes unroofing of parts of the lower crust. d. Tertiary extension leads to the final exhumation of lower-crustal rocks.

A Mid-Crustal Extensional Allochthon

The possibility of extensive high-strength regions in the middle crust suggests the alternative kinematic model for gravitational collapse of the Sevier orogen illustrated in Figure 4. In frame a of this drawing, imbricate thrust faults of the foreland root into a single, basement-involved "master thrust" beneath the Internal Zone. When buoyancy stresses become sufficiently large to trigger gravitational collapse, new décollement surfaces form at weaker horizons above and below the high-strength layer of the middle crust (frame b). We have arbitrarily shown the lower décollement as excising a portion of the footwall of the master thrust. Another possible geometry could involve a reversal of vergence on the master detachment in the Internal Zone rather than the development of a new lower décollement. In either case, the wedge between décollement surfaces forms a "blind" extensional allochthon that moves westward relative to the upper and lower crust (frame c). The allochthon is bound at the top by a foreland-vergent thrust fault and at the base by a hinterland-vergent normal shear zone. In effect, the upper décollement becomes the master thrust for the foreland thrust belt after the extensional allochthon develops. This geometry permits net convergence across the orogen in frames a, b, and c; mid-crustal extension is contemporaneous with upper-crustal shortening.

One important aspect of this model is that it provides a means of denuding lower-crustal rocks without requiring surface-breaking normal faults. This is illustrated by opposing filled triangles in Figure 4 that track vertical movements in the Internal Zone. Between frames b and c, the entire thickness of the extensional allochthon is stripped from the crustal column above the horizon represented by the upright triangle. It is easy to envision an extensional allochthon as much as 20 km thick. Given that the extensional allochthon may have consisted predominantly of high-density lower-crustal material, this thickness is sufficient to produce the Cretaceous decompressional P-T paths inferred for the Funeral and the Ruby–East Humboldt metamorphic core complexes (Hodges and Walker, 1990; Hodges and others, 1992). Tertiary extension accommodates the final transport of lower-crustal rocks to the surface in frame d of Figure 4.

The most obvious questions that arise from Figure 4 are (1) how far did the extensional allochthon move westward, and (2) where did it go? The absolute amount of westward movement is clearly dependent on the gravitational potential energy stored in the overthickened Internal Zone. Although we suspect that the total lateral displacement may not have been large, a more satisfying answer must await a more sophisticated dynamic analysis of the problem. If the wedge moved a significant distance westward, it would have rapidly encountered the Mesozoic continental arc. We speculate that a dense wedge of middle crust might have been subducted into the roots of the warm, less-dense continental arc ("A-type" subduction in the terminology of Bally, 1975).

TESTING THE HYPOTHESIS AND THE MODEL

In this paper, we have presented a working hypothesis (that gravitational collapse of the Sevier orogen resulted in widespread Cretaceous extension in the Internal Zone) and a kinematic model (involving the development of a blind extensional allochthon in the middle crust). How might these be tested? Because the model is a derivative of the hypothesis, it seems prudent first to confirm the hypothesis.

Relatively few major normal faults within the Internal Zone have been reliably dated. Without age constraints, it is common practice to assume that any normal fault in the Basin and Range province is a Tertiary structure, just as it was common (but unwise) practice 10 years ago to assume that any low-angle fault in this region was a thrust fault. In reviewing the evidence for Cretaceous extension (Table 1), we suggested that many undated mylonite zones in the Internal Zone moved in Cretaceous time with a normal displacement sense. These suggestions could be evaluated through detailed geochronologic studies aimed at dating critical deformational fabrics.

Even if many of the mylonitic shear zones in the Internal Zone prove to be of Cretaceous age, there is no reason to believe *a priori* that they were extensional. The modern paradigm seems to be that any Mesozoic shear zone in the Internal Zone that had eastward vergence was a contractional structure, but this is clearly a dangerous oversimplification. Where possible, geologists working on the Internal Zone must use more objective criteria for the assignment of contractional or extensional origins to shear zones, such as (1) relative ages of hanging-wall and footwall units, (2) relative metamorphic grades of the hanging wall and footwall, and (3) the direction of ramping in the hanging wall and footwall relative to the movement direction of the shear zone.

Metamorphic petrology provides another avenue for testing the hypothesis. Studies of Mesozoic metamorphism in the Funeral and Ruby–East Humboldt metamorphic core complexes reveal strongly decompressional P-T paths consistent with tectonic denudation (for example, Ruppel and others, 1988). Our hypothesis implies that such trajectories were characteristic of deep crustal levels within the Internal Zone and could be recovered by detailed metamorphic studies in other metamorphic core complexes.

Our kinematic model was developed in order to suggest one way in which gravitational collapse of the Sevier hinterland could occur without generating significant surface relief within the Internal Zone. It is almost certainly incorrect in detail. For example, the model shown in Figure 3 does not account for east-vergent extensional shear zones such as those in the Little Maria Mountains of California (Ballard and Ballard, 1990). The broader aspects of the model, however, merit testing; if correct, they would have important geodynamic implications for the Late Cretaceous tectonic evolution of the western part of the Internal Zone and eastern part of the continental arc. For example, westward movement of the extensional allochthon could produce local uplifts in this region. One candidate is the Toyabe uplift zone of Speed and others (1988), a north-south belt of moderately metamorphosed rocks of North American cratonal shelf affinity that approximately mimics the position of the $^{87}Sr/^{86}Sr_{initial} = 0.706$ contour for Phanerozoic igneous rocks in central Nevada. Although Speed and others (1988) attribute the Toyabe uplift zone to thermal doming associated with Jurassic plutonism, the evidence used to argue for pre–Late Cretaceous uplift seems largely circumstantial and should be critically evaluated.

IMPLICATIONS OF THE HYPOTHESIS

Verification of widespread Cretaceous extension in the Internal Zone would force significant changes in our perception of the thermal and tectonic evolution of the North American Cordillera. We would be compelled to re-evaluate current estimates of the amount and rate of Tertiary extension in the Basin and Range that are based on the presumption that all major normal faults in the province are of Tertiary age. For example, Neogene extension estimates for the southern Basin and Range province at the latitude of Las Vegas, Nevada, have been based largely on palinspastic reconstructions of the middle to early Mesozoic thrust belt (Wernicke and others, 1988a, 1988b) or facies and isopach trends in the miogeocline (Stewart, 1983). This region includes areas of known and potential Late Cretaceous extension (the Funeral and Panamint metamorphic core complexes), such that reconstructions made using pre–Late Cretaceous structural and stratigraphic features may reveal the combined effects of Mesozoic and Tertiary extension rather than Neogene extension alone.

Cretaceous extension also may have played a role in the magmatic evolution of the Internal Zone. The Cretaceous Period was a time of extensive metaluminous and peraluminous granitoid plutonism in the Internal Zone (Miller and Bradfish, 1980; Barton, 1990). Many of the granitoids have isotopic signatures consistent with derivation from crustal materials with limited or no mantle input (Miller and Barton, 1990). Several authors have suggested that crustal thickening was the primary cause of Cretaceous anatexis at deep crustal levels in the Internal Zone (for example, Armstrong, 1983; Miller and Gans, 1989). Others (for example, Barton, 1990) have appealed to increased mantle heat flow to the middle crust. Gravitational collapse of the Internal Zone could promote crustal anatexis in two important ways. First, extension in the lower crust would decrease the distance between the Moho and the middle crust, leading to an increase in effective mantle heat flux. Second, rapid decompression associated with extension in the middle crust would enhance the degree of anatectic melting in the lower crust (Hodges, 1990).

CONCLUSIONS

Recent geologic studies in the Internal Zone of the North American Cordillera have produced both direct and circumstantial evidence of Cretaceous extension. We postulate that this extension signifies gravitational collapse of the Sevier orogen while the overall tectonic setting was still basically convergent. Geochronologic data from the northern parts of the Internal Zone, most notably the Omineca crystalline belt of southern British Columbia (Brown and Journeay, 1987; Carr, 1990), permit temporal overlap between well-documented Eocene extension and the last stages of Sevier-Laramide contractile deformation. Eocene extension in this region may have been the final manifestation of gravitational collapse of the Sevier orogen. We suggest that Oligocene-Miocene extension in the central and southern Basin and Range and Eocene extension in the northwestern United States and southwestern Canada may have been related to fundamentally different tectonic processes.

Extension in a convergent setting requires decoupling within the lithosphere; compressional stresses must be transmitted across the orogen through some levels of the lithosphere while other levels are extended. In the Himalayan orogen in Miocene time, the upper crust of southern Tibet was under extension while the lower crust was under compression (Burchfiel and Royden, 1985). This does not appear to have been the case in the Sevier orogen in Late Cretaceous time, because there is no firm evidence for large, surface-breaking, normal faults or major extensional basins of Cretaceous age in the Internal Zone. One simplistic kinematic model consistent with geologic observations in the Sevier orogen involves decoupling of the middle crust from the upper and lower crust and displacement of a mid-crustal extensional allochthon westward relative to the foreland.

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