Cordilleran metamorphic core complexes:
Cenozoic extensional relics of Mesozoic compression

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ABSTRACT

Cordilleran metamorphic core complexes form a belt of uplifted metamorphic rock that extends from southern Canada to northwestern Mexico just west of, or astride, the foreland thrust belt of the North American Cordillera. During the past several years the age and tectonic significance of the core complexes have been a topic of considerable controversy. Some geologists view the complexes as an uplifted orogenic core zone that formed behind the thrust belts mainly during Mesozoic regional compression. An opposing view is that they are mainly Tertiary in age and of extensional origin. We support a model that unifies these seemingly inconsistent views by suggesting that Mesozoic crustal telescoping resulted in an overthickened plateaulike crustal welt along the Cordilleran hinterland. During Cenozoic time this gravitationally unstable mass spread laterally, resulting in deep-seated crustal extension. The extension was aided by a thermal pulse of Cenozoic magmatism that reduced crustal viscosity and by a lowering of intraplate convergent stress fields due to changing plate kinematics. The chief advantage of the model is that it reconciles opposing views as to the age and tectonic significance of the complexes and places them in a more comprehensible setting amid Mesozoic-Cenozoic Cordilleran thermotectonic history.

PROBLEM

Cordilleran metamorphic core complexes (Crittenden et al., 1980; Coney, 1979, 1980; Davis and Coney, 1979; Armstrong, 1982) form a discontinuous sinuous belt along the eastern part of the North American Cordillera from southern Canada to northwestern Mexico (Fig. 1). During the past several years the core complexes have been a topic of considerable controversy (DeWitt, 1980; Thorman, 1977; Brown and Read, 1983; Davis et al., 1980, p. 122–126). The principal debate has been about their age and tectonic significance. Age controversy (Armstrong, 1982, p. 132) derives from the fact that evidence for timing of deformation is contradictory in that structural elements thought to relate to one episode of deformation in one complex are shown to be of a different age in another. Controversy surrounding tectonic significance is similar in that structural features that have been interpreted by some geologists as compressional have been interpreted by others as extensional. These contradictions have resulted in two somewhat polarized and opposing views as to the origin, history, and tectonic significance of Cordilleran metamorphic core complexes.

The first perception (Misch, 1960; Armstrong and Hansen, 1966; Price and Mountjoy, 1970) of Cordilleran metamorphic core complexes was that of an infrastructural orogenic core zone in the hinterland behind the foreland thrust belts to the east. Within the more modern concept of

collisional tectonics, models for the Canadian complexes have recently appeared (Monger et al., 1982; Brown and Read, 1983) that invoke obduction of accreted terranes over the North American margin followed by postobduction telescoping extending into the foreland. Although these models vary in detail and emphasis, a commonality lies in the idea that the uplifted metamorphic core zone is related tectonically to the thrust belts to the east and, therefore, that the metamorphic core zone and the thrust belts are of the same age. That is, both are mainly Middle Jurassic to early Tertiary in age. Furthermore, it is implicit in these views that the main structural and metamorphic features of the complexes are compressional in origin.
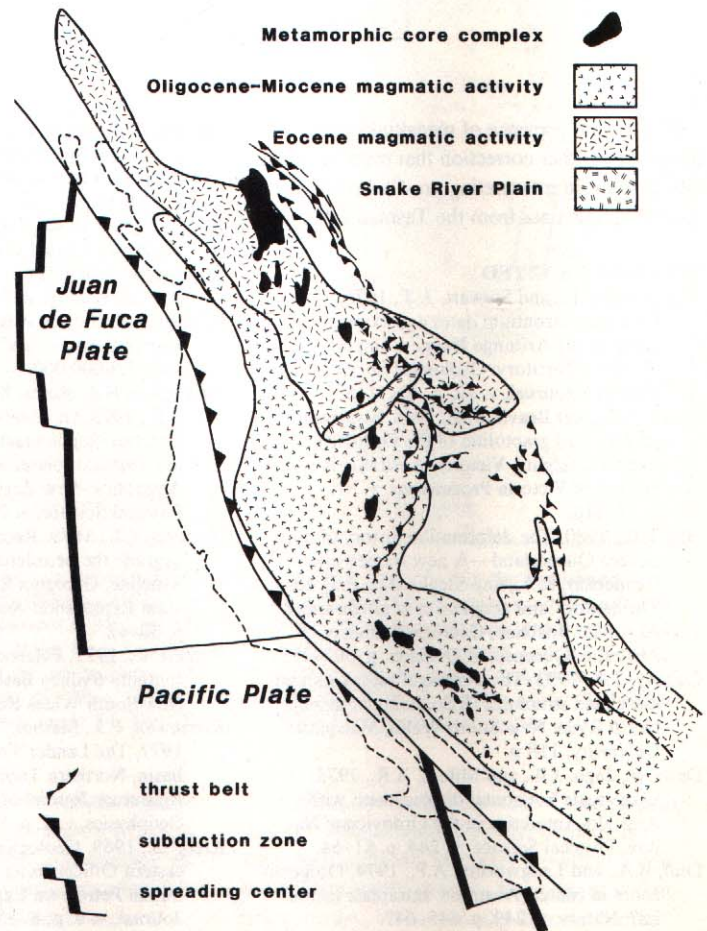

Figure 1. Major regional tectonic features of early and middle Tertiary post-Laramide, pre–Basin and Range time. From Coney (1978, 1980).

A recent perception, which incidentally has caused most of the controversy, is that the metamorphic core complexes are mainly Tertiary in age and extensional in origin (Davis and Coney, 1979; Coney, 1979). This view grew out of arguments for Cenozoic listric normal (denudational) faulting in the Great Basin, from a realization of very young deformation and isotopic "cooling" ages for metamorphic rocks in the hinterland (Armstrong, 1972; Anderson, 1971; Coney, 1974; Davis, 1973, 1975; Moores et al., 1968; Damon et al., 1963), and from evidence presented by Davis (1973, 1975, 1977) and Davis et al. (1975) that the mylonitic gneissic foliation and lineation characteristic of the metamorphic core in southern Arizona complexes were extensional in origin, showing that the Cenozoic extensional process was deep-seated and crustal in scale.

In retrospect it can be said that the compressional models emphasized the Mesozoic compressional aspects of the complexes and either did not recognize or chose to minimize the evidence for younger Tertiary extension. Likewise, the Tertiary extensional models either interpreted most features of the complexes to be due to Tertiary extension or chose to minimize the evidence for Mesozoic compression. In many cases it was a question of emphasis. Both positions are historically and conceptually understandable.

Against these prevailing ideas of genesis of Cordilleran metamorphic core complexes one must consider several regional relationships. First, the age of extension recorded in the complexes is diachronous. Those north of the Snake River Plain are mainly of Eocene age, whereas south of the plain they are mainly of Oligocene-Miocene age (Coney, 1980). Furthermore, the extensional events in both areas occurred during a coeval period of spatially much more widespread volcanic eruptions and emplacement of shallow plutons (Coney, 1980; Dickinson, 1981; Elston, 1976) (Fig. 1). This magmatic pulse is part of a complex pattern of post-Laramide igneous activity that swept generally southwestward across the Cordillera from the Eocene Challis-Absaroka activity in the north to the Oligocene-Miocene "ignimbrite flare-up" of the Great Basin and American Southwest (Armstrong, 1974; Lipman et al., 1971; Coney and Reynolds, 1977).

The regional tectonic setting of the complexes is also problematical. From southeastern California–southern Nevada northward, the complexes lie just west of the thrust belts (Fig. 1). Thus, despite the evidence for Cenozoic extension younger than the thrusting, why is this belt of post-thrusting extension so systematically deployed directly behind the thrust belt? In contrast, the Arizona and Sonora complexes lie astride a wide belt of mainly Laramide deformation.

Finally, middle Tertiary extension in the core complexes apparently began 10 to 30 Ma before initial contact between the Pacific and North America plates and resulting growth of the San Andreas–Basin and Range transform–extensional rift regimen (Atwater, 1970). Thus, it occurred in a period that falls after the high stress and high rates of convergence of the Laramide but before extinction of subduction in the late Tertiary (Coney, 1978, 1980; Engebretson et al., 1982).

ANALYSIS

In order to cut through this controversy, we have conducted a regional analysis that attempts on a broad scale to quantify the tectonic history of Cordilleran core complexes in terms of amount of extension and its resulting effect on crustal thickness as a function of time. We think that on a scale of western North America and over the times involved, intraplate continental deformation is essentially penetrative and approximates pure shear (England, 1982), that upper-crustal telescoping or extension was matched by commensurate crustal thickening or thinning. Restoration of extension values and related crustal attenuation yields, on palinspastically restored base maps, what might be termed paleocrustal
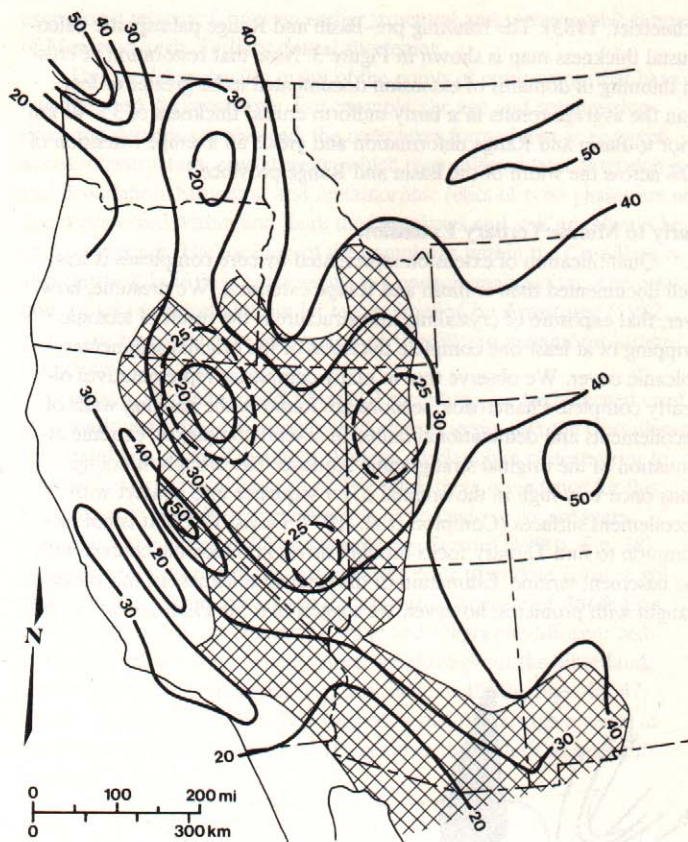

Figure 2. Present crustal isopachs and Basin and Range extensional province. Contours show present crustal thickness (km) on present-day base map. Cross-hatch pattern indicates area of Basin and Range extension.

isopach maps at the beginning of Basin and Range time (about 17 Ma) and at the end of Laramide time just prior to the initiation of Cenozoic extension (about 50 Ma).

We are fully aware of weaknesses inherent in both the method and the data bases used. Extension values applied in the analysis are certainly not applicable to ground truth at any specific point. We suggest, however, that the approach yields reasonable results that are representative of the pattern of crustal conditions at Cordilleran scale.

Basin and Range Extension

Late Tertiary Basin and Range extension (Fig. 2) was averaged east-west across the width of the province, using equations presented by Wernicke and Burchfiel (1982) and LePichon and Sibuet (1981). These equations derive from geometric models relating postextension fault separation and fault-block tilts (see also Stewart, 1980b) to the amount of extension. The procedure yielded a province-wide average of 40% extension. Where possible, domains of greater or lesser extension within the province were identified from regional analyses (Yerrington, Nevada—Proffett, 1977; southern Nevada—Wernicke et al., 1982; southeastern Oregon—Lawrence, 1976) and were used to modify the 40% average. Using these values we palinspastically reconstructed the pre–Basin and Range Cordillera in two dimensions by removing horizontal extension from the domains defined, and in the third dimension by thickening the crust by a factor of the reciprocal of the extension. Present crustal thickness used is shown in Figure 2 (compiled from Smith, 1978; Monger and Price, 1979; Stickney and Sheriff, 1983; Allenby and

Schnetzler, 1983). The resulting pre–Basin and Range palinspastic paleo-crustal thickness map is shown in Figure 3. Note that restoration of crustal thinning in domains of extension documented to be greater or less than the average results in a fairly uniform crustal thickness of 35–40 km prior to Basin and Range deformation and yields an average extension of 40% across the width of the Basin and Range province.

Early to Middle Tertiary Extension

Quantification of extension represented by core complexes is less well documented than is Basin and Range extension. We presume, however, that exposure of crystalline infrastructure is the result of tectonic stripping of at least one complete thickness of the original sedimentary-volcanic cover. We observe that in many complexes representatives of nearly complete Phanerozoic sections are found in the hanging walls of decollements and denudational faults. In several complexes, extreme attenuation of the original stratigraphic sequence has brought lithologic units once very high in the original cover sequence into contact with decollement surfaces (Compton et al., 1977; Davis, 1975). It is not uncommon to find Tertiary rocks brought down into tectonic contact with the basement terrane. Estimation of the original thickness of this cover is fraught with problems; however, we suggest that the Phanerozoic cover

sequence must have been at least 10 km thick. Assuming complete tectonic stripping of at least 10 km of upper-crustal section, we find that extensional values of 40% to 60% are not unreasonable (Wernicke, 1981).

Restoration of extension using this value results in a palinspastic and paleocrustal thickness map representative of conditions just prior to Cenozoic extension and just after Sevier-Columbian-Laramide compression (Fig. 4). The principal feature of this map is an overthickened crustal welt along the trend of the core complex belt. We freely recognize that there exists a certain circularity in this procedure. Palinspastic reconstruction will necessarily result in thickening exactly where extensional features are restored. However, we suggest that this circularity does not dismiss the significance of the Cordilleran crustal welt that the reconstructions indicate must have existed prior to mid-Tertiary extension.

Mesozoic–Early Tertiary Compression

It is our thesis that the overthickened crustal welt shown in Figure 4 is the result of mainly Middle Jurassic to early Tertiary crustal telescoping in and behind the Cordillera thrust belt and within the metamorphic hinterland. A full quantitative analysis of this telescoping would entail reconstructions of the metamorphosed and ductilely deformed hinterland, for which estimates of shortening would be prohibitively complex. Nevertheless, the telescoping must have been significant. Estimates of shortening within the thrust belts that are available range from 50% in the Canadian and Idaho-Wyoming thrust belts (Price and Mountjoy, 1970; Royse et al., 1975) through 30% in southwestern Arizona (Davis, 1979). These amounts, particularly when combined with comparable shortening in the hinterland, are ample to produce the 50- to 60-km-thick crustal welt shown in Figure 4 from a precompressional crustal thickness of 30 to 40 km (see Coney, 1979, p. 21–22, and Fig. 6). We think that Armstrong's (1983) suggestions that the so-called two-mica granites typical of the Cordilleran hinterland–core complex belt (Coney, 1980), the majority of which are Cretaceous to early Tertiary in age, are produced by melting in overthickened crustal roots are entirely supportive of what we are proposing here.

TECTONIC IMPLICATIONS

The principal result of this analysis is that an overthickened crustal welt 50 to 60 km thick formed in the metamorphic hinterland behind, or astride, the belt of Middle Jurassic to early Tertiary thrust faulting of the North American Cordillera. This welt became the site of deep-seated crustal extension in core complexes during Eocene to Miocene time. We suggest that core-complex extension took place only when a sharp pulse of magmatism swept across this thickened welt during Eocene time in the north and Oligocene-Miocene time in the south. We propose that these varied tectonic responses of compression, extension, and magmatism are related; the compressional crustal thickening caused the later extension triggered by the magmatic pulse and a reduction in regional intraplate stress.

Several workers have recently suggested that overthickened continental crustal welts produced by intraplate telescoping will spread laterally because of gravitational instability if there is sufficient topographic head and sufficient lowering of viscosity (England, 1982; Molnar and Chen, 1983). Presumably the flow can occur only if the welt is not laterally confined by stronger regions or under high compressive boundary stress resulting from convergent plate margin and/or intraplate dynamics.

We would propose that an overthickened crustal welt was produced in the Cordilleran hinterland by intraplate crustal telescoping mostly during Cretaceous to early Tertiary time. It is important to realize that in the thin-skinned decollement-style thrust belt most of the deep-seated crustal thickening took place *behind* the foreland fold and thrust belt. In areas where thrusting was more profound and involved the crystalline base-
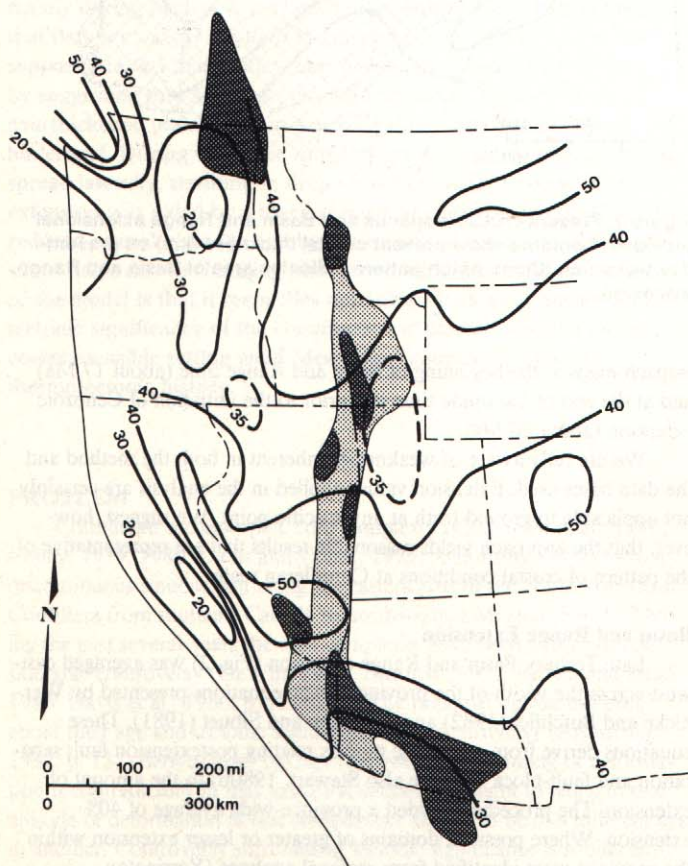

Figure 3. Pre–Basin and Range/post-mid-Tertiary palinspastic and paleoisopach reconstruction. Base map shows a palinspastic reconstruction with effects of Basin and Range extension removed. Paleocrustal thickness contours (km) result from restoration of crustal thinning that accompanied extension and show that intermediate crustal thicknesses extended throughout the Cordillera preceding Basin and Range deformation. Patterned area is region that had been affected by early to mid-Tertiary core-complex extension (cross hatch = 50% extension; stipple = 20%) on restored base.
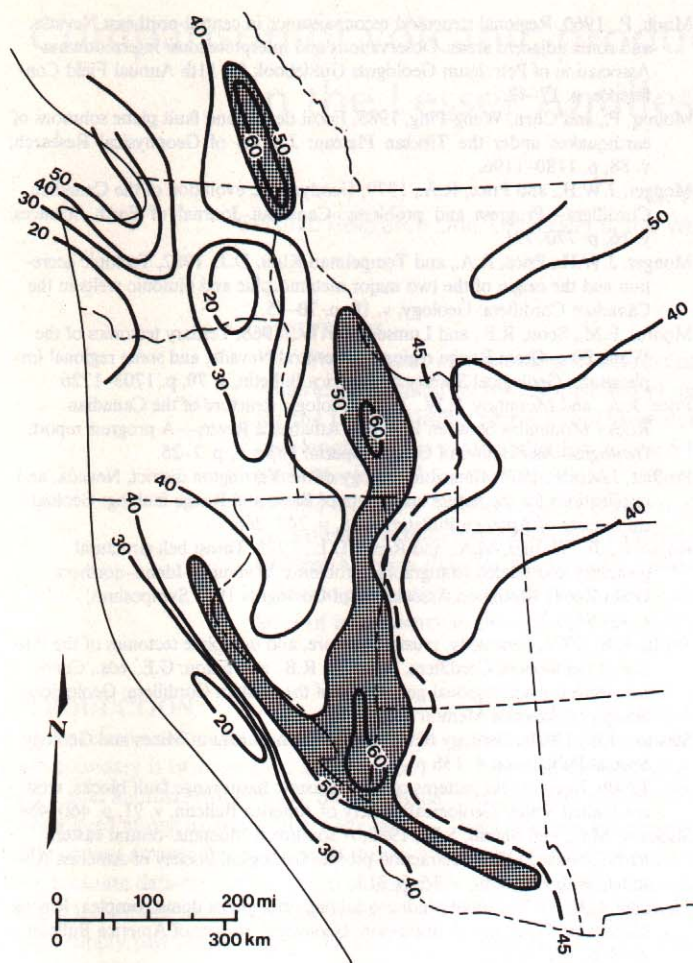
Figure 4. Post-Laramide palinspastic and paleoisopach reconstruction and resulting crustal welt. Crustal thickness contours (km) and palinspastic base derived from restoration of early and mid-Tertiary extension and crustal thinning. Welt of overthickened crust (strippled area), which was the consequence of Sevier-Columbia-Laramide telescoping, runs down axis of Cordillera and coincides with locus of later core-complex extension.

ment, such as in the Laramide belt of Arizona, infrastructural thickening took place within and beneath the telescoping and not behind it. It is significant that the welt may not have formed everywhere at the same time. For example, in Utah-Nevada it was probably mostly Cretaceous (Sevier) in age, whereas in southern Canada it was Late Jurassic–Cretaceous and early Tertiary (Columbian-Laramide), and in Arizona it was Late Cretaceous to early Tertiary (Laramide). Regardless, the unstable crustal welt remained until after its viscosity was lowered by post-Laramide magmatic patterns and the regional intraplate stress was reduced at the drop in high rates of plate convergence at the end of Laramide time (Coney, 1978; Engebretson et al., 1982). The migrating, widespread, post-Laramide magmatic patterns have been interpreted to be due to the collapse and steepening of a previously shallow-dipping Laramide Benioff zone (Coney and Reynolds, 1977), which may in itself have reduced stress in the region and even made it extensional (for example, see Dickinson, 1981, Fig. 10; Coney, 1980, p. 27). Under these conditions the welt spread laterally toward the coast in the direction of least resistance, reversing earlier compression and producing the superposition of Tertiary

extensional tectonic fabrics on earlier structural and metamorphic fabrics of Mesozoic–early Tertiary crustal shortening.

This model reconciles many of the points of controversy that have raged around the complexes. For example, the age and compression-extension debates are resolved; the complexes formed first as compressional infrastructural crustal welts, which then suffered later extension and denudation. Structural and metamorphic relics of both phases are no doubt preserved within and flank the complexes and will not always be easy to separate. The location of the complexes within the Cordillera is also clarified, as is their relationship to Cenozoic magmatism. The position we take is essentially similar to one implied by Armstrong (1982, p. 146) in his recent excellent review of Cordilleran metamorphic core complexes.

Finally, since the model of crustal spreading due to thickened crust is so sensitive to the topographic head, does it imply that the Cordilleran hinterland was a vast Tibetan or Andean altiplanolike plateau prior to middle Tertiary crustal extension? We think there is evidence for this. Cretaceous to early Tertiary sediments or volcanic rocks are sparse throughout the hinterland (for example, see Stewart, 1980a, Fig. 38). Widespread erosion surfaces evolving just prior to middle Tertiary volcanism and extension have been documented (Armstrong, 1968; Epis and Chapin, 1975). In contrast, Eocene and Oligocene-Miocene sediments and volcanics are widely preserved throughout the hinterland, generally tilted to high angles (e.g., see Stewart, 1980a, Figs. 46, 47; Eberly and Stanley, 1978). This suggests a major drainage reversal at the time of initiation of regional extension as the hinterland began its Cenozoic collapse.

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