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The regional tectonic setting and possible causes of Cenozoic extension in the North American Cordillera

P. J. Coney

SUMMARY: Timing and tectonic setting of middle Cenozoic crustal extension in the North American Cordillera supports the concept that an overthickened crustal welt formed behind or astride the thrust belts as a result of compression during the Mesozoic to early Cenozoic. At the end of the Laramide Orogeny the gravitationally unstable welt collapsed by deep-seated crustal extension. The extension was aided by a lowering of crustal viscosity resulting from a complex pattern of volcanism and a reduction in intraplate compressive stress. As plate regimens evolved along the Pacific margin during the late Cenozoic, subduction progressively ceased as did compressive stress also. An evolving transform boundary and a massive Cordilleran-wide lithospheric uplift allowed a second phase of extension to develop across the already thinned and thermally weakened crust to form the Basin and Range Province, being active up to the present time.

The principal manifestation of extensional tectonism in the North American Cordillera has been recognized for years as the Basin and Range Province (Stewart 1978). The Basin and Range Province formed in the central-western United States and northwestern Mexico by block faulting, some strike-slip faulting, and associated relative regional subsidence during the late Cenozoic. The crust has been thinned to less than normal, heat flow is high, and the extension has been accompanied by a sparse bimodal basaltic–rhyolitic volcanism. The Basin and Range Province remains active to this day, as evidenced in seismicity and landscape, but the nature of its origins remains controversial.

An earlier period of mid-Tertiary Cordilleran extensional tectonics has only recently been recognized. This extension affected a larger region than the younger Basin and Range Province extending from northern British Columbia across the western United States and southward into northern Mexico. The mid-Tertiary extension was originally recognized in the sub-horizontal younger on older detachment faults (Armstrong 1972) which juxtapose unmetamorphosed upper-plate Precambrian to Cenozoic sedimentary and volcanic rocks against lower-plate mylonitic gneiss in the peculiar metamorphic core complexes of the Cordilleran hinterland (Coney 1980; Armstrong 1982). Coeval everywhere with this middle-Tertiary extension was a voluminous outburst of generally caldera-centred ignimbrite eruptions (Lipman *et al.* 1971; Elston 1976; Coney & Reynolds 1977; Dickinson 1981). This has resulted today in the paradox of mountain ranges exposing thick ash-flow tuffs nested amongst ranges exposing mylonitic gneiss, both yielding the same mid-Tertiary K–Ar cooling ages. The middle-Tertiary extensional province was superimposed on widespread compressional features of Mesozoic and early-Tertiary age.

Although the earlier mid-Tertiary extension covered an area larger than the younger Basin and Range Province, the two provinces overlap to a very large degree in the western United States. In other words, the Basin and Range Province was superimposed over much of the same ground that had been extended in the middle Tertiary. Thus, the crust of this area was extended and thinned twice. It is important to realize the scale of these features: the combined area of mid- and late-Tertiary extension in western North America is about 10 times longer and five times wider than the Aegean extensional province of the eastern Mediterranean region (Le Pichon 1982) and would comfortably encompass much of western Europe.

The principal problem with Cenozoic extensional tectonics in western North America has been to explain why it took place. After a description of the regional tectonic setting of these two periods of continental extension we will review some possible explanations to this question.

Regional tectonic setting of Basin and Range extension

The Basin and Range Province (Stewart 1978; Eaton *et al.* 1978; Eaton 1982) includes the northern Basin and Range of Nevada and western Utah, the Arizona–Sonora Basin and Range of the southwestern United States and northwestern Mexico and the Mojave region of southeastern California (Fig. 1a). The northern Basin and Range is bounded to the W by the

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Sierra Nevada batholith and to the E by the Colorado Plateau. The northern boundary, which is quite transitional, is the Columbia Plateau and the mountains N of the Snake River Plain. The Arizona–Sonora Basin and Range lies E of the Peninsular Ranges batholith of southern California and the Gulf of California, and S of the Colorado Plateau. The province extends eastward into southern New Mexico and Chihuahua, Mexico and then extends northward into Colorado as the narrow Rio Grande rift. The Rio Grande rift is a conspicuous narrow finger of block faulting that extends northward from northern Mexico into the southern and central Rocky Mountains along the eastern margin of the Colorado Plateau. Although often ignored in conceptual models of Basin and Range tectonics, the Rio Grande rift displays identical geometry and timing to the larger Basin and Range Province of which it is a part. The Mojave Desert is largely that region E of the San Andreas Fault, S of the Garlock fault, and W of the Colorado River. The Basin and Range Province is most characterized by a basin and range topography and a general elevation less than surrounding provinces. Both the Rio Grande rift and Basin and Range Province are young, certainly no older than the past 17 My. Both are also clearly the result of widespread extensional block faulting and associated strike-slip faulting which collapsed and fragmented large segments of the Cordillera during the late Tertiary.

The Basin and Range Province is superimposed over a wide variety of inherited, regional tec-

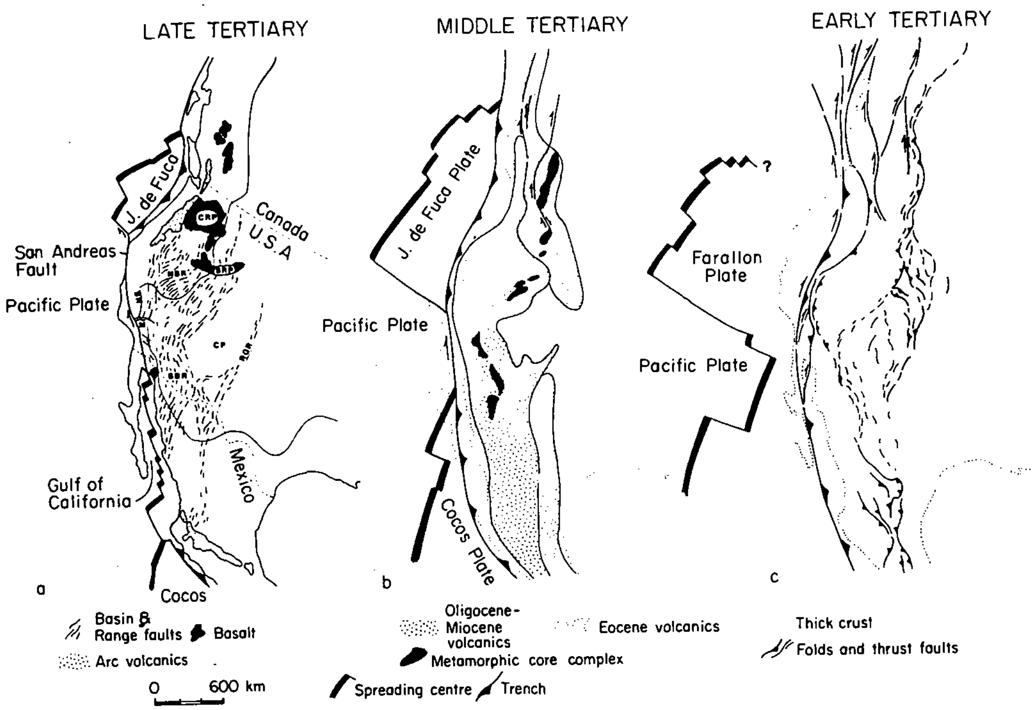

FIG. 1.(a) Regional and plate-tectonic setting of late-Tertiary Basin and Range extension. The Basin and Range Province is shown by fine lines depicting block faults in the western United States and northern Mexico. Heavy barbed line; subduction zone. Heavy line; spreading centres. V pattern; arc volcanic rocks. Black areas; late-Cenozoic flood basalt. Plate configuration is that of today. CRP = Columbia River plateau; SRP = Snake River Plain; SN = Sierra Nevada; NBR = northern Basin and Range; SBR = southern Basin and Range; CP = Colorado Plateau; M = Mojave Desert; RGR = Rio Grande rift. (b) Regional and plate-tectonic setting of mid-Tertiary extension. Dark areas are positions of the Cordilleran metamorphic core complexes. Subduction zones and spreading centres as in (a). Stippled area is the distribution of mainly Eocene volcanic rocks. V pattern is the distribution of mainly Oligocene–Miocene volcanics. The age of extension in each of the core complexes is the same as the age of the volcanic rocks with which each is associated. (c) The North American Cordillera at the end of Laramide Orogeny. Subduction zones and spreading centres as in (a) & (b). Fine lines and small barbed lines represent the fold and thrust belts of Laramide age. The pattern is the approximate position of the proposed thickened crustal welt due to crustal compression that later collapsed to form the belt of mid-Tertiary extension.

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tonic domains. Most of the western half of the northern Basin and Range does not lie on ancient North American continental basement but instead extends well into the region of accreted 'suspect terranes' (Coney *et al.* 1980). In contrast, the eastern part of the northern Basin and Range and most of the Arizona–Sonora Basin and Range lie on ancient cratonic North America. The eastern part of the northern Basin and Range lies within the Palaeozoic miogeocline, the eastern hinge line of which coincides with the eastern edge of the Basin and Range and the western edge of the Colorado Plateau. On the other hand, the northern edge of the Arizona–Sonora Basin and Range is not a noticeable discontinuity in Palaeozoic stratigraphy. The Palaeozoic formations of the Colorado Plateau are essentially identical to those of the Basin and Range to the S. In both areas they are part of the thin interior cratonic sequence of southwestern North America.

The Basin and Range Province similarly has an interesting relationship to Mesozoic–early-Cenozoic compressional features. The eastern part of the northern Basin and Range developed in the mainly Cretaceous, pre-Laramide age, thin-skinned foreland fold and thrust belt which closely tracks the Cordilleran Palaeozoic miogeocline. The western part of the northern Basin and Range evolved in a region of early- to mid-Mesozoic thrusting and metamorphism probably associated with accretionary tectonics there. In contrast, the Arizona Basin and Range developed astride a wide belt of mainly Late Cretaceous–early-Tertiary Laramide deep-seated basement involved thrust faulting. Except for the narrow Rio Grande rift, the Basin and Range avoided the Colorado Plateau and the Rocky Mountains.

The Basin and Range Province is underlain by relatively thin (25 km thick) crust and experiences higher heat flow than adjacent regions (Thompson & Burke 1974; Eaton *et al.* 1978). The differentiation between the Basin and Range and adjacent provinces is particularly well known at the Colorado Plateau, which has a crust nearly 40 km thick, and the Sierra Nevada, which has a crust nearly 50 km thick. Both provinces have lower heat-flow values than the Basin and Range. A related geophysical fact is that the Bouguer gravity is slightly to considerably higher and the general elevation slightly to considerably lower in the Basin and Range as compared with the adjoining Colorado Plateau (Eaton *et al.* 1978). What is more important, however, is that general elevation is significantly higher and the Bouguer gravity is significantly lower over the entire region of the Basin and Range, Colorado Plateau and Rocky Mountains than might be expected. This suggests the Basin and Range Province is simply a slightly collapsed part of a massive regional uplift which affects the entire Cordillera and even the Great Plains, as inspection of a continental relief map reveals.

The Basin and Range Province suffered extensional block faulting over the wide area described above (Stewart 1978) accompanied by scattered bimodal basaltic–rhyolitic volcanism (Christiansen & Lipman 1972). There was also some strike-slip faulting, particularly in the western part of the province, associated with growing transform faults along the Pacific margin. All this activity began, in some sectors at least, by 17 Ma (Eberly & Stanley 1978) and has continued, in some sectors at least, to the present time (Stewart 1978). There has been discussion as to whether the Basin and Range is time-transgressive and has grown northward with time. It is clear that large parts of the Arizona–Sonora region were not as recently active as the northern Basin and Range evidenced by much wide pedimentation, and a lack of evidence of recent faulting. Also, the general elevation there is significantly lower and the Bouguer gravity significantly higher than in the northern Basin and Range. This could suggest that the Arizona sector is now quiescent and perhaps cooling. The quiescence may coincide with the opening of the Gulf of California which might have transferred strain to Gulf spreading centres; whereas before, it had been distributed over the entire region, as it still is to the N in Nevada–Utah.

It is very clear that the Basin and Range Province, including the Rio Grande rift, results from late-Tertiary regional extension. Extension explains the thin crust and lithosphere, and the higher heat flow, and is compatible with normal faulting, present seismicity and general relative elevation. The amount of extension is much debated. Estimates have ranged from about 10 to over 100%, but the value probably lies in the range of 30 to 60% province-wide, with local variations (Stewart 1978; Coney & Harms 1984). If the extension were much more than 40%, some argue, the region would be below sea-level, although higher temperatures due to lithospheric thinning no doubt counteract the effect.

Late-Tertiary plate-tectonic settings of the Basin and Range Province evolved from late-Mesozoic to mid-Tertiary plate configurations (Atwater 1970). By the Late Cretaceous we know that at least three major plates, the Pacific, Farallon, and Kula, paved the eastern Pacific Ocean. Spreading centres lay between them and a trench formed along the accreting transpressive Pacific margin of North America. The trench was subducting first the Kula and then Farallon Plates, probably very obliquely, as these plates spread away from the East Pacific and related rises. Sometime after 30 Ma, but before 20 Ma, the East Pacific Rise made initial contact with North America, probably in the vicinity of southern California–northern Baja California. This placed the northwestward-moving Pacific Plate in direct contact with North America's westward moving margin, and the vector subtraction of these two motions produced right strike-slip transform faults between the two plates trending northwesterly parallel to the Pacific margin. As more and more of the rise crest was annihilated, the transform boundary developed to both N and S and subduction and arc activity ceased between the two separating triple junctions. Dickinson & Snyder (1979) have argued that this would produce a 'window' in the subducting slab NE of the growing transform boundary under the adjacent North American Plate. Their geometry depicts this window evolving directly under the Basin and Range Province.

The transform-fault boundary, which probably initially lay offshore, was nearly 1000 km long before Basin and Range rifting began ≈ 17 Ma during the Miocene (Atwater 1970; Engebretson *et al.* 1982). In any event, the annihilation of the East Pacific Rise has continued to the present and the entire evolution of Basin and Range extensional tectonics took place during this period. One major interruption in this progressive evolution occurred when the transform margin jumped inboard to open the Gulf of California and initiate the San Andreas fault system ≈ 6 Ma. This transferred Baja California and much of western California to the Pacific Plate, and probably stabilized the Arizona–Sonora sector of the Basin and Range. There was considerable clockwise rotation and northward translation of blocks within the coastal ranges of northwestern Mexico and California and in Washington and Oregon during this time.

Regional tectonic setting of mid-Tertiary extension

Mid-Tertiary extensional tectonism (Fig. 1b) in the North American Cordillera has been an illusive feature. It was overprinted and masked by the late-Tertiary extension of the Basin and Range (just discussed), and its resultant structures have been confused with those due to older Mesozoic to early-Tertiary compression. Evidence of extensional tectonism in the mid-Tertiary was discovered only in the past 15 years and the controversy this discovery initiated has centred upon the so-called 'Cordilleran metamorphic core complexes' (Coney 1979, 1980; Davis & Coney 1979; Crittenden *et al.* 1980; Armstrong 1982; Coney & Harms 1984).

Cordilleran metamorphic core complexes occur in a sinuous discontinuous belt along the eastern part of the North American Cordillera extending from British Columbia in southern Canada S through the Cordillera into Sonora, Mexico over a distance of 3000 km. Over this distance all the complexes are characterized by similar rock type, structures and fabric. The complexes typically exhibit two distinctly different domains. These are a metamorphic–plutonic basement terrane and an overlying or adjacent unmetamorphosed cover. Separating the two is a sharp surface, or zone, of sub-horizontal shearing and detachment, usually with a younger on older geometry. The complexes are mostly domal or anticlinal in form and usually constitute the highest mountains in their respective regions.

The basement terranes of core complexes are characterized by low-dipping foliations and a distinctive 'stretching' lineation in mylonitic gneiss formed from protoliths that range from Precambrian basement to mid-Tertiary plutons. The unmetamorphosed cover terranes are replete with listric normal faults which have shattered protoliths, ranging across the entire spectrum of Phanerozoic sedimentary and volcanic rocks including mid-Tertiary continental volcanic and sedimentary rocks. The amount of extension in the cover terrane is often dramatic. Cover stratigraphy is usually strongly attenuated and the Tertiary rocks, the youngest of the original cover, are commonly brought down into tectonic contact with the mylonitic gneisses of the basement terrane. The detachment surface separating the basement and cover terranes is typically sharp and very visible in topography. The mylonitic fabrics of the basement terrane are commonly sub-parallel to the detachment surface, but rocks both above and below the detachment surface are usually intensely brecciated as a result of what appears to be the latest movement on the surface.

During the last few years the core complexes have generated a considerable controversy (Thorman 1977; DeWitt 1980; Brown & Read 1983). The debate has surrounded their age and tectonic significance. The age controversy (Armstrong 1982) stems from the fact that evidence for the age of deformation has seemed con-

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tradictory in that structural elements thought to result from one episode of deformation in one complex are identified as of a different age in another. The controversy surrounding tectonic significance is similar in that features that have been interpreted by some to be of compressional origin have been interpreted by others as extension-related. The debate became quite polarized for several years, but more recently has moved toward the realization that both processes have been important in the evolution of Cordilleran metamorphic core complexes (Armstrong 1982; Coney & Harms 1984).

From southern Nevada northward into southern Canada the metamorphic core complexes lie within a belt which extends about 200 km W of the eastern edge of the thin-skinned foreland fold and thrust belt so characteristic of the North American Cordillera (Fig. 1b & c). The complexes lie mostly within, or along the western edge of, the thick Palaeozoic miogeocline prisms. Here they form an infrastructural orogenic core zone of deep-seated metamorphism and associated plutonism behind the thrust belts to the E. They are in part due to some combination of mid-Mesozoic obduction of accreting terranes over the miogeoclinal margin and widespread intraplate telescoping which ramped the metamorphic core zone upward and eastward as the deformation moved eastward into the foreland during the late Mesozoic and early Cenozoic.

On the other hand, the metamorphic core complexes of Arizona and Sonora, Mexico are not in a 'hinterland' behind a foreland thrust belt, but are in the midst of a belt of rather deep-seated late Cretaceous to early-Tertiary, Laramide-age thrust faulting, which involved both the Precambrian basement as well as cover rocks. No infrastructural metamorphic core zone formed as it did to the N, but there is some syntectonic, rather low-grade, metamorphism found in areas of most severe deformation (Haxel *et al.* 1984).

Spatially associated with the belt of metamorphic core complexes is a suite of distinctive granitic plutons of the so-called two-mica type (Coney 1980). The majority of these are apparently of Cretaceous to early Tertiary age (Armstrong 1983).

Superimposed upon the compressional features, in both areas described above, are the features now nearly universally ascribed to mid-Tertiary extensional tectonics. As this extension began the previously tectonically uplifted hinterland began to collapse. Instead of being a source area, as it had been through the long preceding compressional periods, drainage reversed and it became an area of deposition for continental sediments. Listric normal faulting became widespread, tilting the continental sediments to high angles. Eventually attenuation and tectonic denudation became so extreme that rocks once deeply buried were exposed in domal culminations to reveal mylonitic gneisses in which extensional fabrics are superimposed on earlier compressional features.

The age of mid-Tertiary extension is diachronous (Fig. 1b). The complexes N of the Snake River Plain in southern Idaho are mainly Eocene, whereas S of the plain they are mainly Oligocene–Miocene (Coney 1980). However, the extensional events in both areas occurred during a coeval period of spatially much more widespread volcanic eruptions and shallow plutonic emplacement (Elston 1976; 1984; Coney 1980; Dickinson 1981). This magmatic pulse is part of a very complex pattern of post-Laramide igneous activity that swept generally southwestward across the Cordillera from the Eocene Challis–Absaroka activity in the N to the Oligocene–Miocene 'ignimbrite flare-up' of the Great Basin and the American Southwest (Lipman *et al.* 1971; Armstrong 1974; Coney & Reynolds 1977).

Estimation of the amount of extension in the belt of metamorphic core complexes and associated listric normal faults is difficult, but it must have reached values of 40 to 75% (Coney & Harms 1984). The direction of extension, as revealed by pervasive stretching lineations in the basement terranes and tilted fault blocks in the cover, varies along-strike in the belt. To the N it was generally westward to slightly N of W, while in the central region it was more northwesterly. In the Arizona and Sonora sector the direction of extension was toward the SW.

The plate-tectonic setting of mid-Tertiary extension in the North American Cordillera is more difficult to reconstruct than that of the later Basin and Range extension, but there are reasonable limits on the options. There is considerable agreement that during the Late Cretaceous to early Tertiary Laramide Orogeny convergent rates between the Farallon and/or Kula Plates and the North America Plate were very elevated (9 to 15 cm yr^{-1}) and, particularly so in the case of the Kula Plate, oblique to the Cordilleran margin (Coney 1978; Engebretson *et al.* 1982). It is probable that the exact location of the triple junction between Kula–Farallon–North America will never be known for certain, but there is a growing consensus that it was initially far to the S off southern Mexico during the Late Cretaceous and that it then migrated northward to a more certain position near Vancouver Island by the late Eocene. Construction of vector circuits demonstrates that the convergent rate between the Farallon and North America Plates falls to nearly half of its Laramide value during the late Eocene. This is an artefact of the change in Pacific Plate motion over the Hawaii hot-spot represented by the elbow in the Hawaii-Emperor seamount chain now dated near 44 My. It could also have been due, in part, to a reduction in the North America Plate's westward motion at about this time (Coney 1971, 1978). This abrupt fall in rate has long been correlated with the end of the major compressional tectonics of the Laramide Orogeny in western North America (Coney 1971, 1978). Subduction of the Farallon Plate or its remaining fragments beneath North America's western margin continued at the reduced rate during the mid-Tertiary until the East Pacific Rise was progressively extinguished from near 30 Ma to the present. In other words, the compressional events of Laramide age correlate with high rates of plate convergence, while the extensional events of the mid-Tertiary correlate with reduced rates of convergence. It is important to emphasize that the extension of the middle Tertiary began before subduction ceased.

Analyses of the timing and distribution of structural features and igneous activity associated with the compressional Laramide Orogeny and subsequent extensional tectonics and associated igneous activity of the mid-Tertiary (Fig. 1b & c) have led to the hypothesis that the subducting plate progressively flattened in dip beneath the western United States during the Laramide to the point that it was nearly horizontal by the Eocene (Coney & Reynolds 1977). This geometry has been used to explain the presence of deep-seated, basement cored, thrust-bound uplifts, so typical of the Laramide Orogeny, as far E as Denver, over 1000 km from the assumed subduction zone (Dickinson & Snyder 1979). Likewise, the equally eastward sweep of presumed arc-related Laramide igneous activity to eventual near extinction by the Eocene is similarly explained (Coney & Reynolds 1977). This proposed flattening of the Laramide Benioff zone, and the destruction it is supposed to have produced, correlates with the high rates of convergence of the Laramide discussed above.

Then, during the Eocene, the compressional deformation ceased, ending the Laramide Orogeny, as convergent rates dropped. What followed was a striking retrograde sweep of the massive outburst of ignimbrites back toward the coast during the mid-Tertiary (Coney & Reynolds 1977) associated with the extensional tectonics of the metamorphic core complexes and listric normal faults. The retrograde sweep of presumed arc-like igneous activity has been correlated with a proposed collapse and/or steepening of the earlier flat-dipping Laramide subducting slab during the Eocene to Miocene.

Presumably, as the East Pacific Rise was progressively extinguished, causing a cessation of subduction and initiating the transform regimens between the Pacific and North America Plates during the late Tertiary, the extension of the mid-Tertiary merged and transposed itself into the extension of the Basin and Range. The two phases of extensional tectonics probably overlap in space and time in the southwesternmost United States where mid-Tertiary extension seems to be youngest, and the extension of the Basin and Range may be oldest. Further inland and northward, the two extensional phases must be separated by as much as 20 My or more. This fact, coupled with the observation that the structural styles, directions of extension, and type of igneous activity of the two extensional phases are so distinct seems to suggest that they are best kept separate in our minds and may have a different origin.

A search for a cause

Most models proposed to explain the extensional tectonic features of the mid-Tertiary and Basin and Range have been largely kinematic in character (Davis & Coney 1979; Stewart 1978; Wernicke 1981; Wernicke & Burchfiel 1982). The emphasis has been upon the geometry of the metamorphic core complexes and related listric normal faults in the case of the middle Tertiary, or upon the geometry of the horsts and grabens and related strike-slip faults in the case of the Basin and Range. There has been a general recognition that most of what we see is above the brittle–ductile transition and that the faulting probably shallows with depth to merge into sub-horizontal surfaces of ductile shear. Recent deep seismic sounding seems to confirm these concepts (Smith & Bruhn 1984).

Considering the problem at crustal scales, and assuming that intraplate continental deformation is essentially penetrative and approximates pure shear (England 1982), yields the conclusion that upper-crustal telescoping or extension must be matched by commensurate crustal thickening or thinning. If this approach is applied to western North America (Coney & Harms 1984), restoration of the estimates of extension during Basin and Range and mid-Tertiary time yields crustal geometry at the beginning of each period

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of extension. Most important, the process yields the crustal geometry at the end of the phase of Mesozoic to early-Cenozoic compressional tectonism at about 50 My BP before the initiation of extension. There are obvious weaknesses inherent in both the method and the data bases used, but the approach seems to give reasonable results that might be representative of the pattern of crustal conditions at Cordilleran scale.

The details of this procedure (Coney & Harms 1984) will not be reviewed here, but the broad results of restoration of Cenozoic crustal extension in the western United States yields a pre-Basin and Range palinspastic palaeocrustal thickness map where fairly uniform crustal thicknesses of 35–40 km are obtained based on extension values of about 40–60% across the width of the Basin and Range. If correct, the crustal thickness in the Basin and Range before rifting began was about the same as the crustal thickness of the Colorado Plateau today (Coney & Harms 1984, fig. 3). Quantification of extension during mid-Tertiary development of the metamorphic core complexes is more difficult, but exposure of crystalline infrastructure suggests stripping of at least one complete thickness of the ≈10-km thick original sedimentary and volcanic cover. Extensional values of 40 to 75% are not unreasonable. The restoration of mid-Tertiary extension using these values results in a palinspastic and palaeocrustal thickness map representative of conditions just prior to Cenozoic extension and just after Laramide compression (Coney & Harms 1984, fig. 4). The principal feature of this map is an overthickened crustal welt along the trend of the belt of Cordilleran metamorphic core complexes (Fig. 1c).

The overthickened crustal welt is the result of mainly Middle Jurassic to early-Tertiary crustal telescoping in and behind the Cordilleran thrust belt and within the metamorphic hinterland. Estimates of shortening within the thrust belts range from 50% or more in the Canadian and northern Rocky Mountain thrust belts (Price & Mountjoy 1970; Royse *et al.* 1975) to about 30% in southwestern Arizona (Davis 1979). These amounts, particularly when added to comparable deep-seated telescoping through crustal-scale duplexing and ductile flow in the Cordilleran metamorphic hinterland, are ample to produce a 50–60 km thick crustal welt (see Coney 1979, pp. 21–22 and Fig. 2a). Armstrong's (1983) suggestion 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 supports this proposition.

If we now combine the data on the regional and plate-tectonic setting of Cenozoic extension in western North America discussed in the previous sections with the inferences on the evolution of crustal geometry discussed above, we have before us most of the obvious elements which when summed somehow must have caused that extension. I will discuss in turn those factors that seem most important.

It was argued above that an overthickened crustal welt 50–60 km thick formed from intraplate telescoping in the 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 the core complexes during the Eocene through to the Miocene. A simple calculation (Le Pichon 1982) shows that an overthickened continental crustal welt at or near a continental margin, particularly when it has an isostatically generated topographic head, generates lithostatic pressures as a function of depth greater than those found at equivalent depths in the adjacent oceanic crust. The pressure difference reaches a maximum somewhere between 10 and 15 km depth. Several workers have recently suggested that overthickened continental welts produced by intraplate telescoping will spread laterally because of gravitational instability if there is sufficient lateral density variation, sufficient topographic head and sufficient lowering of viscosity (England 1982; Molnar & Chen 1983; see also Le Pichon 1982). 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 high compressive stress regimes. If all the flow is below the brittle–ductile transition, what we see at the surface in the core complexes and listric normal faults is a brittle 'raft' torn apart as the crust deforms by pure shear below.

A second factor which may have been very important is the observation discussed in the previous section that an extensive outburst of caldera-centred ash flows coexisted with the extending core complexes during the mid-Tertiary. The principal effect of this igneous activity was presumably to lower crustal viscosity through higher heat flow. As was mentioned above, the lowering of crustal viscosity could be a contributing factor in allowing the gravitationally unstable crustal welt to spread. Coney & Harms (1984) suggested that this magmatic pulse may have in fact triggered the crustal extension by providing the necessary ductility to permit flow. The higher heat flow would also have presumably raised the brittle–ductile transition to shallower than normal levels, perhaps placing it at, or even above, the levels of highest pressure gradients generated by the lateral density contrasts discussed above.

A third factor which may have contributed to the Cenozoic extension is the observation that compressive stress at the western margin of North America may have dropped significantly during the Eocene at the end of the Laramide Orogeny. Recall that this reduction in compressive stress derives from changes in plate kinematics in the Pacific realm (Coney 1978; Engebretson *et al.* 1982), and may have even been caused in part by a drop in North America's westward motion (Coney 1971). This stress drop may have been coupled with, or at least accompanied by, collapse and/or steepening of the previously flat-dipping Laramide subducting slab after the Eocene (Coney & Reynolds 1977). The collapse and/or steepening of the slab in itself would create a downward force which translates into the so-called 'roll-back' (Dewey 1980), or 'suction' force which tends to induce migration of the trench and its adjacent continental margin toward the ocean and away from the continent (Le Pichon 1982). In any event, these factors would presumably have reduced the boundary stress to the W releasing the stored potential energy in the thickened welt and allowing it to spread laterally in that direction.

All of the above important factors, particularly when summed, seem adequate to generate the stresses necessary to cause the mid-Tertiary extension seen in the Cordilleran metamorphic core complex belt. It suggests that an overthickened crustal welt formed by intraplate crustal telescoping which took place from the Cretaceous to the early Tertiary (Fig. 2a). It is important to realize that in the thin-skinned decollement-style thrust belt typical of the central and northern Cordillera most of the crustal thickening took place behind the foreland fold and thrust belt in the metamorphic hinterland. In areas where thrusting was more profound and involved the crystalline basement, such as in the Laramide belt of Arizona, the thickening took place within and beneath the telescoping and not behind it. It is also significant that the crustal welt may not have formed everywhere at the same time. For example, in Utah–Nevada it was probably late Jurassic to 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).

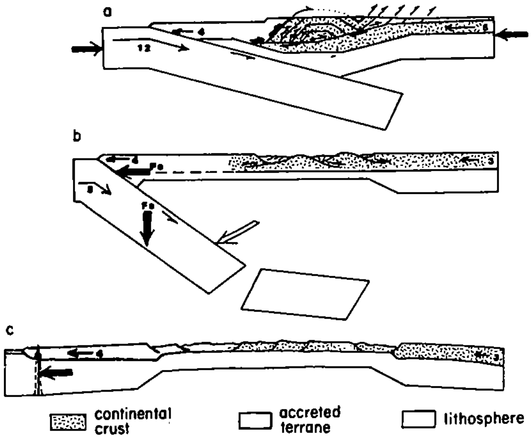

FIG. 2. Possible forces at work during Cenozoic Cordilleran tectonic evolution. (a) Late-Mesozoic–early Cenozoic Laramide compression. The North America Plate moves westward (left) at 5 cm yr^{-1} while the Farallon plate moves eastward at 12 cm yr^{-1} and subducts at a shallow angle. The opposed forces (heavy arrows) produce high intraplate compressive stress. Intraplate telescoping during Laramide compression is assumed to be about 1 cm yr^{-1} producing the crustal welt. Relative motion between the North America and Farallon Plates at the plate margin is thus 16 cm yr^{-1}. (b) Mid-Tertiary extension. North America Plate westward motion falls to 3 cm yr^{-1} and Farallon Plate eastward motion falls to 5 cm yr^{-1}. The crustal welt spreads westward at a rate of about 1 cm yr^{-1} yielding a relative motion between North America and Farallon Plates of 9 cm yr^{-1} at the plate margin. Fc is the spreading force of the extending crust; Fs is the suction force of the collapsing slab. (c) Late-Tertiary Basin and Range extension. The North America Plate continues to move westward at 3 cm yr^{-1} while the Pacific Plate moves into the figure and away on the other side of the San Andreas Fault at the left. A broad Cordilleran uplift produces a gradient down which the fragmenting orogen moves toward a 'free face' opening the Basin and Range.

Regardless, the unstable crustal welt remained until after its viscosity was lowered by the post-Laramide magmatic patterns and the regional intraplate stress was reduced (Fig. 2b). Under these conditions the welt spread laterally toward the coast in the direction of least resistance, reversing the earlier compression and producing the superposition of Tertiary extensional features on earlier structural and metamorphic features of Mesozoic–early-Tertiary crustal shortening (Coney & Harms 1984).

All of the above may offer an explanation for mid-Tertiary extension, but the extension of the Basin and Range remains. Recall that reversal of Basin and Range extension discussed in an earlier section generates a continental crustal section slightly in excess of normal, or at least about the same as the crust under the Colorado Plateau today. Recall also that the evolution of the Basin and Range seems inseparably tied to the progressive demise of the East Pacific Rise and development of a complex transform margin replacing a convergent one (Atwater 1970). This may have further reduced compressive stress, or made it even more extensional as the case may be, creating what amounts to a free face (Fig. 2c). Furthermore, it has been argued (Dickinson & Snyder 1979) that the progressive extinction of the East Pacific Rise would create a so-called slab 'window' beneath the southwestern Cordillera seemingly geometrically required by growth of the Pacific–North America transform margin as subduction ceased. This would allow hot asthenosphere to well up into the window heating the North American lithosphere above. Damon (1979) has suggested the progressive approach of the Earth Pacific Rise towards the North America margin translates into progressive subduction of younger and hotter lithosphere beneath that margin. This also is a source of heat and both factors could have contributed to regional uplift. If we couple this to the observation that the only regional tectonic pattern the Basin and Range comes near to mimicking is the ground previously ignited by the mid-Tertiary magmatism, we are left with the possibility that enough thermally induced gravitational instability exists in a thermally weakened and uplifted lithosphere to be released by the free face. This includes the Colorado Plateau, which is beginning to act like a microplate, as it accelerates westward slightly ahead of a trailing North America Plate opening the Rio Grande rift behind it, and slightly behind the Basin and Range and the rest of the Cordillera W of it. This is beginning to sound like plate tectonics, instead of the intraplate tectonics of the mid-Tertiary, and suggests that the entire fragmenting Cordillera is moving westward down a deep-seated gradient. Such extension usually leads to the opening of oceans.

In conclusion, it should be pointed out, if it has not already been obvious, that all of the arguments proposed above to explain Cenozoic extension are 'passive' in a dynamic sense. The forces appealed to here are bouyancy and body forces generated by the plates themselves and occuring within the plates and perturbations from normality produced by plate interactions and intraplate response. One can think of all sorts of sub-lithospheric currents generated from descending slabs and particularly changes in dip of those slabs, asthenospheric flow patterns generated from delaminating slabs, slab windows, and the like. These would be more 'active' forces from below and may be quite real. They are not discussed here because they do not seem to be required and more importantly because they are so intractable.

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