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Notes

Tectonomagmatic evolution of Cenozoic extension in the North American Cordillera

B.P. Wernicke, R.L. Christiansen, P.C. England & L.J. Sonder

SUMMARY: The spatial and temporal distributions of Cenozoic extension and magmatism in the Cordillera suggest that the onset of major crustal extension at a particular latitude was confined to a relatively narrow belt (<100 km, pre-extension) and followed the onset of intermediate and silicic magmatism by no more than a few million years. Extension began in early Eocene time in southern British Columbia, northern Washington, Idaho and Montana. Farther S, extension began at about the Eocene–Oligocene boundary in the Great Basin and slightly later in the Mojave–Sonora Desert region. The intervening area, at the latitude of Las Vegas, remained quiescent until mid-Miocene time. Compositional and isotopic characteristics of most pre-Miocene magmas are consistent with their containing major components of melted continental crust.

In mid-Miocene time, two major changes occurred: widening of the area of extension and the widespread appearance of basaltic magmas. The area affected by extension, from southwestern Montana to the Lake Mead region, widened to several hundred kilometres. By this time extension in southern British Columbia, northern Washington and northern Montana had ceased (probably before the end of the Eocene), and extension S of Lake Mead (except in the Gulf of California) had waned. Regions affected by the broader belt of extension during late Miocene, Pliocene, and Quaternary time experienced basaltic magmatism, which began along a central rift zone in the northern part of the region, and which had within a few million years spread to include most of the region; later basaltic activity has tended to concentrate in restricted zones, especially near the margins of the extended area.

We recognize a correlation between the amount of earlier crustal thickening and Cenozoic extension, and between the length of time after shortening but before extension and the degree to which a given region was intruded by Late Cretaceous plutons. The localization of extension in areas of previous crustal thickening and the dependence of the timing of extension on the thermal state of the overthickened crust is consistent with a simple thermal-mechanical model developed in a companion paper (Sonder *et al.*). This raises the possibility that stresses inherent in the North American Plate dominated over plate-interaction forces as controls of the Cenozoic tectonomagmatic evolution of the North American Cordillera, especially in its earlier stages.

We distinguish two classes of control for the middle Eocene and younger (<55 Ma) magmatism and tectonism in western North America. One class, purely kinematic, relates the deformation and igneous activity to the post-early Eocene relative motions between North America and the plates to its W (e.g. Atwater 1970; Lipman *et al.* 1972; Christiansen & Lipman 1972; Snyder *et al.* 1976; Coney 1978). These hypotheses are difficult to evaluate, first because of the inconsistency involved in relating the large-scale diffuse deformation of the continents to the relative motions of rigid plates, and secondly because these motions are themselves poorly constrained. The more recent attempts to relate the Cenozoic tectonics of western North America to plate motions have relied on the assumption of fixed hot-spots (Coney 1978; Engebretson 1982); even without this assumption, the quantitative analysis of uncertainties in plate reconstructions by Stock & Molnar (1983) shows that it may be unwise to interpret relative or absolute motion vectors without considering their error bars.

A second class of hypotheses for the origin of the middle Eocene and younger extension and magmatism is related to the evolution of stresses arising within the North American lithosphere itself. This class recognizes that continental lithosphere containing overthick crust has a tendency to spread under its own weight (e.g. Tapponnier & Molnar 1977) and that the key to understanding the Cenozoic extensional tectonics of western North America may lie in its late Mesozoic compressional history (see Molnar & Chen 1983, p. 1184). We consider a simple physical model in which the Cenozoic extension results from the gravitationally driven thinning of lithosphere previously thickened in late Mesozoic and earliest Tertiary times. This paper represents a synthesis of observations concerning the timing and extent of deformation and magmatism in western North America; these data are compared with the results of calculations

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(Sonder *et al.*, this volume) in order to evaluate the physical model. This analysis serves as a first step towards understanding the relative importance of the two classes of controls on the extension and magmatism.

We consider in detail three major regions of Cenozoic magmatism and tectonism (Figs 1 & 2): the Pacific Northwest, the Great Basin region, and a southern Great Basin 'amagmatic corridor'. We briefly discuss a fourth domain to the S comprising the Mojave and Sonoran Desert portions of the Basin and Range Province, previously treated in greater detail by Glazner & Bartley (1984). All of the domains experienced crustal thickening during Late Cretaceous and early Tertiary times before becoming regions of extension later in the Cenozoic.

The minimum amount of Late Cretaceous–early Tertiary shortening is well known in many areas, and locally exceeds 50% for supracrustal rocks in frontal parts of the thrust belt, implying substantial thickening of the crust in 'hinterland' areas to the W (e.g. Price 1981). Shortening reaches values locally as great as 30% in areas of Laramide-style foreland deformation (e.g. Smithson *et al.* 1978). Areas affected by this shortening event either had a non-cratonic hinterland thickened in mid-Jurassic to mid-Cretaceous time, or were

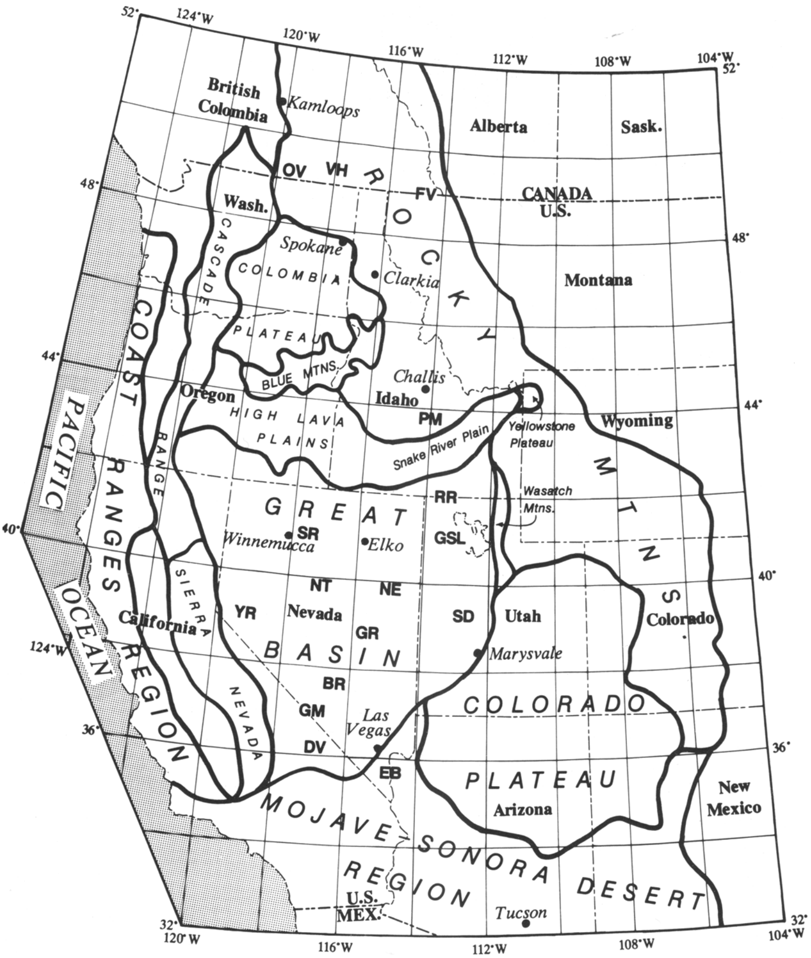

FIG. 1. Map showing geographical regions and localities mentioned in text. State, provincial and international boundaries (dashed lines) are also shown in Figs. 2, 3 and 4. Heavy lines delimit physiographic regions. BR = Belted Range; FV = Flathead Valley; GM = Grapevine Mountains; GR = Grant Range; GSL = Great Salt Lake; OV = Okanagan Valley; NE = Northern Egan Range; NT = Northern Toiyabe Range; PM = Pioneer Mountains; RR = Raft River Range area; SD = Sevier Desert; SR = Sonoma Range; VH = Valhalla area; YR = Yerington area.

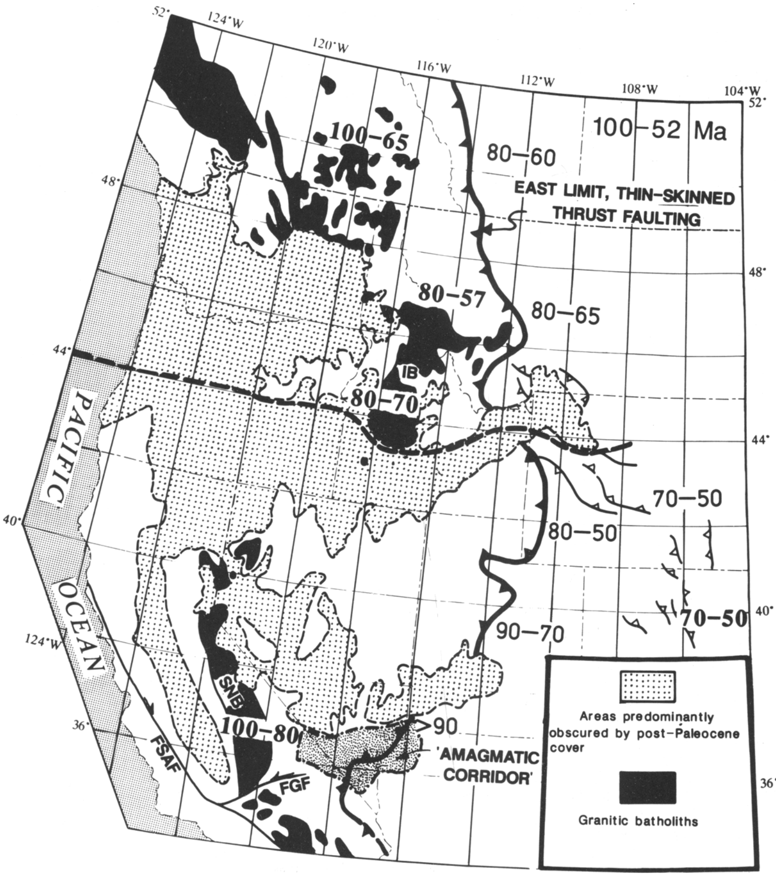

FIG. 2. Map showing key features discussed in text for Late Cretaceous and early Tertiary time. Bold numbers indicate times of emplacement of granitic batholiths; plain numbers—principal times of shortening in thrust belt and Laramide uplift regions; heavy dashed line—boundary between Pacific Northwest and Great Basin regions; thin lines with open barbs—major faults bounding Laramide uplifts. FGF = future trace of Garlock fault; FSAF = future trace of San Andreas Fault; IB = Idaho batholith; SNB = Sierra Nevada batholith.

developed within the craton itself. Thus, the Late Cretaceous–early Tertiary shortening represents a culminating event in which the entire Cordillera attained a crustal thickness greater than that of the craton, and in which cratonic areas well inboard from the continental margin became involved in Cordilleran orogenesis (e.g. Burchfiel & Davis 1975). Also during this time, extensive calc-alkalic magmatism intruded the continental margin in a virtually continuous belt from British Columbia to Mexico.

The approximate synchronism of magmatism and overthickening of the crust in the Late Cretaceous (Fig. 2) contrasts with pronounced differences in timing of the Cenozoic magmatism and extension between various sectors of the orogen. Despite this diachronism, there is a common pattern to the development of extension in any given part of the orogen. We identify a four-stage history for each part of the extensional terrain: (i) the formation of early intermontane basins; (ii) the eruption of predominantly intermediate to silicic volcanic rocks; (iii) areally restricted large-magnitude crustal extension, occurring during or immediately after second-stage magmatism; and (iv) basaltic or bimodal volcanism, accompanied regionally by varied amounts of extension.

There are marked variations on this theme, as well as variations in timing during the development of the extensional and magmatic terrains (Table 1), that permit us to test the simple model presented in Sonder *et al.* (this volume).

TABLE 1. *Constraints on timing of tectonic events in the Cordillera, My BP.*

	Limits on cessation of major compression	Limits on onset of major extension	Limits on interval between compression and extension
Pacific Northwest	58–55	55–49	0–9
Great Basin	75–53	38–20	15–55
Amagmatic Corridor	90–85	20–15	65–75
Mojave–Sonora	55–40(?)	40(?)–20	0–35

Pacific Northwest

Cretaceous tectonism and magmatism

Crustal thickening occurred in this region during the interval 80–55 Ma in the southern Canadian Rockies and the Montana sector of the thrust belt (Fig. 2). In the southern Canadian Rockies, shortening of cratonic strata and their overlying foreland basin deposits exceeded 100 km between the early Campanian, the age of the youngest conformable strata in the fore-deep, and latest Eocene time (Price 1981), the age of the post-tectonic Kishenehn Formation, deposited on the Lewis thrust sheet. Price (1981) has suggested that since fore-deep sedimentation had ceased by the end of the deposition of the Palaeocene Paskapoo Formation, the bulk of the shortening had been completed by this time. However, the Paskapoo, which is deposited conformably on underlying Late Cretaceous strata in the most external part of the thrust belt, is involved in the frontalmost fold of the thrust belt, as well as in the Williams Creek syncline, 35 km W of the thrust front. It is therefore possible that deformation continued into the Eocene. This event involved the stripping of cratonic Palaeozoic rocks and fore-deep deposits from their basement, and thus the shortening that the supracrustal rocks record must have involved substantial thickening of the crust much farther W, where Tertiary extensional deformation has since taken place (Price 1981).

Further S, in the Montana sector of the orogen, the Late Cretaceous–early Tertiary thrust belt changes character, where it involves sub-miogeoclinal, Proterozoic belt strata and, in some areas, cratonic crystalline basement (Ryder & Scholten 1973). S of the Lewis and Clark line (LCL, Fig. 3) the main period of shortening— as interpreted from the time of most rapid fore-deep sedimentation—seems to have been in Campanian and Maastrichtian times, based on recent palynological studies of the syntectonic Beaverhead Group (Nichols *et al.* 1985). Deformation could have continued into the Eocene in the belt of E-directed thrusts, but no post-Maastrichtian compressional orogenic deposits are known in the region. Farther E of the fold thrust belt at this latitude, Laramide-style uplifts were active into the Palaeocene. Since thrusting in the Montana sector of the thrust belt seems to be less 'thin-skinned' than in southern Canada, overthickening of the crust may have been more closely centred upon the area of supracrustal shortening, rather than having occurred to the W as it did in the Canadian sector.

Magmatism in the Pacific Northwest region was intense during Late Cretaceous and early Tertiary times, and, in contrast to regions farther S, occurred *within* the area of maximum overthickening of continental crust (Fig. 2). Plutonism was synchronous with the major pulse of crustal overthickening during Campanian, Maastrichtian, and Palaeocene (?) times, about 85–55 Ma (Fig. 2). Major plutonic centres include the Whatshan batholith at 80 to 70 Ma (R. Parrish, pers. comm.), protoliths of the Valhalla gneiss complex at around 65–55 Ma (Parrish 1984; Parrish *et al.* 1985), numerous bodies of probable Late Cretaceous to early Tertiary age in northeastern Washington (Fox *et al.* 1977), and the Idaho and Boulder batholiths, the bulk of which appear to have intruded between 80 and 57 Ma (Armstrong *et al.* 1977; Criss & Fleck 1983; Sutter *et al.* 1984; L. Garmezy, pers. comm.).

The pattern of Late Cretaceous evolution is thus that of (N of the Lewis and Clark line) thin-skinned thrusting associated with crustal thickening of areas W of the main part of the thrust belt, and (S of the line) a more thick-skinned style of thrusting, causing substantial thickening of the crust, closer to the locus of supracrustal shortening. In both areas, calc-alkaline plutonism and volcanism accompanied deformation within the zone of greatest overthickening. As noted by Armstrong (1978), thrusting throughout this region appears to have

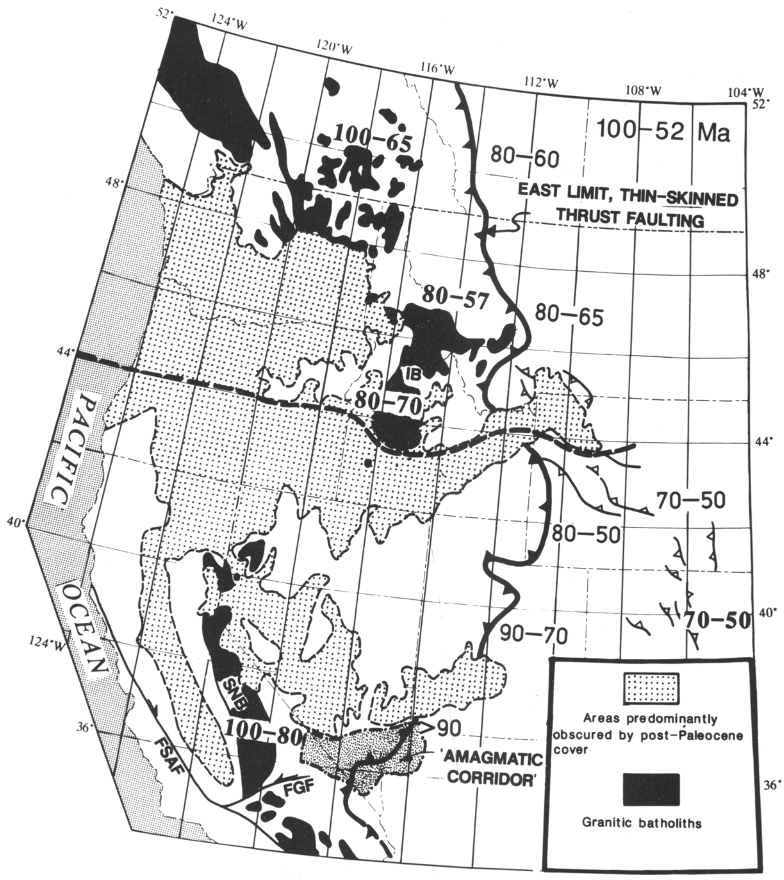

FIG. 3. Map showing key features discussed in text for middle Eocene through mid-Miocene time. Heavy dashed line—boundary between Pacific Northwest and Great Basin regions; heavy, double-hachured lines—principal detachments known to be active during this time interval N of latitude 35°N; opposing arrows depict crustal shortening during Tertiary time as discussed in text; AV = Absaroka volcanic region; CV = Challis volcanic region; GM = Grapevine Mountains; GR = Grant Range; H-S-F = Hope-Straight Creek–Fraser River fault system; LCL = Lewis and Clark line; MC = Monashee crystalline complex; NT = northern Toiyabe Range; OH = Okanagan Highlands; PT = Purcell Trench; RR = Raft River Range area; SR = Snake Range area; VC = Valhalla crystalline complex. Future traces of Garlock and San Andreas faults as in Fig. 2.

ended by 55 Ma and younger volcanism of the Challis belt.

Palaeogene extensional tectonics and associated magmatism

In the last few years, it has become apparent that the Pacific Northwest region experienced major crustal extension, principally during the Eocene (Fig. 3). Intermediate to silicic volcanism over-lapped closely in time with the extension.

In Canada, major Eocene extension occurred in S-central British Columbia (Fig. 3; Price 1979). The major structures identified as having Eocene displacement include the Columbia River fault zone, which appears to have had several kilometres of down-to-the-E displacement, but whose major period of activity was during the middle Jurassic (Read & Brown 1981; Brown & Murphy 1982). Farther S, Parrish *et al.* (1985) and Carr (1985) have shown possible Eocene normal displacement on the Slocan Lake fault zone, which bounds the eastern side of the Valhalla gneiss complex (Fig. 3). To the W, near Kamloops, British Columbia, Ewing (1981a, b) reports a major episode of Eocene tectonism, recorded by a network of faults bounding exposures of the lower and middle Eocene

Kamloops Formation. The lowest units in this succession are predominantly non-volcanic, but grade upward into locally thick intermediate to silicic volcanic piles that yield K–Ar ages of 42–52 Ma.

In northern Washington, S of 49°N, the extensional terrane is apparently wider, as major detachments of Eocene age have been identified from the Okanogan Valley eastward to the Purcell trench (Fig. 3). From W to E, these include faults separating mylonitic gneisses from unmetamorphosed Tertiary strata in the Republic and Toroda Creek 'grabens' (Rhodes & Cheney 1981), the Kettle River fault on the E side of the Kettle River dome (Rhodes & Cheney 1981), the Jumpoff Joe and Newport faults N of Spokane (Cheney 1980; Harms & Price 1983; Rhodes & Hyndman 1984) and an inferred detachment in the Purcell trench forming the E margin of the Priest River crystalline complex (Rehrig *et al.* 1982).

The timing of extension in Washington is recorded by a sedimentary and volcanic succession present at high structural levels within the upper plates of these detachments and K–Ar mineral ages from deep structural levels. According to Pearson & Obradovich (1977) the stratified rocks comprise a lower, tuffaceous fluvio-lacustrine unit, a middle unit of predominantly intermediate to silicic volcanic rocks, and an upper unit of mixed volcanic and coarse-sedimentary detritus, including debris flows. The lower two units are conformable and appear to have been deposited over the entire region prior to severe structural disruption that preceded and accompanied the deposition of the youngest unit in restricted basins. The lower two units were deposited between about 53 and 52 Ma, and may thus be equivalent to the lower part of the Kamloops Formation. The uppermost unit contains Upper Eocene (Bridgerian) floras, and volcanics in the sequence yield ages between 49 and 41 Ma (Pearson & Obradovich 1977), suggesting that the major period of extension occurred between 50 and 41 Ma ago. However, since no deposits older than the mid-Miocene Columbia River basalts overlap the extensional terrane, extension could have persisted past 41 Ma. Corroborating evidence for dominantly Eocene extension comes from K–Ar mineral ages of lower-plate crystalline rocks (Miller & Engels 1975; Rehrig *et al.* 1982), which are highly varied in the region but at the deepest structural levels are no younger than 45–42 Ma. K–Ar ages in lower-plate crystalline rocks of the Valhalla and Monashee complexes farther N in Canada also give ages as young as 42 Ma (Read & Brown 1981).

The extensional terrain of southern British Columbia and northern Washington strikes southward beneath relatively undeformed mid-Miocene basalts of the Columbia Plateau without a noticeable decrease in intensity, and presumably continues for some distance beneath the plateau basalts (Figs 3 & 4). It cannot, however, continue as far S as the Blue Mountains region of NE Oregon since pre-Tertiary rocks there seem to have experienced only minor shortening of Oligocene and younger age (e.g. Brooks *et al.* 1976; Davis 1977).

To the SE, near Clarkia, Idaho, Seyfert (1984) reports the presence of the 'Clearwater core complex', which he infers to be genetically linked to Eocene strike-slip faulting on the Lewis and Clark line (Fig. 3). Rehrig & Reynolds (1981) suggested that the Lewis and Clark line was an intracontinental transform linking Eocene down-to-the-E normal faulting in the Purcell trench to that along the eastern side of the northern part of the Idaho batholith (Hyndman 1980). Garmezy & Sutter (1983), using the ^{40}Ar–^{39}Ar technique, have shown that top-to-the-E shear along the top of the northern part of the batholith occurred at 45–43 Ma.

Farther S preliminary fieldwork by K.V. Hodges (pers. comm.) suggests that much of the tectonic unroofing of the Pioneer Mountains crystalline core (Dover 1982), and the emplacement of low-grade metamorphic rocks on high-grade, post-dates eruption of the Challis volcanics. In that area, the volcanics range in age from about 50–46 Ma (Marvin *et al.* 1982). Lower-plate muscovite K–Ar ages range between 45 and 43 Ma (Dover 1982), similar to those in tectonically exhumed crystalline complexes to the N. The precise age of extensional deformation in the Pioneers remains an outstanding problem, especially because the next recognized extensional complex to the S, in the Raft River Range area, appears to have formed principally during Oligocene and Miocene times (Fig. 3). It is not known whether the Snake River Plain represents a boundary between Eocene extension to the N versus Oligocene and Miocene extension farther S, or whether extension is smoothly time-transgressive toward the S. It appears that Eocene extension ended N of the Snake River Plain and that Oligocene and Miocene extension overprinted that part of the Eocene extensional terrain S of the Lewis and Clark line.

The compositions of Challis-age (53–37 Ma) magmas in the Pacific Northwest are predominantly intermediate to silicic; there is some basalt in the western part of the region. The most extensive igneous activity occurred in areas

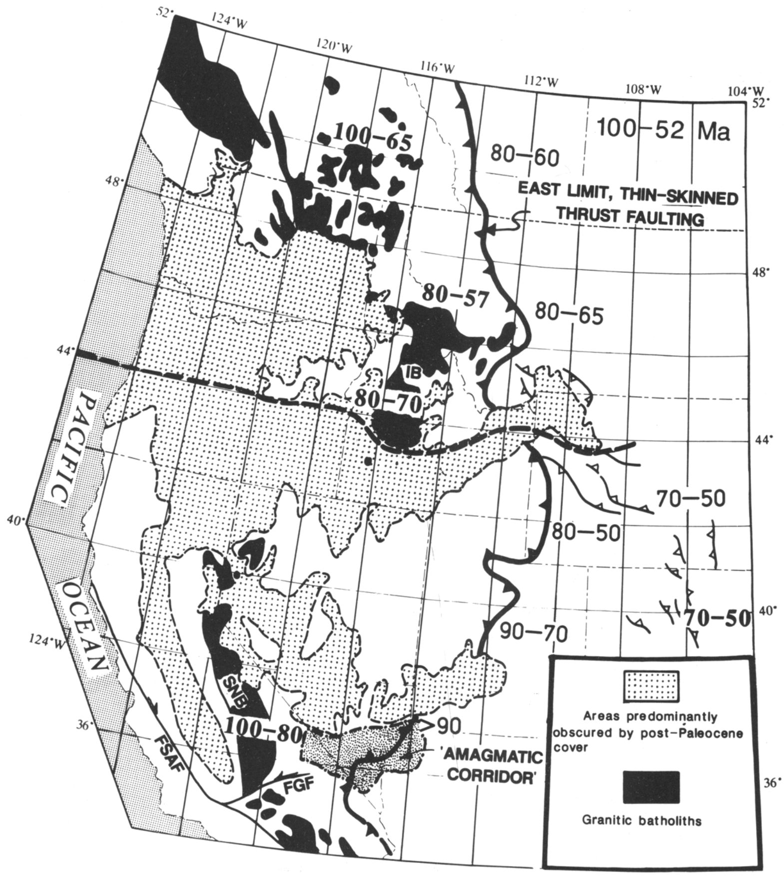

FIG. 4. Map showing key features discussed in text for mid-Miocene and younger time. Heavy dot–dashed line bounds region of significant extension during this time interval. Heavy double-ticked lines—detachments known to be active during this interval. Opposing arrows—region of crustal shortening discussed in text; traces of anticlines schematically depict regions of shortening in California and on the Colombia Plateau active during this interval. GF = Garlock fault; SAF = San Andreas Fault.

of previously overthickened crust, but minor activity also took place outside the areas of crustal thickening (see Armstrong 1978). The increasing prevalence of rhyolites in the central part of the Challis belt suggests a greater role for crustal (probably lower-crustal) melting in the magmatic systems there than in the more andesitic systems around its margins. This may be supported by the presence of two-mica granites, apparently of crustal origin, associated with parts of the Challis belt that produced extensive rhyolites (Miller & Bradfish 1980).

There is no discernible time-transgression of Challis-episode volcanism (Armstrong 1978); both the oldest and youngest K–Ar ages are virtually the same in all areas, principally between about 53 and 43 Ma, although minor volcanism continued until about 37 Ma. After this time, Palaeogene magmatism occurred only W of the extensional terrain. Although regional magmatism and extension are synchronous within this interval, there is no apparent relationship between the intensity of the magmatic event and the intensity of upper- and middle-crustal extensional strain. The main intrusive centres of both the Challis and Absaroka fields, the two most important parts of the volcanic belt, lie outside areas that are known to have undergone extension. Conversely, some areas of severe extension (e.g. the Kettle River and Toroda Creek areas in N-central Washington) are sites of relatively modest Eocene magmatism. Similar relations are apparent in some younger areas to the S (Fig. 3).

Palaeogene compression in western areas

In contrast to the Palaeogene extensional tectonism described above, areas to the W experienced transpressive shortening during this time. The southern part of the Hope-Straight Creek–Fraser River fault system (Fig. 3), a right-lateral strike-slip system, was probably active between deposition of the early to middle Eocene Swauk and Teanaway Formations next to its southern (Straight Creek) part, as suggested by a pre-Teanaway folding event (50–47 Ma; Tabor *et al.* 1984). Deformation may have continued through Eocene to perhaps late Oligocene times (Tabor *et al.* 1984). Farther N, the late Eocene(?)–Oligocene Chilliwack composite batholith truncates the fault (Misch 1966). Although the total displacement on the Straight Creek fault appears to be 100 km or more (e.g. Davis *et al.* 1978), it is not certain whether the bulk of this displacement occurred during Eocene extension farther E or at an earlier time, as features believed to reflect large offset on the fault are no younger than Late Cretaceous. Thus, folding and deformation of Eocene volcanic and sedimentary rocks along the southern portion of the fault system may simply reflect dip-slip reactivation of the structure, perhaps during uplift of the North Cascades crystalline core to the E of the fault (Fig. 3).

Just E of the southernmost exposures of the Straight Creek fault system, middle Eocene strata in the Chiwaukum 'graben' were folded about NNW-trending axes. These strata are overlain with angular unconformity by the early-Oligocene Wenatchee Formation, which in turn is folded and thrust-faulted (Gresens 1980). Whether any of the Eocene or Oligocene Formations in this part of western Washington are related to crustal extension is unclear, as no clearly defined extensional faults have been identified. It is certain, however, that shortening in the region occurred during Eocene–Oligocene volcanism and sedimentation by folding along NW- to NNW-trending axes and local thrust faulting, which are here interpreted to represent transpressional yielding in association with minor (?) mid- to late-Eocene dextral motion on the Straight Creek fault. Major dextral translation on the Hope segment of the fault in southern British Columbia ended before intrusion of the 84-Ma Spuzzum pluton, yet the fault also locally offsets Eocene rocks (Okulitch *et al.* 1977).

It thus appears that the Eocene tectonics W of the Okanagon Highlands may have been entirely compressional or transpressional—an interesting observation in light of the large-scale, roughly E–W extensional tectonism that occurred at the same time further E.

Neogene extension and associated magmatism

A later period of extension, synchronous with regional extension farther S, overprints a part of the Pacific Northwest region (Figs 3 & 4). During Oligocene and Miocene times, the triangular area of thrust-belt and Laramide-style tectonism S of the Lewis and Clark line and N of the Snake River Plain was extended by normal faulting. The extension partly accompanied, but mainly followed, widespread deposition of a thin (<500 m) sequence of Oligocene and early-Miocene tuffaceous clastic rocks (Pardee 1950; Kuenzi & Fields 1971; Reynolds 1979). Angular unconformities between that sequence and late-Miocene strata indicate that the greatest extension was underway by that time and may have begun as early as mid-Miocene time. Fault scarps and active seismicity indicate that this event has continued into the Quaternary (Pardee 1950; Robinson 1963; Smith 1978; Reynolds 1979). Tertiary strata are characteristically tilted to the E and large range-front faults dip W. The northern boundary to this extensional terrane, the Lewis and Clark line, may have been a right-lateral intracontinental transform at this time (Reynolds 1979), as it may during the Eocene (cf. Figs 3 & 4). The trends of major range-front faults and the orientation of *T*-axes of fault-plane solutions (Freidline *et al.* 1976) indicate that the extension direction is NW–SE. This event appears to be a northward continuation of broadly distributed Neogene extension in the Great Basin region S of the Snake River Plain (Fig. 4).

N of the Lewis and Clark line, extension is recorded by the late Eocene (?) and early Oligocene deposition of the Kishenehn Formation in a half-graben that forms the modern-day Flathead Valley (Price 1981). The fault that bounds the half-graben has been interpreted by McMechan & Price (1984) as having reactivated the Lewis thrust fault. This faulting event, reflected also in 'back-slipped' thrusts farther W, is unusual in being younger than most of the extension further W in Washington but older than the down-to-the-W event that affected areas S of the Lewis and Clark line. The Lewis and Clark line thus represents the northern extremity of widely distributed Neogene extension that affected large areas to the S (Reynolds 1979).

Predominantly basaltic and bimodal volcanism did not begin in most of the Pacific Northwest region until approximately 17 Ma (Fig. 4), probably at least 20 Ma after the main crustal-thinning event. It is unclear whether extensive outpourings of the Columbia River Basalt Group (mainly 16.5–13.5 Ma) from vents W of the Idaho batholith intruded a crust that had experienced significant upper-crustal extension.

Although the Columbia River basalts represent the only major post-Eocene magmatic activity to have affected the Pacific Northwest region E of the Cascades, a relatively minor episode of bimodal volcanism (Chadwick 1978; Marvin *et al.* 1982) did accompany the Oligocene and younger extension that has affected the region S of the Lewis and Clark line. Except for these areas, and the distal edges of Miocene and Pliocene plateau basalts erupted N of the extended region in British Columbia, most of the area that experienced upper- and middle-crustal extension during the Eocene was amagmatic after the Oligocene.

Great Basin region and areas to the south

Late Cretaceous and early Tertiary tectonism and magmatism

Although the Great Basin region has a history of intermittent crustal shortening dating from the mid-Palaeozoic, involvement of cratonic North America in large-scale, E-directed thrust faulting (and therefore the earliest clear indication of overthickening of the continental crust) did not occur until Late Cretaceous and early Tertiary times. Thin-skinned thrust faulting apparently shows a northward-migrating time of cessation within the Great Basin region, but at these latitudes early-Tertiary Laramide-style shortening to the E was more pronounced than in much of the Pacific Northwest region (Burchfiel & Davis 1975).

Wiltschko & Dorr (1983) conclude that the movement on the Crawford–Meade, Absaroka, Darby, and Prospect thrust systems in the Idaho–Wyoming sector of the thrust belt (Fig. 2), occurred between Coniacian and earliest-Eocene times ($\approx$88–58 Ma), accommodating at least 65 and perhaps as much as 90 km of shortening, all of which occurred within previously cratonic supracrustal rocks (Royse *et al.* 1975). As in the southern Canadian Rockies, the locus of upper-crustal shortening does not represent the region of maximum crustal thickening, which must lie farther W (e.g. Coney & Harms 1984), beneath terrane also shortened during Jurassic–Early Cretaceous time. Like British Columbia (e.g. Read & Brown 1981; Klepacki *et al.* 1985), the 'hinterland' of the Sevier thrust belt was probably shortened during this time interval, and may have experienced periods of extension as well (Burchfiel *et al.* 1970; Chen & Moore 1982; Allmendinger & Jordan 1981; Allmendinger & Platt 1983; Miller 1983; Jordan & Allmendinger 1983). However, it may not have been until the Late Cretaceous that crustal thickness in the orogenic terrane exceeded that of cratonic North America.

Within the Idaho–Wyoming sector of the thrust belt, both thin-skinned thrusting (in the W) and Laramide-style uplifts (in the E) were active during the Palaeocene, but Laramide-style tectonism continued at least into latest early-Eocene time, and perhaps even later into the Eocene (Dorr *et al.* 1977). S of that sector, in the central Utah segment of the thrust belt, thrusting appears to have persisted no later than the deposition of the latest-Cretaceous Price River Formation (Burchfiel & Hickox 1972; Armstrong 1968). Analysis of foreland-basin deposits in central Utah (Lawton & Mayer 1982) indicates that thrust faulting occurred primarily between Cenomanian and Campanian time, between approximately 93 to 75 Ma. At about 70–75 Ma, shortening at the latitude of central Utah was restricted to Laramide-style tectonism of the the craton in Colorado, which occurred no earlier than the Campanian/Maastrichtian boundary ($\approx$74 Ma), the last time at which marine strata blanketed the entire region (fig. 2; Tweto 1975). Laramide tectonism had begun in many areas by latest-Maastrichtian time (67 Ma), and, in the case of some of the uplifts (e.g. White River uplift in NW Colorado), continued into earliest middle-Eocene time (i.e. at least until $\approx$52 Ma; Tweto 1975), possibly overlapping in time with extensional tectonism in the Pacific Northwest (Fig. 2).

To the W, over 50% of the exposed area of plutonic rock in the central portion of the Sierra Nevada batholith was emplaced in the interval between 100 and 80 Ma (Chen & Moore 1982), coeval with the most intense period of shortening in the thrust belt to the E (Fig. 2). Within the region of Laramide uplifts, plutonism and volcanism began locally as early as 74 Ma, but generally no later than approximately 70 Ma (Obradovich *et al.* 1969). Most K–Ar ages of shallow-level plutons in the Laramide belt fall between about 70 and 60 Ma, at the same time as the early part of the Laramide Orogeny (Tweto 1975). It appears that the end of thrust-belt tectonism and Sierran plutonism (74–80 Ma) and the beginning of Laramide tectonism and plutonism (70–74 Ma) in Colorado were separated by no more than about 10 My and could have been simultaneous or partly overlapping. This swiftness of the shift in plutonism may argue against hypotheses which favour a flattening Benioff zone beneath North America at this time as an explanation for the eastward shift in tectonism and plutonism of latest-Cretaceous time (e.g. Coney 1978).

We emphasize that Late Cretaceous Sierran plutonism occurred well to the W both of early extensional activity (discussed below) and of Cretaceous orogenesis in the thrust belt—in contrast to areas farther N, where extensive Late Cretaceous plutonism took place adjacent to or within the loci of tectonism (Figs 2 & 3).

Pre-mid-Miocene extensional tectonics and associated magmatism

In contrast to the Eocene onset extensional tectonism and intermediate volcanism N of the Snake River Plain, Cenozoic extensional deformation to the S did not begin until latest-Eocene or early Oligocene time. The early phase of extension, here defined as pre-mid-Miocene (before 18–15 Ma), occurred in the eastern Great Basin in a relatively narrow belt that was less than 100 km wide at the surface before extension (Fig. 3). The onset of extension at a particular latitude was synchronous with a generally southward-migrating belt of intermediate to silicic volcanism. At any given time, this magmatic belt trended E–W, at a high angle to the continental margin and was of the order of several hundred kilometres long—much greater than the width of the coeval extensional belt (see e.g. Snyder *et al.* 1976).

The earliest documented extensional events in the Great Basin had begun by the early Oligocene, or perhaps as early as latest Eocene time. Solomon *et al.* (1979) and Smith & Ketner (1977) report both block faulting and folding of the late-Eocene-early-Oligocene tuffaceous clastics of the Elko Formation. An angular unconformity above the deformed Elko, which contains tuff beds as young as 37–38 Ma (latest Eocene), is overlapped by volcanics that give ages as old as 35 Ma, suggesting a latest Eocene–earliest Oligocene age for the onset of extension.

To the S of the Elko area in the Northern Egan Range, Nevada, Gans (1982) and Gans & Miller (1983) have shown that 36-Ma old dykes cut normal faults with up to 1 km of displacement. Eruptive units in the same area, also dated as early Oligocene, were deposited prior to a major tilting of the Egan Range (Gans 1982) block indicating that extension and tilting took place over a brief period in the early Oligocene.

In the northern Toiyabe Range of central Nevada large normal faults pre-date the deposition of 28.5 Ma-old volcanic rocks that were subsequently extended by a younger set of faults (Smith 1984). The entire system is blanketed by relatively undeformed volcanics of late Oligocene–early Miocene age. Smith (1984) estimates extension in this area to be as great as 250%.

In the Raft River Range area, Compton *et al.* (1977) suggested that displacement on one of the larger detachments in the area occurred largely before the emplacement of 25 Ma-old stocks, since the metamorphic aureole around the plutons is only slightly offset by the fault. Jordan (1983) reported two younger-on-older faults in the same area that pre-date intrusion of the latest Eocene (38 Ma) Immigrant Pass pluton, although her interpretation that both faults were involved in an episode of recumbent folding may support a Mesozoic age for them.

Based on stratigraphic analysis of pre-volcanic Tertiary sequences throughout E-central Nevada, Fouch (1979) suggested that the pre-Oligocene Cenozoic palaeogeography consisted of a number of restricted lakes that shifted their depositional loci through time. Although Fouch (1979) suggested that the basins formed by tectonic disturbance during their Late Cretaceous to early-Oligocene period of deposition, the lack of thick sections of coarse detritus and angular unconformities within them indicates that major extension or shortening of the upper crust probably did not take place during pre-Oligocene, post-Cretaceous times. Here, as in the Pacific Northwest, the deposition of thin, conformable lacustrine sediments preceded volcanism and major extension, although for a much longer period of time in this case. These sequences, largely confined to the N of latitude 38°, are typically only a few tens of metres thick but locally may be several hundred metres thick. Their loci of deposition are centred about the narrow pre-mid-Miocene belt of extension (Fig. 3).

S of latitude 39°N, the onset of the early extension appears to have occurred during the late Oligocene (<30 Ma), as did the main period of intermediate to silicic volcanism. Early extensional tectonism included displacement on NE- and NW-trending faults that involve the 25 Ma-old Shingle Pass Tuff, which, in the Belted Range are cut by 14–17 Ma intrusive rhyolites (Ekren *et al.* 1968). Volcanic rocks younger than 17 Ma in the same region generally are cut only by a later set of N-trending faults. Immediately S of that region, in the northern Death Valley area, no normal faults of early-Miocene or Oligocene age are known, but the deposition of up to 1000 m of Oligocene and lower Miocene (?) Titus Canyon Formation in the Grapevine Mountains (Stock & Bode 1935; Reynolds 1969, 1976) may record the onset of extensional tectonism in this area. The basal Titus Canyon contains lenses of non-volcanic megabreccia, above which occur fossils of early-Oligocene age. The top of the formation is overlain by volcanic rocks between 22 and 20 Ma old. Whether the Titus Canyon represents a period of major extension, or is simply a younger analogy to the pre-volcanic sedimentary sequences farther N is not yet known.

Igneous activity that accompanied early extension in the northern Great Basin region resembles in several respects the Eocene magmatism of the Pacific Northwest. In particular, silicic volcanic rocks constitute a high proportion of the volcanic suite, especially in the region around the belt of major early extension (Stewart 1980). The importance of crustal melting in the genesis of this suite is emphasized by the aluminous character of many of the associated granitic rocks (Best *et al.* 1974; Miller & Bradfish 1980). Studies of Nd and Sr isotopes of the granitic rocks of this region suggest their origin principally by the melting of lower-crustal granulitic source materials (Farmer & De Paolo 1983).

Mid-Miocene and younger extensional tectonics and associated magmatism

Two major changes affected the Great Basin beginning between about 20 and 17 Ma, following the early phase of extension, the southward sweep of intermediate to silicic volcanism, and a brief lull in magmatism (McKee *et al.* 1970; Fig. 4). One is the predominantly basaltic to bimodal volcanism, which began in mid-Miocene time near the axis of the province in already-extended terrane, and within a few million years had spread widely across it (Christiansen & McKee 1978). The other major change is the widening of the extensional terrane. The region from the frontalmost part of the thrust belt to the area of extensive Late Cretaceous Sierran plutonism became involved in the extension. The widening of the affected area and the onset of basaltic and bimodal volcanism thus define a larger scale example of the pattern seen in the Pacific Northwest S of the Lewis and Clark line. This widening of the extensional terrane involved neither the cessation of extension in the core of the province nor the cessation of large-magnitude extensional tectonics (Figs 3 & 4).

In mid- to late-Miocene times, the sequence of basin sedimentation, succeeded by intermediate to silicic volcanism, followed immediately by large-magnitude extension in turn followed by predominantly basaltic volcanism occurs in a corridor from the Yerington area of the western Great Basin (Proffett 1977; Hardyman *et al.* 1984; Gilbert & Reynolds 1973) down to the Death Valley region in the southern Great Basin (e.g. Wright *et al.* 1981, 1984; Burchfiel *et al.* 1983; Stewart 1983; Hodges *et al.* 1984, 1986; Ekren *et al.* 1968). N of the Yerington area, large-magnitude extension is perhaps indicated by the steep dips of mid-Miocene volcanics in the Sonoma Range near Winnemucca, (see e.g. Gilluly 1967), suggesting that this part of the Great Basin may have been extended a great deal more than has been generally suspected (see also Zoback *et al.* 1981). N of the latitude of Winnemucca, the High Lava Plains of southwestern Oregon are blanketed by mid-Miocene and younger volcanics that have been broken by normal and strike-slip faults (Donath 1962). Lawrence (1976) analysed WNW-striking, regionally persistent shear zones across which he inferred differential extension had occurred, with increasing amounts of extension to the S.

It is uncertain how much extension has occurred in the High Lava Plains (Lawrence 1976). Firstly, because most of the exposed rocks are less than 16-Ma old, it is unknown how much pre-mid-Miocene extension may have occurred. Secondly, although stratal tilts within the extended volcanic terrane are typically not large, such an observation is insufficient to rule out large-magnitude extension there. For example, strata in the hanging wall of the Sevier Desert detachment (McDonald 1976; Allmendinger *et al.* 1983) as a rule dip at less than about 20°, yet this structure has accommodated several tens of kilometres of crustal extension (Wernicke 1981).

In the Death Valley area, as in the Oregon High Lava Plains, late Miocene to Recent extension terminates to the S against a strike-slip boundary, the Garlock fault (Hamilton & Myers 1966; Davis & Burchfiel 1973; Burchfiel *et al.* 1983). It is noteworthy that the Death Valley area, which represents one of the youngest large-magnitude extensional terranes, experienced the same cycle, noted elsewhere in the Great Basin and Pacific Northwest regions, of local sedimentation, intermediate magmatism, large-magnitude extension and finally basaltic or bimodal volcanism, but entirely within mid-Miocene to Quaternary times (Wright & Troxel 1973; Wright *et al.* 1984). Similarly, the Eldorado Mountains–Black Mountains extensional terrain (Anderson 1971; Anderson *et al.* 1972) developed between about 15 and 11 Ma amid an intermediate-volcanic field. These examples emphasize that the sequence we propose as 'typical' for the development of an extended terrane is independent of its time of development.

Extension within the narrow, pre-mid-Miocene belt continued during mid-Miocene and younger time, and locally may be of large magnitude, not having waned significantly in the last 10–15 Ma. For example, Snoke & Howard (1984) report large stratal rotations of 13.5-My old rhyolitic flows in the Elko area, the locus of some of the earliest extension in the Great Basin. Similarly, Compton (1983) mapped a large-scale detachment complex in the Raft River Range area that involves 11.5-My old volcanic rocks. The opening of the adjacent Raft River basin along a shallowly inclined detachment (Covington 1983) occurred in the last 15 My, and may still be active. Covington's (1983) reconstructions suggest about 30 km of transport of upper-plate rocks. Farther S in the pre-mid-Miocene belt, Bartley *et al.* (1984) have shown that large-magnitude extension was responsible for the development of the Miocene and Pliocene Horse Camp basin (Moores *et al.* 1968) in the Grant Range area, E-central Nevada.

E of the early belt, post-15 Ma extension, some of large magnitude, disrupted the frontal part of the thrust belt, from just S of the Yellowstone Plateau volcanic field to southern Nevada (Fig. 4). Detachments and rotated normal-fault blocks typically are downthrown to the W, and some have been shown to have reactivated older Sevier thrust faults (Royse *et al.* 1975). The magnitude of extension accommodated on these faults is quite varied, ranging from 7–8 km of supracrustal extension across the entire Idaho–Wyoming thrust belt (Royse 1983) to many tens of kilometres of extension in the Great Salt Lake, Sevier Desert, and southern Nevada sectors of the orogen. Davis & Burchfiel (1973), Guth (1981) and Wernicke *et al.* (1982, 1984) have shown that much of the 140-km translation of crustal blocks on large strike-slip faults in southern Nevada is absorbed by crustal extension between blocks. Based on seismic reflection profiling in the Sevier Desert area, Allmendinger *et al.* (1983) and Anderson *et al.* (1983) have suggested offsets of 30–60 km on the Sevier Desert detachment. Given that most of the rotated basin-fill there is of Miocene–Pliocene age and the fact that abundant Quaternary faulting occurs in the hanging wall of the detachment without offsetting it, the bulk of displacement on the detachment appears to be post-mid-Miocene, and it may still be active (Wernicke 1981; Anderson *et al.* 1983; Allmendinger *et al.* 1983; Smith & Bruhn 1984).

While most of the down-to-the-W extension within the thrust belt is post-mid-Miocene, there may be exceptions. Both Allmendinger *et al.* (1983) and Hopkins & Bruhn (1983) have suggested an Oligocene age of initiation for extension in the Sevier Desert and northern Wasatch Mountains areas, respectively. However, evidence for Oligocene extension of a magnitude comparable to that during Miocene and Pliocene times is lacking. Widespread Oligocene and lower-Miocene sheets of rhyolitic ash-flow tuff spanned areas much larger than the present ranges and basins without significant deflections caused by buried topography.

Las Vegas amagmatic corridor and the Mojave and Sonoran Desert regions

Considering the Great Basin as a whole, it is a reasonable generalization that one is never very far from a Tertiary volcanic–plutonic centre. Perhaps one of the most striking exceptions to this is a region W and N of Las Vegas, which experienced large-magnitude extension but shows no sign of igneous activity at any time during the Phanerozoic (Longwell *et al.* 1965; Anderson *et al.* 1972; Guth 1981; Wernicke *et al.* 1984). This 'amagmatic corridor' (Fig. 2; Anderson 1981) is the same area, as mentioned above, that was shortened mainly during the Jurassic (e.g. Carr 1980) with the latest phases occurring at about 90 Ma (Burchfiel & Davis 1971, 1981)—at least 20 My before the end of shortening in central Utah and about 40 My before thrusting ended in the Idaho–Wyoming sector of the thrust belt (Fig. 2). Despite the fact that this is one of the first areas to have thickened the craton, major extension did not begin until about 15 Ma—the latest time of initiation at any latitude along the belt. The southward cut-off in igneous activity is extremely abrupt (e.g. Eaton 1982), and some of the most extensive Tertiary intermediate and silicic volcanism in the Great Basin occurred just to the N of it, where volcanic accumulations are commonly 500–1000 m thick (Stewart 1980). Some of these large fields occur away from areas of major extensional tectonism. For example, the Marysvale field in southwestern Utah (Steven *et al.* 1984) contains a section up to 3 km thick near volcanic centres on the western edge of the Colorado Plateau. Other fields, however, such as the southern Nevada volcanic field (Christiansen *et al.* 1977), are in areas of major extension.

S of the 'amagmatic corridor', in the Mojave and Sonoran Desert regions, extension was of large magnitude and followed the pattern of early sedimentation, intermediate volcanism, extension, and then basaltic or bimodal magmatism. Like the Great Basin, this region experienced extension and intermediate magmatism between early-Oligocene and mid-Miocene times ($\approx$35–15 Ma). The principal distinction between this part of the extending Cordillera and areas to the N is that extension waned immediately following the mid-Miocene onset of basaltic magmatism, while extension continued farther N. Other key distinctions include its position within; (i) pre-Mesozoic cratonic North America; (ii) a long-lived Mesozoic magmatic arc; and (iii) a zone of latest-Cretaceous and early-Tertiary compressional orogenesis and magmatism (Haxel *et al.* 1984; see also Coney & Harms 1984). The more detailed synthesis by Glazner & Bartley (1984) suggests that the most intense magmatism and extension in the region migrated generally northward from the Tucson area during the mid-Oligocene to the Las Vegas area by the mid-Miocene—an apparent "mirror-image" of events farther N, with an axis about the 'amagmatic corridor' (Anderson 1981).

Neogene compression in western areas

As in the Pacific Northwest, the continental margin W of the extended Great Basin region was characterized by either tectonic quiescence or crustal shortening during extensional deformation farther E. Notable events include post-latest-Eocene folding and accretion of Franciscan rocks in the northern California Coast Ranges (e.g. Blake & Jones 1981); movement on the Coast Range thrust during the Tertiary (Page 1981); and Neogene transpression of the southern Coast Ranges next to the San Andreas Fault (e.g. Page 1981; Figs 3 & 4). The presence of mid-Miocene fossils in deep-sea deposits of the Coastal Belt Franciscan (McLaughlin *et al.* 1982) suggests shortening after that time along the margin. While Neogene transtensional basins appear to have opened locally adjacent to the San Andreas (e.g. Crowell 1974; Hall 1981), the dominant tectonic regime along the margin appears to have been compressional or transpressional during much of post-Eocene time. There is little evidence of extensional events affecting the entire margin during the Cenozoic.

The history of the compressional or transpressional shortening of the edge of North America during much of the Cenozoic provides an important constraint for models of coeval extensional tectonics occurring further inland (Sonder *et al.* this volume).

Summary and conclusions

In the Pacific Northwest, extension began in the middle Eocene ($\approx$53 Ma), possibly overlapping in time with the latest phases of foreland thrusting to the E. Its onset was more or less synchronous with intermediate to silicic magmatism. S of the Lewis and Clark line, extension continued in a broader belt after the mid-Miocene, simultaneously with local basaltic or bimodal volcanism.

In the Great Basin region, major extension did not begin until latest Eocene or early-Oligocene time ($\approx$38 Ma) and was initially concentrated in a narrow zone; this extension was also accompanied by intermediate to silicic magmatism. Following the onset of predominantly basaltic or bimodal volcanism in mid-Miocene time, extension developed over a much broader area than in pre-mid-Miocene time. Magmatism has tended to concentrate outward with time since the mid-Miocene, and since the beginning of the Quaternary has occurred mainly near the margins of the region. Post-mid-Miocene extensional strain is not of lesser magnitude than in the early belt in the Great Basin, and extension seems to be as active today in some parts of the Great Basin as it has ever been.

In the southern Nevada 'amagmatic corridor', extension did not begin until the mid-Miocene ($\approx$15 Ma), the latest onset time of any latitude in the Cordillera. This region also has the earliest time of cessation of Mesozoic thrust faulting.

We are impressed by what appears to be a consistent relationship between the timing of onset of extension and the intensity of the Cretaceous–early-Tertiary plutonic history of the various extended regions. Where extension began earliest N of the Snake River Plain at about 55–49 Ma, it took place astride a number of Late Cretaceous–early-Tertiary batholiths. Farther S in the Great Basin region, where only minor Late Cretaceous plutonism occurred within the overthickened crust, extension began 38–20 Ma. In the 'amagmatic corridor', where there are no Phanerozoic plutons, extension began at about 15 Ma, with the longest hiatus between compression and extension, an interval of at least 65 Ma. S of the 'amagmatic corridor,' where Late Cretaceous magmatism is prevalent (though apparently less extensive than in the Pacific Northwest), extension began at about the same time as in the northern Great Basin (e.g. Glazner & Bartley 1984).

We conclude that the locus of extension is controlled principally by crustal thickness, while its timing is governed by the thermal state of the lithosphere at the time of thickening. As we show in a companion paper (Sonder *et al.* this volume), the observations shown in Table 1 are consistent with calculations based on a simple thermal-mechanical model in which extension of the lithosphere results from gravitational spreading of a previously thickened crust. Because the onset of extension is, as a rule, accompanied by calc-alkaline magmatism, a lower crust at or near its minimum-melting temperature ($\approx$650–750°C) is apparently a requirement for it to begin. However, since magmatism of this type also occurs well away from extended regions, it does not appear to be the driving mechanism of extension, as has been proposed in some models.

We also emphasize that the continental margin W of the extensional terrane was the locus of crustal shortening during the Cenozoic, coeval in several places with major phases of extension to the E. Such a kinematic boundary condition is inconsistent with hypotheses that relate inland extension to extensional deviatoric stresses along the adjacent margin, induced by e.g. changes in plate motion.

Recent speculation that a decrease in Farallon–Pacific convergence rates is the cause of extension (Coney 1978; Engebretson *et al.* 1984; Coney & Harms 1984) is not supported by the observation in active systems that tectonic regimes in overriding plates show no consistent relationship to convergence rates (Molnar & Atwater 1978). For example, the Tonga–Kermadec and Peru–Chile systems both have convergence rates of about 10 cm yr^{-1}, yet the tectonics of the overriding plates are strongly extensional and compressional, respectively.

Engebretson *et al.* (1984) suggested that the progressive decrease in age of the subducting Farallon Plate may have brought about the slowing of convergence because of a change from negative to positive buoyancy of the downgoing slab. By contrast, Molnar & Atwater (1978) demonstrated a strong correlation between extensional tectonics and old subducting lithosphere, and between compressional tectonics and young subducting lithosphere. Thus, the reconstruction of Engebretson *et al.* (1984) would predict behind-the-arc extensional tectonics during the Cretaceous and early Tertiary, changing to compressional later in the Tertiary.

We also view the timing of the calculated major transition in plate motions at 40 Ma (Coney 1978) as being too young to explain the earliest-middle-Eocene (55–53 Ma) transition in tectonic style N of the Snake River Plain, where its timing is most tightly bracketed. While Coney (1972) has argued for a fundamental transition in Cordilleran tectonics at 40 Ma, this figure represents only the upper age limit for Laramide tectonism throughout much of the Cordillera. We could not find any examples of post-early-middle-Eocene ($\approx$52–50 Ma) strata deformed by Laramide compression. Based on this evidence, we feel a more likely time for a synchronous, Cordillera-wide transition, *if any*, is 55–50 Ma, centred in time on the peak in convergence rates calculated by Engebretson *et al.* (1984).

While we agree with these authors that some relaxation of horizontal boundary stresses is necessary for extension to begin, it is not clear that the calculated plate motions would predict such a relaxation. It would of course be incorrect to rule out plate-interaction forces as a major factor in Cenozoic Cordilleran tectonics. For example, reorientation of the horizontal stress axes during the past 17 My is likely best explained by variations in plate-interaction forces (Zoback & Thompson 1978; Zoback *et al.* 1981).

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