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TECTONIC SETTING AND VARIATIONS WITH DEPTH OF SOME CRETACEOUS AND CENOZOIC STRUCTURAL AND MAGMATIC SYSTEMS OF THE WESTERN UNITED STATES

ABSTRACT

Convergence of North American and eastern Pacific plates was slow during most of Cretaceous time; the subducting slab sank steeply below the advancing continent, and the magmatic arc was near the coast. Convergence was rapid during latest Cretaceous and early Paleogene time; the continent overrode the slab and was eroded against it, and the magmatic arc migrated far inland. Convergence slowed in late Paleogene time, and the slab again sank steeply. A strike-slip continental margin has evolved since middle Tertiary time.

Where rising arc magmas reacted with old continental crust, this vertical crustal column is seen to be typical: about 30 km depth, migmatites and granitic rocks of low-pressure-granulite facies; about 25-15 km, upper-amphibolite-facies migmatites and granitic rocks, many of them peraluminous, crystallized from melts cooler and wetter than those either deeper or shallower; about 15-4 km, crosscutting plutons of hornblende-biotite granitic rocks; about 4-0 km, calc-alkalic volcanic rocks, mostly as caldera complexes and ignimbrites, and as voluminous ash dispersed to mudstones and shales.

Accreted materials were metamorphosed beneath the leading part of the overriding continental plate when convergence was slow, and high-pressure rocks were cycled up into the gap above the sinking oceanic slab. During subsequent rapid convergence, accretionary-wedge complexes, metamorphosed at greenschist to lower amphibolite facies and locally blueschist facies, were underplated against tectonically eroded continental crust, beneath which they are now exposed.

Much of the foreland thrusting of preexisting stratal wedges was synchronous with steady-state arc magmatism. Gravitational spreading from the zone of great crustal thickening by magmatism may explain the thrusting. Syntectonic metamorphism deep in the thrust wedge records in part ambient geothermal gradients and in part magmatically perturbed gradients.

The western part of the continent was slowed by differential drag on the subducted slab during rapid convergence, and rotation of the Colorado Plateau relatively clockwise toward the continental interior produced Laramide crustal shortening. The great Laramide basement thrusts are seen on reflection profiles to flatten downward into anastomosing zones of ductile shear that define mid-crust lenses. Analogous mid-crust shear zones of the same age outline lenses exposed in south-central California.

Severe back-arc extension, orthogonal to the continental margin, affected magmatically heated Basin and Range crust during middle Tertiary slow convergence. Late Cenozoic oblique extension developed as the strike-slip continental margin evolved. Both orthogonal and oblique extensional regimes produced similar deformation. The middle crust was extended as lenses slid apart along ductile shear zones. The aggregate top--"detachment faults"--of these lenses increased in area as deep lenses emerged from beneath shallow ones. The brittle upper crust responded by block rotations. Range-sized fault blocks are allochthonous above the detachments, against which steeply rotated basin fills are truncated and new fill is deposited directly. Active range-front and strike-slip faults end downward against detachments. Most detachments originate at mid-crustal depths although some surface as range-front faults. Some detachments remain active even after tectonic denudation has brought them to the surface but others are themselves broken by new steep faults related to deeper detachments. The lower crust appears on reflection profiles to be extended by more pervasive ductile flow. The Basin and Range Mohorovicic discontinuity has been magmatically remade.

Similar extension affected Idaho and northeast Washington during Eocene time.

Neogene uplift of the western United States largely records mantle heating, inferred to be due in part to convection consequent on extension and in part to conductive heating of subducted lithosphere.

INTRODUCTION

The plate-tectonic settings and the geometric and temporal relationships of many Cretaceous and Cenozoic structural and petrologic assemblages in the western United States can be inferred with considerable confidence. Geologic and geophysical studies can be integrated to determine the vertical variations in these assemblages and thus to permit definition of the variations with depth of tectonic, magmatic, and metamorphic processes. This essay deduces such relationships in some of these systems.

Plate Motions

The plate regime affecting most of the western United States during Cretaceous and Paleogene time was one of subduction of eastern Pacific oceanic lithosphere of the Farallon (or the Kula) plate beneath North America. Convergence was slow during most of Cretaceous time, subduction was steep, and the continental magmatic arc--represented by the Peninsular, Sierra Nevada, Idaho, and other batholiths--lay within 300 km or so of the plate boundary. Convergence accelerated late in Cretaceous time, and slowed again in the Eocene (Engebretson et al., 1985; Jurdy, 1984; Rea and Duncan, 1986). During the period of rapid convergence, from about 75 to 40 m.y., the subducting slab could not sink out of the way of the advancing continent, and continental tectonic and magmatic styles were very different from those of earlier Cretaceous time. The belt of arc magmatism migrated rapidly far to the east during late Late Cretaceous time (Coney and Reynolds, 1977; Snyder et al., 1976). The base of the continental lithosphere was eroded tectonically against the subducting plate (Cross and Pilger, 1978); metamorphosed oceanic sedimentary and crustal rocks are exposed in windows through the continental crust in southern California. At the same time, the western interior of the United States was deformed compressively, and the Laramide Rocky Mountains were formed. When convergence slowed in middle Paleogene time, the subducting slab again sank steeply, trench rollback was more rapid than the advance of the continent, and severe extension affected much of the interior West (Molnar and Atwater, 1978); voluminous accompanying magmatism was dominantly silicic, intermediate petrologically between arc and extensional types. Shortly thereafter, the [western] Pacific plate came in direct contact with North

America, and a complex boundary dominated by strike-slip motion and oblique extension lengthened progressively along the continental margin as the subduction boundary shortened (Atwater, 1970; Dickinson, 1979; Dickinson and Snyder, 1979). Oblique late Neogene Basin and Range extension has been a response to the boundary change and has been accompanied by basaltic or bimodal basaltic-and-rhyolitic volcanism (Snyder et al., 1976).

Mechanism of Subduction

An understanding of the mechanism of subduction is critical to tectonic analysis of western North America, as of any region of convergent-plate tectonics. Much published paleotectonic analysis incorporates the misconception that plate shortening necessarily accompanies plate convergence. Subduction too often is visualized as the sliding of oceanic lithosphere down a slot fixed in the mantle beneath an overriding plate--and this indeed would require shortening in the advancing upper plate if it occurred. The common case, however, is that the hinge rolls back, away from the overriding plate, with a horizontal velocity equal to or greater than the velocity of advance of the overriding plate. Among those who have documented evidence of many types for this are Carlson and Melia (1984), Chase (1978), Dewey (1980), Garfunkel et al. (1986), Hamilton (1979), Malinverno and Ryan (1986), Molnar and Atwater (1978), and Uyeda and Kanamori (1979). Subduction commonly occurs at an angle steeper than the inclination of the Benioff seismic zone, which marks a position, not a trajectory, of the subducting plate.

A consequence of such subduction is that the dominant regime in an overriding plate above a sinking slab is one of extension or neutrality, not of shortening. I know of no active magmatic arcs, oceanic or continental, involving subduction of oceanic lithosphere without associated collision of light crustal masses, across which crustal shortening can be demonstrated. The Oligocene ashflows that form the great plateau of the Sierra Madre Occidental of Mexico must overlie a batholith dimensionally like the Cretaceous Sierra Nevada batholith of California, yet are subhorizontal. The smaller Oligocene batholith of the San Juan Mountains of Colorado is similarly capped by subhorizontal volcanic rocks. The late Oligocene and early Miocene arc magmatism of the southwestern United States was synchronous with severe extensional faulting. The migration of oceanic island arcs and the opening of back-arc basins behind them are manifestations of the generally extensional regime in overriding plates (Hamilton, in press, e).

Non-shortening explanations should, in my view, generally be sought for deformation in a plate above a steeply subducting slab. This includes the formation of the Sevier belt, the foreland thrust belt of Cretaceous age in the western interior States, but not the Laramide belt of true crustal shortening within what is now the Rocky Mountain region but had previously been part of the craton.

Accretionary Wedge and Fore-arc Basin

Extreme shear in a compressional regime is recorded by the Cretaceous and Paleogene Franciscan Complex of accretionary-wedge melange in coastal California. Such an accretionary wedge, however, represents weak surficial debris pushed in front of an advancing plate (Fig. 1), and does not require shortening of the lithosphere plate itself. The leading edges of overriding continental plates typically bear fore-arc basins of little-deformed strata, the presence of which precludes shortening of those thin, tapering parts of the overriding plates (Fig. 1; Hamilton, 1978, 1979). Such undeformed basins are present atop the thin leading edge even of the Pacific margin of South America (Coulbourn and Moberly, 1977), which most proponents of crustal shortening of overriding plates mistakenly assume to be the site of severe crumpling. The analogous Cretaceous and Paleogene fore-arc basin of California, which underlies the Great Valley and crops out in the eastern and medial Coast Ranges and in the western Transverse Ranges and regions to the south, similarly was little deformed during the long period of deposition of its fill. I have argued elsewhere (Hamilton, 1978, in press, e) that such a fore-arc basin forms, after arc reversal, atop oceanic lithosphere which was earlier generated behind a migrating island-arc complex that collided with a continent--in the case of California, in Late Jurassic time. Such a collision is followed by inauguration of new subduction landward beneath the seaward side of the aggregate, leaving a narrow strip of back-arc basin crust attached to the continental plate as its leading edge. The front of this oceanic strip is raised as accretionary-wedge melange is stuffed beneath it, forming the basin, within which depocenters of successively younger deposits are displaced successively landward.

PRODUCTS OF CONTINENTAL ARC MAGMATISM

Introduction

The long Cretaceous episode of steady-state subduction of oceanic lithosphere beneath North America was a period also of steady-state arc magmatism, the products of which we see now as a belt of great batholiths exposed at upper- and mid-crustal levels. Younger arc-magmatic assemblages are exposed at various crustal levels farther east. Variations with depth in these complexes are broadly similar to those in continental arc-magmatic terrains of all ages around the world. There are global consistencies in the dominant rock assemblages of different levels in continental crust (cf. Fountain and Salisbury, 1981; Hamilton, 1981a; Kay and Kay, 1981; Tarney and Windley, 1977; Weaver and Tarney, 1981; Wells, 1980; and Windley, 1981). No two crustal sections are identical, but the similarities are more impressive than the differences because there is a mainline of crustal evolution. Analyses of western United States batholiths in these terms have been made by Hamilton (1981a, in press, d), Hamilton and Myers (1967, 1974), Hyndman (1981, 1983), Ross (1985), and Sams and Saleeby (this volume, chapter xxx). Understanding of systematic variations permits integration into tectonic analysis of depth of formation of rock assemblages.

Magmatic arcs now form, along either oceanic island arcs or active continental margins, primarily above those parts of subducted slabs of oceanic lithosphere whose tops are at depths of about 100 km (Fig. 1). The initial melting at depth presumably is caused by water expelled by breakdown of hydrous metamorphic minerals in crust, partly-serpentinized mantle, and sedimentary rocks of subducted oceanic lithosphere; the primary magmas must be equilibrated with overriding lithospheric mantle and hence be very mafic basalts. The volcanic rocks erupted at the surface, however, vary systematically in average composition with the character of the crust and mantle through which the magmas have risen. Magmas reaching the surface in a young oceanic island arc are dominantly basaltic; in a mature island arc, andesitic; and in a continental arc, rhyodacitic or quartz latitic. Such variations occur in arcs of the contrasted types, and they occur also as a progression wherever a continuous magmatic arc changes along trend from oceanic to continental (Hamilton, 1979, in press e). Lavas erupted even in the most primitive oceanic arcs must be products of series of partial or complete equilibrations by fractionation, zone refining, assimilation, and secondary melting in the mantle and crust. Fractionates must be complementary to voluminous more mafic materials.

Facies and Equilibria

Facies fields (Fig. 2) apply equally to metamorphic and igneous rocks. Igneous rocks do not have the compositions of melts, for fusibles are lost during crystallization, and solids equilibrated elsewhere commonly are contained in melts. Much of igneous petrology represents an attempt to demonstrate equilibria between solids and liquids. Confirmation is too often interpreted as indicating that liquid plus solid equal a source rock whose partial melting produced the liquid, or equal a magma whose fractionation produced the solid. Such simplistic concepts scarcely begin to account for the observed variations of crystalline rocks with depth of exposure. O'Hara and Mathews (1981) demonstrated the futility of most conventional geochemical modeling even for the simplest systems in which no wallrock reactions are involved and little variation occurs with depth. Walker (1983) reviewed complexities of magmatic evolution that are receiving increasing attention.

Deep continental crust consists largely of rocks in various granulite facies. There is no standard nomenclature for such rocks, which have received far less study than have the rocks of the middle crust; my own suggestions are summarized in Fig. 2. Reactions from amphibolite to granulite facies are dominated by dehydration, whereas reactions between the several granulite facies represent primarily decreasing stability of plagioclase (successively with olivine, orthopyroxene, and clinopyroxene), and increasing density, in the direction of increasing ratios of pressure to temperature. A garnet-amphibolite facies, reflecting intermediate activity of water, often intervenes between amphibolite and middle-pressure granulite; the P-T field of garnet amphibolite is poorly constrained, and it is omitted from the figure.

Volcanism

Active magmatic arcs developed on mature continental lithosphere above subducting oceanic lithosphere, as in Sumatra and the Andes, are characterized by fields of silicic volcanic rocks, dominantly ashflow sheets erupted from large calderas atop granitic plutons, and by stratovolcanoes of rocks of intermediate composition. Little-eroded fossil systems include the vast belt of middle Tertiary ignimbrite fields of the San Juan Mountains of Colorado, Mogollon Plateau and other tracts in New Mexico and Arizona, and the Sierra Madre Occidental belt in Mexico. In the San Juan Mountains, calderas--which have diameters to 40 km, and from each of which great ashflow sheets were erupted--are contiguous or overlapping and, with geophysical data, define an underlying shallow, composite batholith (Lipman, 1984). Where erosion has penetrated such volcanic superstructures, the ashflows frequently are seen to cap plutons from which they were erupted. An example is the Late Cretaceous Boulder batholith of Montana (Hamilton and Myers, 1967, 1974). Most large "epizonal" and "mesozonal" plutons probably breached to erupt voluminous volcanic products; many plutons must form capped largely by their own volcanic ejecta, and be in effect gigantic mantled lava flows. The largest pluton yet mapped in the Cretaceous Sierra Nevada batholith, the Mount Whitney pluton, is about the same size, 25x80 km, as the largest known young caldera in an active magmatic arc, the late Pleistocene Lake Toba caldera of Sumatra.

Silicic magma chambers are zoned thermally and compositionally (Hildreth, 1981). Eruptions are generally from the volatile-rich tops of chambers and drain further volatiles from deeper in the chambers. The most highly fractionated magma is expelled first and hence is deposited stratigraphically lowest within ignimbrite sheets, which are produced primarily by the radial outflows of series of collapsing magma fountains. Volcanic rocks typically are more silicic and alkalic than are the plutons left beneath. Relatively high-pressure minerals (as, muscovite) in uncommon ignimbrites require that some chambers vent abruptly from depths as great as 10 km, but most ignimbrites have shallow sources (cf. Fig. 3).

Volcanic Ash, Hydrocarbons, and Uranium

Many accumulations of hydrocarbons and of uranium may be indirect byproducts of arc magmatism. Volcanigenic shales appear to be major hydrocarbon source rocks, as Weaver (1960) early argued. Clay altered from silicic volcanic ash is dominated by smectite (interlayered illite and montmorillonite-beidellite). Such clays absorb organic molecules, hence tend to be rich in organic material and thus to be potential source rocks. Dehydration of the water-rich montmorillonitic layers to more layers of illite during burial metamorphism occurs in steps, which in part are at conditions appropriate for the maturation of hydrocarbons, and this probably is a major factor both in geopressuring shales and in facilitating migration of hydrocarbons once formed (Bethke, 1986; Bruce, 1984; Burst, 1969; Weaver, 1960).

An enormous volume of ash is dispersed into the atmosphere during major ignimbritic eruptions. The volume of airfall ash on the Indian Ocean floor from the late Pleistocene Toba caldera eruption of Sumatra is about 1000 km^3, equal to the volume of the comagmatic on-land ignimbrites (Ninkovich et al., 1978). The shales and mudstones of the western interior of the United States from the Upper Triassic section upward are dominantly volcanigenic, and represent the air- and water-transported equivalents of the batholiths and ignimbrite fields farther west. Thus, altered volcanic ash comprises about 75 percent, by volume, of the extensive Upper Cretaceous shales of the Rocky Mountains and Great Plains (Schultz, 1978). The ash has been recycled repeatedly, and the shales and muds of the Gulf Coast and Gulf of Mexico also are dominantly volcanigenic. By contrast, the shales of the Atlantic margin of North America are dominated by clays produced by weathering of non-volcanic materials. The great contrast in hydrocarbon productivity of Gulf and Atlantic provinces may be due to the contrast in mineralogy, hence sources, of clays.

The uranium deposits in sedimentary rocks in the western States mostly are associated with nonmarine mudstones rich in silicic ash, and similarly may be largely byproducts of magmatism far to the west. (Most authorities on the deposits have sought more local sources.) Uranium is readily leached from such ash, and transported through nearby sandstones, by oxidizing water; it is deposited where fluids encounter reducing conditions, as at concentrations of organic matter.

Upper and Middle Crust

Beneath the volcanic rocks of continental magmatic-arc complexes are upper-crustal plutons and composite batholiths of calc-alkalic granitic rocks. Among such complexes are those of the great magmatic arc, formed during a span that included most of Cretaceous time, that lies along the Cordillera of North America. The arc setting is shown by the relationship to the coeval accretionary wedge and fore-arc basin to the west; the geometry of wedge, basin, and magmatic arc is strikingly like that of modern Sumatra (Hamilton, 1978; Fig. 1). The Mesozoic magmatic complexes have been variably uplifted and eroded, and are exposed at various crustal levels that show systematic variations with depth.

Sierra Nevada batholith. The Sierra Nevada batholith of California is a composite of hundreds of plutons, mostly of Cretaceous age, dominantly tonalite and granodiorite in the west and more felsic granodiorite and monzogranite in the east (Bateman, 1979; Bateman *et al.*, 1963; Noyes *et al.*, 1983). Plutons mostly are steep sided, show by *their* flow structures *that* they spread outward from rising, replenished medial zones, and have contact-metamorphic aureoles. The eastward compositional progression of the granitic rocks broadly parallels that of the petrologic maturity of pre-batholithic rocks, from the accreted island-arc and accretionary-wedge materials of the west to miogeoclinal assemblages (and, hidden at depth, Precambrian basement?) of the east. The ratio of continental-crustal to mantle components in the granitic rocks increases correspondingly eastward (DePaolo and Farmer, 1984; Kistler and Peterman, 1978). The compositional changes also represent an age progression, for the Cretaceous plutons become in general younger eastward, from 125 m.y. in the west to 80-90 m.y. in the east (Chen and Moore, 1982; Stern *et al.*, 1981). The early assumption by some of us (*e. g.*, Hamilton, 1969) *that* the eastward increase in such variables as the K_2O/SiO_2 ratio represented increasing height above the subducting slab of the time is not valid.

Depths of crystallization of central Sierran plutons can be inferred from broad petrologic features although little petrobarometry has been attempted of either granitic or metamorphic rocks. Crystallization at depths of only 3-10 km is indicated for medial and eastern granites by the few detailed petrologic studies (*e. g.*, Noyes *et al.*, 1983), by such regional petrologic features as the absence of primary muscovite in granitic rocks and the prevalence of andalusite (often with muscovite but not biotite) in aluminous metasedimentary rocks (*cf.* Fig. 3), and by the local preservation of volcanic roof rocks. In general, western Sierran plutons crystallized deeper--no volcanic roof rocks remain, primary muscovite occurs in leucogranites, biotite is ubiquitous with sillimanite although kyanite has not been reported--but still markedly shallower than the depth (13 km?; Fig. 3) of the aluminum-silicate triple point. Individual plutons are bounded sharply, and generally steeply, against each other and against the contact-metamorphosed rocks that separate many of them. Large plutons crystallized over spans of several million years each as new magma was introduced into their interiors, and typically are broadly zoned, the margins representing the hottest and dryest magmas (Bateman and Chappell, 1979; Bateman and Nokleberg, 1978; Chen and Moore, 1982; Noyes *et al.*, 1983). Refractory plagioclase and hornblende were carried upward with the melts of many plutons of intermediate composition (Bateman and Nokleberg, 1978; Noyes *et al.*, 1983), whereas other plutons, mostly leucogranites, crystallized *from* nearly complete high-level melts (Bateman and Chappell, 1979). Migmatites are developed only as local contact phases except in the most deeply eroded tracts in the far west.

Pre-Cretaceous rocks form a broad, discontinuous belt along the east edge of the central part of the batholith. Cambrian to Permian sedimentary rocks are overlain by Upper Triassic, Jurassic, and lowermost Cretaceous volcanic rocks, which are dominantly the rhyodacitic ejecta of arc-magmatic plutons. Although much deformed also in the White and Inyo Mountains, just to the east of the Sierra Nevada, the section is there mostly upright and gently to moderately dipping; but the section rolls downward to the west to steep to vertical west dips in and adjacent to the Sierra Nevada, where it is contact metamorphosed and much more highly deformed. Large Late Cretaceous plutons of the main Sierra Nevada batholith (the Cathedral Peak pluton: Fig. 4; the similar Mono Recesses and Mount Whitney plutons; and the Mount Givens and other plutons) have complex contacts but in a general way lie with steep intrusive contacts against the west edge and stratigraphic top of this faulted pre-Cretaceous section (*cf.* Bateman, 1965, Bateman and Moore, 1965, Bateman *et al.*, 1983, Fiske and Tobisch, 1978, Rinehart and Ross, 1964, and Tobisch *et al.*, 1986, none of whom made this point). I regard these contacts as the depressed and outward-pushed *floors* of essentially extrusive, bathtub-shaped plutons, and not as the "roof pendants" of popular assumption. Elongate semiconcordant Jurassic plutons within the metavolcanic section were rotated with the metavolcanic rocks in Late Cretaceous time. Some older and more deeply eroded large plutons farther west in the batholith likely also formed with extrusive relationships to flanking rocks.

Volcanic rocks, mostly ignimbrites, comagmatic with Cretaceous plutons are preserved primarily between plutons but cap them locally. A caldera complex atop the granitic pluton whence it came was documented by Fiske and Tobisch (1978).

The middle-crust substrate of the batholith is exposed at the south end of the Sierra Nevada batholith, which was tilted and eroded obliquely during latest Cretaceous or early Paleogene time (Elan, 1985; Ross, 1985, in press; Sams and Saleeby, this volume, chapter xxx; Sharry, 1981). Depth of formation of rocks now at the surface increases, over a distance of about 75 km, from less than 10 km to about 30 km. The eastern Sierran belt of felsic plutons trends southward into its substrate of mostly leucocratic granodiorite. Widespread primary muscovite in the granodiorite and the abundance of sillimanite and absence of andalusite in the wall rocks (although kyanite has not been reported) are indicative of middle-crust crystallization (*cf.* Fig. 3). Wall rocks are migmatitic or gneissic: a broad terrain was *heated* to granite-solidus temperature at a pressure great enough to permit richly hydrous melts. The medial and western Sierran belts of mostly granodioritic and tonalitic plutons trend southward into a substrate of variably migmatitic hornblende tonalite and on into tonalitic and more mafic rocks containing brown hornblende, orthopyroxene, clinopyroxene, reddish biotite (which presumably has relatively high ratios of Ti and Mg to Fe), and, with hornblende or orthopyroxene (but not clinopyroxene), abundant pink or red garnet. Mineral assemblages are those of the garnet-amphibolite and low-pressure-granulite facies (Fig. 2). Metapelites in the transitional zone appropriately include the assemblage cordierite + sillimanite + almandine + K-feldspar (Elan, 1985), indicative of the middle-pressure part of the low-pressure-granulite facies, whereas cordierite was not found by Ross (in press) in the more deeply eroded southern rocks.

Peninsular batholith. A southern sector of the Cretaceous composite arc-magmatic batholith is exposed in the Peninsular Ranges of southwestern California and northern Baja California (Silver *et al.* 1979; Todd and Shaw, 1979). Like the Sierra Nevada batholith, the *southern* batholith becomes both younger and more silicic, potassic, and radiogenic eastward, thus showing increasing incorporation of old crustal rocks, or of terrigenous strata proxying for them, in the magmas in that direction. Unlike the Sierra, much deeper rocks are exposed in the east than in the west. Coeval calc-alkalic volcanic rocks are widely preserved atop the shallow, crosscutting plutons of the far western part of the batholith. In the east, by contrast, mid-crustal migmatites and gneisses of uppermost amphibolite facies and concordant granites, including many crystallized from richly hydrous melts and containing primary muscovite, are exposed; dips of foliation and layering are mostly gentle to moderate.

Salinia. A belt of batholithic rocks of middle and Late Cretaceous age is displaced 350 km relatively northwestward from the southern Sierra Nevada along the Neogene San Andreas fault. Upper-crust granites and mid-crust amphibolite-facies migmatites are both widely exposed, and deeper-seated rocks of garnet-amphibolite and low-pressure-granulite facies are exposed in the west-central part of the terrain (Compton, 1960; Ross, 1976, in press). The plutonic rocks are equivalent petrologically and chronologically to the medial parts of the Sierra Nevada and Peninsular batholiths (Kistler and Peterman, 1978; Mattinson, 1978; Ross, 1978). This "Salinian block" is now bounded on both sides by the coeval Franciscan accretionary-wedge complex, from which the plutonic rocks are separated by the San Andreas fault on the east and the Sur-Nacimiento megathrust on the west. Apparently the batholith was sliced longitudinally by the San Andreas fault after its western part and the other belts that initially intervened between it and the Franciscan had been removed by subduction-related tectonic erosion, as discussed subsequently.

Idaho batholith. The Idaho sector of the Cretaceous batholithic belt is exposed mostly at mid-crustal levels (Chase et al., 1983; Hyndman, 1980, 1981, 1983). Shallow features of Sierra Nevada type--steep, sharply-bounded plutons of massive rocks, septa of contact-metamorphic rocks, preserved coeval volcanic rocks--are largely lacking. The migmatitic floor of the batholith is exposed in the broad Salmon River arch, which trends westward across the center of the batholith. The part of the batholith, the Bitterroot lobe, north of this arch is rimmed by deep-seated gneisses and migmatites of upper amphibolite facies, the petrology of which (as, aluminum-silicate assemblages that include kyanite) indicates a general depth of formation of about 12-20 km, and is in broad aspect a synformal mass, the remnant of a great batholithic sheet (Hyndman, 1983). The base of the batholith is a zone of intercalated granitic, migmatitic, and gneissic rocks, in which dips are more commonly steep or moderate than gentle, and in which the proportion of granitic rocks decreases downward through a vertical range of 2 km as exposed in the great canyons of central Idaho (Cater et al., 1973). Granitic rocks are characterized by primary muscovite as well as biotite, hence crystallized from magmas too hydrous to have risen to upper-crustal levels (Hyndman, 1983; Fig. 3). Migmatitic rocks near the west margin of the batholith include such indicators of moderately high pressures as garnet amphibolite and, in granitic rocks, magmatic epidote (Zen, this volume, chapter xxx).

Also present in the medial and eastern parts of the Idaho batholith are Eocene igneous rocks: deep-seated plutons and gneisses on the one hand, and large epizonal plutons and ignimbrites and other volcanic rocks erupted from them on the other hand (Cater et al., 1973; Chase et al., 1983). Tectonic denudation accompanying Paleogene crustal extension may have produced the juxtapositions of deep and shallow rocks, as discussed in a subsequent section.

Arc rocks east of the Sierra Nevada. In part of Jurassic time, and again during latest Cretaceous and Paleogene time, North American and eastern Pacific lithospheric plates converged more rapidly than they did during Early and early Late Cretaceous time, and the magmatic arc formed to the east of the Idaho-Sierra Nevada-Peninsular batholithic belt, in the Basin and Range and other regions. Extremely variable uplift and erosion has affected these eastern magmatic complexes, which can now be seen at all levels of exposure from ashflows down through shallow batholiths and the hydrous-magma bases of batholiths atop migmatites, to middle-crust migmatites and concordant granitic sheets. Much of the erosion was tectonic, for middle-crust rocks are exposed primarily beneath extensional Tertiary detachment faults. Most upper-crust plutons within layered rocks appear to be sills inflated thickly to mushroom shapes. Thus, the small batholiths, mostly Jurassic, of the Inyo Mountains in eastern California in general have steep, outward-dipping contacts, which follow limited stratigraphic zones within the thick Paleozoic section for long distances (Ross, 1967). Best known of the batholiths that reached the surface over a broad area is the composite Late Cretaceous Boulder batholith of Montana, which is 100 km long and 50 wide and which spread laterally over a floor of all pre-magmatic rocks, Middle Proterozoic to Upper Cretaceous, pushing them down so that they steepen toward and dip beneath it; the batholith is overlain only by coeval volcanic rocks, and is in effect a gigantic extrusive mass (Hamilton and Myers, 1967, 1974). Some Sierra Nevada plutons are analogous, as noted previously.

The exposed middle-crust granites, including many as young as middle Tertiary, commonly contain primary muscovite and in many cases garnet, and have isotopic ratios of lead, strontium, and neodymium indicative of generally much more inclusion of crustal material in their melts than do the shallow granites (DePaolo and Farmer, 1984; Haxel et al., 1984; Kistler et al., 1981; Miller and Bradfish, 1980). Some of these plutons have contact-metamorphosed aureoles but many others lie in rocks metamorphosed regionally at amphibolite facies. That these granites crystallized in the middle crust, and hence have depth significance, is indicated by such features as kyanite in wall rocks near some of them, and the richly hydrous character of the magmas recorded by the granites, migmatites, and voluminous pegmatites.

Lower Crust

Exposures of late Phanerozoic magmatic terrains in the western United States represent depths of formation no greater than the upper part of the lower crust, but lower continental crust is exposed in many other parts of the world beneath migmatite terrains such as those of the deeply eroded parts of the Cretaceous batholiths. Typical lower crust, which I assume to belong mostly to the arc-magmatic mainline, consists of distinctive igneous and metamorphic rocks equilibrated under low- or middle-pressure granulite conditions and typically retrograded, particularly in middle-pressure granulite facies but locally to high-pressure granulite and even eclogite facies (Hamilton, 1981a, in press, d). Such retrogression can accompany isobaric cooling (Fig. 2) although many authors assume tectonic settings in which pressure increases with time. Exposed sections of deep crust, calibrated petrologically as representing depths of 30-45 km, generally display magmatic differentiates of granodioritic, tonalitic, and gabbroic bulk compositions, intruded from the mantle, and also the products of granitic magmas melted from wallrocks by the heat of those intrusions. The characteristic differentiates--gabbro, norite, anorthosite, and hypersthene granite (charnockite)--occur either as great layered complexes of denser rocks beneath lighter ones or as thinner intercalations in other rock types. Pre-existing rocks often include metasedimentary rocks, such as quartzite, marble, and metapelite, which have lost most of their initial combined water. A major problem for interpretation is that exposed lower crust is dominantly of Precambrian age, and it is unclear to what extent younger deep crust is similar.

Structure

Contacts between and within granitic and metamorphic rocks typically are steep in shallow complexes and undulating with gentle dips in deep ones. The tendency toward gentle dips in the middle and deep crust is accentuated by ductile transposition accompanying retrograde metamorphism in many regions. Much such metamorphism and deformation probably records postmagmatic extension or shortening, but likely much also records synmagmatic gravitational flow of heated rocks that are displaced outward and downward by rising magmas and then flow subhorizontally beneath shallow spreading batholiths. Depression to deep crustal levels of supracrustal rocks may be due primarily to the repeated injection and eruption of magma above them rather than to the compressive or thrust tectonics commonly inferred.

Wallrock Deformation

Contact-metamorphic wallrocks of Sierra Nevada plutons commonly display superposed folds, more or less coaxial, which often are taken as evidence for successive compressive deformations of widely separated ages (e. g., Nokleberg and Kistler, 1980). Implicit in such analyses of polyphase folding, which mostly are unconstrained by data on changes in external shape of lithologic units, is the assumption that folding in metamorphic rocks records shortening in accordion fashion, and hence that refolding requires a new shortening. I see synmetamorphic folding, by contrast, as recording primarily a combination of pure and simple shear--of flattening plus discontinuous laminar flow--and any number of folds can be superposed within a continuum of deformation by such a mechanism. I described from southeastern California thin, distinctive units of metasedimentary rocks that are complexly deformed internally, with superimposed isoclinal and recumbent folds, yet that have plane-parallel external contacts which preclude accordion folding and require layer-parallel laminar flow with extreme flattening (Hamilton, 1982). Although multiple episodes of deformation must indeed often be recorded in metamorphic rocks, the geometric evidence commonly presented for them--the superposition of coaxial folds--is insufficient to demonstrate their reality. The dominant cause of deformation in contact-metamorphic wallrocks of upper-crust plutons is, I infer, the gravitational rise and spreading of the plutons and complementary downward flow of wallrocks, not regional shortening. Tobisch et al. (1986) argued on other grounds that the synmetamorphic deformation of eastern Sierran wallrocks, for which Nokleberg and Kistler (1980) among others have deduced sequential older deformations, is of Cretaceous age.

Heat and Water

The mainline of crustal evolution involves heating much of the deep and middle crust to the temperature of granite magma, which temperature is controlled by water content (Fig. 3; Hamilton, 1981a). Mature magmatic-arc continental crust consists of largely magmatic rocks in upper sections, of generally more pre-existing rock than new magmatic material in middle sections, and of dominantly magmatic rocks in deep sections. Most of such a crustal column was heated 300-500°C above steady-state geotherms. The enormous influx of mantle heat must have been carried upward in hot material which I deduce to be, in general, magma of arc origin.

Water in micas and other hydrous minerals of wall rocks increases upward in the crust, whereas the solubility of water in melts increases downward. Only in the middle crust is water generally abundantly available in wall rocks and is pressure adequate to maintain a high water content in magma, which hence typically is warm and wet, and does the setting permit accumulation of heat needed to raise large volumes of rock to solidus temperatures. There is little water in the deep crust, so magmas there are dry and hot.

Ordering of complexes by depth of formation permits general interpretation of the evolution of upper mantle and crust in terms of magmas

that originate as very mafic basaltic liquids at depths near 100 km (Fig. 1). The evolution of crustal magma is profoundly influenced by the availability and behavior of water (Fig. 3). The rising magma evolves by zone refining, exothermically crystallizing refractories and endothermically assimilating fusibles. Little mantle material need be present in the final melts, but mantle heat carried by the magma is the primary source of warming of the crust above ambient geotherms.

Olivine, pyroxenes, and garnet are mostly crystallized from the magmas within the subcontinental mantle: arc magmas rising to depths of 40 km in continental lithosphere mostly have evolved to compositions in the range from gabbro to granodiorite, and are relatively anhydrous. Deep-crustal crystallization, assimilation, and metamorphism produce norite-anorthosite-charnockite magmatic complexes and metamorphic rocks typically in middle-pressure granulite facies. Magmas that pass through or rise from this zone produce relatively dry migmatites, in the deeper part of the middle crust, in low-pressure granulite facies. Magmas rising higher commonly assimilate much water released by breakdown of heated wallrock micas and other hydrous minerals, or produce secondary melts by heating of hydrous rocks, so wetter migmatites, of upper amphibolite facies, are formed in the upper part of the middle crust. Magma once hydrated, and hence cooled, cannot rise appreciably above the level at which water pressure exceeds load pressure (Fig. 3), and it crystallizes in the middle crust. The upper part of the middle crust is characterized by migmatites that enclose large and small sheets of pegmatites and low-temperature granites, the latter typically peraluminous (having molecular proportions of Al_2O_3 greater than that of $K_2O + Na_2O$; this is expressed mineralogically by the presence of muscovite, garnet, or other aluminum-rich minerals).

Enrichment in water and alumina is greater for magmas in metapelitic wallrocks than for those in old continental crust, and in one bit of popular terminology sediment-equilibrated granites are referred to as "S-type granites" (White et al., 1986). Such analysis is often accompanied by the unwarranted assumption--as by Clemens, 1984--that equilibration requires crustal melting by heat mysteriously conducted into the crust and unrelated to mantle magmatism. As Miller (1986) emphasized, the "S-type" terminology appears to have outlasted its usefulness and to have degenerated into an exercise in picking nits.

The peraluminous granites of the western United States mostly were equilibrated with older plutonic rocks rather than metapelites. Many of these granites are temporally and spatially related to the exceptional subduction regime operating during latest Cretaceous and Paleogene time, as discussed in a subsequent section.

Magmas that cross the middle crust without equilibrating there can continue to rise because they remain relatively hot and dry. Voluminous magmas that reach the upper crust spread as shallow, steep-sided batholiths above the deeper migmatites and concordant granites, and erupt as capping ashflow sheets and as dispersed airborne ash when their own rise and crystallization produce water saturation. Most magmas of upper crustal batholiths probably contain less than 1.5 percent water and reach water saturation only at shallow depth after considerable crystallization, with resultant expulsion of a vapor-rich phase in pegmatites and volcanic eruptions (Maaloe and Wyllie, 1975). Granites in the middle crust, by contrast, have mostly crystallized from magmas with 3-5 percent water (Green, 1976; Clemens, 1984), hence reach saturation at much greater depth, expelling the voluminous pegmatites that characterize migmatite terrains; forced crystallization, and stopping of the rise of the magmas, necessarily result.

Such a scenario is compatible with experimental data (e. g., Wyllie, 1984) and also with the general requirement of trace-element studies that most granitic magmas have been equilibrated at depth with great volumes of rock rich in pyroxenes, hornblende, and calcic plagioclase (Tarney and Saunders, 1979). The required mafic and calcic differentiates or restites cannot generally lie in the middle crust, which is widely exposed, and presumably are in anorthositic and gabbroic complexes of the lower crust and in largely ultramafic differentiates of the upper mantle.

FORELAND THRUST BELT

Deformation and magmatism are related spatially and temporally, so structural and magmatic aspects of evolution of continental crust must be considered together. Until only 15 years or so ago, compression was widely viewed as a necessary precursor of most magmatism and metamorphism; and now it is widely believed that overriding plates are necessarily shortened. I disagree, and believe futher that crustal shortening is not required even by the foreland thrust belt that formed to the east of the belt of Cretaceous batholiths.

Great shortening is recorded, of course, within the upper-crustal wedge represented by the broad Sevier fold-and-thrust belt. The belt was produced by the tectonic thickening, by imbrication relatively eastward toward the craton, of a preexisting, westward-thickening wedge of miogeoclinal and other strata. Relationships are best defined in southern Alberta, in the eastern 100 km of the belt, where there has been the least disruption by subsequent magmatism and extensional deformation and where geophysical and drilling data add critical constraints (Price, 1981).

The lithostatic head produced by tectonic thickening in the west caused the deforming wedge to flow gravitationally eastward, incorporating new foreland strata as it did so. Thrust sheets in the deep part of the wedge moved upward to the east because the top of the wedge sloped downward in that direction; uninvolved basement dips westward beneath the wedge. Rocks formed progressively deeper in the tectonic wedge are exposed progressively westward. Deformation styles of rocks exposed at the surface change correspondingly from imbricate thrusting plus flexural-slip folding in the east to pervasive synmetamorphic slip in the west. The latter deformation produced typically slate and phyllite of low greenschist facies, recording temperatures of 300-400°C and hence a likely depth in the wedge of the time of about 15 km.

The east front of the thrust belt trends irregularly southeastward and southward through Montana, Wyoming and eastern Idaho, and northern Utah, thence southwestward through southern Utah and southern Nevada into eastern California. The front was controlled throughout by the east limit of thick, shearable strata, primarily miogeoclinal but including strata of the Cretaceous foreland basin and, in Montana, of the Proterozoic Belt basin. The thrust belt ends in California where the stratal wedge trends obliquely into the batholithic belt.

The deep structure of the western part of the Sevier belt is exposed in the many "metamorphic core complexes" raised by extensional tectonic denudation during Eocene time in British Columbia and the northwestern States and during middle and late Tertiary time farther south. (These are discussed in a later section.) Interpretations of these tracts are much debated, and they are complicated by magmatism of both pre- and post-thrusting ages; I see the thrust-belt component of the exposed rocks as representing synmetamorphic top-to-the-east slip, broadly involving basement rocks, at depths as great as 25 km, followed by severe extensional faulting.

I see no requirement that any part of the deformed wedge moved more than 100 km relatively eastward above the deep basement. Price (1981) by contrast argued for more than 200 km of overthrusting on the basis of his quite different inferences regarding the amount and structural manifestations of Tertiary extension.

The thrust belt developed during late Early Cretaceous (Aptian and Albian), Late Cretaceous, and early Paleogene time (Heller et al., 1986), and thus imbrication began soon after inauguration of major Cretaceous arc magmatism to the west, and continued 25 m.y. or so after magmatism had migrated relatively eastward away from the main Cretaceous belt in the southwestern United States. (It should be noted that dating of Cretaceous batholithic rocks is most complete in California, whereas dating of the thrust belt is most complete from northern Utah through southern Alberta.) At the time of completion of thrusting, the east edge of the thrust belt probably lay only some 150 km east of the composite Cretaceous batholiths, the distance having been much increased by subsequent Cenozoic extension (Hamilton, 1978), and compressive Cretaceous structures were continuous from batholiths to eastern thrust faults. Thrusting and batholiths were coupled mechanically: the buttress against which the thrust wedge was thickened lay in the region of the batholiths. Hamilton (1978) and Smith (1981) are among the few who have argued that arc-magmatic growth of the crust produced the topographic high that drove the thrusting. The dominant current view is probably that expressed by Price (1981): eastern cratonic basement was subducted relatively westward beneath the thrust belt and cycled at depth into the main east-dipping subduction system.

The ratio between extension across the arc and the growth of the crust by the mantle component of arc magmatism will determine the altitude of the top of the magmatic arc, and hence the gravitational potential for driving foreland thrusting. Foreland thrusting is now active along the east foot of that part of the Andes which has crestal altitudes generally above 5 km; perhaps thrusting in the Cretaceous foreland belt of western North America was a result of similar altitudes of the associated magmatic arc. No thrusting accompanied formation of the middle Tertiary arc of the Sierra Madre Occidental, the altitude of which (now mostly less than 3 km) may have been below the threshold needed for major gravitational spreading.

LATEST CRETACEOUS AND EARLY PALEOGENE TECTONICS

Many unusual tectonic and petrologic features of the western United States date from latest Cretaceous and earliest Paleogene time and appear to be related products of the rapid overriding of oceanic lithosphere. North American lithosphere dragged on subducting materials and was truncated by erosion against them, and this drag produced shortening of the cratonic continental interior.

Subcrustal Erosion

When North America rapidly overrode subducting Pacific lithosphere in latest Cretaceous and early Paleogene time, the continental plate was eroded tectonically from beneath and oceanic rocks were plated against its truncated base, which is exposed in uplifts, in interior southern California, that include the Tehachapi Mountains (the southernmost Sierra Nevada), the Rand Mountains in the northwest Mojave Desert, the central Transverse Ranges, and the Orocopia and Chocolate Mountains in southeastern California. The subjacent oceanic rocks--the Rand, Pelona, and Orocopia Schists--are mostly metamorphosed terrigenous quartzofeldspathic and pelitic strata but include much oceanic-crustal metabasalt and minor associated (pelagic?) metachert and ferromanganiferous metalimestone; serpentinite is present locally (Jacobson et al., this volume, chapter xxx). The rocks are extremely transposed and have been metamorphosed at greenschist and lower amphibolite facies, and locally at transitional blueschist-greenschist facies (Ehlig, 1981; Haxel and Dillon, 1978; Jacobson et al., this volume, chapter xxx; Postlethwaite and Jacobson, in press; Ross, in press; Sharry, 1981). Coherent high-amplitude reflections at a depth of 5-10 km beneath the thrust in southeastern California may image the top of subducted oceanic lithosphere beneath the schist (Morris et al., 1986).

The contact system least disturbed by subsequent deformation is probably that of the San Gabriel Mountains in the central Transverse Ranges (Ehlig, 1981; Jacobson et al., this volume, chapter xxx). Mesozoic and Proterozoic middle- and lower-crust migmatites, granites, and granulites are truncated downward against Pelona Schist and are retrograded to mylonitic gneiss in a section hundreds of meters thick concordant to the fault. This metamorphism is isofacial with the metamorphism in the subjacent schist and records a temperature in excess of 500°C, but temperature of metamorphism in the schist decreased downward (Jacobson et al., this volume, chapter xxx). Integration of K-Ar and fission-track dating indicates that the lower part of the upper plate cooled from >500°C to <100° during the interval between about 70 and 57 m.y. (Mahaffie and Dokka, 1986): the truncation of the base of the continent occurred in latest Cretaceous or early Paleocene time. The mylonitic fabric records a relatively northwestward overriding of schist by gneiss (Carol Simpson, written commun., 1986); as the range has undergone net Neogene clockwise rotation (Terres and Luyendyk, 1985), the initial direction of relative overthrusting was westward.

As the surface of the upper-plate Cretaceous magmatic arc was 100 km or so above the slab being subducted at the time of its formation, the juxtaposition of rocks formed about 30 km deep in that arc against subducted oceanic rocks requires the tectonic erosion of the lower 70 km of continental lithosphere. The age of this erosion is bracketed between the early Late Cretaceous age of truncated granites and the Eocene age of marine strata that lie upon deeply eroded rocks. The upward increase in temperature of syntectonic metamorphism recorded by the subjacent schists (Jacobson et al., this volume, chapter xxx) presumably represents heating of cool subducted rocks by heat retained in the rapidly truncated continental crust.

The thrust system both in the Rand Mountains and in southeastern California has been much disrupted by Tertiary extensional faulting. Mylonitic fabrics where studied in the latter region record overthrusting of gneiss and granulite relatively northeastward over Orocopia Schist (Haxel and Dillon, 1978). This has led to the inference that the sedimentary protoliths of the Orocopia Schist were deposited in a marginal basin and were overridden from the west by the plutonic crust of a minicontinent, which is bounded by a yet-unrecognized suture against autochthonous North American crust. Further study is essential to determine whether or not this east-directed fabric formed synchronously with the downward truncation of the overriding continental crust or represents instead later deformation, as by middle Tertiary mid-crustal extensional deformation (see discussion by Jacobson et al., this volume, chapter xxx). As the southern Sierra Nevada is certainly part of both the continent and the overriding plate and as overriding by the San Gabriel Mountains (which share distinctive early Mesozoic granitic rock types with undoubted continental regions to the north) was relatively westward, I presently infer that the subduction recorded by the Rand, Pelonia, and Orocopia Schists was relatively eastward beneath the continent.

The truncated base of the continental plate may be exposed also in the southern Coast Ranges of California, where middle Cretaceous "Salinian" plutonic rocks lie structurally above coeval Franciscan accretionary-wedge melange on the Sur-Nacimiento megathrust. The plutonic rocks are equivalent to those of the medial part of the Sierra Nevada and Peninsular batholiths, as noted previously. The terrains equivalent to the western parts of those batholiths, to the pre-Cretaceous accreted assemblages next further west, and to the fore-arc basin all have been removed tectonically, as has the lower 70 km of continental lithosphere that underlay the remaining plutonic rocks in middle Late Cretaceous time (cf. Fig. 1). This Coast Ranges complex lay west of the Rand-Pelona-Orocopia windows through the continental lithosphere before Neogene slip on the San Andreas fault. Page (1982) argued for subduction erosion of the missing Coast Ranges rocks, and I agree; he dated the event as probably Paleocene. Dickinson (1983) argued that, on the contrary, the missing terrains were removed by left-slip faulting.

Water Release

Many hydrous-magma muscovite and two-mica granites in the southwestern United States formed during latest Cretaceous and early Paleogene time, and hence during the general period in which oceanic lithosphere was being rapidly overridden by the continent, in the Basin and Range region. These were discussed earlier in terms of their middle-crust depths of origin. T. D. Hoisch (written commun., 1986; also Hoisch et al., this volume, chapter xxx) has found several of these wet-granite terrains in southeastern California to be associated with latest Cretaceous or early Paleocene regional metamorphism characterized by the passage of enormous volumes of high-temperature water. This is indicated by the reaction of calcite plus quartz to wollastonite through voluminous terrains metamorphosed at middle-crust pressures. Hoisch suggested that much of the water recorded by both the granites and the metamorphism was liberated by dehydration metamorphism of sedimentary rocks subducted at shallow depth beneath the tectonically-thinned continental lithosphere and that the water carried with it the heat needed for melts and metamorphism.

If voluminous sedimentary rocks were indeed subducted at shallow depth beneath the continent and there dehydrated, then magma genesis might have been quite different from the usual arc-magmatic sort, in which it appears that deep-crustal magmas contain little water. Much of the eastward sweep of magmatism in late Late Cretaceous time, away from the earlier Cretaceous site of the magmatic arc in the Sierra Nevada and kindred batholiths, may not have been simply tracking the decreasing depth to the subducting slab with time, but may have recorded qualitatively different processes.

Peninsular Ranges Mylonites

The Cretaceous mid-crustal plutonic rocks of the east side of the Peninsular batholith of south-central California are cut by thick zones of greenschist- to amphibolite-facies mylonite and mylonitic gneiss that dip gently to moderately eastward and outline large lenses of less-deformed rocks (Anderson, 1983; Sharp, 1979; Simpson, 1984, 1985). The deformed plutonic rocks are probably of middle Late Cretaceous age (cf. Silver et al., 1979), and mylonitization was completed by 60 m.y. (refs. in Simpson, 1985). Sense of slip was of westward overthrusting (Simpson, 1984).

The deformation presumably belongs to the family of structures which record drag of the continental lithosphere on oceanic materials subducted at a gentle angle beneath it. I infer the discontinuously ductile style of deformation--of lenses of little deformed rock separated by thick zones of ductile shear--to be common in the middle crust under both extensional and shear regimes, as emphasized subsequently.

Laramide Deformation

The Rocky Mountain region of the continental craton, from southern New Mexico to northern Montana, was distorted by shortening during the Laramide event of latest Cretaceous, Paleocene, and Eocene time, apparently as another manifestation of drag of the fast-moving continent on subducted materials beneath. The typical products of Laramide deformation are large, asymmetric anticlines of Precambrian rocks, bounded on one or both sides by reverse faults or steep monoclines against deep basins that subsided and received sediments concurrent with rise of uplift (Fig. 5). Major uplifts and basins have lengths to 300 km and structural reliefs exceeding 10 km. Although minor shortening affected the Colorado Plateau and Great Plains, the major structures lie in a belt trending northward through New Mexico to Colorado, where they splay out in successive arcs to the west, west-northwest, and northwest. Surface geology, industry drilling, and industry and COCORP reflection profiling all prove great basement shortening.

Deep reflection profiling (Sharry et al., 1985; Smithson et al., 1979), shows the basement thrusts to flatten downward and probably to splay into anastomosing ductile shear zones that break the deeper part of the middle crust into lenses. Analogous and contemporaneous shear-bounded lenses exposed in southern California were discussed in the preceding section. Other analogs are exposed in the Proterozoic Grenville province in Ontario, where the crust has been thickened by northwest-verging imbrication of great lenses of deep-crustal rocks between thick mylonites of amphibolite and middle-pressure granulite facies (Davidson, 1984). Basement thrusts perhaps generally give way downdip to subhorizontal complexes of lenses separated by thick ductile shear zones. The means by which such shortening is transmitted through still deeper crust and mantle is not yet clear, although pervasive deformation can be inferred on rock-mechanic grounds. Arc-magmatic rocks formed in parts of the Laramide province during the general period of shortening, so the lithosphere there presumably was 100 km or so thick at the time of shortening.

The Colorado Plateau and the continental interior each behaved as a relatively undeformed plate during this episode of crustal shortening, thus it must be possible to express the shortening distributed between them in terms of a rotation of the plateau relative to the interior. There is little deformation of any sort within the Laramide belt in central New Mexico; substantial right-lateral strike-slip plus minor shortening in northern New Mexico; and shortening across the belt that increases systematically northward and northwestward from there to a maximum in northeast Utah and Wyoming. I (Hamilton, in press, c; cf. 1981b) deduced from this geometry of the compressive structures that the Laramide rotation amounted to about 4° clockwise relative to an Euler pole in or near central New Mexico (Fig. 6). This specific amount of rotation incorporates the assumption that the shortening is equal to half the width of exposed basement uplifts along small circles to the Euler pole, in reasonable accord with the best-constrained surface and subsurface data. Bird (1984) showed that such rotation accords with sublithosphere drag patterns predicted from analysis of the geometry of the subducted plate.

A subsequent clockwise rotation of about 3°, relative to an Euler pole in northern Colorado, is required by the middle Tertiary opening of the Rio Grande rift. The total of Laramide plus Rio Grande rotations is equivalent to a rotation of about 6° relative to an Euler pole in southern Colorado.

Steiner (1986) analyzed the available high-quality paleomagnetic data for correlative strata of the Colorado Plateau and the continental interior and concluded that the Late Cretaceous and Cenozoic relative rotation of the plateau had amounted to about 11°. Bryan and Gordon (1986) argued for only about 4° of relative rotation, but they incorporated statistically poor paleomagnetic data, poorly constrained ages of some units, and data sets from rocks of very different ages on and off the plateau.

CENOZOIC CRUSTAL EXTENSION

I infer both from analysis of the extensional structures themselves and from attempts to reconstruct palinspastically the Mesozoic components of the Cordillera (Hamilton, 1978) that Cenozoic extension has approximately doubled the width of the Basin and Range province and related terrains in the western United States. The structures on which this deformation was accomplished in the upper and middle crust are widely exposed.

Basin and Range Province

Subduction steepened after the westward advance of North America over Pacific lithosphere slowed in Eocene time. It is unclear whether the old, gently inclined slab sank, or was left at shallow depth and underrun by a new slab. From late Eocene through early Miocene time, a wave of intermediate and, mostly, silicic magmatism broadly affected, and was largely limited to, the region which was extended in middle and late Cenozoic time. The thermal softening of the crust that accompanied this magmatism presumably made possible the uncommon breadth, amount, and duration of accompanying and subsequent extension. The continental margin evolved during the period of extension from an early one of continuous subduction of Pacific lithosphere to one of strike-slip in the south and subduction along a progressively shortening sector in the north (Atwater, 1970; Dickinson, 1979). Early extension was approximately perpendicular to the continental margin and was synchronous with subduction along most of it, hence was back-arc spreading--severe extension of an overriding plate. Late extension has been mostly in a northwesterly direction relative to the continental interior, approximately parallel to the San Andreas plate-boundary direction but much complicated by adjustments of the shape of the continental plate to fit that boundary.

Middle Cenozoic spreading affected much of the Great Basin; the Basin and Range southern parts of California, Arizona, and New Mexico; the Rio Grande Rift system; and regions north of the eastern Snake River Plain in Idaho, western Montana, and southeasternmost British Columbia. (Eocene extension that earlier affected south-central British Columbia, northeastern Washington, and Idaho is discussed subsequently.) Late Cenozoic extension of Basin and Range type has affected most strongly the Great Basin, though with much areal variation; the southern margin of the Colorado Plateau; the region around the eastern Snake River Plain; and eastern Oregon and adjacent areas. The late Cenozoic extension was in part superimposed on earlier extension but also affected new regions, and at any one time extension was rapid in some areas and slow or dormant elsewhere. Exposed structures of comparable crustal depths of formation are similar regardless of age and orientation. Regional altitude has increased during the long period of extension. I have discussed these matters in other papers (Hamilton, in press, a, b) from which this summary is adapted.

The structural style of deformation varies as functions of crustal depth and of amount of local extension. Upper-crust structures begin as rotating blocks and panels separated by brittle normal faults and, more locally, strike-slip faults. These shallow structures initially end downward at undulating zones of ductile shear. Slip on the undulating zones continues, but in increasingly brittle mode, as extension proceeds and tectonic denudation brings the evolving *detachment faults* progressively closer to the surface. The temporal and depth progression is shown by superimposed structures in zones of long-continued slip. Upon the products of early ductile slip--mylonite, formed at temperature >300°C, or even mylonitic gneiss, >500°--are superimposed progressively narrower zones of progressively more brittle fabrics, ending as low-temperature brittle gouge and breccia. Thermal-gradient considerations indicate that such ductile faults commonly began to form at depths greater than 10 km for mylonites and 15 km for gneisses, even in high-heat-flow regimes (Figs. 2, 3, 7), and this is compatible with the general presence beneath detachment faults of crystalline rocks equilibrated at middle-crust conditions before such late deformation.

Detachment faults that evolved with time from middle-crustal to near-surface depths are exposed in scores of ranges in the southern part of the Basin and Range province and in lesser numbers of them in the Great Basin. Upper plates are mostly of upper-crust rocks rotated to moderate to steep dips and truncated sharply at their bases, and abundantly include sedimentary and volcanic rocks deposited in basins synchronously with extension. Lower plates consist of crystalline rocks, of any age, that were formed in the middle crust. A crustal thickness of 10-15 km is missing across many detachment faults, and 20 km across a few of them. Detachment faults are connected to the surface by normal faults. Whether detachment faults at the edges of extended terrains end as shallow normal faults or emerge from beneath nonextended terrains is not yet established. The depth to active detachment faults varies with extensional maturity in the Great Basin, and ranges from 15 km in central Utah to 0-4 km in the Death Valley region.

Detachment faults crop out with undulating or domiform shapes. Slip on detachments commonly is in the same sense over several adjacent domes, up one side and down the other of each, although very late, near-surface slip is down-dip only. The common term "metamorphic core complexes" for sub-detachment assemblages is often used with the incorrect connotation that detachment faults are related to local hot spots; any middle crust rocks, including low-temperature slates, occur beneath the faults.

In the region of most severe Quaternary extension, that of Death Valley in eastern California, some gently-dipping structures that originated in the middle crust have remained active after exposure at the surface and display even Holocene slip (Fig. 8), whereas others have been broken by steep faults related presumably to new detachment faults at depth.

Half of the upper-plate rocks exposed against the late Cenozoic detachment faults in the ranges near Death Valley are synextensional sedimentary and volcanic strata, rotated down to marked truncations against the faults. Half of the upper-plate materials did not exist when extension began. The pre-Cenozoic rocks do not form mere rotated panels, one in contact with the next at the subsurface part of a rangefront fault, but rather are completely allochthonous above the detachments. I regard the structural-geologic evidence as strong that central Death Valley and northern Panamint Valley record the Pliocene and Quaternary separations of the flanking bedrock ranges by the full widths of the basins, above detachment faults at two levels. The older and higher detachment faults in each case are exposed widely in the ranges on the east sides of the valleys, whereas the younger, lower, and presently active major detachments are hidden and emerge in the subsurface from beneath the ranges on the east sides of each basin and floor the modern basin fills at depths of only a few kilometers.

De Voogd *et al.* (1986) interpreted a COCORP seismic-reflection profile to indicate that *active* imbricate normal faults dip moderately downward to a subhorizontal detachment fault deep within crystalline rocks 15 km beneath Death Valley. I have studied this and the other COCORP profiles in the region, and also relevant shot-point gathers and the processing employed. Severe frequency-wave number (f-k) filtration applied before stacking produced in each of the profile displays a variably pervasive artifact fabric, inclined about 30° toward the vibrators along the one-sided geophone spread (regardless of the orientation of the line, and whether the spread was "pushed" or "pulled") and extending between about 2 and 5 seconds on the displays; further, severe editing out of traces was done before stacking. The imbricate faults inferred by de Voogd *et al.* are, in my view, primarily artifacts introduced by this processing. The great inclined possible fault given major emphasis by de Voogd *et al.* (1986, fig. 2, line 11, reflector C) represents this artifact in its *shallow* part, 2-4 seconds. Although the part of this apparent reflector between 4-5 sec appears likely real on a shot-point gather, the lack of a pullup effect for an abrupt change of 1.1 sec of thickness of surficial basin sediments "above" it suggests to me that this part of the apparent reflector is a side echo, not a deep fault. Similarly, the lack of pullup variations for the "detachment fault" (including the "bright spot") near 6.5 sec on line 11 of de Voogd *et al.* (1986), and the lack of confirmation of the reflection on *nearby* and partly coincident line 9, permits the interpretation that this apparent structure also is a side echo.

The ductile shear zones that evolve into detachment faults form carapaces on crystalline rocks which otherwise largely retain their pre-faulting fabric and mineralogy. Where carbonate rocks were present during the ductile stage in either upper or lower plates, they commonly were smeared out as lubricating veneers of foliated marble, 3-50 m thick, that now define the carapaces.

Crustal structure beneath detachment faults is characterized by ductile shear zones that outline large and small lenses that retain pre-extension fabrics. Anastomosing ductile shear zones have been recognized in the field, and can be inferred on many reflection profiles (Frost and Okaya, 1986; Hamilton, 1982), beneath detachment faults. Although the manner in which extension is transmitted through the middle crust, beneath the detachment faults that represent the base of early, brittle deformation, is much disputed, I infer that the middle crust is extended by the sliding apart of lenses bounded by gently dipping zones of ductile shear (Fig. 7). This can perhaps be likened to the sliding apart of a pile of wet fish--halibut, to make the analog dimensionally apt. The brittle faulting of the upper crust is a response to the resulting increase in area of the composite top of the lenses separating at depth. I see the common domiform shapes of exposed detachment faults as due to the interaction of separating lenses; many investigators see them instead as products of post-detachment deformation.

The lower crust in the Basin and Range province is required by heat-flow data to be so hot that deep deformation must be accommodated by pervasive ductile flow (*cf.* Figs. 2, 3). Extensional fault ramps cutting completely through the crust have been postulated by some investigators but could form only with extremely high strain rates; the subhorizontal, unbroken character of the Basin and Range Moho disproves the ramp concept and is discussed in a later section. Lower-crust extensional structures are not exposed within the region but can be inferred from the fabric displayed by reflection profiles to record pervasive ductile flattening.

The style of deformation thus changes downward in the crust from brittle to discontinuously ductile to pervasively ductile.

The structures widely regarded as typical of the Basin and Range province--tilted panels of bedrock rotated against one another at range-front faults, the downdropped part of each panel being covered by basin deposits--are present only where extension has been minor, hence commonly early in the extensional history of any one area. (Symmetrical horsts and grabens are uncommon at any stage.) Wherever detachment faults are exposed, it can be seen that basin fills have dragged directly against them, and that pre-extensional bedrock occurs as tilted blocks that are separated completely from one another atop the detachment-fault lenses. Extension has in many places corresponded to most of the distance between the bedrock of adjacent ranges. Strike-slip faults are limited to assemblages above detachment faults, and range-sized blocks formed by early extension perpendicular to the continental margin are now being further separated by oblique, northwestward slip closer to the San Andreas direction.

Paleomagnetic evidence for motion of the Sierra Nevada. My tectonic analysis requires that Basin-Range extension have been accompanied by a counterclockwise rotation of the Sierra Nevada by 20 or 30° relative to the Colorado Plateau, and by little change in relative latitude, during middle and late Cenozoic time. Frei (1986) argued that, on the contrary, the paleomagnetism of Cretaceous granites of the central Sierra Nevada indicates that the Sierra has not rotated relative to the Colorado Plateau although it has shifted northward about 600 km. Her data from the granites is suspect because neither the age of magnetization nor the lack of tilting can be proved. I earlier argued that the batholith has been eroded 5 km or so deeper in the west than in the east, and this, if applicable to the tracts studied by Frei, would calculate out to a post-magnetization counterclockwise rotation of the range of about 5° from her data. Frei also overlooked the latest Cretaceous and Cenozoic rotation of the Colorado Plateau, discussed previously, by approximately 8° clockwise relative to the continental interior; this is equivalent to a counterclockwise rotation of the Sierra Nevada by 8° relative to the plateau. Further, the Cretaceous paleomagnetic reference pole Frei used for North America east of the Rocky Mountains is not based on reliable data. Her reference pole comes from three studies--middle Cretaceous diabase sheets of Ellef Ringnes Island, Arctic Canada; Upper Cretaceous strata of the Niobrara Formation in eastern Colorado and Kansas; and middle Cretaceous dikes in Arkansas. Map patterns, the attitudes of nearby rocks, and the magnetic data themselves all indicate to me that the Ellef Ringnes diabases sampled are in gently plunging open folds, although they were assumed to be horizontal (wall rocks and contacts of diabases are not exposed at the sample sites); moreover, Ellef Ringnes is separated from mainland Canada by the Northwest Passage plate boundary of poorly constrained character. The Niobrara and Arkansas studies yielded results so scattered as to be of minimal value and were included in the reference pole only because their mean paleomagnetic poles are close to that of the Ellef Ringnes study; the lack of a single reversely magnetized specimen among more than 300 Niobrara samples that spanned most of Late Cretaceous time makes the Niobrara study further suspect. Frei's reference pole requires a Cretaceous polar-wander curve for which there is no explanation in known plate motions.

Eocene Extension in the Northwest

Severe extension affected central and northern Idaho, northeastern Washington, and south-central British Columbia during Eocene time. Widely exposed detachment faults outline domiform masses of mid-crustal crystalline rocks that include the Okanogan, Kettle, and Priest River-Spokane domes in northeastern Washington and adjacent Idaho, and the many more of the Shuswap and allied families in British Columbia. The style of exposed structures is similar to that of the Basin and Range province, although deeper erosion has exposed sub-detachment, middle-crust rocks and major sub-detachment faults much more widely in the Eocene terrain. A subsurface relief of about 10 km on the composite detachment faults is indicated by gravity surveys (Cady and Fox, 1984). Rocks rotated down to truncations against domiform and undulating detachment faults include synextensional lower and middle Eocene sedimentary, volcanic, and granitic rocks, and sedimentary, metamorphic, and granitic rocks variously of Proterozoic, Paleozoic, and Mesozoic ages, whereas subdetachment rocks similarly range from Proterozoic to Eocene in age but are entirely of mid-crustal crystalline types (Brown and Read, 1983; Cheney, 1980; Miller, 1971; Miller and Engels, 1975; Rhodes, 1985; Rhodes and Cheney, 1981). Lower-plate rocks commonly have Eocene K-Ar cooling (uplift) ages regardless of their primary ages, whereas K-Ar ages of upper-plate pre-Tertiary rocks are erratically older (Mathews, 1981; Miller and Engels, 1975). The general direction of extension, as indicated by stretching lineations in mylonites and by axes of rotation of upper-plate Eocene strata, was westward to west-northwestward relative to the continental interior. The last slip on the detachment faults was brittle, but commonly lower plates carry carapaces recording shear that progressed with time from ductile to brittle, from early mylonitic gneiss to late chloritic microbreccia, and early Paleogene granites are among the mylonitized rocks (Carr, 1985; Lane, 1984; Miller, 1971).

Sub-detachment ductile shear zones, with or without superimposed brittle structures, outline many lenses of mid-crustal rocks beneath the capping detachment faults (e. g., Spokane Dome mylonitic zone of Rhodes and Hyndman, 1984; and most faults shown by Journeay and Brown, 1986). The deep-reflection profile presented by Cook (1986) carries from near-outcrop to depth an exposed detachment fault (Standfast Creek fault) and an exposed fault (Columbia River fault) that bounds the next-lower structural lens and that flattens downward. Beneath these faults, as I read Cook's profile, is a stack, as thick as 15 km, of large lenses outlined by rocks transposed in ductile shear zones; and beneath those, the basal continental crust displays subhorizontal reflections that I infer to reflect rocks more pervasively transposed by ductile flattening (cf. Fig. 7). Similarly, I see lenses in the domiform and gently dipping reflectors of the COCORP profiles across the extended terrain of northern Washington (Potter et al., in press; they inferred all west-dipping reflectors to be Mesozoic thrust faults, and outcropping west-dipping detachment faults to be either thrusts or minor normal faults).

Published interpretations of these complexes vary widely. Many geologists (Brown and Read, 1983; Cook, 1986; Journeay and Brown, 1986; Monger et al., 1985) assign the ductile carapaces and deeper ductile faults largely to pre-Eocene overthrusting and infer relatively minor Eocene extension The inference by Price (1981) of more than 200 km of foreland-thrustbelt shortening, referred to earlier, incorporates such an interpretation. The collective features of the Eocene terrain, as mapped and described by many geologists, so strikingly resemble those of the Basin and Range region, however, that I interpret them in similar terms of rise of mid-crust lenses to the surface as the result of great tectonic denudation accompanying extension, and of slip between the rising lenses that evolves from ductile at depth to brittle near the surface.

Other Eocene detachment faults atop mylonitic carapaces on mid-crustal rocks are exposed in the Idaho batholith region. Best known is that of the east flank, exposed along the east side of the Bitterroot Mountains, of a domiform carapace of mylonitic gneisses that affects middle-crust granites and migmatites of both Eocene and Cretaceous ages (Chase *et al.*, 1983; Hyndman, 1980). I have seen a spectacularly exposed, west-dipping detachment fault farther south, in the canyon of the Middle Fork of the Salmon River at Cradle Creek, where upper-plate gneiss dips steeply east to a truncation against a west-dipping detachment fault capping a mylonitic carapace. I expect that detailed study in central Idaho--which mostly is both inaccessible and poorly exposed--will show widespread detachment faulting. Undulating or domiform contacts of epizonal Eocene granites above deep-seated plutonic rocks should be accorded particular scrutiny (as, in the canyon of the Middle Fork in the Camas Creek area; see Cater *et al.*, 1973). Farther south in central Idaho is the domiform Pioneer detachment fault (Wust, 1986).

Rifting and Magmatism

Discriminating cause and effect in rifting and magmatism is difficult. As rifting commonly is much too rapid to permit continuous equilibration by thermal conduction, geothermal gradients are steepened; the lithosphere is thinned both by extension and by incipient melting, due to depressurizing, of its lower part; induced mantle convection (Steckler, 1985) likely moves additional mantle heat upward. The widespread synextensional magmatism and high heat flow of the province both appear to be products, not causes, of the extension (Lachenbruch and Sass, 1978). Nevertheless, the initial middle Tertiary spreading of the Basin and Range province was in a back-arc mode and was accompanied by voluminous magmatism intermediate in character between the types commonly regarded as representing extensional and arc-magmatic settings (*cf.* Best, 1986), and the inauguration of the broad region of spreading may have been due to arc-magmatic heating of the lithosphere.

The late Neogene magmatism of the Basin and Range province has by contrast been largely bimodal, although the ratio of basalt to rhyolite has varied widely both areally and temporally. Silicic magmatism dominates early stages of rapid rifting of the continental in non-arc settings, as, for active examples, the Yellowstone-Snake River province of southern Idaho and northwest Wyoming, and the Owens Valley province of eastern California. A general model (Christiansen and McKee, 1978) for such magmatism, integrating isotopic and other data from the rock assemblages, is that basalt melted in the mantle, because of depressurizing by rapid extension, rises into the lower crust. The heat introduced by the mafic magmas partially melts lower-crustal rocks, and the resulting silicic magmas rise toward the surface. "Hot spots" are invoked for some such provinces, but in my view the concept they express is generally invalid, the melting being a product, not a cause, of extension.

New Volcanic Crust

Much of the interior Northwest exposes only Cenozoic basaltic and mafic-intermediate volcanic rocks and associated sedimentary rocks: northeastern California, the western Snake River Plain, all of Oregon except for the Klamath and Blue Mountains, most of southern and coastal Washington. I have argued (Hamilton and Myers, 1966; Hamilton, 1969, 1978) that these volcanic terrains represent Cenozoic magmatic and tectonic additions to the continental crust, and that pre-Cenozoic continental crust is lacking beneath much of them and is severely attenuated beneath the rest. Palinspastic reconstructions of Cretaceous tectonic and magmatic provinces in my view require such additions of new crust. Cenozoic rotations of western terrains shown by paleomagnetic data (*e. g.*, Beck, 1980; Magill *et al.*, 1982; Wells, 1985) broadly fit the predicted motions. The volcanic rocks are variously of magmatic-arc, rift, and mixed types, but are petrologically primitive and show little incorporation of continental crust or of sediments derived from it (McKee *et al.*, 1983; White and McBirney, 1978).

THE MANTLE AND THE MOHO

Mantle Rocks

Upper mantle material, mostly of Proterozoic age, sampled as inclusions in alkali basalts and kimberlites of the western United States (Wilshire *et al.*, in press) shows the general variety typical of such occurrences elsewhere. Peridotite is the dominant rock type and consists of olivine, subordinate orthopyroxene, and minor clinopyroxene. Spinel is important particularly in uppermost-mantle lherzolite (two-pyroxene peridotite), and garnet in rocks from deeper in the mantle; plagioclase occurs in lherzolite recording pressures appropriate for lower continental crust rather than upper mantle (*cf.* Fig. 2). Garnet granulites may represent either lower continental crust or upper mantle. All of the relevant rock types are also known within lowest crustal and uppermost mantle rocks exposed *in situ* in some parts of the world, although not in the United States. Metamorphic fabrics typify the mantle samples, but the primary assemblages mostly formed in equilibrium with mafic melts or were traversed by such melts (Wilshire *et al.*, in press). Such mantle rocks must include residues after partial melting, precipitates of refractory phases from melts, and products of zone refining, in widely varied sequences, and are quite different from the severely depleted harzburgites and dunites of oceanic upper mantle as exposed in ophiolite sheets.

Mohorovicic Discontinuity

As arc magmas must originate as mafic basalts yet have evolved to mafic and intermediate compositions by the time they reach the lower continental crust, the bulk of the olivine and pyroxene components of the protomagmas must crystallize in the mantle. The continental Mohorovicic discontinuity represents the shallow limit of crystallization of voluminous rocks dominated by olivine, pyroxenes, and garnet as well as the common deep limit of crystallization of silicic and intermediate rocks. In a region of active magmatism or tectonism, the Moho is a dynamic, evolving boundary, not a passive, fossil contact.

Magmatic Basin and Range Moho. Middle and late Cenozoic extension has approximately doubled the width of the Great Basin, yet surface altitudes are now higher than they were early in the extension period (*e. g.*, Axelrod, 1985), and the Moho is subhorizontal at a depth that is semiconstant in reflection time, 9-11 seconds, beneath all of the diverse tectonic and petrologic assemblages of the upper crust (Klemperer *et al.*, 1986). Presumably this crust is being rebuilt by magma from mantle sources, representing partial melting in response to extension, and also is being smoothed by gravitational flattening of the deep crust. Spreading of basaltic sheets atop dense mantle is inferred. Temperature low in the crust of much of the Basin and Range province must be high enough to melt granite where a modest amount of water is available (Fig. 3).

The Mohorovicic discontinuity appears as a strong reflector on many

COCORP profiles in the Cenozoic extensional terrains of the western United States but not generally elsewhere, so a distinctive type of lower crust built by mafic magmatism as a byproduct of extension may characterize extended terrains.

Neogene root of the Sierra Nevada. The crestal region of the great tilted block--4 km high, 100 wide and 600 long--of the Sierra Nevada of California may now stand high because the Moho is 50-60 km deep beneath it (Pakiser and Brune, 1980); but refraction and gravity data can alternatively be integrated to infer that the crust is of normal thickness whereas the mantle is of low density. Most of the rise from low uplands of middle Tertiary time has occurred in the past 10 m.y. (Huber, 1981), so either the crust has been thickened by 15 km or so, or the density of the mantle has been decreased, within that period. The surface rocks of the Sierra crest region are primarily Cretaceous granites and older metamorphic rocks and there is little late Neogene magmatism displayed to which the growth of a crustal root might be attributed. Volcanism has, however, been a locally intense accompaniment of the rapid late Neogene extension in the Owens Valley, which now bounds the Sierra Nevada on the east, and perhaps asthenospheric diapirs consequent on extension decreased the density of the lithospheric mantle and caused the uplift (cf. Buck, 1986; Mavko and Thompson, 1983; Steckler, 1985). Heat flow in the Sierra Nevada remains low because slow conduction through the crust has not yet produced a heat-flow signal at the surface.

A contrary argument was made by Chase and Wallace (1986), who accepted a Cretaceous age for a thick crustal root and suggested that this root was compensated isostatically on a regional scale until the breaking of the crust by late Neogene rifting permitted the operation of isostasy on the scale of the mountain range. This concept is reasonable qualitatively but not, it appears to me, quantitatively. The concept requires an enormously strong pre-rift elastic lithosphere and contains the implicit prediction that the Sierra Nevada of the early Neogene would have had a subregional isostatic residual gravity anomaly of something like 200 mgals. Such anomalies probably do not exist (cf. Simpson et al., 1986).

Uplift of the Western Interior

Colorado Plateau, Laramide Rocky Mountains, and Great Plains were all near sea level--marine deposits are widespread--very late in Cretaceous time. Local relief was much increased by Laramide shortening, but the rise of the entire region to its present general altitudes of 1-3 km above sea level occurred during Neogene time. Crustal thickness (Allenby and Schnetzler, 1983) is mostly near 40 km, a standard stable-continental value; it locally exceeds 50 km, presumably as a result of Laramide shortening, although at the present state of knowledge the overthick regions correlate only in part with those of shortening and of current altitude. Uppermost mantle velocities are near normal, 8.0-8.2 km/sec (Allenby and Schnetzler, 1983), so the regional uplift must be largely compensated deeper in the mantle. The broad correlation between the region of uplift and the region beneath which Pacific lithosphere was earlier subducted at shallow depth (Bird, 1984) suggests that the cause of the Neogene uplift lies in some delayed effect of that plate interaction, perhaps in slow heating of the subducted slab or in sinking of the lower part of the continental lithosphere that had been underplated by Laramide subduction (cf. Bird, 1979).

OVERVIEW

In this essay I have sought integrative explanations for some of the observed vertical, horizontal and temporal relationships between structural and petrologic assemblages formed during the past 100 m.y. in the western United States. Whatever the merit of these specific interpretations, unifying explanations must be possible for processes operating simultaneously in adjacent or subjacent sites; and those explanations are not likely to be viable unless the predictions implicit in them are compatible with knowledge of analogs exposed at different crustal levels or in other parts of the world.

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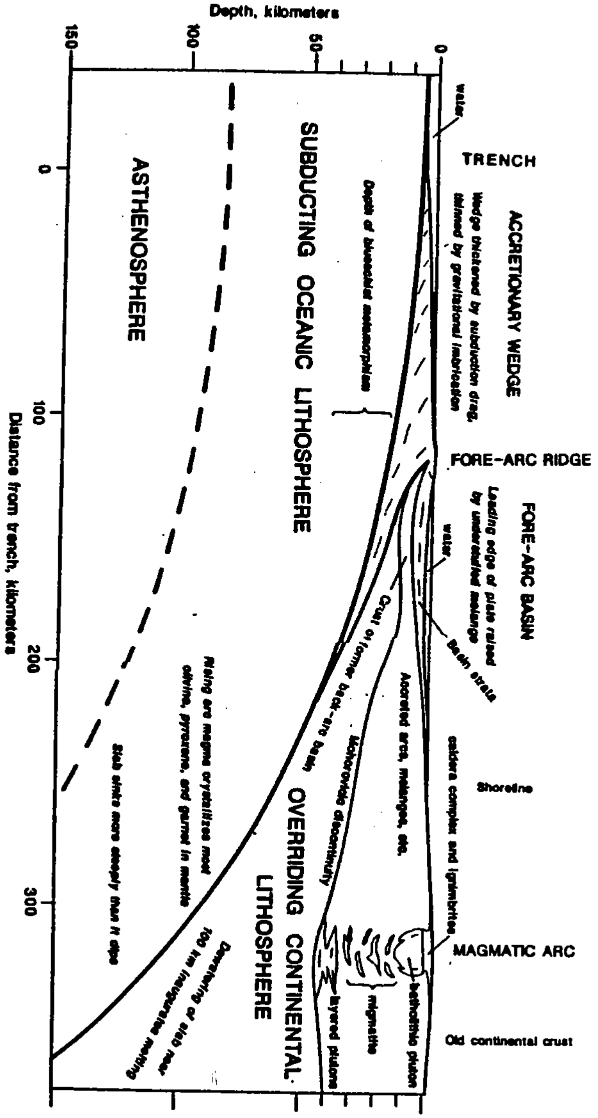


Figure 1. Cross section of a continental-margin subduction system. The dimensions of the model are derived from modern Sumatra (Hamilton, 1979) but are quantitatively like those of the middle Cretaceous components of California.

Fig. 1

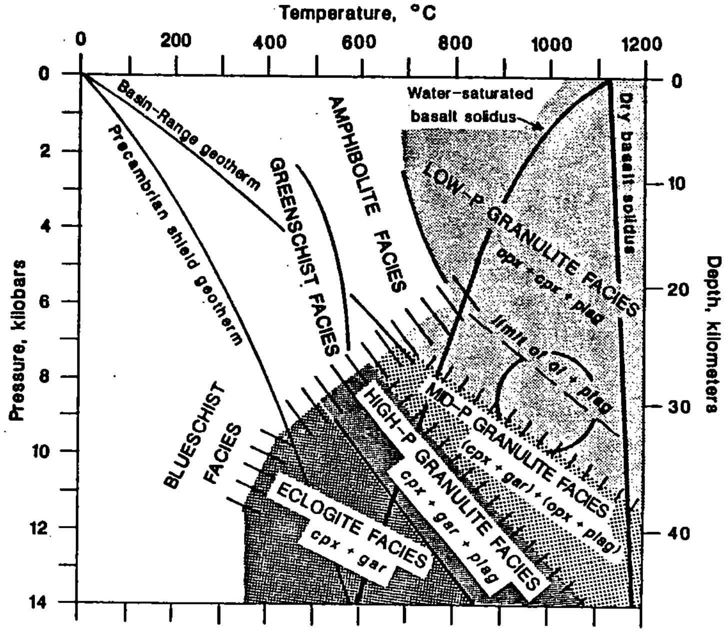


Figure 2. Generalized pressure-temperature diagram of mineral assemblages relevant to the lower continental crust. Boundaries approximate those for mafic and intermediate rocks but vary with bulk composition; coexisting minerals vary in composition across each facies. The boundary between amphibolite and granulite facies at pressures greater than 5 or 6 kilobars shifts greatly with activity of H_2O and CO_2, and a garnet-amphibolite facies (not shown) often intervenes. Abbreviations: **cpx**, clinopyroxene; **gar**, garnet; **ol**, olivine; **opx**, orthopyroxene; **plag**, plagioclase. Rock of similar bulk compositions become progressively more dense going from low-pressure granulite to eclogite as plagioclase reacts with ferromagnesian minerals to produce progressively denser phases; plagioclase reacts out successively with olivine, orthopyroxene, and clinopyroxene (although albite is stable in the higher T/P part of the blueschist facies, and sanidine is stable in high-T eclogite). Adapted from many published papers, including Hansen (1981), Johnson et al. (1983), Newton and Perkins (1982), and papers referred to by each. Geotherms from Sclater et al. (1980) and Lachenbruch and Sass (1978).

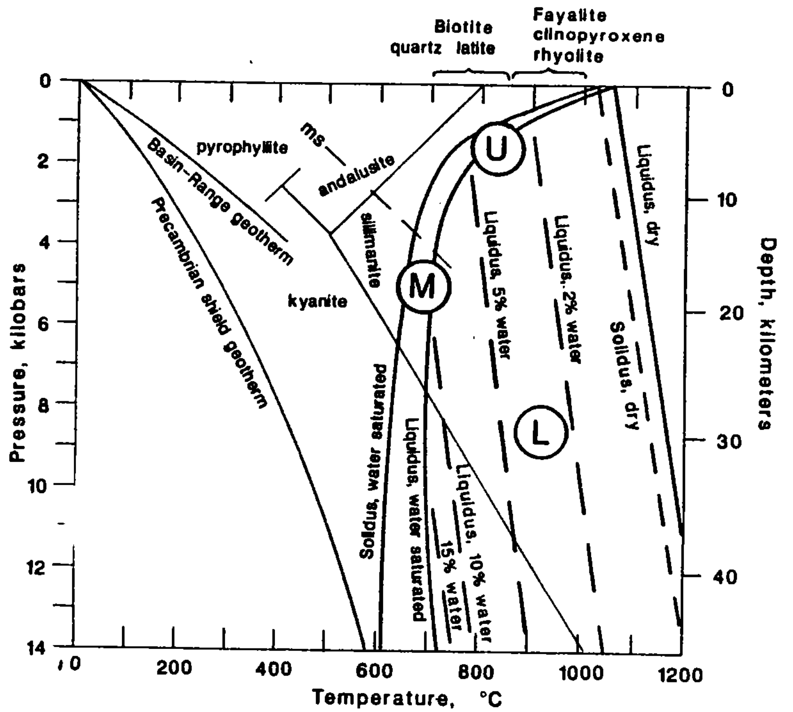


Figure 3. Crystallization relationships for leucogranite, showing the melting interval for water-saturated granite and contours on the liquidus surface for undersaturated magma, after Huang and Wiley (1981) and Stern and Wyllie (1981). Fields of the aluminum-silicate polymorphs are from Holdaway (1971); the andalusite-sillimanite boundary probably should incline more gently to the left. Primary muscovite can crystallize in granitic magma only deeper than the intersection of the stability limit of muscovite plus quartz (line **ms**; after Tracy, 1978; precise position varies with bulk compositions) with the granite solidus. Typical fields are shown by circles for late-stage magmas of the upper (**U**), middle (**M**), and lower (**L**) crust; these could form granites bearing, respectively, biotite, muscovite, and hypersthene. Typical eruption temperatures of biotite quartz latite (commonly a magmatic-arc magma) and of fayalite-clinopyroxene rhyolite (commonly an extensional-setting magma) follow Hildreth (1981) and others. Geotherms from Sclater *et al*. (1980) and Lachenbruch and Sass (1978).

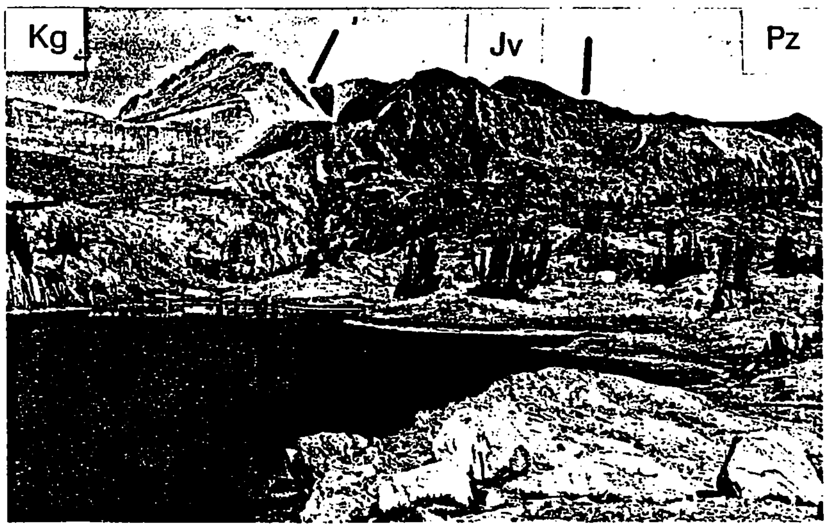


Figure 4. East contact of Cathedral Peak Granite, east-central Sierra Nevada. The subvertical contact is regarded as the depressed and outward-pushed *floor* of the pluton. **Kg**, Cretaceous Cathedral Peak Granite, 88 m.y.; **Jv**, hornfelsed silicic and intermediate volcanic rocks of Jurassic age; **Pz**, hornfelsed sedimentary rocks, mostly clastic, of late Paleozoic age. Metasedimentary rocks dated by fossil collection, and granite by U-Pb determination (Bateman *et al*., 1983); metavolcanic rocks dated along strike to southeast by fossils and U-Pb determinations (Fiske and Tobisch, 1978; Bateman *et al*., 1983, reported Late Triassic ages from whole-rock Rb-Sr determinations, but likely these are too old because of ^{87}Sr assimilated from crustal rocks). Contact between units **Jv** and **Pz** is marked for skyline ridge; contact lies at extreme right end of ridge just below skyline. Older Paleozoic metasedimentary rocks lie farther right, out of the picture. View north-northwestward over Steelhead Lake to Shepherd Crest.

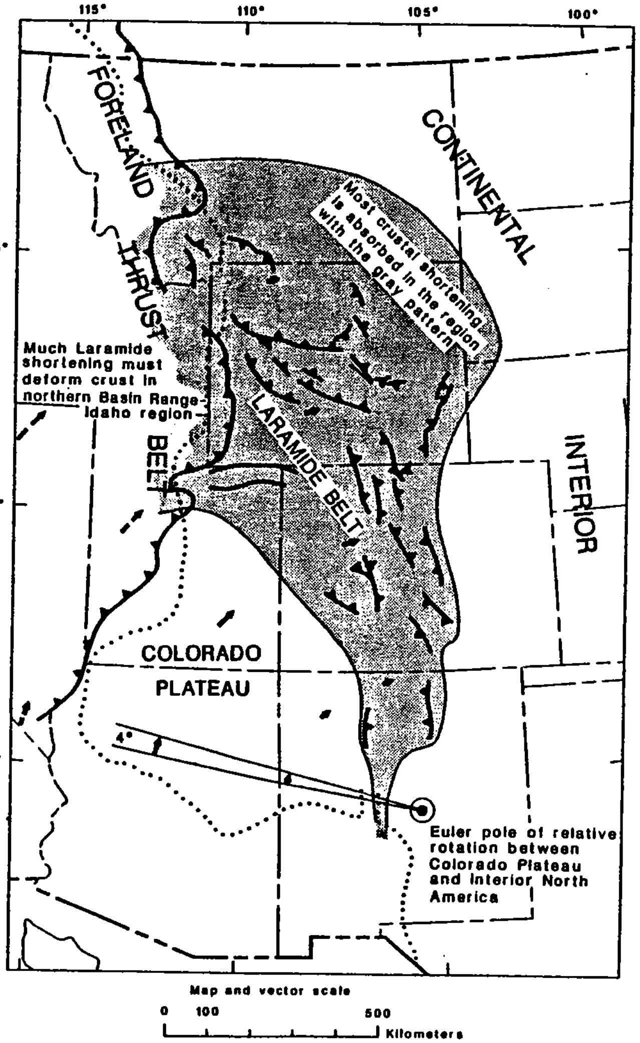


Figure 6. Map illustrating rotation of the Colorado Plateau relative to interior North America, as the cause of the Laramide deformation of the Rocky Mountain region. The vectors depict, to scale, the relative rotation of the plateau by 4° as though about the inferred Euler pole in New Mexico. The motion was absorbed by crustal shortening in the Laramide belt. The southern boundary of the plateau plate is not defined here.

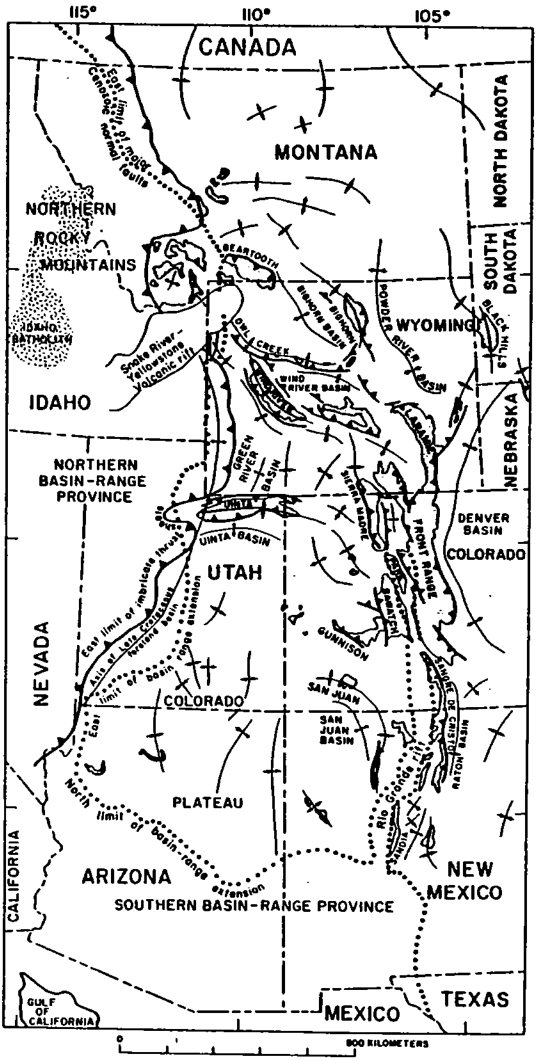


Figure 5. Selected structural elements of the Rocky Mountain region. Most of the uplifts and basins indicated are of Laramide age, latest Cretaceous and early Paleogene. Outcrops of Precambrian rocks east of the foreland fold-and-thrust belt and north of the southern Basin and Range province are shaded.

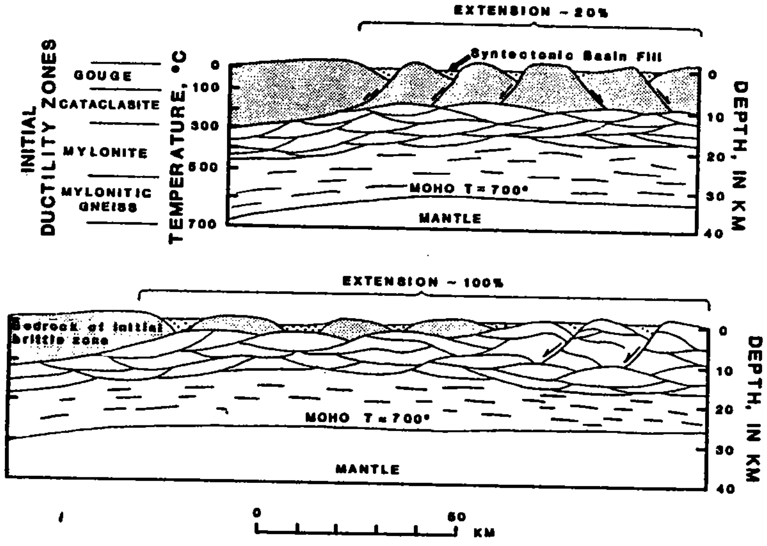


Figure 7. Cross sections of extending crust. Brittle upper-crust blocks rotate and separate. Middle-crust lenses slide apart along ductile shear zones; composite upper surface of lenses forms detachment faults that increase in total area with time. Lower crust flattens pervasively. Structural styles are superimposed as components rise toward surface with continuing attenuation. Crust is partly rebuilt by magmatism, so crust is thinned by a factor less than the extension ratio. Ductility zones after Sibson (1983).

Figure 8. Truncation of normal fault against active detachment fault, Black Mountains, Death Valley, California. Interbedded Pliocene clastic strata, slide breccias, and volcanic rocks (lower left) dip obliquely back and right toward late Quaternary normal-fault scarp along high-standing plutonic rocks (left and center rear). Hanging wall, footwall, and fault are all truncated downward against the active Copper Canyon turtleback (detachment) fault, which forms the smooth face dipping obliquely left through the center of the view. Light-colored rocks on turtleback are a discontinuous carapace of mylonitized dolomite left by the Panamint Mountains block as it slid by early in the detachment history. An active range-front normal fault truncates both upper and lower plates at the top of the alluvial fan.

ARCS FACE TRENCHES

WARREN HAMILTON

25 JAN 88

O'hara & Mathews 1981
JGSL 138, 237-277
PETROLOGY
HISTORY FROM END PRODUCTS

700 Ma ago { Rifting → Stable platforms
_Ord {

Continent unstable, movement

Nature of rifting:
Followed by stable wedge: miogeo. & epicont.

MODEL McKenzie '78, Bond & Pitman '82

Problems: earlier than 530 My, times are difficult to get accurate, much subs earlier

Herb Shaw –
Hawaii hotspot
en echelon cracks
Samoan hotspot lithosphere fracture in Fiji
deformation over non-spherical

20 km thick Ganges fan
STRETCH & POP EXTENSION IN RIFTING
SIERRA NEVADA UPLIFT LAST 6 Ma
THINNED CRUST
MAFIC CRUST INLAND OR COASTLINE
CAN START EXTENSION

LEON T. WANTS ZIRCON DATES
SILVER?

RIFTING BEFORE DOMING: SUBSIDENCE, NOT DOMING, ACCOMPANIED EARLY RIFT
GRAVITY HIGH, SURROUNDED BY GRAV. LOWS. FAILED RIFT or ABORTED ≈ 1100-1080 Ma KEWEENAWAN PEN/LAKE SUPERIOR REGION
AT THE POP STAGE

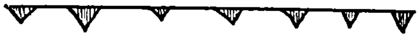
ALK. OLIVE BASALT, PRIMITIVE w/ SURFICIAL YELLOWSTONE RHYOLITES – SNAKE R. VALLEY; FLOORED BY DOMIC
AFTER MELTED CRUST IS EXPANSED, BUT TOPOGRAPHICALLY ~~CRUST~~ low ACTIVE STRETCHING; BEGUN 15 Ma?
{PROPOGATING RIFTS
(CONTROLLED BY ARCHEAN GRAIN}

SLIDE PROJ
Apollo Zoom lens

J vs K granites
?
lower qtz
more mafic for a given feldspar content
(+ grav anomolies)
neg. grav anomolies

Anglebratsen
Okbury & Percotte – Hawaii hot spot

RIFTING
1) STRETCHING BY DETACHMENT
→ POP ←
2) THICK BASALT MODE - 2nd ary CONVECTION OF RISING ASTHENOSPHERE; CAN BE CONTINUOUS
3) NORMAL OCEANIC CRUST FORMATION

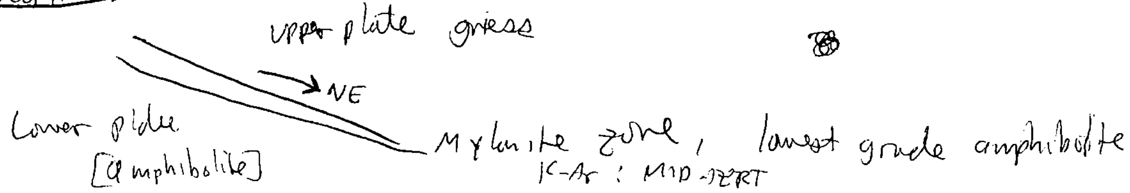


WARREN HAMILTON

27 JAN 88

(30km)
GRANULITES K granite ON SUBDUCTED EPI-AMPH CLASTIC SEDIMENTS
META DEC. DOWNWARD "TRANSPOSED" or DISRUPTED "BROKEN FORMATION"
W/ TECTONIC CONTACT AS VINCENT/ ~~OROCOPIA~~ THRUSTS

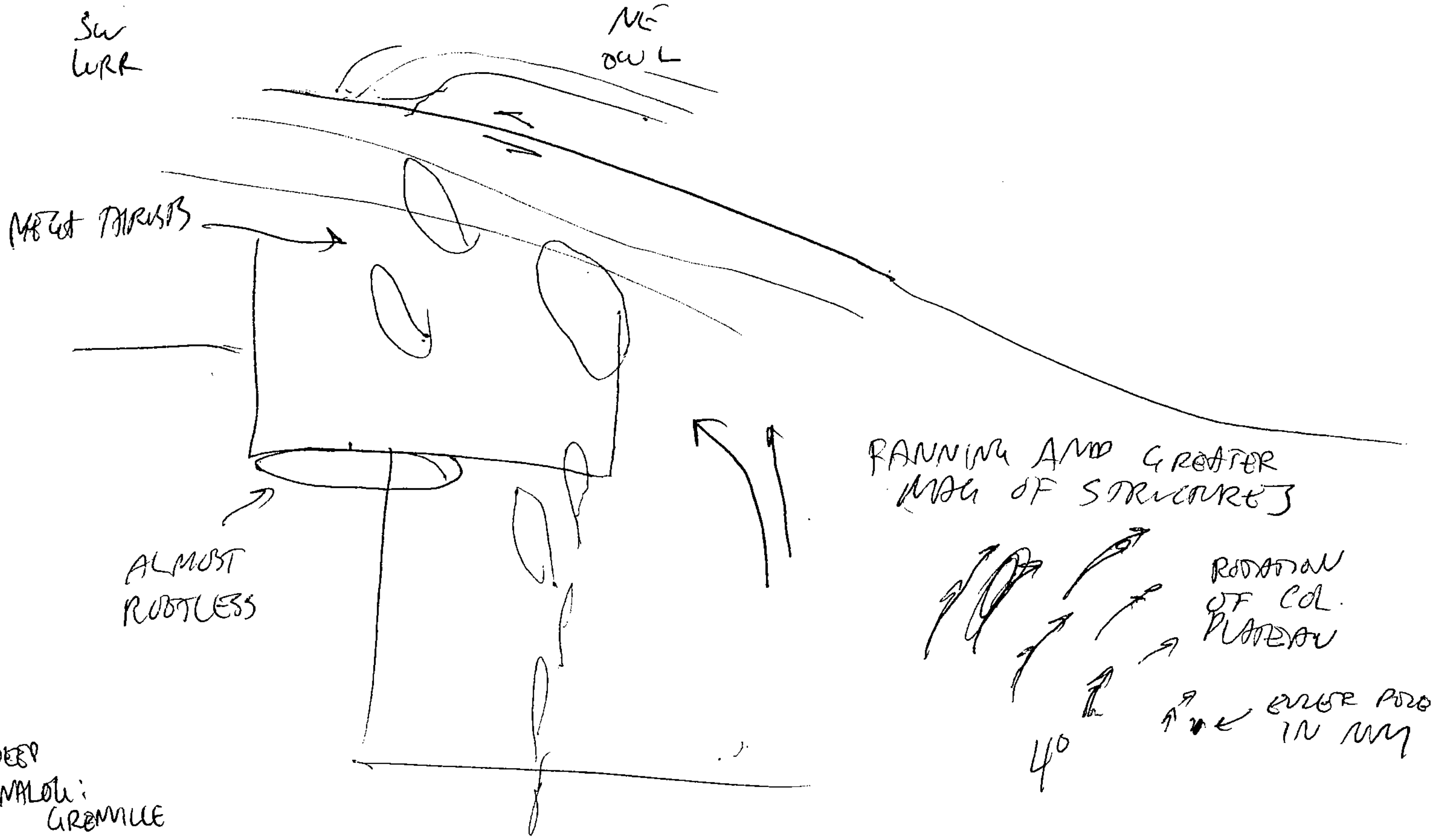
OROCOPIA (10km)



MID-TERT DETACHMENT WHICH CUT OUT

- Al Hydrous granite } Meta from water from subduction
  Hydrous Meta } rapid conv, subd. @ low depth

Laramide
Uplifts + Basins (not compensated)
CLOSE TO LEFT-COMPRESSIONAL STRAIN



DEEP ANALOG:
GRENVILLE