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THE VOLCANIC CENTRAL ANDES--A MODERN MODEL FOR THE CRETACEOUS BATHOLITHS AND TECTONICS OF WESTERN NORTH AMERICA*

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Abstract

Modern analogues for the great Late Cretaceous batholiths of western North America appear to be present only in the volcanic fields of the continental margins about the Pacific basin, and particularly in the central Andes. This paper proposes an analogy between volcanic Andes and Mesozoic batholiths, and then infers the paleotectonic setting of the batholiths from the modern setting of the Andes.

Andean volcanism occurs in a belt 200 to 400 km inland from the axis of the Peru-Chile trench, above the Benioff seismic zone dipping under the continent from the trench. The central Andean volcanic field, 100-200 km wide and 2000 km long, faces and is approximately coextensive with the deepest part of the trench, the region of greatest seismicity, and the fastest-spreading sector of the East Pacific Rise. This volcanic field consists of a broad ignimbrite plateau of upper Miocene and younger rhyodacite and rhyolite, from the central part of which rise high stratovolcanoes of andesite and dacite. A huge late Cenozoic batholith has presumably formed beneath the volcanic field.

The major late Mesozoic batholiths of western North America are dimensionally similar to the Andean volcanic field. Andean and batholithic rocks are compositionally similar calc-alkaline assemblages. The Andean rocks are in bulk more silicic than the Mesozoic batholiths, in accord with the demonstration elsewhere that ignimbrites are frequently more silicic than the magmas that remained lower in the chambers from which they came.

The original positions of the North American Mesozoic batholiths have been much altered by Cenozoic rifting, strike-slip faulting, and the volcanic growth of new crust. Reversal of the deformation leads to the interpretation that the batholiths formed at a uniform 150-200 km from the continental margin, and hence in the same position as the modern volcanic Andes.

Late Cretaceous North America was analogous tectonically to modern South America. Following a latest Jurassic and Early Cretaceous period of relative stability and the continental-rise, abyssal-plain, and abyssal-hill sedimentation of the Franciscan Formation, there was a period of rapid mantle motion in Late Cretaceous time. Pacific mantle moved eastward at a velocity of perhaps 100 km per million years, turned downward at a trench at the continental margin, and flowed along an inclined Benioff seismic zone. Melting in the Benioff zone yielded voluminous magma in a belt centered 250-300 km inland from the trench axis. The magmas produced great elongate fields of ignimbrites, beneath which crystallized shallow batholiths. The Franciscan Formation was scraped off the moving mantle against the continental margin.

Introduction

Deductions in the literature regarding the origin and tectonic setting of ancient batholiths have been made primarily from the geologic relationships of the granitic complexes. A batholith represents one vertical zone of exposures in a feature which obviously must give way both upward and downward to quite different complexes, so broad interpretations based on the exposed geology of these zones alone are necessarily incomplete. (The parable of the blind men and the elephant comes to mind.) Further, interpretations become so interwoven with assumptions regarding such problems as the nature of eugeosynclines and the origin of magmas that the conclusions are often mere restatements of the assumptions. An understanding of batholiths has been further retarded by the assumption that there are no modern analogues for them--that batholiths represent mysterious processes active at past times deep in the earth, unrelated to volcanism or other activity of sorts now visible at the surface. This paper pursues the opposite course by assuming that there are indeed batholiths now forming.

Hamilton and Myers (1967) considered various Paleozoic, Mesozoic, and Cenozoic assemblages

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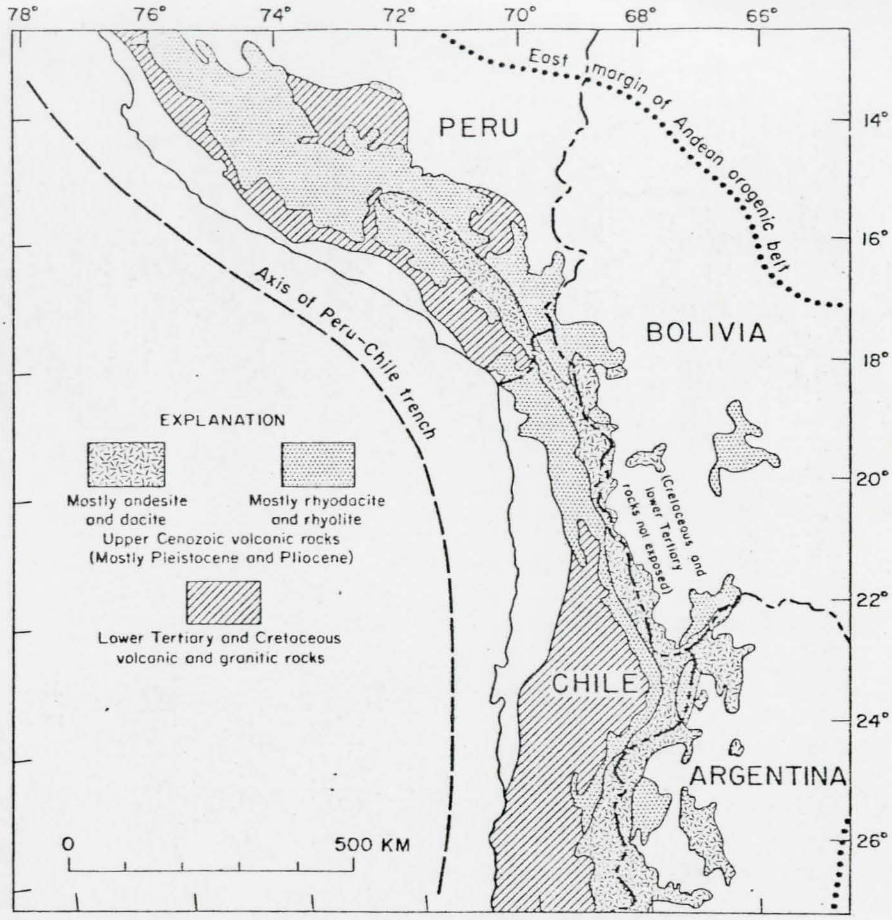

Figure 1. Some volcanic and tectonic elements of the central Andes. Adapted from Zeil and Pichler (1967, fig. 1) and Lamego (1964).

of metamorphic, granitic, and volcanic rocks in the United States to represent different erosion levels in similar complexes. The exposed features of the various assemblages when thus ordered led us to conclude that batholiths are thin, and form from magmas which typically rise completely through the crust and spread out laterally beneath a cover a few kilometers thick of their own volcanic ejecta. The reader is referred to our paper for documentation for these concepts, from which the present paper proceeds.

A corollary is that any very young batholith will be roofed by a broad field of intermediate and silicic calc-alkaline rocks. The problem of finding an active analogue for an ancient batholith then begins with the search for a volcanic field of appropriate composition and dimensions, and proceeds with an analysis of other features of the volcanic and granitic complexes considered to see if they are indeed analogous in other ways. This procedure is followed here to show that an analogy between the late Mesozoic batholiths of western North America and the modern volcanic terrane of the central Andes of South America is reasonable, and that much can be learned regarding the Mesozoic tectonics of North America from the modern tectonics of South America.

Calc-alkaline volcanic rocks are erupted above all of the inclined Benioff seismic zones of intermediate and deep earthquakes of the island arcs and continental margins about the Pacific Ocean. The magmas are erupted mostly about 150 to 400 km from the axes of the submarine trenches. Island-arc volcanism produces predominantly andesite, dacite, and high-alumina basalt, whereas continental-margin volcanism also produces a greater abundance of more silicic rocks.

The only modern volcanic fields comparable in dimensions and compositions to major ancient batholiths are those associated with Benioff zones of the continental margins. If batholiths are now forming anywhere, they should be mostly beneath these zones, as in Sumatra, New Zealand, and South America. The largest of these fields of late Cenozoic volcanic rocks, that of the central Andes, provides the best analogue for a modern batholith comparable in dimensions and other parameters to the great late Mesozoic batholiths of western North America.

The Volcanic Andes

The Andes face the Peru-Chile trench and lie above the Benioff zone dipping under South America from that trench. Calc-alkaline late Cenozoic volcanic rocks have been erupted along most of the Andes in a belt 200 to 400 km inland from the trench axis. The most extensive late Cenozoic Andean volcanic field, that of the central part of the chain, maintains a width of 100 to 200 km for a length of 2000 km, and is mostly included within the area of figure 1. The volcanic terranes north and south of this field are discontinuous and narrower.

The Peru-Chile volcanic field consists of late Miocene to Holocene andesite, dacite, rhyodacite, and rhyolite. The silicic rocks form a broad ignimbrite plateau, from the central part of which rise high stratovolcanoes of andesite and dacite (fig. 1; Bearth, 1938; Hausen, 1938; Jenks and Goldich, 1956; Katsui and Gonzalez-F., 1968; Petersen-B., 1958; Zeil, 1964; Zeil and Pichler, 1967). The axis of the volcanic belt is 150 to 200 km inland from the upper edge of the continental slope. Historic eruptions in Peru and northern Chile have been only of intermediate magmas; rhyolite and rhyodacite have been erupted in addition to more basic rocks in historic time in southern Chile (Casertano, 1963; Parodi-I., 1966). As eruptions of rhyolite are in general far less frequent and far more voluminous than are eruptions of intermediate magma, the central Andean silicic terrane may be active but have a historic record too short for its activity to have been yet observed.

During parts of late Mesozoic and Cenozoic time, the Andean region has been the site of intermittent magmatism of the same type as that now active. Calc-alkaline volcanic and granitic rocks, mostly of Cretaceous(?) and Tertiary ages but including pre-Cretaceous complexes (Levi and others, 1963), are exposed at the sides of the Andean volcanic belt (fig. 1). Late Tertiary granitic rocks, 7 to 20 million years old, also are exposed (Giletti and Day, 1968), but are not separated from the older igneous complexes on the figure.

The pre-Cretaceous rocks oceanward of the igneous terrane are mostly eugeosynclinal materials that may represent ensimatic ocean-floor and island-arc rocks (as Bürgl, 1967, argued for Colombian examples), added tectonically to the continent during Mesozoic and Cenozoic time.

Plate Tectonics and the Benioff Zone

An explosion in tectonic concepts has occurred in the past several years, sparked by interpretation of geophysical data from the ocean basins. Particularly important papers developing the new tectonics include those by Heirtzler and others (1968), Isacks and others (1968), Le Pichon (1968), and Morgan (1968). They and others have demonstrated that the earth's crust and upper mantle consist, in a broad way, of a number of large plates, of which the continents are parts, moving irregularly toward, past, and away from one another. So many features (including paleomagnetism and the classical geologic evidence for continental drift, as well as the oceanic geophysical information) are accounted for by these concepts that they already appear established as an explanation for the broader motions of the earth's outer shell.

A requirement of the data and concepts of plate tectonics is that eastern Pacific crust and upper mantle, spreading relatively eastward from the East Pacific Rise, turns down beneath the west edge of South America, as that continent in turn moves relatively westward as part of the plate moving away from the Mid-Atlantic Ridge. The Benioff seismic zone of intermediate and deep earthquakes, dipping eastward beneath South America, represents the contact between South America and eastern Pacific plates. The central Andean volcanic terrane is opposite that part of the East Pacific Rise which has the most rapid present spreading rate (12 cm/yr across the rise, or 6 cm/yr for each limb) yet determined by the Vine and Matthews magnetic method for any part of the midocean ridge system (Heirtzler and others, 1968, fig. 10).

The Peru-Chile trench is a topographic expression of the Benioff-zone contact between Pacific and South American plates. The modern central Andean volcanic field faces and is broadly coextensive with that part of the trench which is deeper than 6 km, and is coextensive with that part of the Andean Benioff seismic zone in which intermediate and deep earthquakes are most pronounced (compare geologic map of Lamego, 1964, bathymetric map of Udintsev, 1964, and seismic map of Gutenberg and Richter, 1954, fig. 11).

Direct evidence that Pacific crust is indeed moving rapidly toward South America and disappearing beneath the continental margin is provided by the continuous seismic profiles across the trench by Scholl, von Huene, and Ridlon (1968). They found that the thin pelagic carbonatic oozes of the open ocean turn downward with the oceanic crust at the west side of the trench, and lie beneath the terrigenous muds and turbidites across the floor of the trench. The terrigenous trench clastics are so thin--and

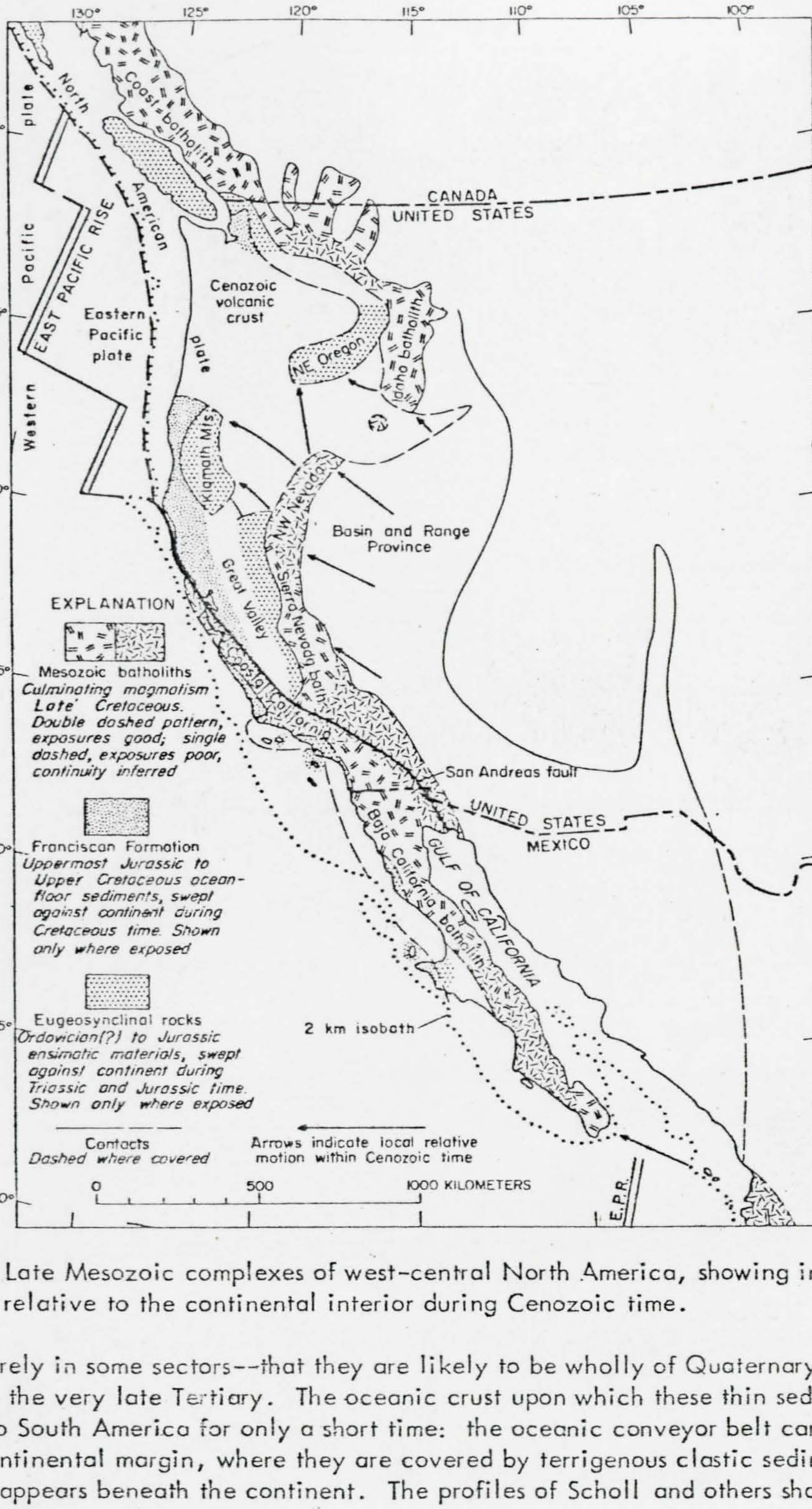

Figure 2. Late Mesozoic complexes of west-central North America, showing inferred motion relative to the continental interior during Cenozoic time.

are lacking entirely in some sectors--that they are likely to be wholly of Quaternary age, and certainly cannot antedate the very late Tertiary. The oceanic crust upon which these thin sediments are riding has been adjacent to South America for only a short time: the oceanic conveyor belt carries the pelagic sediments to the continental margin, where they are covered by terrigenous clastic sediments before the entire complex disappears beneath the continent. The profiles of Scholl and others show no compressive deformation of the trench-floor sediments, so the actual zone of motion between oceanic and continental plates must be either at the juncture between trench floor and continental slope (where the seismic records are ambiguous), or on the landward wall of the trench.

The Benioff seismic zone of intermediate and deep earthquakes dipping eastward from the Peru-Chile trench is poorly defined by published data, being known primarily from the approximate locations tabulated by Gutenberg and Richter (1954). The Gutenberg and Richter data for earthquakes assigned depths of 300 km or less suggest that the Benioff zone may dip only 20 or 25 degrees eastward to this depth (see plots by Harrington, 1963, figs. 3 and 4).

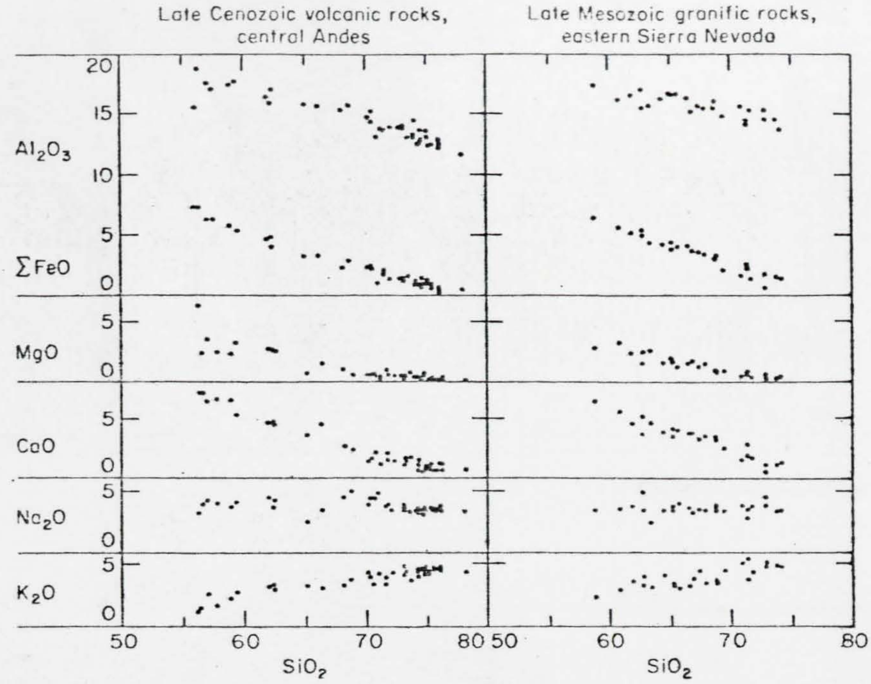

Figure 3. Silica-variation diagrams of chemical analyses of late Cenozoic volcanic rocks of the central Andes of South America, and of late Mesozoic granitic rocks of the east-central Sierra Nevada batholith of California. Analyses from Bateman and others (1963, table 3), Bearth (1938, tables 16 and 17), Jenks and Goldich (1956, table 3), Katsui and Golzalez-F. (1968, table 4), and Zeil and Pichler (1967, fig. 8).

Comparisons of Volcanic Andes and Mesozoic Batholiths

The major late Mesozoic batholiths of western North America are comparable in dimensions to the Andean volcanic fields. The Coast batholith is 100-200 km wide and about 1000 km long. The Baja California, Sierra Nevada, and Idaho batholiths are each 100-150 km wide and hundreds of km long (fig. 2), and these batholiths probably were connected before Cenozoic rifting and strike-slip faulting in a much longer batholith. The late Cenozoic ignimbrite field of the central Andes is mostly wider than the Mesozoic North American batholiths because the volcanic rocks lap across older complexes and extend beyond the underlying batholith.

The volcanic Andes represent only 10 or 15 million years of magmatism, whereas the North American batholiths are composites of plutons formed over a much longer period but, at least in the case of the Sierra Nevada, mostly in parts of Late Jurassic and Late Cretaceous time (Bateman and Wahrhaftig, 1966, p. 117). Andean Cretaceous, early Cenozoic, and late Cenozoic granitic complexes together provide a more complete analogue for the total North American batholiths. So many North American age determinations indicate Lake Cretaceous plutonism, however, that this culminating episode can be compared directly with the late Cenozoic Andes.

The silicic volcanic rocks of the central Andean late Cenozoic field are quite similar in composition to the late Mesozoic granitic rocks of the eastern Sierra Nevada. Silica-variation diagrams (fig. 3) define almost identical curves for both provinces, although the Andean rocks are in general more silicic.

Probably most ignimbrites are more silicic than the granitic magmas which remained below in the magma chambers. Cenozoic ignimbrites of southern Nevada (Lipman and others, 1966), southwestern Colorado (Ratté and Steven, 1967, p. 54), northwestern New Mexico (Smith and Bailey, 1966), and Japan (Lipman, 1968) were erupted from chambers which were graded downward from highly silicic to less silicic magmas. The experimental data of Currie (1968) accord with these observations. Thus we can expect the Andean ignimbrites to be more silicic than the granitic batholiths beneath them.

It is suggested that a great late Cenozoic batholith, comparable in size and composition to the late Mesozoic batholiths of western North America, has formed beneath the young volcanic pile of the central Andes. If the concepts of Hamilton and Myers (1967) are basically correct, this batholith lies beneath only a few kilometers of cover of the volcanic rocks, which were erupted mostly from plutons that rose completely through the earth's crust and spread out between basement and volcanic scum.

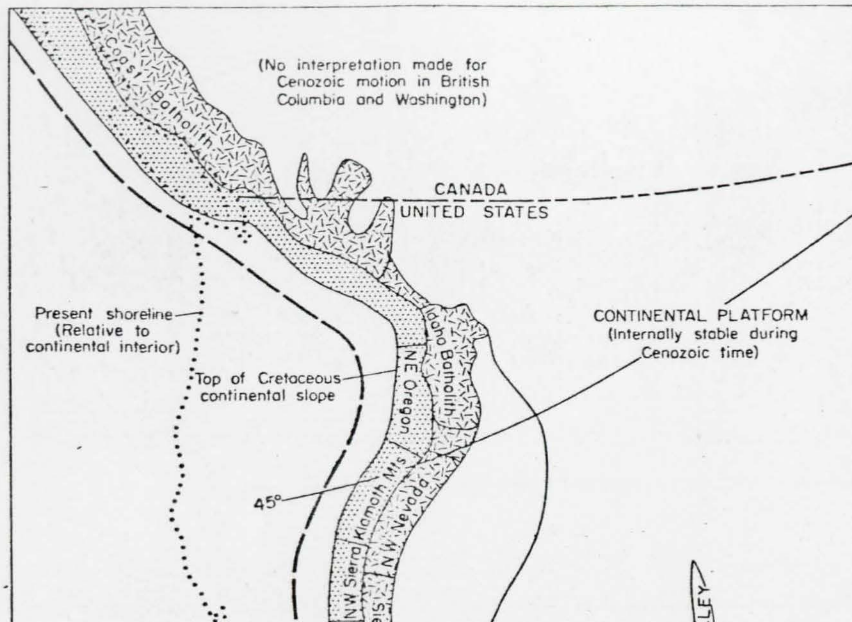

Figure 4. Paleogeographic map of the continental-margin complexes of west-central North America in Late Cretaceous time. Inferred Cenozoic extension has been reversed to derive this map from that (fig. 2) of present geography. The paleolatitudes correspond to a pole at 70° N., 175° E., as suggested by paleomagnetic orientations (Hanna, 1967; Helsley, 1967).

Original Position of Mesozoic Batholiths

Many Mesozoic tectonic elements of western North America match Cenozoic ones of western South America: but the present geometry of the North American elements is quite different from that of their South American analogues. For example, the midlines of the late Mesozoic batholiths of western North America now lie 250 to 750 km inland from the Pacific coast (fig. 2). A detailed analogy between the two continents cannot be made in terms of the present tectonic geometry.

It is however probable that the Cretaceous geometry of western North America was far more like the present geometry of South America, for North America has been affected by much internal deformation during middle and late Cenozoic time. The concept that the Cenozoic has been a period of tensional fragmentation and sundering of the continental crust of the western United States has been developed by various people, and presented in the most detail by Hamilton and Myers (1966); the reader is referred to our paper for documentation. The effect of the motion we inferred on the late Mesozoic complexes of western North America is summarized by figure 2.

Distances of the midlines of the western batholiths from the continental slope in Cretaceous time probably were much more uniform than their present erratic distances, the scatter having been produced by Cenozoic disruption. The Idaho batholith is far inland owing to the Cenozoic volcanic growth of northwestern Oregon and southwestern Washington upon crust that was oceanic in Mesozoic time. The northern part of the Baja California batholith is farther inland than the southern part owing to the tensional fragmentation and extension of the submerged continental borderland in the north. The Sierra Nevada batholith owes its inland position to the northward drift of coastal California in front of it, along the San Andreas fault system. The eugeosynclinal belts which comprise the Klamath Mountains are offset from the correlative belts of the northwestern Sierra Nevada, and have pulled far away from the batholith of northwestern Nevada and from the eugeosynclinal terrane of northeastern Oregon, which has itself swung away from the Idaho batholith.

Figure 4 illustrates the Late Cretaceous paleogeography of west-central North America, as determined by reversal of the inferred Cenozoic deformation summarized by the preceding paragraph. The distance from the edge of the continent to the midlines of the batholiths is seen to be a uniform 150-200 km in this reconstruction. It should be emphasized that this reconstruction is based primarily on an analysis of Cenozoic deformation, and not on assumptions regarding past simplicity of the continental margin. The fact that the analysis leads to a tectonic paleogeometry which has a modern analogue in South America adds confidence to the interpretations.

The major Mesozoic batholiths of the western United States lie approximately along the boundary between crust which was continental before Mesozoic time and that which was oceanic. Rocks west of the main batholiths are eugeosynclinal, and in a paper being submitted elsewhere for publication are interpreted to belong to four major types of assemblages: (1), nearly unfossiliferous slate-graywacke-chert associations, which represent continental rise, abyssal plain, and abyssal hill sedimentation, and their abyssal-tholeiite oceanic crust; (2), belts dominated by andesite and keratophyre, formed in ensimatic island arcs; (3), ultramafic rocks, from the lower oceanic crust or upper mantle, kneaded tectonically into the upper crust and injected along underthrust faults as ocean-floor and island-arc suites were swept and thickened against the edge of the ancient continent; and (4), intermediate and silicic volcanic rocks, erupted across these amalgamated assemblages from the surfacing batholithic magmas.

After Jurassic time, only the uppermost Jurassic and Cretaceous Franciscan terrane was added to the continental margin of California and southwestern Oregon. This terrane is not incorporated in the Cretaceous reconstruction of figure 4 because it was only being welded to the continent during Late Cretaceous time. The Franciscan consists of ocean-floor slate, siltstone, graywacke, chert, and abyssal tholeiite, overridden by correlative continental-shelf and continental-slope strata and by continental crystalline rocks along a system of great overthrust faults followed discontinuously by serpentine sheets (Bailey and others, 1964; Brown, 1964; Hamilton and Myers, 1966; Irwin, 1964, 1966; Page, 1966). Rocks of Franciscan type and age occur also in northwestern Washington, where they have been similarly overthrust by continental crystalline rocks, but tectonic patterns there are poorly understood; and rocks of Franciscan type but unknown age and structural relations occur also along the Pacific margin of central Baja California.

It therefore appears that the great Mesozoic batholiths of western North America formed at the same distance inland from the margin of the continent as have the late Cenozoic volcanic rocks of the Andes. This reinforces the conclusion that the modern volcanic Andes and the Mesozoic batholiths represent the same phenomenon.

Cretaceous Tectonic Setting of North America

If the analogy drawn between the modern volcanic Andes and the Cretaceous batholiths of western North America is valid, and if the Cenozoic deformation of North America has been interpreted correctly in figures 2 and 4, then the Cretaceous tectonic setting of North America can be deduced.

During the Late Cretaceous episode of intensive granitic magmatism recorded by the great batholiths of western North America, the continent was bounded on the west by a deep trench (figs. 4, 5). A Benioff zone of intermediate and deep earthquakes dipped eastward under the continent from the trench, and marked the discontinuity along which Pacific crust and mantle slid beneath the continental mantle. Dehydration reactions in the Benioff zone perhaps weakened the downflowing crustal rocks to permit earthquakes (Raleigh, 1967). Magmas were generated in or directly above the Benioff zone (Coats, 1962; Dickinson and Hatherton, 1967) because the liberated water caused melting of intermediate magmas (Green and Ringwood, 1966). The magmas underwent profound modification by reactions with the mantle and crust through which they rose (Hamilton and Myers, 1967, p. 21). Such a model fits strontium and lead isotopic data (Armstrong, 1968). The melting occurred mostly in a belt 100 to 250 km inland from

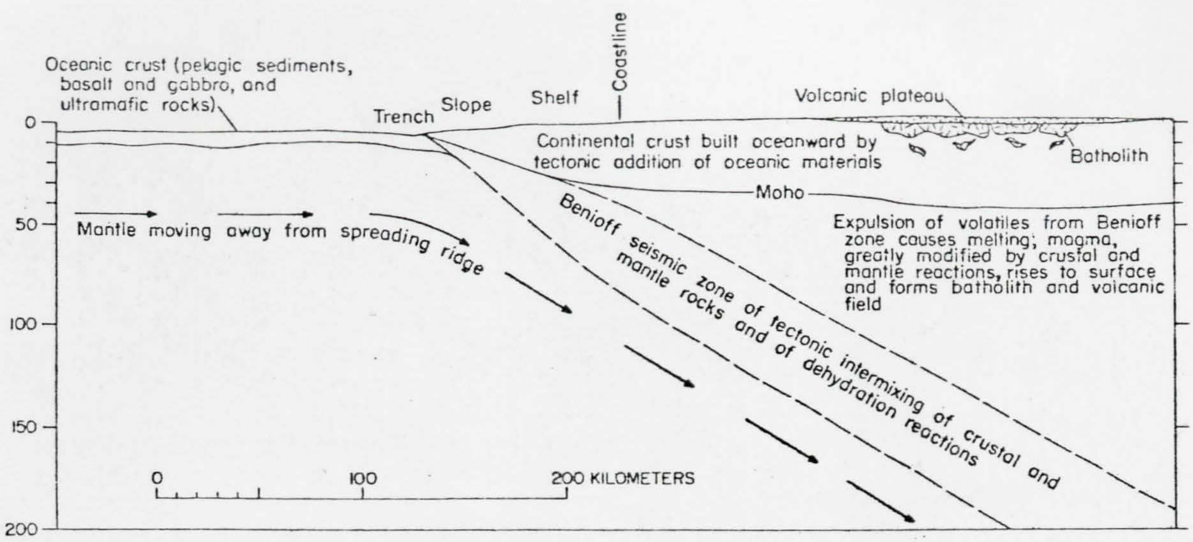

Figure 5. Cross section illustrating possible relationships between moving oceanic mantle, Benioff seismic zone, and the formation of a batholith and its capping volcanic field. This interpretation is made for the modern Andes, and for the Late Cretaceous batholiths of western North America.

the top of the continental slope.

The general eastward increase of the ratio of potassium to silicon in the granitic rocks of the batholithic belt of California (Bateman and others, 1963, fig. 20; Dickinson, this symposium; More, 1959) accords with the concept that the belt formed above an east-dipping Benioff zone. The potassium-silicon ratio of volcanic rocks now forming about the Pacific basin increases systematically with the depth to the Benioff zones beneath them (Dickinson, 1968; Dickinson and Hatherton, 1967; Kuno, 1966; Sugimura, 1967).

The batholiths formed during Late Cretaceous time, as Pacific crust and mantle spread continentward from a mid-ocean ridge at a velocity of perhaps 100 or more km per million years. The rapid-motion episode followed a latest Jurassic and Early Cretaceous period of relative stability, during which the Franciscan sediments accumulated to form a continental rise and abyssal plain. During the episode of motion, the oceanic sediments were carried eastward, depressed into the newly formed continent-margin trench, and covered by trench sediments before being incorporated in the chaos at the edge of the continent.

The analogy between Cretaceous North America and modern South America apparently extends to structures far inland. The broad Cretaceous basin that in North America separates the Cordilleran foldbelt from the Paleozoic platform and Precambrian shield of the eastern half of the continent has about the same dimensions and relative position as the modern lowlands, with their late Cenozoic fill, between the Andes and the Brazilian and Guiana Shields. The east-directed Laramide folding and imbricate thrusting in the western part of the North American Cretaceous basin has as its analogue the continuing late Cenozoic east-directed and eastward-plunging folding and imbrication of the western margin of the modern South American basin.

Older Mesozoic episodes of rapid eastward motion of Pacific crust and mantle beneath the margin of North America can be inferred, on the basis of less complete evidence, to have occurred in Early or Middle Triassic time and in the Middle and Late Jurassic. Plutonism (less widespread than that of the Late Cretaceous) and continental accretion of eugeosynclinal assemblages apparently occurred at these times, and in terms of the model developed here should record ocean-floor spreading episodes of lower velocities than the Cretaceous event.

Overview

Andesites and batholiths are mostly products of the same motion systems, and form where one great plate of crustal and mantle materials turns downward beneath the margin of another. The same motion systems carry oceanic crust and sediments and island arcs to the turndowns, where they are scraped off against the margin of the upper plate. By studying ancient andesites and batholiths, we should be able to learn much about past motions of tectonic plates, both around the margins of continents and in orogenic belts where continental plates have collided.

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