Early Permian volcanic sections preserved in north-central Queensland to lie within volcanic subsidence structures; many of these features clearly are volcanic cauldrons or subvolcanic ring structures, but some are quite large graben-like structures. Oversby and others (1980) later pointed out that these large linear blocks are not all necessarily related to specific eruptive events but are more complex synvolcanic subsided blocks. They regarded the blocks as first-order volcano-tectonic subsidence features that include the individual cauldrons, which they considered to be second-order volcanic subsidence structures. Mackenzie (1987; 1993; Mackenzie and others, 1993) further emphasized the extensional tectonic setting of the volcanism and the range of styles of associated subsidence—graben-like, sag-like, and ring-faulted. The volcanic history and structural pattern of the Yellowstone-Snake River Plain region suggests the further possibility that some of the large linear blocks of northern Queensland, largely filled with volcanic deposits, may be extensional tectonic features analogous to the downdropped fault blocks of the region around Yellowstone and the eastern Snake River Plain, in which are preserved sections of welded tuffs erupted from the associated ring and cauldron complexes and emplaced as ash flows into adjacent tectonic fault basins. Some of the larger subsided blocks might have been synchronous with volcanism but related to regional tectonic stresses rather than to subsidence resulting directly from the transfer of magma from the crust to the surface. The associated cauldron complexes would represent the subvolcanic parts of calderas related to individual volcanic cycles climaxed by major ash-flow eruptions. Furthermore, some of the associated granites might be cognetic late-stage discordant plutons such as I have suggested to be associated with the polybatholithic complex beneath Yellowstone.

MAGMOGENESIS OF THE RHYOLITE-BASALT ASSOCIATION

This paper has attempted to show that basalts and rhyolites of the Yellowstone Plateau volcanic field and of the Snake River Plain and its margins form an essential (nonaccidental) genetic association. Many lines of evidence, summarized earlier, make it clear, however, that the rhyolites and basalts are not related to one another by fractional crystallization. Questions long debated regarding bimodal volcanic fields such as Yellowstone include: How and where are the basaltic and rhyolitic magmas of such a voluminous bimodal field formed? And, what is the genetic link between the basaltic and rhyolitic magmas? Despite the volumetric predominance of rhyolites in the Yellowstone Plateau volcanic field, the history and geophysical characteristics of the Snake River Plain region indicate that basalts ultimately may be comparable in volume. It is now rather commonly accepted that the development of voluminous rhyolite-basalt igneous fields such as the Yellowstone-Snake River Plain region is a largely continental phenomenon related fundamentally to the rise of basaltic magmas from the upper mantle.

Two alternative mechanisms for generation of rhyolite-basalt bimodal systems unrelated to fractional crystallization have been proposed. Some investigators suggest that the basaltic and rhyolitic magmas are from separate or unmixed liquid fractions derived from a common parental material, others that the two major magma types are each derived from primary melts of different source regions. The evidence from Yellowstone seems clearly to favor the latter hypothesis, with separate source regions in the crust and upper mantle, but first some aspects of the case for fractional melting and the formation of separate liquids from a single source region are considered.

Hypotheses of the formation of parental magmas by separation of immiscible liquids were once widely held but dropped from favor with the lack of any convincing evidence for the importance of immiscibility in natural silicate liquids (Bowen, 1928, p. 7-19). More recently, liquid-immiscibility hypotheses have reappeared in petrologic literature, and the existence of quenched immiscible liquids in lunar basalts (Roedder and Weiblen, 1970) has lent support to the idea. Hamilton and Wilshire (1965) and Hamilton (1965) suggested that the bimodal rhyolite-basalt assemblage of the Yellowstone-Island Park region and other similar occurrences result from the separation of immiscible “olivine-basaltic” and rhyolitic magmas from a primary tholeiitic magma. Hamilton’s argument for this origin of the rhyolites of Yellowstone and Island Park rested largely on his conclusion that rhyolitic and basaltic eruptions had alternated frequently in the later volcanic history of both the Island Park and Yellowstone areas. Subsequent work, as pointed out in this paper (see pls. 2 and 3; also, Christiansen, 1982), negates that conclusion. Hamilton also suggested that a mixture of the olivine basalts and rhyolites of the Island Park area would be equivalent compositionally to an average tholeiite of the Columbia River Plateau. It is now widely recognized, however, that the basalts of Island Park as well as those of Yellowstone and the Snake River Plain that were erupted during periods of nearby rhyolitic eruption, are themselves tholeiites. Some of these basalts have very low alkali contents but are as siliceous as some tholeiites of the Columbia River Plateau (tables 16, 17). To form the basalts and rhyolites of the Yellowstone Plateau volcanic field by separation of immiscible liquids in anything like the relative volumes represented would require a primary magma with a composition more like a rhyodacite. The compositions of the low-potassium Yellowstone and Island Park tholeiites are remarkably similar to those of some oceanic-island tholeiites (table 17) and evolved from a primary magma series (Hildreth and others, 1991). Furthermore, Yoder (1971) noted that for rhyolitic and basaltic liquids to be layered in a single crustal magma chamber as envisioned by Hamilton (1965) requires several hundred degrees of superheat in the rhyolites throughout the time of coexistence; this condition is unlikely as most of the rhyolites, including the voluminous ash flows, had abundant phenocrysts when they erupted.
Presnall’s analysis (1969) of the partial fusion process, along with some experimental evidence, gives conceptual support to the hypothesis that two homogeneous liquid phases might be formed by fractional melting of a single parent material in the mantle (Yoder, 1973). The required mechanism would seem to include generation of silicic magma by very small degrees of partial melting, its rise in small batches to a region where it could accumulate into large magma bodies, and then generation of basaltic magmas. This mechanism, however, fits in poorly with the Yellowstone pattern, in which (1) very large batches of rhyolitic magma seem to have been generated repeatedly within the same general area over a period of 2 million years, and (2) basaltic magmas were, from the beginning of activity, erupting around and within this same area.

The contrasting isotopic compositions of neodymium, strontium, and lead in the basaltic and rhyolitic rocks of Yellowstone (Doe and others, 1982; Hildreth and others,
earlier, because the strontium-isotopic ratios of the Gardner were wholly the result of crustal assimilation. Third, as noted their deviation from the typical basalt ratios of about 0.706 generally are much more uniform than would be expected if rhyolites probably does reflect additions of upper-crustal some of the variation in Sr-isotopic ratios of the Yellowstone Zartman, 1973; Doe and others, 1982). Second, although 87Sr/86Sr ratios of 0.740 and higher (for example, Reed and mainy older than about 2.5 Ga. and generally has present the isotopic effects of interaction with upper-crustal materials making them especially susceptible to the isotopic effects of interaction with upper-crustal materials having high 87Sr/86Sr ratios. Three additional points bear on this evidence. First, the 87Sr/ 86Sr ratio of the Yellowstone rhyolites (typically about 0.7103±0.0015) is too low to allow them to be considered as melts of the sialic upper crust, which in this region is mainly older than about 2.5 Ga. and generally has present 87Sr/86Sr ratios of 0.740 and higher (for example, Reed and Zartman, 1973; Doe and others, 1982). Second, although some of the variation in Sr-isotopic ratios of the Yellowstone rhyolites probably does reflect additions of upper-crustal strontium (Hildreth and others, 1984; 1991), the ratios generally are much more uniform than would be expected if their deviation from the typical basalt ratios of about 0.706 were wholly the result of crustal assimilation. Third, as noted earlier, because the strontium-isotopic ratios of the Gardner River mixed lavas fit the same patterns as other rhyolites and basaltic contributions to the basaltic magmas from the lithospheric lower crust. (2) Average total eruptive rates, especially in regions with tholeiitic affinities, are higher in both oceanic basalt and continental bimodal settings than in many other volcanic systems. (3) Tectonic conditions during volcanism in both settings are nonorogenic or extensional, as in the spreading oceanic ridges and in the intraplate linear volcanic island and seamount chains. The linear evolution of the Snake River Plain-Yellowstone province is comparable in rate of volcanic propagation and in average volume rates of magma production to the linear Hawaiian volcanic chain (compare with Jackson and others, 1972) except that silicic magmas account for a considerable proportion of the Snake River-Yellowstone system but not of the Hawaiian system. Voluminous rhyolites are absent from nearly all oceanic occurrences; the single notable exception is that of Iceland, and there the rhyolites are associated with a perhaps exceptionally thick oceanic crust.

These considerations lead to the concept of voluminous bimodal rhyolite-basalt volcanism as a generally continental equivalent of major basaltic volcanism in the ocean basins. The same considerations, along with compositional and isotopic data reviewed previously, point to the lower crust as the likely source of the rhyolitic magmas of the Yellowstone field. Evidence reviewed by Leeman and Manton (1971), Leeman (1979; 1982b), and Doe and others (1982) indicates that a mafic to intermediate lower crust, consisting largely of pyroxene granulites, underlies the Snake River Plain-Yellowstone region. These granulites, sampled locally as inclusions in basalts of the Snake River Plain, have generally high values of 87Sr/86Sr (0.7125-0.727), low 206Pb/204Pb (13.5-16.1), and varied but generally high 208Pb/ 204Pb (34.7-59.1). The lead and strontium data together were interpreted by Doe and others (1982) to suggest significant contributions to the basaltic magmas from the lithospheric upper mantle and derivation of the rhyolitic magmas from...
granulitic lower crust although isotopic patterns in both the rhyolites and the basalts show significant effects of upper-crustal interactions as well.

The nature of some of these crustal interactions was further elaborated by Hildreth and others (1984; 1991) by considering neodymium and oxygen isotopes as well as the lead and strontium isotopes. They showed that all the volcanic rocks of the Yellowstone Plateau volcanic field have been affected to some degree by the assimilation of either wall and roof rocks or hydrothermal brines (or both). The large rhyolitic magma chambers were drastically affected during and immediately following the large eruptions of the first and third volcanic cycles, but internal mixing in or later magma additions to these batholith-sized magma bodies tended to restore them toward initial values.

More fundamentally, Hildreth and others (1991) showed that the relatively limited neodymium, strontium, and lead values of the rhyolites are most consistent with derivation from lower-crustal rocks that were extensively hybridized by basaltic magmas from the upper mantle, probably contemporaneously with evolution of the Yellowstone Plateau magmatic system.

In summary, the generation and evolution of the magmas of the eastern Snake River Plain-Yellowstone Plateau region stems fundamentally from the formation of basaltic magmas by partial melting of the upper mantle. As in many other such regions, this magma generation is associated with regional extension. The common association of oceanic basaltic volcanism and of continental basaltic or rhyolite-basalt volcanism with tectonic extension suggests generation of many of the basaltic magmas by the reduction of pressure in the upper mantle during tectonic extension. It might be further suggested that if it were not for the presence of a crust thicker than about 15 km in the region of magma generation, the volcanism of voluminous bimodal volcanic regions would have been essentially the same as that of various oceanic volcanic zones; the Snake River Plain-Yellowstone province would resemble the Hawaiian chain. This formation and rise of basaltic magma is a mechanism of increased local heat flow from the mantle. The radiogenic heat production of continental crust is high relative to that of the mantle, and the thick crust in effect insulates its own lower part. The rise of major amounts of basaltic magma into and through a thick continental crust—and perhaps in certain other areas of relatively thick crust and high heat flow such as Iceland—may raise geothermal gradients sufficiently to allow partial melting in the crust by the pressure reduction accompanying tectonic extension. Lower crust, probably consisting of pyroxene granulites of mafic to intermediate composition, may be partially melted to form a primary rhyolitic magma. The process may be similar to that proposed by Bailey (1964) for the generation of alkalic magmas beneath zones of uplift and rifting. Bailey (1964; 1970) also pointed out that the physical conditions existing in the lower crust in such a setting might be expected to cause an influx of volatiles to the site of magma generation, further aiding in the process of partial melting.

By such mechanisms the rhyolitic magmas do not necessarily form in direct thermal equilibrium with the basaltic magmas or require superheat during their formation, but they nevertheless owe their origins directly to the formation and rise of basaltic magma into the crust. The basaltic and rhyolitic magmas may rise and differentiate independently in the crust; in such instances, basalt-rhyolite mixed-lava complexes may be the result of no more than an accidental encounter of separate magmas finding their ways to the surface through available tectonic fractures. In voluminous and long-lived systems, however, the basaltic component must play a more important role in providing a continued supply of thermal energy from the mantle to maintain the high-level rhyolitic magmas in a partially liquid state for geologically long times, enabling them to accumulate in large shallow chambers and to undergo extreme differentiation processes that lead to the enrichment of volatile constituents and their release in voluminous pyroclastic eruptions (Smith 1979; Christiansen, 1979; Hildreth, 1979; 1981; Christiansen, 1984). However, the suggestion of Gibson and Walker (1963) that the immediate presence of a basaltic component may always be necessary for viscous rhyolitic magmas to rise in near-surface fissures or to be triggered into eruption is not borne out at Yellowstone, where rhyolitic lava flows with no visible basaltic component are voluminous.

### REGIONAL EVOLUTION OF THE CRUST AND UPPER MANTLE

The origin and evolution of such a massive magmatic system as that of the Yellowstone Plateau is but one manifestation of processes that involve the entire crustal and upper-mantle column and perhaps parts of the deeper mantle.

### PLATE-TECTONIC FRAMEWORK

A rationale for placing the extensional late Cenozoic tectonics of the Western United States into the picture of global plate-tectonic movements was provided by Atwater (1970) and Atwater and Molnar (1973). More recently, aspects of this framework have been amplified and refined by Stock and Molnar (1988) and Atwater (1989). Lipman and others (1972), Christiansen and Lipman (1972), Christiansen and McKee (1978), and Werner and others (1987) attempted to show that this framework is useful in understanding much of the Cenozoic volcanic and tectonic history of the Western United States.

In brief, the Cenozoic Western United States is the leading edge of a migrating North America lithosphere plate. Before about 30 Ma, the plate was bounded on the west by a trench along which the Farallon and related plates, constituting the eastern Pacific Ocean floor, were undergoing subduction into the upper mantle beneath North America (McKenzie and Morgan, 1969; Atwater, 1970). An ances-
tral East Pacific Rise farther west produced new crust as the Farallon plate and the more westerly Pacific plate diverged from it. Volcanic arcs lay parallel to the continental margin of the Pacific Northwest and Mexico, and a complex volcanic system, predominantly andesitic and calc-alkalic, extended far toward the continental interior in the area between these arcs (Christiansen and Yeats, 1992). These volcanic systems affected most of a very large region that had undergone major compressive deformation and igneous activity during Mesozoic and earliest Tertiary time (Lipman and others, 1972; Elston and Bornhorst, 1979; Wernicke and others, 1987). During the Eocene this continental-margin system extended as far east as the Yellowstone region and produced the Absaroka Volcanic Supergroup. After the Eocene, however, calc-alkalic volcanism at this latitude occurred only in a relatively narrow volcanic arc that was restricted to areas nearer the Pacific margin. The East Pacific Rise and the continental-margin trench approached each other throughout early and middle Cenozoic time. At about 29 or 30 Ma they intersected. As they did, subduction of the Farallon plate in the area of intersection ceased, that segment of the trench closed, and a new kinematic pattern affected the margin of the North America plate, reflecting now the relative motion of the America and Pacific rather than the America and Farallon plates (McKenzie and Morgan, 1969; Atwater, 1970). This right-lateral relative motion is represented most conspicuously by the San Andreas fault zone of California and related faults. With further convergence of the East Pacific Rise and the continental margin, a progressively longer contact between the Pacific and North America plates developed and both the rise and the trench ceased activity along this contact.

The cumulative relative motion between the Pacific and North America plates is greater than that represented by the San Andreas fault system alone. Atwater (1970) and Atwater and Molnar (1973) proposed that the remainder of the motion is distributed over a wide “soft” marginal zone of the North America plate. Christiansen and Lipman (1972), Snyder and others (1976), Wernicke and others (1987), and Christiansen and Yeats (1992) showed that changes in the types of tectonic and igneous activity occurred throughout the area of Mesozoic and earlier Cenozoic orogenic and igneous activity in the Western United States during late Cenozoic time, perhaps shifting in locale to some degree as the zone of Pacific-American contact continued to lengthen. Whereas volcanism before this transition tended to be predominantly intermediate in composition, afterwards it tended to be either predominantly basaltic, mafic and alkalic, or bimodally basaltic and rhyolitic. Following Christiansen and Lipman, (1972), this younger volcanic regime is referred to as “fundamentally basaltic” (although, as pointed out by Hildreth, 1981, in a more profound sense perhaps all terrestrial magmatism is fundamentally basaltic).

After middle Miocene time, the remnant of the magmatic arc system became progressively restricted northward as the Pacific-America plate interface widened and is now represented by the volcanic Cascades of the Pacific Northwest. The history of tectonic extension is more complex; before about 17 Ma extension characterized only specific, generally narrow zones, and from then until 14-10 Ma it produced mainly wide tectonic basins of relatively low relief (Christiansen and Yeats, 1992). The early tertiary extension may have been affected by both back-arc and post-orogenic stress regimes (Zoback and others, 1981). As extension became more widely distributed to form essentially the present-day basin-range system, volcanism changed from predominantly andesitic and generally calc-alkalic to fundamentally basaltic. By about 17 Ma, much of the region east of the continental-margin volcanic arc was characterized by basaltic and bimodal rhyolite-basalt volcanism (Scholz and others, 1971; Christiansen and Lipman, 1972; Noble, 1972; Snyder and others, 1976; Christiansen and McKee, 1978; Christiansen and Yeats, 1992). By 10 Ma, a wide region south of the Snake River Plain and the High Lava Plains of Oregon was undergoing tectonic extension in the modern basin-range mode (Christiansen and McKee, 1978; Zoback and others, 1981; Christiansen and Yeats, 1992).

MacLeod and others (1976) showed that another propagating volcanic system began at about the same time as the Snake River Plain-Yellowstone system in about the same area, the region surrounding the Oregon-Idaho-Nevada boundary. That system, however, extended northward across Oregon and now reaches the Newberry volcano at the Cascade front. A line that connects the Newberry volcano, back along the trace of this propagating volcanic system to the region west of the Snake River Plain and then northeasterward along the eastern Snake River Plain to the Yellowstone Plateau lies within a diffuse but important boundary zone. To the south along this entire line, the late Cenozoic tectonic pattern is a strongly and typically developed basin-range fault system that continues southward into the Great Basin, where the faults reflect major crustal extension—probably aggregating at least 250 km (Hamilton and Myers, 1966; Stewart, 1971; Proffett, 1977; Hamilton, 1978; Davis, 1980; Wernicke and others, 1988). Numerous earthquakes occur in this region, most of them in diffuse belts toward the margins (fig. 48). The region north of the Newberry-to-Yellowstone boundary zone also contains extensional normal faults and some strike-slip faults, but the faults are fewer, their aggregate extension is much less than to the south, and they generally cease to be the dominant elements of topography within several tens of kilometers north of the boundary. Seismicity declines markedly but continuously northward from near this boundary zone across the Northern Rocky Mountains and Columbia Plateau (fig. 48). This boundary zone itself is essentially aseismic. Not only is this boundary the trace of two diverging volcanic systems that propagated from between about 12 and 10 Ma to the present, but it also has been the locus of continuing basaltic volcanism throughout the Quaternary.
The basaltic magmatism that has accompanied late Cenozoic extensional tectonism in the Western United States results from partial melting of the upper mantle and probably is an intimate part of the processes that cause high regional heat flow (Lachenbruch and Sass, 1977), a thinner crust and lithosphere, and anomalously low mantle seismic velocities in the basin-range region. These anomalous crustal and upper-mantle properties coincide with the region of late Cenozoic basaltic and bimodal rhyolite-basalt volcanism.

The plate-tectonic framework of late Cenozoic volcanism and tectonic extension leads directly to a basic question: Are the fundamentally basaltic volcanism of the Western United States in general, and of the Yellowstone Plateau and eastern Snake River Plain in particular, direct consequences of the plate interactions as they guide tectonic development of the region, or does the volcanism result from processes of deeper origin that may even be the causes of plate motion? Wilson (1963) and Morgan (1971; 1972) proposed a worldwide framework of convection plumes that rise from the base of the mantle to produce “hotspots” near the global surface where partial melting may produce voluminous magmatism and where the tractive force of the spreading plumes at the base of the lithosphere may tend to break the lithosphere and drive the resulting plates apart. Morgan proposed that Yellowstone marks the site of such a deep mantle convection plume and that the eastern Snake River Plain records the trace of the North America plate over the resulting hotspot. Several points have been raised in favor of this concept. First, as a global group and to a suitable approximation, the hotspots do appear to have remained fixed relative to one another as the lithospheric plates move in relation to them (Minster and others, 1974; Minster and Jordan, 1978; Gripp and Gordon, 1990; Acton and Gordon, 1994). Second, the mantle-plume concept suggests a mechanism that allows long-lived localized melting anomalies like Hawaii to draw on continuously renewed mantle from beneath the depleted asthenosphere as a source material for partial melting. And, third, the mantle-plume hypothesis correlates the average rate of volcanic propagation of certain linear volcanic chains very well with the relative motions determined for the lithospheric plates. In the particular case of Yellowstone and the eastern Snake River Plain, the orientation and linear volcanic propagation rate of the Snake River Plain-Yellowstone axis accords, within the resolution of the data and allowing for the effects of subsequent crustal extension, with the late Cenozoic relative movement of the Pacific and North America plates and the movement of the Pacific plate with respect to a fixed Hawaiian hotspot (Morgan, 1972; Smith and Sbar, 1974; Rodgers and others, 1990; Smith and Braile, 1994).

The concept of a convective plume rising from the lower mantle has, thus, proven attractive and has been applied to the Yellowstone-eastern Snake River Plain system by many investigators, notably including Morgan (1971; 1972), Matthews and Anderson (1973), Smith and Sbar (1974), Suppe and others (1975), Duncan (1982), Westaway (1989), Pierce and Morgan (1992), and Smith and Braile (1994). Several of these authors even credit a Yellowstone mantle plume with being one of the main driving forces of continental tectonics in the Western United States during the late Cenozoic. Hadley and others (1976) also explicitly applied

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the related concept of a chemical plume to the Yellowstone hotspot—a buoyantly rising mass within the sublithospheric mantle that is anomalously enriched in incompatible and heat-producing elements. Despite the prevailing view, I wish to examine critically the evidence cited in favor of applying the deep-mantle plume model to Yellowstone and to discuss a possible alternative explanation for the region’s “hotspot” magmatism.

To begin with, the somewhat negative if obvious point should be made that the consistency of certain data with a hypothesis does not necessarily constitute a sufficient proof of the hypothesis. Thus, if all of the evidence cited above in favor of the mantle-plume hypothesis can be accounted for by alternative explanations, the evidence neither proves nor disproves any of the hypotheses. The evidence for relatively fixed positions of a group of proposed deep-mantle plumes, for example, may allow for relative movements between these sites of as much as 1-2 cm/yr (Minster and others, 1974; Molnar and Stock, 1987), a significant rate in the plate-tectonic movement picture of the earth. Secondly, the existence of more or less fixed melting anomalies or “hotspots,” the velocity model of plate movements in relation to these hotspots, and a mechanism for continuously replenishing the source of mantle material for partial melting are equally consistent with other hypotheses such as McDougall's asthenospheric counterflow model (1971) or Shaw and Jackson's shear-melting and thermal-feedback model (1974) for the Hawaiian melting anomaly. None of the geophysical parameters globally concomitant with hotspots uniquely requires that the associated mantle convection originates in the lower mantle (Moriceau and others, 1991; Anderson and others, 1992).

The following deficiencies in application of the primary deep mantle-plume model to the volcanic and tectonic history of the Yellowstone melting anomaly may be noted:

1. The deep mantle-plume model carries no specific mechanism to explain, not merely volcanic propagation along the eastern Snake River Plain-Yellowstone axis, but also continuing basaltic volcanism that characterizes the Snake River Plain along both its western and eastern branches, in distinction, for example, to the pattern of activity in the Hawaiian volcanic chain.

2. The model provides no inherent explanation for the beginning of volcanism near the southwest end of the eastern Snake River Plain in the middle Miocene during a time of major tectonic reorganization from limited linear belts of extension associated with andesite-rhyolite volcanism to regionally distributed extension and fundamentally basaltic volcanism throughout much of the basin-range region, an area more than 2,000 km across. Some models, for example those of Pierce and Morgan (1992) and Parsons and others (1994), relate all of this early regional extension and magmatism to a diffuse plume head, but others, for example Geist and Richards (1993), require the plume to have been focused at the north edge of the region between 17 and 14 Ma in order to account for the voluminous flood-basalt volcanism of the Columbia River Plateau.

3. Effects attributed to the Yellowstone hotspot arose, apparently spontaneously, at about 17 Ma (Pierce and Morgan, 1992; Parsons and others, 1994), within a complexly generated part of the North American continental lithosphere (Christiansen and McKee, 1978); systematic northeastern propagation along the eastern Snake River Plain axis did not begin until about 12.5 Ma (Christiansen and Yeats, 1992). Duncan (1982) proposed that the Yellowstone melting anomaly was in fact continuous from an oceanic spreading center in Paleocene and Eocene time and was overridden by the North America plate along a curving path to generate magmas of the Columbia River Basalt Group and the volcanism of the western Snake River Plain before starting its linear path up the eastern Snake River Plain. Duncan's evidence for ridge-centered hotspot volcanism to form the Paleocene to Eocene basalts of the Oregon and Washington Coast Ranges can be evaluated independently of its identity with the Yellowstone melting anomaly; that identity seems unlikely. There is no record of volcanism on the North America plate above this hotspot between about 49 and 17 Ma; it presumably was shielded by the subducting slab beneath the ancestral Cascades (Duncan, 1982; Hill and others, 1992). In Duncan's model, after having taken 32 m.y. to move (relative to the present surface) 400 km eastward from the Washington Coast Range to the eastern Columbia Plateau (1.3 cm/yr), the hotspot must have turned and migrated 400 km southeastward down the western Snake River Plain between 17 and 15 Ma (20 cm/yr) before turning again and starting northeastward up the Snake River Plain at about 3.5 cm/yr; no such plate path or pair of velocity discontinuities is evident in the oceanic magnetic record relative to the independent hotspot frame of reference.

4. The propagating Yellowstone melting anomaly seems to be one of a pair that evolved at about the same time from the initial widespread basaltic and bimodal magmatism of 17-14 Ma in the region of southeastern Washington, eastern Oregon, western Idaho, and northern Nevada. The other volcanic belt, also a bimodal rhyolite-basalt system, has propagated northwestward across eastern and central Oregon at about the same rate as the propagation of the Yellowstone-eastern Snake River Plain volcanism (MacLeod and others, 1976). The two melting anomalies are basically similar and would seem to have been formed by the closely related processes. Yet, if the propagating Yellowstone melting anomaly were a direct reflection of a deep mantle convection plume, then the propagating Oregon melting anomaly would require a different process of formation. Pierce and Morgan (1992) interpreted such a dif-
ference for this eastern Oregon belt by comparing only its propagating part (less than 10 Ma) to the entire post-17-Ma history of the Yellowstone hotspot (although its propagating part too dates only from 12-10 Ma) and by noting its lower magmatic productivity. Nevertheless, its magmatic productivity—though less than Yellowstone’s—was significant, including voluminous ash-flow fields of 9.3-6.5 Ma (Walker, 1979), and its symmetry with and similarity in rate of propagation to the Yellowstone hotspot strongly suggest a linked origin of these two systems.

5. The region south of the two zones of propagating rhyolitic volcanism has undergone large amounts of basin-range extension, probably 200-300 km (Wernicke, 1992), whereas that to the north has undergone appreciably less extension, which ends within several tens of kilometers to the north (Lawrence, 1976; Christiansen and McKee, 1978; Christiansen and Yeats, 1992). The primary deep-mantle plume model can explain this only as coincidence.

6. Although the Snake River Plain-Yellowstone axis conforms to the kinematic constraints of North America plate motion (fig. 49), as Smith and Braile (1994) demonstrated in detail, it also coincides with a unique crustal tectonic setting. The hotspot began to propagate at the west edge of the Archaean continental crust of the Wyoming province (Reed, 1993). Eaton and others (1975) and Mabey and others (1978) showed that a regional aeromagnetic anomaly pattern along the axis of the eastern Snake River Plain continues both southwestward into Nevada and northeastward (interrupted only by a magnetic low associated with the Yellowstone magma

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**Figure 49.—Selected tectonic elements of Western North America in relation to right-lateral relative motion of the Pacific and North America lithospheric plates. The map is plotted on a Mercator projection with its pole at the pole of relative rotation of these two plates so that structures oriented horizontally in the projection and related to plate motion have strike slip; oblique structures in the projection that are related to plate motion have oblique deformation, with components of both strike slip and either extension or contraction. After Atwater (1970) with volcanic features added from Luedke and Smith (1984).**
extensional stress relief in causing partial melting along the mid-line of a region of intense earlier mid-Tertiary magmatism.

Within less than 3 million years after initiation of this extensional tectonic system at about 17-18 Ma, volcanism of fundamentally basaltic character extended outward from the initial rift axis to blanket a large region of eastern Washington and Oregon, western Idaho, and northern Nevada (Christiansen and McKee, 1978; Draper, 1991; Christiansen and Yeats, 1992). With the increasing width of a zone of lithospheric extension and thinning by about 10 Ma, virtually to the west and east margins of the present Great Basin region, the upper crust became segmented into blocks, with extensional faults aligned in directions consistent with a continuously adjusting stress field (Zoback and others, 1981; Zoback and Zoback, 1989) that may reflect the influence of Pacific-North America right-lateral relative motion on parts of the extending region. In some places the normal faults that produce this later segmentation probably are guided by preexisting structures. The melting caused by regionally distributed tectonic stress relief probably resulted in low percentages of partial fusion and the production mainly of an alkaliolivine basaltic suite (Leeman and Rodgers, 1970). Only near the margins of the region of great extension have tholeiites erupted (Christiansen and Lipman, 1972; Christiansen and McKee, 1978; Draper, 1991), perhaps indicating locally shallower melting or higher percentages of partial melting in zones of concentrated extension near those boundaries. These combined tectonic and magmatic processes have produced buoyant rise of upper-mantle material beneath the extending region and a feedback relation between lithospheric extension and upper-mantle convection. With time, perhaps as heightened regional heat flow has reduced the rigidity of the lithosphere within the center of the active zone and that lithosphere has approached a stable configuration, active extension, seismicity (fig. 48), and the production of basaltic magmas have tended to become increasingly concentrated toward the margins of the region (Christiansen and McKee, 1978). Along the Yellowstone hotspot track, a zone of enhanced extension has migrated both along with the hotspot and outward from the margins of the eastern Snake River Plain (Anders and others, 1989; Pierce and Morgan, 1992).

In this model, tectonic stress relief and resultant partial melting in the upper mantle occur upon a diffuse north boundary of the basin-range region. As the formerly wider zones of large extension and crustal basaltic intrusions concentrated outward and narrowed toward the east and west margins of the region of extension, their trailing margins projected along the mid-line of a region of intense earlier mid-Tertiary magmatism.

The foregoing considerations lead me to outline the following qualitative conceptual model that treats the late Cenozoic basaltic and basalt-rhyolite volcanism of the Western United States, and of the Yellowstone system in particular, as a direct result of late Cenozoic intraplate extension, which in turn is intimately related to late Cenozoic interactions of the lithospheric plates. This model may serve as a future basis for comparison to the widely discussed deep-mantle convective plume concept.

In the model proposed here, as the zone of direct interaction between the Pacific and North America plates grew at the expense of oceanic ridge and trench in early and middle Miocene time, a relaxation of stress affected the adjacent region of the North America plate (Zoback and Zoback, 1989) that previously had been compressively deformed and heated by magmatism during late Mesozoic and earliest Tertiary time. Specific more or less linear zones through this region had also undergone large extensions and voluminous magmatism in Eocene and later mid-Tertiary time. This previously deformed and heated region first responded to region-wide extensional stress by stretching, thinning, and uplifting. By about 17 Ma the remnant arc was restricted to a relatively small part of the continental margin, and extensional thinning affected not only a zone directly inland from the coastal strike-slip system but also the northern basin-range and Columbia Plateau regions behind the arc.

As the remnants of the Farallon plate shrank, stress relief and associated thinning of the previously deformed and heated lithosphere produced regional tectonic extension, rise of the underlying upper mantle, and widespread partial melting in that mantle. Buoyant rise of these melts in turn caused widespread basaltic intrusion into the lower crust, increased regional heat flow, markedly decreased the rigidity of the lithosphere, and further enhanced lithospheric extension and thinning and the development of anomalously low upper-mantle seismic velocities. This chain of heating events seems to have begun at about 17-18 Ma along the axis of the region from the southeastern Great Basin to the Columbia Plateau with a north-northwest strike, reflecting a uniform regional west-southwest minimum horizontal stress orientation (Zoback and Thompson, 1978; Christiansen and McKee, 1978; Christiansen and Yeats, 1992; Zoback and others, 1994; Parsons and others, 1994). The occurrence of the mid-Miocene rift zone along the center of an extended and uplifted region of earlier deformation and volcanism might be interpreted as indicating the greatest efficiency of extensional stress relief in causing partial melting along the
region marks the border between a broad region of high heat flow and the cooler, more or less rigid plate beyond. The intersection of this progressively restricted and focused border zone with the structurally controlled Snake River Plain axis has localized and concentrated voluminous magmatism along the north boundary zone of the basin-range extensional region.

If the Yellowstone melting anomaly in this conceptual model was initially localized by a preexisting structural boundary, it was enhanced because this controlling structure was fortuitously oriented in the direction of motion of the lithospheric plate relative to the underlying mantle (compare with Smith and Sbar, 1974; Smith and Braile, 1994). For this reason, it is proposed shear melting at the base of the lithosphere accelerated the local partial melting process, heating the lithosphere and initiating a thermal feedback cycle, as proposed by Shaw and Jackson (1974) for Hawaii. That is, as large volumes of melt were produced, they rose buoyantly, reduced pressure in the upper mantle, and resulted in further melting of the mantle. This feedback process has sustained the most productive magmogenetic system in the Western United States during late Cenozoic time. These factors of enhanced lithospheric extension, shear melting, and thermal feedback have combined to make this a self-sustaining melting anomaly comparable in magnitude to the Hawaiian system.

The Yellowstone melting anomaly produces a relatively high percentage of partial melting in the affected part of the upper mantle so that the primary magmas are low-potassium tholeiitic types with trace-element patterns comparable to the theoleites of high-volume oceanic-island systems. Because of the thick continental crust above the zone of basaltic magma generation, however, a higher percentage of the magma may remain low in the crust as intrusive bodies than in an oceanic setting. As the wave of enhanced magmatism has passed northeastward along the axis of the Snake River-Yellowstone system, decreased degrees of partial melting, the rise of relatively undepleted mantle, and increased lithospheric interactions may produce the successively higher-potassium basalts with higher Fe/Mg, Ti, P, and incompatible trace elements, typical of the Snake River basaltic magmas.

In the propagating zone of concentrated extension, enhanced partial melting of the lower crust resulting from the increased regional heat flow and from basaltic intrusions into the lower crust has produced rhyolitic magmas which, being less dense than the basaltic magmas, have risen higher in the crust along the Snake River Plain axis and have accumulated into batholith-sized bodies at favorable structural intersections. As long as continued high rates of basaltic magma production in the mantle sustained these silicic magmatic systems, they produced cycles of voluminous rhyolitic volcanism at the surface. However, as plate motion slowly displaces the lithosphere, it eventually migrates away from the self-sustaining focus of melting. Eventual cooling of the granitic batholiths may result in volume decrease and subsidence along the volcanic axis (Brott and others, 1981; Smith and Braile, 1994); continued regional extension, however, favors episodic rise of smaller volumes of basaltic magma, resulting in occasional eruption of relatively more potassium-rich basalts along the subsiding axis of the plain, loading it and causing further subsidence. The lack of a well-marked graben along this rift may indicate less rigid deformation of this hot, still partly molten zone than of surrounding regions. Thus, if a slice beneath the eastern Snake River Plain at several kilometers depth would be expected to reveal a chain of ring intrusions invaded by a discordant batholithic complex, as suggested in the previous chapter, a slice at perhaps 15 or 20 km might reveal an intrusive complex of differentiated tholeiites. Hamilton’s suggestion (1959) that Yellowstone is the surface expression of a lopolith may indeed be conceptually useful although with reference to a greater depth and more complex processes than Hamilton proposed.

The few seismic experiments to date designed specifically to investigate the roots of the Yellowstone magmatic system (Iyer, 1975; 1978; 1984; Evoy, 1978; Iyer and others, 1981; Daniel and Boore, 1982; Humphreys and Dueker, 1994a; b) have shown that anomalous geophysical properties are associated with the system to a depth of about 200 km. Plume-like convection related to the Yellowstone hotspot should result from upward and lateral inward flow of hotter, relatively undepleted mantle material to replace that depleted by partial melting and added to the extending lithosphere.

To summarize this discussion of crustal and mantle evolution and to simplify its rather long speculative reach, the plutonic and upper-mantle components of the Yellowstone magmatic system constitute by far the bulk of its volume. Considered in its entirety, this system extends downward from the volcanic field and its subvolcanic rhyolitic intrusions, through a batholith-sized body of rhyolitic magma—complexly mixed with more mafic magmas in its lower regions—on through a basaltic intrusive regime within and around which the lower crust has been partially melted, into an upwelling zone of basaltic magma generation in the upper mantle. Within and beneath this zone of melting a residual mantle is at least partially displaced by lateral inflow of undepleted mantle. Whether this convective system in the upper mantle is sustained by plume-like convection from the lower mantle—even the core-mantle boundary—remains even more highly speculative and is unresolved.

THE FUTURE OF YELLOWSTONE VOLCANISM

It seems appropriate to conclude this speculative final chapter on magmato-tectonic evolution of the Yellowstone Plateau volcanic field with a brief appraisal of the prospects for its volcanic future. The problem is considered here from three points of view. First, the Yellowstone Plateau possibly represents the later stages of a resurgent cauldron cycle with possibilities for further, but generally declining rhyolitic vol-