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Reconstructing the ancestral Yellowstone plume from accreted seamounts and its relationship to flat-slab subduction

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Abstract

Recent geodynamic analyses have emphasized the relationship between modern flat-slab subduction zones and the overriding of buoyant oceanic crust. Although most models for the evolution of the Late Mesozoic–Cenozoic Laramide orogeny in the southwestern United States involve flat-slab subduction, the mechanisms proposed are controversial. An examination of the geological evolution of the 60–50-Ma Crescent terrane of the Coast Ranges indicates that it was formed in a shallowing-upward Loihi-type oceanic setting culminating in the eruption of subaerial lavas. Plate reconstructions indicate that the Crescent terrane was emplaced into ca. 20-Ma crust, and the presence of subaerial lavas implies an uplift due to the plume of ca. 4.2 km, which we use to calculate a minimum buoyancy flux of 1.1 Mg s^{-1}, similar to that of the modern Yellowstone plume.

Published paleomagnetic data indicate that the Crescent terrane was formed at a paleolatitude similar to that of the Yellowstone plume. The Crescent seamount was accreted within 5 My of the cessation of plume magmatism. Plate reconstructions indicate that it would have originated about 750 km to the west of the North American plate margin if it developed above a fixed Yellowstone plume, and are therefore consistent with the recorded very short interval between its formation and tectonic emplacement.

We interpret the Crescent terrane as due to the ancestral Yellowstone plume. Such a plume would have generated an elongate swell and related plateau that would have been overridden by the North American margin. Taken together, the relationship between flat-slab and overriding of oceanic plateau in Laramide times would have been analogous to the relationship between modern Andean flat-slab subduction zones and the Juan Fernandez and Nazca oceanic plateaus.

Keywords: Flat-slab subduction; Coast Ranges; Crescent terrane; Yellowstone plume

1. Introduction

It has long been recognized that the geometry of subduction zones profoundly influences the tectonic style of orogenesis at convergent margins. The western

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margin of North America has been affected by various episodes of subduction-related accretionary tectonics since the Late Paleozoic, resulting in the Antler (Mississippian), Sonoma (Permian–Triassic), Nevadan (Jurassic), and Laramide (Late Cretaceous–Tertiary) orogenies (e.g. Lipman et al., 1972; Dickinson and Snyder, 1978; Livaccari et al., 1981; Severinghaus and Atwater, 1990; Burchfiel et al., 1992). Although each orogenic event is complex in detail, with the exception of the Laramide orogeny, the geological expression of these orogenies is consistent with accretionary tectonics. The Laramide orogeny in the southwestern United States is atypical in that it is characterized by an almost complete absence of magmatism (the Paleocene magmatic gap, Fig. 1), widespread deformation, and thick-skinned tectonics associated with basement uplifts located up to 1500-km inboard of the continental margin. Most authors attribute these features to flat-slab subduction (e.g. Dickinson and Snyder, 1978; Livaccari et al., 1981; Bird, 1988; Severinghaus and

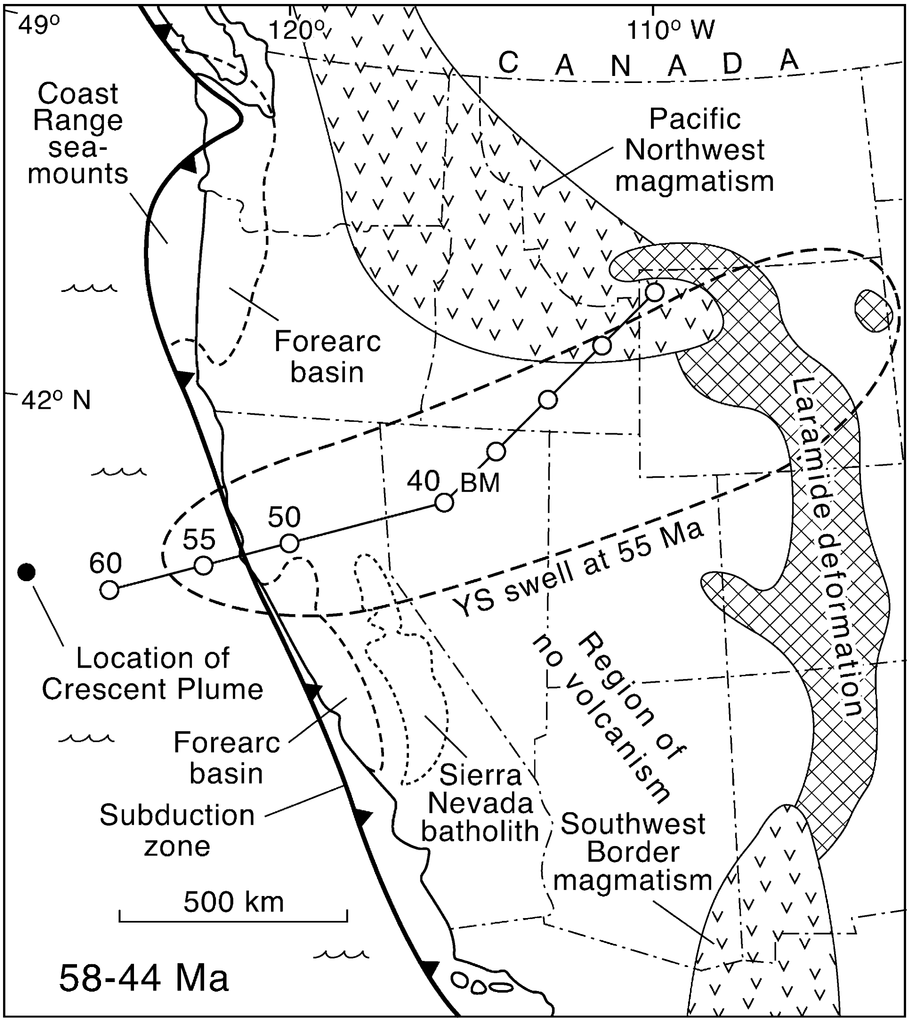

Fig. 1. Simplified Eocene paleotectonic map (modified from Burchfiel et al., 1992) showing the track of the Yellowstone plume from ca. 60 Ma to present (using data of Engebretson et al., 1985), and the present location of the Coast Range complexes. Dashed line indicates the approximate region of the proposed buried plume-related swell at 55 Ma (from Oppliger et al., 1997; Murphy et al., 1998).

Atwater, 1990). However, origin of the flat slab is controversial, and not well constrained.

Recent geodynamic analysis of modern flat-slab subduction zones has drawn attention to their spatial and temporal correlation with subducting oceanic plateaus (e.g. Gutscher et al., 2000; Yáñez et al., 2001; Ramos and McNulty, 2002), suggesting a similar possibility for the Laramide orogeny. The Andean margin, for example, has several flat-slab segments, up to 500 km wide, each of which correlated with subduction of anomalously buoyant oceanic crust, represented by oceanic plateaus (Pilger, 1981; Gutscher et al., 2000). Murphy et al. (1998) speculated that flat-slab subduction in the western United States was due to overriding by the continental margin of a mantle plume and an associated swell related to the ancestral Yellowstone hotspot. According to plate reconstructions, the ancestral Yellowstone plume would have been beneath the Kula plate prior to 55–50 Ma, at which time it would have collided with the continental margin.

Evidence for the existence of the plume in the oceanic realm is derived from Late Cretaceous basaltic terranes of the Coast Ranges of British Columbia and Washington State, and from the Yukon territory. Duncan (1982) and Wells et al. (1984) proposed that some basaltic provinces of the Coast Ranges (such as the 60–50 Ma Crescent terrane) were seamounts generated by the Yellowstone plume that were accreted to western North America in the Eocene. In the Yukon territory, the ca. 70 Ma Carmacks basaltic volcanics have plume-type geochemistry. Paleomagnetic data indicate that the Crescent and Carmacks basalts were both erupted at paleolatitudes similar to that of the Yellowstone hotspot (e.g. Johnston et al., 1996). Since their eruption, the Carmacks basalts were translated $17.2 \pm 6.5^{\circ}$ northward (Johnston and Thorkelson, 2000), whereas the Crescent volcanics were translated $4.72 \pm 8.9^{\circ}$ northward (Babcock et al., 1992).

In this paper, we further assess the relationship between the Crescent volcanics and the Yellowstone plume. We combine estimates of the paleoelevation of the Crescent volcanics and the age of the ocean floor onto which they erupted to determine the excess elevation at the time of eruption. This excess elevation is then used to assess the characteristics of the plume thought to have fed these volcanics, and the characteristics are compared with those of the modern Yellowstone plume.

2. Geologic setting

The Crescent terrane is the most voluminous sequence of mafic flows in the Coast Ranges (Fig. 2). The northernmost rocks of the Crescent terrane are the Metchosin volcanics of southern Vancouver Island (e.g. Massey, 1986). In general, the Metchosin stratigraphy records a shallowing-upward sequence from pillowed basalts and turbidites near the base through subaerial flows near the top (Fig. 3). The lower pillowed basalt unit grades up through a 1000-m-thick

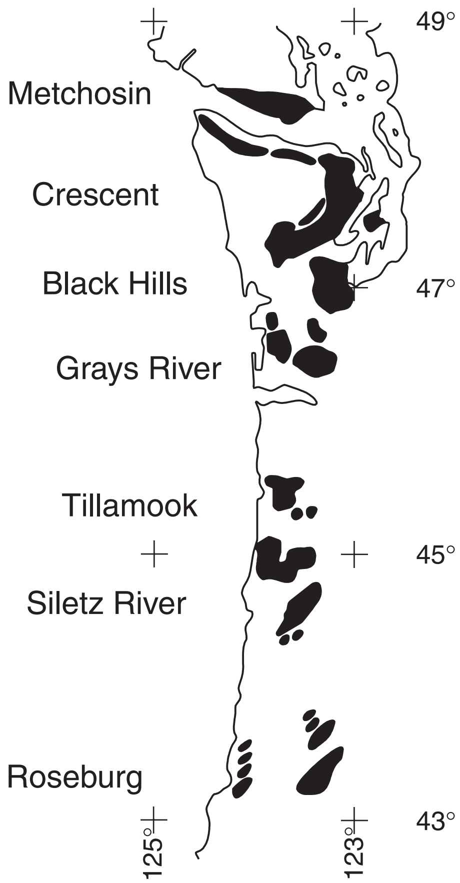

Fig. 2. Location of the Crescent complex within the Coast Ranges (see Massey, 1986; Babcock et al., 1992; Yorath et al., 1999). Location of Coast Ranges along the western margin of North America is shown in Fig. 1.

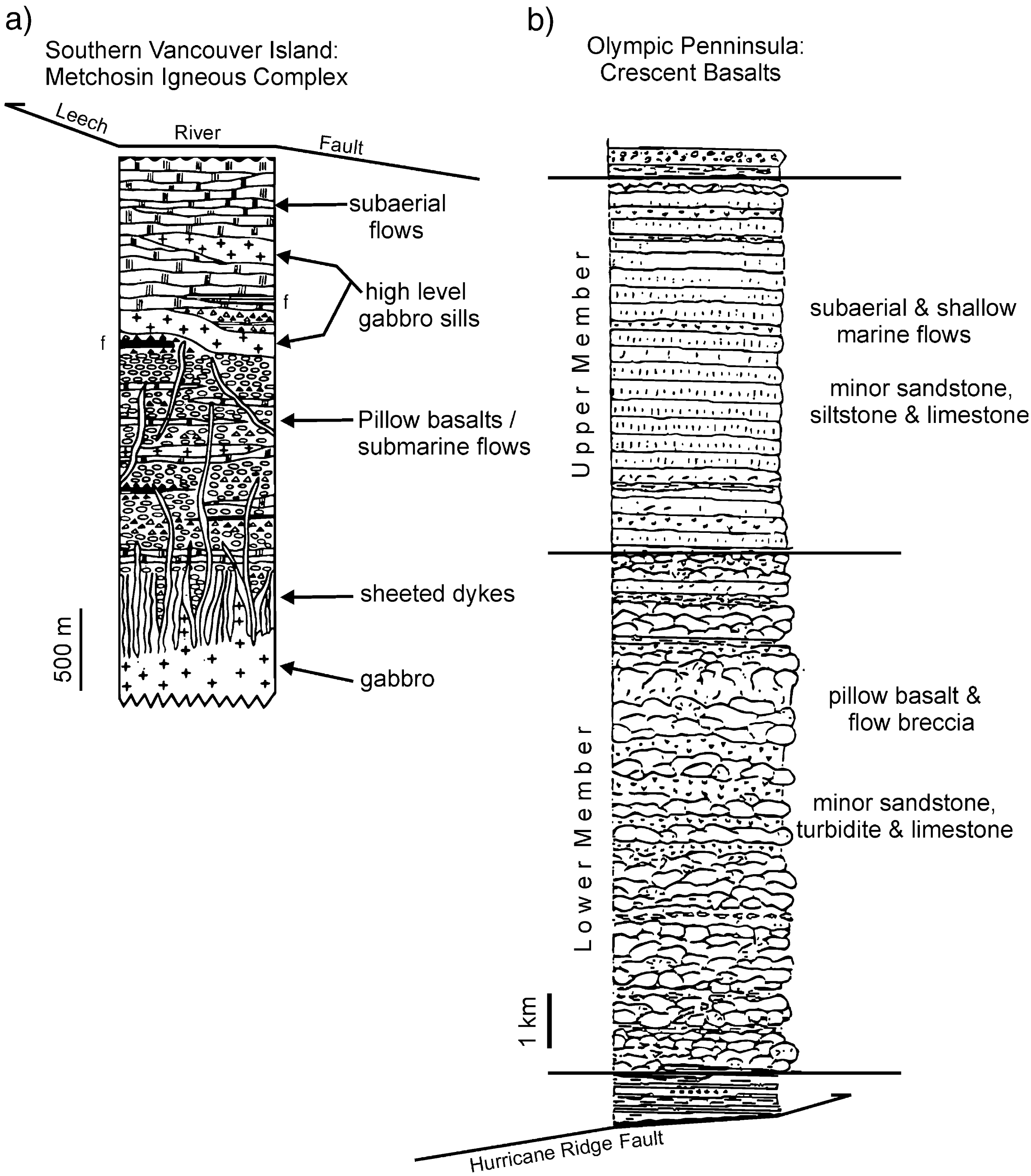

Fig. 3. Composite stratigraphic columns of two complexes within the Crescent terrane. (a) Metchosin Complex, Southern Vancouver Island (modified from Yorath et al., 1999). (b) Dosewallips River section (modified from Babcock et al., 1992). Note—the 'f' symbol indicates the presence of shallow water/near shore fossil assemblages. Note the difference in scale of (a) and (b).

sequence of bedded aquagene tuffs and broken pillow breccias into a 3000-m-thick unit of massive flows that are interpreted as subaerial (Muller, 1977). The lower pillow basalt has tholeiitic affinities and is interpreted to have erupted in a deep marine setting. The overlying tuff and breccia are thought to have resulted from shallow marine explosive eruptions and wave turbulence. This interpretation is supported by the presence within the tuffaceous rocks of *turritella* gastropod fossils, foraminiferal and algal limestones, bryozoa, bivalve fragments, and echinoid spines, all indicative of a shallow marine setting (Muller, 1977; Yorath et al., 1999).

In the Olympic Peninsula, Crescent basalts are divided into lower and upper units (Glassley, 1974). The lower unit contains abundant pillow lavas, consistent with a submarine environment. The upper basalt is characterized by massive to columnar flows 1–10 m thick. Thick flow-top paleosols (1–10 cm) are common. Rare pillow basalts at the bases of some of the flows are indicative of eruption at or near the strand line in a near-shore environment (Glassley, 1974). Crescent basalts outcropping along the Dosewallips River in the Olympic Peninsula are divisible into a lower pillowed to massive submarine unit 8.4 km thick, and an upper basalt unit 7.8 km thick (Babcock et al., 1992). Columnar flows, oxidized flow tops, and flow-top paleosol development indicate subaerial eruption for parts of this upper unit (Babcock et al., 1992).

Farther south, in the Siletz River area of Oregon, a 3000–6000-m-thick basalt sequence is characterized by a lower tholeiitic unit and an upper alkalic unit (Snavely et al., 1968). Abundant pillows in the lower unit indicate eruption in a marine setting. The upper unit is characterized by massive to columnar-jointed flows. Red oxidized paleosols are common between flows. Thick mudflow breccias and near-shore sandstone and conglomerate layers are interlayered with the basalt. These observations indicate eruption at or above sea level. Subaerial flows are locally interlayered with pillowed flows and may indicate the presence of unconformities within the sequence (Snavely et al., 1968).

In general, the stratigraphy in each area is consistent with a shallowing-upward sequence. Evidence for subaerial basalts near the top of the Crescent terrane stratigraphy comes along the length of the Coast Range. In every case, these subaerial flows are found within an upper alkalic basalt sequence that overlies the lower tholeiitic sequence.

Accretion of the Crescent terrane (on southern Vancouver Island) pre-dates undeformed sandstone and conglomerate of the latest Early Eocene–Oligocene Carmanah Group, which unconformably overlies the Crescent, Pacific Rim, and Wrangellia terranes. Accretion was coeval with, and has been linked to, formation of the Eocene and younger Tofino basin, which lies west of southern Vancouver Island, and of the late Early Eocene Cowichan fold and thrust belt of southern Vancouver Island (Johnston and Acton, in preparation).

The Crescent terrane has been interpreted as a thin (< 4 km) east-tapering thrust sheet scraped from a subducting slab that structurally underplated Wrangellia and previously accreted Pacific Rim terranes (Hyndman, 1995). More recent tomographic studies (Ramachandran, 2001) suggest, however, that the Crescent terrane beneath southern Vancouver Island may be as much as 25 km thick. Seismic refraction studies along the length of the Coast Range are consistent with the crust of the Crescent terrane being 16–20 km thick (Berg, 1966). In the absence of evidence for structural imbrication, this is thought to approximate its stratigraphic thickness.

3. Estimation of excess elevation associated with plume

Assuming the Crescent volcanics were produced over a mantle plume, the pre-accretionary stratigraphy of the seamounts may be used to constrain the uplift history associated with the plume. For example, the shallowing-upward stratigraphy culminating in subaerial eruptions evident in the Crescent terrane is suggestive of a Loihi-type setting; i.e. on the upstream side of a plume centre, rather than on the downstream side where the more common subsidence-related history and atoll development might be expected.

The presence of erosional surfaces indicates that the Crescent volcanics were exposed above sea level at 50 Ma. An estimate of the amount of excess elevation associated with the putative plume responsible for the Crescent volcanics can therefore be obtained by estimating the age of the ocean floor onto which the Crescent volcanics were emplaced, and comparing this elevation with that of the Crescent terrane.

The relative positions of the Yellowstone plume and marine magnetic anomalies on the Pacific plate at 50 Ma may be estimated by reversing the last 50 My of rotation of the Pacific plate with respect to Pacific hotspots, assuming the Yellowstone plume was fixed in the hotspot reference frame (Fig. 4). Anomaly 21 (present positions of all anomalies were taken from Addicott et al., 1982) identifies the position of the Pacific–Farallon ridge at 50 Ma, and the positions of the Kula–Pacific and Kula–Farallon plate boundaries may be estimated by assuming a 120°/120° triple junction at the northern end of anomaly 21. In Fig. 4, we have included estimates of the positions of anomalies 26 and 32 on the Farallon plate. The positions of the NW-trending segments of these anomalies, which formed at the Pacific–Farallon ridge, were determined by reflection through the Pacific–Farallon ridge of the segments of anomalies 26 and 32 north of the Surveyor fracture zone. This assumes only symmetrical spreading and is unlikely to be seriously in error. The positions of the bends in the anomalies, marking former positions of the Kula–Pacific–Farallon triple junction, were estimated by rotating the equivalent bends in the anomalies on the Pacific plate through 120° about the triple junction that must have existed near the northern termination of anomaly 21. This reconstruction assumes equal spreading rates at the Pacific–Farallon and Kula–Farallon plates, and is therefore somewhat less robust, but unlikely to be significantly in error. Positions of the NE-trending segments of the anomalies, formed at the Kula–Pacific ridge, were estimated by assuming they formed at 120° to the NW-trending segments. This assumption itself is probably reasonable, but the distance for which the segments may be propagated in this direction depends on the position of the first offsetting transform, which is unknown. Thus, we have sketched in anomaly segments that are only as long as those between the triple point and the Surveyor fracture zone. These reconstructions (Fig. 4) suggest that at 50 Ma the Yellowstone plume was beneath the ocean floor slightly older than that formed at anomaly 32 (~ 70 Ma), unless there was major offsetting of the Kula–Pacific ridge on a transform or transforms between the triple junction and the plume. Although we cannot completely exclude this latter possibility, we use the reconstruction of Fig. 4 to suggest that the oceanic crust into which the Crescent volcanics was emplaced was 20–25 My older than the volcanics themselves.

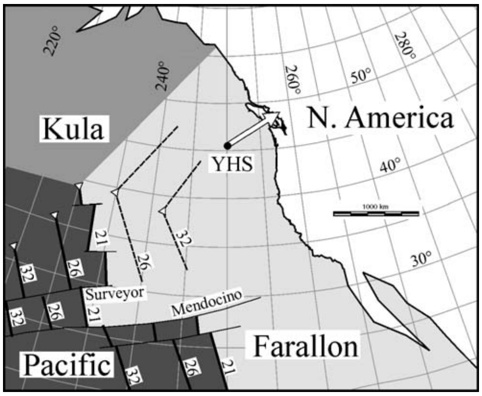

Fig. 4. Magnetic anomalies and plate boundaries west of North America in the Pacific hotspot reference frame at 50 Ma. Pacific-plate anomalies derived from Euler poles for rotations of North America and the Pacific plate with respect to the hotspot frame after Engebretson et al. (1985). Farallon-plate anomalies derived as discussed in text. Triangles: locations of triple points. YHS: Yellowstone plume. The white arrow by YHS depicts the amount of motion of the Farallon plate towards the North American plate in the interval from 50 to 45 Ma.

Undisturbed ocean floor 20–25 My old typically lies 4.1–4.3 km below sea level (Parsons and Schlater, 1977). We adopt a figure of 4.2 km, and note that since the erosional unconformity indicates that the Crescent volcanic rocks were at or above sea level, the arrival of the plume and the associated volcanics must have effected an elevation change of this magnitude.

4. Estimation of plume characteristics

In recent years, there have been significant advances in our understanding of the relationship between plume characteristics and genetically related basalts. As a result, accreted seamounts may preserve traits that constrain the characteristics of the plumes responsible for them. In the case of the Crescent terrane, such an analysis may yield information on the composition of the lithospheric mantle, and the buoyancy and volume flux of the plume, which may then be compared with those of the Yellowstone plume. In addition, stratigraphic evidence that the Crescent volcanics originated upstream of the plume head may be used in conjunction with plate velocities and the volume flux of the plume to estimate how long it took for the seamount to develop.

The excess elevation of the surface above plumes results from a combination of uplift from hot lithosphere and asthenosphere, and the addition of volcanic strata, the effect of which is partly cancelled by isostatic compensation. The uplifts due to hot material in the lithosphere U_L and in the asthenosphere U_A are given by (Sleep, 1990):

$$U_L = \alpha \Delta T_L L \rho_m / (\rho_m - \rho_w) \quad (1)$$

and

$$U_A = \alpha \Delta T_A A \rho_m / (\rho_m - \rho_w) \quad (2)$$

where α is the thermal expansion coefficient, ΔT is the excess temperature in the lithosphere or asthenosphere, L is the lithospheric thickness, A is the thickness of the asthenospheric channel of the plume, and ρ_m and ρ_w are the densities of the mantle and water.

We assume α is 3×10^{-5} °C^{-1}, ρ_m is 3300 kg/m^3, and that ΔT is 250 °C for both lithosphere and asthenosphere. The Crescent terrane was emplaced in 20-My-old lithosphere which implies a lithospheric thickness (L) of about 53 km (e.g. Cloos, 1993). A is poorly constrained, and we follow Sleep (1990) in assigning a value of 100 km so that we can compare our results with those he estimated for modern plumes. Substituting these values into Eqs. (1) and (2) yields uplift values of 0.5 and 0.9 km, respectively. Ignoring the relatively minor effects of lithospheric flexure, the remaining 2.8 km of excess elevation is attributed to the effects of basaltic volcanism. Assuming lithospheric loading associated with the development of the Crescent volcanics was isostatically compensated at the Moho, a basaltic load with an average density of 2900 kg/m^3 would require a crustal root about 13.3 km thick for a mantle density of 3300 kg/m^3 (cf. Gutscher et al., 2000), yielding a total thickness of basalt of ca. 16 km. This estimate is in accord with stratigraphic measurements.

Thus, use of the excess elevation of the surface at the site of the Crescent volcanics from a combination of field relationships and plate reconstructions to reconstruct the lithospheric structure above a plume yields a result that is broadly compatible with stratigraphic data. Encouraged by this compatibility, we use the elevation to estimate the buoyancy flux of the plume responsible for the excess elevation, so that we can compare this flux with that estimated for the modern Yellowstone plume.

The buoyancy flux of a plume (Sleep, 1990) is given by:

$$B = WE(\rho_m - \rho_w)V_L \quad (3)$$

where W is the width of the swell, E is the excess elevation averaged across the swell, and V_L is the propagation rate of the plate.

The minimum width of the swell is given by the width of the seamount. According to Cloos (1993), a seamount 4.2 km high would have a width of about 70 km. This figure compares favourably with the width of the Metchosin Complex on Vancouver Island and its offshore continuation (about 75 km, measured east–west). We assume that there is a steady-state relationship between the swell and the supply of magma to the resulting seamount. If so, the cross-sectional area of the seamount provides a minimum estimate of the cross-sectional area of the swell (i.e. WE). Using plate-motion models of Engebretson et al. (1985), the rate of motion of the Farallon plate across the Yellowstone hotspot at 50 Ma was about 10 cm/year. With an asthenospheric density ρ_m of 3300 kg m^{-3}, these values yield a minimum buoyancy flux of 1.1 Mg s^{-1}. This value compares favourably with the buoyancy flux of modern Yellowstone. The cross-sectional area of the swell beneath modern Yellowstone is 400 km^2 (Sleep, 1990), and the propagation rate of the Snake River plain is 35 mm/year (Anders, 1994), which corresponds to a buoyancy flux of 1.02 Mg s^{-1}.

5. The Yellowstone connection

Taken together, stratigraphic, geochemical, and paleomagnetic data indicate that the Crescent volcanics were formed as a subaerial oceanic seamount at a paleolatitude similar to that of the Yellowstone plume. As the seamount was accreted within 5 My of the cessation of plume magmatism, this indicates that the plume was close to the continental margin. This suggestion is clearly supported by the reconstruction of Fig. 4. Furthermore, according to the plate-motion data of Engebretson et al. (1985), the relative motion of the Farallon and North American plates in the vicinity of the Yellowstone plume was 150 km/My in an ENE direction between 50 and 45 Ma, so that our reconstruction provides independent support for collision of the plume-generated volcanics with North America in less than 5 My (see white arrow in Fig. 4).

The calculated buoyancy flux of 1.1 Mg s^{-1} associated with the Crescent terrane volcanics is similar to values for the modern Yellowstone hotspot. At the very least, this demonstrates that a plume of comparable vigour was present in the vicinity of the modern Yellowstone hotspot about 60–50 My ago and, given the motion of the Kula plate, would have generated a swell whose downstream component was directed towards the North American plate. Even allowing for the possibility that the Yellowstone hotspot itself may be a younger feature, these results suggest the presence of a plume (and its associated swell) adjacent to the North American margin at the time of the Laramide orogeny, in a geometric relationship similar to that of the modern flat-slab subduction zones of the Andes.

Direct evidence of the longevity of the Yellowstone plume is confined to the last 18 My, and the plume track is expressed by the Snake River Plain. However, since plumes have difficulty penetrating oceanic lithosphere, let alone continental lithosphere (McNutt and Fischer, 1987; Johnston and Thorkelson, 2000), the successful penetration of continental crust by plume-derived magma implies an earlier origin for the plume. Equally, the plume responsible for the 60–50 Ma Crescent volcanics is of comparable vigour, and similar location to modern Yellowstone.

6. Summary and discussion

The Andean margin has several flat-slab segments, up to 500 km wide, that are each correlated with subduction of anomalously thick oceanic crust, represented by oceanic plateaus (Pilger, 1981; Gutscher, 2002; Gutscher et al., 2000; Yáñez et al., 2001, 2002; Ramos et al., 2002). These flat-slab regions are characterized by an absence of magmatism, widespread deformation, and thick-skinned tectonics up to 1000-km inboard of the plate margin. Although similar features in the Late Cretaceous–Eocene Laramide orogeny in the southwestern United States have been ascribed to flat-slab subduction (Dickinson and Snyder, 1978), mechanisms proposed for the origin of the flat-slab are controversial. For example, Maxson and Tikoff (1996) attribute the Laramide orogen to the collision of a terrane known as "Baja BC" that was subsequently dismembered by strike-slip tectonics.

In previous studies, we attributed the generation of the flat-slab subduction associated with the Laramide orogeny to the overriding of an elongate swell and oceanic plateau associated with the ancestral Yellowstone plume (Murphy et al., 1998). Reconstructions in a hotspot reference frame indicate that the ancestral Yellowstone plume was located beneath the Kula plate until about 50 Ma. Evidence for the existence of the plume beneath the oceanic plate before this is derived from 70–50 Ma accreted terranes such as the Crescent mafic complexes of western Canada. These terranes have geochemical and paleomagnetic characteristics compatible with an origin as seamounts above the ancestral Yellowstone plume. Reconstructions indicate that the Crescent seamount was emplaced into oceanic crust that was 20–30 My old and buoyancy flux calculations yield a value comparable with that of the modern Yellowstone plume. The Crescent seamount was accreted within 5 My of the cessation of plume magmatism, a time span that is consistent with the modelled proximity of the Yellowstone plume to the continental margin at 50 Ma.

A plume at a similar location to Yellowstone and with comparable vigour was responsible for generation of the Crescent seamount. Such a plume would have generated a swell up to 2400 km long and an oceanic plateau that would have been subducted as North America drifted westward in a hotspot reference frame. The relationship between the plume, oceanic plateau, and flat-slab subduction in Laramide times is analogous to the relationship between Andean flat-slab subduction zones, and the Juan Fernandez and Nazca ridges and their related oceanic plateaus and hotspots.

The Late Mesozoic–Cenozoic Laramide orogeny of the western United States has been interpreted to reflect the overriding of the Yellowstone plume by the North American margin. Assuming the present distribution of hotspots and underlying plumes are representative of the past, overriding of plumes and their buoyant swells at convergent margins should be common in the geologic record. This orogenic activity profoundly changes the geometry of subduction zones, and hence the style of orogenic activity.

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