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IMPLICATIONS OF VOLCANO-TECTONIC PATTERNS IN THE OREGON CASCADES FOR GEOTHERMAL EXPLORATION

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ABSTRACT

Basin and Range and subduction-related processes may have combined to produce voluminous mafic volcanism and very high heat flow in the central Oregon High Cascades during the last 9 m.y. This high rate of volcanism and heat flow prevails south of the Clackamas River right lateral wrench fault zone. South of this zone the volume of mafic volcanic rocks less than 9 m.y. old increases abruptly and regional heat flow increases by at least 20 mW/m^2. A similar, but larger, increase in volcanism and heat flow characterizes the transition from the Blue Mountain block to the Basin and Range Province at the Brothers right lateral wrench fault zone. The northwest-trending Clackamas River-Brothers fault system may be a fundamental structural boundary limiting northward influence of Basin and Range tectonic forces. A significant amount of the 0 to 9 m.y.B.P. mafic volcanic rock in the Cascades is basalt, with one or all of the following attributes of contemporaneous basalts of the Brothers Fault Zone-Basin and Range province: 1) anomalously high alkali and iron content relative to normal calc-alkaline rocks; 2) diktytaxitic texture with titaniferous groundmass clinopyroxene. This suggests a common petrogenesis for these basalts, perhaps from partial melting related to Basin and Range spreading. Absence of large volumes of intermediate lava and associated strato-cones in the Brothers Fault Zone and Basin and Range province indicates the lack of a partial melting process that is operative in the High Cascades, probably subduction. Potential operation of two partial melting mechanisms in the Oregon High Cascades may cause a high rate of magmatic heat transferral from mantle regions relative to transferral in the Basin and Range. This means that the High Cascades probably has the highest geothermal potential of any province in Oregon, especially where intercepted by youthful faults. North-south faults which bound a large area of Pliocene to Pleistocene subsidence along the High Cascade axis are good exploration targets, especially at intersections with the northwest-trending Brothers, Clackamas, and Eugene-Denio fault zones. Silicic volcanism at the Brothers Fault zone intersection makes this the best exploration target in Oregon.

INTRODUCTION

This paper is a brief summary of major conclusions and supporting data from Oregon Department of Geology and Mineral Industries (DOGAMI) Special Paper 15, <u>Geology and geothermal resources of the Cascades of Oregon</u>, which is in preparation. Special Paper 15 will be the final product of a five-year investigation of the Oregon Cascades conducted by DOGAMI with financial support from the United States Department of Energy.

MAJOR VOLCANIC PROVINCES

The Oregon Cascades may be divided into two physiographic provinces, which are also distinctive geologic provinces (Figure 1). The Western Cascades are geomorphically mature mountains composed chiefly of late Miocene to Oligocene volcanic rocks with minor Pliocene to Quaternary intracanyon flows and volcanic centers. The High Cascades are, in contrast, a geomorphically immature terrain dominated by volcanic landforms of Pliocene and younger rocks. The axis of volcanism for Miocene and Oligocene Western Cascade rocks was a few tens of kilometers west of the High Cascade axis (Peck and others, 1964). The geologic data summarized here is based chiefly on 1:24,000 to 1:62,500 scale mapping by university and DOGAMI personnel.

VOLCANIC STRATIGRAPHY

Introduction

The Cascades sequence is here informally subdivided into four age groups; the early Western Cascades, late Western Cascades, early High Cascades, and late High Cascades. Each group possesses certain distinctive lithologic and field characteristics (Figure 2). The resulting nomenclature is useful for comparison of rocks from widely separated areas, particularly when testing for regional compositional changes in volcanism through time. The subdivisions are based primarily on observations in the central Oregon Cascades, though they may be useful for other parts of the Cascades as well. This nomenclature is not intended for formal usage and should not be considered a revision of existing rock-stratigraphic nomenclature.

Volcanic Rocks of the Early Western Cascades (35-18 m.y.B.P.)

Early Western Cascade rocks are chiefly silicic ash flows, debris flows, lava flows, and epiclastic mudstones and sandstones, with some distinctive siliceous, iron-rich, tholeiitic lavas interbedded in the upper part. Smith and others (1980) have obtained a K-Ar date of 34.9 m.y. on a biotite-bearing ash flow at the base of the sequence in the central to southern Cascades. White (1980a; 1980b) and McBirney and others (1974) list K-Ar ages from 27 to 19.4 m.y. on tholeiitic lavas in the upper part of the early Western Cascades section.

The siliceous pyroclastic and epiclastic lower part of the sequence has generally been called the Little Butte Volcanic Series (Peck and others, 1964) and Breitenbush Tuff or Breitenbush Formation (Thayer, 1936; 1939; Hammond, 1979; Hammond and others, 1980; White 1980a; 1980b). The tholeiitic rocks have frequently been mistaken for Columbia River Basalt Group (see White, 1980a; 1980b for a review of this problem). These tholeiitic rocks have been named the Scorpion Mountain lavas in the North Santiam area (White 1980a; 1980b), and the lavas of Black Canyon in the Lookout Point Reservoir area (Woller and Priest, 1982).

Volcanic Rocks of the Late Western Cascades (18-9 m.y.B.P.)

Rocks of the late Western Cascades are chiefly calc-alkaline lavas and debris flows of intermediate composition, with subordinate dacitic ash-flow and ash-fall tuffs. Basalt to basaltic andesite may be locally abundant, as at Swift Creek near Willamette Pass (Woller, 1982). McBirney and others

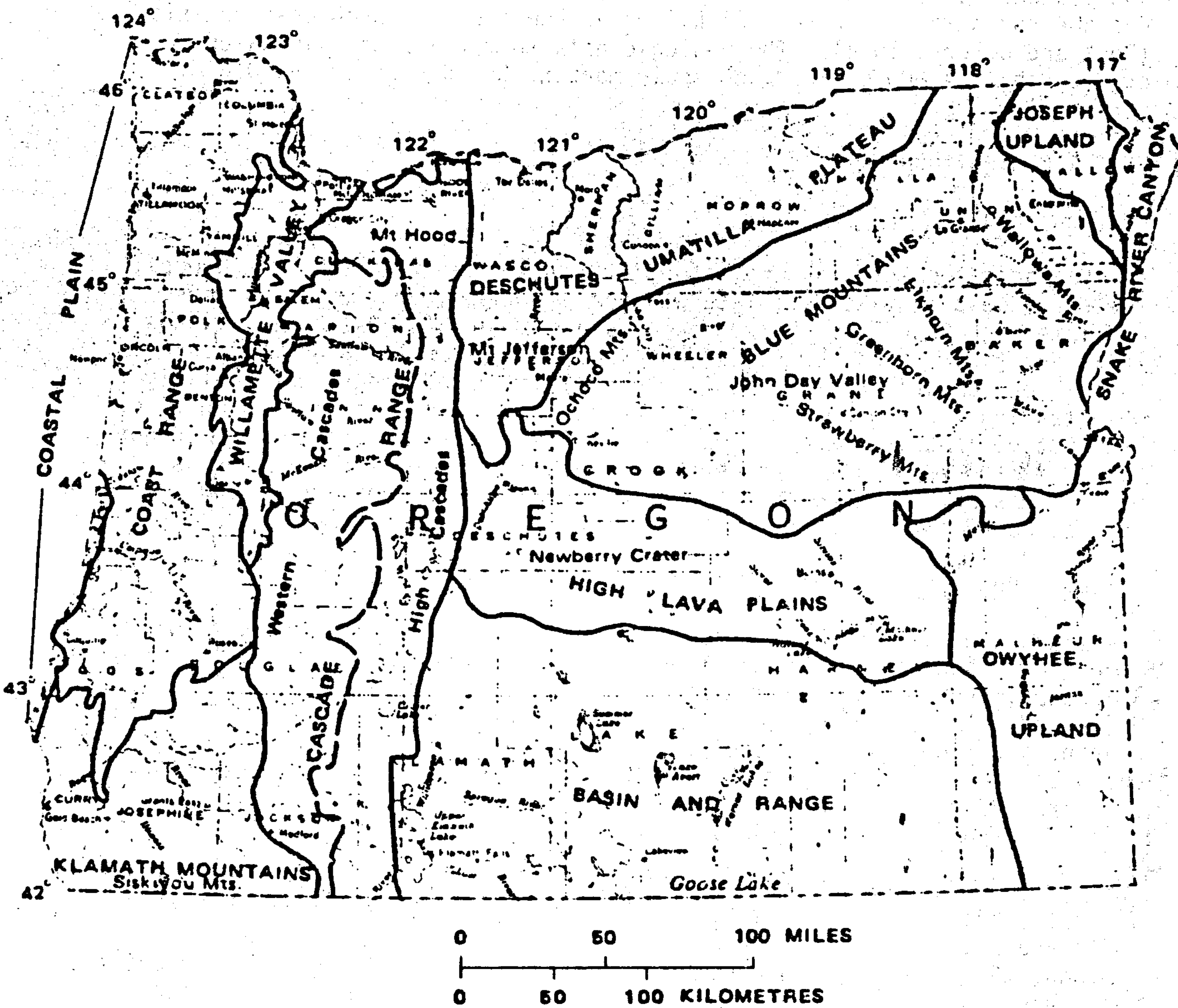

Figure 1. Physiographic provinces of Oregon.

	Brief Description	Correlative Rock - Stratigraphic Units
late High Cascades	4 to 0 m.y.B.P. mafic volcanic rocks; some are slightly alkaline high-alumina olivine tholeiites; commonly highly diktytaxitic in lower part; more silicic in upper part. Includes the High Cascade composite cones.	High Cascade lavas (McBirney and others, 1974; White, 1980a; 1980b), younger and older High Cascades basalt and volcanic deposits of Mt. Jefferson (Hammond, 1979; Hammond and others, 1980), and partially equivalent to volcanic rocks of the High Cascades and Boring lavas (Peck and others, 1964).
early High Cascades	9 to 4 m.y.B.P. mafic lavas and some interbedded tuffs; many lavas are slightly alkaline olivine tholeiites with diktytaxitic texture; includes some alkali basalt and many compact high-alumina basalts and basaltic andesites. Also includes many andesites and some ash-flow and ash-fall tuff. May be largely absent from the southern Cascades (Smith, 1979).	Outerson Volcanics (Thayer, 1936; 1939), Outerson Formation (McBirney and others, 1974; White, 1980a; 1980b), Outerson Basalt (Hammond, 1979; Hammond and others, 1980), partially equivalent to volcanic rocks of the High Cascades and Boring lavas (Peck and others, 1964); probably correlative to the Deschutes Formation (Hales, 1975; Taylor, 1981).
late Western Cascades	18 to 9 m.y.B.P. intermediate volcanic rocks with common interbedded dacitic tuffs; includes voluminous, highly phyric two-pyroxene andesite with less basalt, basaltic andesite, and dacitic tuff. Basalts of this group are generally compact and often contain orthopyroxene in the groundmass. This sequence may be very thin or absent in much of the southern Cascades (Smith, 1979).	Sardine Series (Thayer, 1936; 1939), Sardine Formation (Peck and others, 1964), Sardine Formation and Elk Lake Formation (McBirney and others, 1974; White, 1980a; 1980b), Rhododendron Formation (Hammond, 1979; Hammond and others, 1980) and Miocene volcanic rocks (Brown and others, 1980a; 1980b).
early Western Cascades	35 to 18 m.y.B.P. silicic and tholeiitic volcanic rocks. Interbedded rhyodacitic tuffs and iron-rich tholeiitic basalt, tholeiitic basaltic andesite, and icelandite with minor rhyodacitic, rhyolitic, and dacitic lavas; locally abundant clastic interbeds. This description applies mainly to rocks of the central Cascades, but ages probably apply to the entire Oregon Cascades.	Breitenbush Tuffs (Thayer, 1936; 1939), Little Butte Volcanic Series (Peck and others, 1964), Breitenbush Formation (Hammond, 1979; Hammond and others, 1980), and Breitenbush Formation and Scorpion Mountain flows (White, 1980a; 1980b).

Figure 2. Informal regional time-stratigraphic nomenclature for the central Oregon Cascades. This system is probably applicable to other parts of the Cascades as well.

(1974) show K-Ar dates on late Western Cascade lavas ranging from 9.2 m.y.B.P. to 17.2 m.y.B.P. The youngest rock of this sequence was obtained at Lookout Ridge near McKenzie Bridge and yielded a date of 8.80 $\pm$ .34 m.y.B.P. (Priest and Woller, 1982). A sample collected in the Swift Creek area was dated at 17.0 $\pm$ 0.9 m.y.B.P., but this may not be the base of the section at Swift Creek (Woller, 1982). A paucity of rocks with ages between about 11 and 14 m.y. has been interpreted by some workers as evidence for a lull in volcanic activity (McBirney and others, 1974; White, 1980a; 1980b; Flaherty, 1981), but a large volume of rocks mapped in the Cougar Reservoir area has ages in this time interval (Priest and Woller, 1982a). Much more detailed mapping and geochronology is necessary before the periodicity of regional volcanism can be determined to this degree of detail.

The break between the early and late Western Cascades volcanism, sometime between 17 and 19 m.y., may also have been a lull in volcanic activity, since there are no reliable radiometric dates in this interval. Peck and others (1964) and many other workers also found a widespread unconformity corresponding to this time period. The early and late Western Cascades units are here arbitrarily divided at 18 m.y.B.P. Rocks grouped with the late Western Cascades sequence have been mapped as the Sardine Series or the Sardine Formation by Thayer (1936; 1939) and Peck and others (1964), respectively, and as the Sardine Formation and overlying Elk Lake Formation by White (1980b).

Volcanic Rocks of the Early High Cascades (9-4 m.y.B.P.)

Between about 8 and 10 m.y.B.P. a shift to more mafic volcanism occurred throughout much of the central Cascades. This shift in composition coincided with a shift in the axis of volcanism toward the east of the late Western Cascade volcanic axis (Peck and others, 1964). The early High Cascade volcanic centers produced voluminous basalts and basaltic andesites and less abundant andesites and dacitic ash-flow and ash-fall tuffs from a somewhat broader area than the current High Cascade physiographic province. Numerous vents for these rocks have been recognized a few kilometers west of the present High Cascade province (Hammond, 1979; Hammond and others, 1980; White 1980a; 1980b), and compositionally and temporally similar rocks of the Deschutes Formation were erupted from vents along the central High Cascades and its eastern margin (Hales, 1975; Taylor, 1981). In the Western Cascades physiographic province, early High Cascade rocks are the relatively unaltered mafic to intermediate lavas which cap the highest ridges.

The oldest basal flows of the early High Cascades have been K-Ar dated at 8.34 $\pm$ 0.36 m.y.B.P. (near Belknap Hot Springs) and 7.80 $\pm$ 0.77 m.y.B.P. (at Cougar Reservoir) (Priest and Woller, 1982a). The 7.8 m.y.B.P. sample is overlain by a flow dated at 9.4 $\pm$ 0.4 m.y.B.P. and other, even older dates have been obtained in nearby areas in stratigraphically higher flows (e.g. 10.2 $\pm$ 1.0 m.y.B.P. at English Butte, and even older dates found by George Walker (personal communication) in the adjacent area). A similar problem occurred in the Columbia Gorge area where a diktytaxitic Boring Lava, probably no older than about 10 m.y.B.P. was dated at 15.0 $\pm$ 0.8 m.y.B.P. The bulk of the K-Ar data and stratigraphic relationships suggest that the basal early High Cascade flows are probably no older than about 9.0 m.y.B.P.

It may be that the gas-charged diktytaxitic lavas which seem to most often yield anomalous dates have not completely outgassed radiogenic argon during eruption.

The youngest reliable K-Ar date so far obtained on early High Cascades rocks is 4.3 ± 0.4 m.y.B.P. at Bear Mountain near Willamette Pass (Woller, 1982). Sutter (1978) obtained a 3.88 m.y.B.P. age on lava which may be part of the early High Cascades section near Belknap Hot Springs, but some doubt about the sample location has been voiced by several workers in the area.

Volcanic rocks of the early High Cascades correspond to the upper part of the Outerson Series (Thayer, 1939), part of the Collowash and Triangulation Peak volcanics (Clayton, 1975), the Browder-Bunchgrass and Iron Mountain Formations (Avramenko, 1981), the Intermediate Series (Flaherty, 1981), lavas of Tipsoo Butte (Priest and Woller, 1982a) and probably the Devils Canyon Formation (undated rocks of Barnes, 1978). They also correspond to much of the unit designated QTv and QTba on various regional compilation maps (e.g. Wells and Peck, 1961, and Brown and others, 1980a; 1980b).

Volcanic Rocks of the Late High Cascades (4-0 m.y.B.P.)

Following north-south faulting and axial subsidence of much of the central Oregon High Cascades between 4 and 5 m.y.B.P., voluminous flows of diktytaxitic basalt and basaltic andesite erupted from contiguous shield volcanoes forming a low platform in the High Cascades (Taylor, 1981). The early basalts reached deep into the Western Cascade province through canyons carved into escarpments bounding the axial grabens. These Pliocene to earliest Pleistocene intracanyon basalts are clearly related to present topographic lows, distinguishing them from similar early High Cascades basalts which cap the highest Western Cascade ridges. Basaltic andesite eruptions increased in frequency relative to basaltic eruptions during the Quaternary (Taylor, 1981), and the increasingly viscous lavas became more restricted to High Cascade axial grabens. Volumetrically smaller eruptions of basaltic andesite and less abundant andesite and dacite formed prominent composite cones in local area during the Quaternary amid continuing eruptions of basalt and basaltic andesite in the platform (Taylor, 1981). Mt. Hood, Mt. Jefferson, the Three Sisters and Mt. Mazama (Crater Lake) are some of the largest composite cones. The oldest flow of the late High Cascades so far dated is 3.9 m.y.B.P. (Taylor, 1981); the youngest eruptions in Oregon are the Belknap Crater eruptions, about 1,500 m.y.B.P. (Taylor, 1968), and the Old Maid mudflow eruption from Mt. Hood about 200 y.B.P. (Crandell, 1980).

FAULTS

North-south trending normal faults form the boundary of the High Cascades province in several places where the High Cascade axis has been obviously downdropped (Figure 3). These faults bound grabens at Mount Hood (Williams and others, 1982; Priest, 1982; Priest and others, 1982), Green Ridge (Hales, 1975), the McKenzie River-Horse creek area (Brown and others, 1980a; Taylor, 1973; 1981; Avramenko, 1981; Flaherty, 1981), the Walker Rim area (Wells and Peck, 1961), and the Mt. Bailey-Diamond Lake area

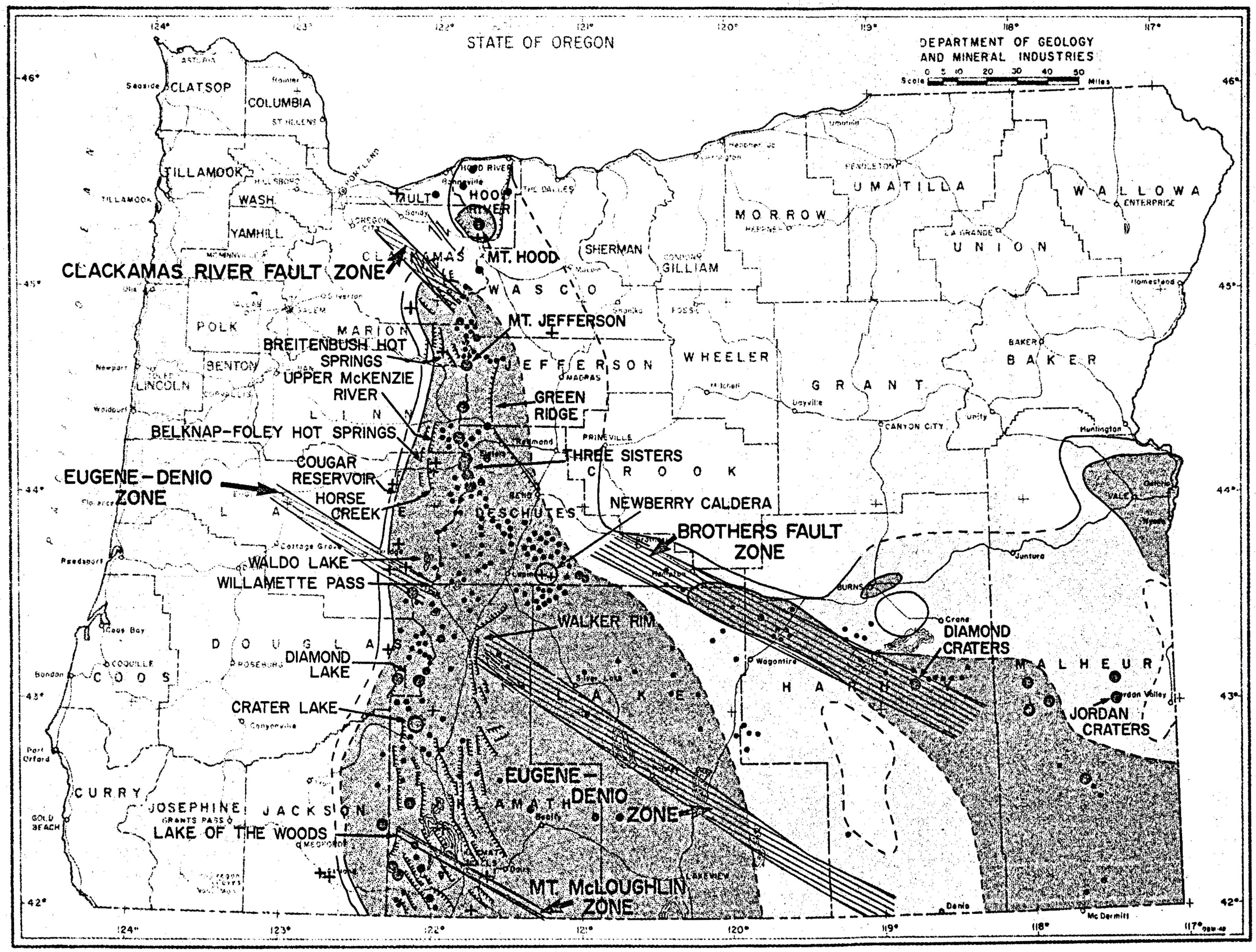

Figure 3. See next page for caption.

Figure 3. Summary of faults, volcanic centers, heat flow and Cascade thermal springs. Dark gray = heat flow over 100 mW/m^2; light gray = heat flow between 100 mW/m^2 and 80 mW/m^2; hachured lines = mapped normal faults hachured on downthrown side (only shown in the High Cascades and areas immediately adjacent); dots = volcanic centers (size of dot is very crudely related to relative size of the center); circles = calderas (diameter = actual diameter); diagonal line pattern = major zones of actual or inferred lateral faulting (mapped lateral faults are shown with offset arrows); crosses = thermal springs in and adjacent to the Cascades. Geologic data is from Avramenko (1981), Barnes (1978), Beeson and Moran (1979), Beeson and others (1982), Brown and others (1980a); Flaherty (1981), Hales (1975), Hammond and others (1980), Kienle and others (1981), Lawrence (1976), Maynard (1974), Naslund (1977), Peterson and others (1976), Priest and others (1982), Walker (1977), and Wells and Peck (1961). Heat flow data is from Blackwell and others (1978) and Black and others (1982).

(Barnes, 1978). Similar faults probably occur north and east of the Breitenbush Hot Springs area and along lineations following the western boundary of the High Cascades province from Horse Creek to Crater Lake (e.g. see Venkatakrishnan and others, 1980; Kienle and others, 1981). The graben-bounding faults at Mount Hood are probably somewhat younger than 3.0 m.y. (Priest, 1982), but most of the subsidence in the central Cascades occurred between 4 and 5 m.y.B.P. (Taylor, 1981). Avramenko (1981) has shown some movement on these Central Cascade faults between 1.0 and 0.7 m.y. as well, and some shearing affects lavas as young as 2.1 ± 0.2 m.y. adjacent to the east side of the Mount Hood graben (unpublished data of N. M. Woller). Total subsidence in the central Cascades may total several thousand feet (Taylor, 1981).

Naslund (1977) has found northwest-trending Basin and Range-style faults less than 0.7 m.y.B.P. in age cutting across the southern High Cascade axis. It is not known if these and other southern High Cascade faults cause net subsidence of the High Cascade axis, but a north-south trending fault on the west side of the Lake of the Woods, near Mt. McLoughlin (Maynard, 1974) appears to bound an axial graben.

The above fault systems are intercepted by four prominent N40W to N60W trending lineations and lateral fault zones (Figure 3). The Clackamas River right lateral wrench fault zone (Anderson, 1978) is interpreted by Beeson and Moran (1979) and Beeson and others (1982) to be an extension of the Brothers Fault Zone of Lawrence (1976). Most movement on this fault zone occurred after late Western Cascade time (Beeson and Moran, 1979). Our mapping near Willamette Pass and at Lookout Point Reservoir has revealed little evidence of major wrench faulting younger than about 13 m.y.B.P. in the Western Cascade portion of the Eugene-Denio Zone, although there is abundant shearing in Oligocene early Western Cascade rocks (Woller and Priest, 1982; Woller 1982). Faults associated with the Eugene-Denio Zone in the Walker Rim area (Figure 3) appear to cut Pliocene-Pleistocene units (Wells and Peck, 1961; Kienle and others, 1981). The Mt. McLoughlin Zone (Figure 3) terminates at the High Cascade axis by merging with north-south trending faults (Barnes, 1978).

Northeast trending faults with chiefly dip-slip displacement are also common locally (e.g. in the Diamond Lake area of Barnes, 1978) and lineaments with this orientation occur throughout the Western Cascades (Venkatakrishnan and others, 1980; Kienle and others, 1981). Thrust faults associated with northeast trending middle to late Miocene folds in the Mount Hood area also strike northeasterly (Beeson and Moran, 1979; Beeson and others, 1982).

FOLDS

Folds in the central Cascades generally trend northeast to north-south. Gentle dips of 10 to 20° typically occur on the limbs, although dips of 60° occur on the western limb of the Breitenbush Anticline (Thayer, 1939; White 1980a). Folds are chiefly limited to the northern Oregon Cascades (Barnes, 1978) where they affect late Western Cascade and older volcanic rocks. Folding probably began in the middle Miocene and ended between 11 and 7 m.y. (e.g. see Beeson and Moran, 1979; Beeson and others, 1982; Hammond, 1979; Hammond and others, 1980; White 1980a; 1980b; Flaherty, 1981). The change to mafic early High Cascade volcanism about 9 m.y.B.P. coincided with a relaxation of the east-west compression which caused middle Miocene folding. If various speculations below are valid, Basin and Range spreading processes may have begun to affect the central Cascades at this same time.

STRUCTURAL INTERPRETATION

The pattern of northwest trending right lateral strike-slip faults and north-south trending normal faults in the Cascades can be generated by a stress field with a north-south maximum compressive stress axis, a horizontal east-west minimum stress axis, and a vertical intermediate stress axis (Venkatakrishnan and others, 1980; Kienle and others, 1981). Because the major right lateral, strike-slip boundary fault at the Clackamas River, probably began movement in High Cascade time (i.e. after 9 m.y.B.P.; see Beeson and Moran, 1979), it is probable that this stress regime is characteristic of the Cascades since that time. This is supported by focal mechanism studies on recent earthquakes (Couch, 1971).

Folding along northeast to north-south axes during the middle Miocene suggests that the maximum compressive stress axis may have been oriented closer to east-west in late Western Cascade time relative to High Cascade time. This shift of stress axes, shift of the axis of volcanism toward the east, and change in magmatic composition all occurred between Western and High Cascade time. A major change in the plate tectonic regime is probably necessary to account for all of these phenomena. It is beyond the scope of this paper to review all of the plate tectonic models which incorporate a change in regime between 8 and 10 m.y.B.P., but some do, in fact, require such a change (e.g. Atwater, 1970; Zoback and Thompson, 1978). It was also at about this time that the current Basin and Range topography became well-defined (Stewart, 1978).

Regional northwest trending late Neogene fault zones appear to either terminate or be deflected by the High Cascade axis. Barnes (1978) notes that faults associated with the Mt. McLoughlin Zone of Lawrence (1976) become increasingly parallel to the High Cascade axis as they approach the axis. The Brothers Fault Zone also appears to swing toward parallelism with the Cascades, if the Green Ridge-Tumalo fault zone may be considered part of the Brothers Fault Zone. The Eugene-Denio Zone is the only northwest trending zone which crosses the High Cascade axis undeflected, and, as mentioned above, the faults on the west end of this zone across the High Cascade axis are probably older than High Cascade time. This suggests that the High Cascade volcanic axis is a thermally weakened zone which deflects or terminates Basin and Range lateral faults. This anomalous weakness might also explain the concentration of normal faulting along the axis.

PETROCHEMISTRY

Silicic rocks from all of the Cascade units are similar in composition, owing to the tendency for magmas to evolve toward similar cotectic and eutectic compositions during high level differentiation processes. In order to reduce the clutter on the compositional diagrams, fields of composition for early and late High Cascades rocks of intermediate to silicic composition are not shown, although the data of Taylor (1978) for the late High Cascade Broken Top volcano is shown (Figures 4 through 7). Were all of the High Cascades compositional range plotted, it would completely overlap the range of Western Cascades silicic and intermediate rocks. There is also complete overlap between the compositional fields of early and late High Cascade mafic rocks, so these fields are combined. The mafic lavas of the High Cascades and Western Cascades, however, have diverse compositions indicative of differing sources and conditions of partial melting (Figures 4 and 5). The High Cascade mafic lavas are, in the extremes of their compositional range, much more alkaline than any of the Western Cascade samples, a property they share with contemporaneous basaltic rocks of the Basin and Range province (Figures 4 and 5). Only the tholeiitic lavas from the upper part of the early Western Cascades sequence are as iron-rich, as the High Cascade and Basin and Range lavas (Figures 6 and 7).

Many of the High Cascade basalts, and basalts of the Basin and Range, possess diktytaxitic textures and some contain a brownish, probably titaniferous, clinopyroxene in ophitic to subophitic intergrowth in the groundmass. The majority of these mafic lavas contain 16% or more alumina and plot on the borderline between high-alumina and alkali basalt (Figure 4), and they may be characterized as slightly alkaline high-alumina basalts, although a few are nepheline normative and can be called alkali basalt (Figure 5). The alkali- and alumina-rich nature of eastern Oregon basalts has been documented by Walker (1970), and, more recently, in southeastern Oregon, by Hart and Mertzman (1980) and Hart (1981). Flaherty (1981) pointed out similarities between eastern Oregon and late High Cascade basalts. Priest and others (1981) noted the similarities between early High Cascade and Basin and Range basalts.

PETROLOGIC SPECULATION

The chemical and textural similarity of basalts of the Basin and Range to those of the early and late High Cascades is evidence that similar processes of magma generation, perhaps related to Basin and Range spreading, are operative in both areas. This speculation, of course, carries the implicit assumption that there is a causal relationship between volcanism and tectonism - an unproven hypothesis. Taylor (1981) first suggested this relationship between late High Cascade and Basin and Range processes. Flaherty (1981) provided a more extensive discussion of this relationship for late High Cascade basalts, and Priest and others (1981) first speculated that Basin and Range processes might have affected generation of early High Cascade magmas at Cougar Reservoir. Some petrologic arguments of Flaherty (1981) require rapid ascent of early High Cascade basaltic magma from deep levels, possibly by extensional faulting. We suggest that this faulting may have been the result of extensional Basin and Range-type tectonism.

Lack of a north-south trending line of composite cones and lack of large quantities of lava of intermediate composition in the Basin and Range province suggest that there is also a fundamental difference in sources and/or processes of magma generation in the Basin and Range relative to

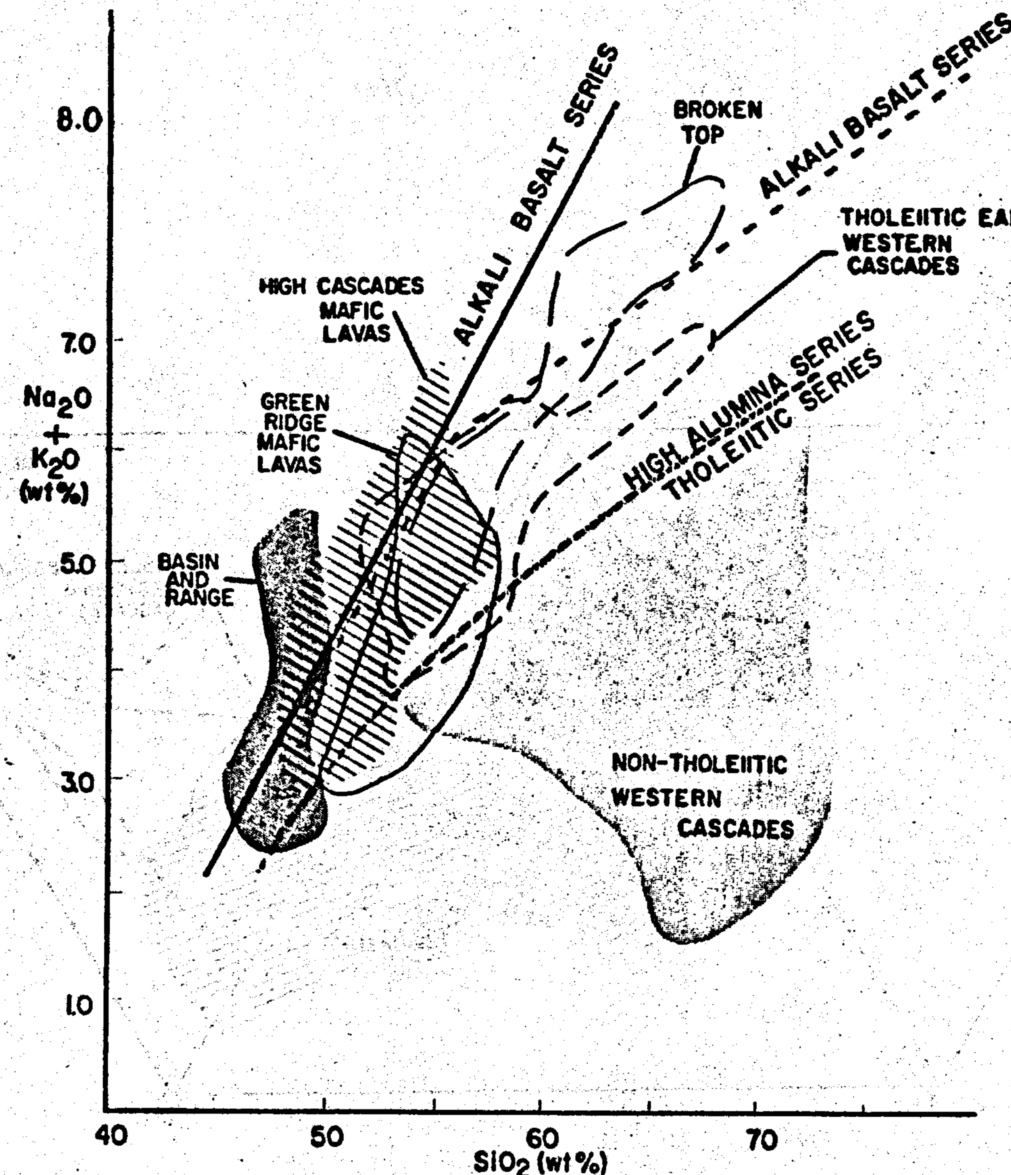

Figure 4. Compositional fields of Cascade and Basin and Range rocks shown relative to the fields of composition of Kuno's (1966) alkali basalt series (straight dashed lines) and the line separating Macdonald and Katsura's (1964) alkali basalt and tholeiitic basalt fields (straight solid line). The Basin and Range field is from Hart (1981). The High Cascade field is from data of this study with selected samples from Barnes (1978), Jan (1967), Maynard (1974), and White (1980b). The non-tholeiitic Western Cascade field is from this study. The tholeiitic early Western Cascade field is from data of this study and samples of the Scorpion Mountain lavas of White (1980a; 1980b). The Broken Top field is from Taylor (1978) and the Green Ridge field is from Hales (1975).

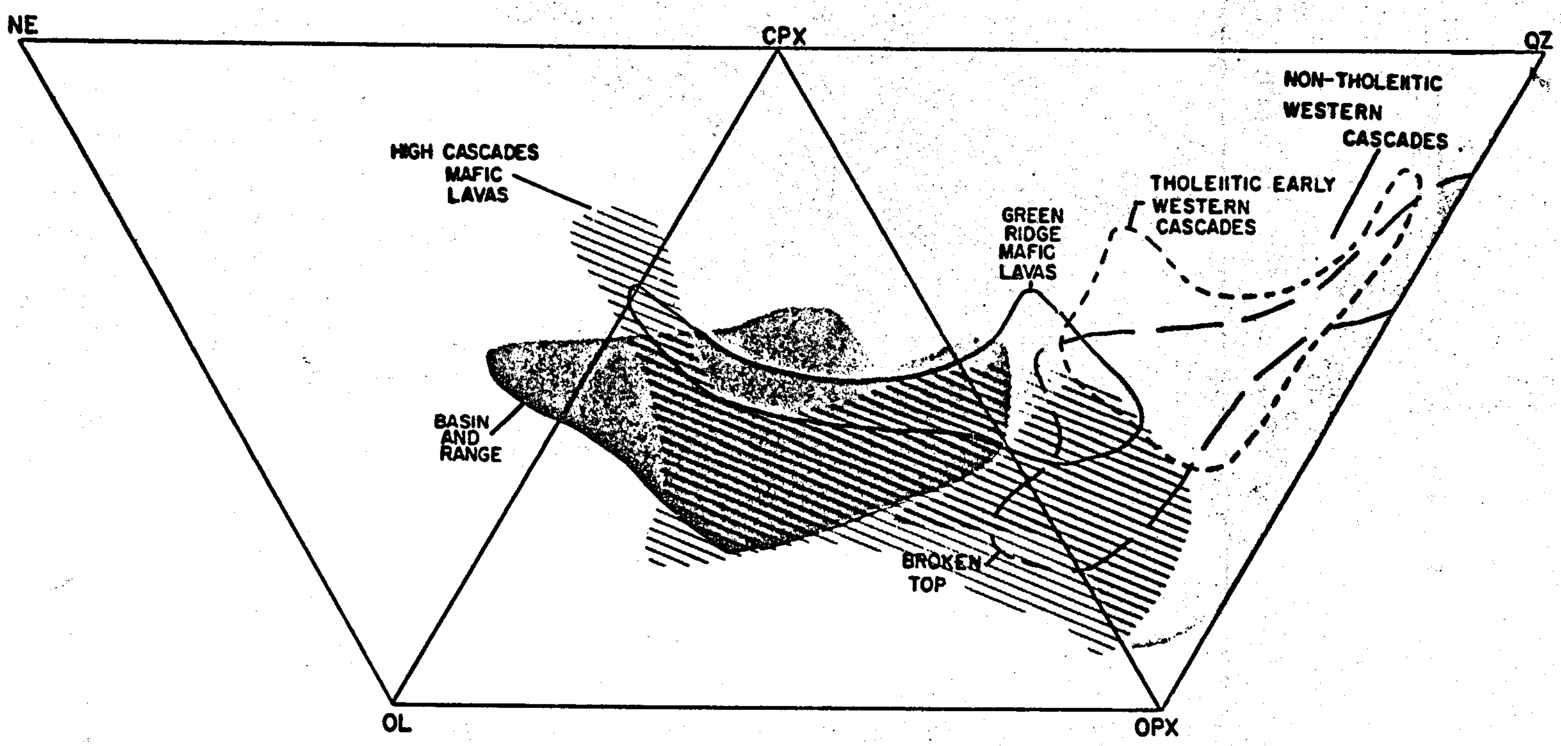

Figure 5. Nepheline (NE) - clinopyroxene (CPX) - olivine (OL) - orthopyroxene (OPX) - quartz (QZ) quadrilateral showing the same fields of composition as Figure 4. Normative minerals calculated with an Fe_2O_3/FeO molecular ratio of 0.28.

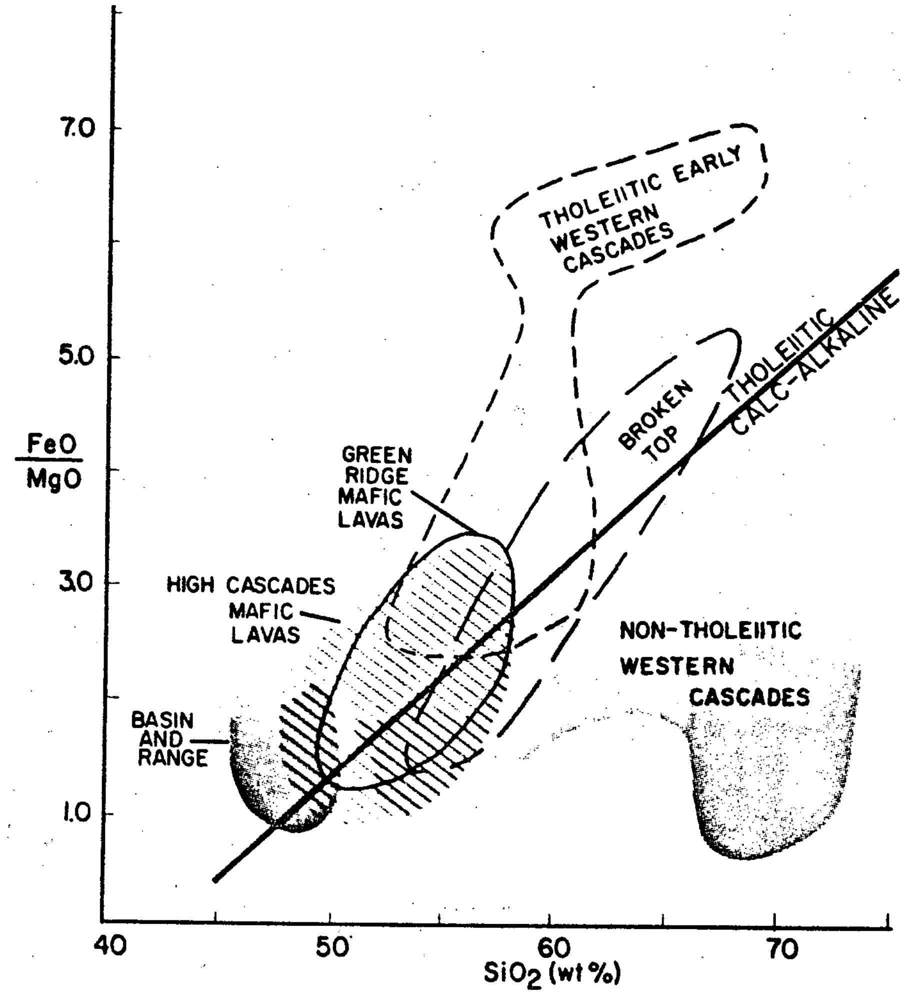

Figure 6. Iron to magnesium ratio versus silica showing the same compositional fields as Figure 4 relative to fields of tholeiitic differentiation series and calc-alkaline differentiation series of Miyashiro (1974). FeO = total iron recalculated to Fe^{+2}.

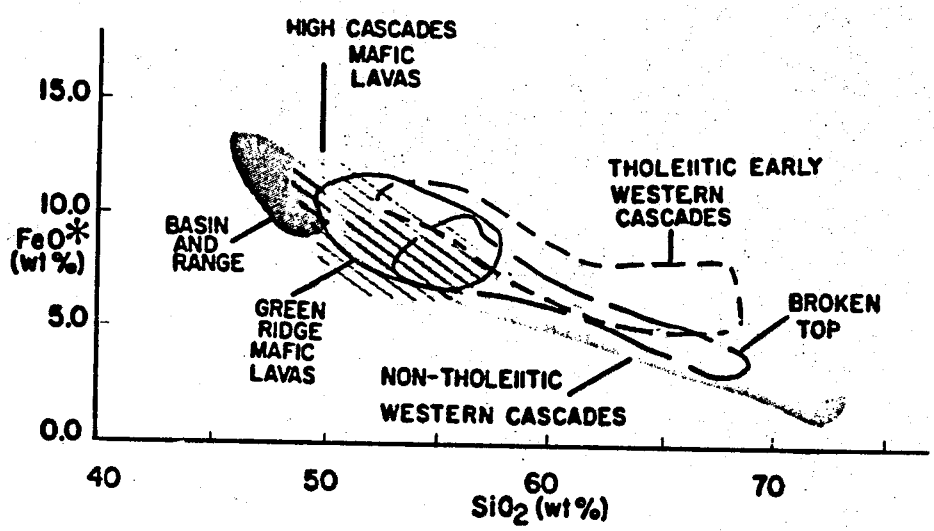

Figure 7. FeO* (total iron recalculated to Fe^{+2}) versus silica for the same fields as Figure 4.

the Cascades. It may be that subduction processes under the High Cascades have produced composite cones and intermediate to silicic lavas, as in other circum-Pacific volcanic arcs, whereas only processes related to Basin and Range spreading have generated magmas in the Basin and Range. Thus both Basin and Range and subduction processes may have produced partial melting episodes in the Cascades during the last 9 m.y. This implies that the rate of magma generation in the Cascades during the last 9 m.y. may have been higher than in the Basin and Range province, where only one partial melting process was operative. It also implies that areas of the High Cascades which have experienced less influence from Basin and Range-type tectonics should have lesser rates of magma generation. This is supported by variations in regional heat flow discussed below.

RELATION OF HEAT FLOW TO VOLCANISM AND TECTONISM

Heat flow values of over 100 mW/m^2 are associated with youthful volcanism throughout much of the Brothers Fault Zone-Basin and Range and High Cascades (Figure 3). The ultimate amplitude of the anomaly in the High Cascades province is unknown, owing to a lack of reliable heat flow data in the hydrologically active carapice of young volcanic rocks mantling the High Cascades. Potential operation of two magma generation processes in the High Cascades, as discussed above, could cause the heat flow to be higher than in the Brothers Fault Zone and Basin and Range. Deep drilling on the central High Cascade axis will be necessary to test this hypothesis.

Aside from a small local anomaly associated with Mount Hood, regional heat flow over 100 mW/m^2 appears to end at the Clackamas River wrench fault zone (Figure 3). A lower amplitude regional heat flow high continues into the area around Mount Hood (Figure 3) (Steele and others, 1982) and north into the Washington Cascades (Blackwell and others, 1978). Reduced heat flow at the Clackamas River fault zone corresponds to a reduction in the total volume of late Neogene volcanism, primarily because of a reduction in basaltic lavas (e.g. see calculations of White and McBirney (1978) for Washington versus Oregon Cascade rocks). The increase in regional heat flow across the Clackamas River fault zone towards the south may give a measure of the amount of magmatic heat added by Basin-and-Range-related mafic volcanism relative to subduction-related andesitic volcanism. This calculation cannot be accomplished until the heat flow is measured in the central High Cascades, but it must be at least 20 mW/m^2 based on heat flow data from the Western Cascades (e.g. from data of Blackwell and others, 1978; Black and others, 1982).

Termination of the highest part of both the Basin and Range and High Cascade heat flow anomalies at major wrench fault zones is additional evidence that there is a relationship between the Basin and Range and the Cascades (Figure 3). There is, however, a greater contrast in heat flow across the Brothers Fault Zone relative to the contrast in Cascade heat flow across the Clackamas River Fault Zone. This is a reflection of the higher background heat flow characteristic of the Cascades. The Blue Mountains contain almost no young volcanic rocks and have moderately low heat flow, whereas the Cascades both north and south of the Clackamas zone have significant youthful volcanism and relatively high heat flow (Figure 3).

Small volumes of youthful diktytaxitic basalts in the Mount Hood area (Boring-type lavas) and southern Washington (Paul Hammond, personal communication) are evidence that some of the same volcanic processes distinctive of the central Oregon Cascades also operate with reduced intensity north of the Clackamas zone. It is thus probable that a small component of the subduction-dominated heat flow north of the Clackamas zone is also the result of extensional tectonism.

IMPLICATIONS FOR GEOTHERMAL EXPLORATION

The best regional target for geothermal resources in Oregon is the High Cascade province south of the Clackamas River wrench fault zone. Individual drill sites should be placed where fracture premeability and heat flow are at a maximum. Major intersections of youthful faults with sites of Holocene volcanism or with other faults are the best exploration sites. North-south trending faults may have more open fractures, since they are parallel to the major compressive stress axis discussed previously. Silicic volcanic centers are most favorable because they are frequently underlain by shallow plutonic bodies.

The Three Sisters-Newberry volcano area is the best exploration site in the Cascades, because it meets all of the above criteria. Pliocene to Quaternary faults with northeast, northwest, and north-south strikes converge in this area (e.g. Wells and Peck, 1961; Peterson and others, 1961), and silicic volcanic centers occur both at the South Sister, where a broad silicic highland 24 km in diameter occurs (Taylor, 1981), and at Newberry volcano (McLeod and others, 1981). A gravity anomaly, possibly associated with a silicic plutonic complex, covers an area of 275 km^2 at Newberry volcano (Black, 1982). The potential at Newberry is underscored by recent discovery of hydrothermal fluids with temperatures of 265° C at a depth of 932 m (3,057 ft) in the caldera (Sammel, 1981).

Other secondary targets include the following areas where fracture permeability is combined with heat flow high enough for temperatures greater than 175° C within 3 km (9,843 ft) of the surface (i.e. within the highest heat flow area of Figure 3):

1. All north-south trending faults in the High Cascades and areas immediately adjacent to the High Cascades. Mapped faults of this type include margins of High Cascade axial grabens at the upper McKenzie River (Avramenko, 1981), Belknap hot springs (Brown and others, 1980a; Flaherty, 1981), the Green Ridge-Tumalo Fault Zone (Hales, 1975; Peterson and others, 1976), Diamond Lake (Barnes, 1978), Walker Rim (Wells and Peck, 1961), and Lake of the Woods (Maynard, 1974). Other areas with lineations on strike with these mapped faults are also good targets (see Allen, 1965; Venkatakrishnan and others, 1980; Kienle and others, 1981).

2. Northwest-trending faults parallel to Basin and Range trends in the southern Cascades may also be good targets (e.g. see Naslund,

1977; Kienle and others, 1981). The Klamath Graben area is probably one of the best prospects. Even though it is part of the Basin and Range physiographic province, it is so closely adjacent to the High Cascades that it probably shares many geological and heat flow characteristics with the High Cascades. This is supported by recent Curie-Point isotherm studies which show that temperatures of 580° C may be encountered as shallow as 4 km under the Mt. McLoughlin-Klamath Lake area (McLain, 1981).

3. The intersection zone of northwest-trending faults of the Eugene-Denio lineament with north-south and northeast striking faults of the Walker Rim may be an area of unusually high fracture permeability (e.g. see Wells and Peck, 1961; Kienle and others, 1981). Similar intersection zones may occur where the Eugene-Denio zone meets the Cascade axis in the Western Cascades, and at the intersection of the Clackamas River and Mt. McLoughlin zones with the High Cascade axis.

CONCLUSIONS

Extensional deformation, probably related to Basin and Range spreading, has been localized in thermally weakened crust of the High Cascade volcanic arc. Northwest trending Basin and Range structures swing into a north-south orientation within the arc forming a general zone of subsidence. Extensional deformation, mafic volcanism less than 9.0 m.y. old, and heat flow all increase abruptly south of the Clackamas River right lateral wrench fault. Similar, but more pronounced changes occur across the Brothers wrench fault zone. Compositional and textural similarity of some basalts in both the central Cascades and the Basin and Range Province suggests a similar petrogenesis. The Brothers-Clackamas fault zone may thus have been a fundamental plate boundary limiting northward spread of Basin and Range-style deformation and associated mafic volcanism since about 9 m.y. ago. The High Cascades have acted as a similar boundary zone limiting westward influence of Basin and Range deformation.

Basaltic andesite to dacite composite volcanoes form a north-south trending chain which crosses the Clackamas boundary into Washington and continues south into California. This unique chain of composite cones is missing from the Basin and Range province but is common in other circum-Pacific volcanic arcs over subduction zones. Coexistence of this subduction-related feature with basalts similar to basalts of the Basin and Range indicate that both subduction and processes related to Basin and Range spreading probably cause partial melting beneath the central Cascades. The resulting high rate of magmatism has produced very high heat flow in the central High Cascades and, where permeable rocks are present, this may result in numerous high-temperature geothermal systems. Youthful fault systems and Holocene volcanic centers, particularly silicic centers are the best geothermal targets.

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