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# TEMPORAL VARIATIONS IN PLATE CONVERGENCE AND ERUPTION RATES IN THE WESTERN CASCADES, OREGON

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Abstract. New K-Ar age determinations on basalts, basaltic andesites, and ash flow tuffs from the central Western Cascades in Oregon range in age from 32 to 3 Ma. The ages decrease from west to east and with increasing elevation. Volcanism has been continuous throughout the evolution of the Western Cascades, with some periods of greater activity: 13-16 Ma, 22-26 Ma and 29-31 Ma. Relative volume estimates indicate that eruption rates decreased by a factor of 6 from 35 Ma to the present. The eruption rates during formation of the Western Cascades Volcanic Arc were influenced by changes in the direction and rate of convergence between the Farallon and North American plates. We have developed a model of the Tertiary convergence of these two plates, based on the mantle-fixed hotspot reference frame, which indicates a factor of 5 decrease in convergence rate (16.0 to 3.2 cm/a). Clockwise rotation of the western margin of the North American plate led to a decrease in the convergence angle since about 35 Ma. Apparently, slower, more oblique subduction resulted in a decrease in the volume of erupted magmas.

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## INTRODUCTION

The Cascades Volcanic Arc extends from northern California to southern British Columbia, a distance of over 1000 km. Along this linear belt, volcanic activity began at approximately 42 Ma [Lux, 1981] with the eruption of basalt and basaltic andesite lavas and dacitic ash flow tuffs. This continental margin volcanic arc is associated with the subduction of the Juan de Fuca (Farallon) plate beneath the Pacific Northwest margin of North America (Figure 1). The Cascades Volcanic Arc is composed of two provinces; rocks of the older Western Cascades exposed along the western slope of the range are 42-10 Ma, and rocks of the younger High Cascades on the eastern margin are 10-0 Ma.

Geologic processes at subduction zones are complex and difficult to separate. The timing, spatial variation and volume of erupted volcanic material may depend on a number of parameters, such as the age of the subducting lithosphere and its volatile content, the dip angle of subduction, the thickness of overlying continental lithosphere, and the convergence rate. While it is impossible to isolate any one variable, the parameter of convergence rate can be examined in the evolution of volcanism in the Cascades Volcanic Arc for the following reasons:

(1) The age of the plate entering the subduction zone has remained young (between

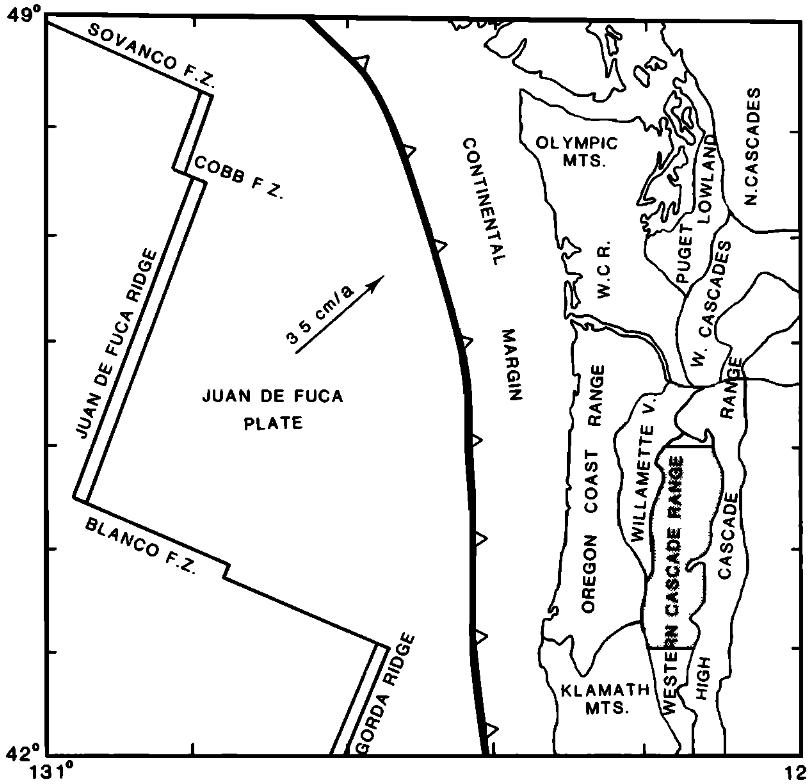

Fig. 1. Physiographic boundaries of western Oregon and Washington and plate boundaries of the Pacific, Juan de Fuca and North American plates. Study area is indicated by stippled pattern.

10 and 20 Ma age) during the time of Western Cascades development [Engebretson, 1982; Duncan and McElwee, 1984]. (2) The dip of the Benioff zone and depth of melting are dependent on the age of the subducted slab [Abbott and Hoffman, 1984], which from (1) has been constant. (3) The present crustal thickness beneath the Cascades increases eastward from 22 km under the Willamette Valley to 37 km under the High Cascades axis [Ganoe, 1983]. Plutonism has added material beneath the volcanic arc during the last 40 m.y., but crustal thickening is unlikely to have exceeded a factor of 2. (4) There has been, however, a fivefold decrease in the convergence rate between the Farallon and North American plates during the formation of the older Western Cascades of 42 to 10 Ma age (Engebretson [1982] and below).

Thus we can expect that the volume and character of volcanism can be related principally to the effects of slowing subduction with time in the Cascades Volcanic Arc. In this paper we examine this hypothetical relationship through a geochronological study of Western Cascades lavas and tuffs.

## THE CENTRAL CASCADES VOLCANIC ARC

Eruptive activity began approximately 42 Ma [Lux, 1981] in the westernmost exposed part of the Cascades Volcanic Arc (Figure 1). Lava and ash flows of this early eruptive sequence have been uplifted, tilted slightly eastward, and subsequently eroded, resulting in a deeply dissected and rugged topography [Peck et al., 1964].

Eocene marine sedimentary rocks of the Spencer, Tyee, and Umpqua formations consist of sandstone, mudstone, and conglomerate which overlie and are interbedded with the westernmost Cascades volcanic rocks [Peck et al., 1964]. Priest and Vogt [1983] proposed to divide the volcanic stratigraphy into an early Western Cascades episode of 42 to 18 Ma and a late Western Cascades episode of 18 to 9 Ma on the basis of an erosional unconformity which spans 19 to 17 Ma. The early Western Cascades rocks consist of massive beds of ash flow tuffs of andesitic to dacitic composition, with interbedded olivine basalt and basaltic andesite lava flows. The late Western Cascades episode, of 18-9 Ma age, is characterized by flows and flow breccias of andesite, basaltic andesite, and basalt. The lavas are interbedded with volcaniclastic and epiclastic continental rocks. In the northernmost part of the study area (Figure 1) the late Western Cascades strata are approximately horizontal and unconformably overlie the early Western Cascades lavas, which generally dip gently eastward [Priest and Vogt, 1983; G. Walker, personal communication, 1984], whereas in the south the two units are conformable [N. MacLeod, personal communication, 1984].

Small intrusive bodies, which occur as pipes, dikes, sills, and small stocks, are thought to be eruptive centers for portions of the Western Cascades volcanism [e.g., Hammond, 1979]. These lie in a belt along the western slope of the Cascades in the eastern half of the study area, which is coincident with a zone of hydrothermal and propylitic alteration. Younger volcanic rocks of Pliocene and Pleistocene age, related to early High Cascades volcanism, are found in the eastern margin of the Western Cascades and have flowed west onto the eroded surface as intracanyon flows.

McBirney et al. [1974] have estimated the volume of erupted material in the Cascade Range from Miocene to Quaternary time and identified a large pulse of activity in the middle Miocene (16-14 Ma), followed by smaller episodes during the late Miocene (11-9 Ma), Pliocene (6-4 Ma), and Holocene (1.5-0 Ma). They proposed that pulses of volcanic activity have occurred in approximately 5 m.y. intervals, which they correlated with synchronous activity in the circum-Pacific area. Variations in the rate of plate convergence have been suggested as the cause of episodicity in island-arc and continental margin volcanic activity [Scheidegger and Kulm, 1975; Kennett and Thunell, 1975; Kennett, 1982]. Correlations between East Pacific Rise spreading rate, hotspot activity, ash accumulation, and circum-Pacific volcanism during the last 4 m.y. were reported by Rea and Scheidegger [1979].

The geochronological data presented by Sutter [1978] and Lux [1981, 1982] from the Cascades of Oregon appear to extend the 5 m.y. periodicity back to 40 Ma. However, Priest and Vogt [1983] contended that the periodicity observations could be merely the result of a sampling bias; that is, a relatively continuous regional volcanic history can be interpreted as being episodic due to incomplete sampling, particularly in regions between volcanic centers which may exhibit age gaps in the volcanic stratigraphy.

For younger rocks, such as the High Cascade volcanoes of Quaternary age, reasonably accurate volume estimates can be made. For older Western Cascade rocks it is impossible to know the original volume of volcanic material. An unknown volume of pyroclastic material has been transported by winds to areas outside the volcanic arc, and much material has been removed by erosion. In addition, the areal extent of older units covered by younger units is unknown. If we make the assumption that erosion rates were constant through time, then relative volumes of the older erupted material can be calculated by measuring thicknesses of volcanic layers of known age range in areas where the stratigraphic relationships are well mapped.

## TIME-SPACE DISTRIBUTION OF THE VOLCANISM

The main objective of this geochronological study is to estimate eruption rates in the Western Cascades Volcanic Arc. Two other objectives are to determine the spatial variation of ages in the Western Cascades and to determine whether the volcanic activity has been episodic or continuous during the past 42 m.y.

Samples for this study were collected in collaboration with George W. Walker and Norman S. MacLeod (U.S. Geological Survey), who are completing geologic mapping of the Salem and Roseburg 1:250,000 sheets. The present investigation was planned to complement their mapping by providing K-Ar age determinations on stratigraphically controlled lava flows and ash flow tuffs. We thus have a total of 55 new dated sites from the central Western Cascades in Oregon. When combined with the age determinations of Lux [1981, 1982], Sutter [1978], Hammond [1979], Priest and Vogt [1983], there are now over 150 K-Ar age determinations of volcanic rocks from the Western Cascades of Oregon (summarized by Fiebelkorn et al. [1983]).

All of our sample sites are between 43° and 45° north latitude and 122° and 123° west longitude. The types of outcrops sampled include roadcuts, active and abandoned quarries, stream cuts, and

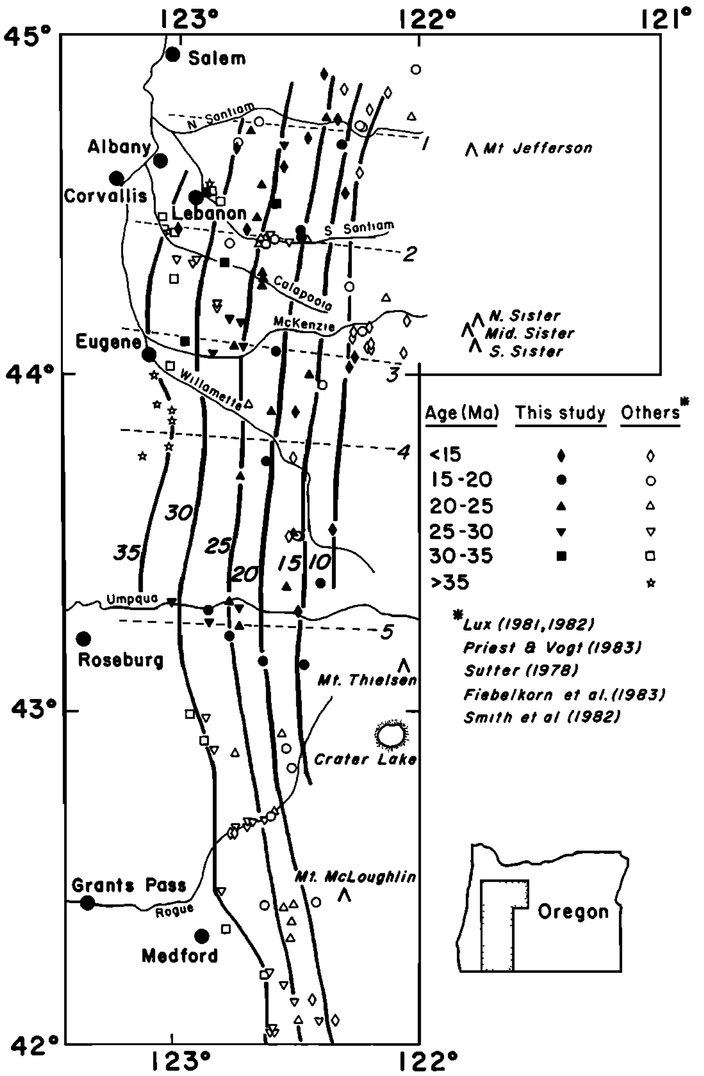

Fig. 2. Spatial variations of age determinations in the Western Cascades, Oregon. The isochrons which are interpolated from dated lava flows and ash tuffs are oriented aproximately north-south and decrease from west to east. Isochrons are projected across drainages to simplify the diagram; in reality, they closely follow the topographic contours. The locations of five east-west cross sections are indicated by numbered line segments.

ridge-capping lavas. Intrusive rocks were avoided because of their uncertain stratigraphic relation with the lavas and ash flow tuffs. With the guidance of the field geologists, we were able to sample fresh-appearing rocks from locally continuous, mapped units. In some places, age determinations assisted in identifying stratigraphic horizons for correlation between drainages.

Conventional K-Ar techniques [Dalrymple and Lanphere, 1969] were employed to determine ages for the 55 samples from the central Western Cascades in Oregon: 51 were whole rock, three were plagioclase separates, and one was a glass separate. Most dated specimens are from basalt, basaltic andesite, or andesite lava flows, except for a few ash flow tuff samples of dacitic or rhyodacitic composition. Almost all of the rocks are plagioclase-phyric, and some also contain clinopyroxene phenocrysts. A few of the samples have olivine phenocrysts, most of which have been partly altered to iddingsite or clay minerals. Ages on these samples range from 3.0 to 32.1 Ma, and most are between 12 and 32 Ma. These new age determinations are

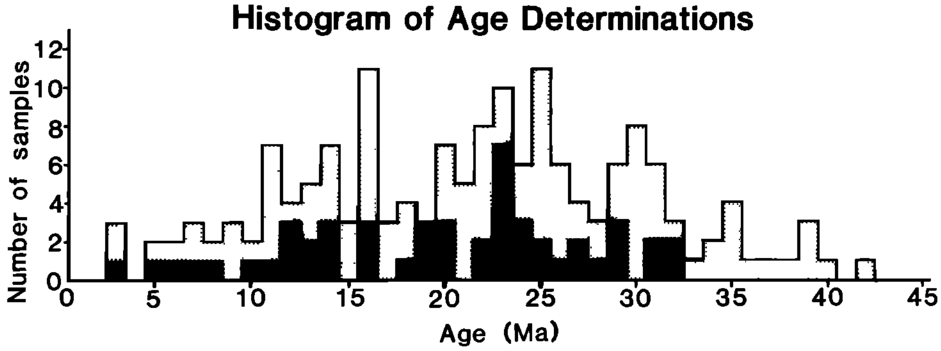

Fig. 3. Histogram of age determinations (K-Ar and 40Ar/39Ar). Solid black: this study. Stippled pattern: Lux [1981, 1982], Priest and Vogt [1983], Sutter [1978] and Fiebelkorn et al. [1983]. All data are from the Western Cascades, Oregon.

available from the AGU data file, on microfiche.[1] See Verplanck [1985] for complete sample descriptions and further details on age determinations.

## Spatial Variations

As noted previously, the regional dip of the Western Cascades volcanic strata is approximately 3°-10°E, except for some of the younger flows (<18 Ma), which dip more gently. With this relatively continuous regional structure, the oldest volcanic rocks should be exposed on the western margin, with ages decreasing progressively eastward. Not surprisingly, this is what is observed in the distribution of crystallization ages in the Western Cascades. Complicating factors such as minor faults, folds, and intracanyon flows, which disrupt the continuous stratigraphic relations, do occur, but overall, the ages of the Western Cascades volcanic units decrease eastward and with increasing elevation.

Spatial variations of the ages of the volcanic units are illustrated in Figure 2. The new K-Ar age determinations are combined with reported geochronological data from the Western Cascades [Sutter, 1978; Lux 1981, 1982; Priest and Vogt, 1983; Fiebelkorn et al., 1983; Smith et al., 1982]. Isochrons, i.e., lines of constant age in 5-m.y. intervals from 35 to 10 Ma, were constructed by interpolation between dated locations. Several samples are from intracanyon flows which are out of sequence; their ages are not used in this representation of the volcanic stratigraphy. The isochrons are projected across drainages to simplify the diagram and, in general, follow the topographic contours. Wider spacing between isochrons suggests that thicker amounts of volcanic material were deposited, assuming the volcanic stratigraphy has a regionally constant dip.

The new K-Ar age determinations plus all previously reported geochronological data for the volcanic rocks of the Western Cascades province are plotted on a histogram in Figure 3. The results do not appear to indicate a periodicity in the volcanism. There are certainly no significant periods of quiescence. The data show more or less continuous volcanic activity throughout the mid-to-late Tertiary, with possibly greater activity between 13-16 Ma, 22-26 Ma, and 29-31 Ma. Hence, there is little if any support for a 5-m.y. episodicity in volcanism in the Western Cascades from these age data. However, longer-term changes have occurred in eruption rates, which we discuss next.

## Temporal Variations in Eruption Rates

Previous workers have attempted to estimate volumes of erupted material in the younger, Quaternary-age, High Cascades volcanic rocks, where the exposures are good and the volcanic units have been well mapped [McBirney et al., 1974]. Reasonably accurate quantitative volumetric data have been obtained; the only serious unknown factor is the amount of volcanic material removed via wind and water transport. The Western Cascades are deeply dissected by erosion and extensively covered by

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[1] Supplement (data, tables, calculations, etc.) is available with entire article on microfiche. Order from American Geophysical Union, 2000 Florida Avenue, N.W., Washington, DC 20009. Document T87-002; $2.50. Payment must accompany order.

vegetation, and it is much more difficult to estimate volumes of erupted material. Also, the volcanic material produced by the Western Cascades volcanoes is more extensive than the High Cascade lavas. Robinson et al. [1984] suggested that, beginning about 37 Ma, voluminous dacitic to andesitic air-fall material of the John Day Formation of north central Oregon was derived from the volcanoes within the Western Cascades Range. Therefore, there is presumably Oligocene and Miocene age Western Cascades volcanic material underlying the High Cascades whose volume cannot be measured.

We can approach this problem in a different way. Instead of volume calculations, relative thickness estimates can be used to compare rates of volcanic activity through time. To do this, however, certain assumptions are necessary. First, erosion rates are assumed to have been more or less constant during the time period 40-10 Ma. Presumably there have been minor temporal fluctuations in the erosion rate, but we do not know of a method to quantify these changes. Second, the variation in distances from volcanic centers is assumed to be averaged by the density and breadth of sampling. In general, proximity to a volcano will result in thicker lava and ash flow deposition. This effect can be neglected if sufficient transects are taken, thereby averaging out the variations in distances from eruption sites. Third, the sedimentary layers are assumed to be interbedded in approximately equal proportions between the volcanic units throughout the Western Cascades stratigraphic sequence. This assumption is only valid for an extended time frame. The thickness of sediment deposited between 30-20 Ma and 20-10 Ma is roughly the same [G.W. Walker and N.S. MacLeod, personal communication, 1984]. The sediment input increases the eruption rate (equal to accumulation rate) estimates, but the erosion of material decreases the estimates by a greater amount. Therefore the calculated eruption rates are probably minimum estimates of the original thicknesses of volcanic material deposited with time.

In areas where the structure is well known from mapping [Smith et al., 1982; G.W. Walker and R.A. Duncan, unpublished manuscript, 1987; N.S. MacLeod, personal communication, 1984], it is possible to use the geochronological data to produce east-west cross sections of the volcanic stratigraphy (e.g., Figure 4). We have constructed five such cross sections perpendicular to the Western Cascades in the study area (locations shown in Figure 2). The new and previously dated samples are located by elevation and longitude. Each cross section combines age data within an east-west swath approximately 20 km wide.

An average dip slope of 5° was used for the early Western Cascades sequence (>18 Ma). A 2° dip slope was used for the late Western Cascades sequence (<18 Ma) in the northern half of the study area and a 5° dip slope, conformable with the earlier sequence, in the southern half. We next calculated the stratigraphic thickness between dated samples (lavas and ash tuffs). Ages from closely spaced samples were averaged to date some volcanic horizons. Samples from intracanyon flows and landslide blocks were not included in the calculations.

The thicknesses were converted to eruption rates by dividing by the time interval between dated samples. These eruption rate estimates, from the five cross sections, are plotted in Figure 5 against age and plate convergence rate (calculated in the next section). It is apparent that eruption rates have consistently decreased with time throughout the Western Cascades study area.

Another possible mechanism to explain the decrease in thickness of volcanic material is the progressive eastward migration of volcanic centers. The basalt and basaltic andesite volcanic centers of the early Western Cascades are located up to 50 km west of the late Western Cascades centers [Peck et al., 1964]. However, the early Western Cascades volcanic sequence is exposed to the west of the late Western Cascades volcanic sequence. The horizontal distance between the 30 Ma and 10 Ma isochrons varies from about 25 to 55 km. The distance from the ancestral volcanic centers to the sampling sites, then, has not changed significantly with time. The decrease in thickness of volcanic material with time, therefore, appears to reflect a true decrease in eruption rate.

Table 1 compares average eruption rates for 5-m.y. intervals from 35 Ma to the present. We conclude that eruption rates have decreased by at least a factor of 6, from 400 m/Ma to 60 m/Ma, during the evolution of the Western Cascades. In the next sections we relate this decrease in volcanic activity to slowing convergence

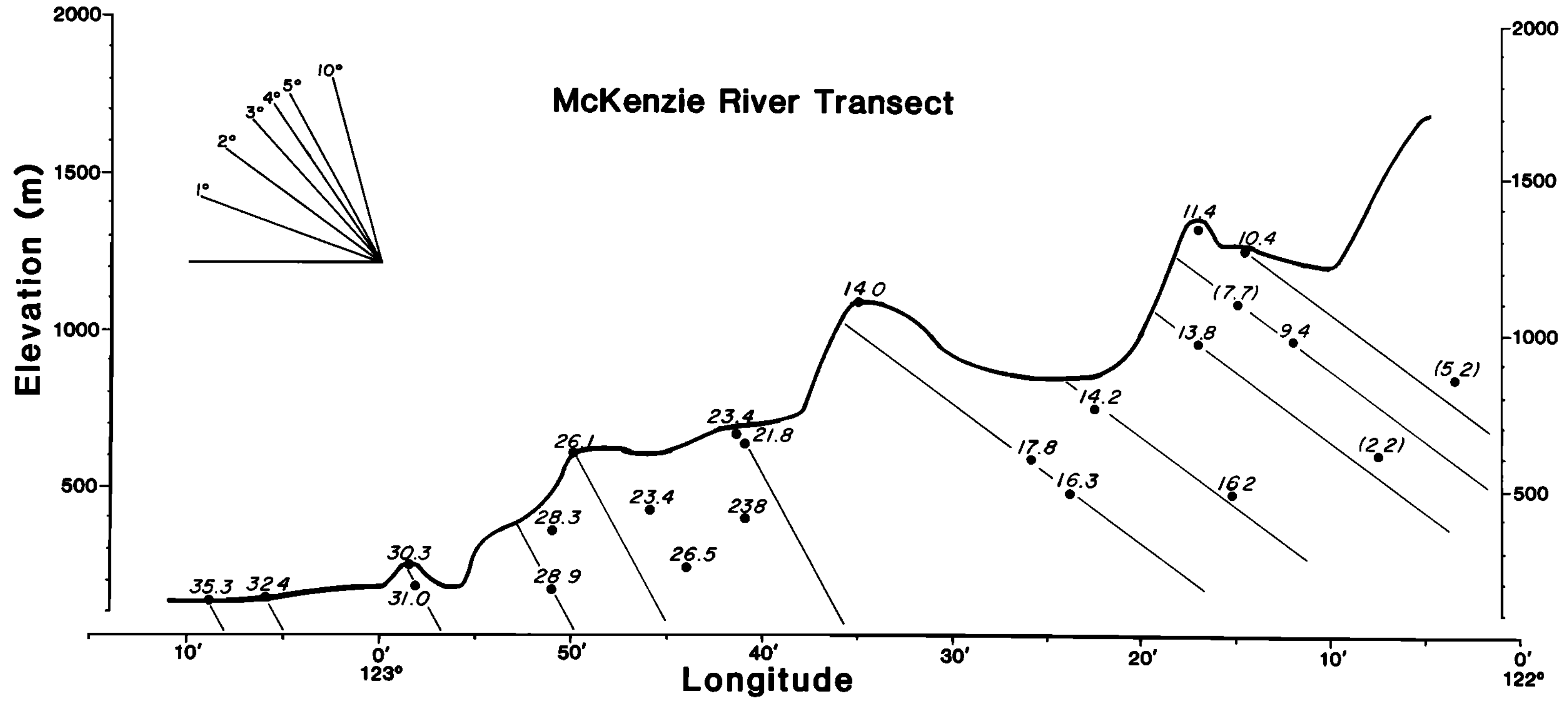

Fig. 4. Representative cross section of the Western Cascades, Oregon, through the McKenzie River drainage (line 3 on Figure 2). Samples are located by elevation and longitude. Closed circles are K-Ar and $^{40}Ar/^{39}Ar$ age determinations from Lux [1981, 1982], Sutter [1978], Priest and Vogt [1983] and this study. Intracanyon flow ages are shown with parentheses. Vertical exaggeration is 21:1. Regional dips of 5° for the early Western Cascades and 2° for the late Western Cascades are shown. The stratigraphic thickness between dated samples was calculated and divided by the time intervals to obtain estimates of eruption rates (Figure 5).

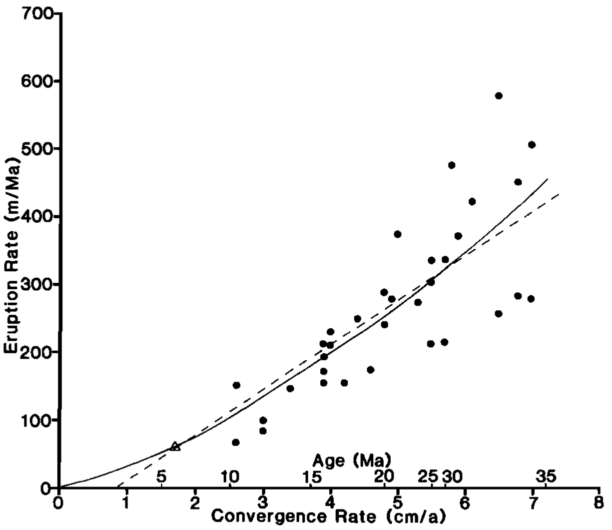

Fig. 5. Eruption rates versus age and plate convergence rate during the evolution of the Western Cascades volcanic arc. Triangle is based on volume and area estimates of late Miocene to recent volcanic activity [McBirney et al., 1974]. Eruption rate and convergence rate are highly correlated and proportional. Nominal best-fitting linear and quadratic functions are shown.

between the Farallon and North American plates.

## MODELLING CONVERGENCE BETWEEN THE FARALLON AND NORTH AMERICAN PLATES

Numerous authors have proposed that there is a relationship between the rate of plate convergence and the rate of magmatic activity in the associated island arc or continental arc [Scheidegger and Kulm, 1975; Kennett and Thunell, 1975; Kennett, 1982; Wells et al., 1984]. To examine this relationship for the Cascades Volcanic Arc, we have developed a model for the convergence of the Farallon and North American plates during Tertiary time. The convergence model is based on two major assumptions: that hotspots in the Atlantic and Pacific basins have remained fixed with respect to each other and that symmetrical spreading occurred along the ocean ridge separating the Farallon and Pacific oceanic plates. The former assumption has been tested by Minster and Jordan [1978], Morgan [1981], and Duncan [1981], who conclude that hotspots move less than 0.5 cm/a with respect to one another. This is about 1 order of magnitude less than the plate velocities, and, therefore, inter-hotspot movement is small enough that hotspots constitute a useful reference frame.

The second assumption is necessary because most of the Farallon plate, all that is older than 11 Ma (polarity chron 5), has been subducted beneath North America. Therefore the only record of the spreading history prior to late Miocene time is the magnetic anomaly pattern on the Pacific plate. Symmetrical spreading is a reasonable assumption because it has been observed in the last 11 Ma at the Juan de Fuca-Pacific spreading ridge south of the Sovanco Fracture Zone [Riddihough, 1977].

The convergence calculations can be described in three steps. First, the absolute motion of the Pacific and North

TABLE 1. Estimated Eruption Rates During Formation of the Western Cascades, Oregon

| Time Interval, Ma | Average Eruption Rate[a], m/Ma | Plate Convergence Rate[b], cm/a |
|---|---|---|
| 35-30 | 399 | 6.0 |
| 30-25 | 297 | 5.2 |
| 25-20 | 236 | 5.2 |
| 20-15 | 190 | 4.0 |
| 15-10 | 109 | 3.2 |
| 10-0 | 59[c] | 1.3 |

[a] From estimates in Figure 5.
[b] From Figure 7.
[c] From volume and area estimates of McBirney et al. [1974].

TABLE 2. Stage Poles for Farallon-North American Plate Convergence, 70 m.y. to Present

| TIME, Ma | Rotation Pole | | |
|---|---|---|---|
| | Latitude(+°N) | Longitude(+°E) | Angle(+°Clockwise) |
| 0- 5 | 35.1 | -121.5 | 4.9 |
| 5-10 | 55.9 | 133.7 | -2.2 |
| 10-15 | 27.6 | 108.7 | -2.1 |
| 15-20 | 40.1 | 119.6 | -1.9 |
| 20-25 | 42.1 | 127.6 | -2.2 |
| 25-30 | 58.9 | 139.4 | -3.2 |
| 30-35 | 58.5 | 139.4 | -3.1 |
| 35-40 | 51.2 | 107.5 | -5.1 |
| 40-45 | 45.4 | 102.4 | -6.6 |
| 45-50 | 49.2 | 115.3 | -6.7 |
| 50-55 | 55.1 | 136.4 | -6.8 |
| 55-60 | 39.5 | 131.9 | -6.5 |
| 60-65 | 31.1 | 128.2 | -6.5 |
| 65-70 | 24.8 | 141.1 | -7.4 |

American plates is found from the reference frame of hotspots which are fixed with respect to the mantle [Duncan and Clague, 1985; Duncan, 1984]. The second step is to establish the motion of the Farallon plate relative to the Pacific plate. The magnetic lineations on the Pacific and Juan de Fuca plates [Atwater and Menard, 1970; Riddihough, 1977] are used in conjunction with the magnetic polarity time scale [Harland et al., 1982] to determine rotation poles for Farallon-Pacific relative motions, following Engebretson [1982]. The third step is to add the Farallon-Pacific relative motion to the Pacific absolute motion; their sum is the Farallon absolute motion. The North American absolute motion is added to the Farallon absolute motion; their resultant is the convergent motion of the Farallon and North American plates. The stage poles for the Tertiary to present history of this plate convergence are given in Table 2.

Figure 6 illustrates the results of the convergence model in terms of vectors whose length indicates the rate and whose azimuth is the direction of convergence between the Farallon and North American plates at Cape Blanco, Oregon. Each vector is an average over a 5-m.y. interval, and the number beside each vector indicates the beginning of the time interval. It is apparent that the convergence has always been to the northeast from beginning Tertiary to the present, with a variable component of northward translation. There has been a drastic decrease in convergence rate, however, from 16.5 cm/a at 70 Ma to the present rate of 3.4 cm/a. The decrease occurs relatively continuously with time except for a more sudden decrease at 40 Ma. This significant decrease in rate is partly a result of the change in Pacific plate absolute motion recorded by the Emperor Seamounts and Hawaiian Ridge intersection

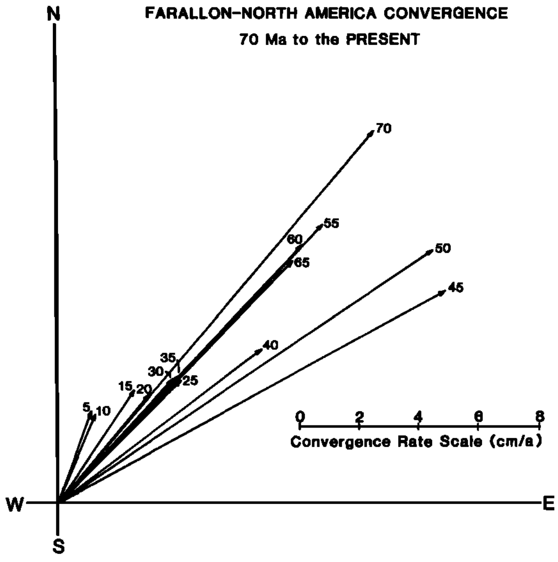

Fig. 6. Farallon-North American plate convergence model. The vectors indicate the rate and direction of convergence between the Farallon and North American plates at Cape Blanco, Oregon, during the Tertiary. The number beside each vector indicates the beginning of a 5-m.y. time interval.

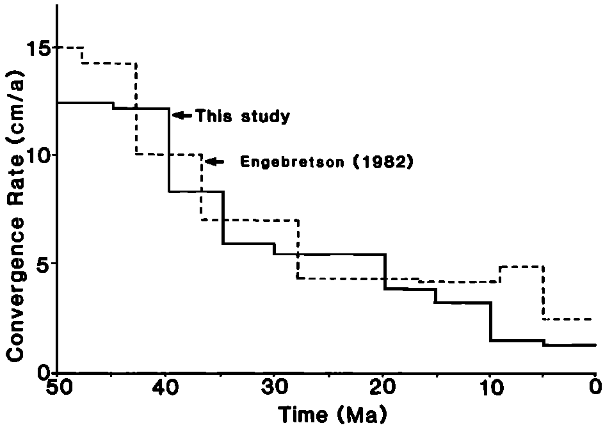

Fig. 7. The normal component of convergence between the Farallon and North American plates since 50 Ma: (1) This study. Model is based on the absolute reference frame, and the site of convergence is Cape Blanco, Oregon. The normal component of convergence is calculated assuming the Western Cascades have rotated clockwise since 40 Ma, as determined from paleomagnetic data (see text). (2) Engebretson [1982]. Model is based on the absolute reference frame. Shown is the normal component of Farallon plate motion near present day San Francisco, relative to a fixed North America.

at 43 Ma [Clague et al., 1975]. Coincidentally, this is also the time of the Coast Range accretion [Duncan, 1982; Heller and Ryberg, 1983] and the initiation of Western Cascades volcanic activity [Lux, 1982].

Engebretson [1982] has modeled the convergence of the Farallon and North American plates during Tertiary time, also based on the absolute reference frame (mantle-fixed hotspots). His results are compared to our new calculations in Figure 7. The normal component of convergence near present-day San Francisco (Engebretson's model) and near present-day Cape Blanco (this study) are quite comparable. Both models indicate a decrease in convergence rate with time, the most significant decrease occurring between 45 and 35 Ma.

The direction of convergence between the Farallon and North American plates during Tertiary time had an average azimuth of N45°E. Since 40 Ma, however, the 5-m.y. interval convergence vectors have rotated progressively counterclockwise from N53°E to N20°E. At the same time, the Oregon Coast Range and Western Cascades Range have rotated clockwise [e.g., Simpson and Cox, 1977; Magill and Cox, 1980], thereby increasing the obliquity of convergence motion at the margin with time. If we assume that the Cascades and Coast Range have rotated together since the accretion of the latter at about 42 Ma, then the orientation of the subduction zone associated with Cascades volcanism can be reconstructed. Figure 8 illustrates the changes in both the convergence motion and the subduction zone orientation with time, in 5-m.y. intervals, since 40 Ma. Prior to 40 Ma and the Coast Range accretion, the orientation of the northwestern margin of the United States is not well enough constrained to make predictions of the convergence angle.

In summary, the rate and orthogonal component of convergence motion between the Farallon and North American plates has decreased during the evolution of the Western Cascades Volcanic Arc. The

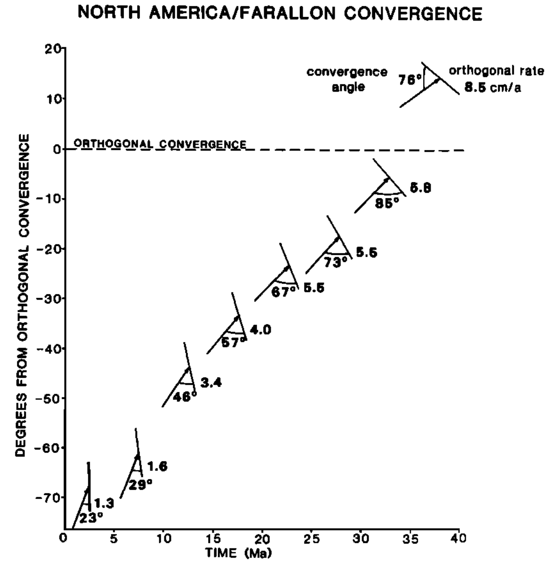

Fig. 8. The change in convergence motion between the Farallon and North American plates since 40 Ma. Vectors indicate direction of convergence, and line segments illustrate the orientation of the continental margin as deduced from paleomagnetic data from the Coast Range and Western Cascades. Numbers on the right are the orthogonal rates of convergence (cm/a), and degrees indicate the convergence angle. Convergence has become increasingly oblique with time since about 35 Ma.

orthogonal rate has decreased by a factor of 5 from 8.5 to 1.6 cm/a, and the angle of convergence has decreased by two thirds, from 90° to 30°, between 40 and 10 Ma. The next step is to compare this quantitative convergence model with temporal variations in volcanic activity in the Western Cascades.

## CORRELATION OF ERUPTION RATES WITH CONVERGENCE HISTORY

This study provides evidence that the temporal variation in eruption rate is a result of the change in subduction rate of the Farallon plate beneath North America. The depth of partial melting is dependent on the age and subduction rate of the oceanic lithosphere [Abbott and Hoffman, 1984]. In the Cascades Volcanic Arc, the portion of the Farallon plate which entered the subduction zone has remained young (10-20 Ma, Engebretson [1982]) for the past 40 m.y., and therefore the age of the descending plate has not changed significantly. The convergence rate, however, is a significant variable and decreased drastically by a factor of 5 during the evolution of the Western Cascades.

Faster convergence rates increase the depth at which the subducting plate attains thermal equilibrium with the surrounding mantle [Abbott and Hoffman, 1984] and, therefore, dehydration reactions take place at a deeper level. This conceivably causes more melting in the region 80-200 km and consequently more magma to be produced. Volcanism is not necessarily proportional to magma generation, however. Additional factors are the geochemical composition of the magma, the stress and strain regime, and the thickness of the overlying crust. Intuitively, however, one would expect that more subducted material would result in a greater amount of volcanism in the overlying arc.

Variations in volcanic activity in island-arc and continental-margin areas have been proposed to result from changes in the rate of plate convergence [Scheidegger and Kulm, 1975; Kennett and Thunell, 1975; Kennett, 1982]. Wells et al. [1984] suggested that the decrease in Farallon-North American convergence may be responsible for shifting the location of the volcanic arc to the west, decreasing the horizontal compressive stress on the continent and increasing ash flow tuff volcanism. Marsh [1982] observed that the Aleutian volcanic centers decrease in size from east to west, coincident with a decrease in the velocity and angle of convergence of the Pacific plate. Karig [1982] suggested that intensity of arc volcanism is influenced by the rate of subduction. Karig and Kay [1981] compiled data on rates of magmatism and of plate convergence for numerous active arc systems. A positive correlation between rates of subduction and eruption was shown within the Lesser Antilles, Mariana, Central America and Cascades volcanic arcs. Orogenic periods of increased plutonism in the Andean Volcanic Arc coincided with periods of relatively higher plate convergence [Frutos, 1981; Bussell, 1983].

As shown in Table 1 and Figure 5, subduction (orthogonal convergence) rates have decreased from about 6.3 cm/a to 1.3 cm/a at the same time that eruption rates in the Cascades Volcanic Arc dropped from about 400 to 60 m/Ma. Therefore it appears that subduction and eruption rates show similar trends and are roughly proportional to one another during the evolution of this volcanic arc. This is an important result because it may be used to correlate plate motions and magma production in volcanic arcs around the world.

The convergence rates were significantly greater (11 to 16 cm/a) prior to 40 Ma. It will be an interesting future study to compare the eruption rates of volcanic material which predates the Western Cascades and test whether the subduction rate and eruption rate are indeed proportional to one another in this earlier period. The subduction zone is thought to have been located further east in the past, and volcanism was located along the Challis axis in Washington and Idaho. The emplacement of the Coast Range by approximately 42 Ma clogged the previous subduction zone and thereby caused the subduction to jump seaward [Simpson and Cox, 1977]. We would expect the eruption rates of volcanic material in the ancestral volcanic arc to greatly exceed those of the Western Cascades if all other factors remained equal.

## SUMMARY

Geochronological data correlate time variations in eruptive history of Western Cascades volcanism with changes in the convergence pattern between the Farallon and North American plates. Our results, combined with those for previously reported ages, indicate that the oldest volcanic material is exposed on the western margin of the arc and the ages decrease with increasing elevation and distance eastward, which agrees with the volcanic stratigraphic relations. Volcanism has been continuous throughout the evolution of the Western Cascades, although some intervals between 13-16 Ma, 22-26 Ma, and 29-31 Ma appear to be have been more active. Most important, the geochronological data presented here are used to estimate eruption rates during Western Cascades volcanic activity. We find that eruption rates have decreased by at least a factor of 6 from 35 Ma to the present.

From our model calculations of the history of convergence between the Farallon and North American plates we find that the convergence direction has become more oblique and the convergence rate has decreased by a factor of 5 during the volcanic evolution of the Western Cacades. The changes in direction and rate of convergence directly influence the volume of volcanism in the associated volcanic arc. The decrease in convergence rate results in less material being subducted in a given time and a corresponding decrease in the amount of magma produced and erupted. We suggest that a slower convergence rate results in a shallower loss of volatiles and therefore a decreasing degree of partial melting at depth.

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