TECTONIC, VOLCANIC, AND GEOTHERMAL COMPARISON OF THE TOHOKU VOLCANIC ARC (JAPAN) AND THE CASCADE VOLCANIC ARC (USA)

L. J. Patrick Muffler[1] and Shiro Tamanyu[2]

[1] *Branch of Volcanic and Geothermal Processes, U. S. Geological Survey, MS 910, 345 Middlefield Road, Menlo Park, CA 94025, USA*
[2] *Geothermal Research Department, Geological Survey of Japan, 1-1-3 Higashi, Tsukuba, 305 Japan*

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ABSTRACT

Both the Tohoku volcanic arc of N Honshu and SW Hokkaido, Japan, and the Cascade volcanic arc of NW United States and SW Canada are related to subduction of an oceanic plate beneath a continental plate. The Tohoku arc, however, displays much greater volcanic and geothermal activity than the Cascade arc. A cooperative project between the Geological Survey of Japan and the U.S. Geological Survey seeks to document the factors responsible for these differences and to quantify the implications for geothermal resource assessment. Large modern geophysical and geological data sets for both arcs are being compiled digitally at 1:2,000,000. Preliminary analysis suggests that the greater volcanic and hydrothermal vigor of the Tohoku arc may be due to enhanced hydration of mantle peridotite and consequent greater magma generation. in turn caused by the greater age and hydration of the Pacific Plate and the faster rate of its subduction as compared to the Juan de Fuca plate under the Cascade arc. In addition, more extensive mechanical interaction between the Pacific plate and the mantle wedge beneath the Tohoku arc may promote increased convection in the mantle wedge and consequent greater generation of magma than in the mantle wedge beneath the Cascade arc.

1. INTRODUCTION

Both the U.S. Geological Survey and the Geological Survey of Japan are actively conducting research on geothermal resources. In particular, the respective geothermal research programs of the two countries have produced large, encyclopedic data sets for the Cascade Range and the Tohoku volcanic arc. Interpretation of these data sets in a comparative manner will greatly sharpen and improve the conclusions with respect to geothermal energy and volcanic hazards. This comparison is Project Annex No. 5 (Geothermal Energy Research and Volcanic Hazard Mitigation—Comparison of Cascade and Tohoku volcanic arcs) of the Memorandum of Understanding signed on June 24, 1993 by the Directors of the Geological Survey of Japan and the U.S. Geological Survey.

Inasmuch as the Tohoku-Cascade comparison is a project in progress, this paper treats only the tectonic setting and its first-order relationship to the volcanic and geothermal activity, based upon available data. We find even this apparently simple comparison difficult to carry out, primarily because of the different approaches that Japanese and United States scientists have taken in collating and summarizing volcanic and geothermal data. Hence, under the cooperation between the Geological Survey of Japan and the US Geological Survey, all pertinent geophysical and geological data sets available for both arcs are currently being compiled digitally at 1:2,000,000 to allow ready comparison of parameters such as distribution of volcanic vents and thermal features, nature of volcanism as a function of time and composition, convective and conductive flux, and distribution of gravity, magnetic, and electrical anomalies.

2. TECTONIC SETTING

The Tohoku volcanic arc is situated above a westward-dipping subduction zone along which the Pacific plate moves westward under the northern part of the Island of Honshu and the southernmost part of the Island of Hokkaido (Figure 1). In the early development of plate-tectonic models, the overlying plate to the west was considered to be part of the Eurasian plate. Modern plate-tectonic models (e.g., DeMets. 1992a and 1992b), however, depict the overlying plate as part of the North American plate, which in turn passes under the Eurasian plate along an incipient subduction zone developed at 0.5 Ma along the eastern edge of the Sea of Japan (Nakamura, 1983; Kobayashi, 1986; Shimizu and Itaya, 1993). Other authors (e.g., Seno, 1985; Hashimoto and Jackson, 1993) suggest that northern Honshu comprises a separate microplate. All of the analyses, however, agree that the Tohoku volcanic arc lies above a major, long-lived, west-dipping suduction zone.

The Cascade volcanic arc also lies above a subduction zone. commonly termed the Cascadia subduction zone (Rogers, 1988), along which three microplates (south to north. the Gorda, Juan de Fuca, and Explorer microplates) are being subducted eastward under the large, coherent North American plate (Figure 2). The three microplates are remnants of the Vancouver plate (Menard, 1978), which is being progressively fragmented during the past 30 Ma in response to the encroachment of North America (Atwater, 1990; Severinghaus and Atwater, 1990). Prior to 55 Ma, the Vancouver plate was part of the Farallon plate, a single very large plate probably filling much of the eastern Pacific (Atwater, 1990).

In both the Tohoku volcanic arc and the Cascade volcanic arc, as in various volcanic arcs around the world (Gill, 1981; Tatsumi *et al.*, 1983), the subducting slab is at ≈100 km depth directly beneath the volcanic arc (Zhao *et al.*, 1994; Michaelson and Weaver, 1986). In northern Honshu, the volcanic chain is 250–300 km west of the Japan trench (Hasegawa and Zhao, 1991; Tichelaar and Ruff, 1993). In northern Washington and British Columbia, the Cascade arc is 300–400 km east of the convergent margin (Sherrod and Smith, 1990; Dragert *et al.*, 1994), whereas in southern Washington, Oregon, and northern California, the arc is only 250–300 km east of the convergent margin.

Although the Tohoku and Cascade volcanic arcs share a similar tectonic setting as volcanic arcs above subduction zones, several aspects of the subduction zones are strikingly different:

- *Definition of subduction zone.* The Wadati-Benioff zone under the Tohoku volcanic arc is spectacularly defined by numerous earthquakes and by seismic tomography (Hasegawa *et al.*, 1994; Zhao *et al.*, 1994, Plate 1). In striking contrast, the Wadati-Benioff zone under the Cascade volcanic arc can be defined by earthquakes only in western Washington (Taber and Smith, 1985; Weaver and Baker, 1988), northern California (Cockerham, 1984; Walter, 1986), and southwestern British Columbia, Canada (Dragert *et al.*, 1994). The Cascade range in Oregon is essentially aseismic, and the geometry of the subduction zone in that region is known only from teleseismic tomography (Weaver and Michaelson, 1985; Michaelson and Weaver, 1986; Rasmussen and Humphreys, 1988; Harris *et al.*, 1991). Even in the regions where the Wadati-Benioff zone can be defined by earthquakes, the seismic activity is much lower than in the Tohoku volcanic arc, and the Wadati-Benioff zone is accordingly much less precisely defined. In addition, there are no contemporary thrust earthquakes on the plate interface, and there have been no great earthquakes (magnitude ≥8) in the historical record (Rogers, 1988).
- *Dip of subduction zone.* The subduction zone under the Tohoku volcanic arc dips at ≈5° to 25-30 km depth and then steepens to a uniform dip of 25-30° to a depth of ≈670 km

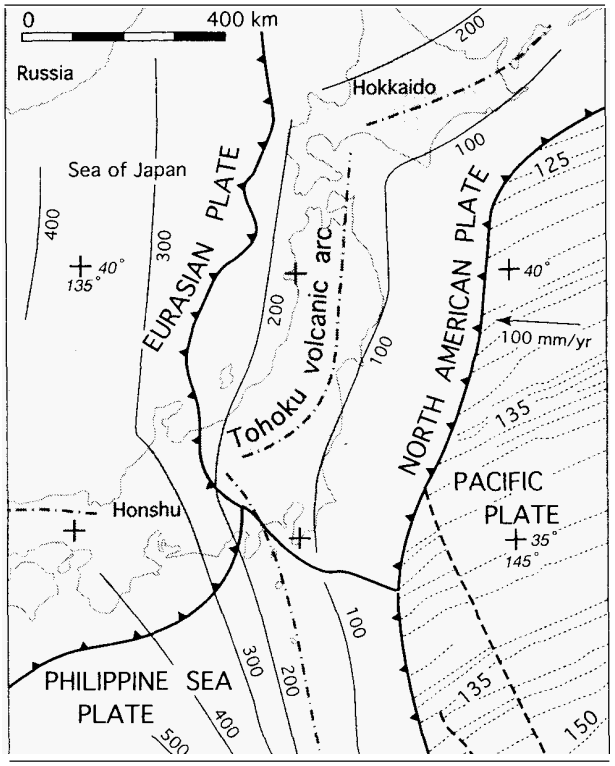

FIGURE 1. *Plate-tectonic setting of the Tohoku volcanic arc, Japan. Plate houndarier (heavy solid lines), depth of Wadati-Benioff zone in km (thin solid lines), volcanic front (dot-dashed lines), and convergence rate of Pacific and North American plates from Shimizu and Itaya (1993). Faults (heavy dashed lines), seafloor magnetic anomalies (dotted lines). and ages of oceanic crust (in Ma) from Nakanishi et al. (1989).*

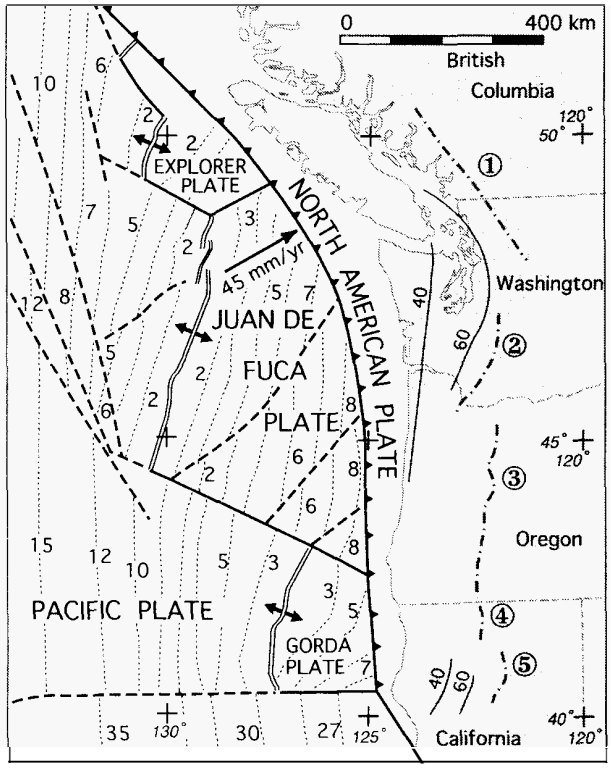

FIGURE 2. *Plate tectonic setting of the Cascade volcanic arc, United States and Canada. Plate boundaries (heavy solid lines), faults (heavy dashed lines), seafloor magnetic anomalies (dotted lines), and ages of oceanic crust (in Ma) from Atwater and Severinghaus (1989). Depth of Wadati-Benioff zone in km (thin solid lines), volcanic front (dot-dashed lines), and segments of volcanic arc (indicated by numbers in circles) from Guffanti and Weaver (1988). Convergence rate of Juan de Fuca and North American plates from DeMets et al. (1990).*

(Hasegawa *et al.,* 1994; Zhao *et al.*, 1994). The subduction zone under the Cascade arc dips at 11° to a depth of 40 km under Puget Sound (Weaver and Baker, 1988) and then steepens to ≈25°. At depths greater than ≈75 km, however, teleseismic P-delays suggest that the dip of the plate increases strikingly. The plate dips ≈45° under the Cascades of central and northern Washington and dips 60–70" under the Cascades of southern Washington and Oregon (Weaver and Michaelson, 1985; Michaelson and Weaver, 1986; Rasmussen and Humphreys, 1988; Harris *et al.,* 1991). In Oregon, Weaver and Michaelson (1985) propose that the slab under the Cascades is broken off from the shallower near-surface slab to the west that dips only 13°–16° (Trehu *et al.*, 1994).

- *Age of subducting lithosphere.* The oceanic crust being subducted under northern Honshu is some of the oldest crust of the Pacific Plate. 120–145 Ma depending on the position along the subduction zone (Figure 1). In contrast. the oceanic crust being subducted under the Cascade volcanic arc is very young, ranging from zero to 11 Ma, depending again on the position along the subduction zone (Figure 2). The differing ages of subducted crust of the two subduction zones results in strikingly different temperatures in the crust by the time that it reaches the subduction zone, since a plate cools with time as it moves away from the spreading center at which it is created (see review in Severinghaus and Atwater, 1990). Furthermore, cooling of a plate causes the plate to thicken, with the net result that the thickness of a plate increases at a rate proportional to the square root of its age. The old oceanic crust subducting under the Tohoku volcanic arc is thus relatively cool and thick, whereas the young oceanic crust subducting under the Cascade volcanic arc is relatively hot and thin.
- *Rate of subduction:* The Pacific plate subducts under northern Honshu at approximately 100 mm yr^{-1} (Shimizu and Itaya, 1993). The Juan de Fuca plate, however, subducts under the North American plate at 45 mm yr^{-1} (DeMets *et al.,* 1990). Verplanck and Duncan (1987) estimate that the convergence rate along the Cascadia subduction zone has decreased systematically from 165 mm yr^{-1} at 70 Ma to 34 mm yr^{-1} during the past 10 m.y.
- *Maximum depth of seismicity.* The Wadati-Benioff zone under northern Honshu can be traced by earthquake locations in the subducting slab to more than 600 km deep and as far as 1200 km from the trench axis (Aramaki and Ui, 1982; Hasegawa *et al.*, 1994; Zhao *et al.,* 1994). Even if two very deep epicenters are not used (as argued by Jarrard, 1986), the maximum depth of the zone is still nearly 400 km. The Wadati-Benioff zone under the Cascade arc, however, can be traced by earthquake locations only to ≈80 km deep and only to ≈300 km from the trench (Walter, 1986; Weaver and Baker. 1988; Dragert *et al.,* 1994). These contrasting maximum depths of seismicity are compatible with the prediction that the time required for a slab to warm up to a temperature above which it is aseismic is approximately 0.1 of its age upon subduction (Severinghaus and Atwater, 1990). This prediction derives from the observation that a lithospheric plate moving away from a spreading center cools proportionally to the square root of its thickness, whereas upon subduction, the plate warms up as the square of its thickness upon subduction (Severinghaus and Atwater, 1990). Seismicity within a hot, thin, and weak plate will therefore extend to a much shallower depth and shorter distance from the subduction zone than seismicity within an old, cool, thick, and strong plate.
- *Stress regime.* Jarrard (1986) ranked subduction zones in terms of their positions along a continuum from strongly extensional (Class 1) to strongly compressional (Class 7). He assigns the Cascade arc to Class 4a (neutral) or Class 3 (mildly extensional, with normal faulting but no substantial crustal thinning). In contrast, he assigns the Tohoku arc to Class 6 (moderately compressional, exhibiting consistent folding and/or reverse faulting). The Tohoku arc has been in compression for the past 3.5 Ma (Sato, 1994), perhaps due to acceleration of Pacific-plate motion at ≈5 Ma (Pollitz, 1986).

Prior to 3.5 Ma, the arc was either neutral (13–3.5 Ma) or in extension (25–13 Ma), with the extensional regime at 25–13 Ma related to the opening of the Japan Sea (Sato, 1994).

- *Angle between convergence and subduction zone.* Subduction of the Pacific plate under northern Honshu is nearly normal to the trench (Shimizu and Itaya, 1993; DeMets, 1992b). On the other hand, motion of the plates subducting under the Cascade arc is significantly oblique, particularly in the Oregon and California parts of the arc (Muffler *et al.*, 1982; Rogers, 1985; Wells and Heller, 1988). This oblique convergence results in a somewhat extensional tectonic regime in Oregon, compared to a slightly compressional regime in Washington and British Columbia. Both Muffler *et al.* (1982) and Rogers (1985) correlate this change in crustal stress with the lesser abundance of volcanism in Washington and British Columbia. Muffler *etal.* (1982) note that in the central and southern Cascade Range, Quaternary volcanism produced mostly basalt and mafic andesite; large andesite-dacite composite volcanoes and silicic domes occur in restricted areas of long-lived activity. Volcanic activity to the north, however, produced widely spaced centers in which mafic lavas are minor. The volcanic chain is also broader in Oregon and California than it is in Washington and British Columbia.
- *Segmentation ojthe subducting slab.* Segmentation of the slab subducting under Cascade volcanic arc is suggested by along-strike differences in the dip of the plate (Weaver and Michaelson, 1985), and the segments thus defined have been correlated by Guffanti and Weaver (1988) with segmentation in the pattern of 2821 volcanic vents less than 5 Ma shown on the maps of Luedke and Smith (1981, 1982). The conspicuous segmentation of the Cascade volcanic arc may be related to the fragmentation of the weak Vancouver plate as it breaks up into the Gorda, Juan de Fuca, Explorer, and even smaller platelets. Such obvious segmentation is not apparent in the Pacific Plate beneath the Tohoku volcanic arc, although Acharya (1984) attempted to correlate hot springs, geothermal fields, and volcanoes with the discontinuities between rupture zones of great earthquakes (Seno, 1979).

Furukawa (1993) has recently summarized the mode of subduction and the resulting thermal structure under volcanic arcs, with particular reference to the Tohoku arc. At depths less than 70 km under northern Honshu, subduction proceeds as thrust movements at the boundary between the subducting plate and the rigid, overlying North American plate. At depths greater than 70 km there is no longer brittle failure at the upper surface of the slab, and the subducting plate interacts with the overlying mantle in a manner such that flow is induced in the mantle wedge (Figure 3). Under the volcanic zone, temperature structure in the upper plate is controlled by this induced flow and is insensitive to the values of the subduction parameters (Furukawa, 1993). Isotherms within the mantle wedge under the volcanic front are elevated. Water and other volatiles rising from the subducting slab, particularly as a result of the basalt-eclogite transition at 2 GPa pressure (Furukawa, 1993), induce melting in the mantle wedge. Magmas thus formed rise to form the volcanic chain.

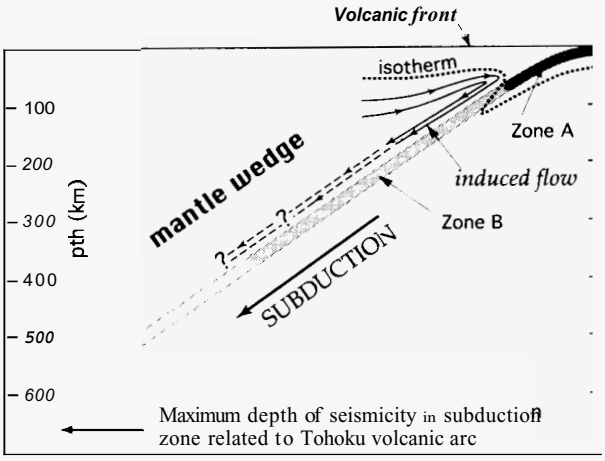

FIGURE 3. *Generalized thermal structure and flow in the mantle wedge above a schematic subduction zone. Upper right corner (<170 km depth) adapted from Figure 7 of Furukawa (1993). Solid flow lines are taken directly from Furukawa (1993); dashed flow lines at depths >170 km are extrapolated by us. Zone A: region of thrust movements at the boundary between the subducting plate and the rigid, overlying plate. This zone is termed "uncoupled" by Furukawa (1993) but corresponds to the seismically coupled zone of Ruff and Kanamori (1980; 1983). Zone B: region in which the subducting plate interacts with the mantle of the overlying plate in a manner such that flow is induced in the mantle wedge. Dashed region of zone B indicates depths >400 km at which existence of a slab in the region of the Sea of Japan is considered equivocal by Jarrard (1986).*

3. VOLCANISM

3.1 Tohoku arc

Northern Honshu consists of an active orogenic belt composed of Paleozoic and Mesozoic rocks on the Pacific side (Finn *et al.,* 1994) and a volcanic arc on the Japan Sea side (Aramaki and Ui, 1982). The boundary line between the two regions is a zone of steep gravity gradient. Most of the Quaternary volcanic rocks are distributed along the axial range, termed the Sekiryo; the rest are further to the west, facing the Japan Sea. Uplift of the axial range is ongoing, with active faults and earthquakes.

The eastern margin of the row of major volcanoes lies along the axial range and is parallel to the Japan trench. In northeast Honshu, 27 major volcanic edifices lie along the volcanic front, separated by gaps of 6 to 40 km, except for five larger gaps of 60–80 km (Aramaki and Ui, 1982). The map of Ono *et al.* (1981) shows that Quaternary volcanoes on the volcanic front occur in clusters 50–100 km apart, suggesting that the arc might comprise eight segments. Eruption centers of large Quaternary felsic pyroclastic-flow deposits as well as calderas, are restricted to the axial range. At least 25 of the volcanoes in the Tohoku volcanic arc have erupted in the ≈ 1,500 years of historic records, some many times (Simkin *et ul.,* 1981).

The Quaternary volcanic rocks in the Tohoku Volcanic Arc have been divided into four volcanic zones (Yoshida, 1989). East to west, from the trench to the back-arc side, these are:

- Aoso-Osore: low-K calcalkaline rocks with subordinate low-K tholeiites,
- Sekiryo (the axial range): medium-K calcalkaline rocks, associated with and often following low-K tholeiites,
- Moriyoshi: medium-K calcalkaline rocks with subordinate medium-K tholeiites,
- Chokai: medium-K calcalkaline rocks and high-AI basalts on the eastern side, and high-K calcalkaline rocks and alkali basalts on the western side.

The position of the volcanic front in the Tohoku volcanic arc has shifted strikingly with time (Ohguchi *et al.*, 1989). During the past 12 Ma, the volcanic front has been almost the same as the present one. However, the volcanic front at **16–14** Ma and at 20 Ma was ≈90 km and ≈200 km further east from the present front, whereas the volcanic front at 30 Ma was ≈30 km further west.

Aramaki and Ui (1982) estimated a rate of 2.2 km^3 per km of arc length per million years for volcanic eruption in the Tohoku volcanic arc. Kagiyama (1986), using essentially the same data base, confirmed this figure, which appears to apply only to the volcanic rocks of the axial range (Sekiryo) and thus must be a minimum value.

3.2 Cascade arc

The Cascade volcanic arc consists of two physiographic and geologic provinces (Peck *et al.*, 1964; Duncan and Kulm, 1989): the 42–10 Ma Western Cascades, and the 10–0 Ma High Cascades. East of the High Cascades are two large, essentially bimodal, basalt-rhyolite volcanoes: Newberry Volcano in Oregon (MacLeod and Sherrod, 1988), and Medicine Lake volcano in northern California (Donnelly-Nolan, 1988). According to Verplanck and Duncan (1987), the rate of accumulation of volcanic rocks (expressed in meters of thickness per m.y.) in the central Oregon Cascades decreased from 290 m $m.y.^{-1}$ at 30–20 Ma to 190 m $m.y.^{-1}$ at 20–10 Ma to 70 m $m.y.^{-1}$ during the past 10 m.y. of the High Cascades. The width of the volcanic zone has also decreased greatly with time to the present width of ≈75 km for the High Cascades (Blakely and Jachens, 1990).

Major composite volcanoes that have erupted andesites, dacites, and even rhyolites occur at intervals of approximately 100 km along the Cascade Range. In addition, there are many smaller,

commonly monogenetic vents that erupted primarily calcalkaline basalt and basaltic andesite throughout the history of the arc. The volcanic arc is active, with documented historic eruptions at Lassen Peak, Mount St. Helens and probable eruptions within the last several hundred years at Mount Shasta, Mount Baker, Mount Hood, Mount Rainier and Cinder Cone. As noted above, segmentation of the modern Cascade arc is clearly demonstrated by both the distribution of volcanic vents and seismicity (Guffanti and Weaver, 1988), and this segmentation correlates with convective and conductive heat discharge (Guffanti *et al.*, 1990) and to some degree with differential rotation of tectonic regions of the overlying plate as determined from paleomagnetism (Magill *et al.*, 1982; Wells, 1990, 1994). The influence of upper-plate structures on Cascade magmatism is emphasized by Blakely and Jachens (1990) and by Trehu *et al.* (1994). The latter suggest that variations in magmatic character along the Cascade arc may be influenced by the four-fold variation in thickness of a prominent Paleocene and early Eocene accreted oceanic terrane along the strike of the arc.

Sherrod and Smith (1990) systematically estimated extrusion rates for the past 2 Ma along the Cascade Range. The extrusion rate north of Mount Rainier is ≈0.21 km^3 per km of arc length per million years ($km^3\ km^{-1}\ m.y.^{-1}$), the rate in southern Washington and northern Oregon is ≈1.6 $km^3\ km^{-1}\ m.y.^{-1}$, the rate in central Oregon is 3–6 $km^3\ km^{-1}\ m.y.^{-1}$, and the rate in northern California is 3.2 $km^3\ km^{-1}\ m.y.^{-1}$. Superficially, these rates seem to bracket the rate of 2.2 $km^3\ km^{-1}\ m.y.^{-1}$ estimated by Aramaki and Ui (1982) for volcanic eruption in the Tohoku volcanic arc. Such a simple volumetric comparison, however, is probably of little geothermal significance without consideration of the composition of the volcanic rock. For example, the high extrusion rates for Oregon and northern California are determined in great part by the large volumes of basaltic andesites in Oregon and the Lassen region of California (See Figure 3 of Sherrod and Smith, 1990). Since mafic volcanic vents support few, if any, geothermal systems (Smith and Shaw, 1975), these large volumes of basalt or basaltic andesite have little geothermal relevance (Guffanti and Muffler, 1995). In contrast, intermediate and silicic volcanic rocks undoubtedly result from complex crustal process of fractional crystallization, partial melting, and assimilation that produce a whole suite of intrusive rocks not represented at the surface (e.g., Guffanti *et al.*, 1995) that could have great importance as geothermal heat sources. Any meaningful comparison between the Tohoku and Cascade volcanic arcs therefore must take into account the relative abundances of mafic, intermediate and silicic volcanic rocks. This task is being addressed in our ongoing comparison of the two arcs.

4. THERMAL CHARACTERISTICS

4.1. Tohoku arc

Honda (1985) reported that heat flow from the trench to the east coast of Honshu is about 20-50 $mW\ m^{-2}$ and that of Japan Sea is about 92 $mW\ m^{-2}$. Between the two regions, along the volcanic front, is a narrow peak in heat flow, with values >120 $mW\ m^{-2}$.

Nagao and Uyeda (1989) detailed the transition between the low and high heat-flow zones in northern Honshu. They showed that the heat-flow increases steeply from the east coast of Honshu (20–40 $mW\ m^{-2}$) to the volcanic front (120–130 $mW\ m^{-2}$). If the heat transfer in the crust is purely conductive. the temperatures beneath the east coast of Honshu and the volcanic front at a depth of 30 km will be about 100°Cand 1000°C, respectively.

Sumi (1980) estimated the convective heat flux from hot springs in the zone of Neogene volcanism (Av-1) of the Tohoku arc and the volcanic arc of eastern Hokkaido to be 1513 MW_t. From the map data given by Sumi (1980), we calculate that the heat flux from hot springs in eastern Hokkaido is only 28 MW_t, leaving 1485 MW_t attributable to the Tohoku volcanic arc. This value is a minimum because it includes neither "natural steaming" nor thermal water discharging directly into streams and rivers.

4.2 Cascade arc

Blackwell *et al.* (1990a) reviewed the heat flow data related to the Cascadia subduction zone in Oregon, concluding that the average heat flow is about 100 $mW\ m^{-2}$ in the High Cascade Range and at the eastern edge of the Western Cascade Range in Oregon, compared to 40–50 $mW\ m^{-2}$ to the west in the outer arc block of the subduction zone. Blackwell *et al.* (1990b) report that the heat flow in the Cascade Range of southern Washington averages 75 $mW\ m^{-2}$, compared to 40 $mW\ m^{-2}$ in the coastal provinces and the western part of the Cascade Range. Heat flow in the back-arc areas of the Okanogan Highland and Columbia Basin averages 75 $mW\ m^{-2}$ and 62 $mW\ m^{-2}$, respectively. Lewis *et al.* (1985, 1988) present similar data for southwestern British Columbia. Blackwell *et al.* (1990b) interpret the Cascade heat-flow data to indicate midcrustal temperatures of 400"–800°C. They conclude that the source of these high temperatures is a long-lived, midcrustal zone of magma residence at 10±2 km depth.

Ingebritsen *et al.* (1989; 1994) proposed an alternative, lateral-flow model to explain near-surface heat-flow observations in the central Oregon Cascade Range. Instead of an extensive midcrustal magmatic heat source, they proposed that high heat flow in the older rocks may be a relatively shallow phenomenon caused by regional ground-water flow. Any deeper anomaly may be relatively narrow, spatially variable, and essentially confined to the Quaternary arc. Magmatic intrusion at a rate of 9–33 km^3 per kilometer of arc length per million years can account for the total heat-flow anomaly (Ingebritsen *et al.*, 1989).

Mariner *et al.* (1990), using a chloride-inventory method that detects both thermal water discharged in springs and thermal water discharged into streams, estimated that the total discharge of thermal springs in the Cascade Range of California, Oregon, and Washington was 340 L s^{-1}, corresponding to =82 MW_t of heat. This value is approximately **5%** of that estimated above from Sumi (1980) for the minimum discharge of hot springs of the Tohoku volcanic arc. This difference in hydrothermal discharge between the two arcs also correlates qualitatively with the far greater number of thermal springs in the Tohoku arc (compare Sumi, 1975, with Figure 1a of Mariner *et al.*, 1990).

5. TENTATIVE COMPARISONS AND SPECULATIONS

When we began the comparison of the Cascade and Tohoku volcanic arcs, we naively assumed that, after decades of study in both Japan and the United States, the basic volcanic and geothermal data sets were well known and could be compared easily. Preparation of this paper, however, has shown this not to be the case. In neither arc is the compilation of the data on volume *vs.* composition of volcanic rocks sufficient to allow a comparison that takes fully into account the geothermal significance of rock composition and intrusive equivalents. Even the data on discharge of thermal waters and contained heat are not directly comparable, in that the Tohoku data deal only with hot springs, whereas the Cascade data include **all** fluids discharged in thermal features and directly into streams and rivers.

Despite the shortcomings of the volcanic data for both arcs, the Tohoku arc appears to have both a greater volcanic vigor, as expressed by the number of Holocene volcanoes, the frequency of known eruptions, and the number of large explosive eruptions (VE≥3) in the last 100 yr, all normalized by arc length (Simkin and Siebert, 1984). Furthermore, although data yet compiled do not allow a definitive comparison, the Tohoku arc appears to have a greater percentage of andesites and dacites, contrasting with the large volumes of basaltic andesite that characterize the bulk of the Cascade Range in Oregon and northern California. Following the reasoning of Guffanti *et al.* (1995), this suggests that intrusive rocks beneath the Tohoku volcanic arc are significantly more abundant than under the Cascade volcanic arc. This situation is compatible with the much greater convective thermal flux of the Tohoku volcanic arc, and both presumably reflect greater influx of magma from the mantle wedge.

Greater igneous activity of the Tohoku arc might at first seem incompatible with the fact that the slab subducting beneath the Tohoku arc is much cooler than the slab subducting beneath the Cascade arc. Further consideration, however, focuses attention upon **(a)** the rate at which water is being subducted, and (b) convection in the mantle wedge and its influence on magma generation.

The model of Tatsumi (1989) suggests that hydrous materials in subducted lithosphere are decomposed in the forearc region, with the resultant fluids reacting with the overlying mantle wedge to produce hydrated peridotite. Continued interaction of the mantle wedge with the subducting plate (Furukawa, 1993) drags the hydrated peridotite dragged downward along the subduction zone until amphibole and chlorite in the hydrated peridotite break down at –3.5 GPa, releasing water that causes partial melting of mantle-wedge peridotite beneath the volcanic front.

Under the model of Tatsumi (1989), the amount of melting in the mantle wedge is in general a function of the amount of hydrated

peridotite available to be partially melted. This in turn is a function of the amount of water available in the subducting plate per unit time. The much greater age of the Pacific plate compared to the Juan de Fuca plate allows much more time for hydration to take place and thus a greater fraction of water in the subducted slab. The greater thickness of the Pacific Plate, if it is hydrated throughout, may also contributed to a greater amount of subducted water. Even more importantly, the subduction rate beneath the Tohoku arc is over twice as fast as that beneath the Cascade arc, thus effectively doubling the rate of volatile input. All of these factors tend towards a greater amount of water per unit time being available for hydrating mantle peridotite in the Tohoku region than in the Cascade region.

In addition, mechanical considerations may favor magma generation in the Tohoku arc compared to the Cascade arc. The Pacific plate being subducted in the Tohoku region is cool, thick, and unfragmented, thus extending to much greater depth than under the Cascade arc and interacting with the mantle wedge for a much greater length. Following the model of interaction between a subducting plate and a mantle wedge (e.g., Furukawa, 1993), this greater interaction down-dip along the subduction zone promotes increased convection in the mantle wedge and consequent increased generation and supply of magma under the Tohoku volcanic arc. In contrast, the thin, hot, weak, and fragmented slab under the Cascade arc interacts with the mantle wedge only for a relatively short distance along the subduction zone before it becomes disrupted and incoherent, resulting in less vigorous convection in the mantle wedge and consequently less vigorous generation and supply of magma to the volcanic arc.

This preliminary contribution has focused on the tectonic setting, the gross nature of the two volcanic chains, and the thermal (both conductive and convective) regimes. Ongoing cooperation between the Geological Survey of Japan and the U.S. Geological Survey seeks to refine these factors and to compare the major geological and geophysical data sets, including volcanic vents. gravity data, magnetic data, Curie Point isotherms, electromagnetic signatures, and seismicity on 1:2,000,000 maps. Preliminary versions of many of these maps will be displayed at the 1995 World Geothermal Congress in Florence.

6. ACKNOWLEDGMENTS

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