Journal of Volcanology and Geothermal Research 179 (2009) 149–156

Contents lists available at ScienceDirect

Journal of Volcanology and Geothermal Research

journal homepage: www.elsevier.com/locate/jvolgeores

The Cascadia megathrust earthquake of 1700 may have rejuvenated an isolated basalt volcano in western Canada: Age and petrographic evidence

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ARTICLE INFO

Article history:
Received 7 May 2008
Accepted 22 October 2008
Available online 5 November 2008

Keywords:
CSDs
crystal size distribution
textures
Cascadia earthquake
coarsening
British Columbia
Canada

ABSTRACT

The basaltic Tseax flow is the product of one of only two eruptions in western Canada during the last thousand years. Reinterpretations of ^{14}C and paleomagnetic data indicate that Tseax volcano last erupted between 1668 and 1714 CE. This date straddles that of the Cascadia megathrust earthquake of 26 January 1700, whose rupture lay 450 km to the south. Hence, the largest recent earthquake in northwest North America may have rejuvenated an existing magmatic system and produced this isolated flow. Although the flow is chemically uniform there are significant textural differences between the early and late parts of the flow. It is proposed that both magmatic components were contained within a steep conduit. Gas produced by degassing of magma in the lower part of the conduit ascended, heated magma in the upper part, coarsening plagioclase, and then continued to the surface along fissures. This stable configuration was disrupted by the Cascadia earthquake: dilatation widened the conduit and enabled both magmas to rise to the surface along existing fissures.

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1. Introduction

The west coast of Canada has live volcanoes, but for the most part they have long repose times. One of the most recent and important eruptions was the Tseax volcano (pronounced see-ax). Although there are no written records, the oral traditions of the Nisga'a people tell how the scoria-cone eruption destroyed two villages and killed several thousand people, making it Canada's most deadly natural disaster (Hickson et al., 2007). Such scoria-cone eruptions have only recently been recognised as a significant hazard on a local scale (Ort et al., 2008).

Another disaster also occurred at about the same time: the Cascadia megathrust earthquake of 26 January 1700 CE. Again there are no written records, but the oral traditions of first peoples ('Indians') indicate major effects both of the earthquake and the tsunami on coastal villages (Ludwin et al., 2005). It is clearly established that large earthquakes can trigger explosive and effusive volcanic eruptions at remote locations (see review of Manga and Brodsky, 2006). Hence, it is tempting to try to link these two events. Here I will show that the last eruption of the Tseax volcano occurred between 1668 and 1714 and hence may have been triggered by the Cascadia earthquake of 1700 that ruptured 450 km to the south (Fig. 1). Petrographic textures of the volcanic products help reveal a possible trigger mechanism.

2. The Tseax volcano

The Tseax volcano (also known as the Aiyansh volcano) is situated near New Aiyansh, about 60 km north of Terrace, in central British Columbia, Canada (Fig. 1) (Sutherland Brown, 1969). The volcano is the southernmost unit of the Northern Cordillera volcanic province, which continues northwards to eastern Alaska (Edwards and Russell, 2000). Only two volcanic centres are known to have been active in British Columbia during the last 1000 years, Tseax and Lava Fork, 150 km to the northeast. Lava Fork volcano will not be considered further as the eruption age is very poorly determined.

The Tseax lava flow debouches from the base of a complex ash cone with an overall diameter of 460 m (Fig. 2). Radiocarbon dates (see below) suggest that the outer part of the cone may be part of an earlier eruption during the 14th century (all dates are Common Era, CE, unless otherwise mentioned). In that case the inner parts of the cone and flow are a rejuvenation of the volcano. The flow is 32 km long with a volume of 0.5 km^3 (Fig. 2). The flow has lava tubes (Marshall, 1975), hence it is assumed that most of the proximal part of the flow was produced during the early part of the eruption, and the distal part is the last erupted magma.

Petrographic variations are readily visible in the field: the proximal part of the flow has abundant plagioclase tablets up to 1.5 mm long and olivine is present as much smaller equant crystals. Plagioclase megacrysts up to 20 mm long are present but uncommon — perhaps one per square metre of solid lava. This rock is termed 'coarse facies' in this paper. The distal part of the flow appears almost aphyric, with plagioclase tablets less than 0.5 mm long. This is termed the 'fine facies'.

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doi:10.1016/j.jvolgeores.2008.10.016

3. The age of last eruption

The first non-native expedition to visit this area was that of Juan Francisco de la Bodega y Quadra, a Peruvian sailing for the Spanish crown. His ship, the Sonora, arrived in Bucareli Bay in 1775. The pilot and chaplain observed light in the distance which they attributed to a volcano (de la Sierra, 1930). Their anchorage was about 240 km from the Tseax volcano, which is much too far from the eruption for it to have been visible. It is more likely that what they saw was a large forest fire. Captain James Cook arrived in the region in 1778 and made the first magnetic measurements (see below). He was followed by a number of expeditions, including that of George Vancouver who penetrated much closer to the Nass River.

The earliest published account is by the missionary Collinson (1900). He records how he heard the story of the eruption from an old man born in about 1795, who related that it happened when his grandfather was a boy. Collinson used this to estimate an eruption age of about 1770. However, chronometric data presented below suggest that this cannot be so and hence that the man who related the story was mistaken or, more likely, that the word ‘grandfather’ was incorrectly translated by Collinson. This problem has been encountered in similar situations elsewhere and much care must be taken with the interpretation of generations through oral history (Barber and Barber, 2004; Blong, 1982).

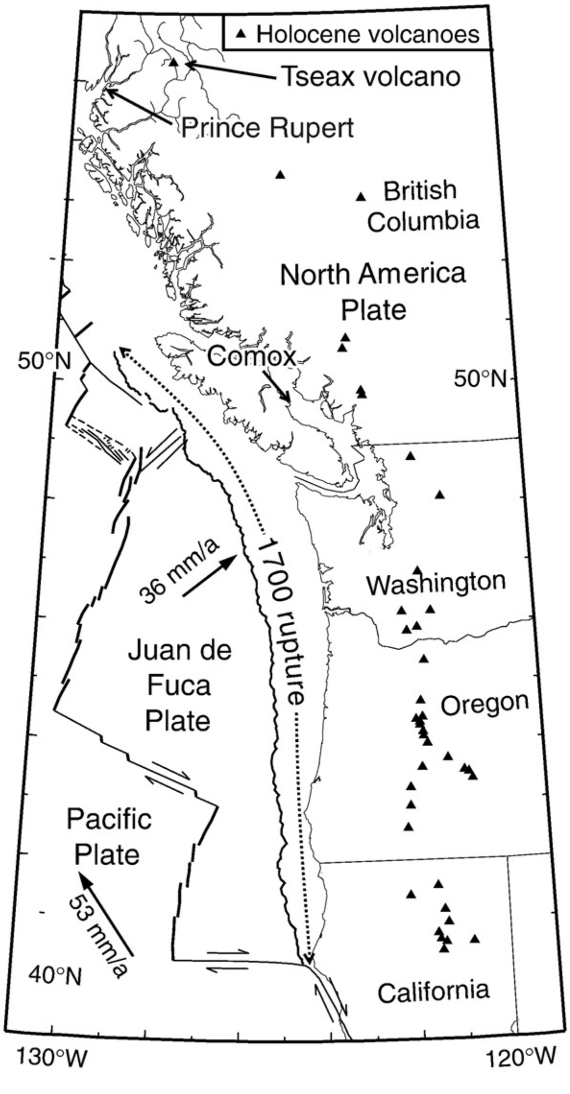

Fig. 1. Volcanoes and plate tectonics of the Pacific northwest of North America (after Wang et al., 2003).

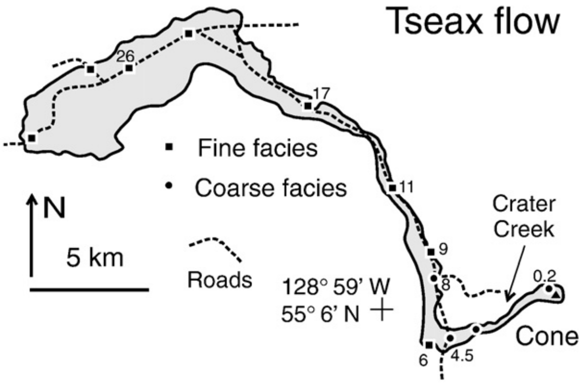

Fig. 2. The Tseax volcano, British Columbia, Canada (after Sutherland Brown, 1969).

In 1918 another missionary published more details of the eruption in the introduction to a poem (McCullagh, 1918). He related that trees were felled in 1898 at a site traditionally held to be where those displaced by the eruption had settled. The trunks showed evidence that bark had been stripped 128 years earlier, that is in 1770, and this was assumed by McCullagh to have been immediately after the eruption. In subsequent publications this age was cited as a dendrochonological age of the flow, despite the lack of a direct link (e.g. Sutherland Brown, 1969). In 1935 the anthropologist Marcel Barbeau published a popular, but more detailed account of the eruption (Barbeau, 1935). His conclusion again was that the eruption occurred in the late 18th century.

There have been several attempts to date the eruption using ^{14}C, but the method is not straightforward in material that is so young. Lowdon et al. (1971) analysed wood recovered from a cast in the lava and found an age of 220±130 BP. The large error makes this data not very useful. Roberts andMcCuaig (2001) analysed wood from another tree preserved in the flow. They estimated that the outer 50 annular rings had been destroyed by fire and erosion, hence that the analysed wood formed about 50 years before the eruption. The raw ^{14}C age of the wood was 280±50 BP. If this more precise ^{14}C age is calibrated using the CALIB program (Reimer et al., 2004; Stuiver and Reimer, 1993) and corrected to the eruption date by adding 50 years, then three time periods are possible for the eruption of the lava flow (1 sigma): 1567–1645, 1668–1714 and 1839–1841 (Fig. 3A). Historical and magnetic data (below) suggest that the first period is too old, and the last period is ruled out on historical grounds. Hence the best estimate of the age is 1668–1714 CE.

The cone has a double concentric structure and a tree trunk encased in ash from the outer part of the cone was dated at 625±70 BP (Wuorinen, 1978), which gives a calibrated age of 1292–1329 or 1346–1396 (1 sigma) using the program CALIB. This earlier eruption does not appear to have produced a lava flow, or if it did, the flow is now buried or eroded. Other pre- and interglacial basalt flows in the same area are mentioned but not described in the literature (van der Heyden et al., 2000), hence there is a longer history of recent magmatism in the region.

Another estimate of the age of the flow may come from magnetic measurements because secular variations are rapid in this area. Symons (1975) analysed many samples from the whole length of the flow and determined a remanence direction of +14.0° (declination), 72.9° (inclination) with an α_{95} of 0.8°. The steep inclination of the magnetic remanence means that the error in the declination is 3°. These data could give a more precise age than ^{14}C if the secular variation at this location can be established. In some regions the secular variation is well established from observations and archaeological materials, and a master curve has been defined (e.g. Lengyel and Eighmy, 2002) that can be used for dating (e.g. Ort, 2002). However, this is not the case for the Pacific Northwest and magnetic variations must be pieced together from different sources.

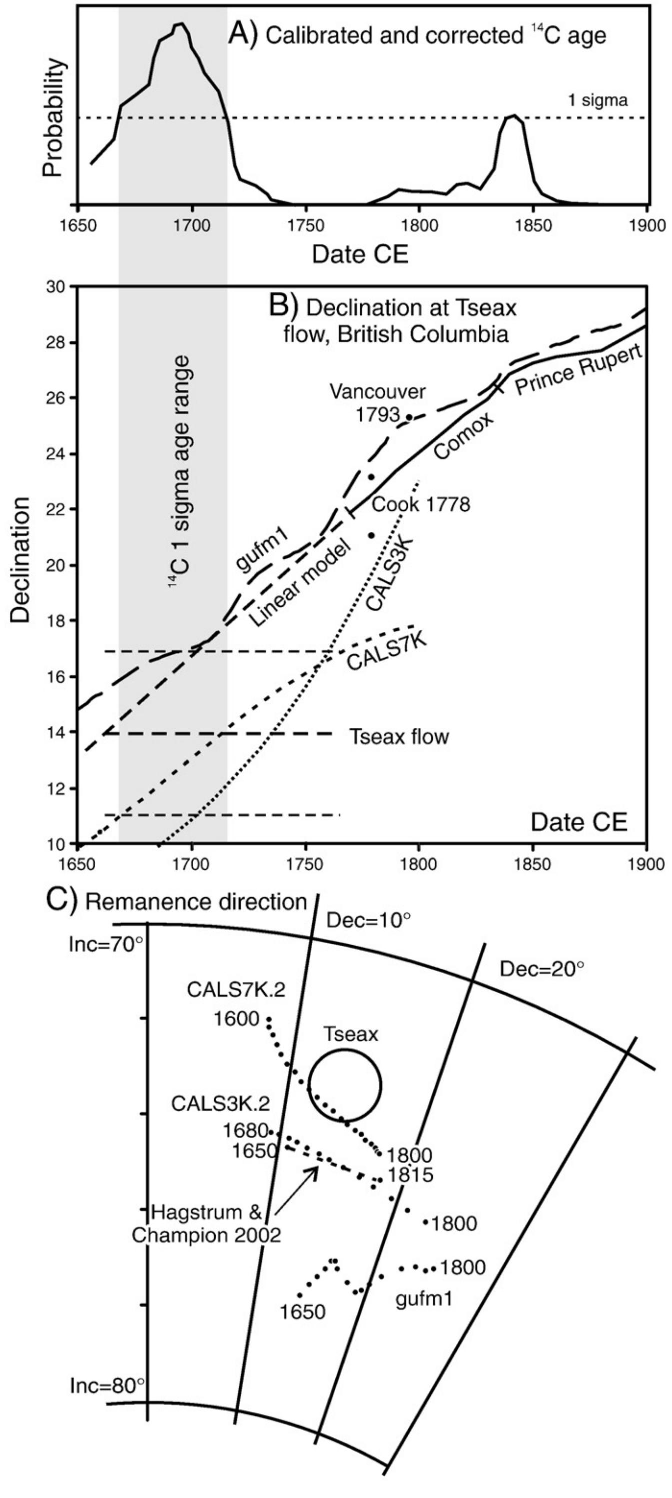

Fig. 3. A) Probability map for a ^{14}C age of 230±50 BP (Roberts and McCuaig, 2001), determined using the CALIB software (Reimer et al., 2004; Stuiver and Reimer, 1993). Data were shifted forward 50 years to give the age of the flow, following Roberts and McCuaig (2001). B) Magnetic declination variation for the position of the Tseax flow (data from Herbert, 1926; Jackson et al., 2000; Korte et al., 2005; Symons, 1975) and measured remanence data from the Tseax flow (Symons, 1975). C) Stereonet of declination and inclination variations at Tseax from the CAL7K.2 and CAL3K.2 models of Korte and Constable (2005), gufm1 model of Jackson et al. (2000) and two points from the dipole model of Hagstrum and Champion (2002).

Magnetic declination observations have been made at Prince Rupert since 1840 (Herbert, 1926) (Figs. 1, 3B). These data can be extended back to 1770 using data from Comox on Vancouver Island (Fig. 3B). Individual measurements from 1778 during the Cook expedition and from 1793 during the Vancouver expedition have also been added to Fig. 3B to confirm the validity of Herbert's compilation. Data were obtained from a large marine magnetic database (Jonkers et al., 2003). All data were adjusted to give the declination at Tseax volcano using the current difference in declination. There are no actual magnetic observations from the region before 1778 and other methods must be used to establish earlier secular variation. Symons (1975) used a linear extrapolation of secular variation with time to estimate that the declination was 14° at 1650±40 CE, which he considered to be the age of eruption. However, other approaches are also possible.

There are a number of global and local models of the geomagnetic field that can be applied to this problem. The global models have many non-dipole components hence the best way to examine the problem is using the directions of remanence (inclination and declination) at Tseax (Fig. 3C). Korte and Constable (2005) have developed two global models of secular variation: the 7000-year CALS7K model and the 3000-year CALS3K model. The CALS7K model gives a variation curve for Tseax that intersects the flow data from 1680 to 1720 (Fig. 3C); however, this model does not accord well with actual observations of declination (Fig. 3B). The CALS3K model does not intersect the Tseax data (Fig. 3C), but accords better with observed declination values than the CALS7K model (Fig. 3B). The global gufm1 model of Jackson et al. (2000) is based on 400 years of marine magnetic observations. Although it predicts declination variations that agree closely with observations (Fig. 3) it lies far from the Tseax data in Fig. 3C. Finally Hagstrum and Champion (2002) have constructed a dipole model for western North America using volcanic rocks, which closely follows data from sediments sampled at Fish Lake, Oregon. Inclinations again lie far from the Tseax data, and declinations are similar to those of the CALS3K.2 model, although slightly displaced in time.

In all these models predicted declinations are close to observed values, but inclinations are always overestimated. This probably reflects deficiencies in the database from which the models were derived. Hence, a better estimate of the age of eruption may be derived from the declination measurements alone. In 1780 the declination was estimated to be ~22° (Fig. 3B), which is outside the error limits for the Tseax flow. Hence the eruption cannot have been in 1780 as previously proposed by many authors. All models predict declinations that lie within the error limits of the Tseax flow for the age range indicated by the ^{14}C measurements (Fig. 3B). Hence, it is considered that the flow erupted sometime during the period 1668–1714.

4. Discussion of eruption age

The association between major earthquakes and volcanism is well established, both for explosive (Manga and Brodsky, 2006) and effusive eruptions (Gudmundsson and Saemundsson, 1980), hence it is useful to consider the recent seismicity of this region. The Cascadia earthquake of 9 pm 26 January 1700 was the largest earthquake in northwestern North America in recent times (Atwater et al., 2005; Satake et al., 1996). It was a megathrust event with a rupture parallel to the coast from northern California to northern Vancouver Island (Fig. 1). The probable rupture was identified from coastal subsidence (Jacoby et al., 1997) and the timing from observation of the tsunami in Japan (Satake et al., 1996). Although there are no written records of the earthquake, first nation peoples have stories of shaking and environmental destruction at this time, some from as close as the northern tip of Vancouver Island (Ludwin et al., 2005). The Cascadia earthquake must have caused considerable shaking at Aiyansh, the nearest community to the Tseax volcano.

Scoria-cone eruptions can also be accompanied by earthquakes. The only recent such eruption, Paracutin volcano in 1943, was preceded by earthquakes with a magnitude of up to 4.5 (Yokoyama and de la Cruz-Reyna, 1990). Such earthquakes would have certainly been felt at Aiyansh, 20 km to the north of the cone. Barbeau was told that 'the [Tseax] eruption started with trembling of the ground, followed by smoke and fire' (Barbeau, 1935). If the Cascadia earthquake and the Tseax eruption were distant in time then ideally there would be an oral tradition for two separate shaking events. It is of course possible that the two shaking events could have been conflated, and hence this absence of oral historical evidence should not be given undue weight.

The age range of the main Tseax eruption straddles the date of the Cascadia earthquake; hence it is possible that the earthquake triggered the eruption. The Tseax volcano is one of only two eruptions in central and southern British Columbia in the last 1000 years and hence could be associated with the most significant seismic event during that period.

The link between megathrust earthquakes and volcanic eruptions has been recently explored by Walter and Amelung (2007). They examined the links between four recent megathrust earthquakes and volcanic eruptions. They classified the volcanoes according to their previous activity and calculated the changes in stress following each earthquake. They found that the eruptions temporally associated with the earthquakes occurred in the region of volumetric expansion and that rarely erupting volcanoes are more susceptible to such 'extrinsic triggering'. It might be assumed that the Tseax volcano is too far from the rupture of the Cascadia earthquake to have been affected. However, a recent compilation of data indicates that such a distance would not be unusual for a triggered eruption (Sumita and Manga, 2008).

It is also possible that the Cascadia earthquake also triggered other eruptions, especially in the USA. Indeed, Hill et al. (2002) suggested that a peak in eruption frequency of the American Cascade volcanoes around 1850 may have been a result of stress changes produced by the Cascadia earthquake. However, eruptions closer in time to the Cascadia event may not be well dated as the lack of written records for the period also hampers research in Oregon and Washington. In addition, the work of Walter and Amelung (2007) suggests that frequently erupting volcanoes may be less susceptible to triggering by earthquakes.

If the Cascadia earthquake did trigger the Tseax eruption then what was the trigger mechanism? Many mechanisms have been proposed (Manga and Brodsky, 2006; Walter and Amelung, 2007), but a useful approach may be to see what the geochemistry and petrology of the eruptive products can tell us.

5. The petrology of the Tseax lava flow

In 1980 the Tseax lava flow was sampled from previously blasted cuts along public roads, supplemented by samples from outcrops in Crater Creek (Fig. 2). No samples were taken from undisturbed parts of the flow in the Nass valley, out of respect for the people who died during the eruption and were buried by the flow. Samples were selected from the most rapidly cooled parts of the flow, to ensure that the groundmass was as fine as possible. This enables automatic methods to be used for textural measurements (see below). Samples were crushed coarsely and dried at 105C for chemical analysis.

6. Geochemistry

The chemical composition of the flow is not unusual: it is an alkali basalt with SiO_2=45.8% (Sutherland Brown, 1969). Trace element abundances are generally a more sensitive way of examining compositional variations within flows, hence twenty samples were analysed using neutron activation (Bedard and Barnes, 2002). Comparison with in-house standards showed that analytical precision was about ±2% for Na, Fe, Sc, Th and REE.

All analysed elements showed a variation of about 10% and all were strongly positively correlated. Such a situation can be produced by analytical error, such as errors in weighting or sample placement with respect to the detector. Repeat analysis of in-house standards indicates that this probably only accounts for 3% of the observed variation. Another possibility is that a phase was present in variable quantities that did not contain any of the analysed elements. Such a phase cannot be any of the minerals present in the lava – plagioclase, olivine or iron oxides – as they all have Na or Fe. A more likely phase is water: The samples had a glassy matrix which may have become altered, adding further variation to the analytical error. Hence, there is no evidence for chemical heterogeneity with the lava flow.

7. Quantitative petrography

Plagioclase crystals were imaged in polished thin sections using cathodoluminescence (Fig. 4). The images were thresholded and edited by hand to separate touching crystals. The smallest crystal that could be consistently measured was 0.05 mm long. The binary image was analysed using the program 'ImageJ', a Java version of the popular program NIHImage. Crystal shapes were estimated from intersection aspect ratios and specially oriented crystals (Higgins, 2006). An aspect ratio of 1:5:5 was used to convert intersection lengths to crystal size distributions (CSD) using the program CSDCorrections (Higgins, 2000). Fig. 5A shows the results displayed on a population density versus size diagram. It is easier to understand CSD dynamics if the characteristic lengths (L_C=−1/slope) are considered rather than the slopes, as they have the units of length (Fig. 5B). For crystals that have a perfect semi-logarithmic size distribution, the characteristic length is equal to the mean size.

The two petrographic facies distinguished in the field have clearly different CSDs (Fig. 5). Samples from the coarse facies are fairly uniform with 10–15% plagioclase crystals up to 1.5 mm long. The porphyritic texture is expressed as strongly curved, concave-up CSDs. It is difficult to paramatize curved CSDs. Here the CSD is considered as the sum of two straight CSDs, as was done by Higgins (1996), but without the implication that the texture was produced necessarily by mixing. L_C is about from 0.3 mm for the population of larger crystals and 0.06–0.09 mm for the population of smaller crystals (Fig. 5). Fine facies samples have overall plagioclase contents of 20–26% with almost straight CSDs (Fig. 5). Maximum crystal size is 0.5 mm and L_C=0.043–0.067 mm.

8. Discussion of petrography

The fine facies samples will be considered first as they have simpler CSDs. The straight CSDs conform to the model of Marsh (1988) and can be interpreted in terms of a steady state crystallisation model. The residence time in the magma chamber can be estimated if the growth rate can be established. However, the growth rate is always the most difficult parameter to determine, as it is dependent on the cooling rate and other factors. A 100 times increase in cooling rate will only produce a 10 times increase in growth rate (Cashman, 1993). A value of 10^{-10} mm s^{-1} was chosen for plagioclase in similar basaltic rocks from Eldfell volcano, Iceland (Higgins and Roberge, 2007). Application of this growth rate here gives a residence time of about 14–21 years. This indicates that plagioclase crystals in the fine facies grew in a crustal chamber, with negligible overgrowth during the eruption.

Lavas produced during the effusive phase of the Eldfell eruption have plagioclase CSDs that strongly resemble those of the fine facies at Tseax (Higgins and Roberge, 2007). Earthquakes recorded during the 1973 Eldfell eruption suggest that the magma originated at a depth of 10–25 km in the crust. Although the geological context of Eldfell and Tseax volcanoes is very different these data suggest that Tseax fine facies magma originated in the mid-levels of the crust.

Curved CSDs, as seen in the coarse facies, can be produced by many more processes than straight CSDs (Higgins, 2006). Higgins (1996)

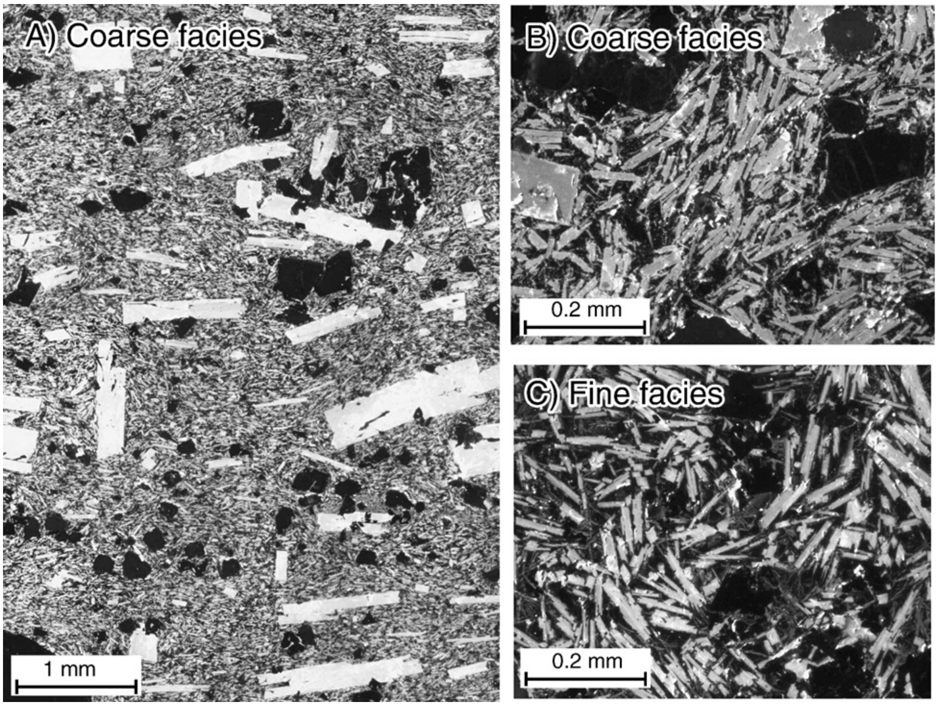

Fig. 4. Cathodoluminescent images of basalt from the Tseax flow. Plagioclase is bright and all other minerals are dark. A) Sample of the coarse facies, showing the plagioclase phenocrysts. B) Matrix of the same sample. C) Fine facies sample at the same scale as (B).

proposed that mixing of two magmas with straight CSDs can produce a concave-up CSD. This model can also be applied to a rock formed by two consecutive processes that each alone would yield CSDs with straight segments. In either case the origins of the larger and small crystal populations can be separated.

The larger crystal population must have been formed earlier than the small crystal population and hence represent the first phase of magmatic development. If the same magma that produced the fine facies was emplaced higher in the crust than the fine facies magma, we would expect it to have been more undercooled, all other factors being equal. In this case the intercept would be higher and the slope shallower than for the fine facies (Fig. 6A). Although the slope is indeed shallower, the intercept is much lower. Another possible model is that the population of larger crystals first formed by the same processes and the same region as those in the fine facies magma and hence had a similar initial CSD. At some later period some process must have acted to decrease the intercept and slope of the CSD. Simple growth will just displace the CSD upward — the intercept will increase, but slope will be constant (Fig. 6B). Accumulation of crystals can lead to decreases in slope (Higgins, 2002), but would also produce variations in the europium anomaly, which is not seen here (Fig. 6C). Textural coarsening can also lead to the observed decreases in intercept and slope (Higgins, 2002) without producing a europium anomaly (Fig. 6D). In an igneous system coarsening (=Oswald

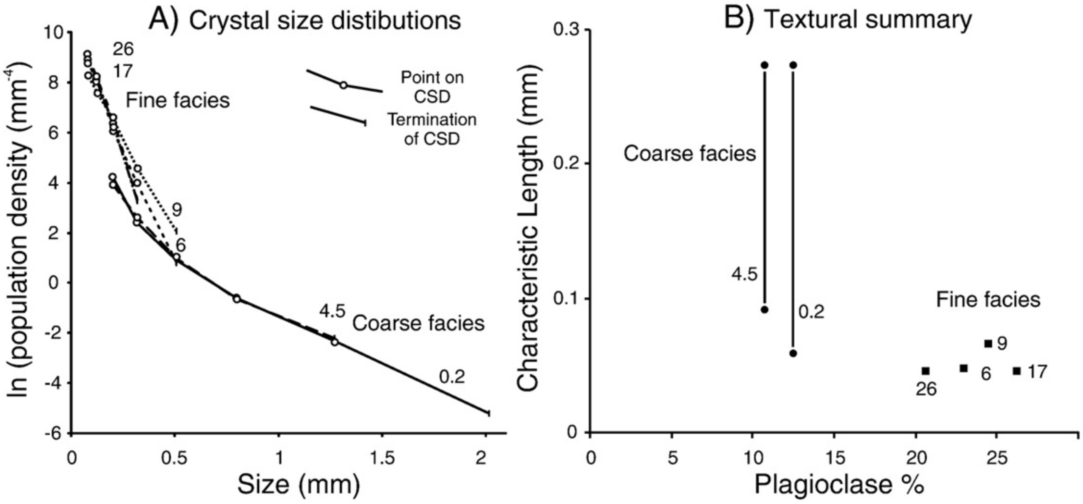

Fig. 5. A) Crystal size distributions of plagioclase in basalt from the Tseax flow. Numbers adjacent to points refer to the distance in kilometers along the flow from the cone. The left termination of the CSDs is a measurement artifact: That is, smaller crystals are present, but were not measured for technical reasons. Coarse facies samples have strongly curved CSDs, but fine facies samples are straight. B) Summary of textural parameters. The characteristic length ($L_C = -1/\text{slope}$) versus plagioclase abundance. The straight CSDs of the fine facies samples give a single value of L_C, but the curved CSD of the coarse facies samples give a range of values for the smallest and largest crystals.

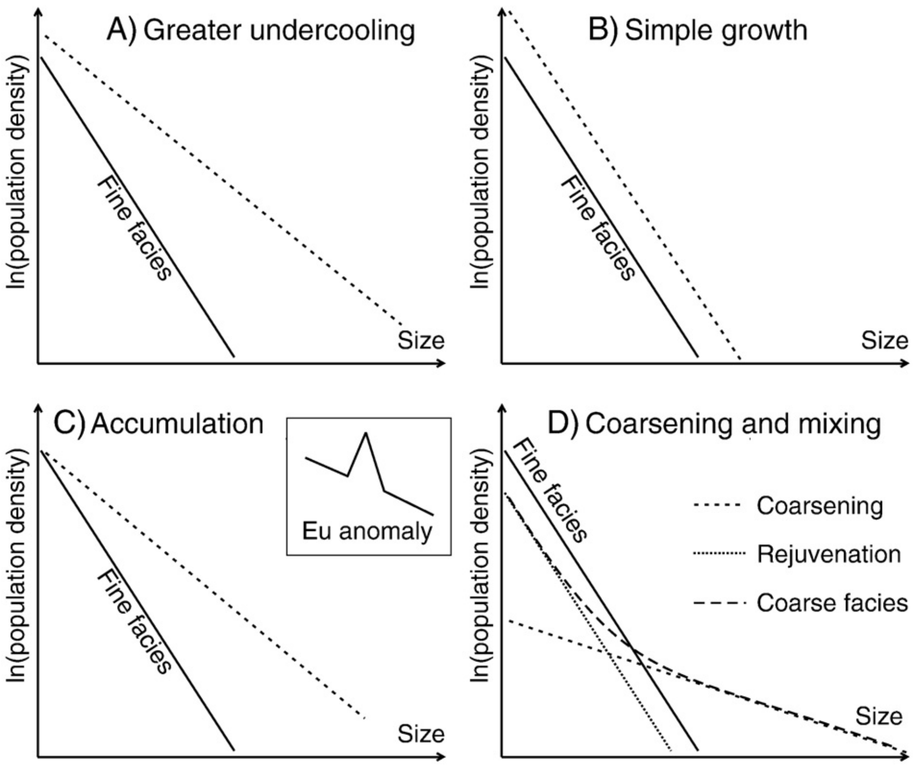

Fig. 6. Models for the origin of the coarse facies magma. The fine facies CSD is indicated as a departure point for textural development and as a 'benchmark'. A) Greater undercooling will increase the slope and intercept. B) Simple growth will just displace the CSD to the right. C) Accumulation of plagioclase crystals will rotate the CSD counterclockwise, but will produce a Eu anomaly, or enhance an existing anomaly. D) Coarsening will produce a hump shaped CSD with almost straight right side. The projected intercept is lower than in the original magma and the slope is lower also. Addition of a steep, straight CSD produces a curved CSD similar to that seen in the coarse facies.

ripening, textural equilibration) is the simultaneous growth of large crystals and solution of small crystals in order to minimise total surface energy (Voorhees, 1992). It occurs if the temperature is kept close to the liquidus of that phase. It will transform a straight CSD into a hump-shaped CSD, lacking small crystals and with an almost straight right side (Fig. 6D). As coarsening progresses the slope of the right side of the CSD will decrease (Higgins, 1998). It is proposed that the large crystal population was produced by coarsening. I will now discuss the origin of the small crystal population and how coarsening occurred.

Smaller crystals are relatively abundant in the coarse facies, hence coarsening cannot be the whole story. One possibility is that the coarsened magma was mixed with fresh, uncoarsened magma from deeper in the system to produce a curved CSD. Such a process would probably produce a single uniform magma and not the two magmas observed in the Tseax flow. Another possibility is that the coarsened magma was rejuvenated by cooling. Nucleation and growth would restart and a new steeper part of the CSD would develop to the left. Such rejuvenation could occur by ascent of the magma in the crust or by increased cooling. There are, however, problems with this idea. The coarse facies magma was the first to erupt, therefore it was probably already relatively high in the crust. The smaller crystals in the coarse facies have a CSD which resembles that of the fine facies, which should come from a deeper level. Finally, it is possible that only parts of the coarse facies reservoir were coarsened. Mixing within the chamber would then have produced the curved CSD. This seems the simplest solution and is favoured here.

If the coarse facies magma has a component that has been coarsened, then how did the coarsening happen? Coarsening of a mineral in magma can only occur if the temperature is kept close to the liquidus of that phase. This is not difficult in a plutonic environment as there is a large thermal mass available that is discharging latent heat. However, coarsening in a volcanic environment requires other mechanisms. Andesitic systems can be reheated by injection of more mafic magma (Higgins and Roberge, 2003), but this is not possible in basaltic systems like Tseax. Another possibility is that the magma is kept close to the liquidus by the streaming of hot gas exsolved from deeper mafic magmas. One possible configuration is shown in Fig. 7A and B. Partial melting in the mantle produced mafic magma that rose into a conduit in the crust. The magma destined to be the coarse facies was retained in a relatively shallow, steep conduit (Fig. 7A). Magma of the same chemical composition, destined to become the fine facies magma, was stored at deeper levels in a connected conduit. The whole structure may have been emplaced in a single event and subsequently segmented by crystallisation on the conduit walls or by partial closure of the dyke.

Degassing of the deeper magma produced a stream of hot gas that migrated upwards through a fissure or dyke system (Fig. 7A). The hot gas passed through the coarse facies reservoir where it maintained parts of the magma at near the liquidus temperature of plagioclase, enabling plagioclase to coarsen (Fig. 7B). Heating and bubbling produced advection which mixed coarsened magma with cooler texturally rejuvenated magma at the edges of the conduit. It is also possible that the process was intermittent, allowing the magma to cool between gas-driven coarsening events. In both situations plagioclase would have the observed curved CSD, with the larger crystals produced by coarsening and the smaller crystals growing in the undercooled magma. At the top of this upper chamber the gas separated and continued to the surface along fissures. The gas may have appeared as fumaroles, it may have mixed with groundwater and produced hot springs or it may have been dissipated along fractures. I will now return to the nature of the trigger mechanism of the eruption.

The time scale of coarsening is difficult to determine. If the same growth rate and model is used as for the fine facies then the residence time is about 90 years. A simpler model of continuous growth would

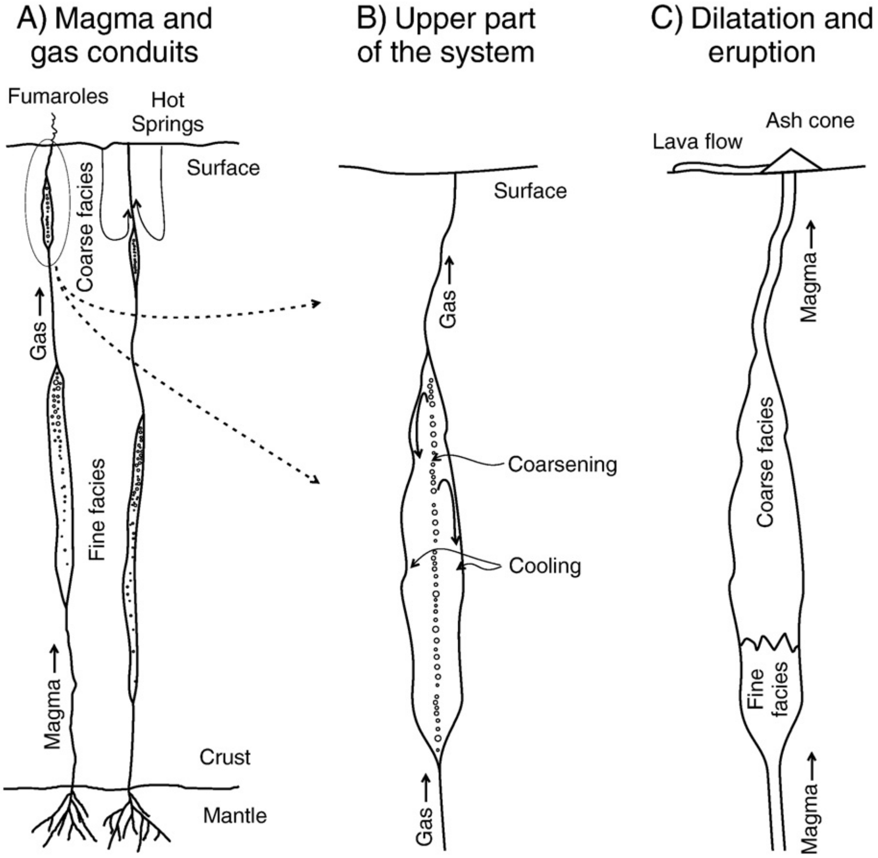

Fig. 7. A) Initial magmatic structure beneath Tseax. B) Enlargement of the upper part of the system. C) The distant Cascadia megathrust produced dilatation, enlarged the magma conduit and triggered the eruption.

indicate a growth time of 500 years for the largest crystals. It is likely that growth is much slower during coarsening, hence these values are minimums. The plagioclase megacrysts may have been retained in the conduit through many cycles of eruption and coarsening. If a continuous growth model and a growth rate of 10^{-10} mm s^{-1} are used again then the size of the megacrysts suggests that they may have crystallised over 6000 years. Similar megacrysts have also been observed in rocks of the Eldfell volcano where coarsening of retained magma has also been suggested (Higgins and Roberge, 2007).

Walter and Amelung (2007) have shown that during a megathrust earthquake a zone of volumetric expansion exists behind the megathrust plane and that triggered eruptions tend to occur there in rarely erupting volcanoes. Volumetric expansion of the gas/magma conduit described above could enlarge the conduit and enhance the flow of gas and magma (Fig. 7C). The initial magma would have been present in the shallow conduit. It could have risen easily to the surface along fractures used earlier by the gas and now widened by dilatation. This early magma would have been charged with gas and erupted explosively to form the ash cone. As the magma drained from the upper chamber it would have been replaced by fine facies magma from the lower chamber, again rising along fissures used earlier for gas transfer. The system was now open and the fine facies magma could degas more readily during ascent, enabling effusive flow onto the surface. At the end of the eruption some magma may have been retained in the upper chamber and the whole cycle could start again. The megacrysts may bear witness to many cycles of eruption and recharge.

9. Conclusions

The last eruption of Tseax volcano occurred between 1668 and 1714 CE. This is permissive of a link with the Cascadia megathrust event of 1700 CE. A detailed tree ring study, such as that done by Jacoby et al. (1997) on Pacific Northwest coastal sections or Elson et al. (2005) for Sunset Crater, Arizona, may reduce the error in the age of the flow, but a direct link can never be proved due to the lack of written or instrumental records. This problem is not unique to Tseax volcano. However, magnetic dating techniques may be useful throughout the Pacific Northwest region of North America, where secular variation of the magnetic field is particularly rapid.

The Tseax flow has two facies with contrasting textures, but similar chemical compositions. It is proposed that both magmas originated in a single magmatic system. Gas produced by degassing of the lower part rose into the upper part of the conduit where it heated and coarsened parts of the magma. The whole system was disrupted by the Cascadia earthquake. Volumetric dilatation enlarged the conduit, enabling magma to ascend along paths previously used by gas alone. Once triggered, continued degassing drove the eruption to completion.

The model developed here may also be applied to other eruptions. The 1973 Eldfell eruption in the Vestmannaeyjar magmatic province, Iceland also started with the explosive eruption of coarsened magma (Higgins and Roberge, 2007). It was followed by two slightly different magmas with finer plagioclase crystals. The success of a textural approach should encourage quantitative study of the petrography of eruptive products, in addition to the more common chemical studies.

Ort et al. (2008) have shown that scoria-cone eruptions, like the Tseax eruption, can have profound effects on local populations. At Tseax, the most important effects may have been poisoning from gas discharge and burial of villages (Hickson et al., 2007). However, if the eruption was concurrent with the Cascadia earthquake then these local effects may have been compounded by a regional malaise related to the earthquake.

A megathrust earthquake similar to the Cascadia earthquake could trigger volcanic eruptions in the Pacific Northwest region. In British Columbia possible sites would those with recent eruptions, such as Mt. Edziza and Lava Fork.

Acknowledgements

This paper is dedicated respectfully to the ancestors of the Nisga'a people that lost their lives during the eruption. I would like to thank the Nisga'a people for access to traditional lands. Earlier versions of this paper benefited from comments by Michael Manga, Cathy Hickson and Michael Ort. Judit Ozoray made helpful editorial comments. Terry Spurgeon provided information on the early Spanish explorers. Andy Jackson made available the marine magnetic measurement database. This research project was funded by a Discovery grant from the Natural Science and Engineering Research Council of Canada.

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