The Processes of Melt Differentiation in Arc Volcanic Rock: Insights from OIB-type Arc Magmas in the Central Mexican Volcanic Belt: Reply to a Critical Comment by Claus Siebe (2013)

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In a comment on our recent paper on the chemical evolution of the central Mexican monogenetic arc volcanoes V. Chichinautzin and Texcal Flow (Straub et al., 2012), Siebe (2013) expressed concern about the exact location and morphology of the vent(s) and the timing and eruptive style of the eruption that produced the Texcal lava flows. Siebe (2013) asks for better explanations on (1) why we discounted the Guespalapa volcano as the main vent of the Texcal Flow lavas, (2) the evidence for the proposed c. 700 years BP formation age of the Texcal Flow, and (3) how cone structures that resemble hornitos may have formed above fissure vents.

We welcome the opportunity to discuss the origin and emplacement of the high-Nb arc magmas of the Texcal Flow in the Sierra Chichinautzin Volcanic Field (SCVF). According to Siebe et al. (2004a, 2004b), the Guespalapa Volcanic Complex formed between 2800 and 4690 years ago, and began with an initial voluminous extrusion of the high-Nb (17–26 ppm, Straub et al., 2012) Texcal Flow basaltic magmas that cascaded down to the...
Cuernavaca plain. Later extrusions of low-Nb (3.5–13.6 ppm, Straub et al., in preparation) basaltic-andesite magmas constructed the volcanic shield and scoria cones of the Guespalapa volcano proper. However, our own field observations, corroborated by geochemical analyses of lava flows in the Cuescomates area at the SW flank of Guespalapa, suggest that the Texcal Flow does not originate from the Guespalapa proper, but was erupted after the formation of the Guespalapa cones, from two separate fissure vents, named the eastern and western ‘Cuescomates’ vents respectively [referred to as ‘Cuezco- mates’ by Siebe (2013)]. Our evaluation is supported by geochemical analysis of 35 samples, with 12 samples from five trips between 2004 and 2009 being taken in proximity of the Cuescomates vents, where Texcal Flow lavas are emplaced within meters of the lavas flows of the Guespalapa volcanic shield (Straub et al., 2012, in preparation). Our observations can be summarized as follows.

(1) Texcal Flow and Guespalapa shield lavas differ subtly in petrography, but more clearly in morphological appearance. The Texcal Flow displays flat morphologies with thin flow-units, and platy and sometimes pahoehoe surface structures (the exception being the hornito-type cones). In contrast, Guespalapa shield lavas are blocky, meter-thick flows with steep flow fronts up to several meters in height. Because these morphological differences correlate with contrasting geochemical compositions (Fig. 1), they were effectively used to recognize the spatial distribution of the Guespalapa vs Texcal Flow lavas in the field.

(2) V. Guespalapa and Texcal Flow lavas have consistently different incompatible trace elements patterns (Fig. 1). Guespalapa lavas display the typical arc signatures (e.g. Nb–Ta depletions, high abundances of fluid-mobile large ion lithophile elements relative to rare earth and high field strength elements) whereas Texcal Flow basalts resemble enriched intraplate magmas. Figure 1a shows all the samples analyzed (Straub et al., 2012, in preparation), and Fig. 1b highlights the magmas in the immediate vicinity of the Cuescomates vents. If all magmas were derived from a single vent, one would expect those emplaced closest to each other to be most similar. However, this is not the case, as these magmas show particularly clear differences.

(3) We found no evidence that Texcal Flow lavas extend beyond the NE of the Cuescomates area in the direction of the Guespalapa cones. Rather, Texcal Flow lavas tend to pond against the flow fronts of the bulky Guespalapa shield lavas, showing that they were emplaced after the Guespalapa shield lavas. Importantly, tree molds are observed in the near-vent Cuescomates lavas, which show that the Texcal Flow was emplaced on top of older, vegetated Guespalapa lavas. This agrees with the fact that a Guespalapa low-Nb lava (sample 12 A, Straub et al., in preparation), was retrieved from below the Texcal Flow at this location.

(4) A single lava flow from the Guespalapa shield (sample CH05-14, Straub et al., in preparation) is emplaced between the lavas from the eastern and western Cuescomates vents. The fact that the Texcal Flows do not cross over this lava flow rules out that the Texcal Flow lavas were emplaced as a single flow coming from the Guespalapa cones. Rather, the field relationships agree with the origin of the Texcal Flow lava flows from two separate vents that only joined ~1km further to the south and prior to the descent down the steep escarpment towards Cuernavaca.

(5) The lava tubes near the Cuescomates vents mentioned by Siebe (2013) are all built on lavas directly emitted by those vents, and there is no evidence that the Guespalapa flows were tube-emplaced. The major Texcal lava tubes explored by one of us (Espinasa-Pereña & Espinasa, 2006) are located much farther downflow and show by their morphology (canyon-shaped and/or with superimposed tubes) that they functioned as the master-tubes feeding the pahoehoe flow front for a long period of time, and not as a voluminous but short-lived blocky or aa flow as proposed by Siebe et al. (2004a, 2004b). The surface morphology of almost all the Texcal Flow is consistent with pahoehoe tube-fed flow emplacement, with ropy textures, tumultus and lava-rise structures, and many other diagnostic features.

(6) The striking ‘hornito-type’ cones are imposed on the western Cuescomates vent (Siebe, 2013). In contrast, the eastern Cuescomates vent resembles a jagged ridge of c. 100 m in length that is more typical of a volcanic fissure vent. We have no information on the volatile content or degassing history of the Texcal magmas, although Cervantes & Wallace (2003) have shown that high-Nb magmas from the SCVF usually have much lower water contents than lavas with more typical arc signatures, and therefore may not erupt as explosively. Although it is not possible to know from the field or geochemical evidence if these ‘hornito-type’ vents have a deeper feeding root, we note that they follow an east–west alignment that is consistent with the structural fracture system of the region. The ‘hornito-type’ vents may have formed in the late stages of a waning eruption when the magma flow diminished and was reduced to localized ‘sputtering’ that formed spatter cones on top of the fissure vent. The aphyric, strongly vesicular nature of the spatter cone-forming magmas and the presence of agglutinates are consistent with fast magma ascent and chilling in the final stage. In contrast, the chemically
indistinguishable, olivine–plagioclase-phyric lavas were emplaced in the immediate proximity of the vent [the <50 m Cuescomates vent lavas of Straub et al. (2012)] that apparently cooled more slowly and crystallized before freezing.

**AGE RELATIONSHIPS**

Our field observations suggest that, although being closely associated in space and time, the emplacement of the high-Nb Texcal Flow post-dates the formation of the low-Nb Guespalapa shield and cone magmas. Such close temporal and spatial association of the high-Nb (>16–35 ppm Nb) and low-Nb (<16–3 ppm) mafic arc magmas is common in the central SCVF, where these magmas erupt within only a few thousand years, and sometimes within only a few kilometers, of each other (Siebe et al., 2004b; Espinasa-Pereña, 2006; Straub et al., 2012, in preparation). The age relationship between high-Nb and low-Nb magmas is significant, as high-Nb magmas have been proposed to best approximate the magmas derived from the sub-arc mantle prior to subduction modification in the Mexican Volcanic Belt (e.g. Luhr, 1997; Wallace & Carmichael, 1999). If this is the case, one would expect that the eruption of high-Nb magmas may precede the low-Nb calc-alkaline magmas that derive from a mantle modified by subduction processes.

Age relationships in prehistoric monogenetic fields are notoriously difficult to establish. We note, however, that the geochronological data of Siebe et al. (2004b) and our own observations suggest that the high-Nb magmas were the youngest magmas erupted in the SCVF and that they follow the eruption of low-Nb magmas by several hundred to thousand years. The best examples are the high-Nb...

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**Fig. 1.** Incompatible trace element patterns of Texcal Flow and V. Chichinautzin. (a) All samples. (b) Texcal Flow and V. Chichinautzin samples from Cuescomates area only. Data from Straub et al. (2012, in preparation).
magnas of V. Chichinautzin (~1800 years; Siebe et al., 2004b) and V. Xitle (~1600 years; Siebe, 2000). The Xitle eruption is the youngest known eruption in the central SCVF (Siebe et al., 2004b). The high-Nb magnas of V. Chichinautzin (Nb = 21–36 ppm, Straub et al., 2012) pond against and flow around the low-Nb scoria of the Suchiooc cone El Hoyo (Nb = 3.5–4 ppm, Straub et al., in preparation). At V. Suchiooc the temporal relationship between the eruption of low-Nb and high-Nb magnas is less clear. Cone-forming scoria and the proximal flows (<1 km distance from cone) of Suchiooc are all low-Nb basalts and basaltic andesites (10–13 ppm Nb), whereas the distal lavas are all high-Nb basals (21–25 ppm Nb, Straub et al., in preparation). Although the high-Nb magnas were traced back to near the base of the Suchiooc cone (sample CH07-2, Straub et al., in preparation), no vent structure could be identified beneath the dense vegetation. All the same, field observations suggest that the high-Nb magnas were probably emplaced after the formation of the low-Nb Suchiooc cone. Overall, we tentatively propose that the available data allow for the possibility that the youngest high-Nb magnas of the central SCVF were produced nearly simultaneously (within a few hundred years) at multiple locations between V. Xitle in the north and the Texcal Flow in the south. It could well be that the Texcal Flow was part of such a pulse. Radiocarbon dates of Siebe et al. (2004b) bracket the age of the Texcal flow to between 4690 and ~690 years. Although we concur that the 690 year age is a minimum (C. Siebe, personal communication), we still consider the Texcal Flow to be younger than the magnas of the Guespalapa shield. Assuming the 4690 year age of a soil below Texcal Flow as an upper age limit, the Texcal Flow could have formed closer to the periods of V. Xitle and V. Chichinautzin activity. Although this is speculative, we note that a pulse of high-Nb magma within a short period of time would indicate that the high-Nb magnas are a special, highly enriched subgroup of arc magnas rather than being only proxies for residual pristine sub-arc mantle domains that were somehow spared subduction processing.

REFERENCES


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