

Brehm, S.K., and Lange, R.A., 2022, Origin of low Mg# hawaiites carrying peridotite xenoliths from the Cima volcanic field, California, USA: Evidence of rapid magma mixing during ascent along intersecting fractures: GSA Bulletin, <https://doi.org/10.1130/B36390.1>.

Supplemental Material

Figure S1. Geologic maps of (a) Marl Mountain Quadrangle presented by Wilshire et al. (2002b) and (b). Indian Springs Quadrangle presented by Wilshire et al. (2002a) with Cima localities superimposed.

Figure S2. Peridotite mantle xenoliths found in Cima-4a and -4b, and DH-1.

Figure S3. Histogram of Fo mol% ($= X_{\text{MgO}}/(X_{\text{MgO}} + X_{\text{FeO}}) \times 100$) for Cima-4a. The most Mg-rich olivine compositions (Table 2), whole-rock MgO wt% (Table 1), and number of analyses (n) are shown. Plotted for comparison are analyses of olivine from within the Cima-4 mantle xenolith.

Figure S4. Representative BSE images of clinopyroxene phenocrysts from each textural category including (1) non-spongy/non-vermicular (2) spongy/vermicular and (3) oscillatory/sector-zoned.

Figure S5. Histograms of clinopyroxene Mg# for five Cima hawaiites. Crystals are plotted based on the assigned textural categories presented in Figure S2. Calculated $^{\text{Fe-T-Mg}}K_D(\text{cpx-melt})$ values for the most Mg-rich clinopyroxene crystal paired with the whole-rock composition (Table S.4) are shown in red.

Figure S6. Plots of Na_2O , TiO_2 , and Cr_2O_3 (wt%) versus Mg# from analyzed clinopyroxene phenocrysts. Individual spot analyses are all characterized by texture including (1) non-spongy/non-vermicular (NS/NV) (2) spongy/vermicular (S/V) and (3) sector- or oscillatory-zoned (OZ/SZ).

Figure S7. Histograms of anorthite content ($\text{An mol\%} = X_{\text{CaO}}/X_{\text{CaO}} + X_{\text{Na}_2\text{O}} + X_{\text{K}_2\text{O}} \times 100$) for three Cima basalts. The most calcic plagioclase composition (An mol%), liquid An number, and number of analyses ($= n$) are given for each sample.

Table S1. Standards employed for electron microprobe analyses of olivine, clinopyroxene, plagioclase, and Fe-Ti oxides.

Table S2. Analyzed trace element concentrations for all Cima and Dish Hill samples.

Table S3. Olivine phenocryst analyses for all Cima and Dish Hill samples.

Table S4. (A) Clinopyroxene analyses for five Cima hawaiites (B) Composition of the most Mg-rich clinopyroxene phenocryst.

Table S5. (A) Microprobe analyses of ilmenite and titanomagnetite from six Cima hawaiites. (B) Fe-Ti oxide thermometry and oxybarometry (Ghiorso and Evans, 2008) results for all possible pairs of ilmenite and titanomagnetite. (C) Composition (wt%) of onset ilmenite and titanomagnetite pair that pass the Bacon and Hirschmann (1988) test for equilibrium.

Table S6. (A) Plagioclase phenocryst analyses for three Cima hawaiites. (B) Analyses of most calcic plagioclase phenocryst.

Table S7. Olivine-melt thermometry applied to all Cima and Dish Hill samples.

INTRODUCTION

The supplemental material presented below is intended to support the major results and interpretations presented in the main body of the paper. The Supplemental Materials below are divided into three parts. Part 1 provides probe analytical methods and results for all analyzed plagioclase crystals from this study. Part 1 also discusses the clinopyroxene results in more detail than provided in the main body of the text. Note that due to abundant evidence of magma mixing in the Cima hawaiites, it is not possible to apply either clinopyroxene-melt barometry or olivine-melt thermometry/hygrometry at the liquidus. Part 2 introduces five supplemental figures and associated figure captions. Part 3 includes a list of all headers for supplementary data files. Tables can be found in a separate Excel file containing all analyzed and calculated data presented in this study.

Plagioclase: Analytical Methods and Results

Plagioclase was analyzed using a Cameca-SX 100 electron microprobe at the University of Michigan. All crystalline standards for all analyses are contained in the University of Michigan collection and are presented in Table S1. Phenocrysts from three representative samples (Cima-1, -2, -8) were analyzed using a 15 kV accelerating voltage and a focused beam with a 4 nA current. Nine elements (Mg, Na, Si, Al, Ti, Fe, Mn, Ca, K) were analyzed with peak and background counting times of 20 s each. A total of 214 plagioclase phenocrysts (66–76 per sample) were analyzed yielding 185–291 effective analyses per sample. The 1 σ error according to the counting statistics are ± 0.24 Na₂O, ± 0.06 MgO, ± 0.70 Al₂O₃, ± 0.96 SiO₂, ± 0.10 K₂O, ± 0.51 CaO, ± 0.08 TiO₂, ± 0.07 MnO, ± 0.14 FeO_T. Analyses were filtered to exclude those with analytical totals outside of 98.5–101 wt%.

All individual plagioclase analyses are presented in Table S6A. Histograms of An mol% for each sample (Figure S7) show a continuous range that spans ~10 mol%, ranging from An_{54–64} (liquid An₄₇) to An_{58–68} (liquid An₄₉). Compositions of the most calcic plagioclase analysis in each sample are presented in Table S6B.

Clinopyroxene Results (see main text for Analytical Methods)

Individual clinopyroxene analyses obtained on five representative Cima hawaiite samples are presented in Table S4. Individual spot analyses along a transect for each crystal are classified into three textural categories including: (1) sector- or oscillatory-zoned crystals, (2) spongy (vermicular), and (3) non-spongy (non-vermicular). BSE images of representative crystals from each textural category are shown in Figure S4 with some displaying multiple textures within the same crystal. To illustrate the distribution of textural categories within a given sample, (stacked) histograms of Mg# ($= \text{XMgO} / (\text{XMgO} + \text{XFeO}_T)$) plotted by texture are presented in Figure S5. In most samples the dominant population of clinopyroxene crystals are classified as spongy (vermicular). Non-spongy (non-vermicular) crystals are next in abundance, and in most samples sector- or oscillatory-zoned crystals are relatively sparse to absent (e.g., Cima-5). Cima-1 is the only case where sector or oscillatory crystals dominate the phenocryst population. Clinopyroxene phenocrysts span a continuous range in Mg# (Figure S5) with a few exceptions (Cima-8, -2, -5). The most Mg-rich clinopyroxene composition of the continuous range (≤ 1 mol% gap) for each sample is presented in Table S4B. Estimates of $^{\text{FeT-Mg}}K_D(\text{cpx-melt})$ values using the most Mg-

rich clinopyroxene crystal and the whole-rock composition range from 0.21 to 0.30 (Figure S5). Plots of wt% Na₂O, TiO₂, and Cr₂O₃ versus Mg# are shown in Figure S6. Two distinct populations of clinopyroxene, in terms of Na₂O content, are only observed in Cima-1 and Cima-3. Both samples feature a population of non-spongy, dark cores with ≥ 1 wt% Na₂O, consistent with growth at lower crustal depths (Neave and Putirka, 2017). Most other clinopyroxene phenocrysts have lower Na₂O contents, consistent with crystallization at shallower depths.

Limitations of Cpx-Liquid Barometry Applied to Cima Hawaiites

Having evaluated numerous hypotheses, the only remaining scenario that cannot be ruled out is that the Cima hawaiites formed due to rapid magma mixing of a high-MgO basanite and a low-MgO mugearite during ascent along fractures. This hypothesis not only precludes the application of olivine-melt thermometry at the liquidus to the Cima hawaiites, but also the application of cpx-liquid barometry. This differs from the results of Brehm and Lange (2020) where the most Mg-rich clinopyroxene crystal paired with the whole-rock composition of six high-MgO Big Pine basalts was used to calculate pressure at the onset of phenocryst growth using the model of Neave and Putirka (2017). This method was successfully applied to the Big Pine basalts as there was no evidence of magma mixing during ascent, the most Mg-rich clinopyroxene composition was preserved based on equilibrium values of $^{FeT-Mg}K_D(cpx-liquid)$, and an independent constraint on temperature at the onset of phenocryst growth using the Ni-thermometer of Pu et al. (2017) could be made. In the Cima hawaiites, there is clear evidence of mixing and inheritance of clinopyroxene crystals (and olivine) from a high-MgO basanite, resulting in $^{FeT-Mg}K_D(cpx-liquid)$ values that are too low to be in equilibrium with the whole-rock composition (Figure S5). Additionally, an independent estimate of temperature at the onset of phenocryst growth cannot be made for the Cima hawaiites due to inherited high-Mg olivine phenocrysts, and thus no quantitative estimate of pressure can be made using clinopyroxene.

Brehm and Lange (2020) noted the presence of two distinct populations of clinopyroxene in six high-MgO Big Pine basalts on the basis of both crystal geochemistry (Na₂O wt% and Mg#) and texture. This includes a population of non-spongy/non-vermicular, Mg-rich, high-Na₂O clinopyroxene, typically occurring as cores, which is consistent with an elevated jadeite component or crystallization at higher pressures. A second population of sector/oscillatory-zoned and vermicular/spongy crystals, typically occurring as rims, have relatively lower Na₂O content, which is consistent with rapid crystallization during an effective undercooling at relatively lower pressures (e.g., Welsch et al., 2016).

Similar textural and compositional populations are observed in the five Cima hawaiites where clinopyroxene phenocrysts were analyzed (Cima-1, -2, -3, -5, -8). The most dominant textural population of clinopyroxene are classified as spongy (vermicular) (Figure S4) indicative of rapid diffusion-limited crystal growth. This is closely followed by non-spongy (non-vermicular) clinopyroxene phenocrysts (Figure S4). Only one sample (Cima-1) shows a dominant population of sector or oscillatory zoned crystals.

In plots of Na₂O wt% vs vs Mg#, only two Cima samples (Cima-1 and -3) show distinct populations on the basis of geochemistry (Figure S6). The high-Na₂O (≥ 1 wt%) non-spongy (dark core) phenocrysts observed are consistent with crystallization at lower crustal depths (Hammer et al., 2016; Welsch et al., 2016). All other clinopyroxene phenocrysts analyzed in the Cima hawaiites have Na₂O contents and crystal textures consistent with crystallization at shallower depths. Thus, while a quantitative estimate of pressure at the onset of crystallization

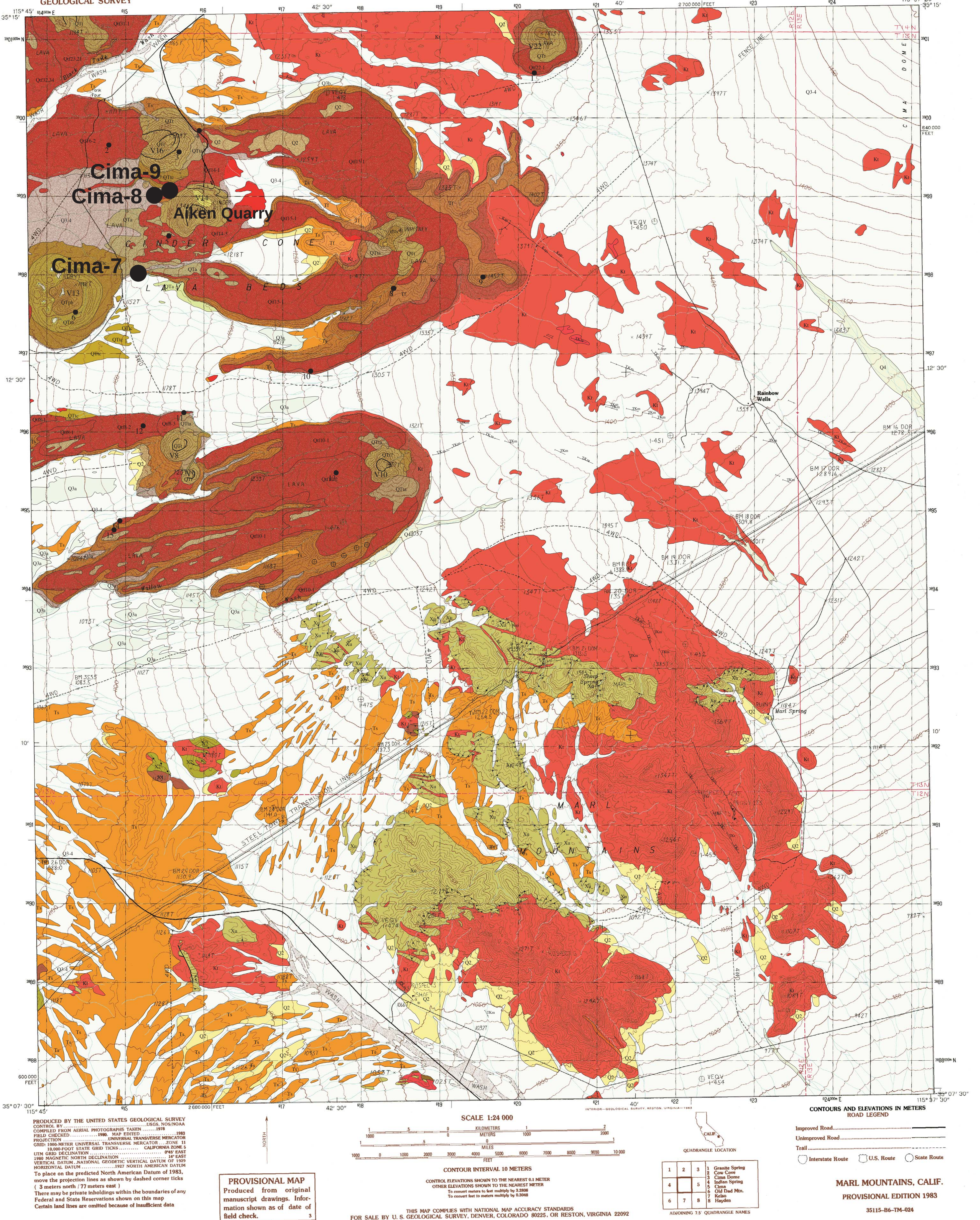
cannot be made for the Cima hawaiiites, it is inferred that the majority of these samples crystallized at depths shallower than those estimated for the Big Pine basalts. The clear bimodality in crystal composition and texture observed in Cima-1 and Cima-3 suggests polybaric crystallization of clinopyroxene similar to that observed in the majority of Big Pine basalts (Brehm and Lange, 2020). This is consistent with other recent studies, which report the preservation of polybaric crystallization of clinopyroxene within a sample or individual crystal (Hammer et al., 2016; Mollo et al., 2020).

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Geology By

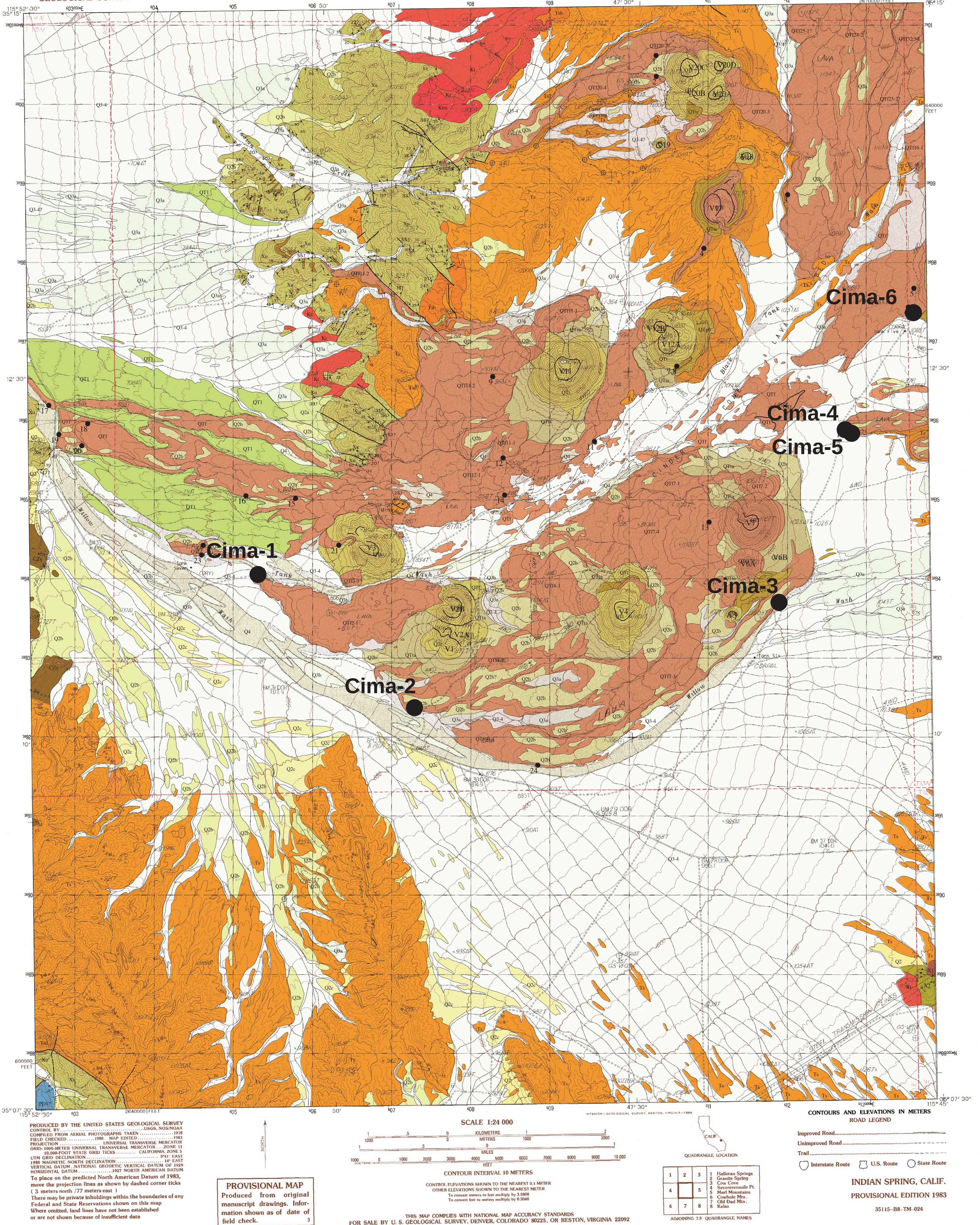
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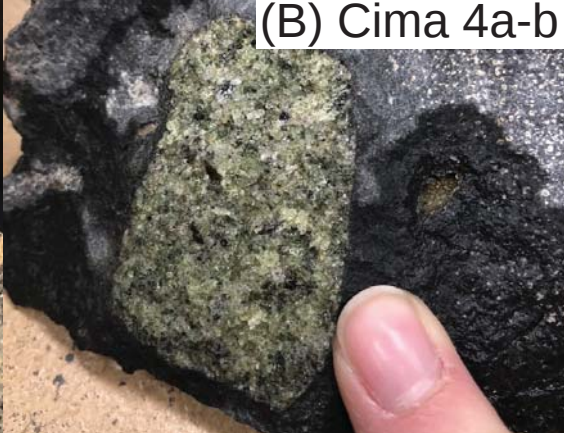
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(A) DH-1



(B) Cima 4a-b

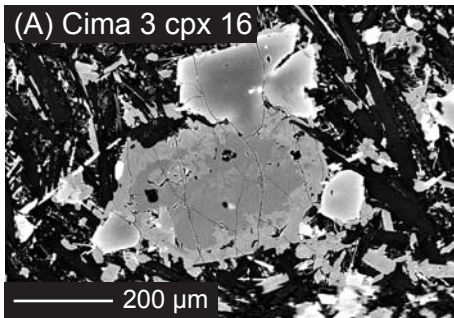


(C) Cima 4a-b

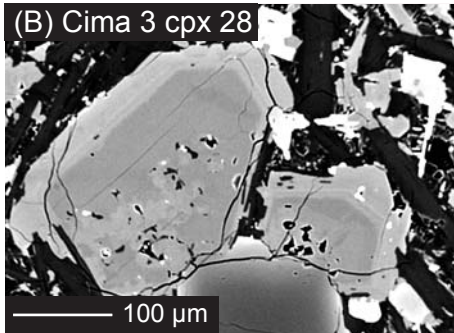


non-spongy/non-vermicular

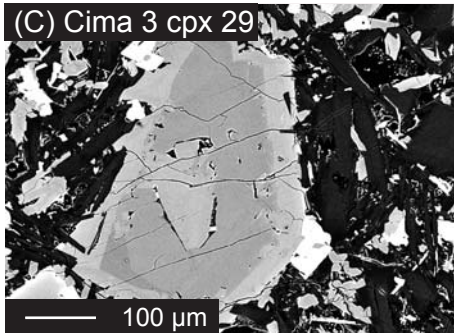
(A) Cima 3 cpx 16



(B) Cima 3 cpx 28

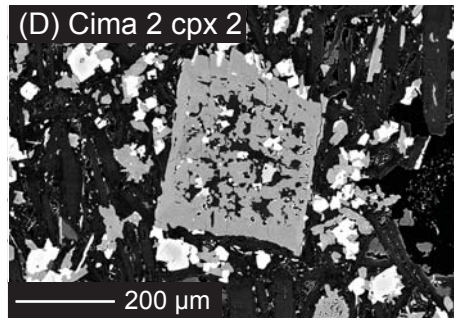


(C) Cima 3 cpx 29

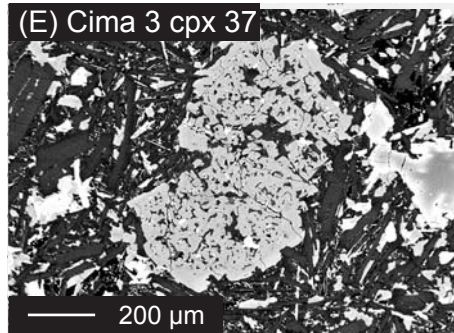


spongy/vermicular

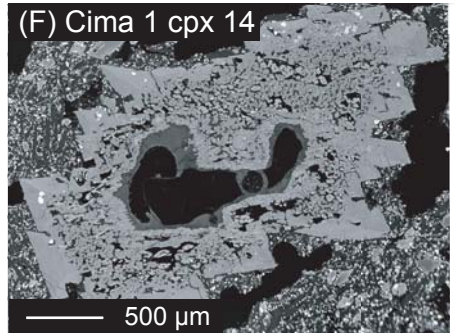
(D) Cima 2 cpx 2



(E) Cima 3 cpx 37

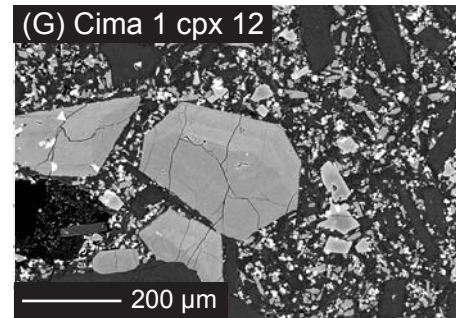


(F) Cima 1 cpx 14

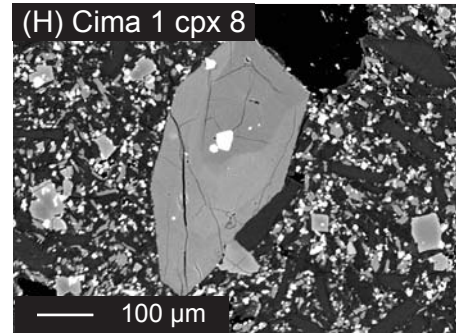


sector/oscillatory zoned

(G) Cima 1 cpx 12



(H) Cima 1 cpx 8



(I) Cima 1 cpx 16

