Stratigraphic Correlation of Late Cretaceous Volcanic Rocks along the Eastern Flank of the Boulder Batholith, Southwestern Montana

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Statement of Purpose

The Ratio Mountain and Boulder East 7.5 minute quadrangles include exposures of the contact between the Elkhorn Mountain Volcanics (EMV) and Butte granite along the eastern flank of the Boulder Batholith, southwestern Montana (Figure 1.). This project aimed to correlate a section of the EMV in the Boulder East 7.5' quadrangle, to the southwest, with a 900 meter thick section of the EMV in the Ratio Mountain 7.5' quadrangle, as well as understand the timing and volume of the eruptions.

Introduction and Previous Work

The EMV and Boulder Batholith are both arc magmatic rocks formed during the late Mesozoic (~85 to 63 Ma). Magmatism emplaced shallow plutons (Boulder Batholith) covering central and southwestern Montana (Lageson et al., 2001). These late Cretaceous plutons and comagmatic volcanic cap represent an exceptional record of continental arc magmatism. Synchronous with magmatism, east-west shortening of the Laramide Orogeny produced folding and thrust faults that affected the EMV. The late Cretaceous EMV are made up of roughly 3.5 to 4.6 km thick heterogeneous volcanic and volcaniclastic sedimentary rocks, primarily rhyolitic to andesitic ash-flow tuffs and lava flows with common basaltic-andesite/diorite intrusions. K-Ar ages for the EMV range from ~85 to 80 Ma (Tilling et al., 1968) indicating they erupted during the early stages of the Boulder Batholith emplacement (Rutland et al., 1989). Along the contact the EMV are strongly metamorphosed, locally altered and sheared. John Dilles, Kaleb Scarberry (MBMG), Nansen Olson, Thomas Horton, and Ian Kallio mapped and measured section of the Ratio Mountain and Boulder East 7.5 minute quadrangles last summer of 2015. The 1:24,000 (EDMAP) mapping was in conjunction the 1:100,000 (STATEMAP) Butte North mapping done by Kaleb Scarberry and others at (MBMG). Weeks (1974) mapped both the Ratio Mountain and Boulder East 7.5' quadrangles at 1:48:000 scale. Past geochemical work divided the EMV into three sections, the lower, middle and upper members (Rutland et al., 1989). The EMV range in age from 84 -75 Ma but recently published dates (summary in Mahoney and others, 2015) lack stratigraphic context. Most recently, Ar-Ar ages from Thomas Horton at Oregon State University confined the EMV to between 83.72 ± 0.32 and 84.65 ± 0.36 Ma. Prostka (1966) measured the EMV section in the Dry Mountain 7.5' quadrangle immediately south of Ratio Mountain quadrangle and established a stratigraphy based on texture and mineralogy.

Methods for Analysis

The sections were measured and described in the Ratio Mountain and Boulder East quadrangles using a Jacob staff and field observations during the summer of 2015. In addition to field

observations, detailed analysis of chemical composition and petrology to look at subtle differences in mineralogy and alteration give a better understanding of the sections and is required for correlation and interpretation of EMV stratigraphy. Petrology and geochemical data were used to define subdivisions of the well-exposed section at Ratio Mountain, substantially modifying and improving Prostka's columnar section of the EMV (1966). The EMV are strongly metamorphosed and cooked due to emplacement of the Boulder Batholith, and locally exposed, making these analyses necessary for correlation outwards to the northeast in the Boulder East quadrangle.

Geochemistry: The samples were prepared at the XRF and ICP-MS lab at Washington State University where they completed the chemical analysis of the EMV. Geochemistry is important for differentiating between EMV units and correlation between the Boulder East and Ratio Mountain quadrangles Identifying minor similarities and major and trace elements refine the correlation. Refer to "XRF Analysis of Rocks and Minerals for Major and Trace Elements on a Single Low Dilution Li-tetraborate Fused Bead" and "Trace Element Analyses of Rocks and Minerals by ICP-MS" by Johnson et al. for the methods used by the WSU geoanalytical lab.

Petrography: Thin sections from the major units in the measured EMV section were examined with a petrographic microscope. Identifying differences in mineralogy and textures is helpful for defining the lithologies and correlating stratigraphy of the EMV along the eastern flank of the Boulder Batholith. Thin section billets were cut by Kallio and the University of Utah prepared the thin sections.

With the addressed analyses, this project studied the chemical similarities, described section, and correlated strata of the Elkhorn Mountain Volcanics.

Figure 1. Quadrangle and measured section (stars) locations.

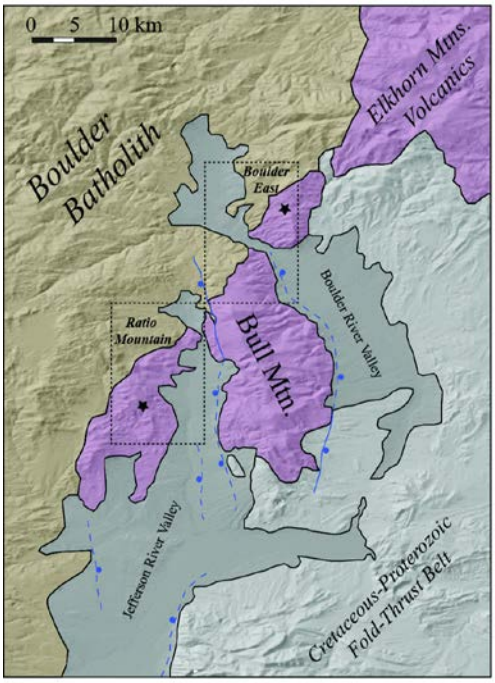
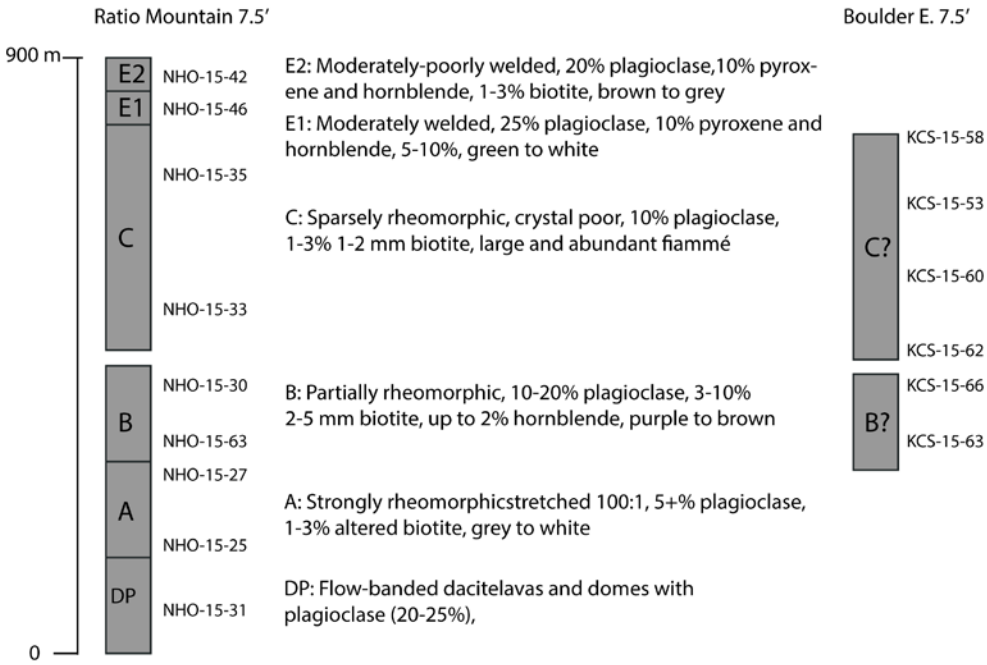


Fig. 2: Strat collumns (to Scale)



Results

Geochemistry:

Figs. 3: Chemical/stratigraphic variability

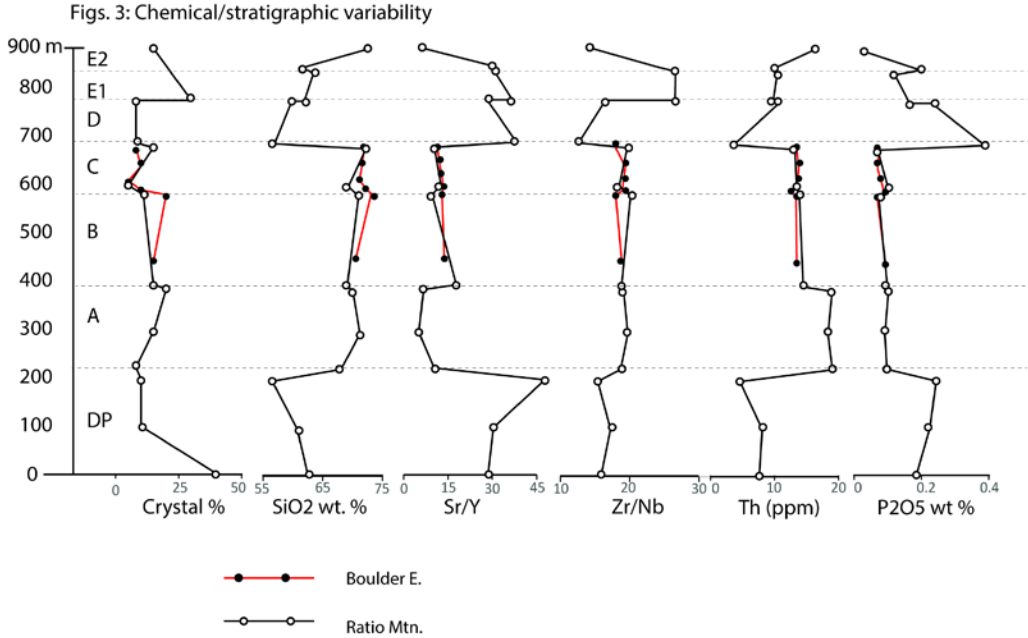
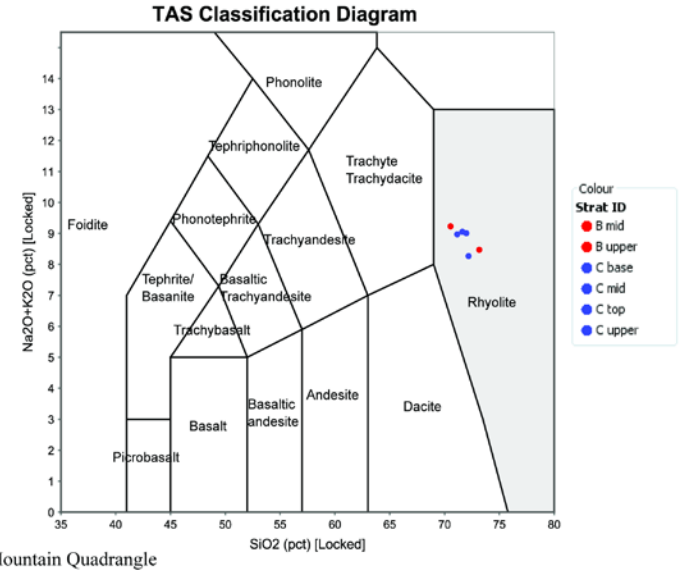


Figure 4. TAS diagrams

Boulder East Quadrangle



Ratio Mountain Quadrangle

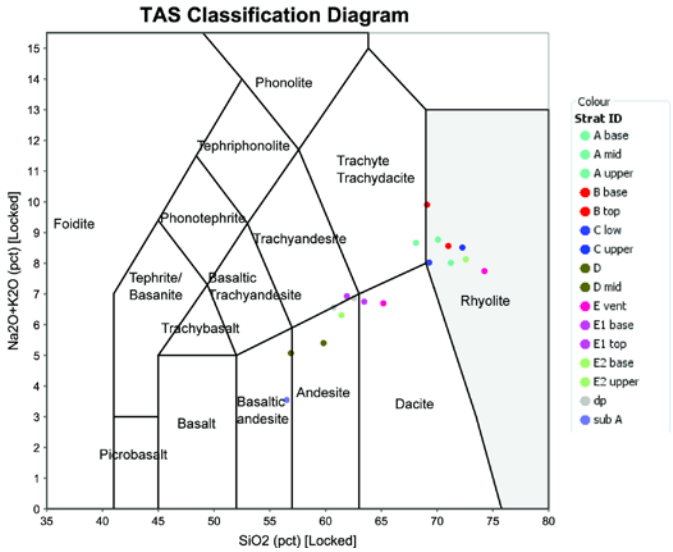
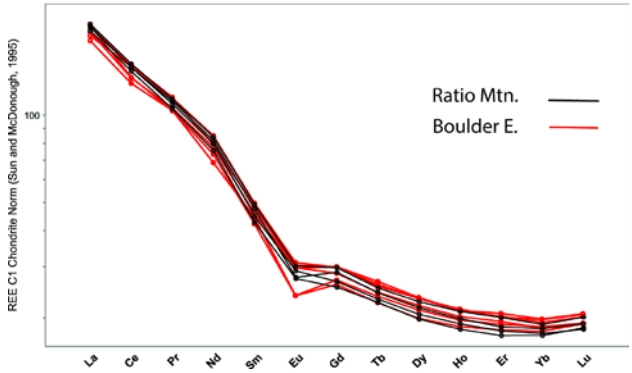


Figure 5. Chondrite normalized REE spider plot for units B and C in the Boulder East and Ratio Mountain 7.5' quads



Petrography: Refer to appendix A for the thin section descriptions and images.

Discussion

The field observations suggested that the measured section in the Boulder East quadrangle contained units B and C that were identified in the Ratio Mountain quadrangle. The geochemical and petrographic studies show correlations in tuffs B and C in the EMV between the Ratio Mountain and Boulder East quadrangles.

Figure 3 shows the correlations with crystal percentage, silica, thorium and phosphate abundances, and strontium/yttrium and zirconium/niobium ratios; these correlations are strong and show evidence that the B and C units identified in the Ratio Mountain quadrangle exist in the Boulder East quadrangle. The chemical analyses for figure three were chosen on the basis that: (a) phosphorus, thorium, silica, zirconium and niobium are relatively immobile, and are less likely to be affected by hydrothermal alteration, metamorphic fluids and meteoric fluids; (b) thorium and niobium are incompatible, further avoiding metamorphic fluids and hydrothermal alteration; and (c) strontium is mobile and yttrium is immobile, and strontium/yttrium ratios are commonly used to show crustal assimilation, however, for the context of this study, the ratio showed a strong correlation. Figure 4 shows that units B and C in both Boulder East and Ratio Mountain plot as a rhyolite on the total alkali silica diagram. This differentiates the Boulder East samples from other units in the measured section such as tuffs E1 and E2. Figure 5 contains a spider plot of the rare earth elements (REE). The REE within tuffs B and C in Boulder East and Ratio Mountain have very similar concentrations and both exhibit small europium anomalies, as shown in figure 5.

The petrography identified similarities in crystal percentages, mineralogy, color and texture for units B and C in both quadrangles. In both quadrangles, unit B ranges from brown-purple to grey, is moderately welded, has book shaped biotite and 15-20% total crystals. Unit C is more crystal poor, grey-brown and moderately welded in both quadrangles. The tuffs from Boulder East are very cooked, making it difficult to find small similarities in mineralogy.

Conclusion

Our data suggest that the middle member of the EMV contains at least two (B and C) large ignimbrites that can be correlated over 30 km in the Ratio Mountain and Boulder East quadrangles. The correlations were refined through chemical and petrographic similarities within the measured sections in each quadrangle, after general observations and predictions were made in the field.

Appendix A: Petrography

Ratio Mountain:

NHO-15-03: Dacite Lava

Euhedral plagioclase 30% with carlsbad twinning, up to 3mm in size, 10% quartz, <3% opaques. 60% quartz and plagioclase fine grained matrix. Porphyritic texture. No flow banding in thin section.

NHO-15-25: Base A

Light to dark grey moderately welded tuff. Plagioclase10% and oxides 1% present in glassy/vitric matric. Lacks mafics. 10% crystals.

NHO-15-26: Middle A

Grey moderately welded tuff. Small broken plagioclase and quartz within matrix. Large euhedral plagioclase ~5%. Quartz 5%. Large plagioclase is skeletal/pitted. <2% opaques. 10% total crystals.

NHO-15-27: Upper A

Light grey moderately welded tuff with porphyritic texture and vitric groundmass. Fiamme´ and flattened pumice 3-5 mm present. Tabular plagioclase aligned with flow. <10% crystals, 5% plagioclase (1-3mm), 3% quartz, 2%opaques.

NHO-15-28: B middle

Grey to purple fiamme´ (black-purple) rich porphyritic, welded tuff. 15% crystals (bimodal), glassy matrix with. 10% euhedral plagioclase ~1mm. 5-10% book shaped biotite, aligned, up to 2mm. <5% opaques. 10% small, broken plagioclase and mafics. Pyroxenes <5%. Plagioclase shows zoning and Carlsbad twinning.

NHO-15-29: Upper B

Grey purple moderately welded tuff with glassy matrix and porphyritic texture. Large euhedral plagioclase dissolved with quartz. 20% crystals – 15%plagioclase, 5% biotite, and <5% opaques. Biotite is .5-1.5 mm, book shaped, aligned with welded texture and bimodal.

NHO-15-30: Top B

Grey brown moderately welded tuff. 15% crystals in a vitric matrix. 10% plagioclase, 5% biotite and pyroxene, <2% opaques. Brown alteration (weathering?) throughout section.

NHO-15-33: C Base

Crystal poor, moderately-poorly welded tuff. 10% plagioclase, <5% elongate biotite and 1% opaques. Abundant plagioclase micro-fiame (200um).

NHO-15-34: Middle C

Crystal poor <5%, silica rich tuff with large, flattened pumices 15% >5mm. Rheomorphic texture is dominant. Texture flows around crystals.

NHO-15-35: Middle C

Reddish grey poorly welded tuff ~15% crystals. Porphyritic texture with very fine groundmass. Mostly broken, subhedral plagioclase 10%, quartz 3% and few opaques. Reddish brown alteration throughout.

NHO-15-36: C top

Light grey brown crystal poor, poorly welded tuff. 5-10% crystals - <5% plagioclase, <5% quartz, sparse opaques, sericite/muscovite. Sericitc alteration. Large grey porphyritic clasts containing plagioclase and amphibole? Could be poikolitic~1000um.

NHO-15-39: D

Unwelded green tuff. Highly chloritized/epidotized. 30% plagioclase, ~5-10% opaques, and some biotite in a fine grained plagioclase and quartz matrix.

NHO-15-41: E1? Dacite Porphyry

Plagioclase rich, moderately welded, grey vitroclastic tuff. Porphyritic texture with very fine grained groundmass. 30% crystals - 25% plagioclase crystals, mostly broken and subhedral. Some opaques and sparse biotite. <5% pyroxene. Chlorite and epidote alteration.

NHO-15-47: E1? Dacite porphyry
Vitroclastic, moderately welded, grey porphyritic tuff with 30% crystals - 20% plagioclase crystals, 5-10% hornblende and 5% pyroxene. Plagioclase is broken and subhedral. Hornblende is euhedral. Pyroxene mostly altered to chlorite/epidote and some contain opaque inclusions.

NHO-15-42: E2?

Moderately welded, vitric, crystal poor tuff with 10% plagioclase, 5% pyroxene and 1% opaques. Chlorite and epidote alteration on pyroxenes.

Boulder East:

KCS-15-12: DP

Porphyritic texture with large abundant plagioclase. Brown, oxidized matrix, overprint alteration.

KCS-15-63: Middle B

Brown welded tuff full of fiamme' Silica rich. 15% crystals, <15% euhedral 0.3-1mm and small broken .1-.5 mm plagioclase. Large flattened pumices up to 5mm. Some opaques.

KCS-15-64: Middle Upper B

Strongly welded tuff with volcanic clasts a glassy matrix. Plagioclase 1-2mm and biotite ~1mm. Glassy matrix.

KCS-15-66: Upper B

Light grey- purple, poor-moderately welded tuff with porphyritic texture. 20% crystals, 15% plagioclase .5-5mm, 5%biotite .5-1 mm books, and 5%oxides. Biotite is oxidized

KCS-15-65: Sed Bed

Volcanogenic sedimentary bed. Rounded/subrounded, dark igneous clasts. Quartz and calcite cement.

KCS-15-62: C Base

Purple welded, rheomorphic tuff. Large flattened pumices- very large >5mm- silica rich. Chlorite alteration. 10% crystals, 10% plagioclase <0.8mm, sparse opaques and biotite.

KCS-15-61: Lower C

Moderately welded tuff with sparse opaques biotite. 15%small plagioclase crystals.

KCS-15-57: Mid C

Grey- purple welded crystal poor tuff. Abundant fiamme´. Vitroclastic. Chloritized.

KCS-15-56: Mid C

Grey welded crystal poor tuff with large flattened pumice. Chloritized and contains some biotite, pyroxene and opaques.

KCS-15-53: C upper

Purple brown, strongly welded, silica rich tuff. Large and abundant fiamme'. 8% crystals, 5% euhedral plagioclase 0.5-1mm, 3% biotite ~1mm, and <2% pyroxene.

KCS-15-58: C top

Vitric, slightly welded tuff. 10-12% crystals. Plagioclase 10%, biotite 5%, pyroxene 5%. Chloritized.

KCS-15-54: C

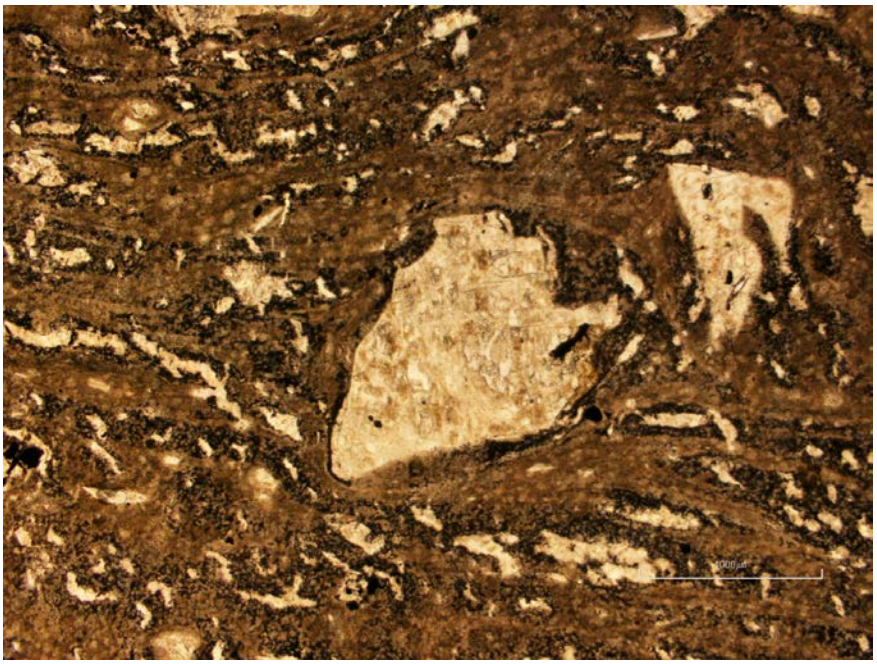
Strongly welded. Abundant fiamme´. Plagioclase, pyroxene and opaques. Chloritized.

Images

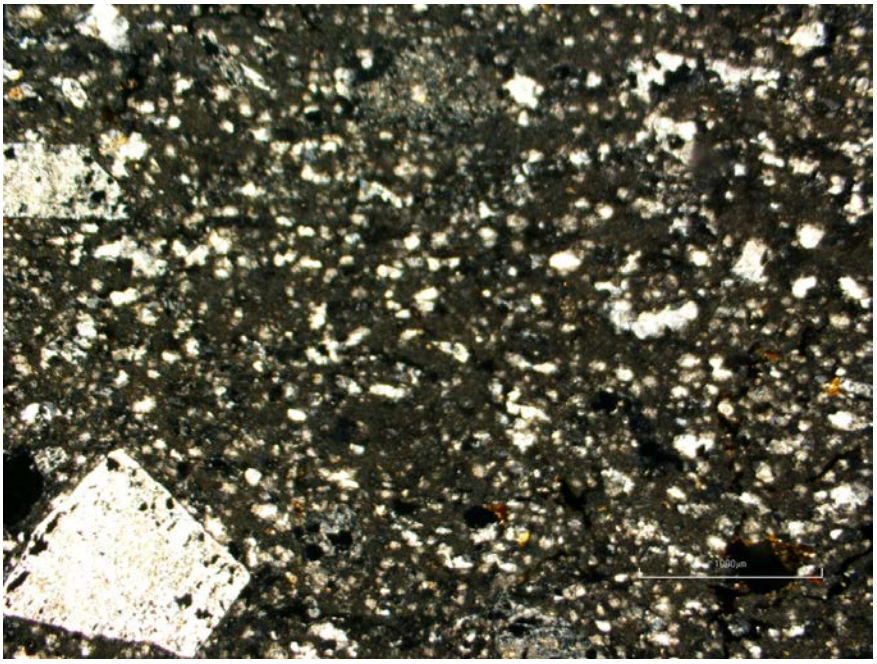
Ratio Mountain:

NHO-15-03: Dacite Lava xpl

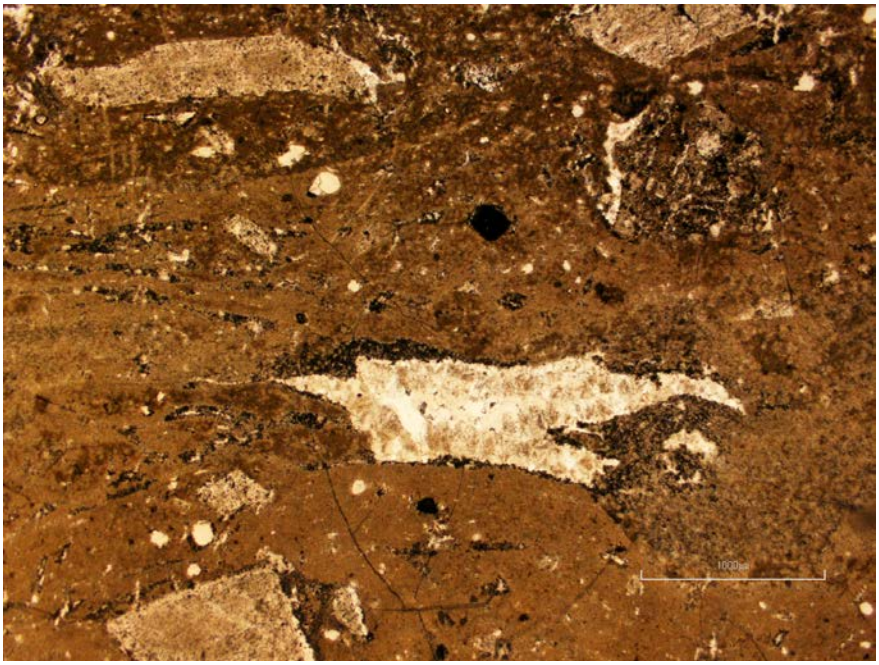
NHO-15-25: Base A ppl



NHO-15-26: Middle A xpl



NHO-15-27: Upper A ppl

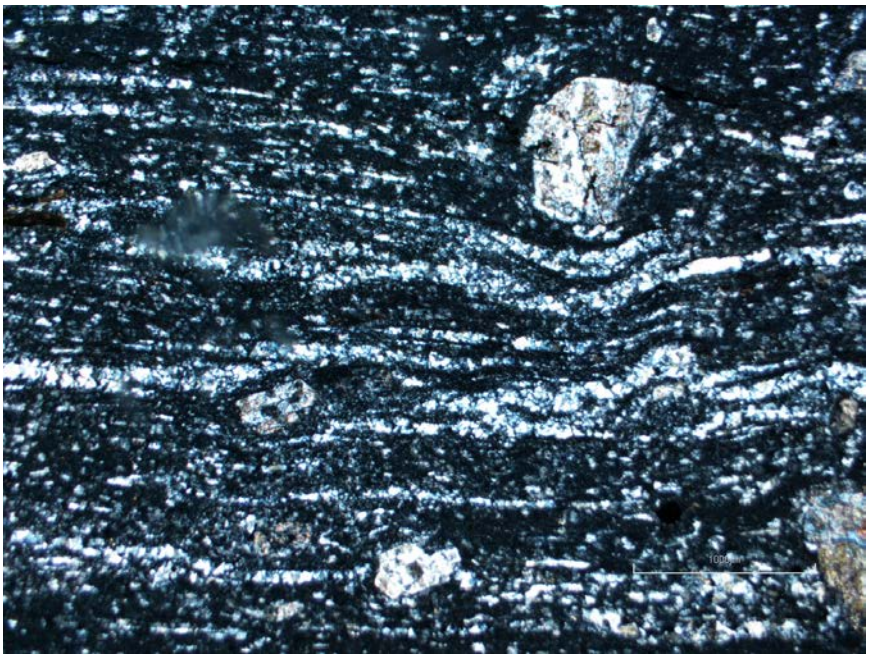


NHO-15-28: Middle B ppl

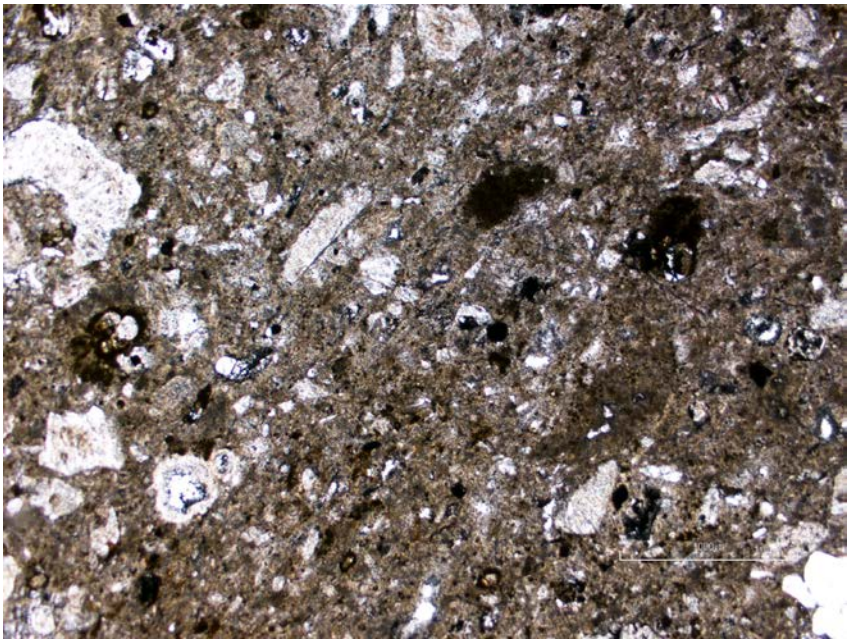
NHO-15-29: Upper B ppl

NHO-15-33: Base C ppl

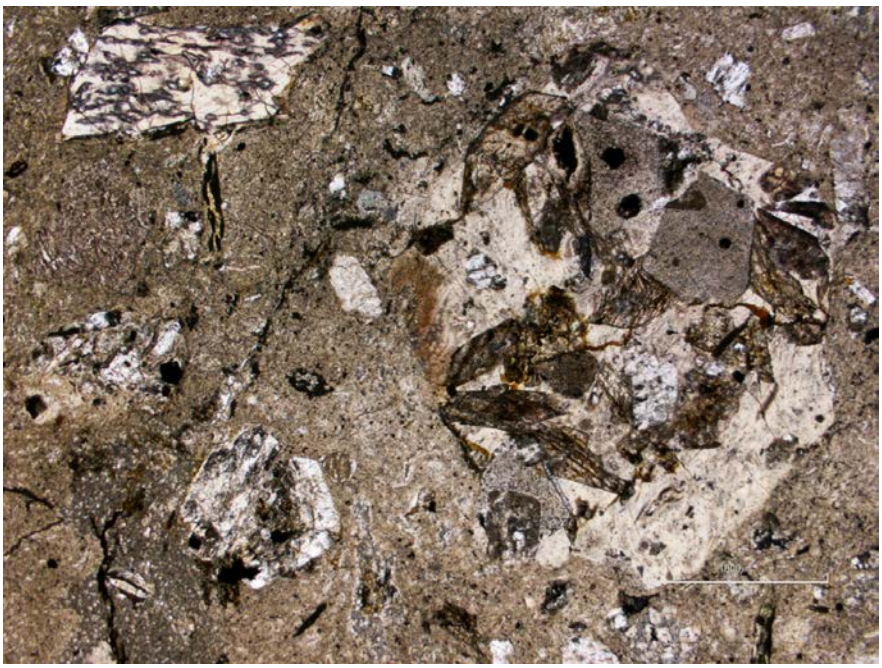
NHO-15-35: Middle C xpl



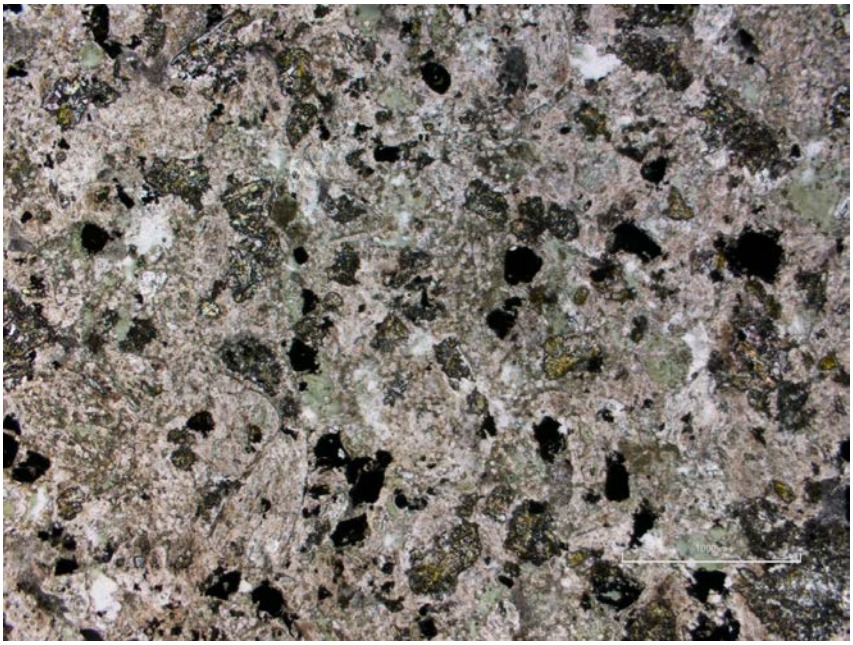
Middle C ppl



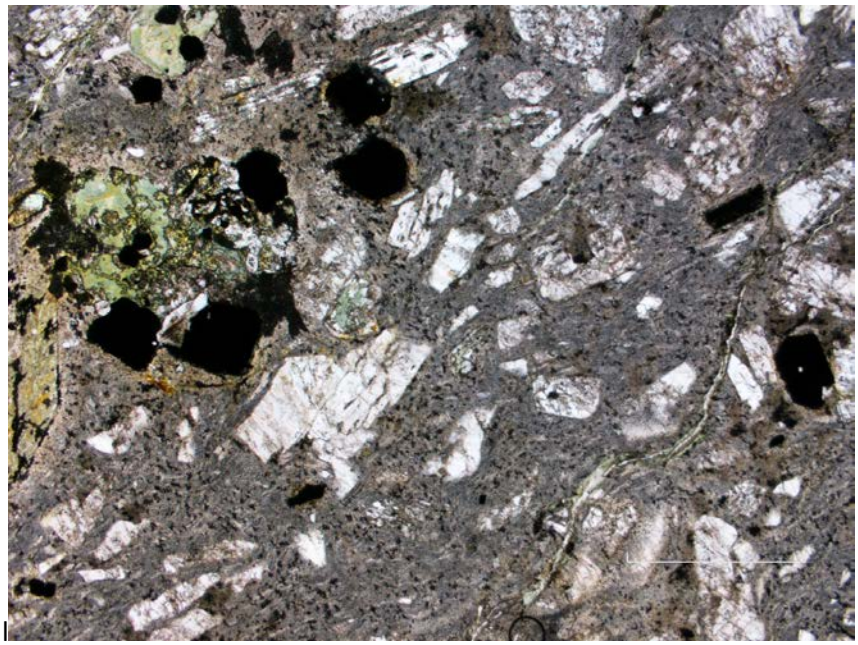
NHO-15-36: Top C ppl



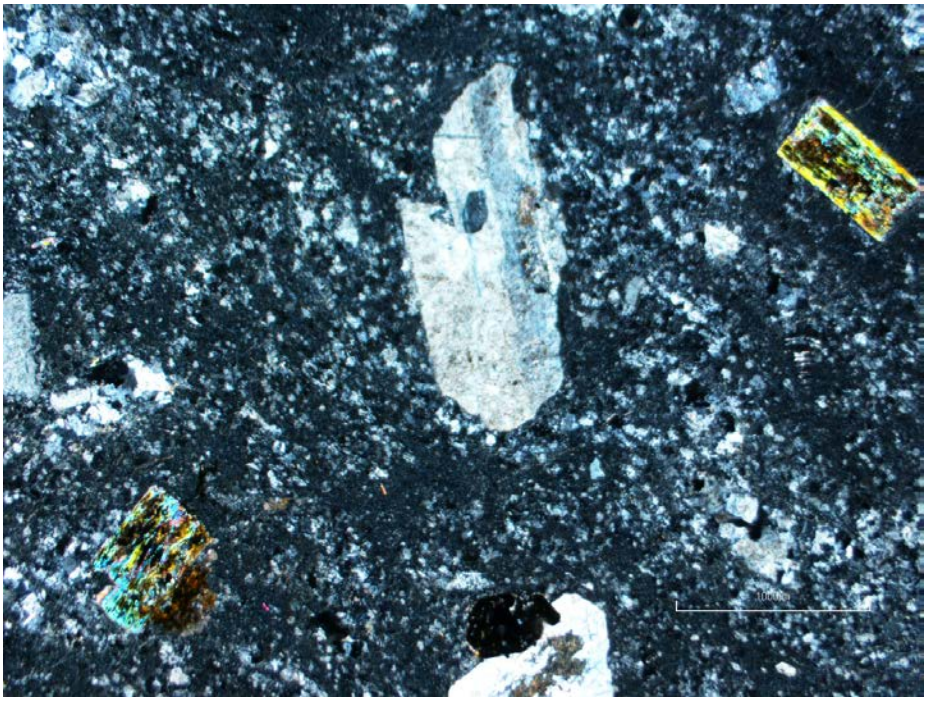
NHO-15-39: D ppl



NHO-15-41: E1 pp

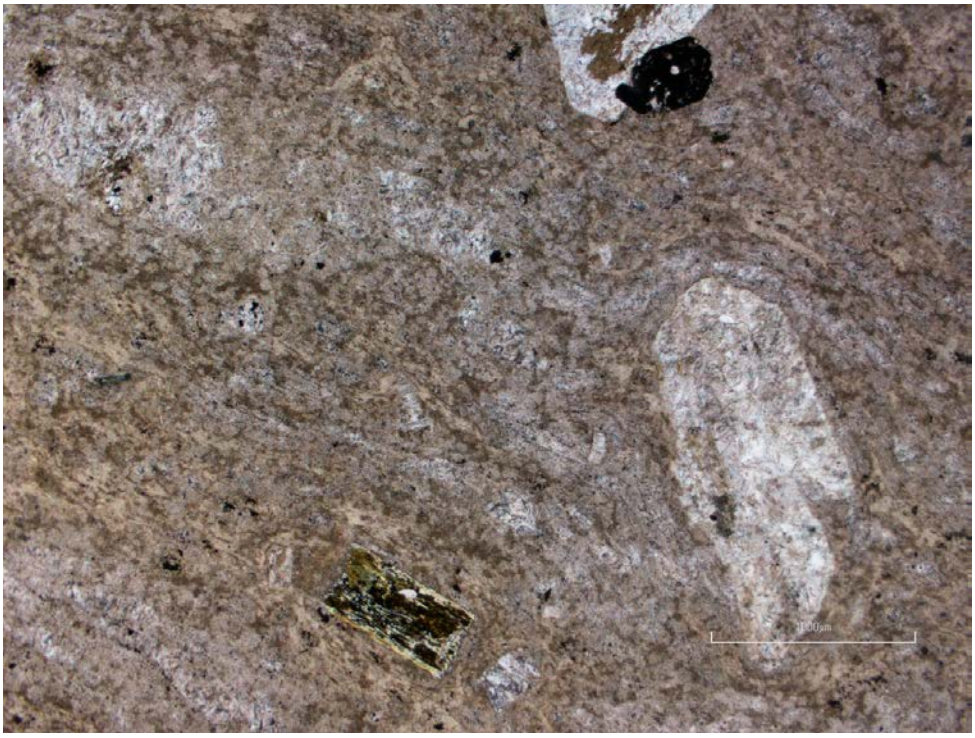


NHO-15-42: E2? xpl



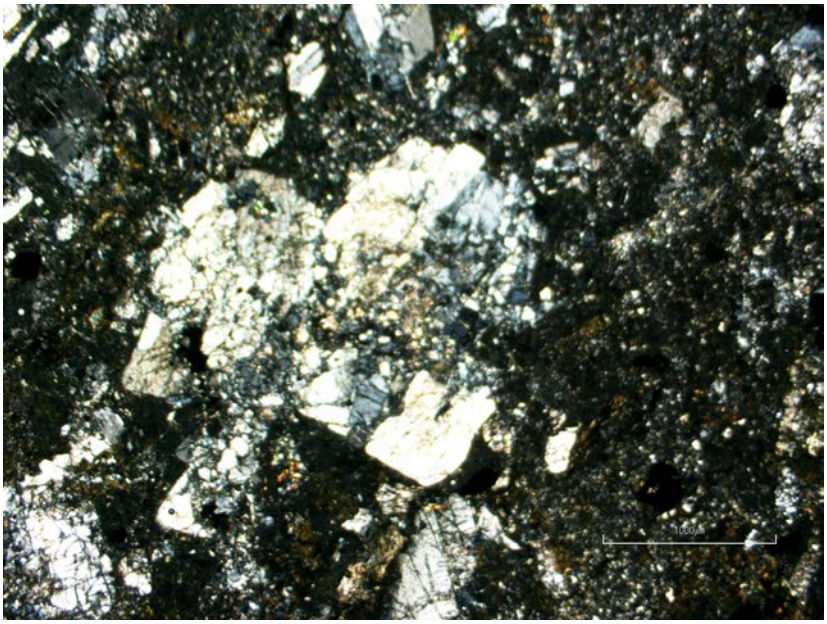
NHO-15-42: E2? ppl

NHO-15-47: E1 ppl



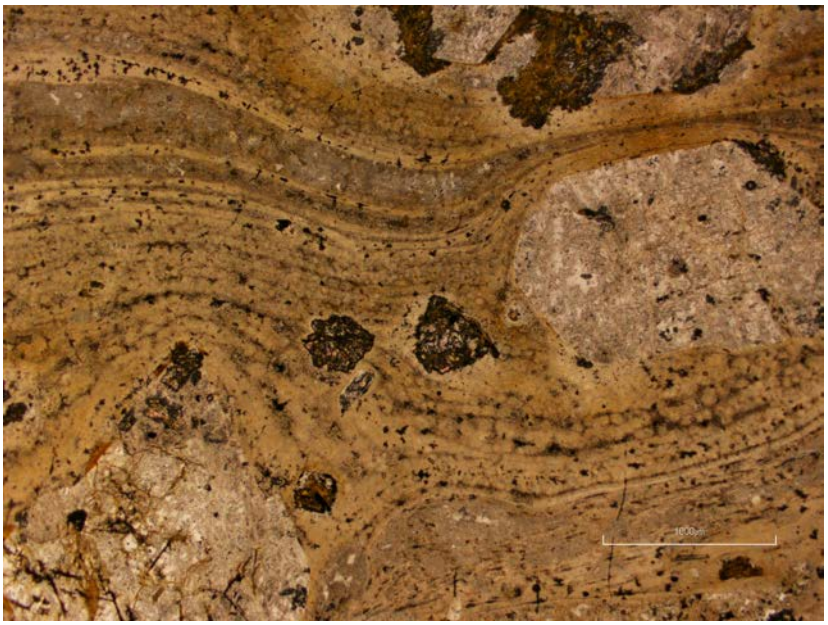
Boulder East:

KCS-15-12: DP xpl

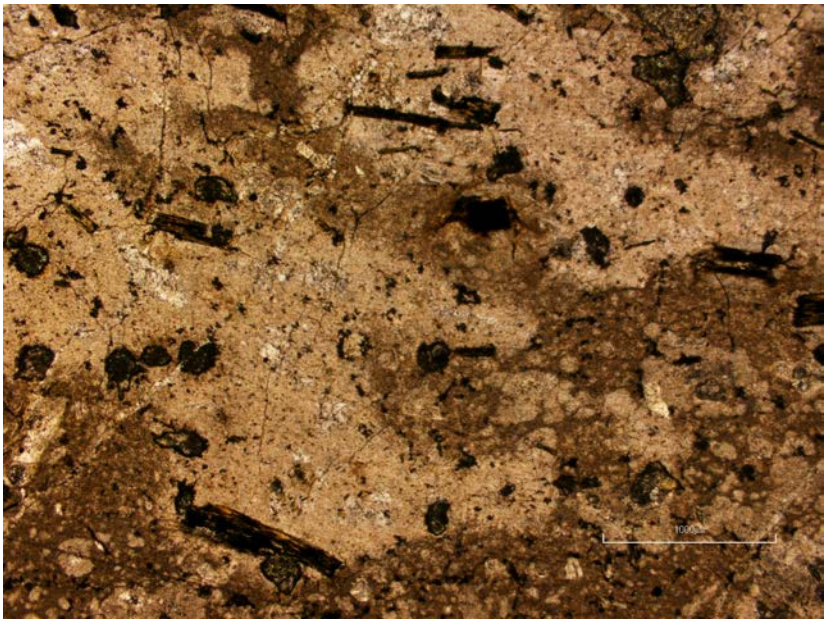


KCS-15-63: Middle B ppl

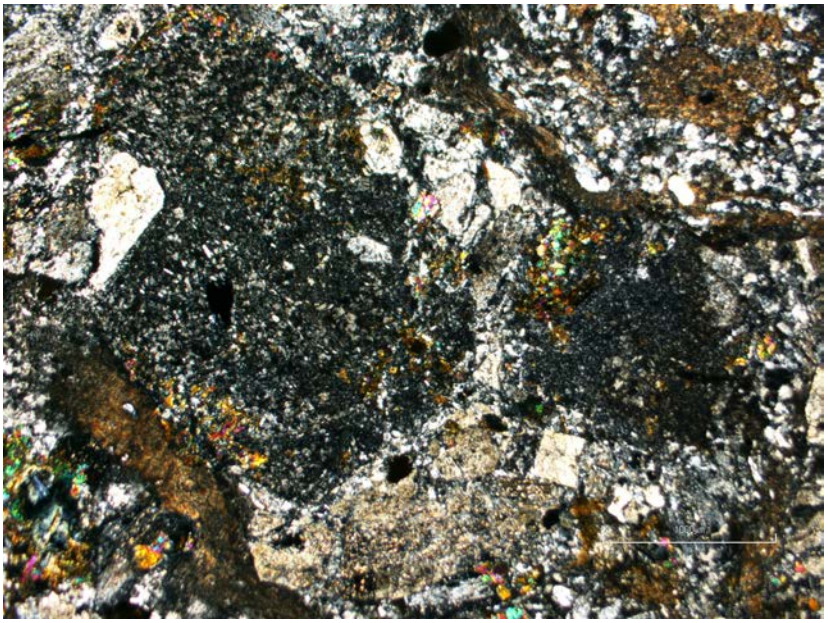
KCS-15-64: Middle Upper B



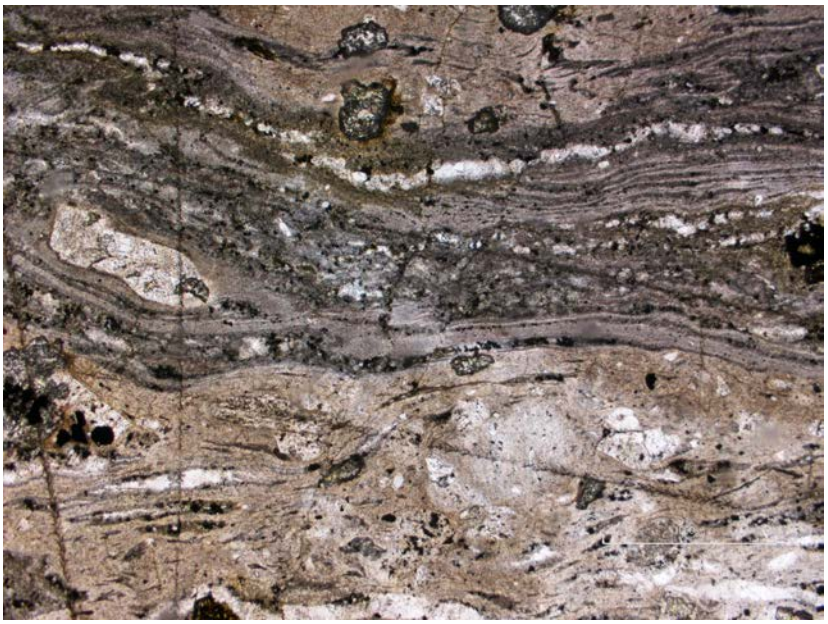
KCS-15-66: Upper B ppl



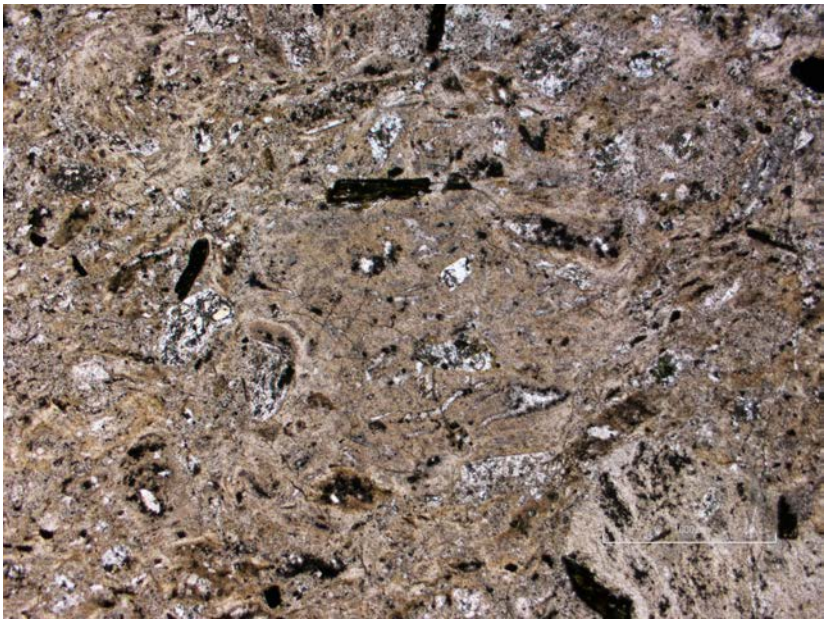
KCS-15-65: Sed Bed xpl



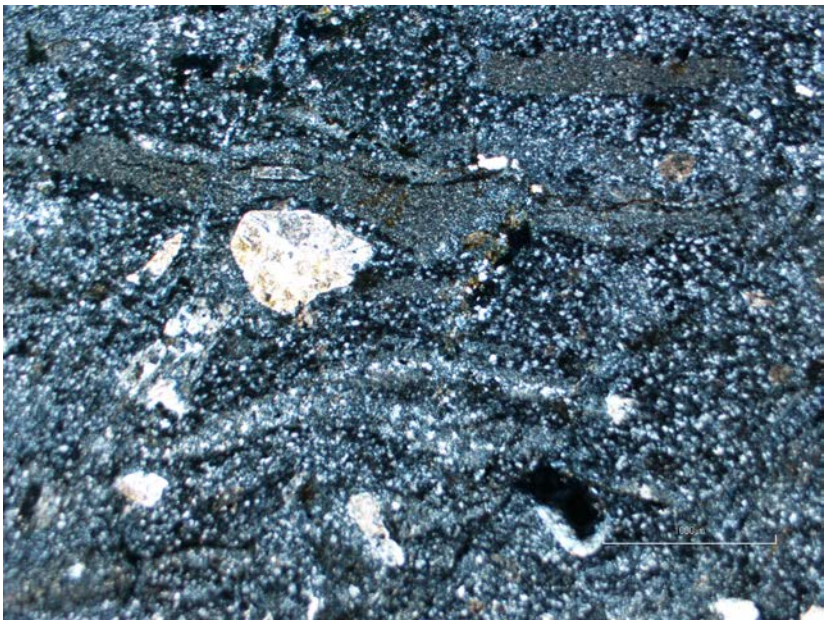
KCS-15-62: C Base ppl



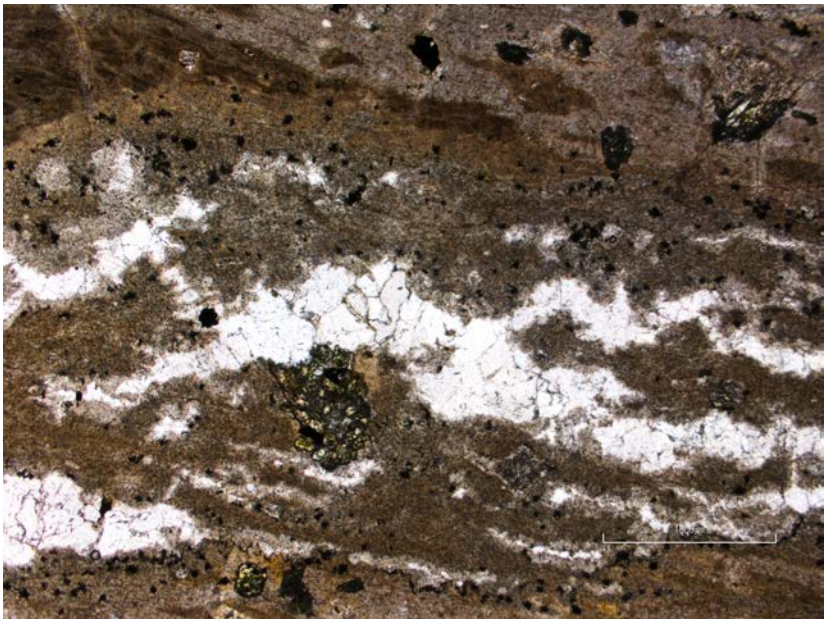
KCS-15-61: Lower C



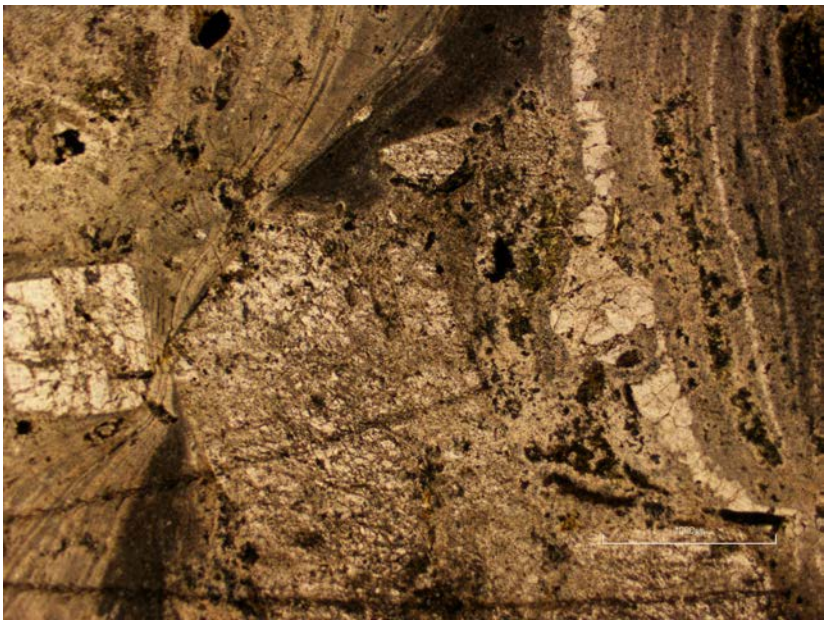
KCS-15-57: Mid C ppl



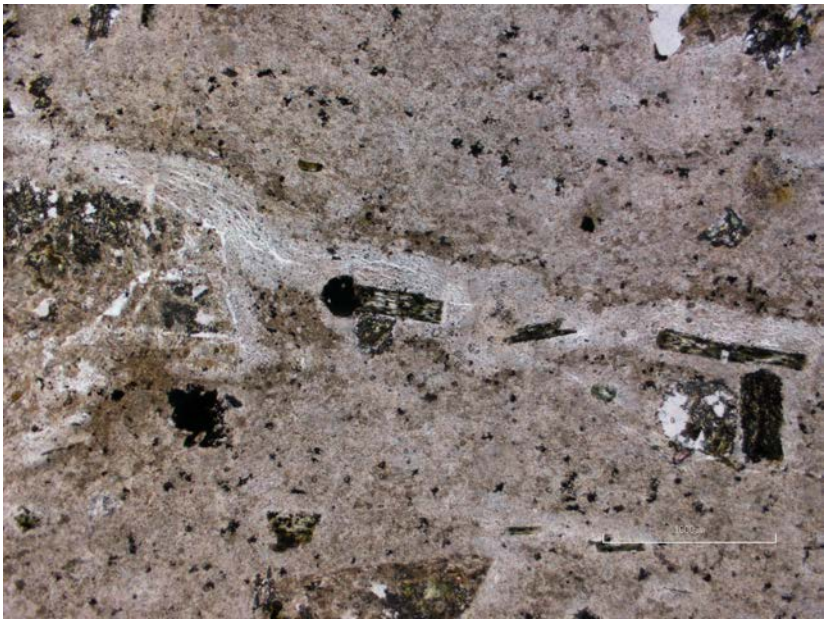
KCS-15-56: Mid C ppl



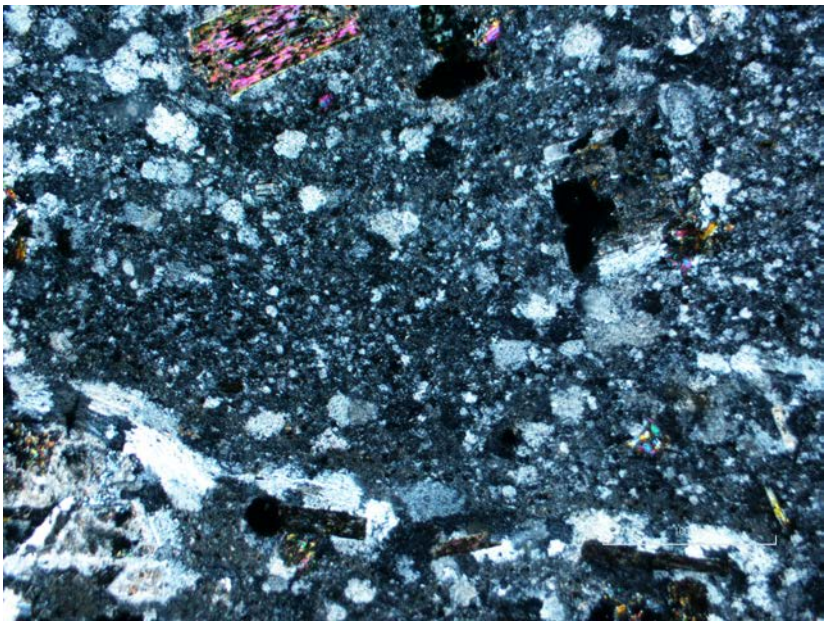
KCS-15-53: C upper ppl



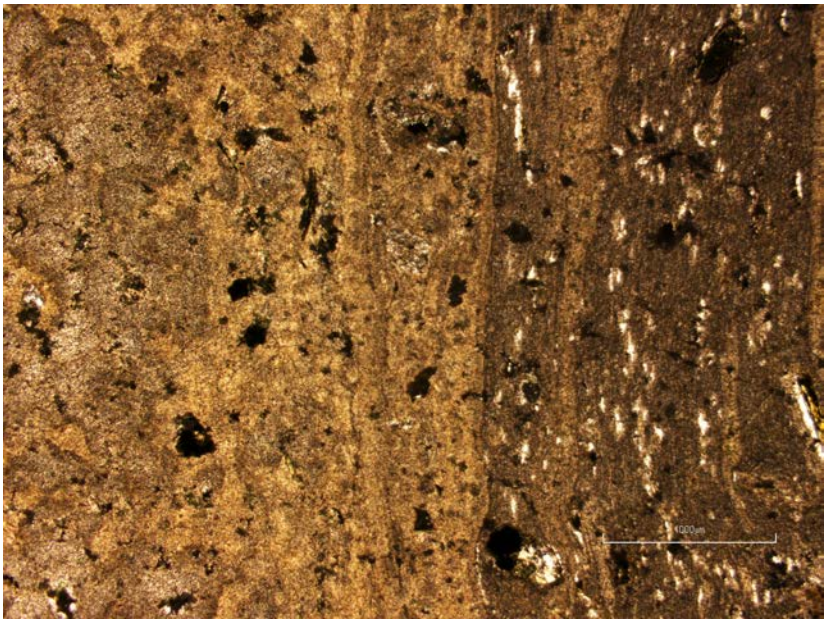
KCS-15-58: C top ppl



Xpl



KCS-15-54: C? ppl



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