Volcanic material and eruption style

By Raffaello Lena (text and images) and Guy Heinen (mineral microscopy), Jim Phillips (images)

Introduction

In previous works I have described the Strombolian eruptions, which may have formed the largest dark mantle deposits on the Moon, the Plinian eruptions including the Vesuvius volcano and trachydacitic and rhyolitic volcanism of Mount Amiata complex including the lunar highland domes.

In this fourth note we examine the volcanic material linked to the style of volcanism, e.g. extrusive and explosive activity.

Volcanic material and short glossary

Ash: fine volcanic material with dimensions less than 2 mm.

Caldera: almost circular depression generally due to the collapse of a sector above the magma chamber which empties following a large eruption.

Dike: dikes can be described as fractures into which magma intrudes or from which they might erupt. The fracture can be caused by the intrusion of pressurized magma, or vice versa, the rise of magma can be caused by and exploit existing or tectonically forming fractures.

Dome: swelling of the volcanic building due to an accumulation of lava.

Eruption: spillage, often violent, of molten, solid or gaseous volcanic material (see also previous note Strombolian eruptions).

Laccolith: sheet-like intrusion that has been injected within or between layers of sedimentary rock. The pressure of the magma is high enough that the overlying strata are forced upward and folded, giving the laccolith a dome like form with a generally planar base.

Lahar (mud flow): movement of pyroclastic material impregnated with water deposited on the flanks of the volcano.

Lapilli: volcanic material with dimensions between 5 and 50 mm.

Lava fountain: emission of jets of fluid lava at a considerable height from the outlet due to the pressure of the gases dissolved in it.

Lava: magma erupted on the surface, for chemical composition see also previous note trachydacitic and rhyolitic volcanism of Mount Amiata complex including the lunar highland domes.

Magma chamber: area of accumulation of magma below the earth's surface.

Magma: molten material at high temperature (generally between 900 and 1200 degrees Celsius) found inside the earth.

Plinian: strong explosive eruption similar to that of Vesuvius in 79 AD described by Pliny the Younger in two letters to Tacitus (see also previous note Plinian eruptions including the Vesuvius volcano).

Pumice: light, glassy and very porous effusive rock due to the high presence of voids due to the expansion of gas inside the magma and subsequent rapid cooling.

Pyroclastic flow: high speed lateral movement of pyroclastic material due to the decrease in pressure of the volcanic column.

Pyroclasts (tephra): solid volcanic material such as ash, sand, lapilli, blocks, volcanic bombs emitted during an explosive eruption.

Sill: a tabular sheet intrusion that has intruded between older layers of sedimentary rock, beds of volcanic lava or tuff, or along the direction of foliation in metamorphic rock. A sill is a concordant intrusive sheet, meaning that a sill does not cut across preexisting rock beds.

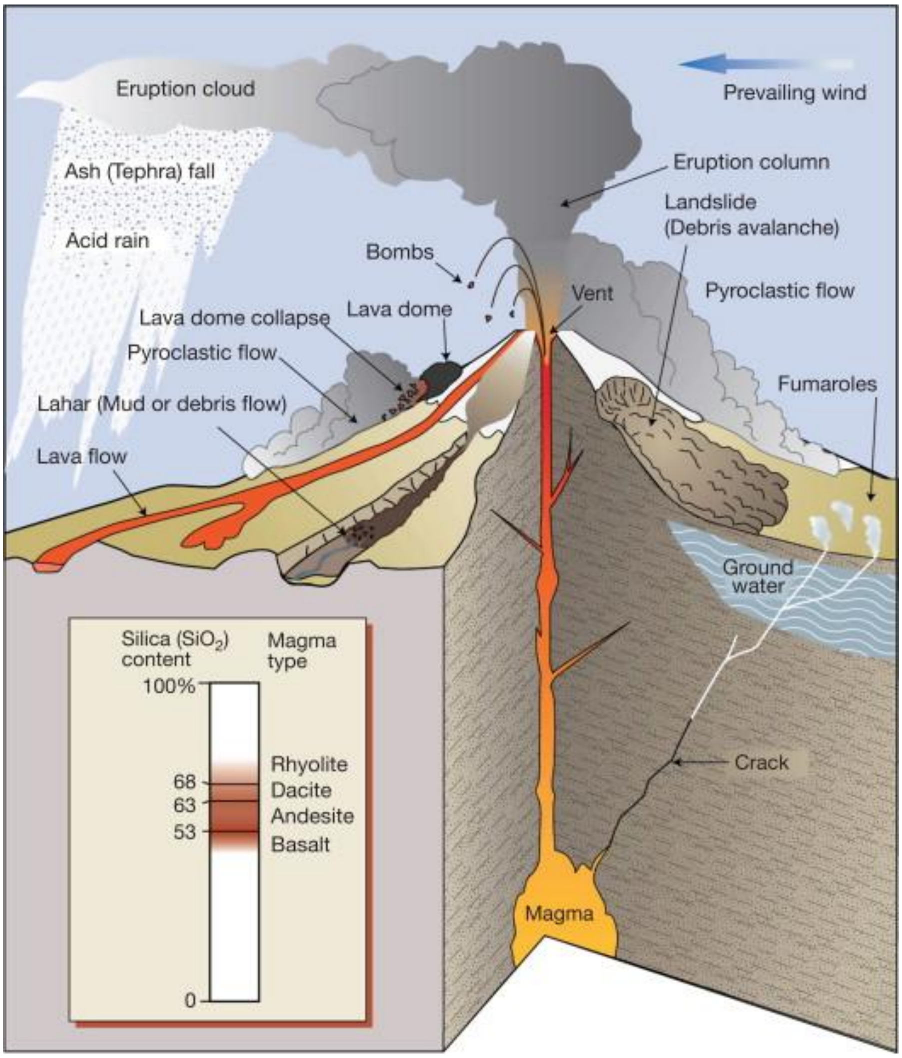
Slag: fragments of still fluid magma that deposit around a mouth during an eruption.

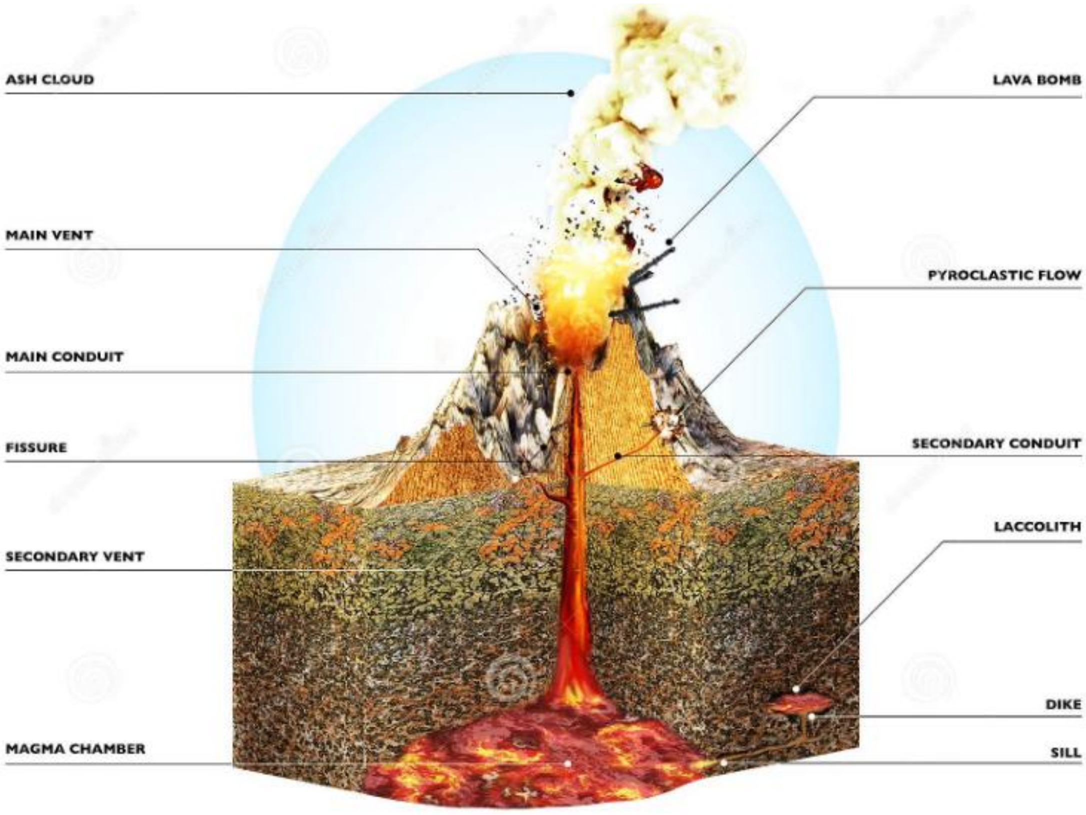
Stratovolcano: volcano formed by the alternation of lavas and pyroclasts.

Surge (base): steam mixed with ash that flows quickly along the flanks of the volcano from the base of the explosive column, setting fire to and destroying everything in its path.

Tuff: type of rock made of volcanic ash ejected from a vent during a volcanic eruption. Following ejection and deposition, the ash is lithified into a solid rock. Rock that contains greater than 75% ash is considered tuff.
Volcanic blocks: solid material of various sizes thrown during an eruption.
Volcanic bomb: large volcanic material (greater than 64 mm) produced by a volcanic explosion.
Volcanic conduit: chimney through which the magma flowing into the crater rises.
Volcanic crater: depression generally located on the top or flanks of the volcano building in which the volcanic conduit culminates.
Volcanic explosion: more or less violent emission of pyroclasts due to the release of gas from magma.

The figures, shown below, display some volcanic features:





Basic magmas tend to flow behaving like fluids rather dense and giving rise to large sub-horizontal lava covers (basaltic shelves). Acid (less fluid) magmas damage instead, it leads to type phenomena explosive, with emission of dust, ashes, lapilli and bombs.
These phenomena are much more dangerous of the precedents because the rashes can result in gravitational phenomena (castings pyroclastic and basal surge), which cause rapid descent along slopes of large chaotic masses (gas, liquid and solid) to high temperature.

Lava bomb and reticulite from explosive eruptions
A lava bomb is a "drop" of lava that solidifies during flight, being able to travel even kilometers away and often acquiring particular shapes aerodynamic, by virtue of its partial plasticity (Figs. 1-2)

Figure 1: Olivine lava bomb (private collection of Phillips) from Mortlake Australia.

Pumice is a glassy volcanic rock that is so full of bubbles that most examples will float on water. Reticulite is an extreme form of pumice in which the bubbles have coalesced, leaving only a tenuous reticular network of glassy lava behind in the interstitial spaces between the bubbles (Fig. 3). While pumice is more characteristic of the ejecta from the silica-rich magmas of stratovolcanoes such as Mount St. Helens, Lipari, Vesuvius, it may also be formed from the more silica-poor basaltic magmas of shield volcanoes such as those of Iceland and the Hawaiian Islands.

Reticulite is formed only by very high fountains of basaltic lava that contain dissolved gasses such as water vapor and carbon dioxide. The specimen of reticulite shown in Fig. 3 was probably formed by lava fountaining at Kilauea Volcano's Pu'u O'o vent sometime during the early to mid-1980s. Reticulite is so light that it's frequently transported many miles downwind of an eruption site. The Pu'u O'o vent lies roughly 7 miles (11 km) to the north of the Pu'u Loa site.

Figure 2: Olivine lava bomb (private collection of Phillips) from Mortlake Australia.

Figure 3: Reticulite (private collection of Phillips).

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A document of the eruption in Leilani Estates is also visible in internet (see video clip below)

Eruption of Leilani Estates (see historical document below)

https://www.youtube.com/watch?v=YwXgk2HtAwA

Fumarolic activity

Vulcano island (Italy) is a volcano characterized by vulcanian activity. Vulcanian eruptions may throw large metre-size blocks several hundred metres, occasionally up to several kilometres.

Since the end of the last magmatic eruption of Vulcano (1890), activity has consisted of fumarolic emissions of fluctuating intensity (La fossa crater). Several minerals may be identified in the fumarolic activity as described in the section "Mineral microscopy" below.

Stratovolcanoes

These volcanoes are characterized by effusive and explosive activity and are built up by the accumulation of material erupted through the conduit and increases in size as lava and pyroclastic particles are added to its slopes.

A volcanic eruption in Russia's far eastern Kamchatka P is shown in the video below

https://www.youtube.com/watch?v=mEhNb1I2xAk%20eninsula

Mount Etna (Italy) is one of the world's most active volcanoes and is in an almost constant state of activity (https://www.youtube.com/watch?v=WngG4gXbcHw).

Vesuvius, Vulcano and Phlegraean Fields caldera (Campi Flegrei) in Italy have a very low eruptive frequency and are found in conditions of plugged crater. Not everybody quiescent volcanoes present the same level of risk, both for the danger of the phenomena expected, both for the different size of the exposed population. Furthermore, some exhibit phenomena of secondary volcanism - such as degassing from the soil, fumaroles - which can normally induce to risky situations.

Volcanic activity in Italy is also concentrated in the submerged areas of the Tyrrhenian Sea and the Channel of Sicily. Some underwater volcanoes are still active, others now extinct represent real submarine mountains. The best known are Marsili, Vavilov, Magnaghi, the submarine volcanoes Palinuro, Glauco, Eolo, Sisifo, Enarete. Information on the distribution of Italian volcanoes is reported in the following video:

https://www.youtube.com/watch?v=-YVw7YfFkqk

Tuff from explosive eruptions

Tuff is relatively soft and porous rock that made of ash and other sediments from volcanic vents that has solidified into the rock (Fig. 4).

Figure 4: Tuff from Ventotene island in Italy (private collection of Lena).

Spinels

The group of minerals produced by explosive eruptions may include the minerals essentially present in zeolitized lava projectiles and metamorphosed carbonates, e.g. meionite, vesuvianite and also spinels described below. The spinels are any of a class of minerals of general formula AB_2X_4 which crystallize in the cubic (isometric) crystal system; other combinations incorporating divalent, trivalent, or tetravalent cations, including magnesium, zinc, iron, manganese, aluminum, chromium, titanium, and silicon, are also possible.

The spinel is referred to $MgAl_2O_4$. The anion is normally oxygen. A and B can also be the same metal with different valences, as is the case with magnetite, Fe_3O_4 (as $Fe^{2+}Fe^{3+}{}_2O^{2-}{}_4$), which is the most abundant member of the spinel group.

Thus these species are sub-divided into three series: Spinel series (B = Al), Magnetite series (B = Fe), and the Chromite series (B = Cr). Some samples of the private collection of Lena are shown in Figs. 5a-b (Magnetite) and 6 (Chromite).

Figure 5a: Magnetite (private collection of Lena), with magnetic properties.

Figure 5b: Magnetite (private collection of Lena), with magnetic properties.

Figure 6: Chromite (private collection of Lena).

One unexpected result was the discovery of a new feldspathic rock with spectral features dominated by (Mg, Al)-spinel exposed at localized areas on the lunar surface.

The spinels identified on the Moon are Fe, Cr or Ti rich opaque minerals. Small amounts of transparent (Mg, Al)-rich spinels (pink spinel) have been identified in few lunar samples, but they have always been found to occur in association with olivine or other mafic minerals. An overview of this issue is reported in the article by Pieters at al. (October 2014, American Mineralogist 99(10):1893-1910).

Mineral microscopy

In the following Figures (Figs. 7-22) are shown some images taken by Heinen using the mineral microscopy (from his private collection). A 9Si Leica microscope was used. It has a built-in camera of 10 Mpix. Magnification is from 6.3 to 55 X, but can be extended to 110X. Heinen stacks 10 to 40 images using the software HeliconFocus. Images are treated with Lightroom, Sharpen projects pro and Photoshop Elements. The samples shown below are from Vesuvius, Etna and Vulcano island in Italy and Tolbachik volcano in Russia.

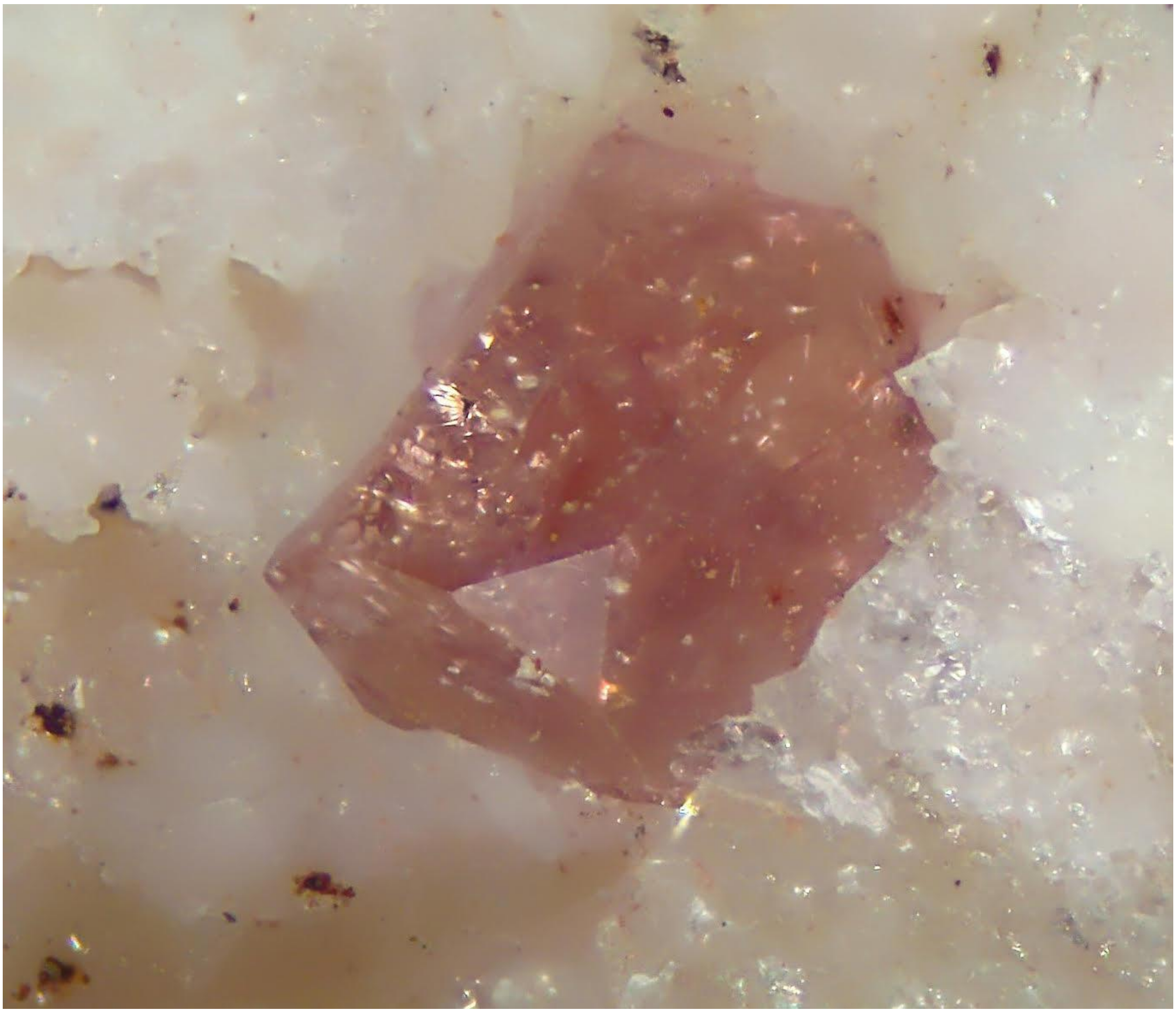


Figure 7: Spinel. The picture measures 1.5 mm, Cava San Vito (Vesuvius). Image taken by Heinen from his private collection.

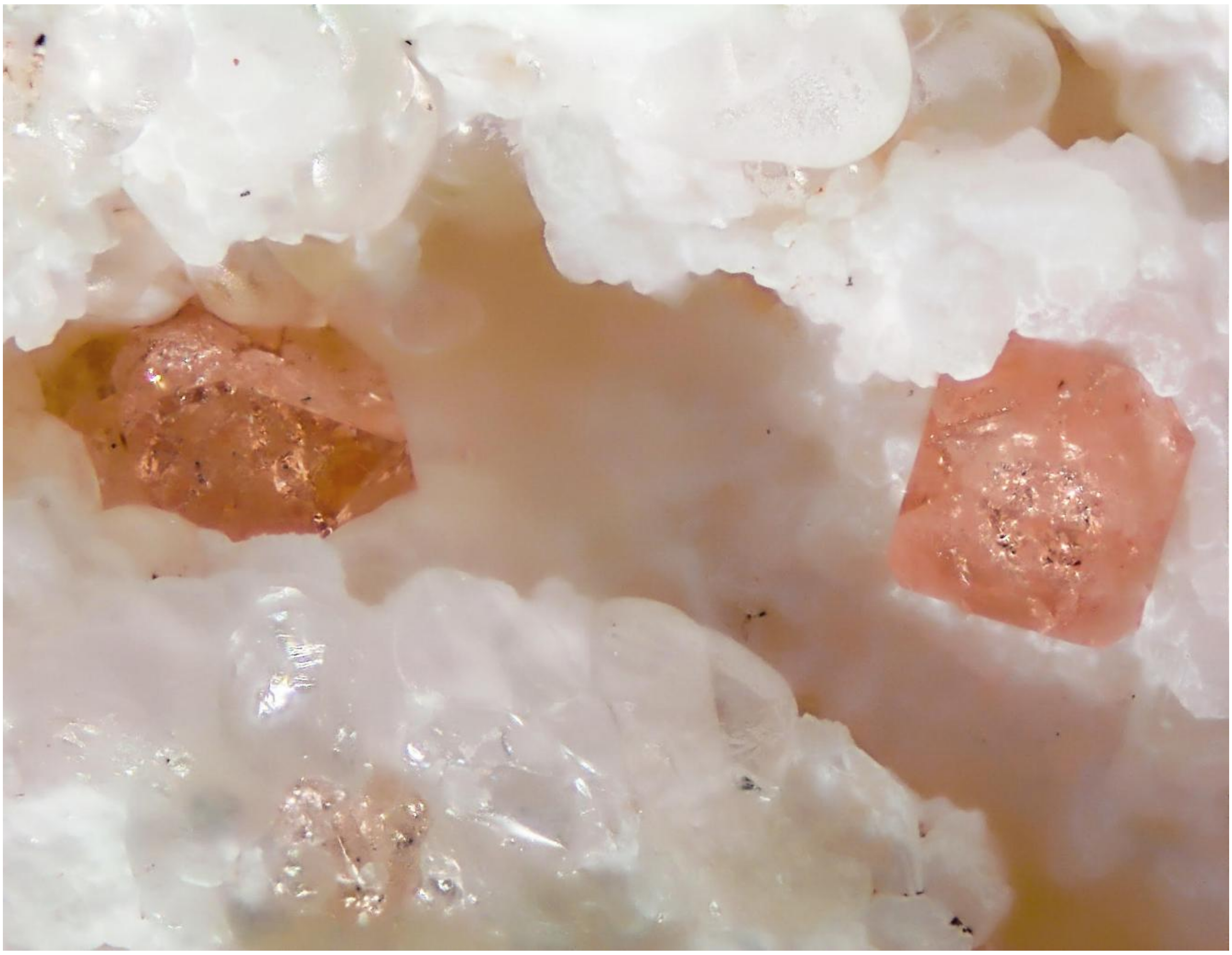


Figure 8: Spinel two crystals. The picture measures 3.3 mm, Cava San Vito. Image taken by Heinen from his private collection.

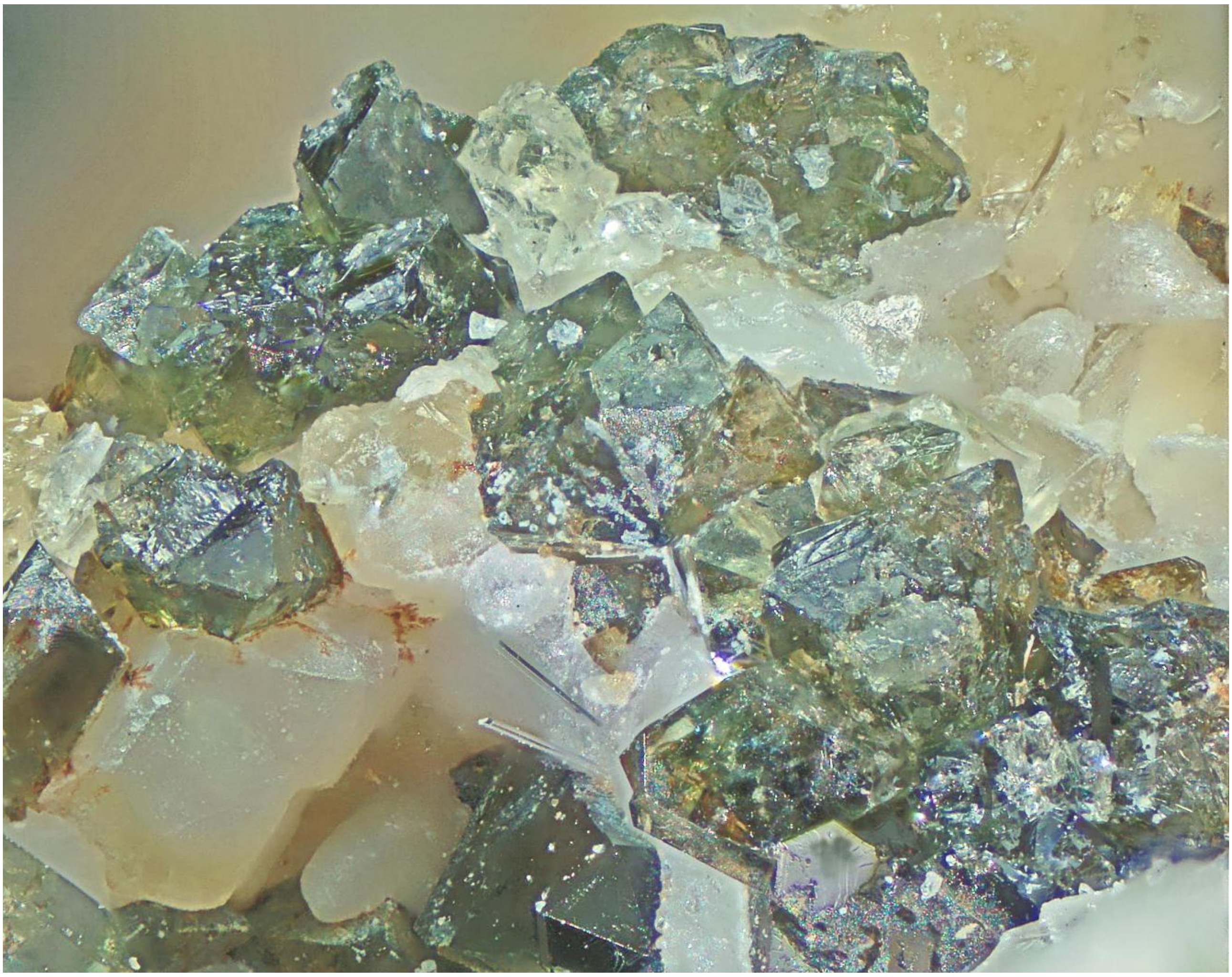


Figure 9: A Cl-Spinel. The picture measures 4 mm, Cava San Vito. Image taken by Heinen from his private collection.

Figure 10: Spinel. The picture measures 2.5 mm, Cava San Vito. Image taken by Heinen from his private collection.

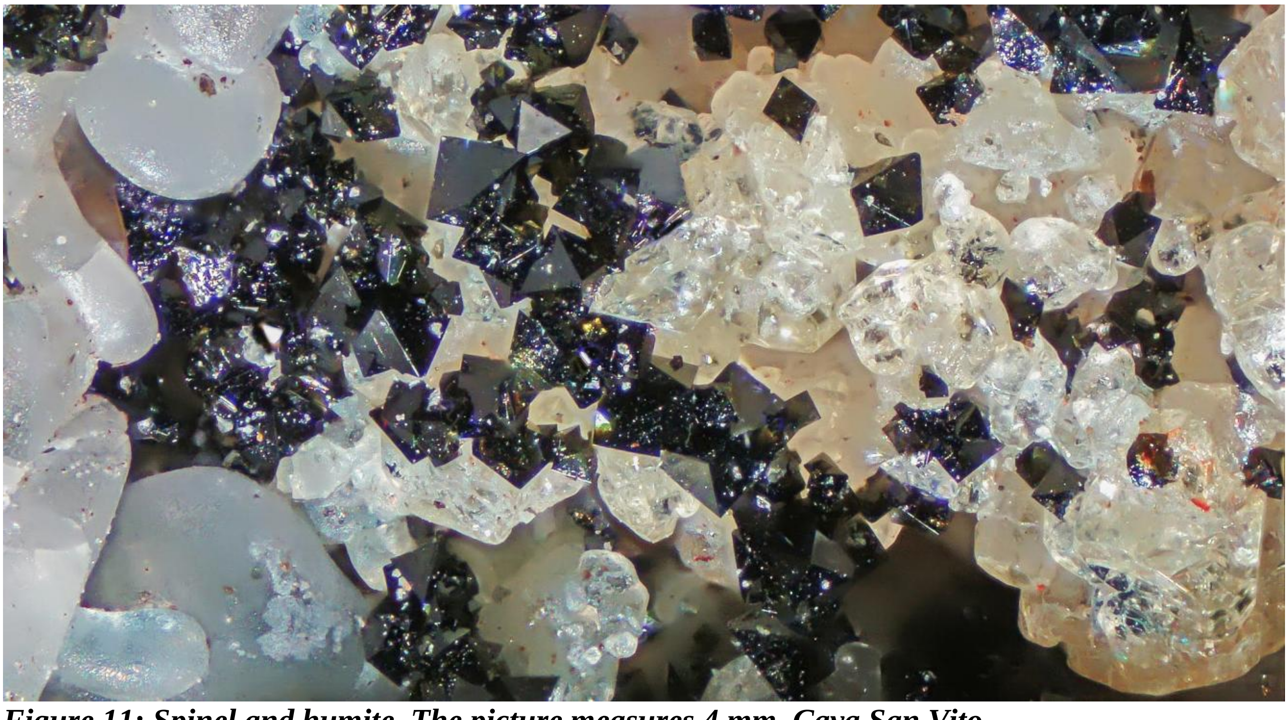


Figure 11: Spinel and humite. The picture measures 4 mm, Cava San Vito.
Image taken by Heinen from his private collection. Humite is a group of nesosilicates, as $(Mg,Fe)_7(SiO4)_3(F,OH)_2$.

Figure 12: Lazurite, magnetite and diopside (pyroxene), 30X, Somma Vesuvius. Image taken by Heinen from his private collection.

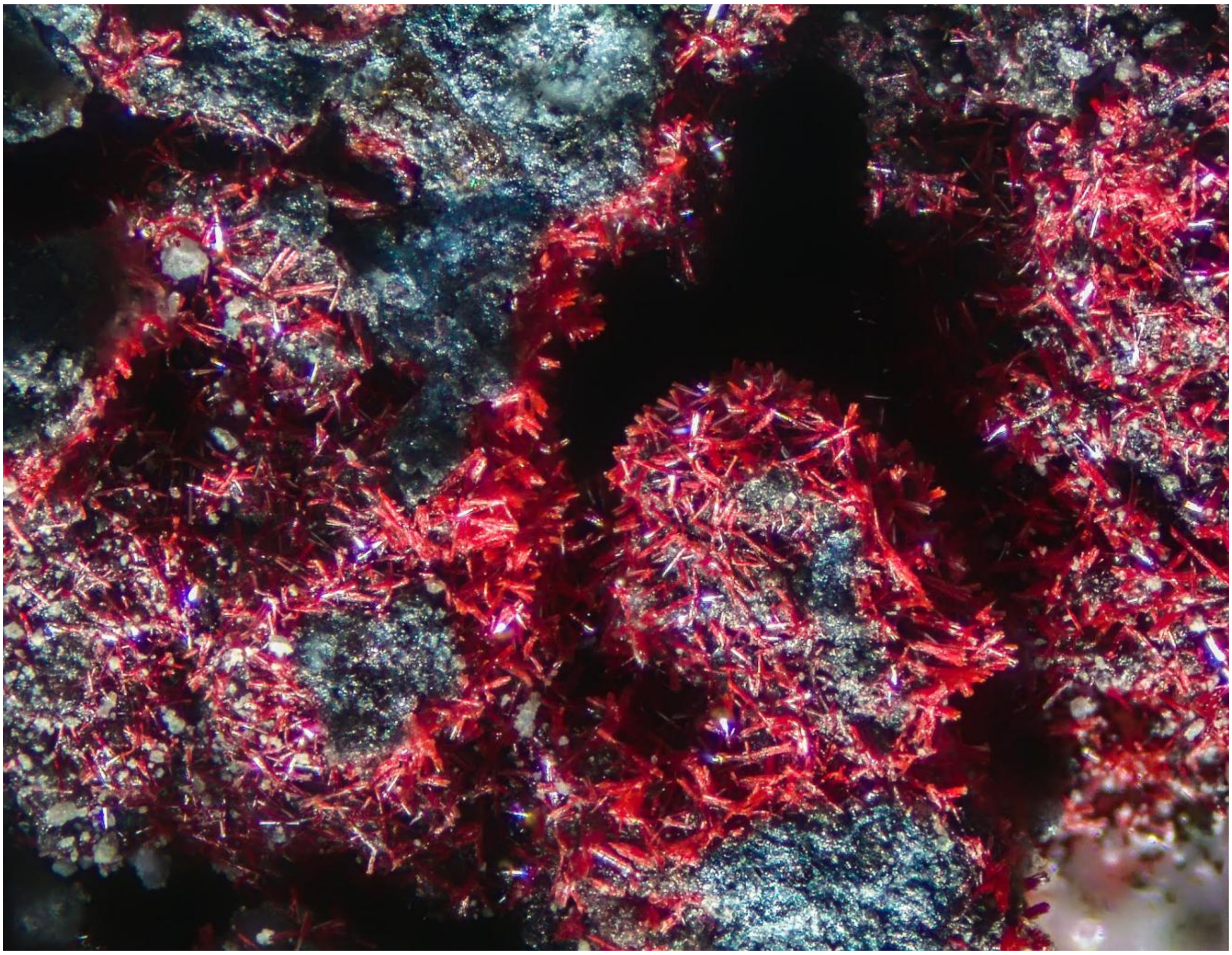


Figure 13: Demicheleite, 55 X, La fossa Vulcano island. Image taken by Heinen from his private collection. Demicheleite (BiSBr) is a bismuth sulfohalogenide found in an active high-temperature fumarole at the rim of La Fossa crater, Vulcano Island, Aeolian archipelago, Sicily, Italy. It is associated with other minerals as pseudocotunnite, bismoclite, bismuthinite, cotunnite, and challacolloite.

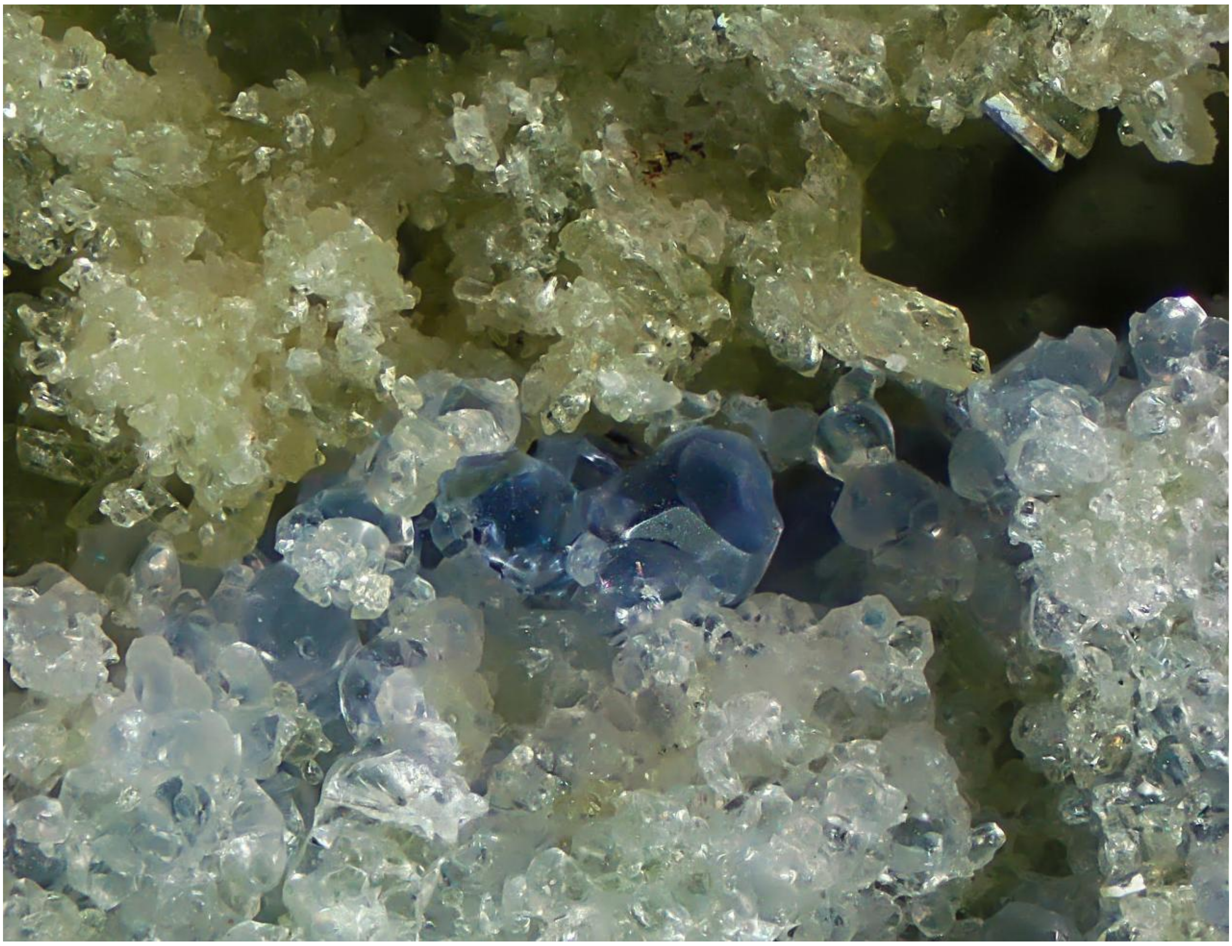


Figure 14: Haüyne, 40X,Cava San Vito. Image taken by Heinen from his private collection.

Figure 15: Sassolite, 3.6 mm, La fossa Vulcano island. Image taken by Heinen from his private collection. It is a fumarolic material corresponding to boric acid, H_3BO_3.

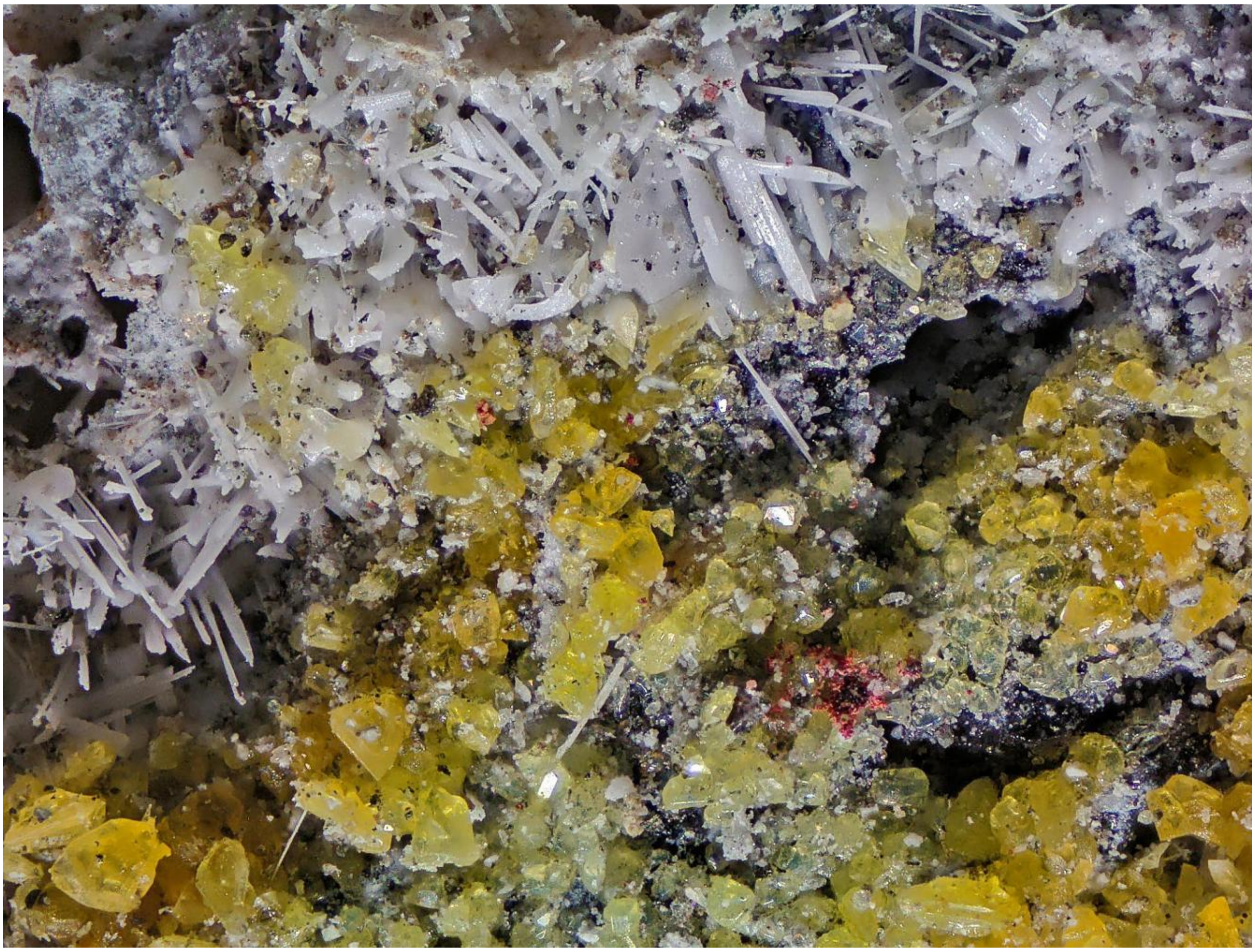


Figure 16: Pseudocotunnite (K_2PbCl_4) and challacolloite (KPb_2Cl_5), 4 mm, La fossa Vulcano island. Image taken by Heinen from his private collection. A rich sample, with white prismatic crystals of Pseudocotunnite and yellowish crystals of challacolloite. These rare minerals are exclusive of the fumaroles of the Italian volcanoes Vesuvius and La Fossa Crater, Vulcano island.

Figure 17: Vonsenite ($Fe^{2+}_2Fe^{3+}(BO_3)O_2$), 7 mm, Villa Inglese, Somma Vesuvius. Image taken by Heinen from his private collection.

Figure 18:** Dimorphite,(As_4S_3), and Realgar (As_4S_4), 4 mm, Solfatara, Phlegraean Fields caldera. **Image taken by Heinen from his private collection.** Dimorphite is a very rare orange-yellow arsenic sulfide mineral. In nature, dimorphite forms primarily by **deposition in** volcanic **fumaroles. More data on the fumarolic activity is reported in our previous note.

***Figure 19:** Alumoklyuchevskite, Tolbachik volcano, Kamchatka. **Image taken by Heinen from his private collection.** Alumoklyuchevskite, a copper mineral, $K_3Cu_3(Al,Fe^{3+})(SO_4)_4O_2$, was discovered in a fumarole in the North Breach of the Great fissure Tolbachik eruption in 1975.*

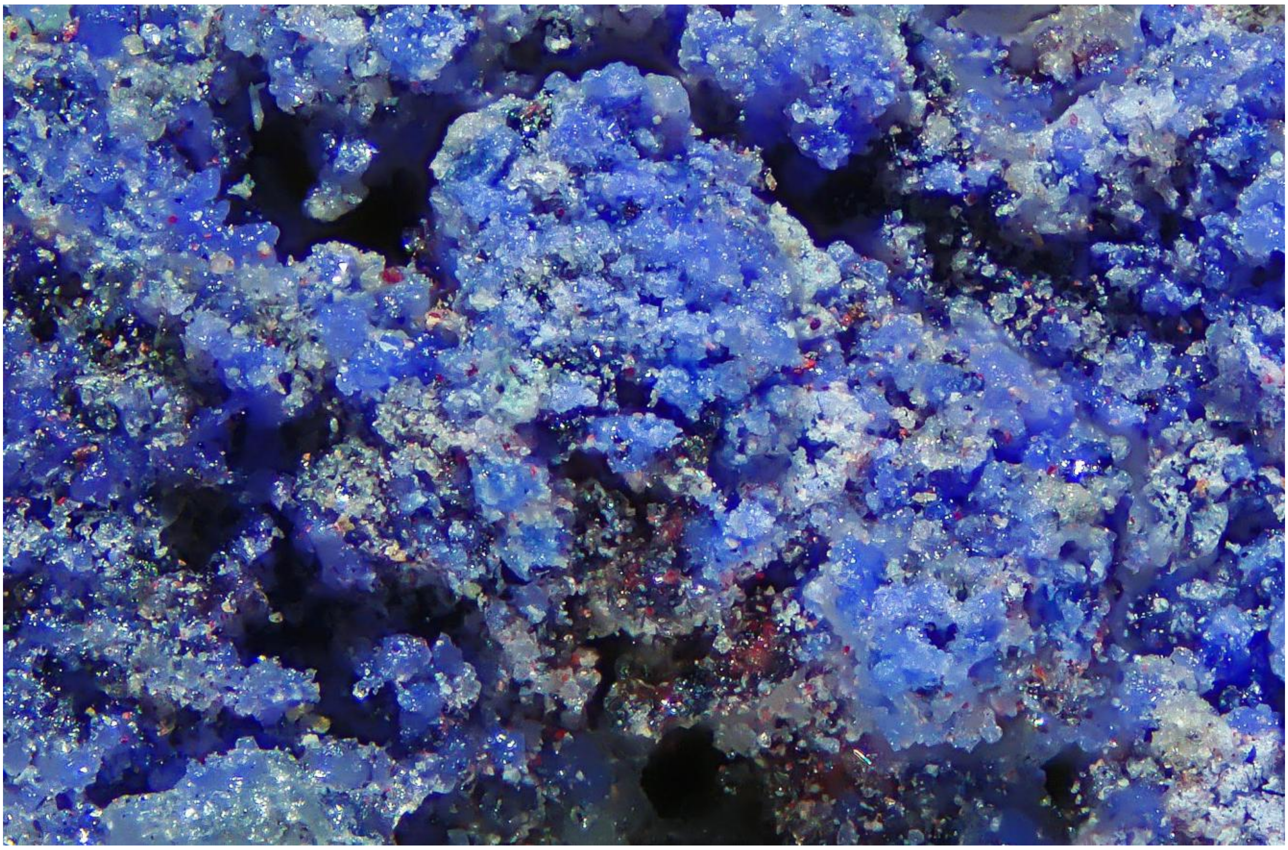


Figure 20: Bradaczekite, Tolbachik volcano, Kamchatka. Image taken by Heinen from his private collection, $NaCu_4(AsO_4)_3$. It was discovered in a fumarole in the North Breach of the Great fissure Tolbachik eruption in 1975.

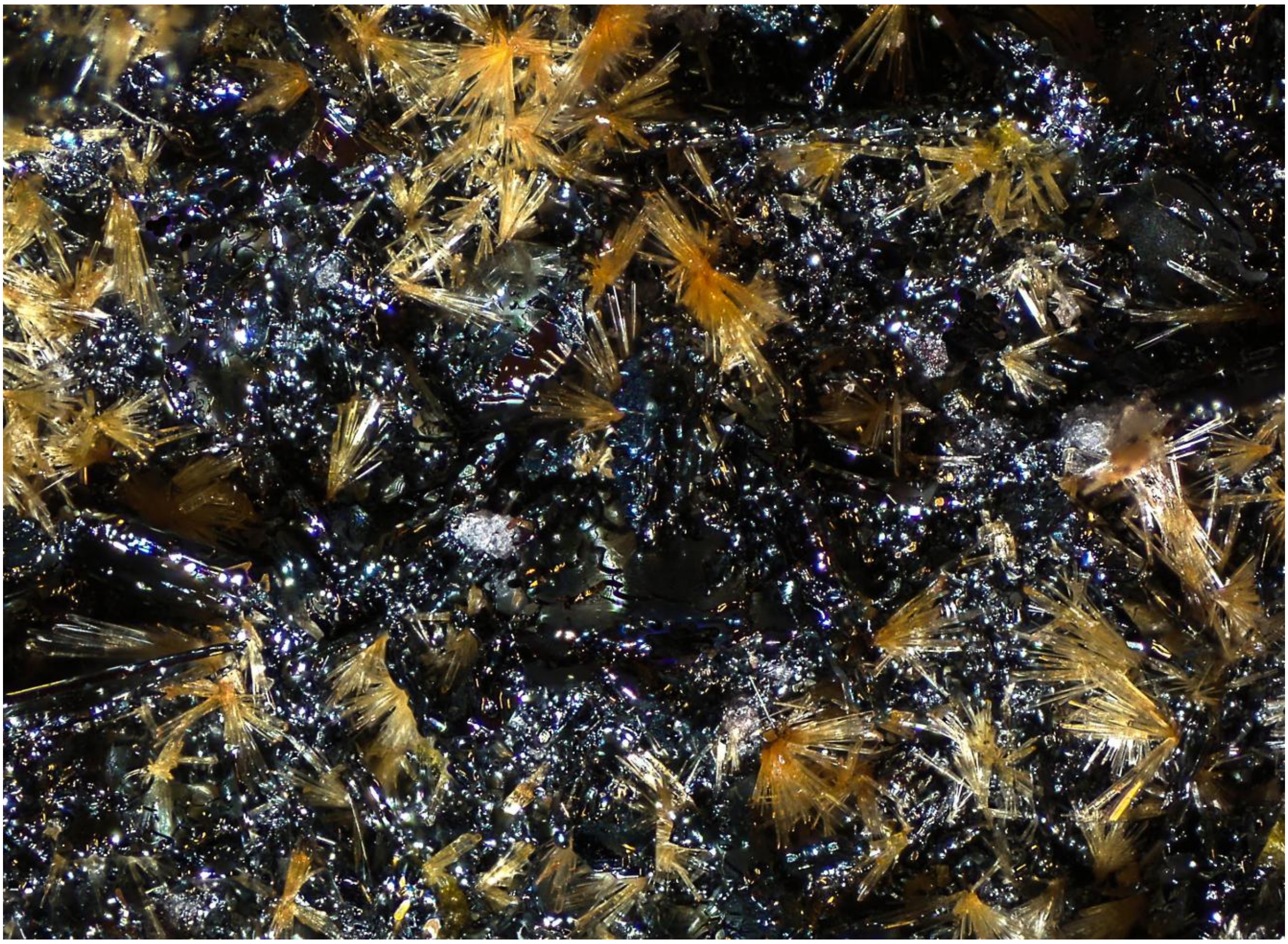


Figure 21: Fluoro-Edenite, *$NaCa_2Mg_5(Si_7Al)O_{22}F_2$,* ***Biancavilla/Etna. Image taken by Heinen from his private collection.***

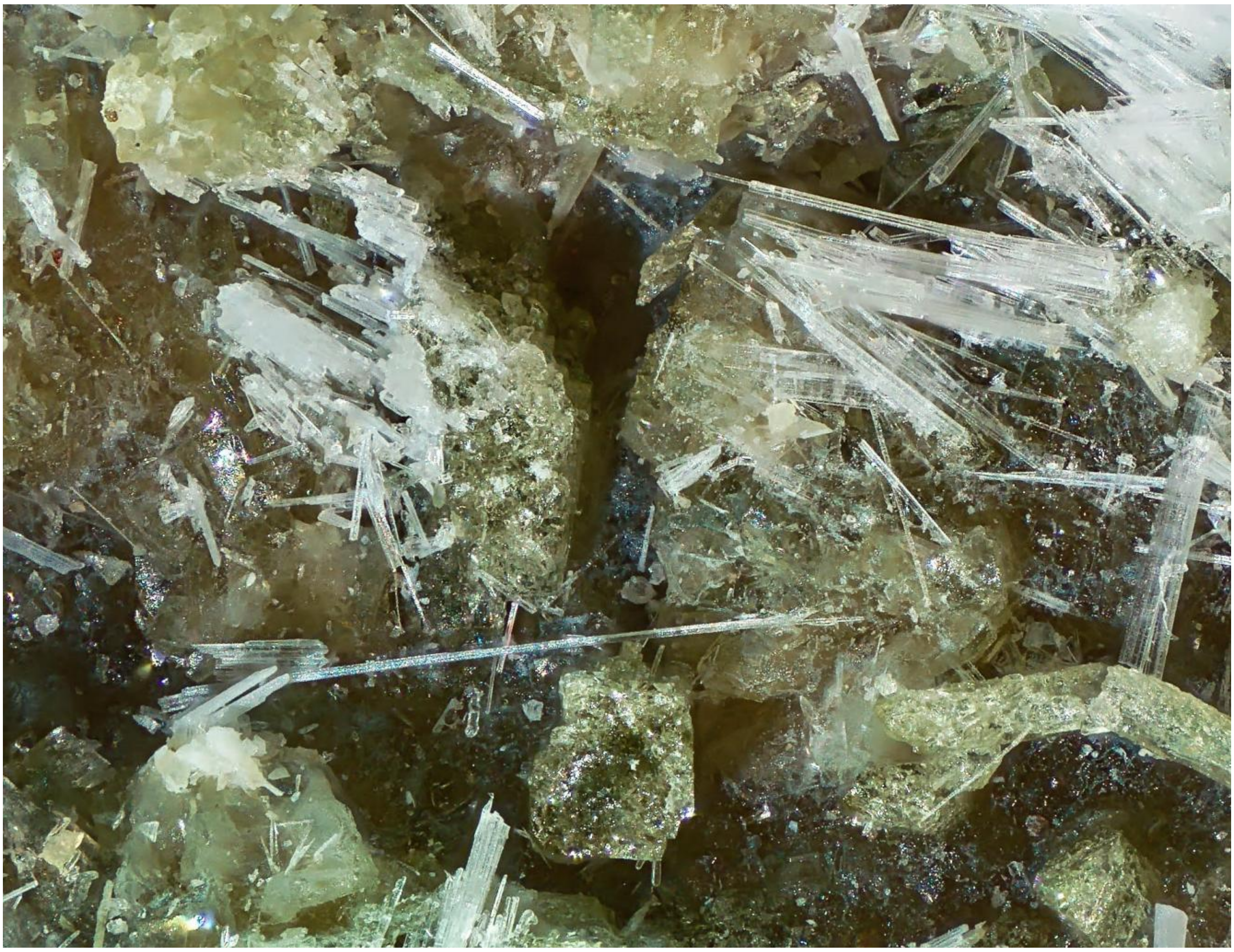


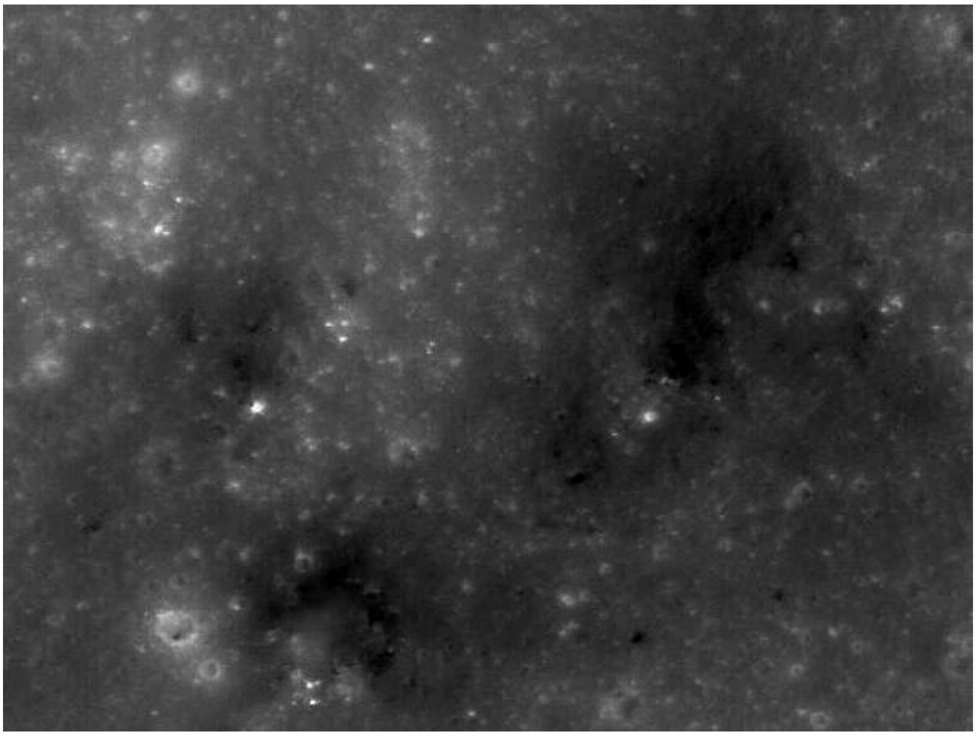
Figure 22: Kaliophilite, $KAlSiO_4$, Cava san Vito. Image taken by Heinen from his private collection.

Lunar Pyroclastic deposits and spinels

The distribution of lunar pyroclastic deposits (LPDs) bears on the problem of the nature of lunar volcanism. LPDs are low-albedo units observed as dark smooth areas in the highlands, on the floors of craters as well as near mare deposits and they are often associated with fractures, irregular depressions and other likely volcanic vents.

These pyroclastic deposits often appear to drape over or mantle the underlying surface, which may be at mare, smooth plains, or hummocky highland deposits. A recent work by Weitz et al. examined the M^3 mineralogical parameter mosaic across the *Sinus Aestuum* province, confirming spectrally the presence of possible pyroclastic glasses, including spinels.

The spinel deposits are strongly correlated to the distribution of pyroclastic deposits, indicating the two materials were most likely emplaced together (Fig. 23).



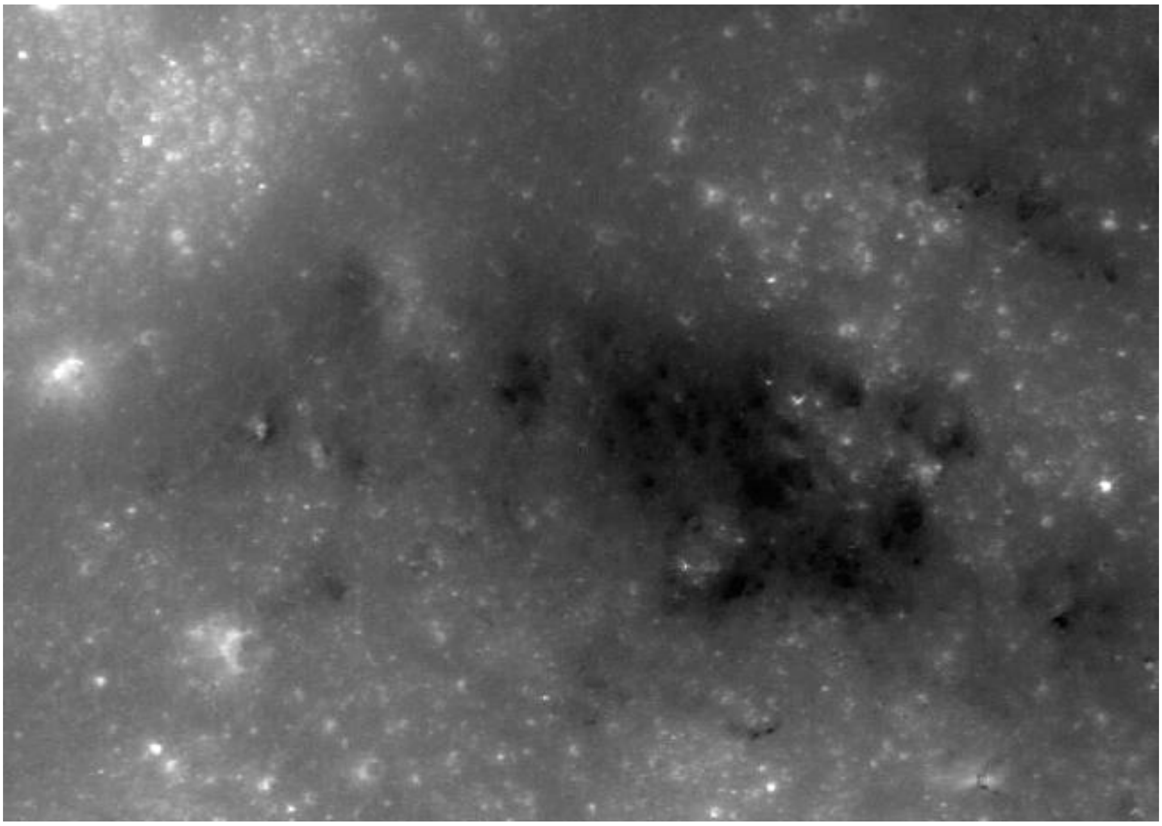


Figure 23: NAC imagery of Sinus Aestuum province with lunar pyroclastic deposits (dark patches).

These spinel-rich deposits are found among the *Sinus Aestuum* pyroclastic/dark mantle deposits (DMD) and are notably absent from the adjacent Rima Bode DMD, as reported by Sunshine et al (2010), see also their work.

The spinel deposits are defined spectrally in the near infrared by their strong 2,000 nm absorptions and extremely weak or absent 1,000 nm absorptions, as is characteristic of spinel group minerals. The spectral signatures of spinel/chromite are reported in Fig. 24.

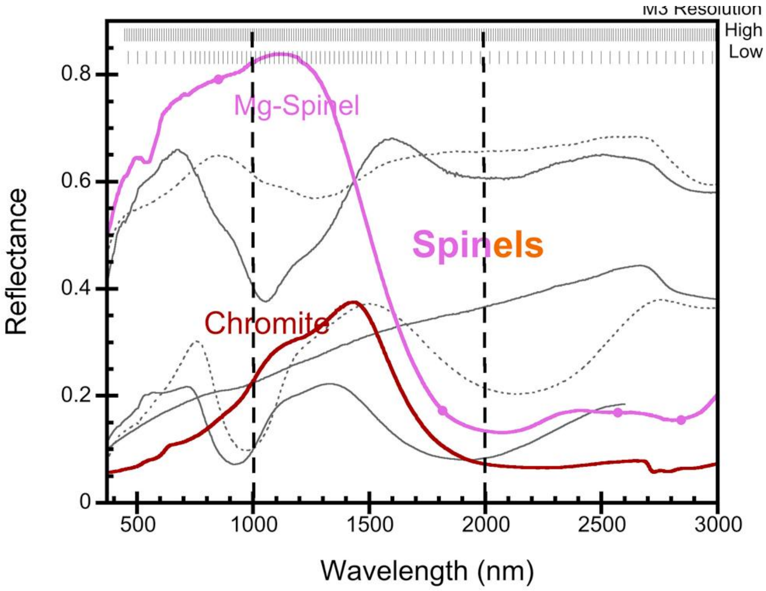


Figure 24: M^3 spectral analysis of spinel and chromite.

Another aspect on which future studies might concentrate is spectral studies to identify the dome-forming minerals based on the recent data acquired by the Chandrayann-1 Moon Mineralogy Mapper (M^3) dataset, accessing to ACT react quick map, as described below, including spectra of some lunar regions.

The spinels may have formed in the same magma chamber that produced the pyroclastic beads, or the spinels may reside in a pluton at depth that was assimilated into the magma as it made its way to the surface. Although the spinels and pyroclastics may have once existed as a homogeneous deposit on the highlands, mixing by craters and regolith development over billions of years has created a heterogeneous distribution of both spinels and pyroclastics within the highlands of *Sinus Aestuum*, and buried the deposit beneath younger lava flows on the mare [Sunshine et al., 2010; Sunshine et al., 2014].

All the strongest visible wavelength features in M^3 data correspond to the freshest-looking craters, although there are examples of young fresh craters in the highlands that do not display a spinel signature, consistent with a heterogeneous distribution of spinels within the highland soils.

According to previous works [Sunshine et al., 2010; Sunshine et al., 2014], I have identified the presence of spinel-rich deposits in *Sinus Aestuum* region as demonstrated by the spectral signature, for some sampled area, characterized by a strong 2,000 nm spectral absorption (Fig. 25).

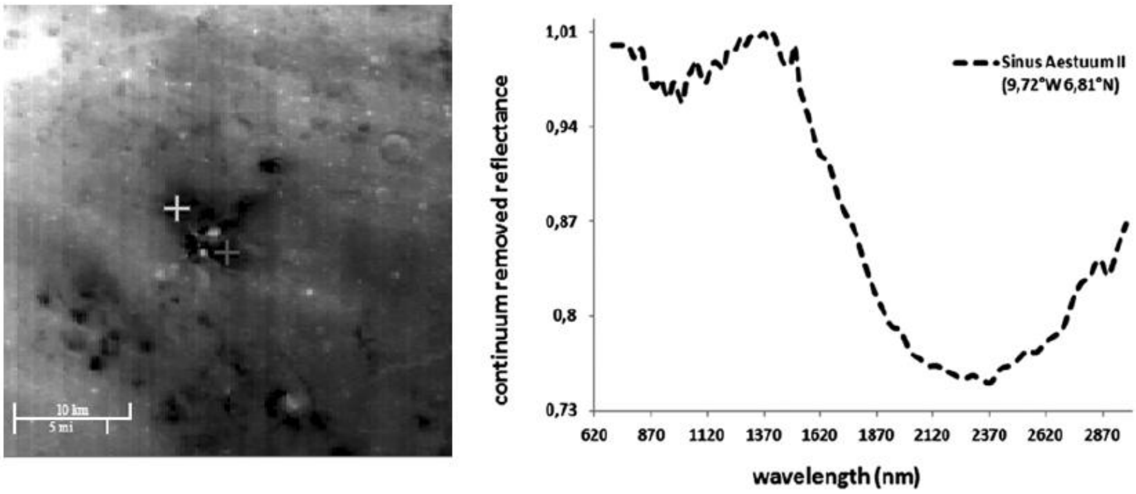


Figure 25: M³ spectral analysis. Spectra of the Sinus Aestuum showing the presence of spinel rich deposit. (Left) The sampled area located at latitude 6.81° N longitude 9.72° W and 6.94° N and longitude 9.86° W, respectively. (Right) Spectra with continuum removal of LPDs characterized by spinel-rich deposits reported in the Sinus Aestuum region. OP2C1 orbital period.

The presence of spinel-rich deposits is also detectable near Schröter and in several locations shown in Fig. 23. I have identified these deposits as demonstrated by the spectral signature, characterized by a strong 2,000 nm spectral absorption (Fig. 26).

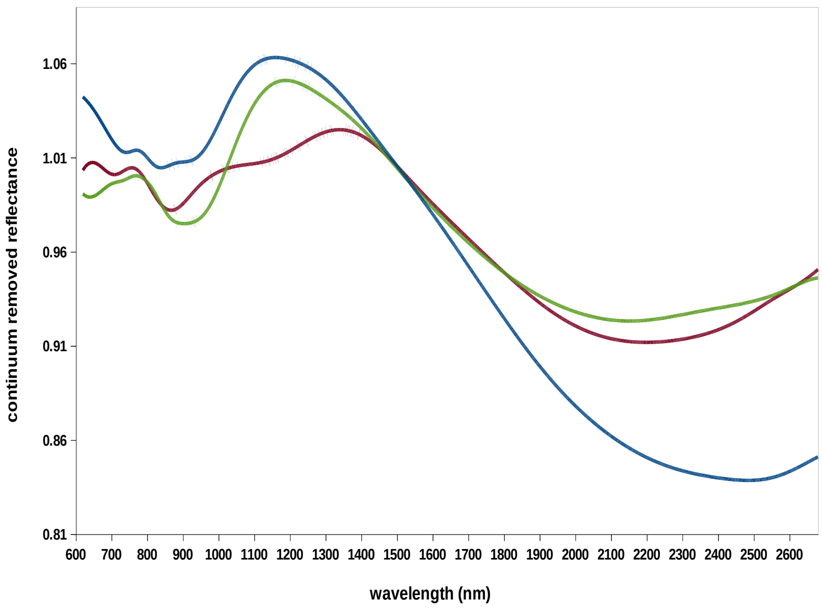


Figure 26: M³ spectral analysis. Spectra of the Sinus Aestuum region (see text for detail).

Especially, the materials that lack a 1,300 nm feature could be interpreted as Fe-rich spinel rather than chromite, although the existence of the small amount of chromites cannot rule out.

There is also a clear difference in the occurrence trends of the spinels at *Sinus Aestuum* and the Mg-spinels. Detection areas of the spinels at *Sinus Aestuum are* on DMD, while most of the Mg-spinels are associated with impact basins such as Moscoviense, Nectaris, Humboldtianum, Smythii, and Ingenii, as reported by Yamamoto et al (2013).

In conclusion, the identification of the presence of spinels on the Moon represents a particularly interesting field of investigation, using the information obtained from the data acquired by the Chandrayann-1 Moon Mineralogy Mapper (M^3).

References

[1] Sunshine, J. M., Besse, S.N., Petro, E., Pieters, C. M., Head, J. W., Taylor, L. A., Klima, R. L., Isaacson, P. J., Boardman, J. W., Clark, R. C. and the M3 Team. 2010. Hidden in Plain Sight: Spinel-Rich Deposits on the Nearside of the Moon as Revealed by Moon Mineralogy Mapper (M^3). 41th Lunar and Planetary Science Conference, abstract #1508.
[2] Sunshine, J. M.,. Petro, N. E., Besse, S., Gaddis, L. R., 2014. Widespread Exposures of Small Scale Spinel-Rich Pyroclastic Deposits in Sinus Aestuum. 45th Lunar and Planetary Science Conference, abstract# 2297.
[3] Bhattacharya, S., Chauhan, P., Ajai, A., 2012. Mg-spinel-rich lithology at crater Endymion in the lunar nearside, 39th COSPAR, E1.5-7-12, 173.