Textural and Petrographic Features of the Felsic Volcanic Rocks of the Middlesex Fells Reservation, eastern Massachusetts

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PURPOSE

The Fells is a key area of the eastern Avalon Terrane in New England because of its excellent exposures north of Boston within an urbanized area where categorizing the geology can be difficult. Study of rocks here provides an opportunity to better understand Neoproterozoic volcanic events. As compared to other rock types of the Middlesex Fells, the textures and composition of felsic volcanic rocks have received little attention as to their genetic origins and detailed chronology. In the past, they have frequently been lumped with subvolcanic plutonic bodies, obscuring possible surface vs. subsurface relationships. In many places on previous maps, subvolcanic plutonic units have also been misidentified as volcanic (tuffs) or artificially lumped with volcanic units.

To better understand the character of volcanic activity, and the relationships between volcanic and plutonic bodies, a detailed analysis of the composition, textures, and genetic types of Fells volcanic rocks is critical. Unfortunately, looking at volcanic rocks in the Fells is not as simple as using recent volcanic rocks as close analogs. Devitrification of volcanic rocks, recrystallization and alteration because of hydrothermal and contact metamorphic processes make studying volcanic rocks in the Fells challenging. To advance the study of the felsic volcanic rocks, this document serves as a compilation of the features found in them, both in hand samples and thin section. This guide also gives someone reading the Fells bedrock geologic map (Ridge, 2024) a clear understanding of how volcanic rock terminology was used by the author in describing map units.

The features shown in this guide are critical to understanding volcanic rocks as either tuffs, volcaniclastic rocks, volcanic flows, or associated shallow feeder pipes linked to subvolcanic intrusions. It represents an important set of observations for: 1) identifying pyroclastic rocks vs. flows; 2) determining whether pyroclastic rocks are non-welded, or partly to fully welded; 3) determining how volcanic rocks may have been altered by devitrification, local contact metamorphism, and brecciation adjacent to faults; and 4) determining the relative ages and stratigraphy of volcanic units as determined by compositions and features that are specific to individual units. This guide was largely inspired by the more detailed and general publication of McPhie and others (2010) that uses both recent and ancient examples. McPhie and others deserve thanks for a truly unique compendium of features and textures in volcanic rocks.

Referencing This Document

Please reference this document as:

Ridge, J.C., 2024, Textural and Petrographic Features of the Sialic Volcanic Rocks of the Middlesex Fells Reservation, eastern Massachusetts (version: January 10, 2024): https://sites.tufts.edu/fellsgeology/, 132 p. (*date accessed*)

A brief word on images in this document

The digital images that accompany this document are of several types. They may be images of weathered rock surfaces, slabs and chips cut for making thin sections, or thin section views in either plane polarized light or with crossed polarizers. Images of slab and chip surfaces were collected from wet surfaces (beneath water) under illumination with a full spectrum fluorescent light source. Scale bars on these images are in centimeters. Sites listed in the image captions are sample localities on the Geologic Map of the Middlesex Fells found at: https://sites.tufts.edu/fellsgeology/.

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1. GENERAL OVERVIEW OF SIALIC VOLCANIC ROCK TYPES

1.1 Genetic Volcanic Rock Types

There are four genetic types of felsic volcanic rocks within the volcanic rock formations in the Middlesex Fells. These types are:

Flows – rocks formed by magma extrusion to form lava flows or domes.

Pyroclastic rocks or tuffs – rocks formed by the accumulation of particles thrown into the air by volcanic eruptions and deposited on the land surface without remobilization significantly changing the original character of the deposit, i.e., remobilization does not change particle shapes or the overall texture and composition of the material.

Volcaniclastic rocks – rocks formed by the remobilization of volcanic materials by surface erosion processes and re-deposition by runoff, stream flow, and mass movement, which alter particle shapes and mix geologic materials of different ages and origins. These rocks may be dominated by volcanic particles and can be difficult to distinguish from pyroclastic deposits.

Passage Fillings - rocks formed in the passageways through which magmas moved either when they passed to the surface or as the re-filling of a passage evacuated or formed by an explosive eruption. Passageways are generally preserved as porphyritic intrusions (dikes) in near surface rocks and in some cases, they continued to the surface. They can simultaneously have textures and features of plutonic rocks at greater depth but are closely related to volcanic units at the surface. There is only one example of this rock type in the Fells.

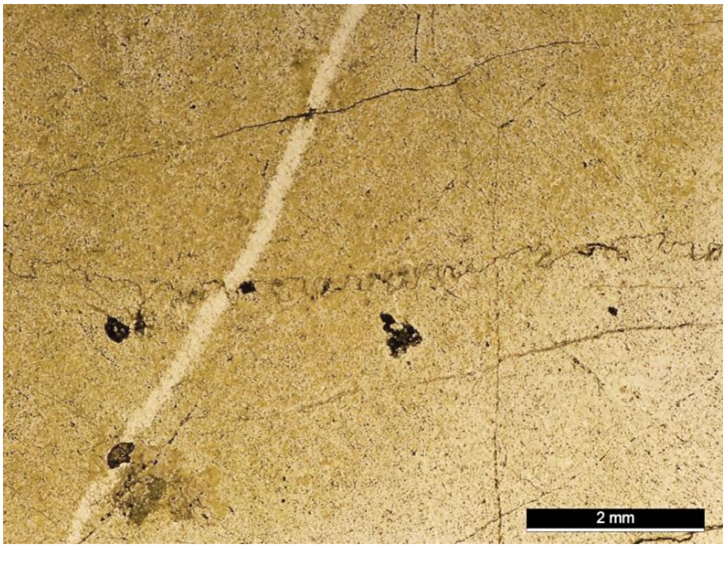
Volcanic rocks are presented below in an order that makes them easier to discuss. Pyroclastic rocks are described first because they are the most abundant type, followed by lava flows. Volcaniclastic rocks require a knowledge of pyroclastic rocks and lava flows and are therefore described third. Presented last, are passage fillings, which are not common, but the Middlesex Fells provides an opportunity to distinguish these rocks from the other types by comparison of there texture, shape, and geographic position.

1.2 Volcanic Rock Alteration

Significant changes occur to volcanic rocks after their time of original deposition or emplacement. Important in this regard is **devitrification** (crystallization) of glass and recrystallization of crystallites, either while they remain hot for an extended time following their initial formation or due to reheating. It is highly unlikely that we would ever find glass in rocks in the Middlesex Fells given the age of the rocks (Neoproterozoic) and the synchronous or later tectonic and reheating events that they experienced.

Volcanic rocks can also experience **hydrothermal alteration** either while they are still hot or during later contact or regional metamorphism. Important in this regard is the contact metamorphism that occurred during later emplacement of large sialic intrusions, some perhaps co-magmatic with the volcanic rocks, and intrusion of abundant mafic dikes of several mostly Paleozoic through Mesozoic age. Two ubiquitous minerals that were created by later alteration are chlorite and epidote. **Stylolites** also occur in the volcanic rocks, as well as metasedimentary rocks in the Fells, and provide evidence of pressure solution imposed by tectonic stresses and hot fluids. Stylolites are more common in carbonate rocks but can occur in other rocks, especially felsic volcanic rocks (Bloss, 1954; Golding and Conolly, 1962). Additional evidence of fluids, hydrothermal or otherwise, circulating through the volcanic rocks is abundant **veins** that may be quartz, epidote, calcite, chlorite or opaque oxides (mostly hematite). Veins occur in some form in every rock formation in the Fells, even in the youngest dikes.

Figure 1.2-1. Vitric tuff in the Lynn Volcanic Complex (site 10955) with stylolitic vein running across center of image. The stylolite crosscuts the large clear vein of quartz. The dark vein angling across the upper part of the image is hematite, which also crosscuts the quartz.



2. ASH-LADEN PYROCLASTIC ROCK OR TUFF

2.1 Tuff Components

Tuff, or ash-based pyroclastic rock, is by far the most abundant volcanic rock type in the Middlesex Fells as is true with most other felsic volcanic sequences. Tuff is composed of four distinct components that in the Fells are now devitrified or altered as mentioned above.

1. Glass particles – during deposition these were hard or still soft **shards**, sand to sub-sand sized glass fragments, and molten droplets of ash size (< 2 mm) that are now devitrified. This material makes up most of a tuff and surrounds the other three components as a ground mass or matrix.

2. Fragments of sialic glass (obsidian) and frothy sialic glass (pumice) – coarse (>2 mm) and derived from the erupting magma, these fragments were usually soft, molten or fragile when deposited as indicated by their flattened shapes. The fragments are multi-component fragments, i.e., mostly glass plus other entities such as phenocrysts, microlites, or crystallites, and less frequently small lithic fragments.

3. Crystals – individual mineral grains are mostly formed in the erupting magma, or as **juvenile crystals**, and may have had adhering molten glass that is now devitrified. In the Fells, tuffs are dominated by juvenile, euhedral and broken euhedral **plagioclase crystals** as well as secondary **hornblende**. Crystals that are fragments from older rocks associated with the same eruptive center, also called **cognate crystals**, may be indistinguishable from juvenile crystals unless they have compositions inconsistent with the overall rock type. **Accidental crystals** from unrelated rock units include some types of quartz, plagioclase, and perthitic alkali feldspar. In some cases, accidental crystals show evidence of **rounding** and **embayments** resulting from **resorption**. This is most common with quartz crystals. In the field pyroclastic crystals often give the appearance of a porphyritic texture.

4. Lithic fragments – pieces of already solidified volcanic rock from tuff and lava flows of the current eruption (**juvenile**), from recent eruptions of the same eruptive center (**cognate**), or from older rock formations unrelated to the current volcanic activity (**accidental**). Accidental lithic fragments in the Fells may be quartzite, argillite (often as hornfels), granodiorite, granophyre, and basalt.

2.2 Types of Tuff

Most sialic tuffs in the Middlesex Fells have at least small amounts of all the components above. Tuffs are further classified by which components are most abundant.

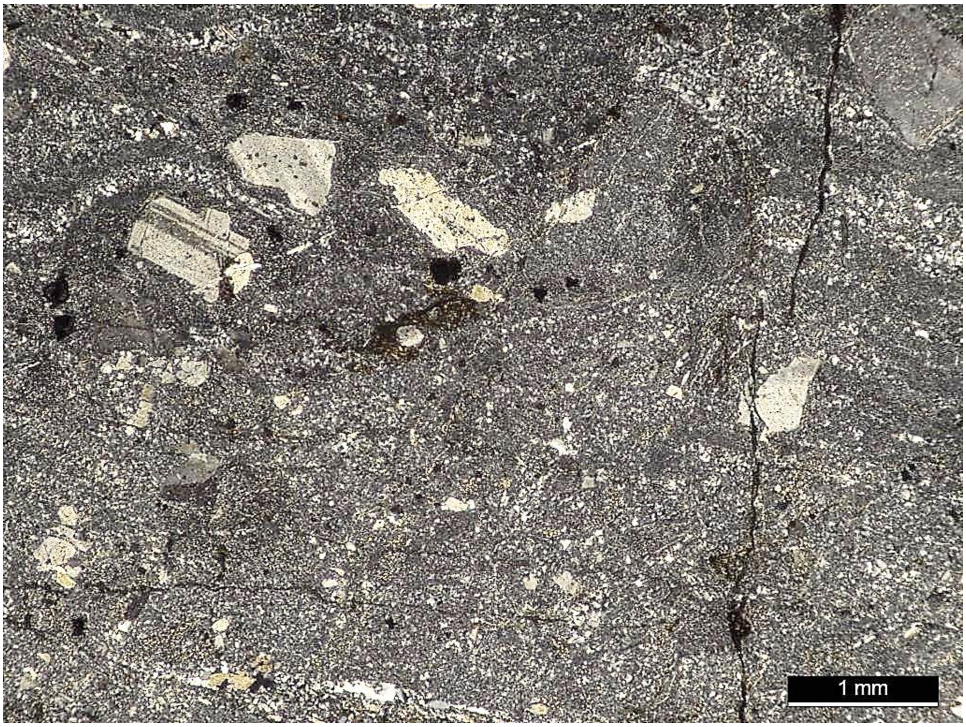
Vitric tuff - tuff dominated by glass particles and obsidian or pumice fragments (Figs. 2.2-1 to 3) with sparse crystals or lithic fragments.

Crystal tuff – tuff with abundant crystals, sometimes over 50% (Fig. 2.2-4 to 8).

Lithic tuff – tuff with abundant lithic fragments (Fig. 2.2-9 to 12). Identification of lithic fragment types usually requires magnification and observation in a thin section.

As is true elsewhere, many volcanic rock units in the Middlesex Fells are combinations of the above rock types with more than one component being common and conspicuous in field exposures and thin sections.

Figure 2.2-1. **Vitric tuff** in the Lynn Volcanic Complex near Boojum Rock (site 10242). Above: Cut rock slab showing faint layering and occasional very fine crystals barely visible on broken surfaces in hand samples. The layering in this rock is thought to be relict ash beds and not a lava flow structure since the crystals in this unit are mostly broken. Below: The same rock as above in thin section (with crossed polarizers) showing wisps of devitrified glass and a rare cluster of small broken crystals.



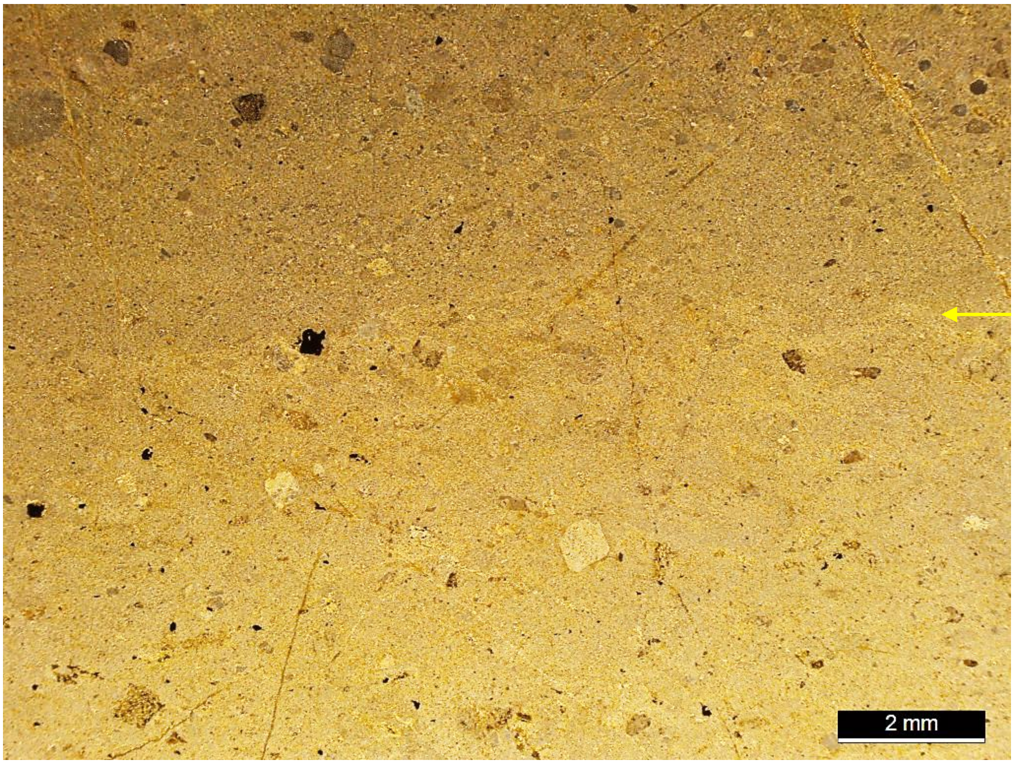
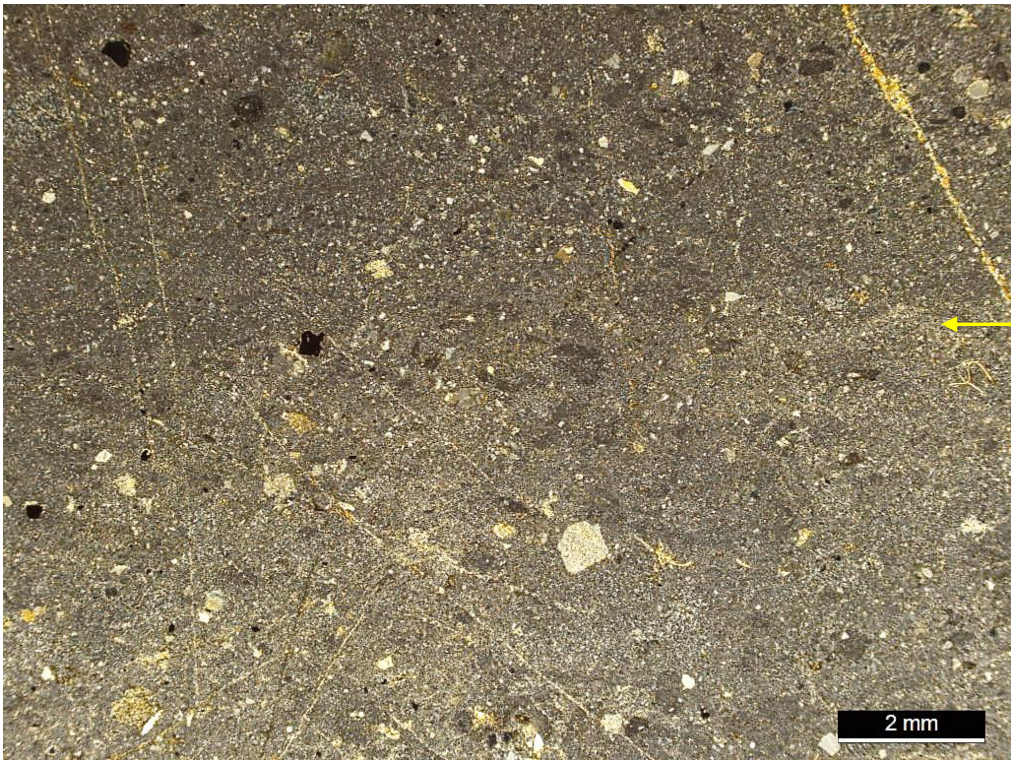


Figure 2.2-2. **Vitric tuff** in the Lynn Volcanic Complex (site 10473). This vitric tuff has occasional crystals and lithic fragments. Relict outlines of glass particles are too fine to see in this view. Across middle of view is the boundary (arrow) between two layers with the upper unit coarser and darker than the unit below. The coarser unit above has fewer crystals and lithic fragments. <u>Above</u>: View in plane polarized light. <u>Below</u>: Same view as above with crossed polarizers.



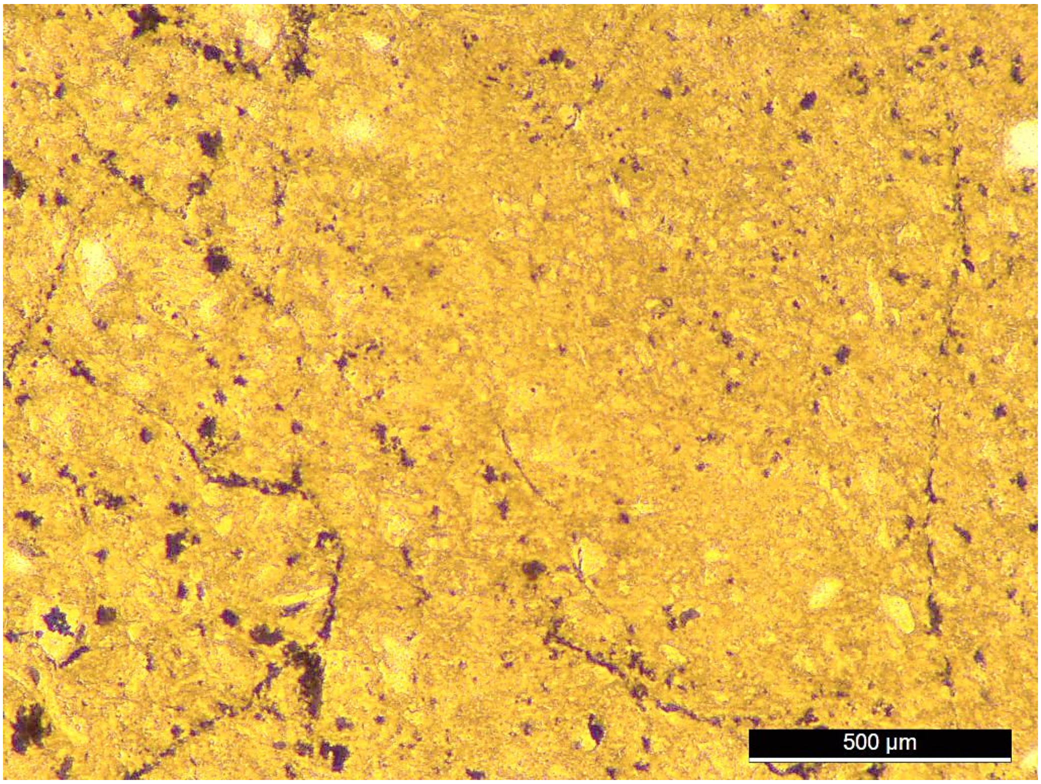


Figure 2.2-3. **Vitric tuff** in the Lynn Volcanic Complex at Boojum Rock (site 10231). Above: Relict outlines of glass particles in matrix are faintly visible with occasional small broken crystals. View in plane polarized light. Below: Same view as above with crossed polarizers.

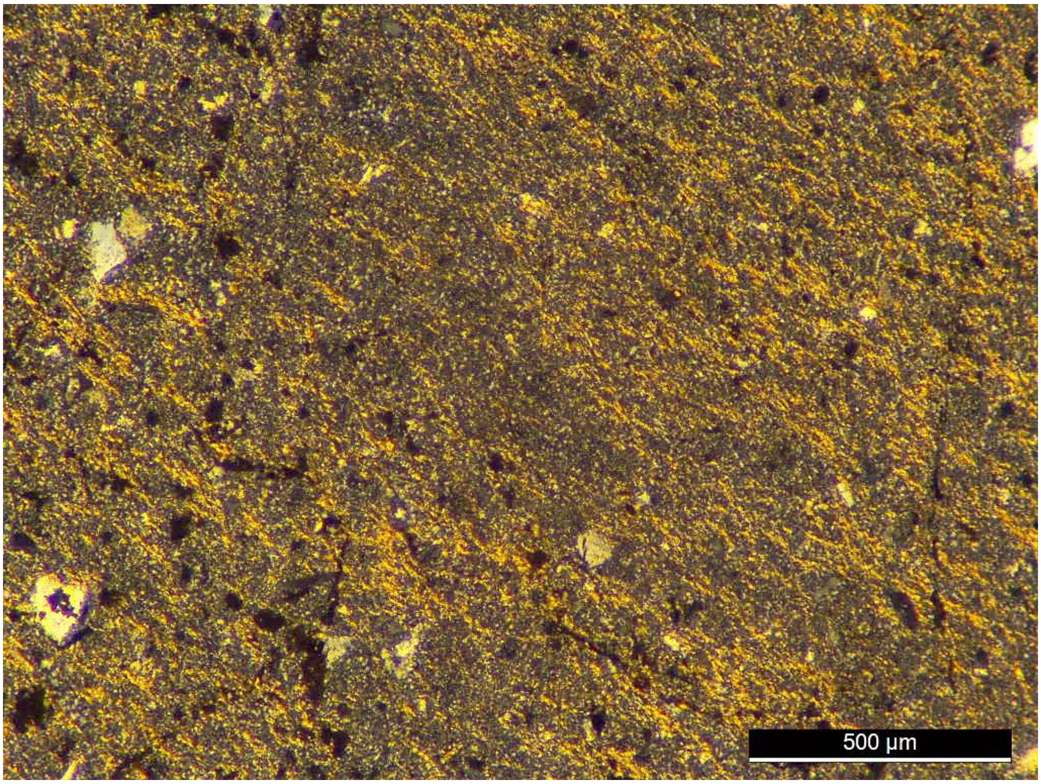
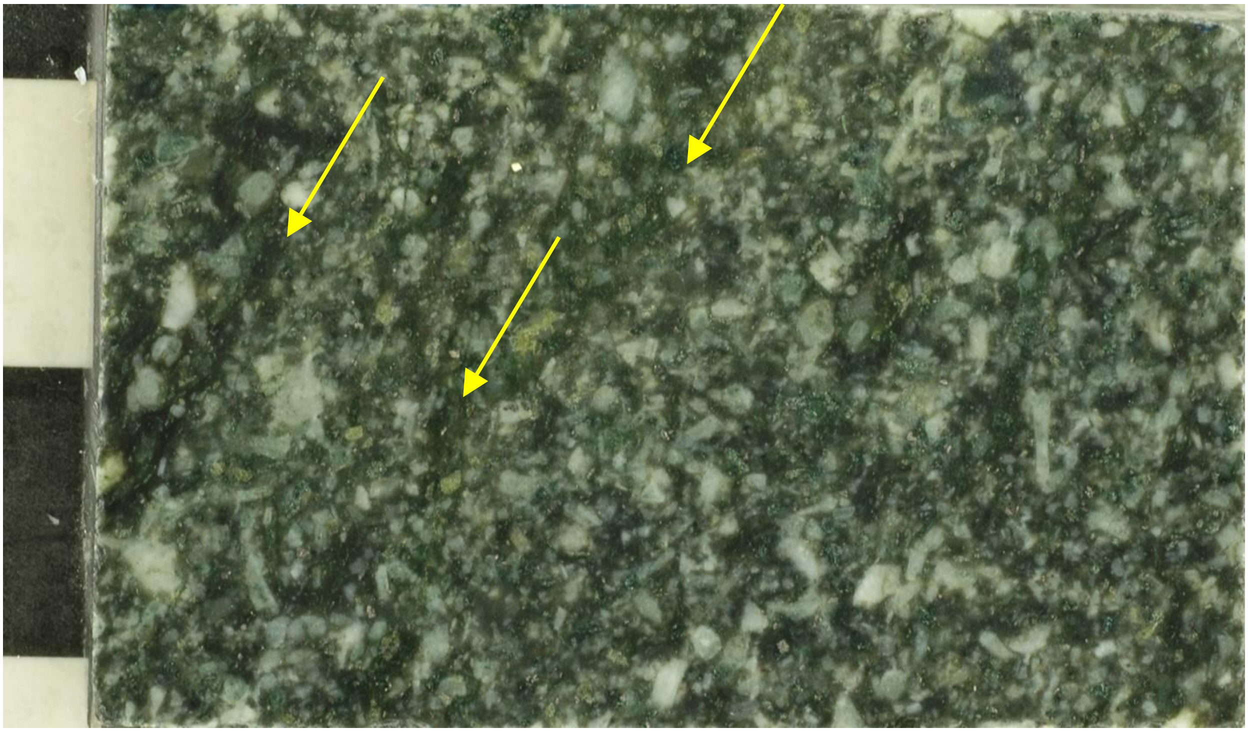


Figure 2.2-4. Above: Outcrop view of **crystal tuff** in the Boojum Rock Tuff (site 10289) with speckled appearance on fresh surfaces created by a dense concentration of broken plagioclase crystals. Below: Same rock in cut rock chip. Visible are euhedral and broken plagioclase crystals. Arrows indicate crude alignment of dark reddish-gray, flattened, relict glass fragments that define a faint layering and fabric in the rock. Oriented features like this are usually very difficult to see in outcrops.



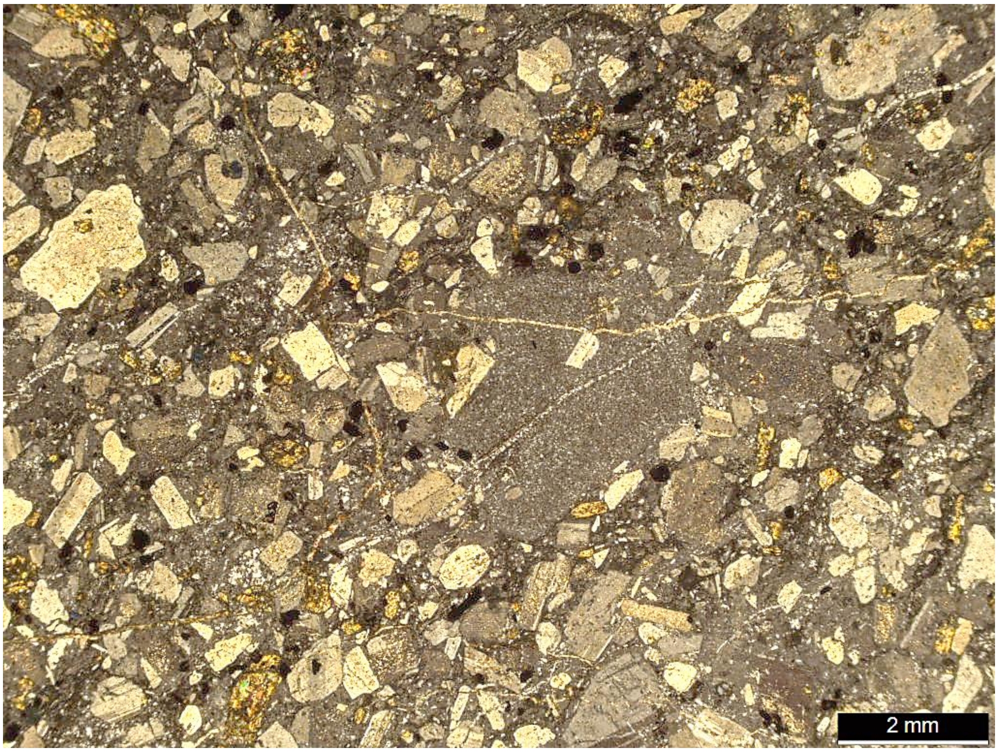


Figure 2.2-5. **Crystal tuff** in the Boojum Rock Tuff (site 725BN) with tightly packed euhedral and broken plagioclase crystals and occasional partly altered hornblende crystals (orange) in an ultra-fine matrix. In the center is a very fine-grained volcanic lithic fragment. View with crossed polarizers.

Figure 2.2-6. **Crystal tuff** in the Boojum Rock Tuff (site 10903) with broken plagioclase crystals and occasional partly altered hornblende crystals (partly orange grains) in an ultra-fine matrix. The hornblende crystals are mostly altered to chlorite and epidote. Plagioclase crystals are very fresh, which is unusual for this unit. Compare to Figs. 2.2-7 to 8. View with crossed polarizers.

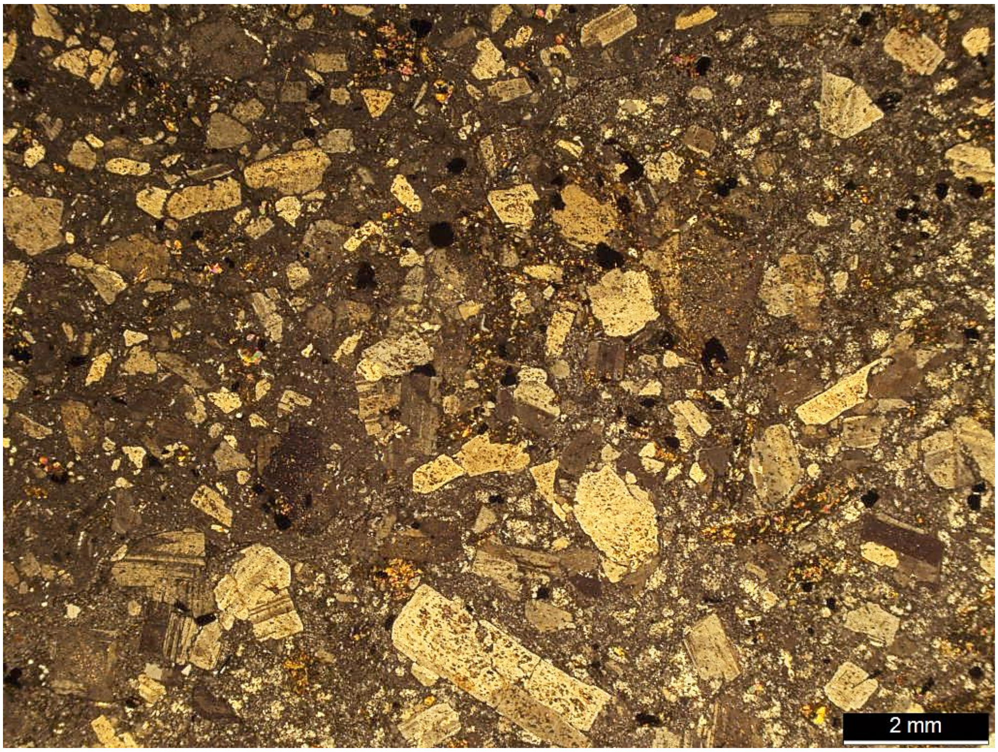


Figure 2.2-7. **Crystal tuff** in the Boojum Rock Tuff (site 450BN) with altered plagioclase crystals and occasional altered hornblende crystals (orange grains). Note sieve texture in large plagioclase crystal near bottom. The upper left half of the view has an ultra-fine dark **granular matrix** and smaller crystals, while the lower right has a matrix that appears to have a patchy-appearing **micropoikilitic texture.** View with crossed polarizers.

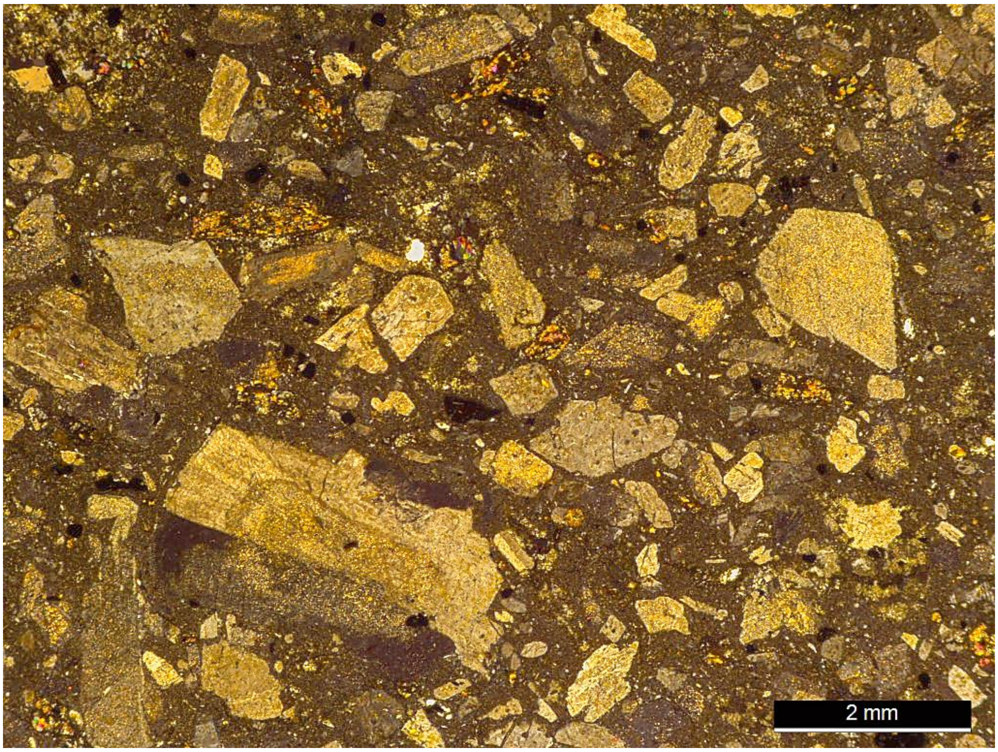


Figure 2.2-8. **Crystal tuff** in the Boojum Rock Tuff (site 10924) with broken, zoned, and twinned plagioclase crystals and occasional altered hornblende crystals (orange grains) in an **ultra-fine granular matrix**. View in crossed polarizers.

Figure 2.2-9. **Lithic tuff** in the Boojum Rock Tuff (site 10353). The large lithic fragments are all volcanic and angular in a crystal tuff matrix. Weathered outcrop surface.

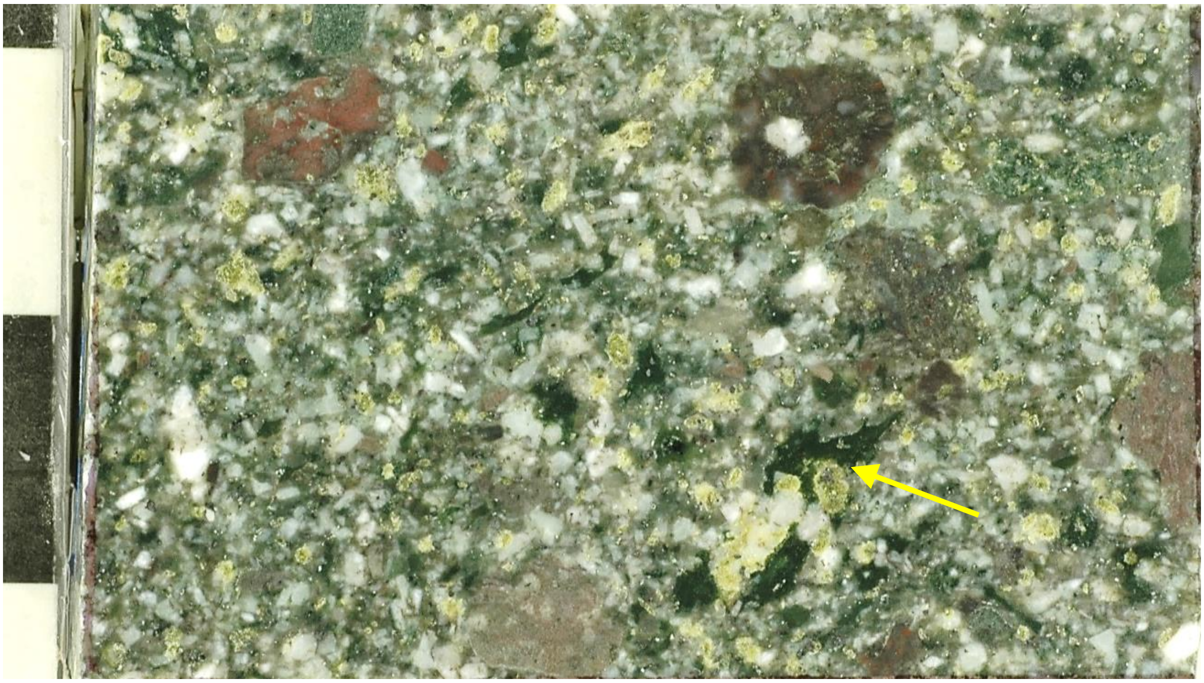


Figure 2.2-10. **Lithic tuff** in the Boojum Rock Tuff (site 10020). The lithic fragments here are all red volcanic fragments with some smaller flattened black devitrified glass fragments. Note the dark pinched blob just to the right of lower center (arrow), which is devitrified glass with epidote filled vesicles. Cut rock chip.

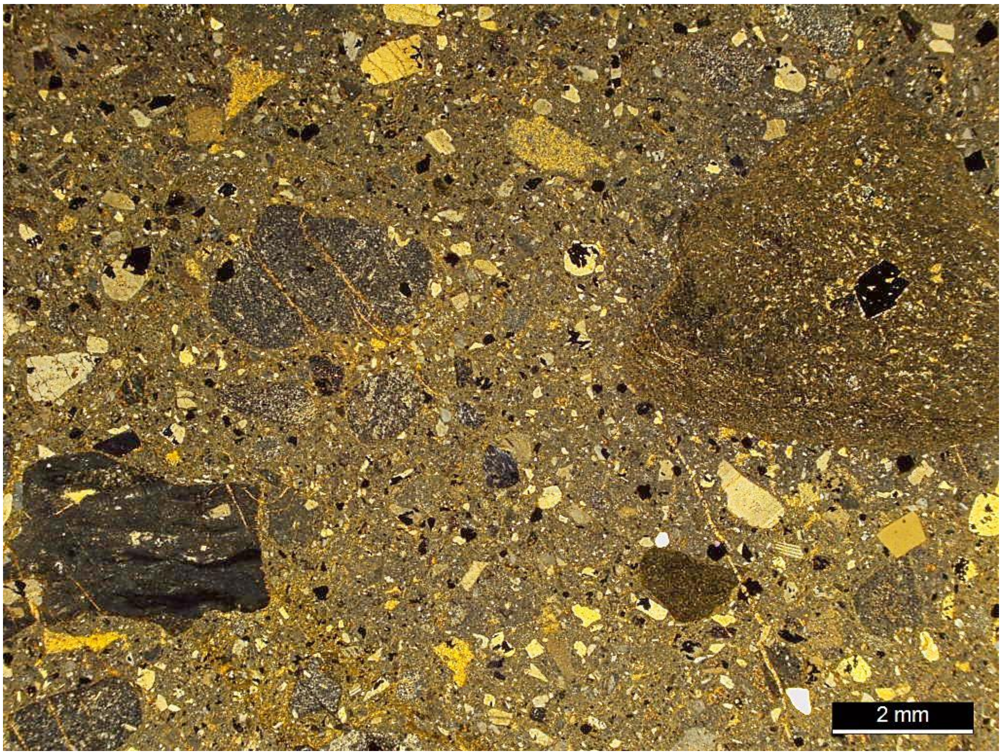


Figure 2.2-11. **Lithic tuff** in the Lynn Volcanic Complex (site 10361) with three large volcanic fragments in a fine matrix containing many broken crystals and smaller volcanic lithic fragments. Volcanic lithic fragment in lower left has pyroclastic banding. View with crossed polarizers.

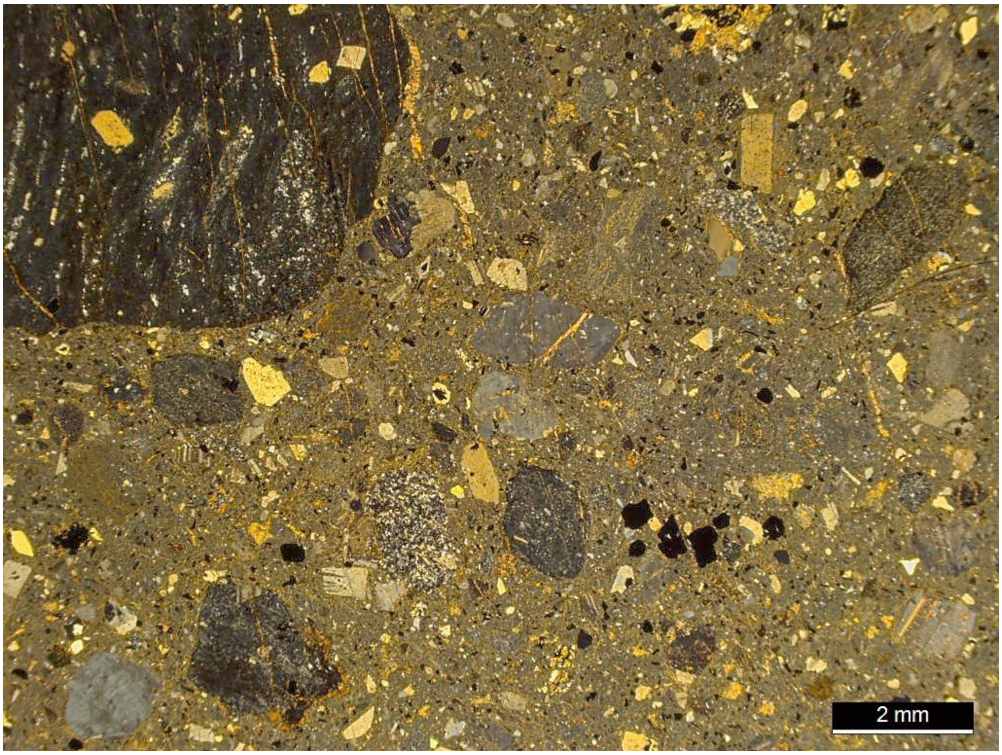


Figure 2.2-12. **Lithic tuff** in the Lynn Volcanic Complex (site 10361) with several volcanic lithic fragments. Large volcanic fragment in upper left has pyroclastic banding with devitrified and compressed glass fragments and very thin epidote veins (orange) that cross into the matrix. View with crossed polarizers.

2.3 Glass Particles and Shards

Glass particles and shards can land as still molten droplets, solidified but still soft particles, or rigid particles. The trick is being able to distinguish these fragments after devitrification based on relict outlines of their shapes because they are all now composed of crystalline material. The particles can sometimes be too small to identify with magnifications generally available on a petrographic microscope and the outlines of glass fragments are often obscured by the fusion of glass fragments and devitrification. In a microscope the identification of original glass shards with **bubble wall faces** may be difficult, especially when observed with crossed polarizers, which highlights individual mineral grains formed during devitrification. In some cases, the outlines of glass particles and shards may still be visible in plane polarized light with the original devitrified glass shards or particles having a cleaner appearance or a different color than the surrounding finer matrix.

Hard glass shard outlines may be more easily identified if they have preserved **bubble wall faces** (Fig. 2.3-1 to 3; see also volcanic lithic fragments in section 2.10 below). Unfortunately, many glass fragments don't have well developed, curved bubble wall faces and shapes. After devitrification they can be difficult to distinguish from very small crystal fragments. When glass shards are large enough for observation it is common that only a few of the shards will show curved bubble walls, while others simply have **broken trapezoidal shapes** (Fig. 2.3-4). Whether curved bubble wall faces are observable is also dependent on the orientation of a thin section relative to the direction in which the shard fragments tended to lie flat during deposition. Bubble wall structures are most easily discerned in cross section and the apparent absence of bubble wall structures in thin sections cut parallel to layering can be deceiving.

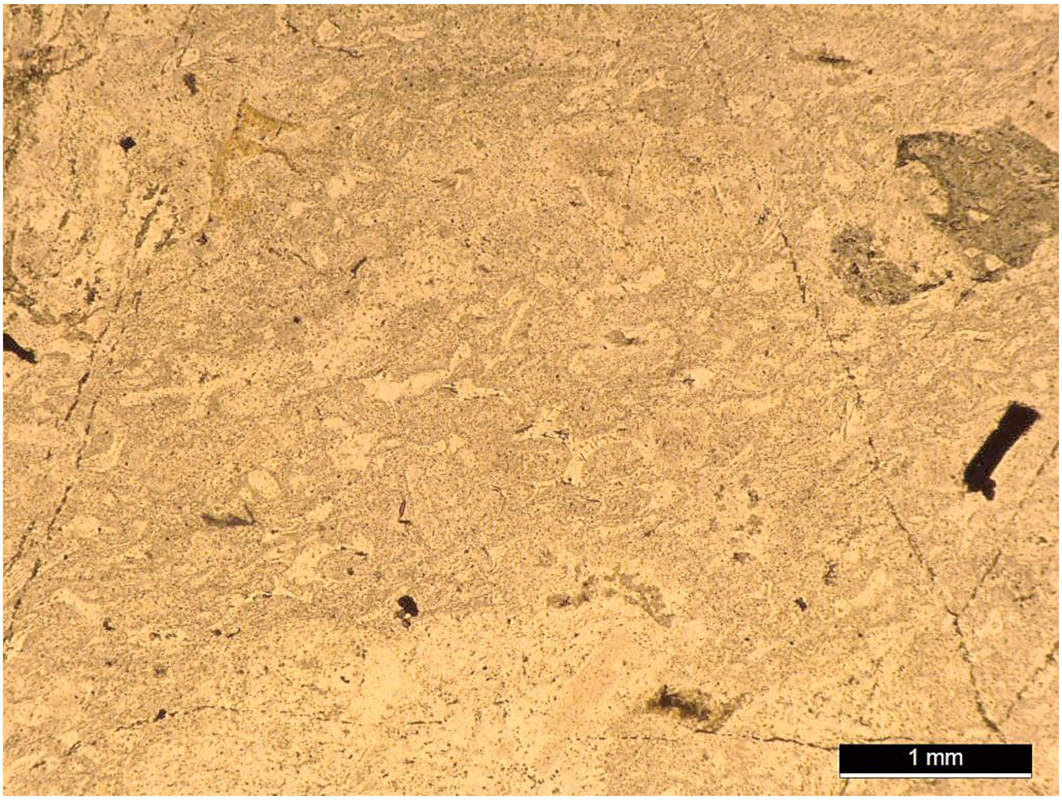
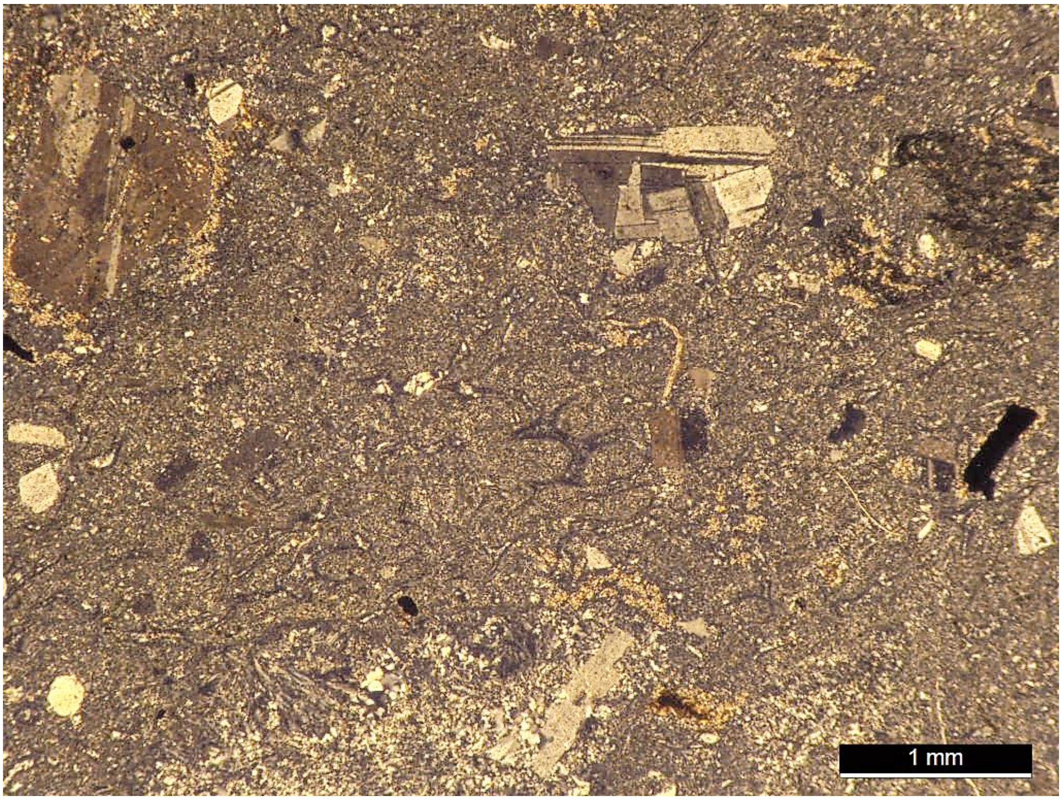


Figure 2.3-1. Crystal tuff in Lynn Volcanic Complex (site 530BN) with hard, non-welded glass shards that have bubble walls. Above: View in plane polarized light. Below: View with crossed polarizers. Note how most shards are less visible when viewed with crossed polarizers. Crude layering runs horizontally across the image. Note also how the feldspar crystals are almost invisible in plane light.



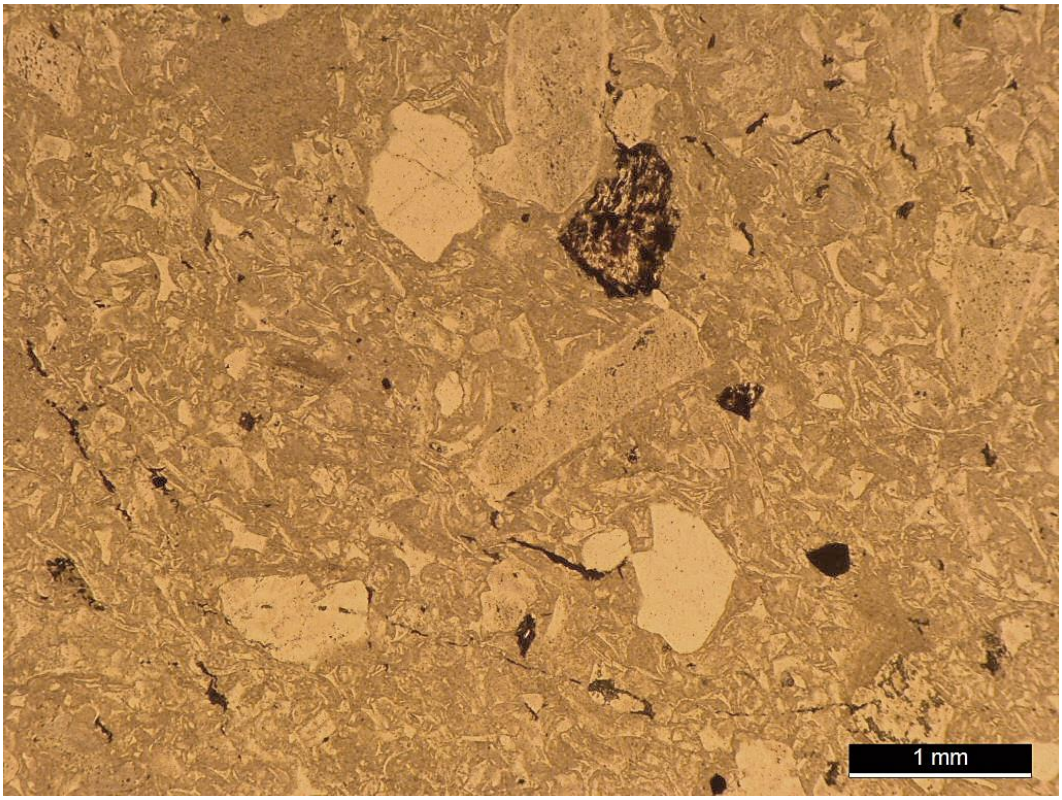
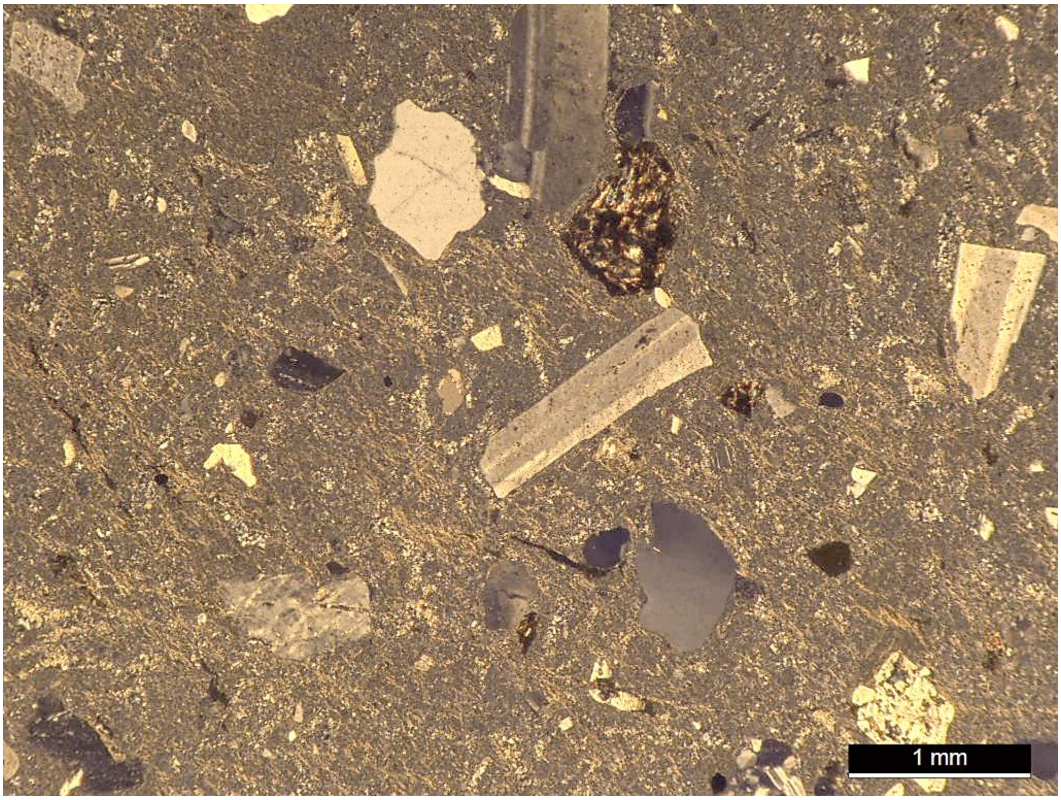


Figure 2.3-2. Crystal tuff in Lynn Volcanic Complex (site 590BN) with hard, non-welded glass shards that have bubble walls. Large clear grains are quartz. Above: View in plane polarized light. Below: View with crossed polarizers.



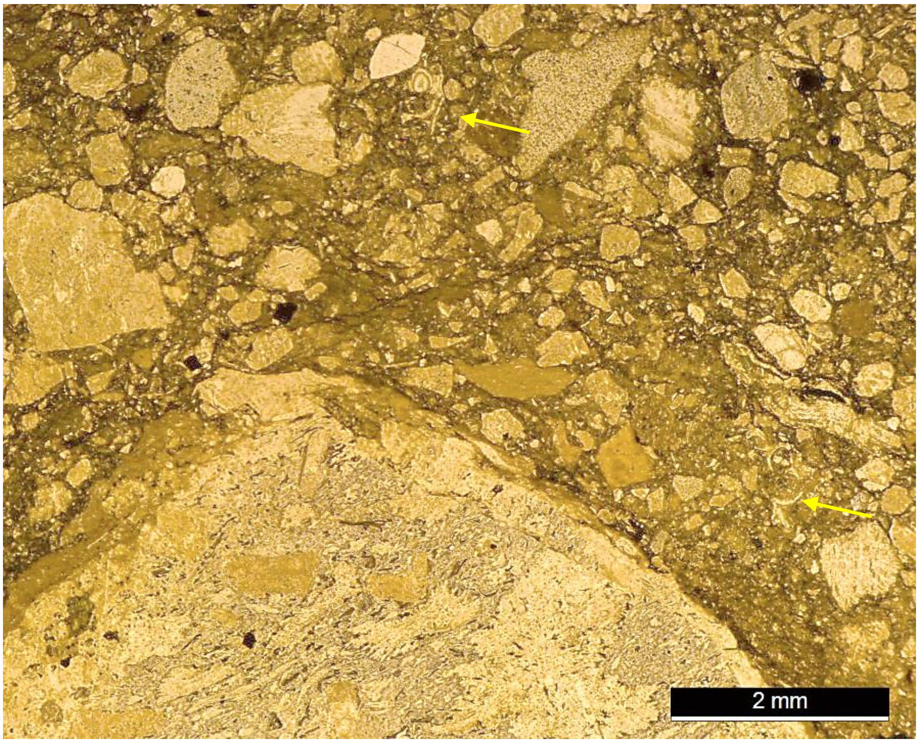


Figure 2.3-3. Tuff in the Lynn Volcanic Complex at Boojum Rock (site 10164) with a few hard, non-welded glass shards in its matrix. Some shards have thin bubble walls (arrows). The large lithic fragment at the bottom of image has flattened and welded glass shards. View in plane polarized light.

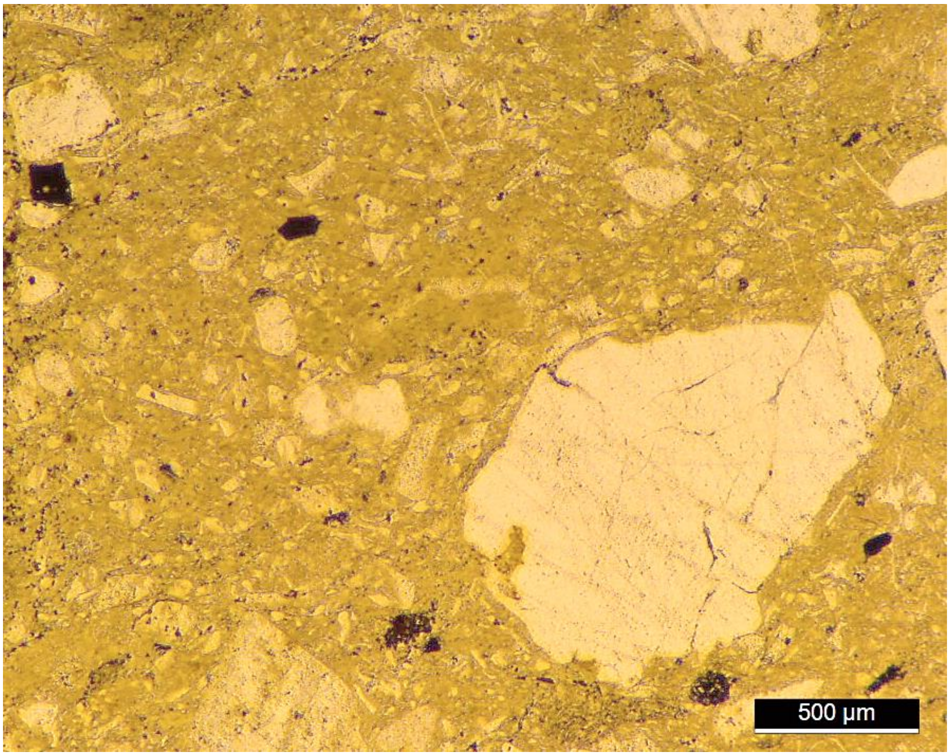


Figure 2.3-4. Crystal tuff in the Lynn Volcanic Complex (site 10600) with hard, **non-welded glass shards** in its matrix. Most of the shards have **broken trapezoidal shapes** with only a few having clear bubble wall outlines. The large grain in the lower right is quartz. View in plane polarized light.

A cross sectional view of shards is ideal, but this orientation is almost always impossible to determine in a hand specimen before it is cut to make a thin section, especially when the shards are microscopic and have experienced devitrification or post-depositional alteration. Faint clues may exist about orientation. In some cases, the consistent orientation of coarser solid platy glass particles can lead to faint layering or **pyroclastic banding**, but this is also not usually visible in a hand specimen. In other cases, there may be larger flattened pumice and obsidian fragments or platy lithic fragments that create a fabric that is parallel to the finer glass shards and particles in the matrix. Compaction of a fine matrix with glass shards and particles may result in these constituents showing a microscopic fabric that aligns with the surfaces of larger crystals and fragments.

Soft or molten glass particles and shards will be partly to entirely welded and will flatten under a lithostatic load forming a **eutaxitic texture** and **pyroclastic banding** that shows the deformation of individual soft glass shards (Figs. 2.3-1 and 2.3-3; also see both volcanic and accidental lithic fragments in section 2.10 that can have these features).

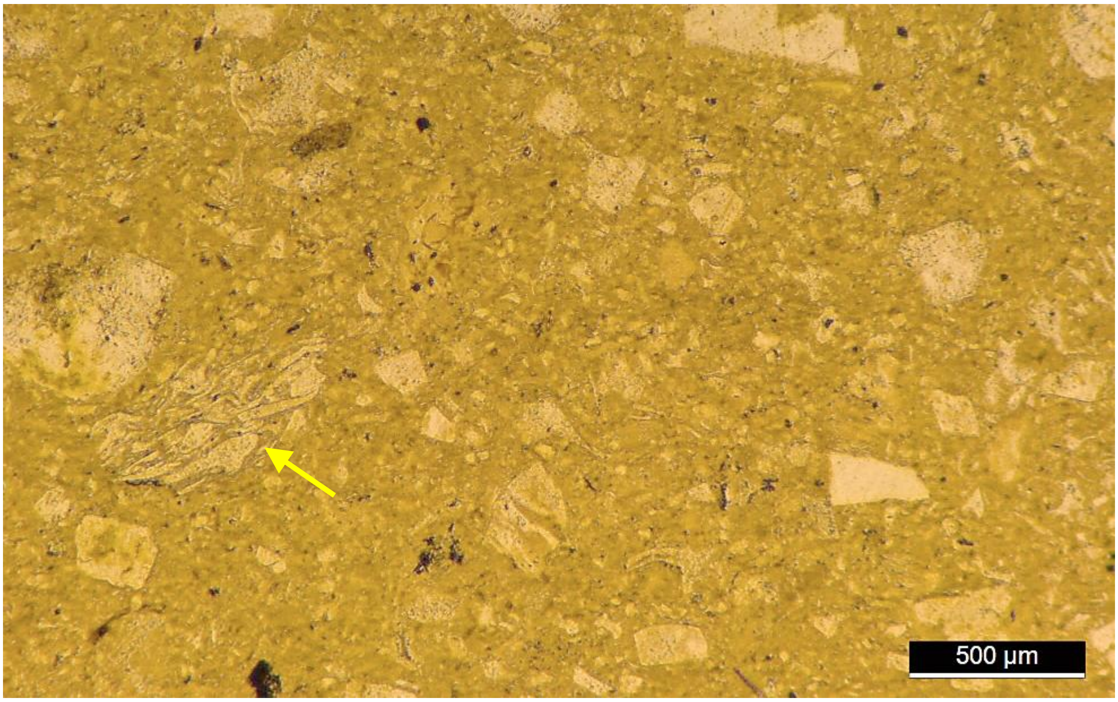


Figure 2.3-3. Crystal tuff in the Lynn Volcanic Complex (site 10600) with a lithic fragment (arrow) that has **flattened and deformed glass shards** forming a **eutaxitic texture**. These shards were soft and were then welded when deposited. The surrounding matrix has many broken and rigid glass fragment outlines, but clear bubble wall surfaces are scarce. View in plane polarized light.

2.4 Crystals

Scattered throughout most tuffs in the Middlesex Fells are abundant **juvenile** or **primary crystals**. These crystals are dominantly euhedral or broken euhedral **plagioclase** (see Figs. 2.2-4 to 8). Most plagioclase crystals show some degree of alteration with replacement by sericite and epidote (compare Fig. 2.2-6 with Figs. 2.2-7 and 8). Also occurring in some tuff units, especially the Boojum Rock Tuff, are scattered euhedral and broken **hornblende** crystals that are usually at least partly altered to chlorite and epidote (see Figs. 2.2-4 to 8 above and Fig. 2.4-1). In many tuffs the high abundance of crystals (up to 50% of rock) suggests that they have been concentrated by ash flow processes during emplacement.

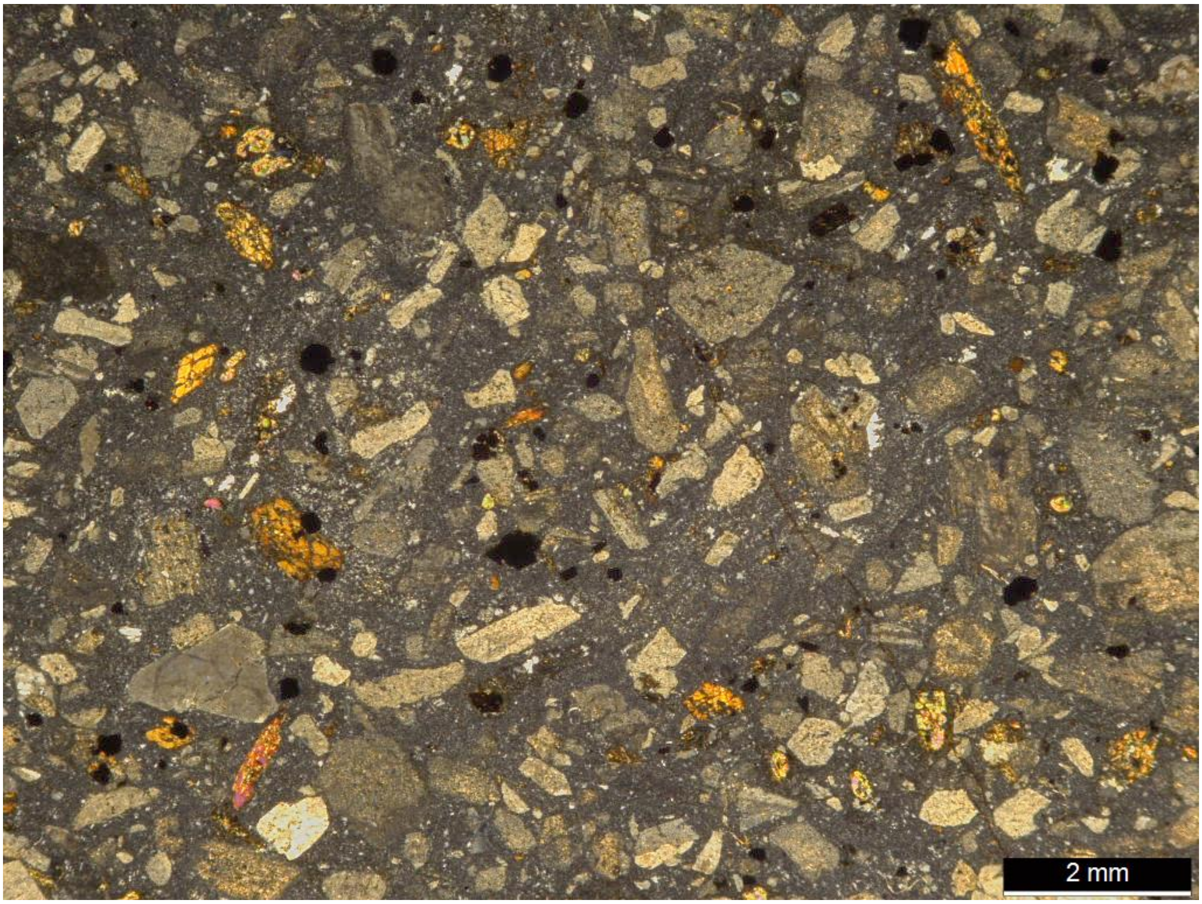


Figure 2.4-1. **Crystal tuff** in the Boojum Rock Tuff (site 10011) with altered plagioclase crystals and euhedral and broken, partly altered hornblende crystals (orange grains) that sometimes display amphibole cleavage and an elongate or diamond-shaped crystal outline. View with crossed polarizers.

In addition to plagioclase, some pyroclastic units have **resorbed quartz crystals** (Fig. 2.4-2). Resorption of quartz caused them to become **rounded** and **embayed**. Embayments and fractures may cause crystals to break into smaller fragments that have both rounded and broken surfaces. These quartz crystals are mostly accidental grains taken up by magmas that passed through coarse granitic bodies, especially if the quartz grains are relatively large (several millimeters). Occasional euhedral **skeletal** and **dipyramid shapes** (Fig. 2.4-3) suggest some quartz grains may have had a primary origin.

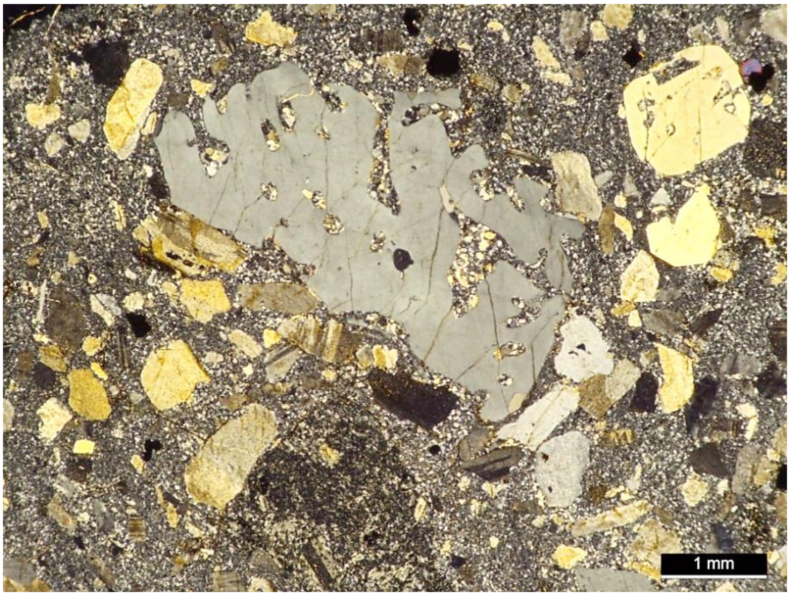


Figure 2.4-2. **Crystal tuff** in the Lynn Volcanic Complex (site 10407) with a large **embayed quartz crystal**. Fractures will eventually allow the crystal to separate into fragments. Smaller rounded and fractured quartz crystals also appear in the view. View with crossed polarizers.

Figure 2.4-3. **Crystal tuff** in the Lynn Volcanic Complex (site 669BN) with a **skeletal dipyramid quartz crystal**. A highly rounded (resorbed) quartz crystal (dark gray) also appears beneath the skeletal crystal. View with crossed polarizers.

2.5 Flattened Pumice and Obsidian Fragments

Separate textural domains that are flattened with pinched ends are fragments of soft or molten glass, either **pumice** or **obsidian**. Because of the flattening of these fragments and devitrification it is difficult to determine whether individual fragments were pumice or obsidian. It is thought that fragments without any hint of internal layering, that might indicate flattened bubbles, were non-bubbly **obsidian** when deposited. These fragments were also more coarsely crystallized during devitrification. Both pumice and obsidian fragments can have euhedral phenocrysts as crystals, microlites, or crystallites.

Obsidian and pumice fragments take four common forms, which are:

1) very dark gray to greenish-gray highly pinched blobs with a yellow potassium stain and faint very thin bands (Fig. 2.5-1). They are porphyritic with euhedral plagioclase crystals and have **faint axiolitic strands** (see section 2.7.2) when viewed with crossed polarizers,

2) medium to light gray relatively large blobs that have a dark yellow potassium stain and conspicuous layering with either **axiolitic** or **micro-spherulitic bands** (see section 2.7.2) when viewed with crossed polarizers (Fig. 2.5-2),

3) medium to light gray highly pinched fragments (obsidian) with a yellow potassium stain that exhibit a speckled appearance (**patchy texture**, see section 2.7 below) when viewed with cross polarizers, no banding, and either very few or no crystals (Fig. 2.5-3 and 4), and

4) rare porphyritic flattened blobs with a high density of small euhedral plagioclase phenocrysts (Fig. 2.5-5).

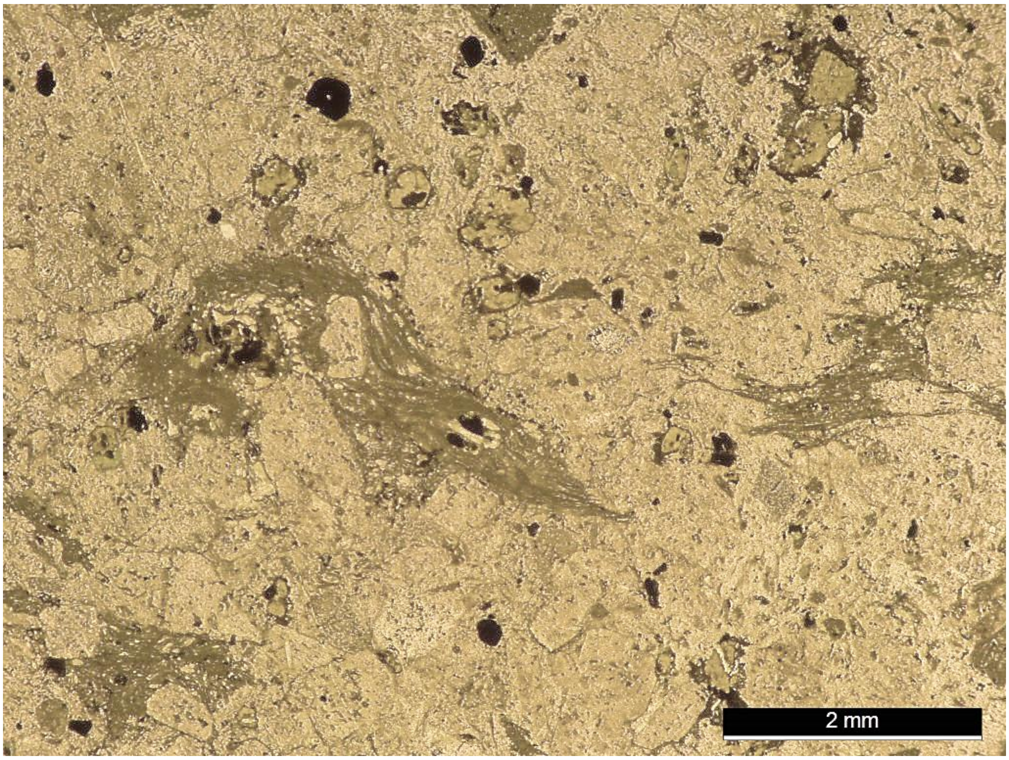
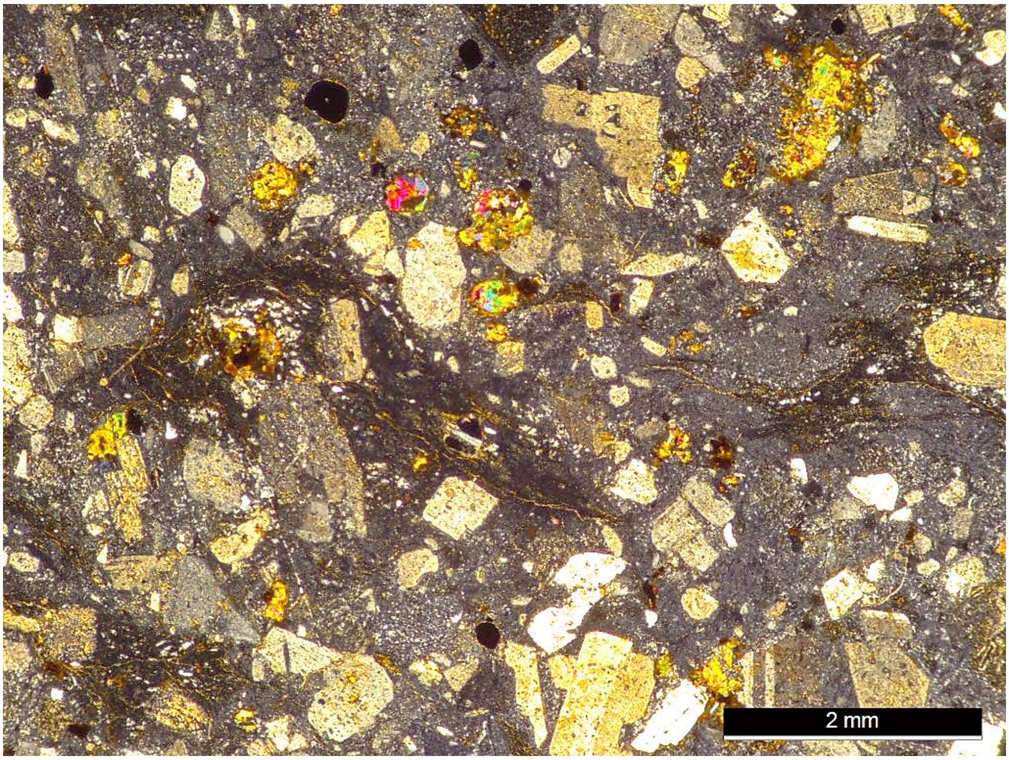


Figure 2.5-1. **Lithic tuff** in the Boojum Rock Tuff (site 10352) with glass fragment type 1. Above: Dark gray pinched and **flattened pumice fragments** that have very thin **internal banding** and plagioclase crystals. View in plane polarized light. Below: Same view with crossed polarizers. Brightly colored grains are hornblende altered to epidote.



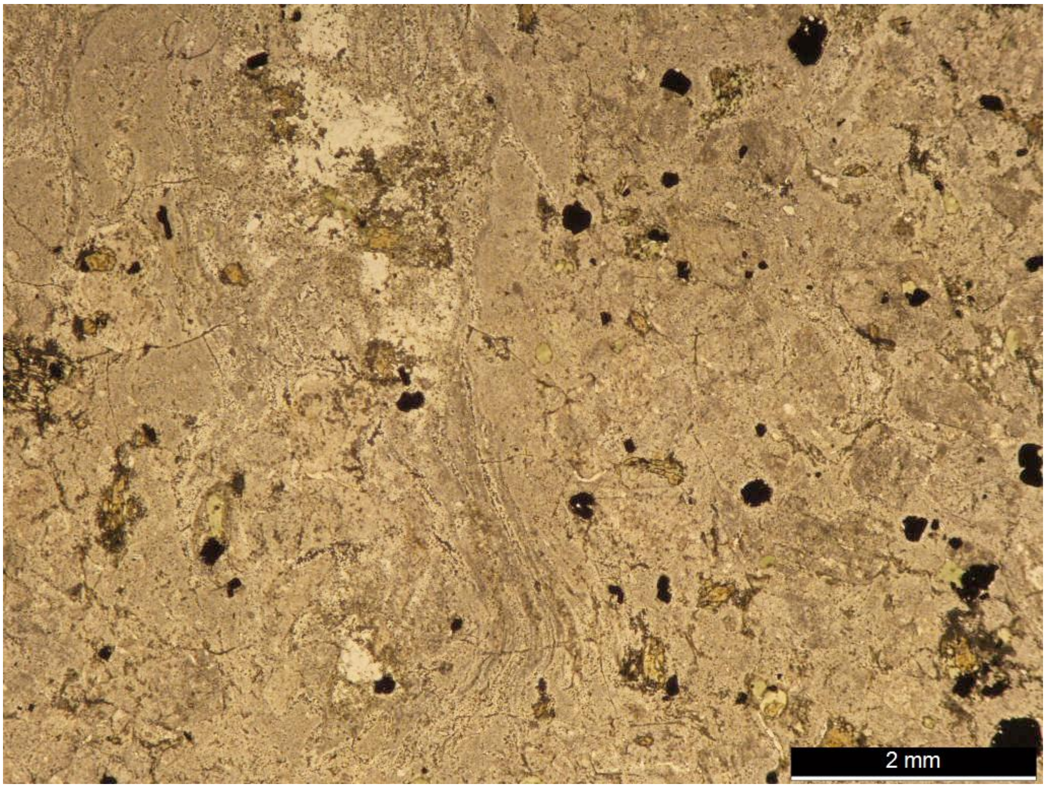
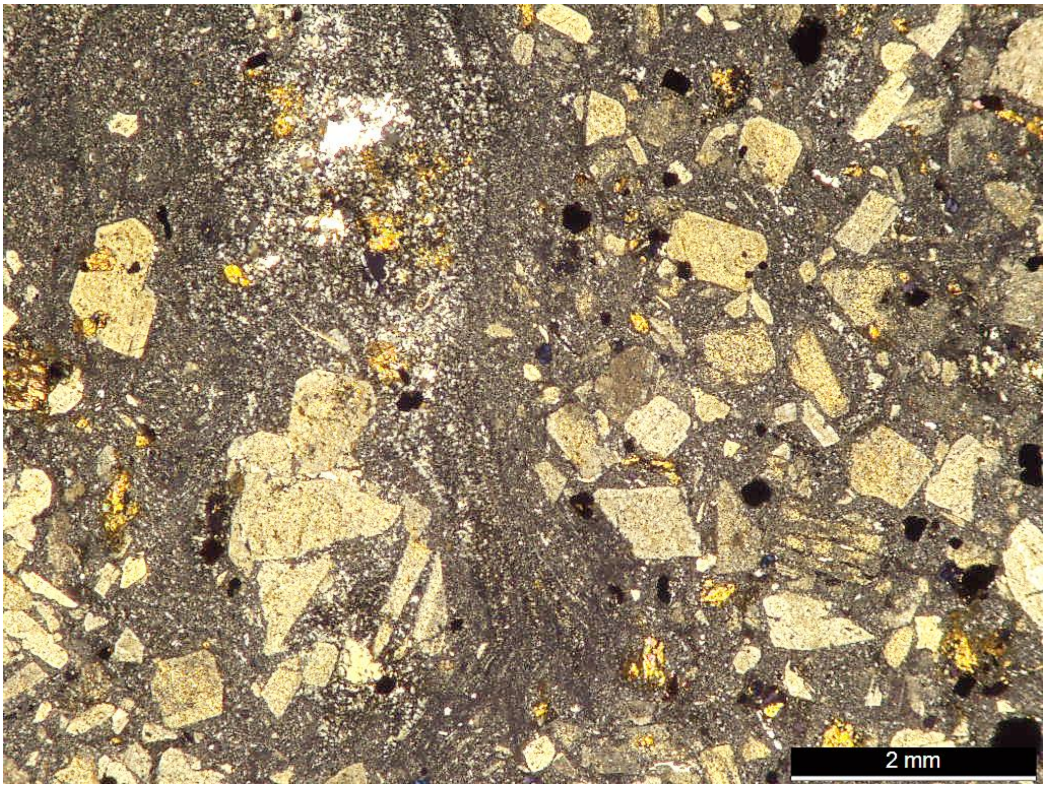


Figure 2.5-2. **Crystal tuff** in the Boojum Rock Tuff (site 10010) with glass fragment type 2. Sample is not stained for potassium. <u>Above</u>: Light gray **flattened pumice fragment** in center (vertical) that has **internal banding**, faint **axiolitic strands**, and no plagioclase crystals. View in plane polarized light. <u>Below</u>: Same view with crossed polarizers. Note **axiolitic strands** in lower portion of glass fragment.



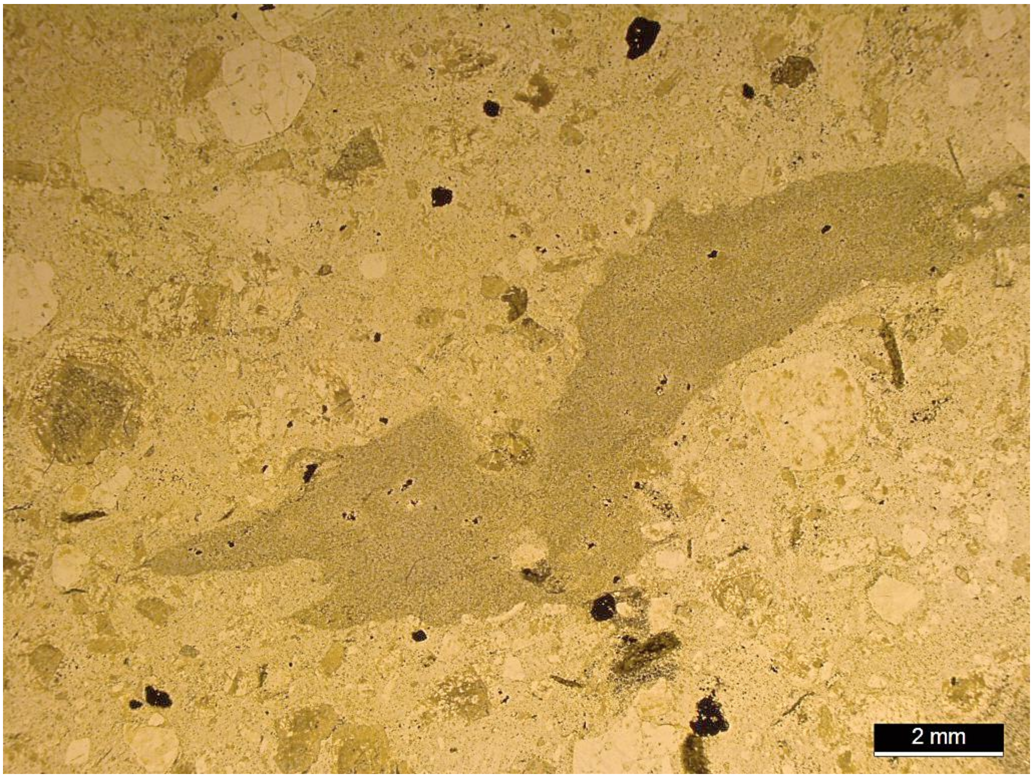
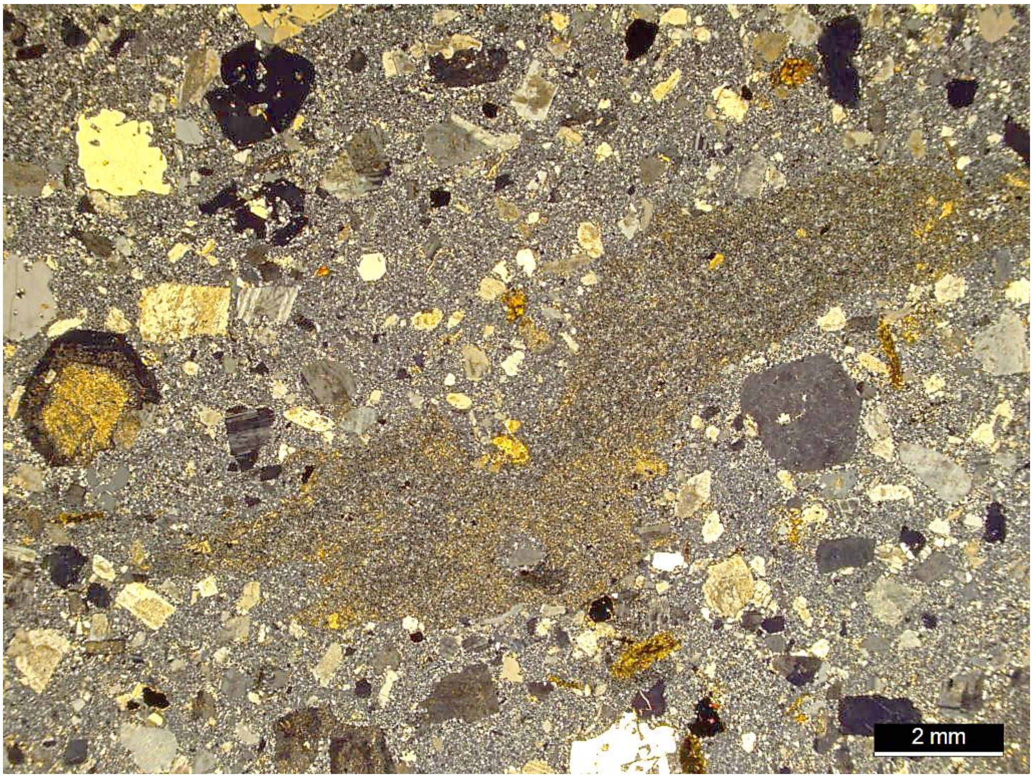


Figure 2.5-3. **Crystal tuff** in the Lynn Volcanic Complex (site 10418) with glass fragment type 3. <u>Above</u>: Medium gray **flattened obsidian fragment** with no internal banding or crystals. View in plane polarized light. <u>Below</u>: Same view in crossed polarizers. Clear grains above and to the left of the fragment are embayed quartz crystals.



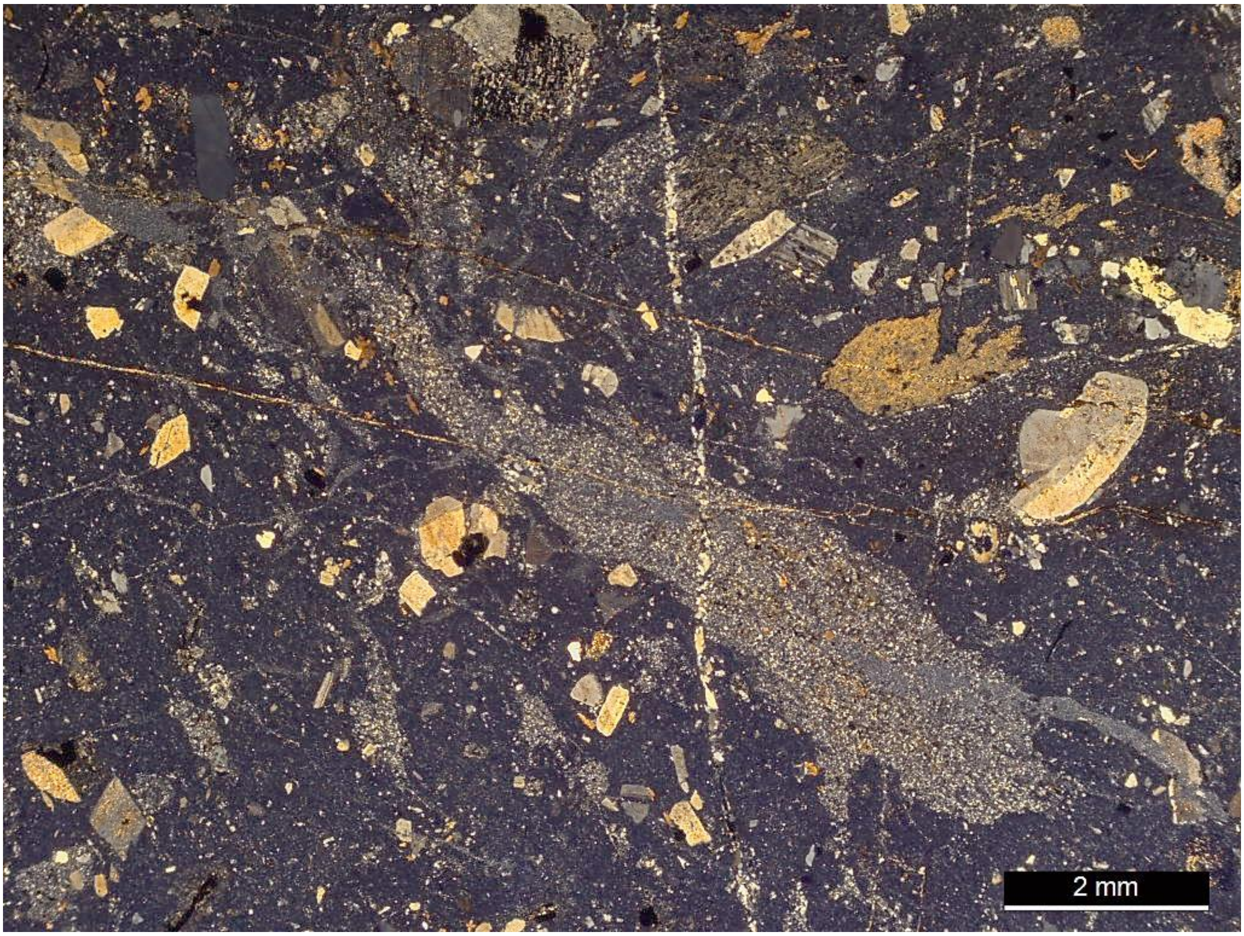


Figure 2.5-4. **Crystal tuff** in the Lynn Volcanic Complex (site 881BN) with glass fragment type 3. Medium gray **flattened obsidian fragments** that have no internal banding or crystals. This is likely obsidian and not pumice as indicated by the lack of internal bands that result from flattened bubbles. Note smaller and very similar glass fragments in surrounding matrix. View with crossed polarizers.

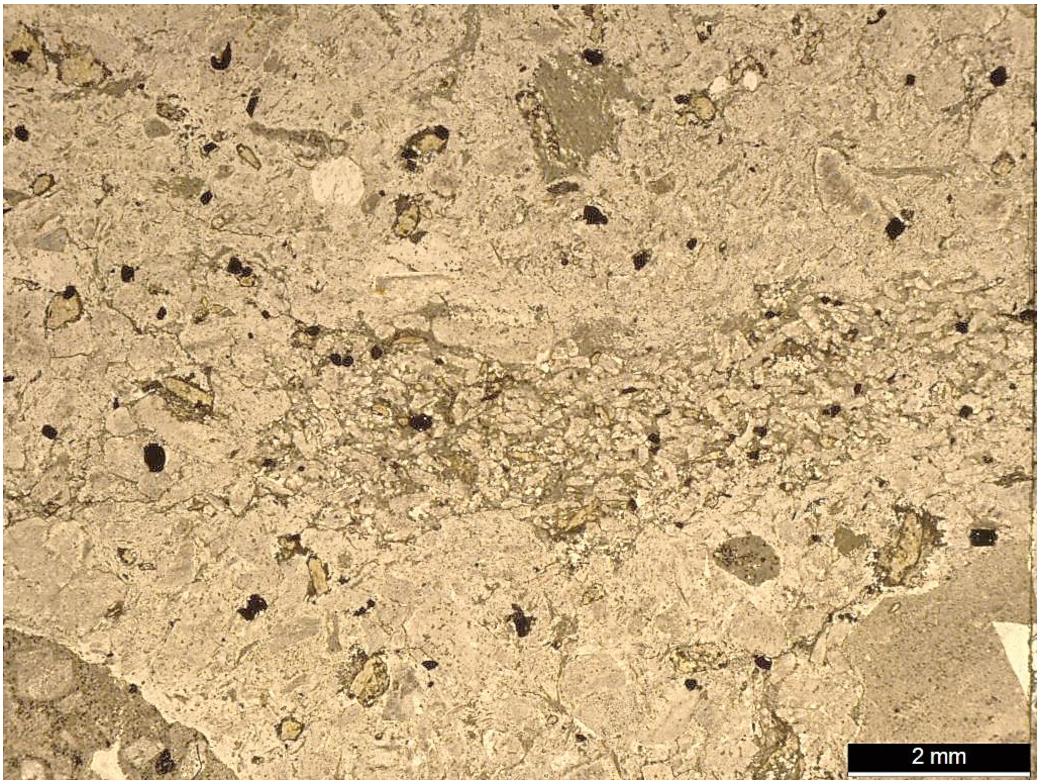
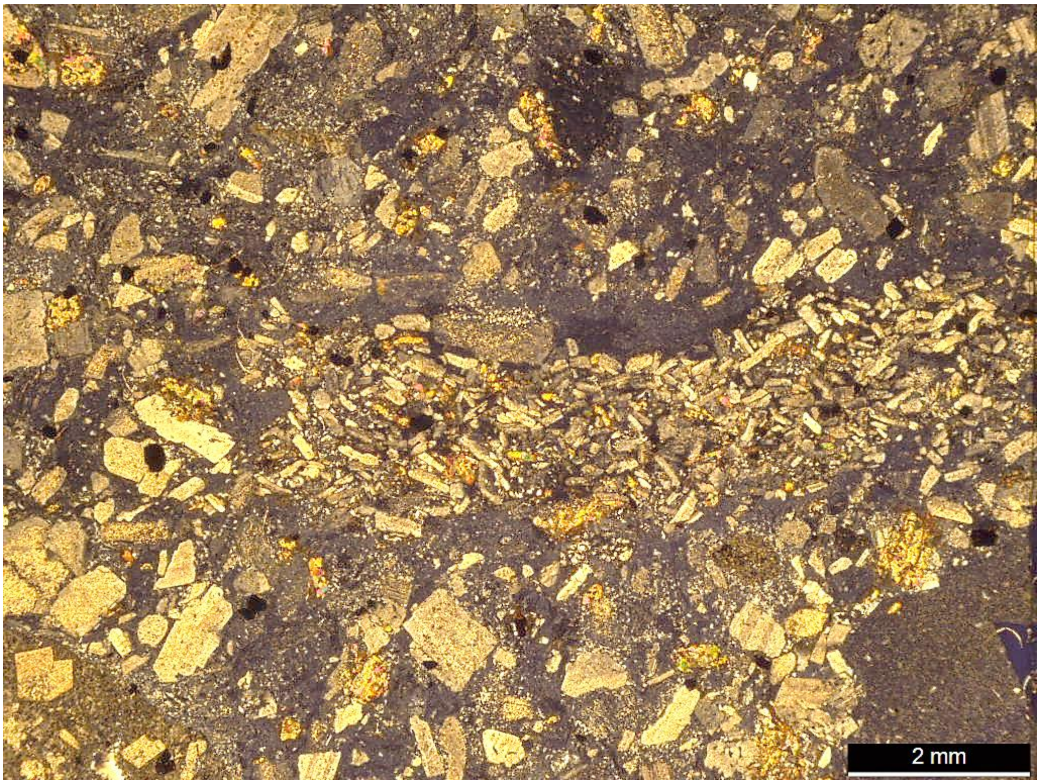


Figure 2.5-5. **Lithic tuff** in the Boojum Rock Tuff (site 10020) with glass fragment type 4. Above: Rare, densely **porphyritic obsidian fragment** with very fine plagioclase phenocrysts. In lower left and right corners are lithic fragments. View in plane polarized light. Below: Same view with crossed polarizers.



2.6 Pyroclastic Banding

Deposition of pyroclastic material can lead to **pyroclastic banding** where inhomogeneities occur during deposition either due to contrasts in particle size, glass concentration, crystal abundance, composition, or degree of welding in adjacent pyroclastic layers (Figs. 2.6-1 to 6; see also volcanic and accidental lithic fragments that have banding in section 2.10). The banding can also result from the extreme flattening of soft or molten glass shards and small glass fragments that form discontinuous layers. Typically, **pyroclastic bands** will appear to be delicately compressed around the sides of hard crystals and lithic fragments with no sign of rotation of the impinging hard objects that might indicate shearing during flow. There can be folding or shearing of pyroclastic bands only if hot and soft glassy material is sheared after deposition, also known as **rheomorphic deformation**.

Pyroclastic banding is distinguishable from banding in sialic lava flows and this topic is covered later in section 3.1 on lava flows. In **pyroclastic banding**, layers have rapid changes in thickness and are discontinuous. Pyroclastic bands have a higher abundance of broken crystals and lithic fragments than are typically found in banded lavas, which tend to have highly euhedral plagioclase crystals as phenocrysts or **cumulophyric** clusters. What is here taken to be a synonymous term for cumulophyric is **glomerophyric**.

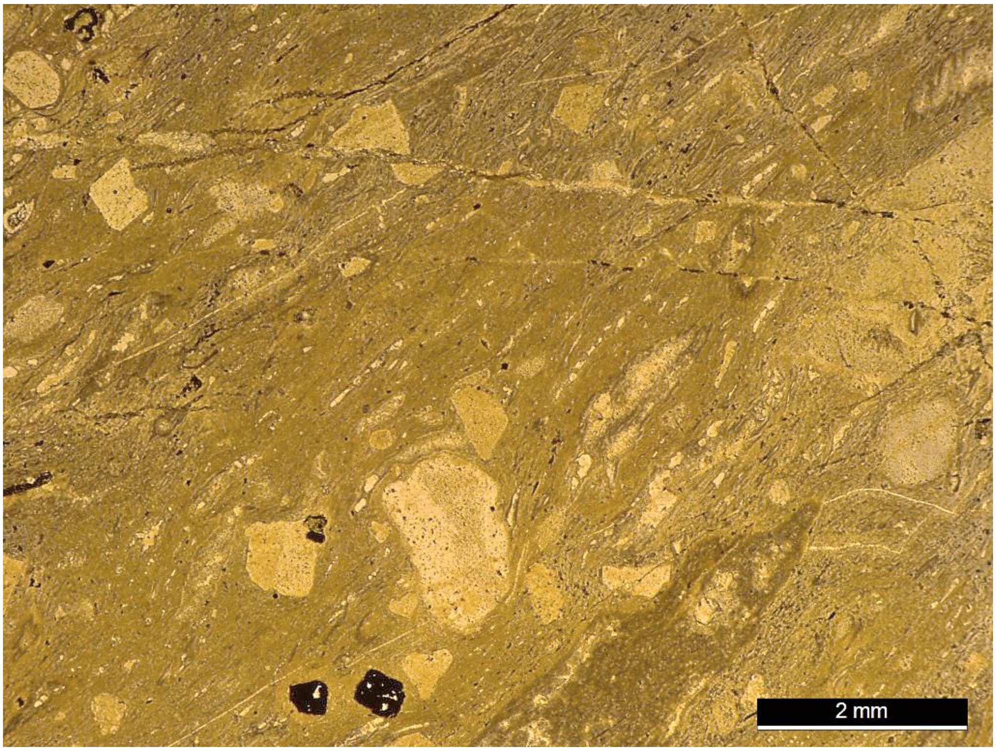
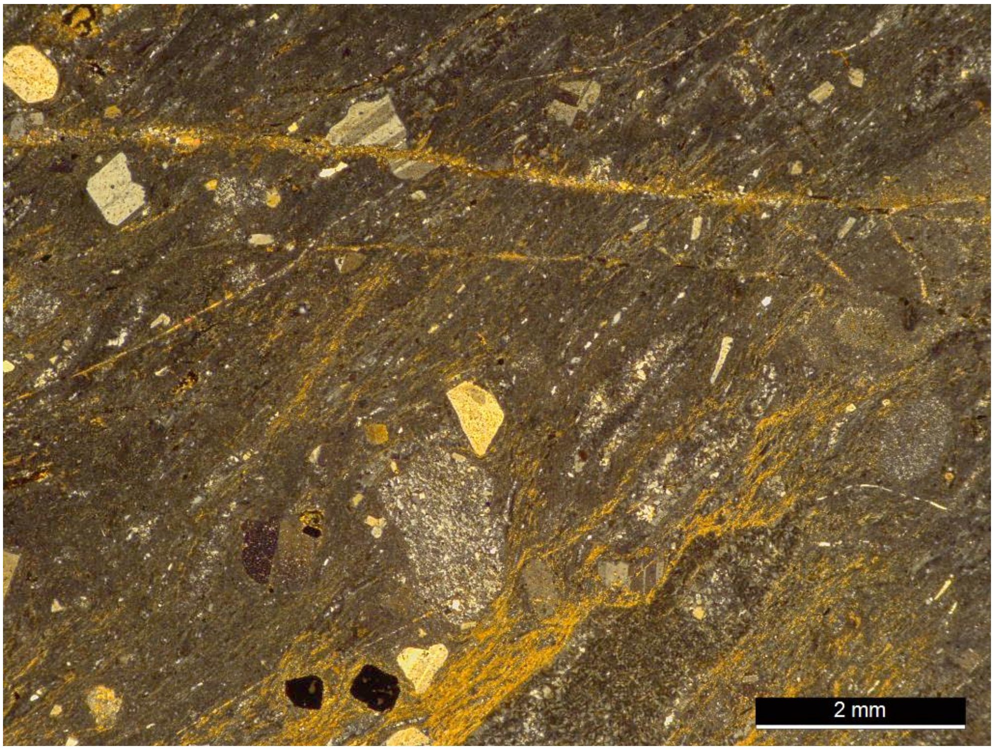


Figure 2.6-1. **Banded crystal tuff** in the Lynn Volcanic Complex at Boojum Rock (site 10236) with **pyroclastic banding**. Above: Note discontinuous nature of **devitrified glass fragments** that appear as flattened beads. Also in the rock are broken crystals, lithic volcanic fragment (largest grain), and a **flattened and pinched pumice fragment** (large dark area in bottom right). View in plane polarized light. Below: Same view with crossed polarizers. Fine orange mineralization parallel to banding is epidote and calcite.



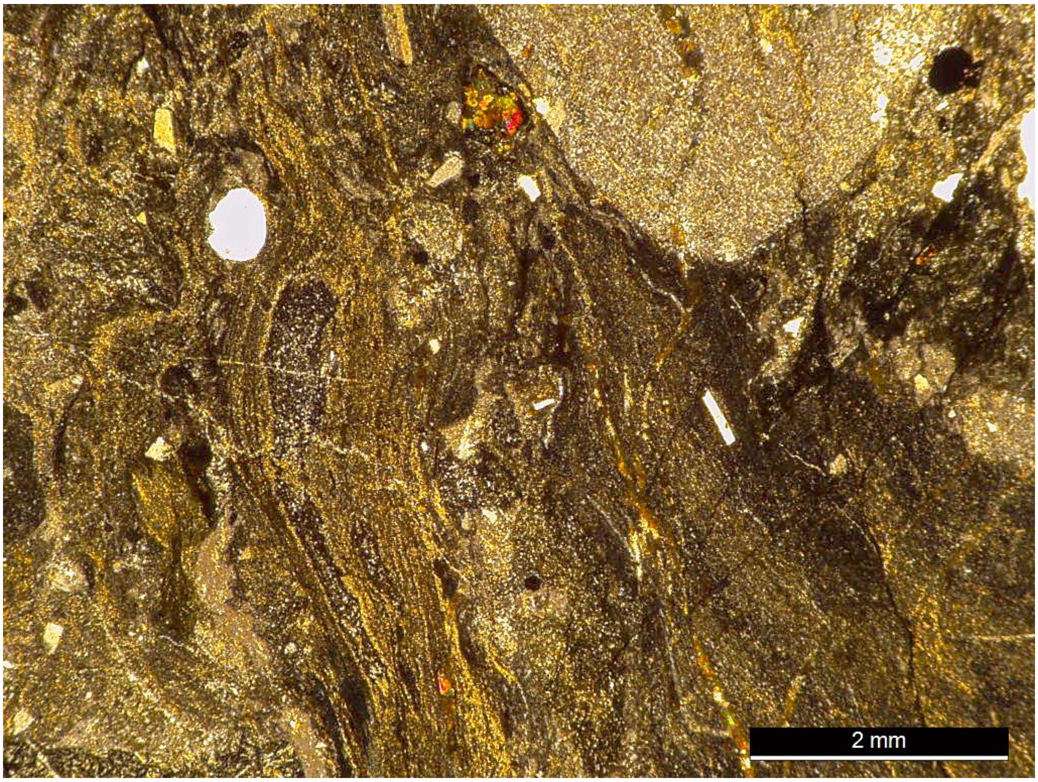


Figure 2.6-2. **Tuff** in the Lynn Volcanic Complex at Boojum Rock (site 10245) with **pyroclastic banding**. Bright white rounded crystal is quartz. View with crossed polarizers.

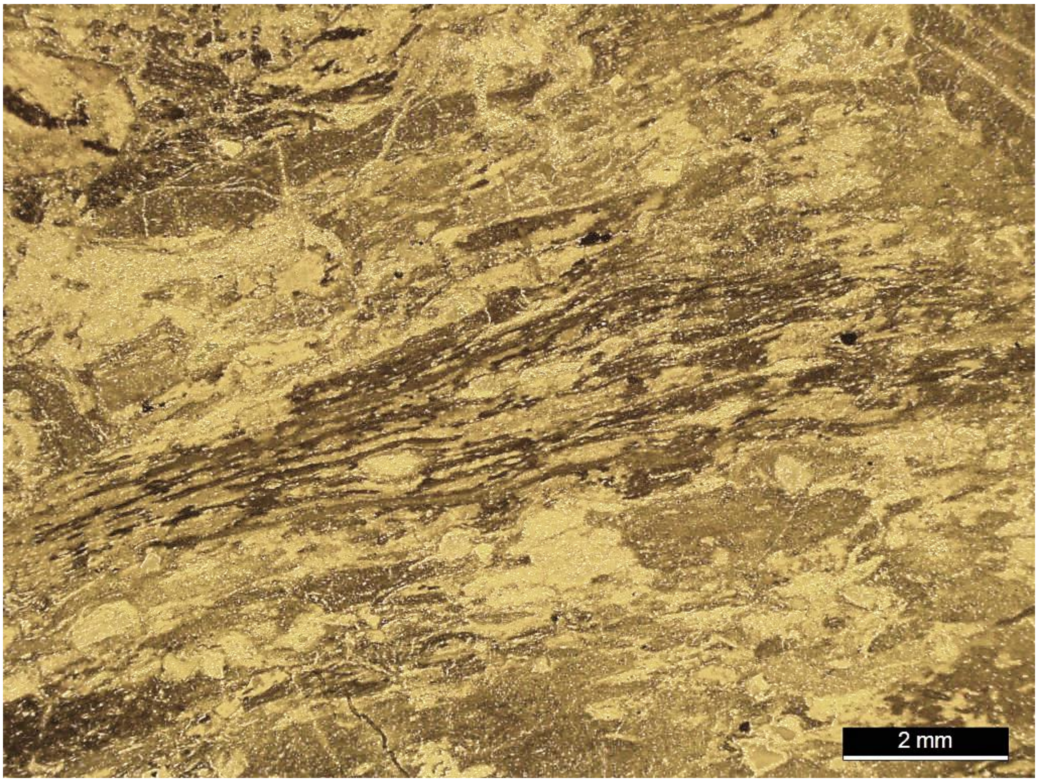


Figure 2.6-3. **Tuff** in the Lynn Volcanic Complex (site 10467) with **pyroclastic banding**. View in plane polarized light.

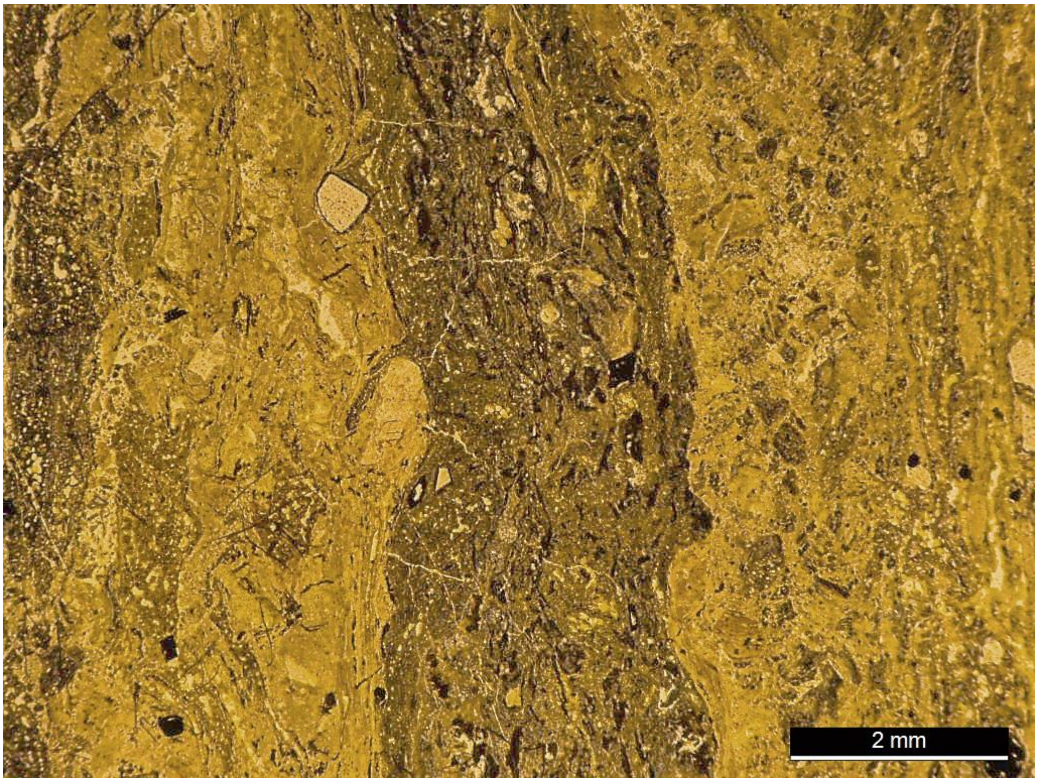


Figure 2.6-4. **Tuff** in the Lynn Volcanic Complex at Boojum Rock (site 10551) with **pyroclastic banding**. Flattened black fragments in central band are relict **flattened glass fragments**. View in plane polarized light.

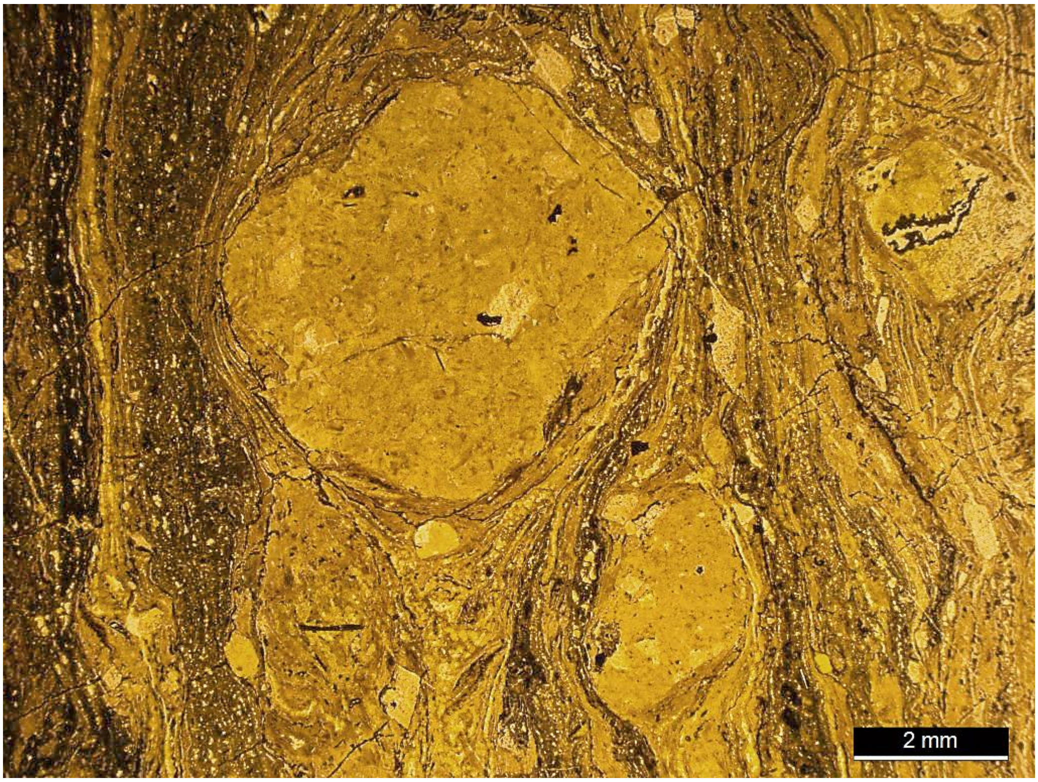


Figure 2.6-5. **Tuff** in the Lynn Volcanic Complex at Boojum Rock (site 10551) with **pyroclastic banding**. Note the warping of **pyroclastic bands** but a lack of continuity and rotational structures. View in plane polarized light.

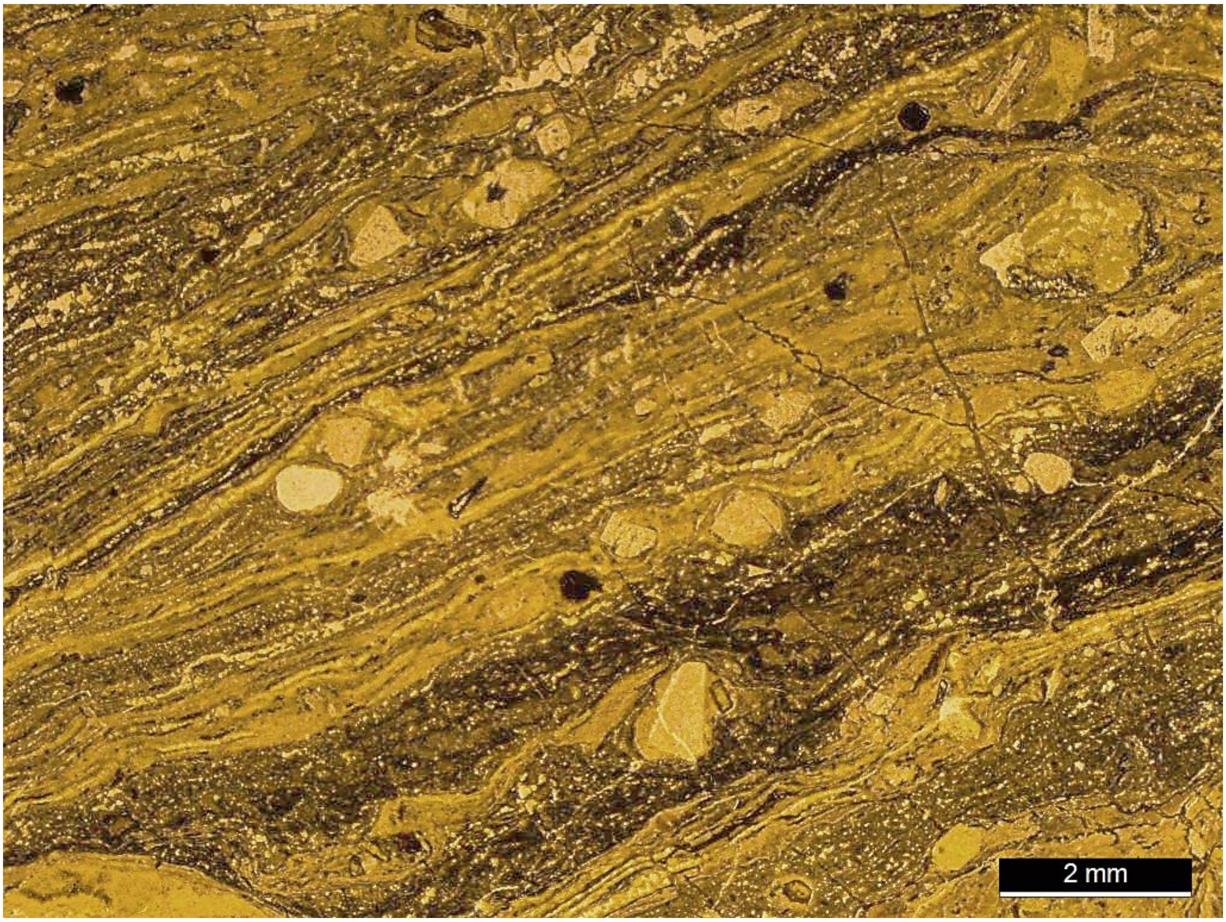


Figure 2.6-6. **Tuff** in the Lynn Volcanic Complex at Boojum Rock (site 10551) with **pyroclastic banding**. Note lack of continuity in bands and broken crystals. View in plane polarized light.

2.7 Pyroclastic Matrices: Primary and Devitrification Textures

The matrices of tuffs are mostly made of devitrified sub-sand sized glass particles or shards and crystal fragments. The exact texture of a tuff matrix varies due to initial particle size and composition and later devitrification processes, which depend on the glass composition, particle size and abundance, and temperature changes. Crystallization during devitrification of glassy material may lead to crystals growing across the boundaries of glass particles that have adhered and fused to each other in a **welded tuff**. In poorly adhered and non-adhered glass particles in a **non-welded** tuff, crystallization during devitrification generally forms crystals confined to the boundaries of original glass particles and shards. Devitrification textures may give clues as to whether the tuff was welded or non-welded and there can be a mixture of welded and non-welded units creating a complex interlayering within a single rock unit or even within a single thin section. The ability to tell the difference between welded and non-welded tuffs based on matrix textures has not been fully developed.

2.7.1 Devitrification Dominated by Quartz and Plagioclase Growth

Ultra-fine to very fine granular textures

In tuffs in the Middlesex Fells that have the equivalent of a largely quartz and plagioclase mixture with lesser amounts of alkali feldspar, i.e., dacitic tuff of the Boojum Rock Tuff, there seems to be a continuum of textures that starts with **ultra-fine granular** materials in which the tuff had a minimal amount of welding. Ultra-fine granular textures show little evidence of recrystallization by devitrification, partly because particles are too tiny to observe in a regular petrographic microscope (Fig. 2.2-6, 2.7-1 to 2). Fine granular textures do not show evidence of adjacent glass particles fusing together as larger crystals during devitrification. It is suspected that this type of matrix results from the deposition of solid and substantially cooled very fine glass particles in non-welded tuff. Solid glass shard/particle outlines are absent, possibly because they are mostly too fine to observe.

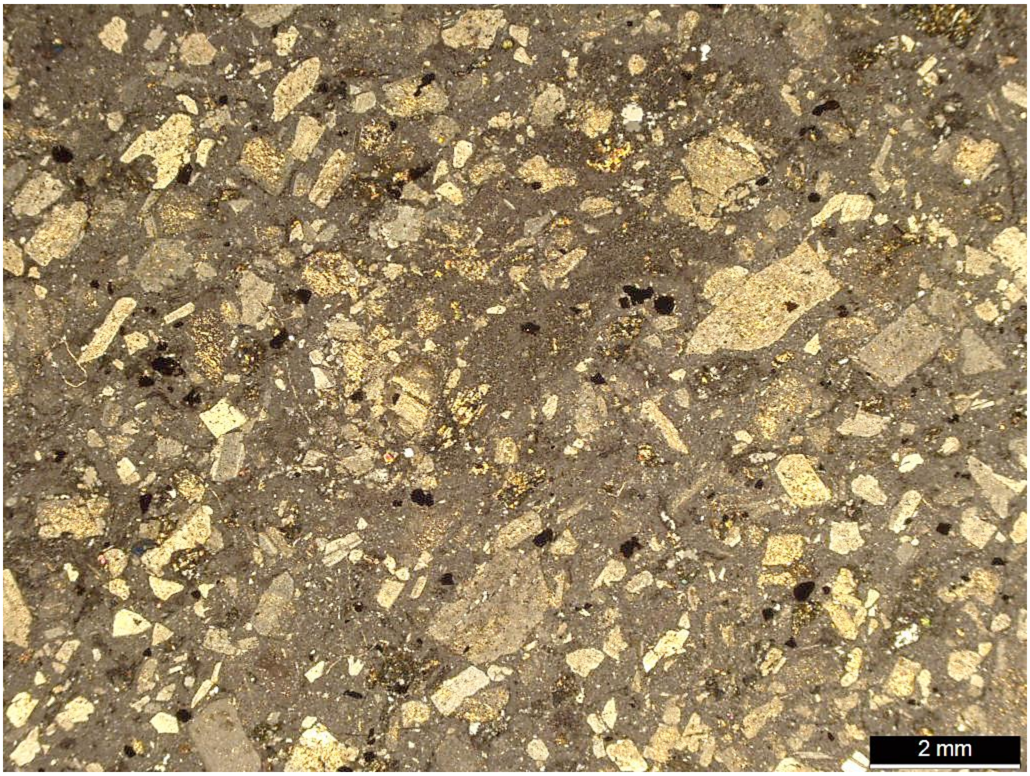


Figure 2.7-1. **Crystal tuff** in the Boojum Rock Tuff (site 10275) with an **ultra-fine granular matrix** surrounding many crystals. View with crossed polarizers.

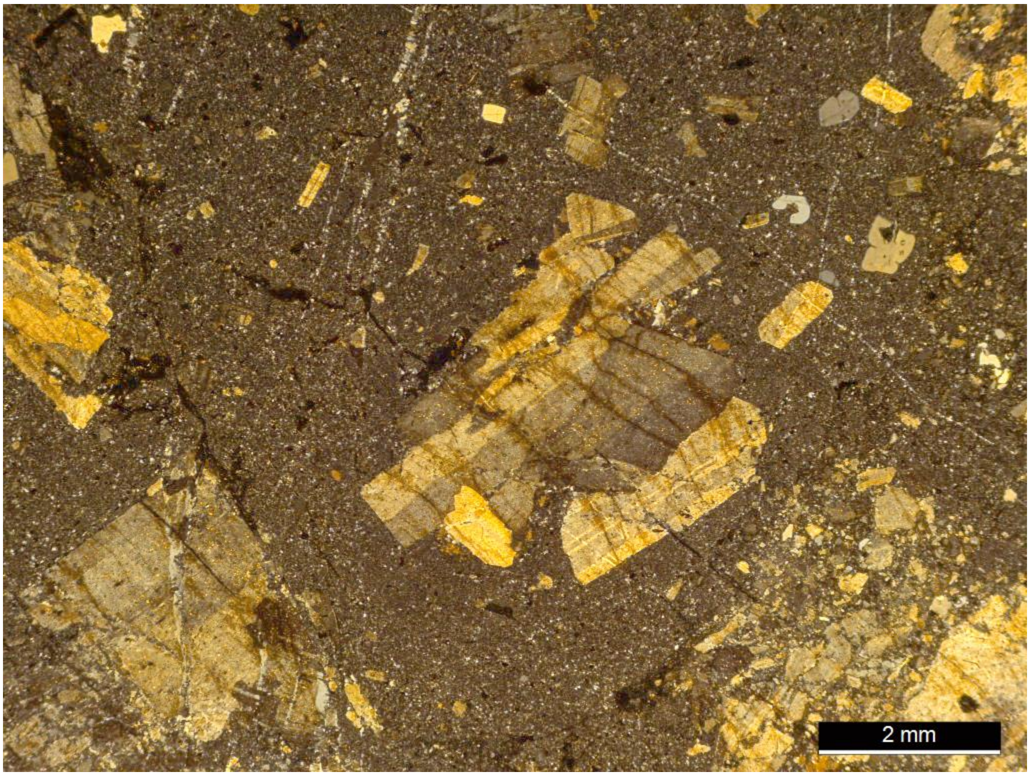


Figure 2.7-2. **Crystal tuff** in the Lynn Volcanic Complex (site 10476) with a **very fine granular matrix** that has very fine devitrification crystals. View with crossed polarizers. In this rock are euhedral and broken plagioclase crystals and embayed and rounded quartz crystals that are sometimes broken.

Section 2.7.1 (cont.) - Felsitic patchy texture

If a matrix has larger than very fine particles, or if a few adjacent glass particles devitrify together as single crystals, the matrix starts to take on a **felsitic texture** or one made of a patchwork of quartz and feldspar grains with some samples showing the beginning if **tabular plagioclase growth** in the matrix. A very fine **felsitic texture** is here referred to as a **fine patchy texture** with visible individual grains that formed during devitrification (Fig. 2.7-3 to 6; see also volcanic lithic fragments in section 2.10 that have these textures). This may be partly a function of the original grain size of glass particles or alternatively, it may result from prolonged high temperatures in the deposited material. Prolonged high temperatures promote formation of single quartz and plagioclase crystals across adjacent glass shard/particle boundaries during devitrification. Glass particles in this case might not have been welded, or only slightly welded, and crude outlines of glass shards might still be found under magnification in plane polarized light. They are frequently visible because the recrystallized parts of glass shards are relatively clear and surrounded by dark impurities that outline the original shard. As devitrification occurs with the crystallization of quartz and plagioclase the identification of shard outlines may be enhanced if impurities are excluded by crystallization and pushed to the edges of original glass shards. It is suspected that iron components in the original glass may be excluded leading to dark outlines of the original glass particles or shards. Devitrification that is too fast for this exclusion process may simply create crystalline material that encloses the impurities.

Figure 2.7-3. **Crystal tuff** in the Boojum Rock Tuff (site 10024) with an **ultra-fine granular matrix** in the upper left and a **fine patchy (felsitic) matrix** in the lower right that shows greater alteration and mineralization by epidote (yellowish-orange areas). View with crossed polarizers.

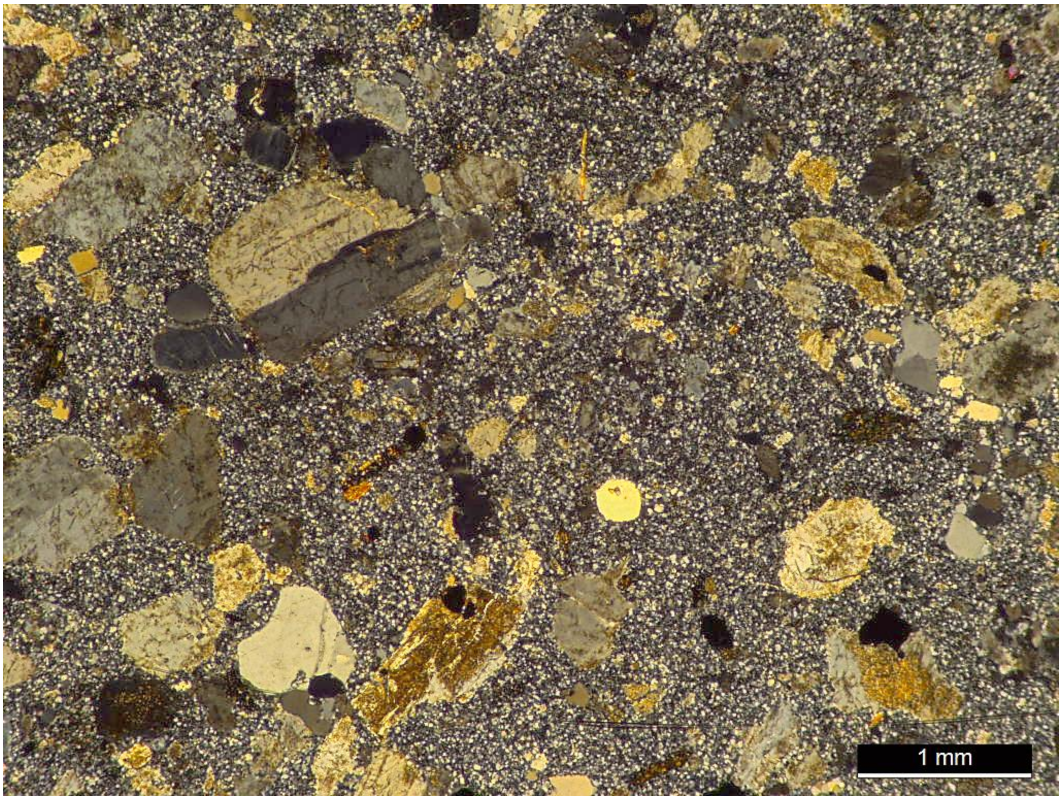


Figure 2.7-4. **Crystal tuff** in the Lynn Volcanic Complex (site 10411) with a **fine patchy (felsitic) matrix**. View in crossed polarizers. Bright clear grains in center and lower left are rounded (resorbed) quartz.

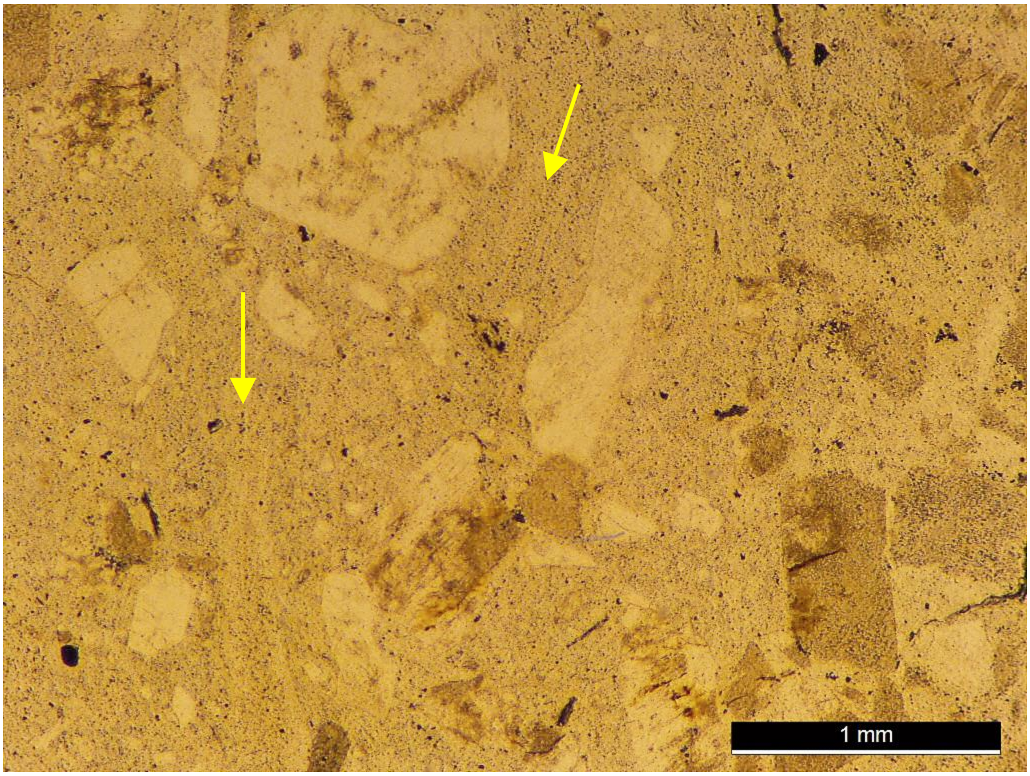
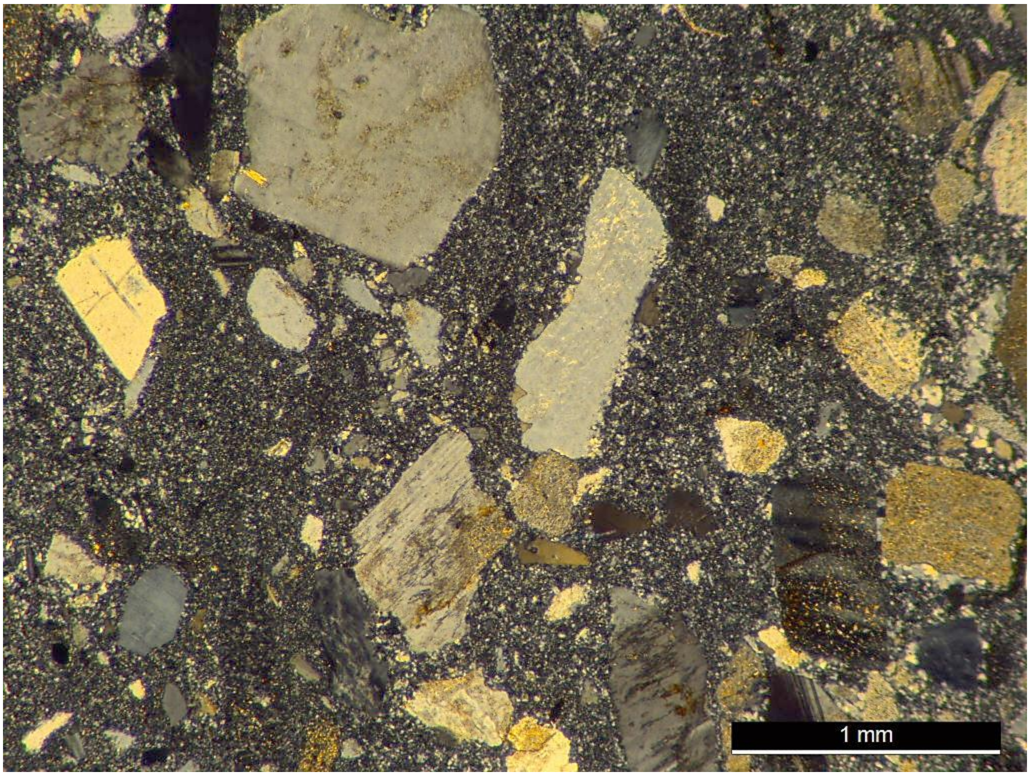


Figure 2.7-5. **Crystal tuff** in the Lynn Volcanic Complex (site 669BN) with a **fine patchy felsitic matrix.** <u>Above</u>: Note faint trace of **pyroclastic banding** (arrows). View in plane polarized light. <u>Below</u>: Same view with crossed polarizers. Banding in the rock essentially disappears with crossed polarizers.



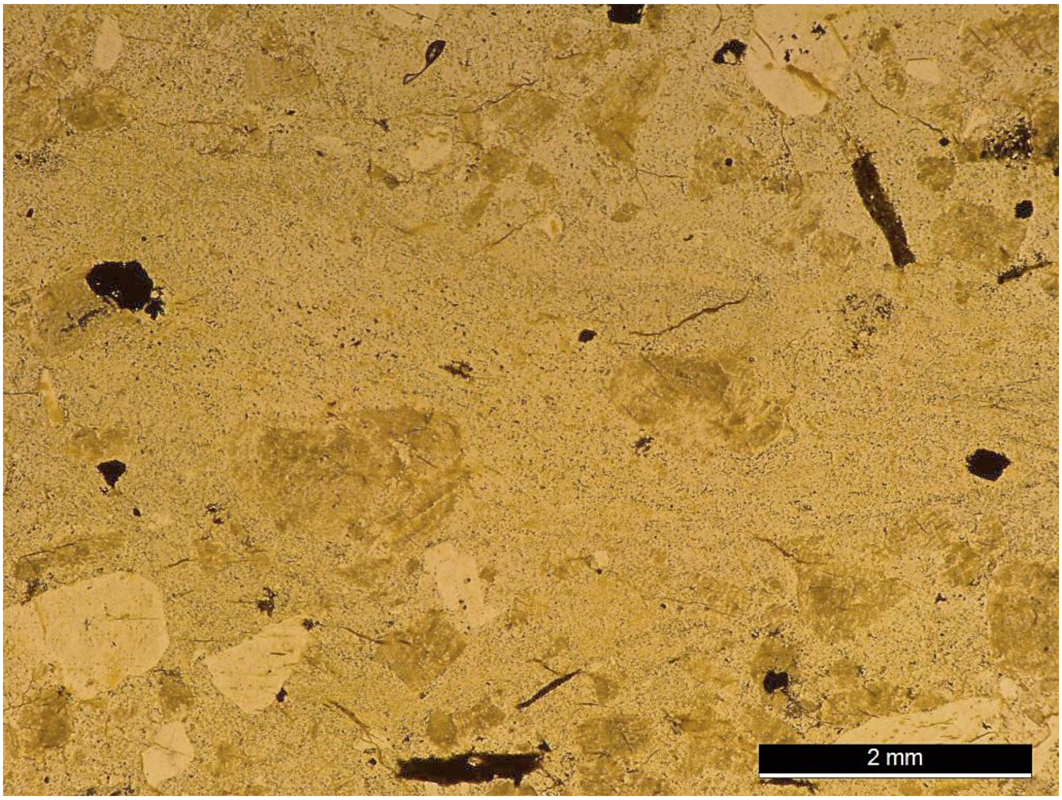
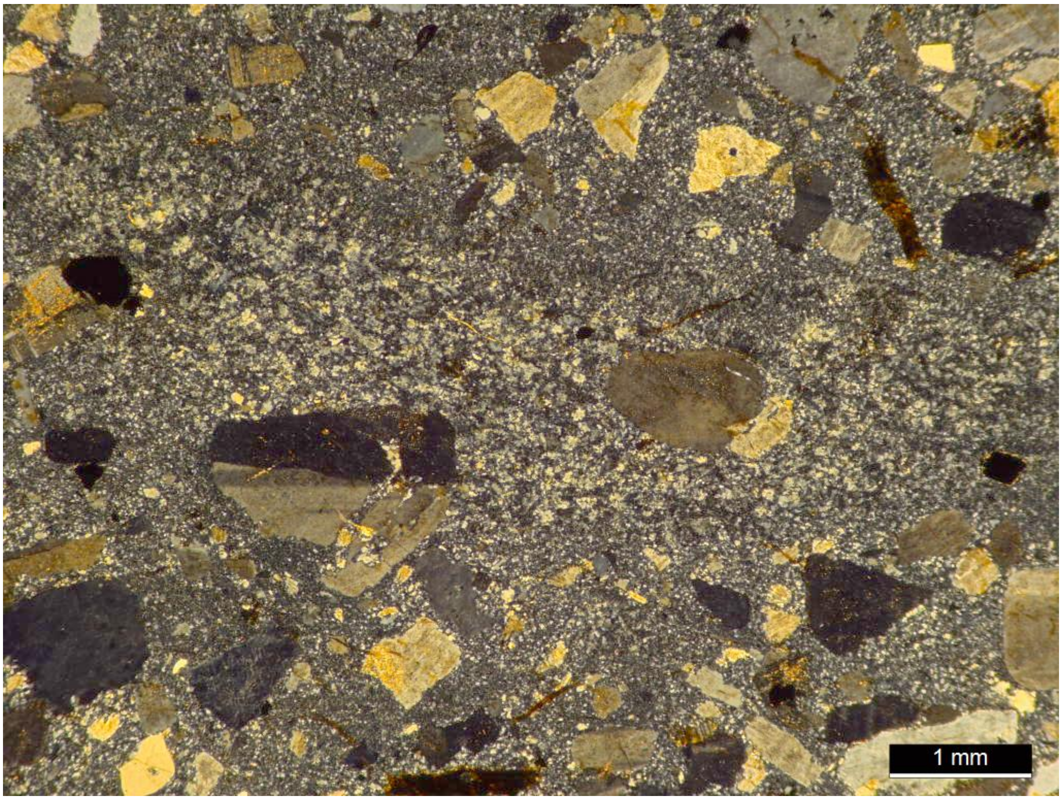


Figure 2.7-6. **Crystal tuff** in the Lynn Volcanic Complex (site 10407) with mostly a **fine patchy matrix.** <u>Above</u>: Note faint trace of **pyroclastic banding** across center of view from left to right. View in plane polarized light. <u>Below</u>: Zone of **pyroclastic banding** in same view as above has a coarser **patchy** to **micropoikilitic felsitic texture**. Same view as above with crossed polarizers.



Section 2.7.1 (cont.) – Felsitic splotchy texture

During devitrification, fully welded glass particles and shards at higher temperatures likely lead to larger crystals across original shard boundaries and a coarser **felsitic texture** that obscures original glass particle or shard outlines (Fig. 2.7-6; see also lithic fragments that have this texture in section 2.10). Single crystals of quartz begin to invade and take over multiple glass particles and they begin to surround smaller plagioclase crystals and other matrix materials. The quartz will first take on the appearance of a **splotchy texture** either as **isolated single crystal splotches** or **splotchy clusters and strings** having the appearance of inkblots (Figs. 2.7-7 to 8). The splotches seem to moderately enclose other matrix materials and are very clear.

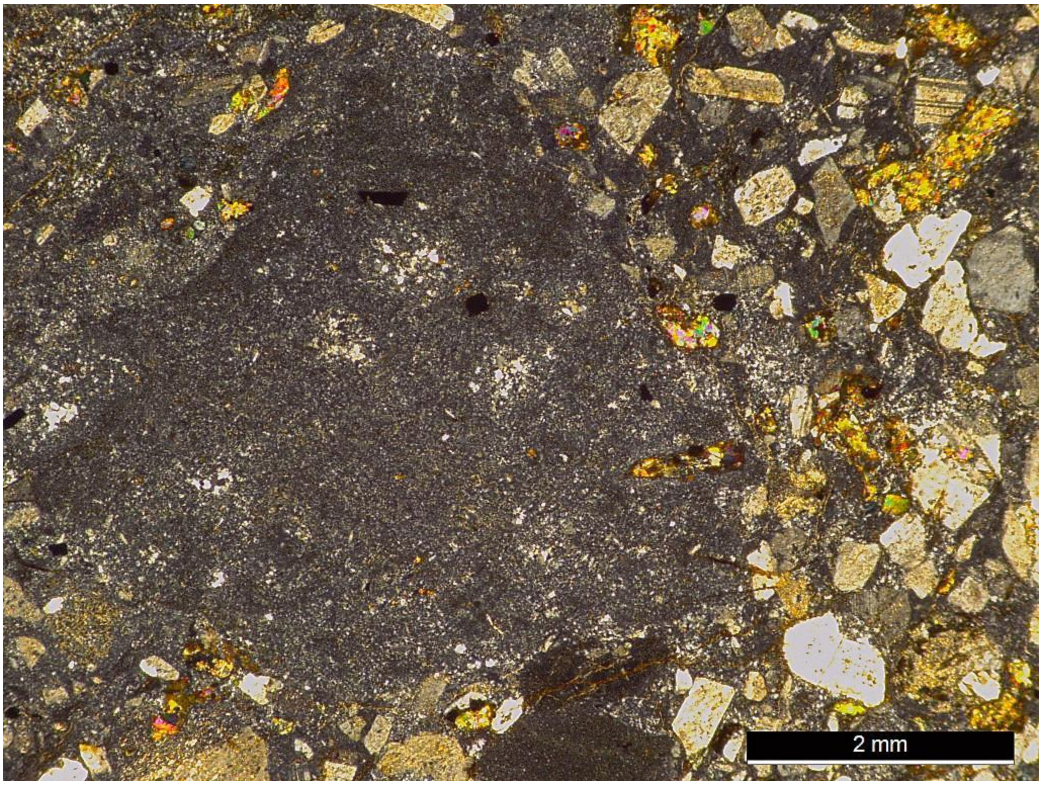


Figure 2.7-7. **Lithic fragment** in the Boojum Rock Tuff (site 10352) with a **fine patchy matrix** that has **splotchy quartz growths**. View with crossed polarizers.

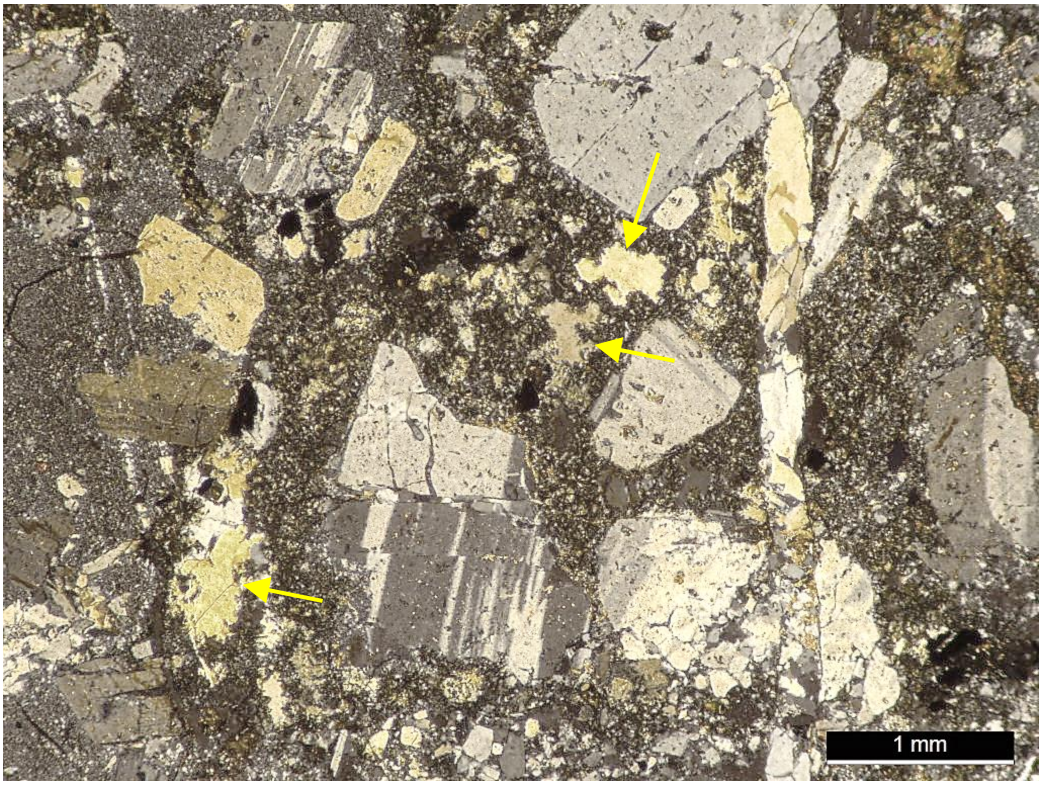


Figure 2.7-8. **Crystal tuff** in the Boojum Rock Tuff (site 10947) with mostly a **fine patchy matrix** that has coarser **splotchy quartz growths** (arrows show large examples but adjacent to them are smaller splotches) in the finer **patchy matrix**. The patches seem to exclude adjacent crystals and have the appearance of jigsaw puzzle pieces. View with crossed polarizers.

Section 2.7.1 (cont.) – Felsitic micropoikilitic texture

As quartz growth gets more extreme, more pervasive quartz growths with better defined boundaries create a **micropoikilitic texture** (sometimes called "snowflake texture") of quartz surrounding other materials, especially finer plagioclase crystals (Figs. 2.7-9 to 11). This texture is only discernable with crossed polarizers. It appears to be the case that plagioclase does not as easily form crystals that cross glass particle boundaries and they tend to form smaller **patchy** or **tabular crystals**, perhaps partly because the magma has already used up much of its plagioclase component on much larger juvenile crystals. The **micropoikilitic texture** can occur in isolated domains or bands and suggests a compositional or particle size difference, or perhaps welding in these areas or temperature gradients.

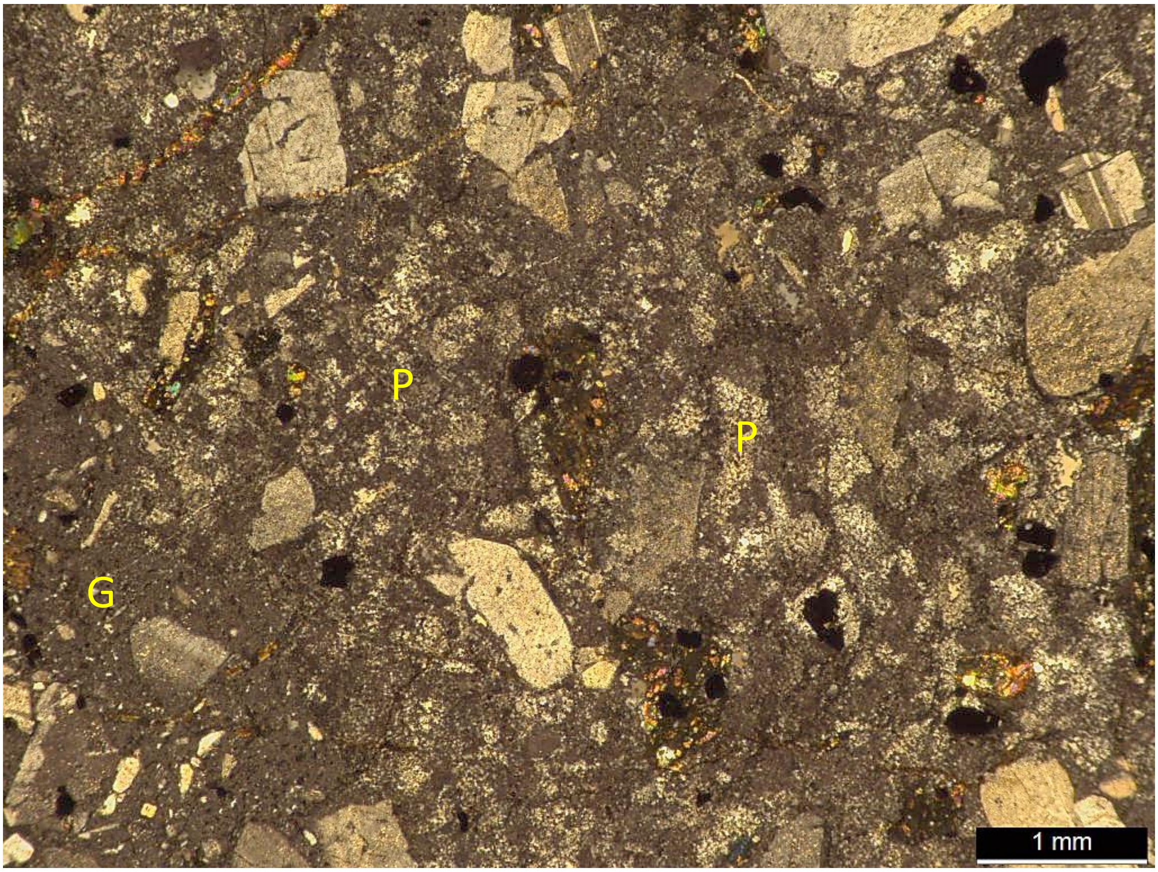


Figure 2.7-9. **Crystal tuff** in the Boojum Rock Tuff (site 10274) with mostly a **micropoikilitic texture** (**P**; "snowflake texture") with quartz enclosing plagioclase and heavily altered hornblende crystals. Within the micropoikilitic domains are **quartz splotches**. In the lower left is a **fine granular texture (G)** in which the matrix does not seem to have been as coarsely recrystallized during devitrification. View with crossed polarizers.

Figure 2.7-10. **Crystal tuff** in the Boojum Rock Tuff (site 10347). On the right is a **micropoikilitic texture (P)** adjacent to a **fine granular texture (G)** on the left. View with crossed polarizers.

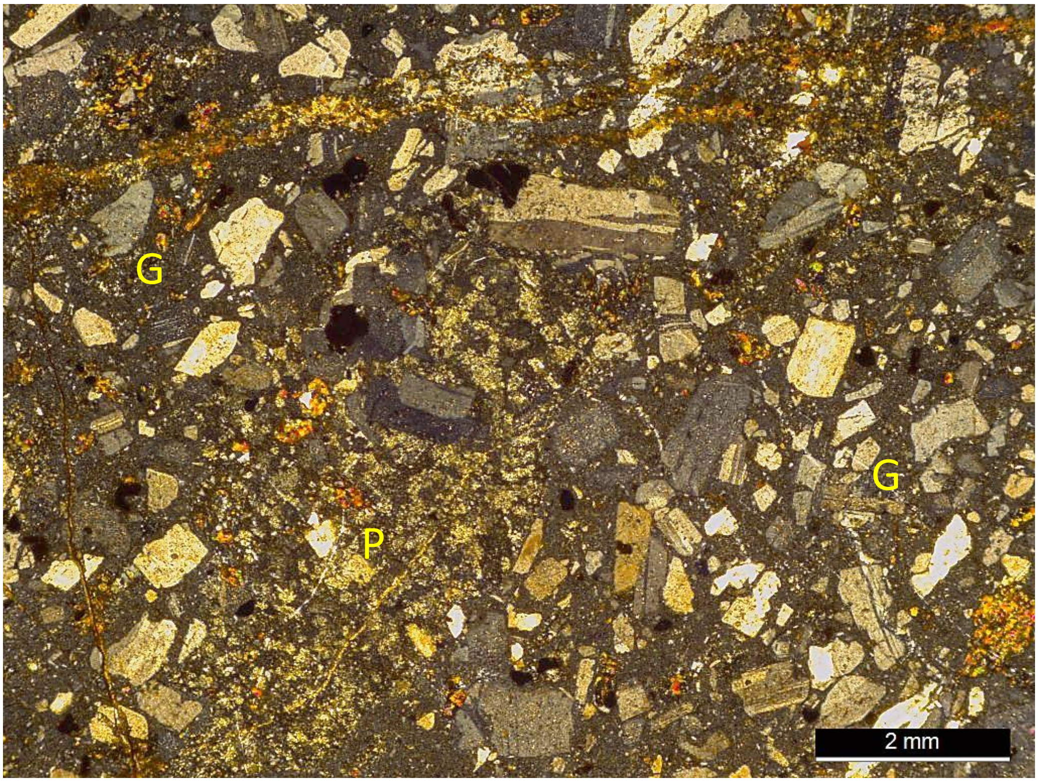


Figure 2.7-11. **Crystal tuff** in the Boojum Rock Tuff (site 10910). Most of the view shows a **fine granular texture (G)** but crossing from the lower left to upper right is a zone of well developed **micropoikilitic texture (P)**. View with crossed polarizers.

Micropoikilitic quartz growths may eventually impinge on each other forming a **poikilomosaic texture** in which the **micropoikilitic** areas develop either irregular or polygonal sutured boundaries with each other and give the appearance of separate grains (Figs. 2.7-12 to 13).

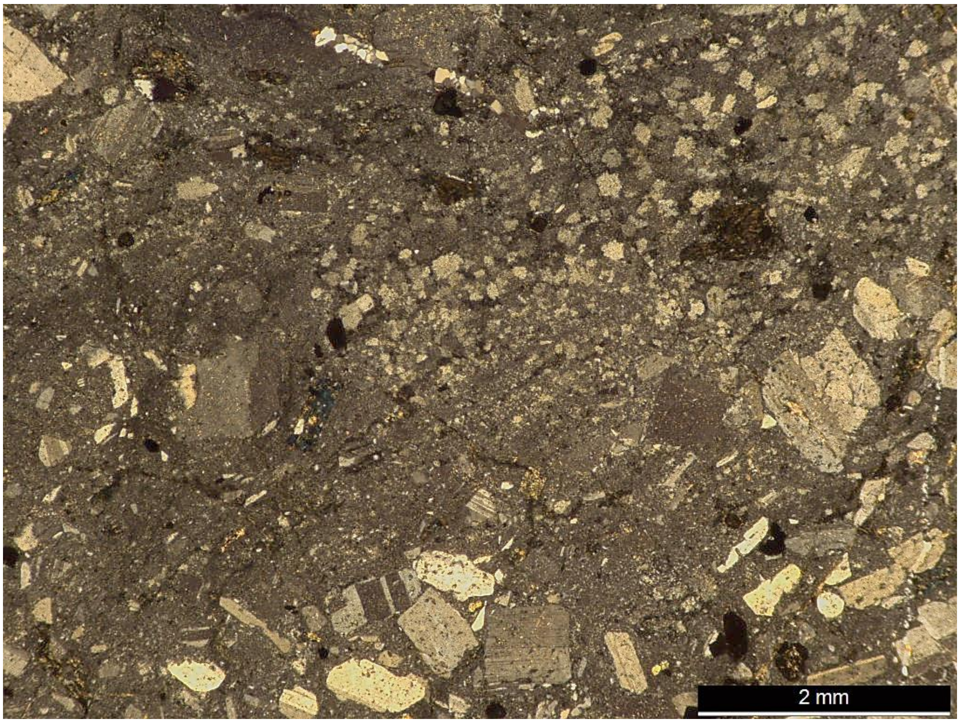


Figure 2.7-12. **Crystal tuff** in the Boojum Rock Tuff (site 10294) with mostly a **fine granular texture**. In the upper right is an area with sharply defined **micropoikilitic** quartz growths in a **poikilomosaic texture** in which quartz growths impinge on each other and have well-defined boundaries or form a mosaic. View with crossed polarizers.

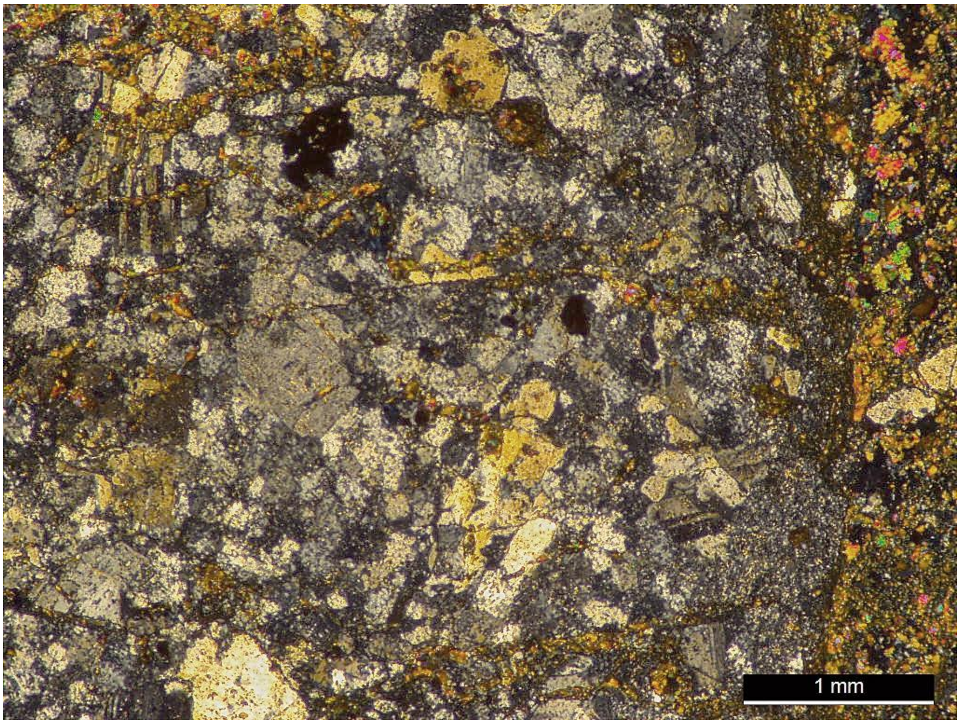


Figure 2.7-13. **Crystal tuff** in the Boojum Rock Tuff (site 10350). An enlarged view of an area of **poikilomosaic texture** with impinging **micropoikilitic** quartz growths. View with crossed polarizers. Colorful areas on right side and in upper left are epidote.

Section 2.7.1 (cont.) – Felsitic texture continuum (?)

The sequence of **felsitic textures** proposed above, grading from **ultra-fine granular** and early **patchy** and **splotchy textures** to **micropoikilitic** and **poikilomosaic textures** is best observed in the Boojum Rock Tuff. Do the textures outlined above form a continuum? In other words, can a fine granular texture progressively recrystallize leading to a poikilomosaic texture with the right devitrification conditions?

The Boojum Rock Tuff has a dacitic composition, and thus a lower potassium concentration than some of the other pyroclastic volcanic units. This lower potassium concentration is indicated by a much fainter overall staining for potassium than in more rhyolitic rocks. It is also a rock unit with abundant primary plagioclase crystals and scattered euhedral to broken hornblende crystals. Matrix quartz growth during devitrification seems to be the most important part of the devitrification process, while matrix feldspar growth produces smaller plagioclase crystals that are often barely visible and surrounded by quartz as devitrification progresses. This idealized devitrification scenario is not as prevalent in areas of higher potassium concentration. With more potassium, simultaneous devitrification to intergrowths of alkali feldspar and quartz, perhaps shortly after glass formation, leads to the development of **axiolitic** and **spherulitic growths** and is discussed below.

2.7.2 Quartz and Alkali Feldspar Growth – Axiolitic and Spherulitic Textures

Simultaneous quartz and alkali feldspar growth during devitrification occurs mostly where potassium concentrations are relatively high as indicated by staining for potassium. These textures are more abundant in rhyolitic than dacitic rocks and occur as:

1) wavy **axiolitic bands** or **strands** (<0.2 mm wide) in matrix material and flattened glass/pumice fragments with parallel to slightly radiating crystals crossing the strands, and sometimes with spherical pure quartz growths (Figs. 2.7-14 to 17)

2) layers or strands of impinging **micro-spherulitic texture** (spherules that are 0.02-0.2 mm with extinction cross patterns when viewed with crossed polarizers) sometimes mixed with **axiolitic strands** (Figs. 2.7-18 to 20; see also lithic fragments in section 2.10),

3) isolated large (0.2-1.0 mm), circular to arcing, highly fibrous to plumose **spherulitic** growths (Figs. 2.7-21 to 22; see also lithic fragments in section 2.10), and

4) areas of large (0.2-0.8 mm), competing, fibrous **spherulitic** growths nucleating off altered plagioclase crystals and in areas that are altered to epidote (Figs. 2.7-23 to 25).

Spherulites are a common structure in rhyolitic lava flows and welded tuffs and the type 3 and 4 spherulitic growths identified above resemble macro-spherulites frequently cited in literature on volcanic rocks (McPhie and others, 1993; Breitkreuz, 2013). The macro- and micro-spherulites identified here differ only in being in a fully devitrified host rock, while most citations are studies of much younger glassy rocks, especially obsidian flows and glassy welded tuffs. Micro-spherulites of type 2 above have not received much attention in volcanic rocks.

The slender radiating crystals that make up micro-spherulites produce a dark extinction cross when viewed with crossed polarizers. The crosses in spherulitic materials in general have also been called Brewster (see Raith and others, 2011) or Maltese (see Wikipedia for “spherulite - polymer physics”) crosses.

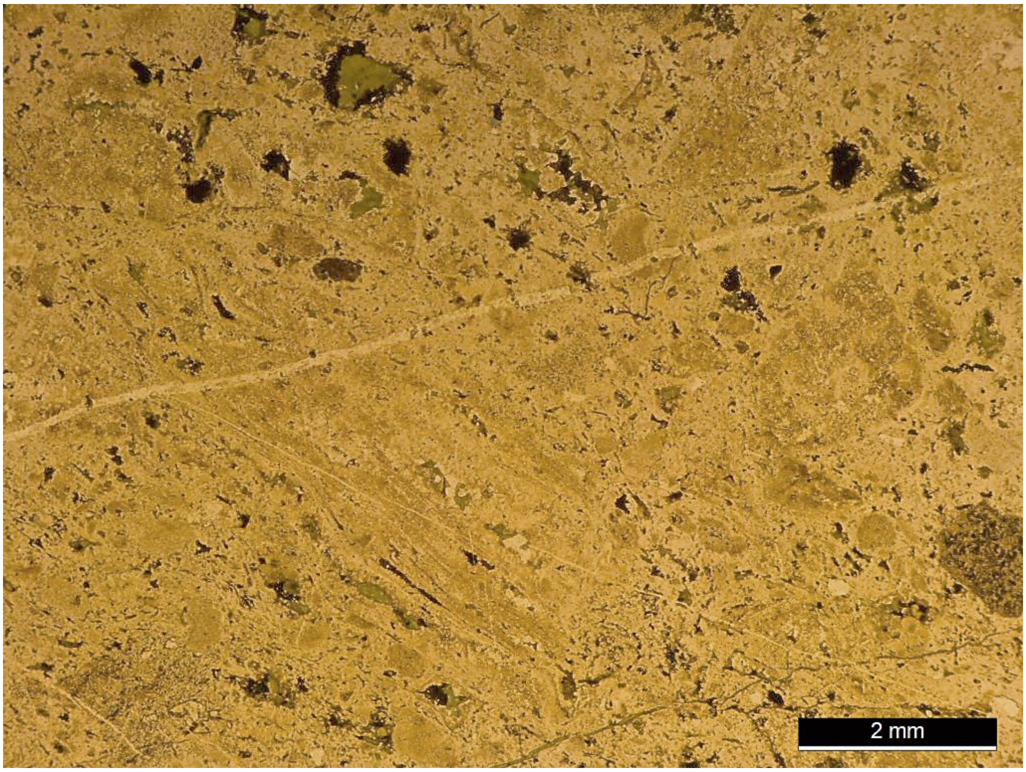
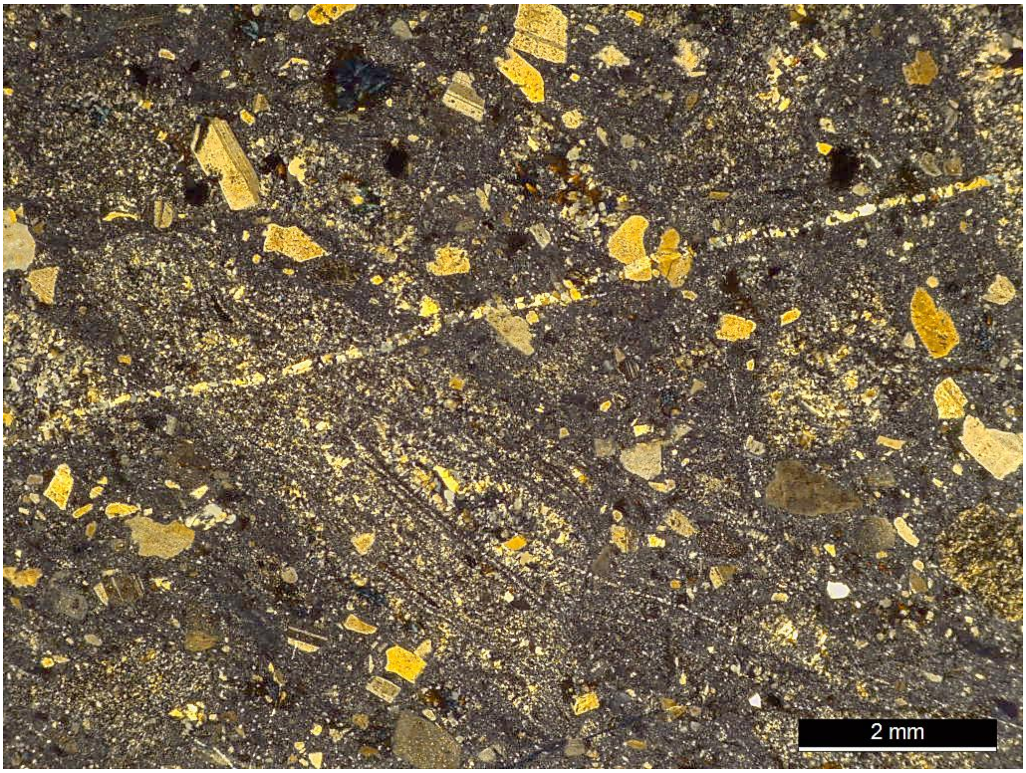


Figure 2.7-14. **Crystal tuff** of the Lynn Volcanic Complex on Whip Hill (site 595BN). Above: In the left center of image is an area of **axiolitic strands** trending from upper left to lower right. View in plane polarized light. Below: Same view with crossed polarizers showing **axiolitic strands** within an area of **patchy texture**. The vein is quartz and epidote.



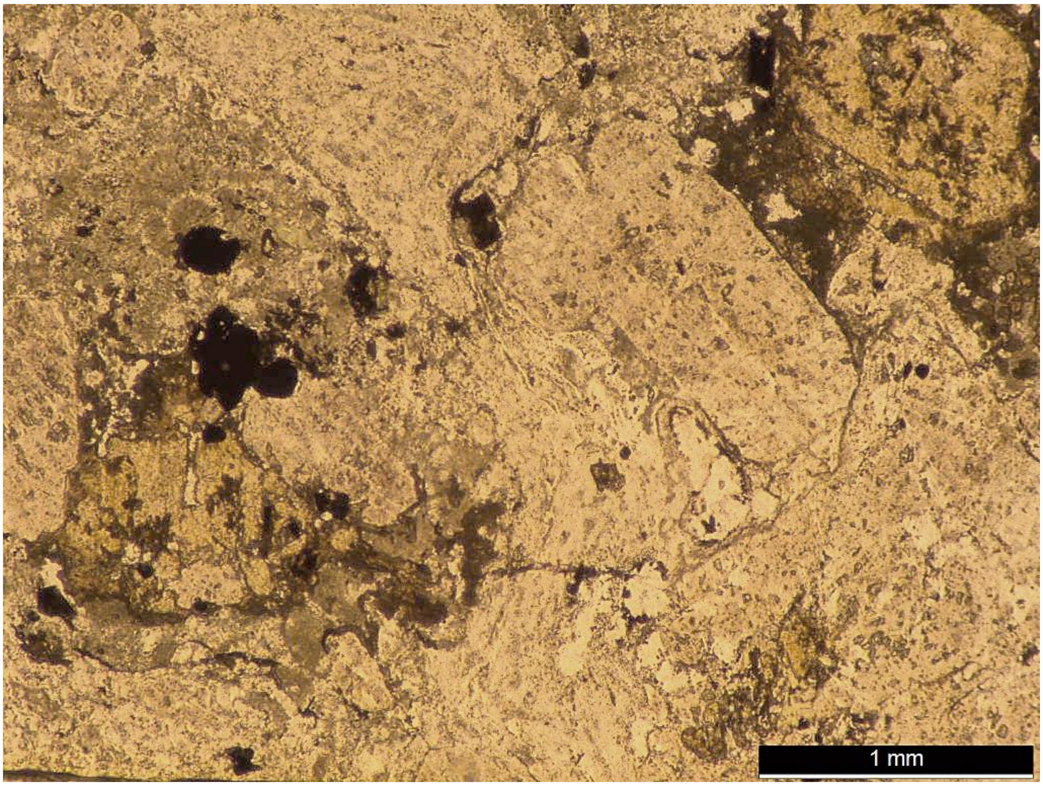
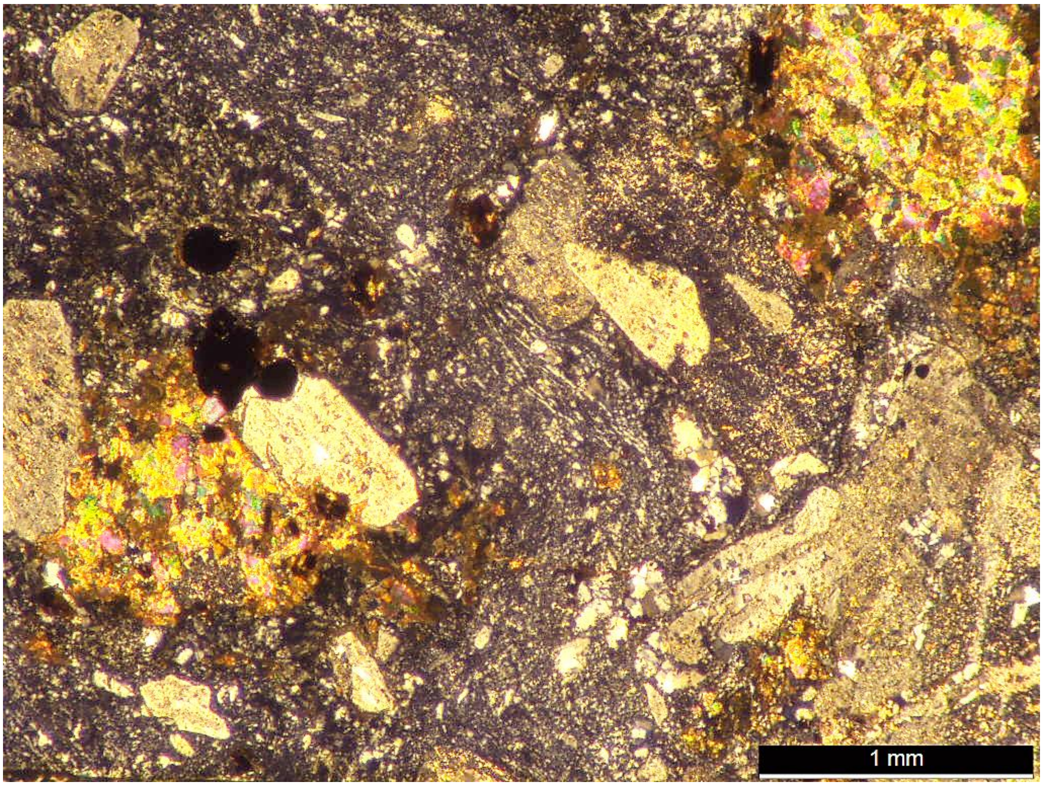


Figure 2.7-15. **Crystal tuff** in the Boojum Rock Tuff (site 10023). Above: View in plane polarized light. In the center of image are **axiolitic strands**. Below: Same view showing **axiolitic strands** with crossed polarizers. Brightly colored areas are epidote.



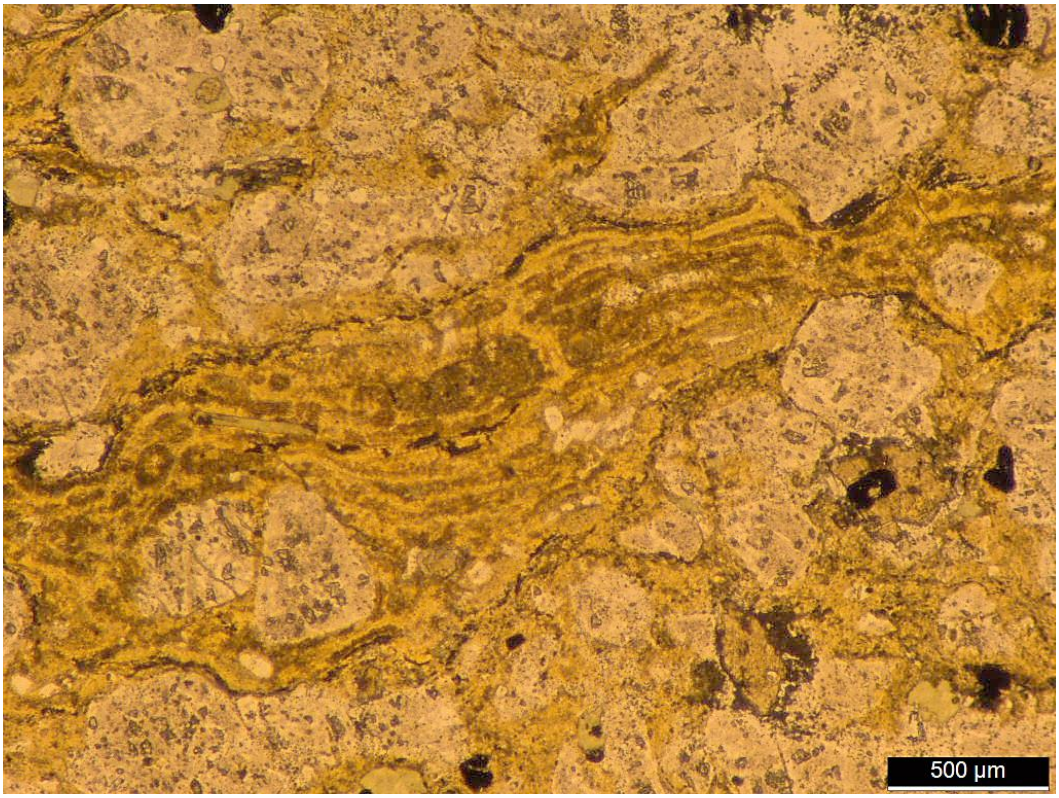
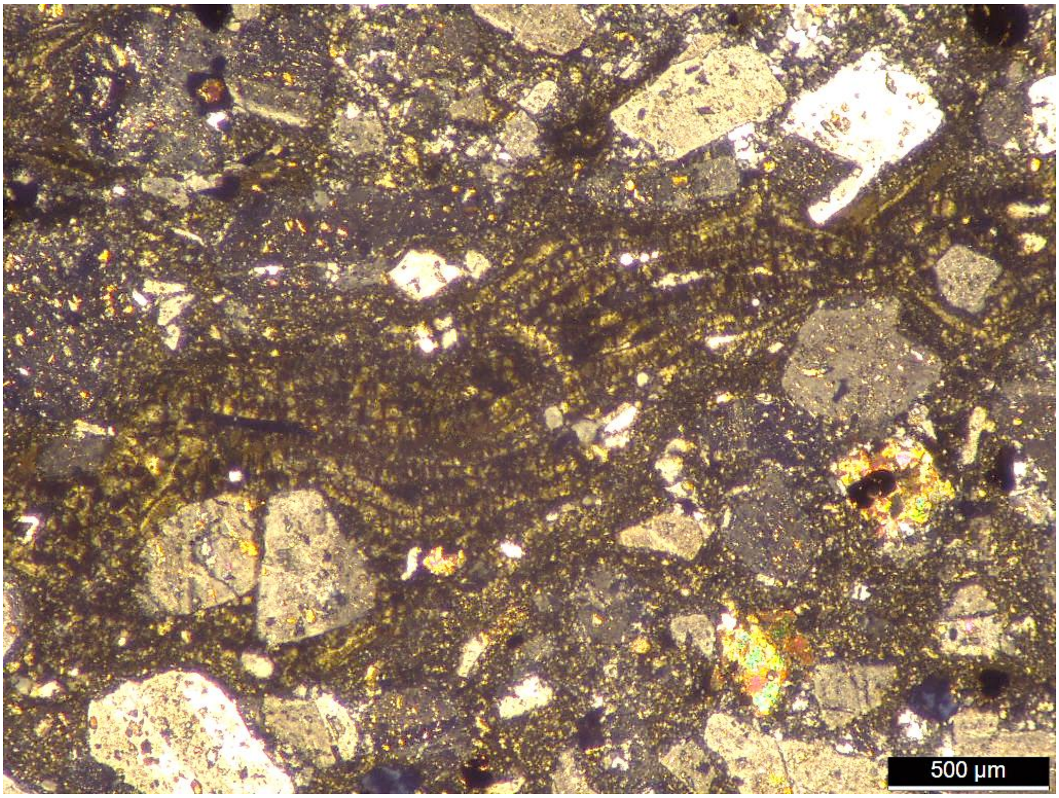


Figure 2.7-16. **Crystal tuff** in the Boojum Rock Tuff (site 10027). Above: **Axiolitic strands** with yellow potassium stain. View in plane polarized light. Below: Same view showing **axiolitic strands** with crossed polarizers. Some strands contain partly formed micro-spherulites.



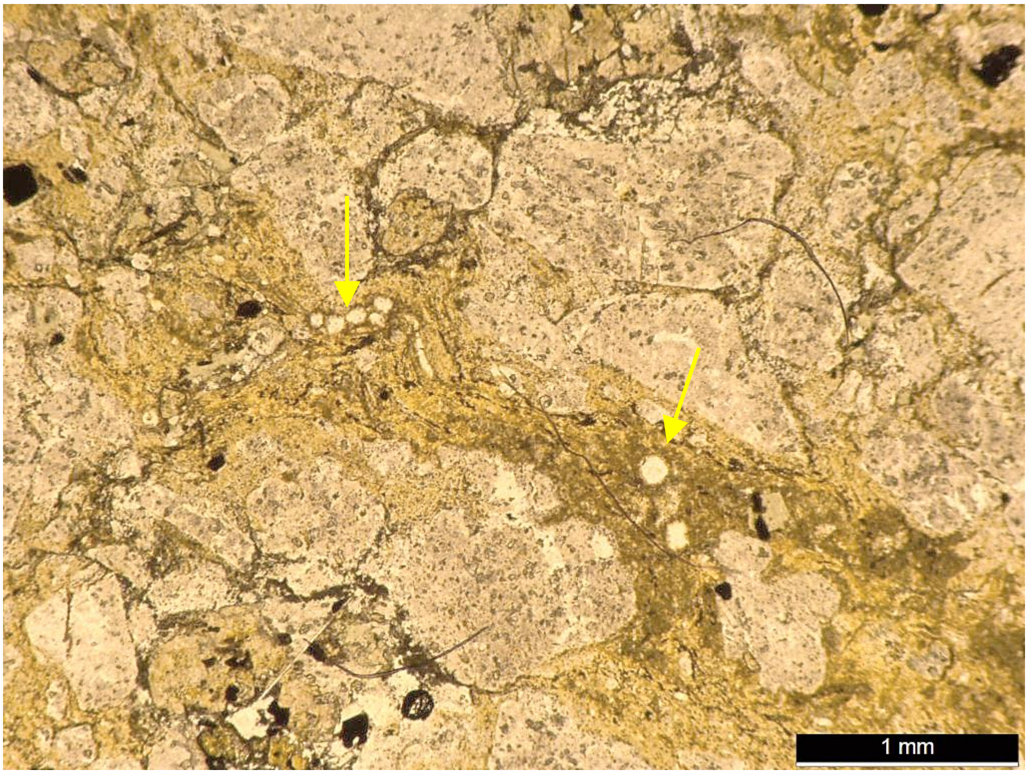
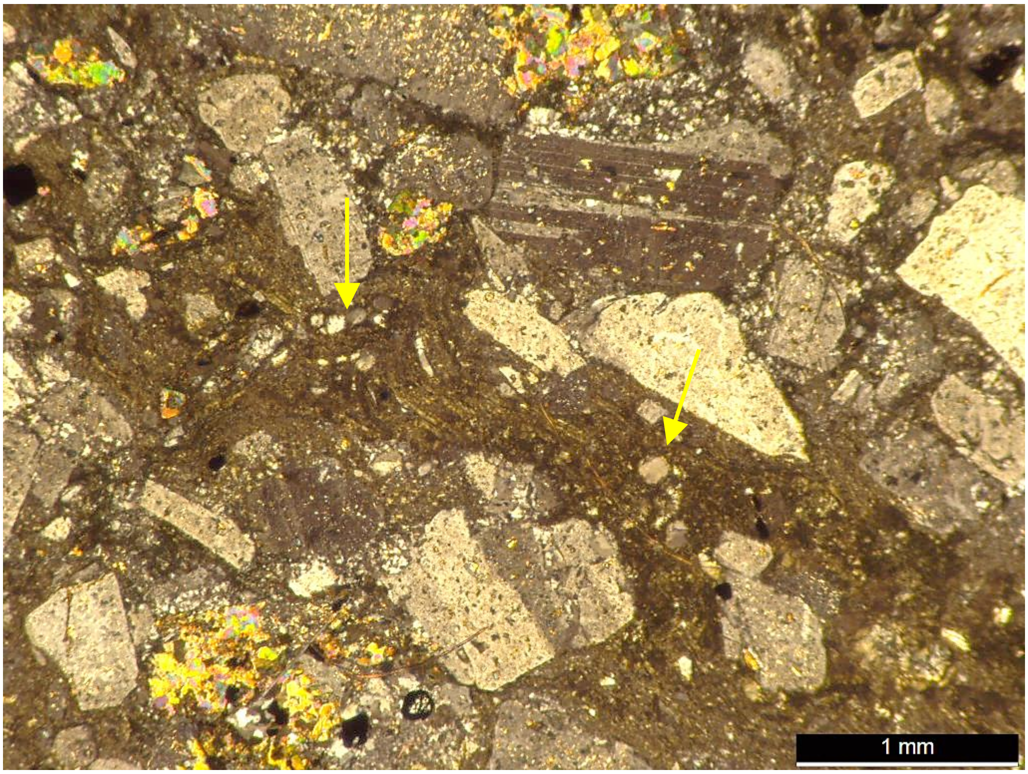


Figure 2.7-17. **Crystal tuff** in the Boojum Rock Tuff (site 10027). Above: Faint **axiolitic strands** with yellow potassium stain and clear **spherical quartz growths** (arrows). View in plane polarized light. Below: Same view with crossed polarizers.



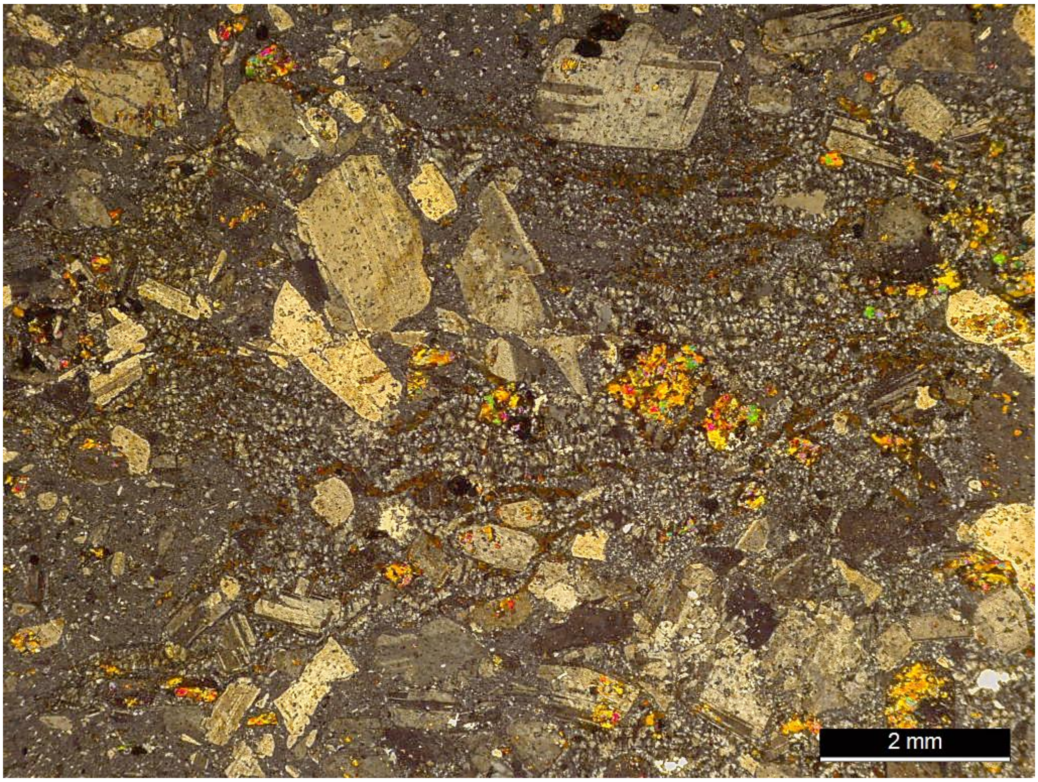


Figure 2.7-18. **Crystal tuff** in the Boojum Rock Tuff (site 10926) with mixture of **axiolitic strands** with **micro-spherulitic texture**. Colorful areas are epidote. View with crossed polarizers.

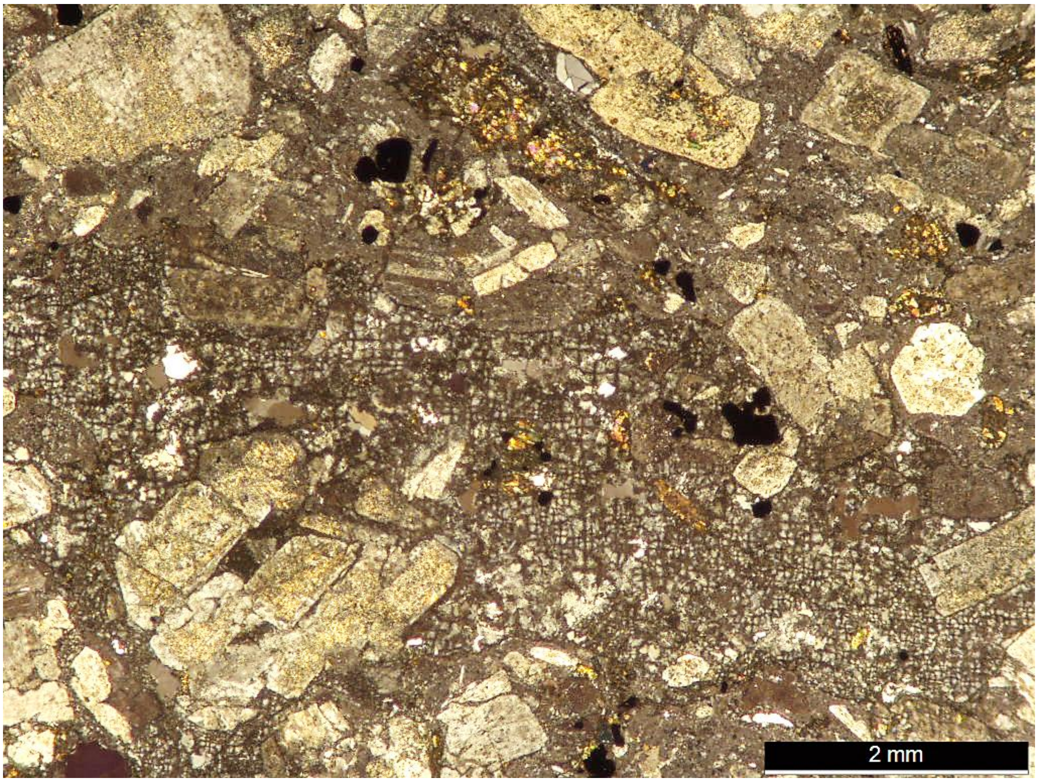


Figure 2.7-19. **Crystal tuff** in the Boojum Rock Tuff (site 10013) with band of **micro-spherulitic** texture across center of image that has well developed extinction crosses. View with crossed polarizers.

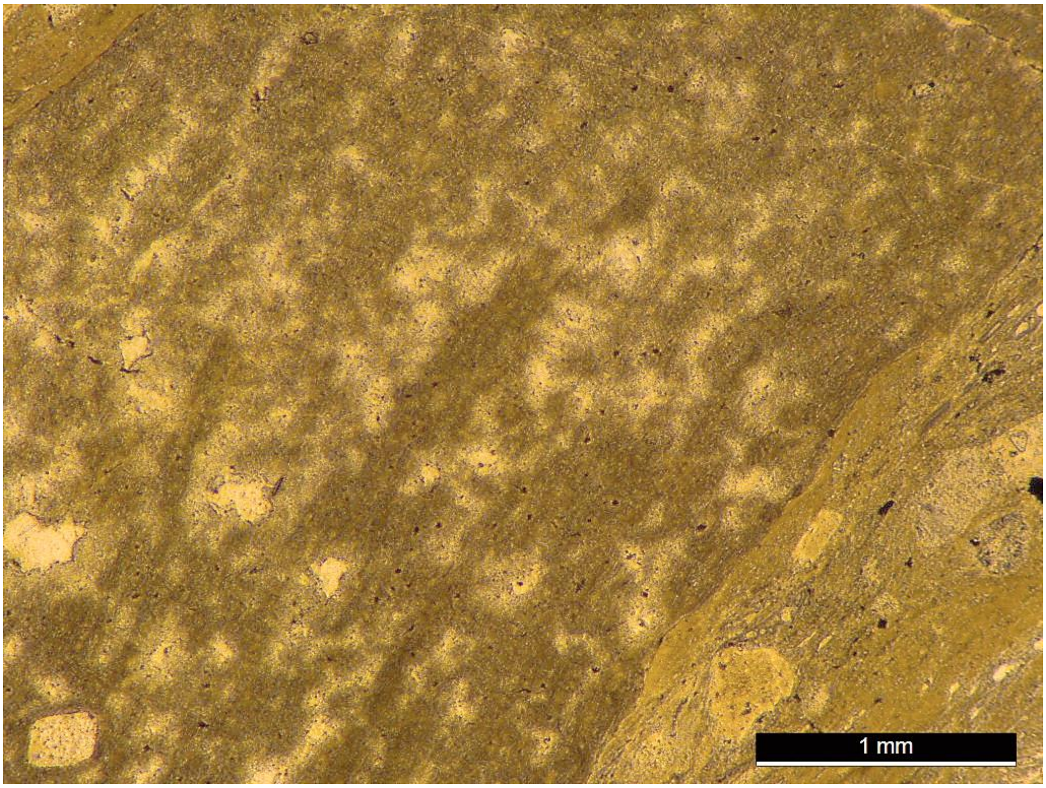
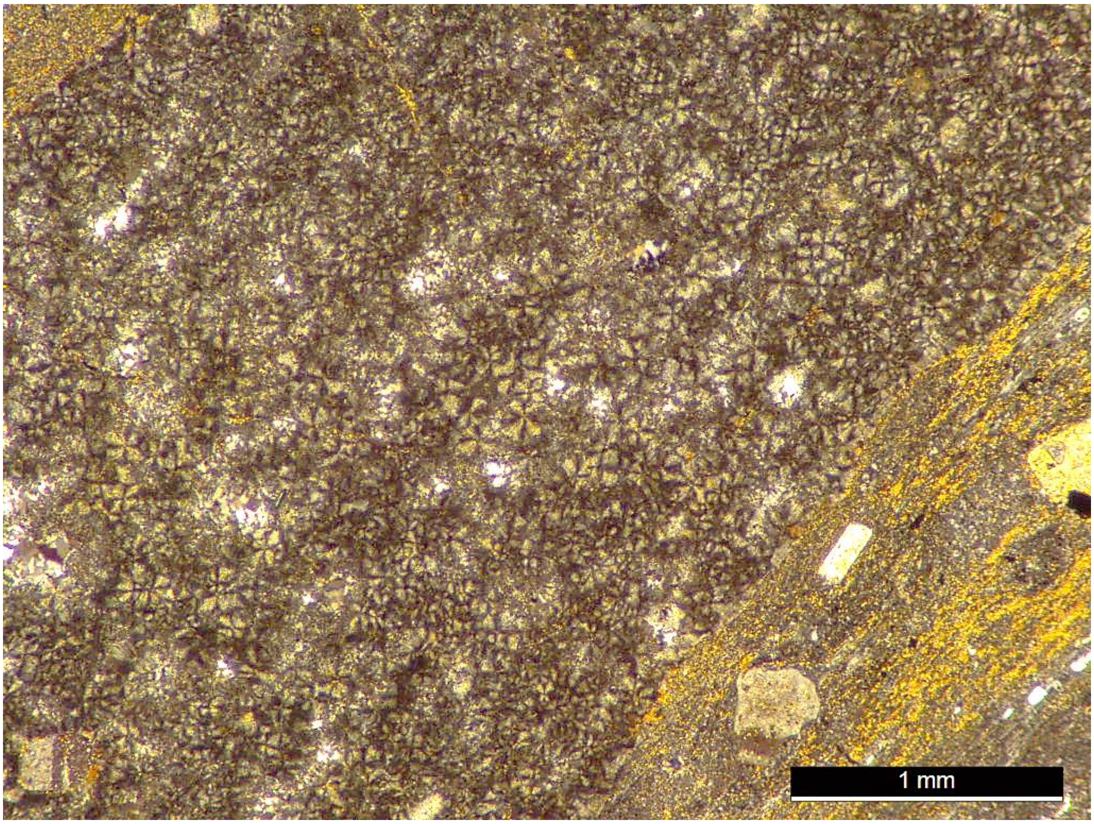


Figure 2.7-20. **Tuff** with **pyroclastic banding** in the Lynn Volcanic Complex at Boojum Rock (site 10236). Upper band has **micro-spherulitic texture** and in lower right is **pyroclastic banding**. Above: View in plane polarized light. Below: Same view with crossed polarizers showing **micro-spherulites** with extinction crosses and occasional **quartz splotches**. Orange color in lower right is epidote.



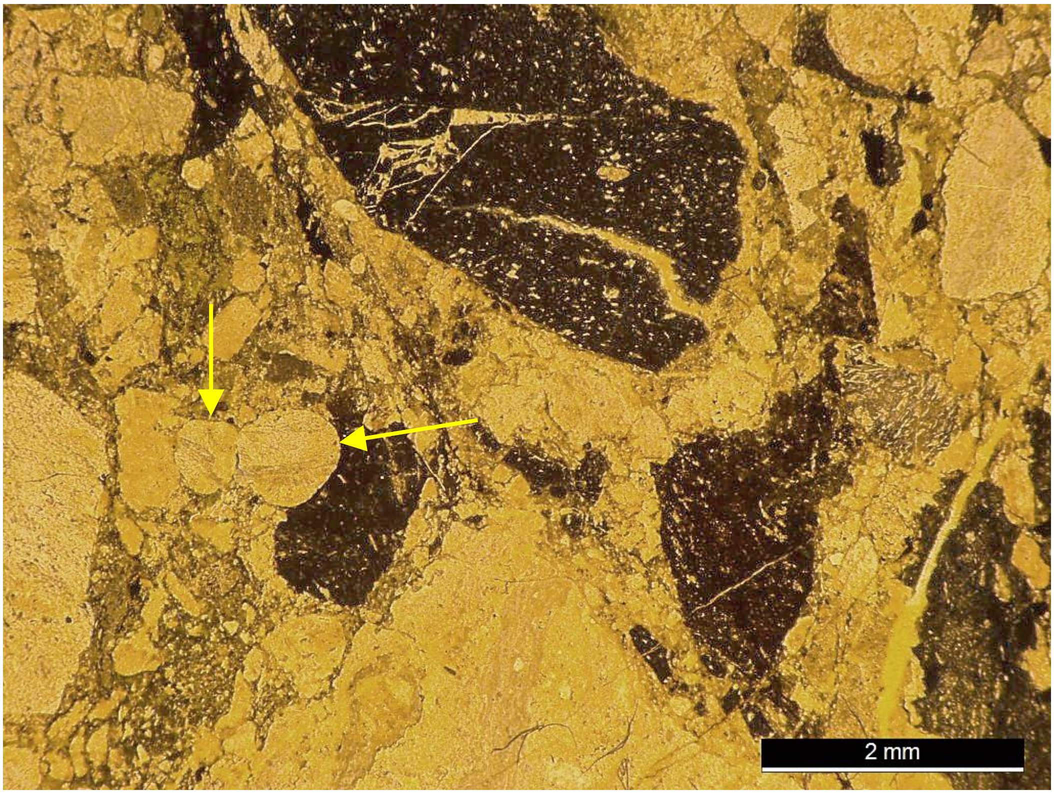
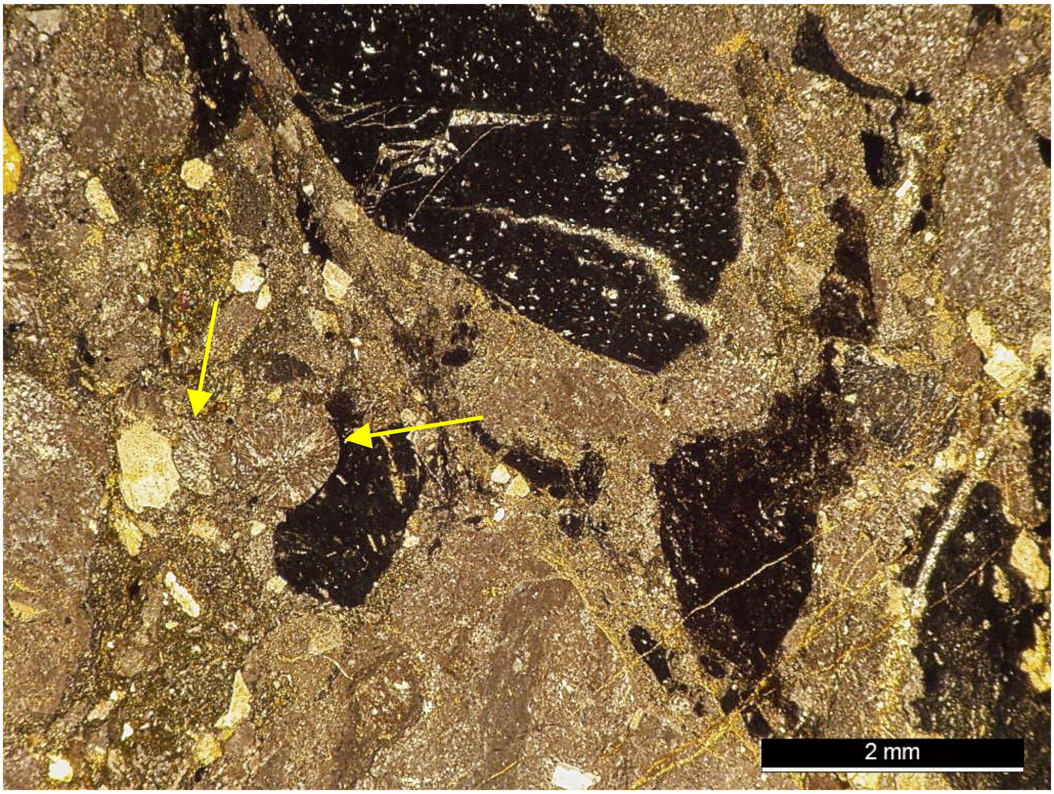


Figure 2.7-21. **Tuff** in Lynn Volcanic Complex at Boojum Rock (site 10246) with large **spherulites** (arrows). Above: View in plane polarized light. Below: Same view with crossed polarizers showing internal radial structure of **spherulites**.



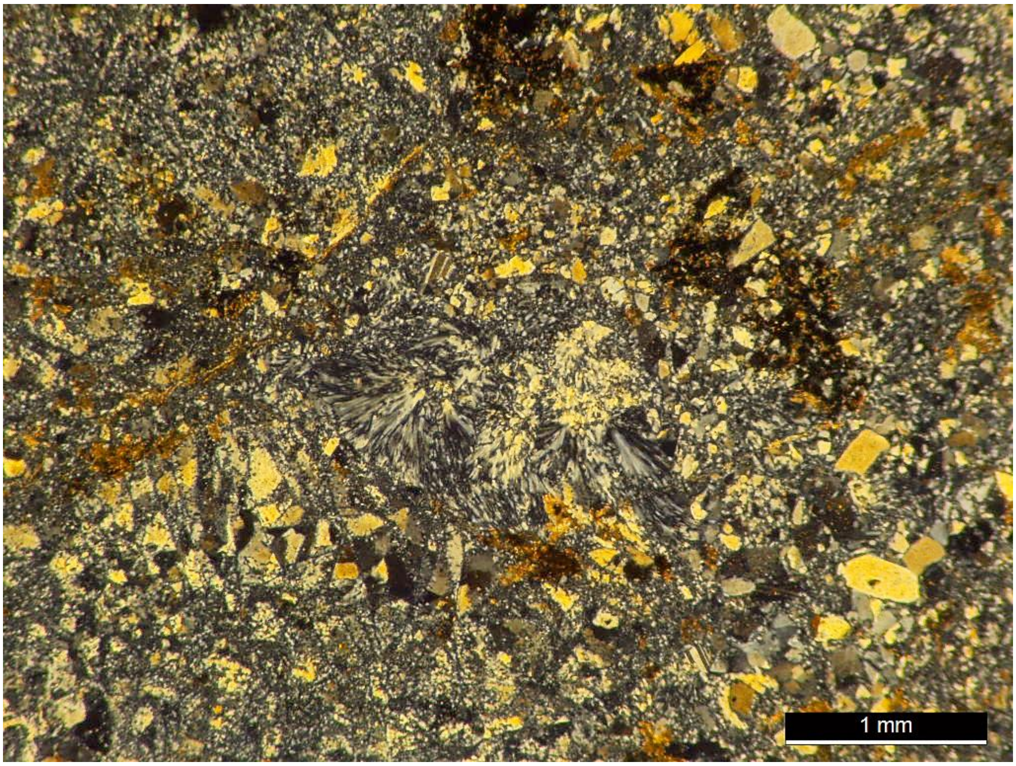


Figure 2.7-22. **Tuff** in Lynn Volcanic Complex (site 10366) with large plumose **spherulites** (center). View with crossed polarizers.

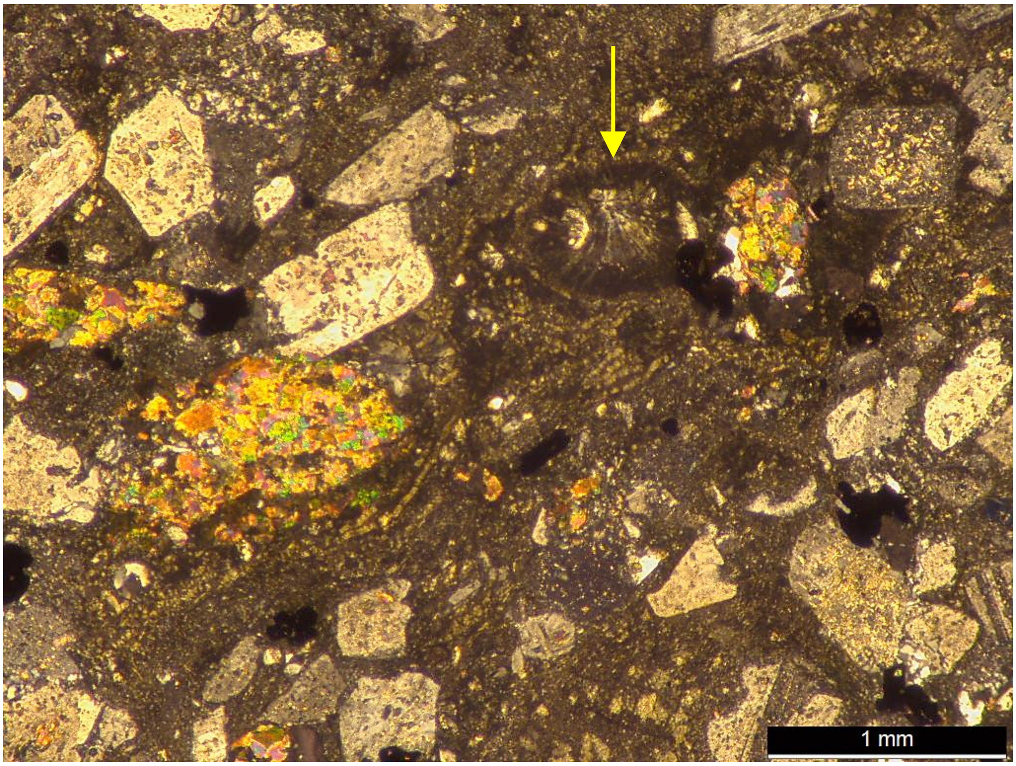


Figure 2.7-23. **Crystal tuff** in Boojum Rock Tuff (site 10027) with large, dark-rimmed, plumose **spherulites** (arrow) in area of **axiolitic texture** (across center of image). Colorful areas are epidote. View with crossed polarizers.

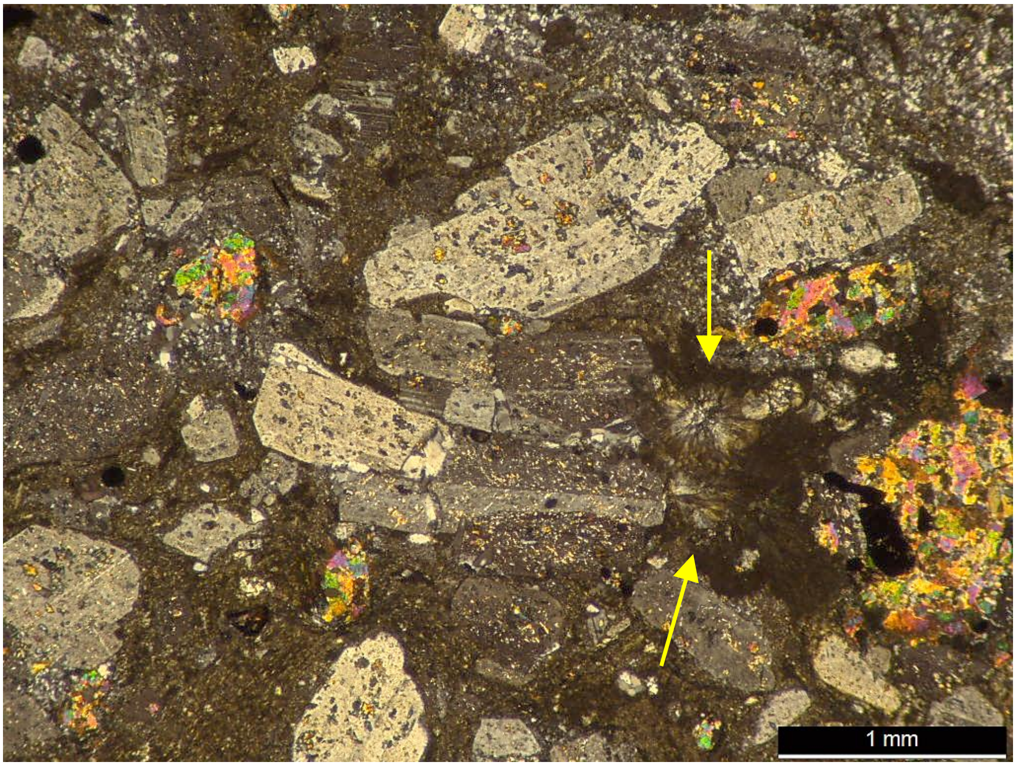


Figure 2.7-24. **Tuff** in Lynn Volcanic Complex (site 10366) with large dark-rimmed **spherulites** (arrows) growing on altered plagioclase crystals with **sieve texture**. View with crossed polarizers. Colorful areas are epidote.

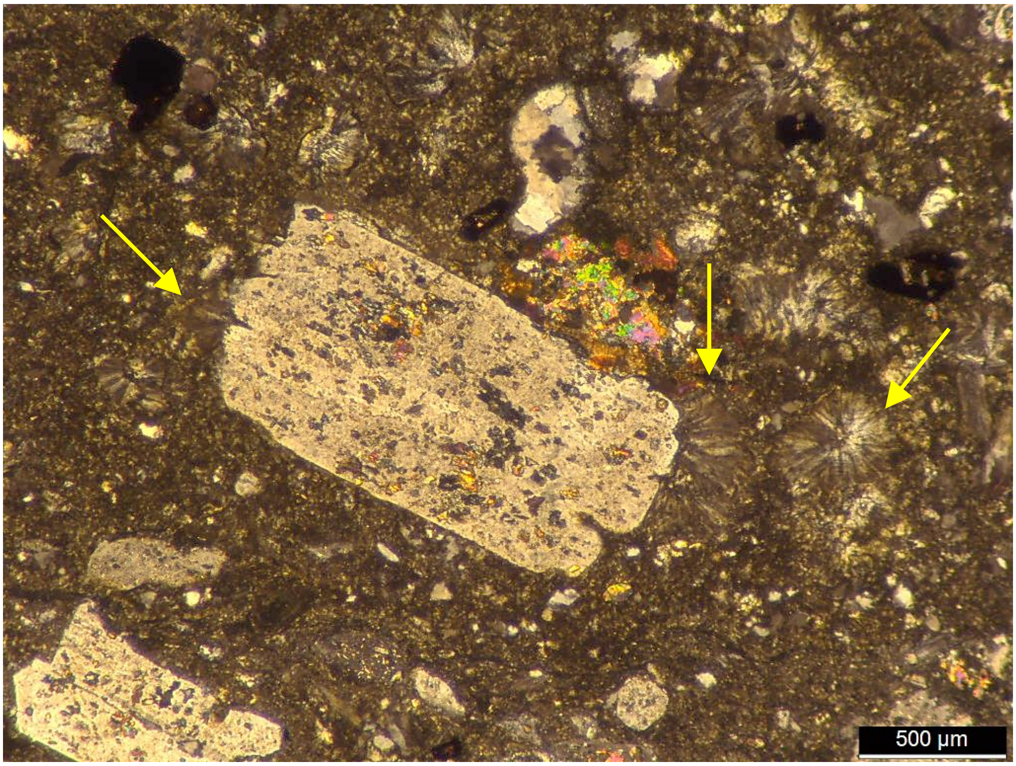


Figure 2.7-25. **Crystal tuff** in Lynn Volcanic Complex (site 10027) with large **spherulites** (arrows) growing on altered plagioclase crystal with **sieve texture**. Large plagioclase crystal is lightly resorbed. Bright colors inside and outside altered plagioclase are epidote. View with crossed polarizers.

2.7.2 (cont.) – Axiolitic and micro-spherulitic textures

Areas with axiolitic and microspherulitic textures are well crystallized without many impurities, and they are also found in juvenile or cognate volcanic lithic fragments, where their internal structure is truncated at the edges of broken fragments. Thus, these structures appear to form very quickly, likely during initial cooling and glass formation. When stained (yellow) for potassium these areas also have a color contrast with surrounding matrix areas due to their higher potassium concentration. This indicates that they may have been glassy layers or fragments distinct from the surrounding matrix, which has less potassium (Figs. 2.7-16 to 20). This suggests mixing of pyroclastic materials of different composition and texture, and axiolitic and micro-spherulitic areas of the matrix appear to have still been very hot and soft when deposited. Smaller versions of these areas are described above as flattened and pinched pumice and obsidian fragments (glass fragment types 1 and 2, section 2.5) that have thinner and less conspicuous axiolitic and spherulitic structures, perhaps due to their smaller size and more rapid cooling rates.

2.7.2 (cont.) – Large spherulites

Spherulitic growth types 3 and 4 are larger and more isolated with a coarser fibrous or plumose texture. Type 3, which is not common, has thin fibers and is very circular with a well-developed radial structure and dark rim. This type of spherulitic texture is also seen in sialic lava flows.

Type 4 structures develop as plumose lopsided or asymmetric growths and not as perfectly radiating spherical structures. Type 4 growths appear to be growing on the ends of tabular plagioclase crystals or other nucleation objects and seldom have a perfectly developed radial structure. The outer parts of these growths usually have a finer texture and darker color that forms arc-like patterns. Types 3 and 4 may be related to perlitic texture development.

2.8 Relict Perlitic Texture

Relict **perlitic texture** occurs as occasionally preserved circular and concentric patterns enclosing a crude plumose texture. They may develop as fractures that formed in **obsidian** during early cooling and contraction or expansion by **hydration** while the rock was still hot (Fig. 2.8-1; see also section 2.10.1 on volcanic lithic fragments). Devitrification may wipe out these structures through crystallization and they were probably more abundant in original obsidian. Traces of **perlitic texture** can still be seen in thin section in plane polarized light in sample matrices and in lithic fragments. Plumose crystallization of quartz and feldspar aligns with these patterns during devitrification leading to doughnut-like areas or concentric bands of the new minerals.

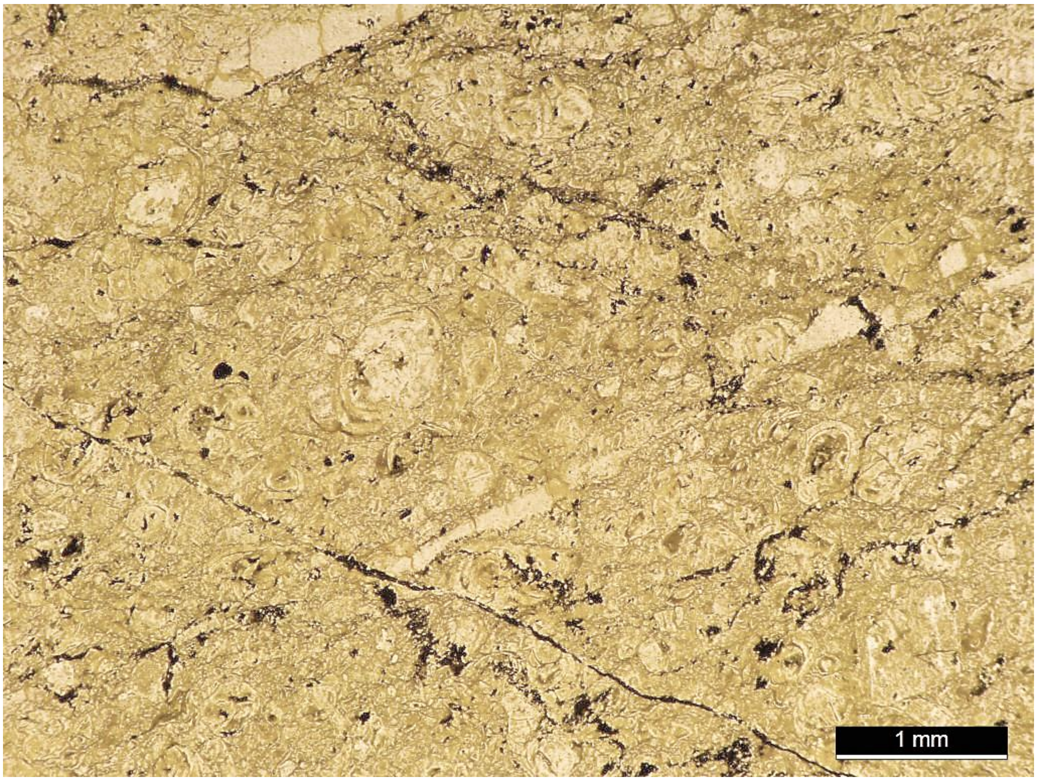
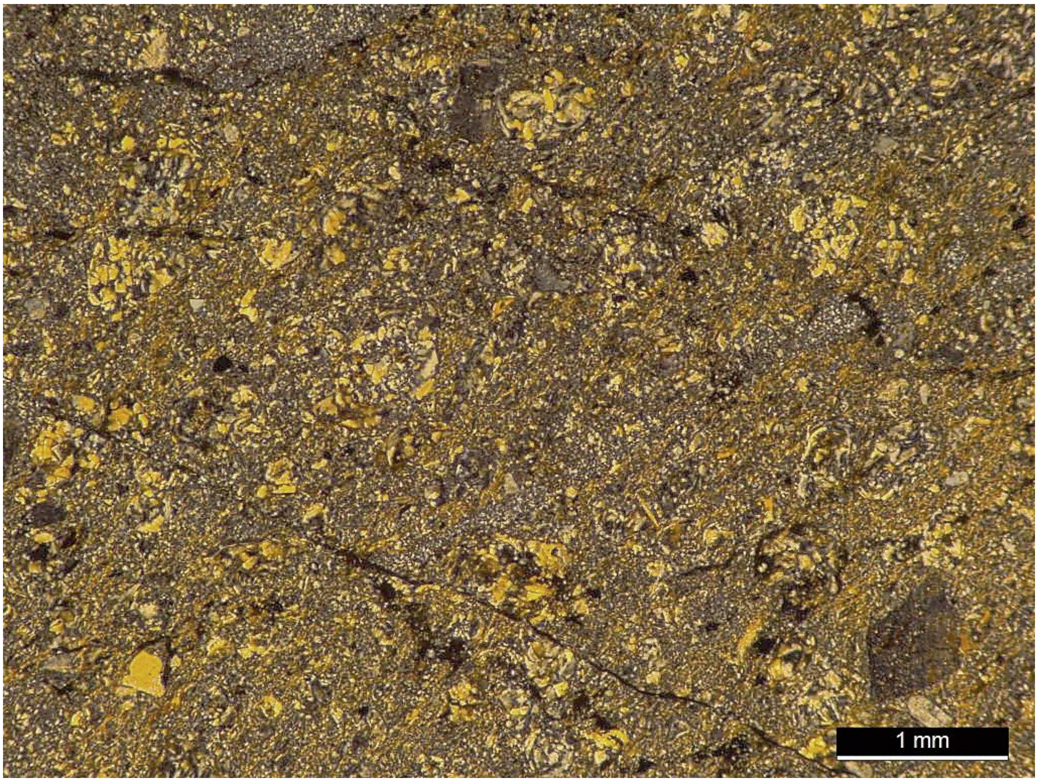


Figure 2.8-1. **Tuff** in Lynn Volcanic Complex (site 10524) with relict **perlitic texture** (circular structures). <u>Above</u>: View in plane polarized light. <u>Below</u>: Same view with crossed polarizers showing growth of larger crystals in perlitic structures than in surrounding materials that have a **patchy texture**.



2.9 Amygdules in Tuffs

Amygdules or **vesicle fillings** are relatively rare in pyroclastic rocks of the Fells other than those occasionally preserved in lithic fragments. There can also be rare vesicles in fragments of devitrified obsidian (Figs. 2.9-1 to 2). Obsidian vesicles, occurring as epidote-filled amygdules, have only been observed, and rarely at that, in the Boojum Rock Tuff. Some caution should be used here in identifying vesicle fillings by their epidote mineralization because they can look like broken hornblende or plagioclase crystals that are completely altered to epidote. Although the vesicle fillings so far identified do not appear to have any relict plagioclase or hornblende and are adjacent to only lightly altered plagioclase, their rounded shapes can be mimicked by altered mineral grains and alteration intensity can change drastically over very small distances (<1 mm).

It is not likely that original vesicles would survive in soft or molten obsidian since even moderate burial would flatten vesicles. It is suspected that either: 1) the vesicles were formed in obsidian that solidified and then later was deposited in pyroclastic debris, or 2) the vesicles formed in buried molten obsidian fragments after deposition and shortly before hardening, all while they were shallowly buried and prior to significant loading from above.

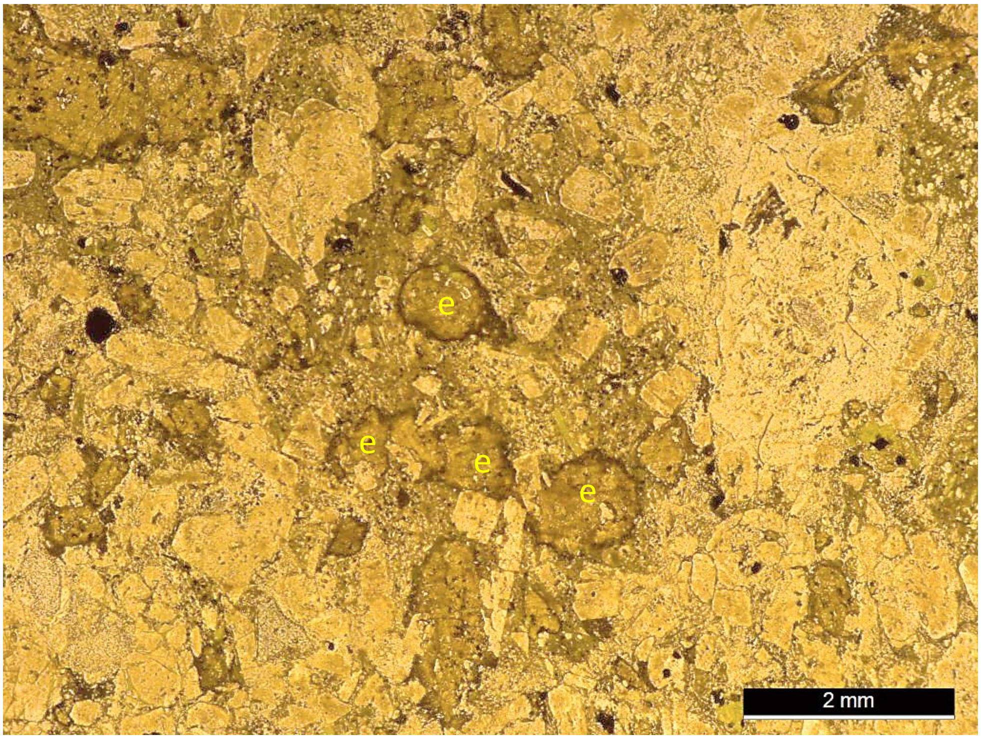
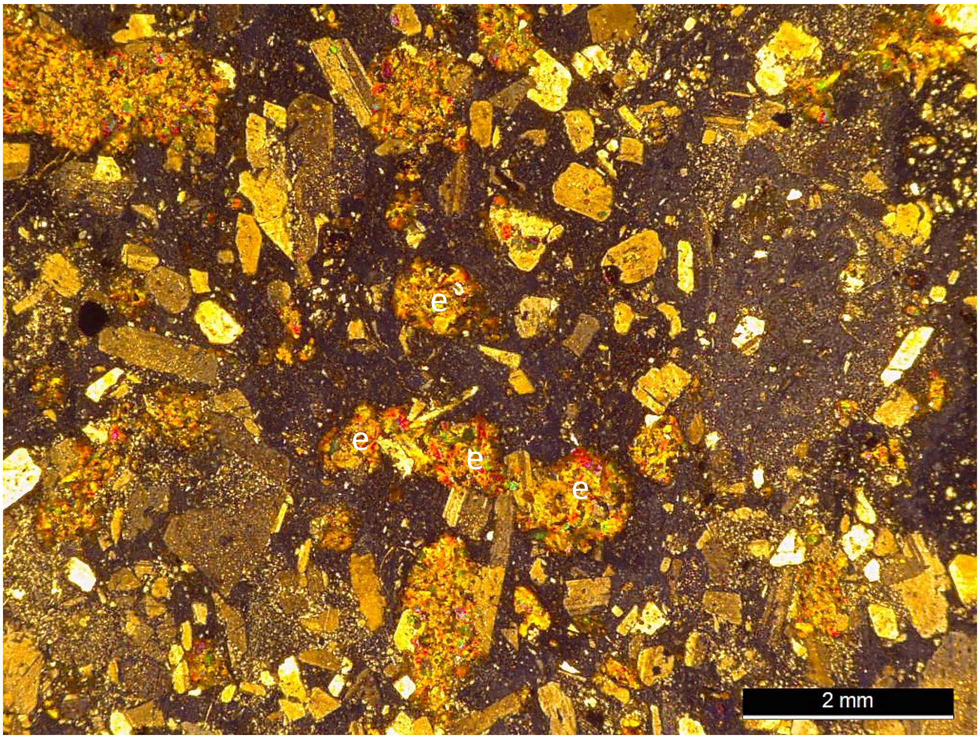


Figure 2.9-1. **Crystal tuff** in the Boojum Rock Tuff (site 10355) with **amygdules** filled with epidote (e) in a dark area that appears to be devitrified porphyritic obsidian. Epidote occurs elsewhere as an alteration product of plagioclase and hornblende. Above: View in plane polarized light. Below: Same view with crossed polarizers.



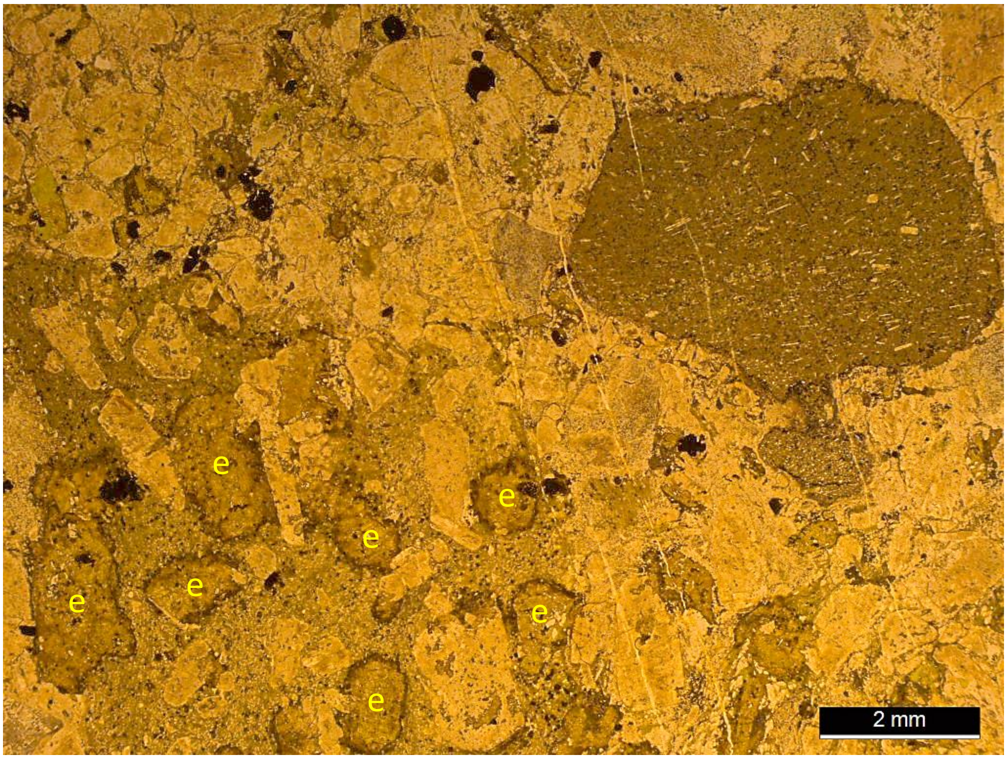
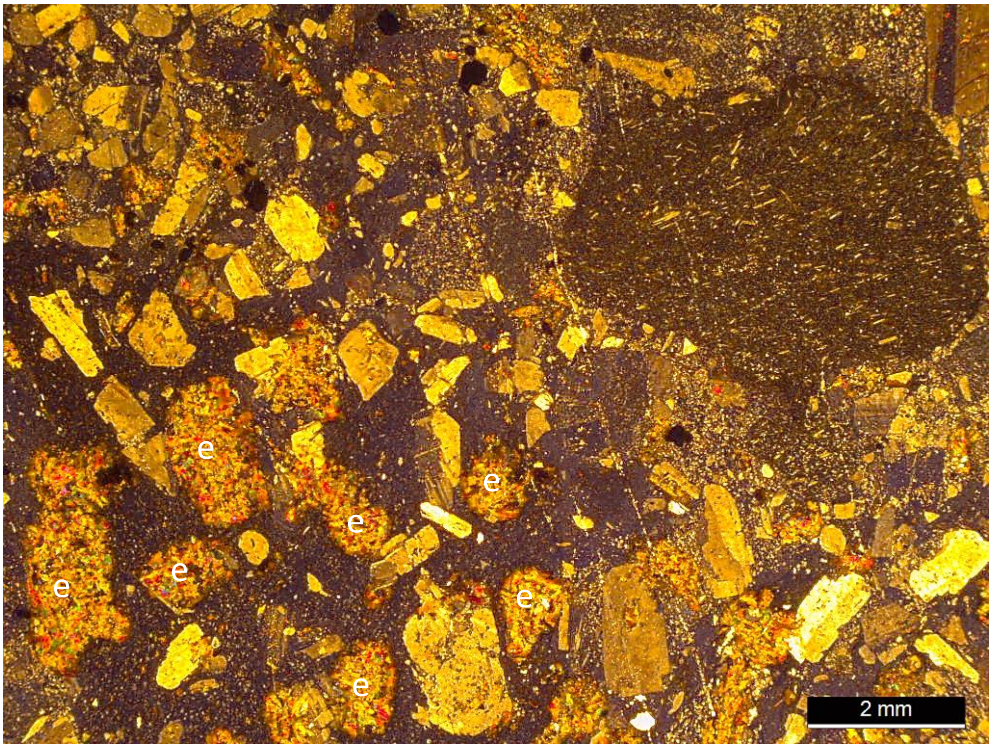


Figure 2.9-2. **Crystal tuff** in the Boojum Rock Tuff (site 10355) with **amygdules** filled with epidote (e) in a dark area that is devitrified obsidian. Epidote occurs elsewhere as an alteration product of plagioclase and hornblende. Also shown in the upper right is a very fine-grained volcanic lithic fragment with **microlites** and **trachytic texture**. Above: View in plane polarized light. Below: Same view with crossed polarizers.



2.10 Lithic Fragments

Most of the lithic fragments found in the pyroclastic rocks of the Middlesex Fells are **juvenile and cognate volcanic fragments** related to the same eruptive phase that generated the tuff or other eruptive events probably spanning no more than 5 Myr. There are also **accidental lithic fragments** that are from older rock formations and that are usually non-volcanic including quartzite, argillite (hornfels), basalt, and granodiorite.

2.10.1 Volcanic Lithic Fragments

The volcanic lithic fragments have almost all the textures of the volcanic rocks described above including **eutaxitic**, **micro-spherulitic**, **banded**, and **perlitic** textures (Figs. 2.10-1 to 7). In some cases, fragments may appear to be banded in plane polarized light. However, under crossed polarizers these fragments exhibit a **micro-spherulitic texture** that cuts across banding (Fig. 2.10-4) and was formed during early crystallization or devitrification. **Glass shard** outlines, both hard and flattened, appear in some lithic fragments along with broken crystals and other volcanic fragments (Figs. 2.10-8 to 9). Glass shards are usually only visible in plane polarized light. **Felsitic textures** are represented by **fine patchy textures**, often with more abundant **tabular plagioclase** (Figs. 2.10-10 to 12) than is seen in the matrix of any tuff unit in the Fells, and **splotchy quartz growths** (see Fig. 2.7-7 above). **Micropoikilitic texture** is rare and fragments with **poikilomosaic texture** have not been found in lithic fragments. This suggests that these devitrification textures may not have enough time to form in the rock units from which volcanic fragments are derived, but this remains inconclusive. In rare cases, dark very fine volcanic fragments exhibit a **trachytic texture** with aligned **plagioclase microlites** (see Fig. 2.9-2 above). This rock type has not been found as a part of any of the felsic volcanic rock units in the Fells except in lithic fragments.

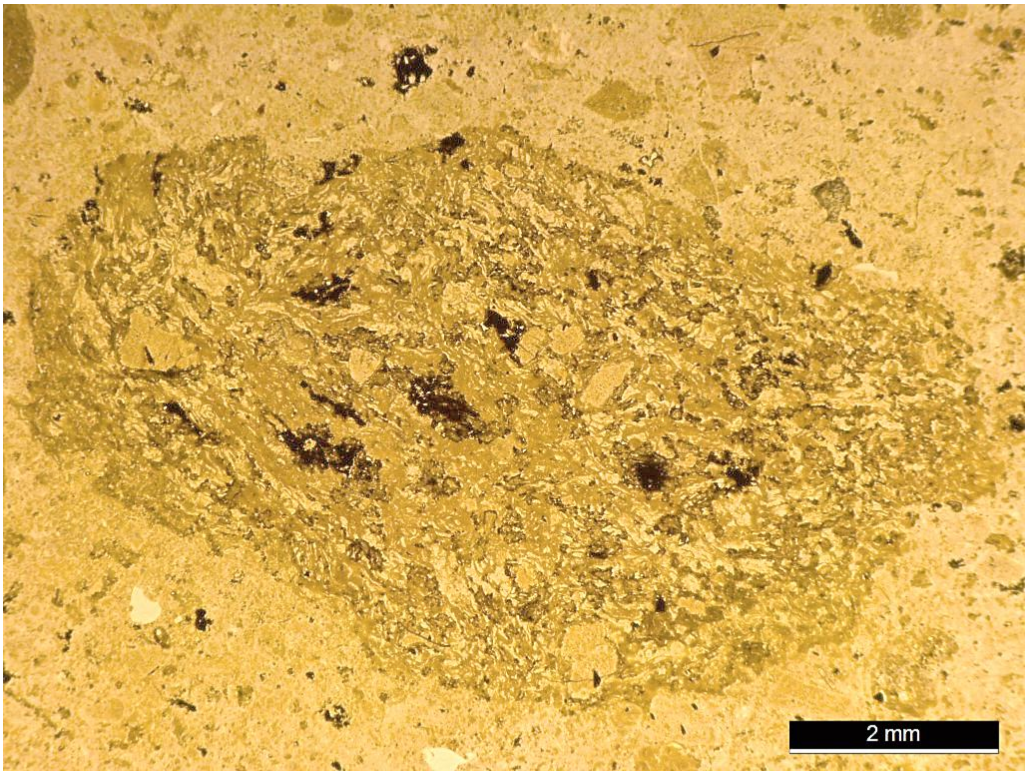


Figure 2.10-1. **Lithic tuff** in the Lynn Volcanic Complex (site 10368) with a volcanic **lithic fragment** that has **flattened glass shards** forming a **eutaxitic texture**. View in plane polarized light.

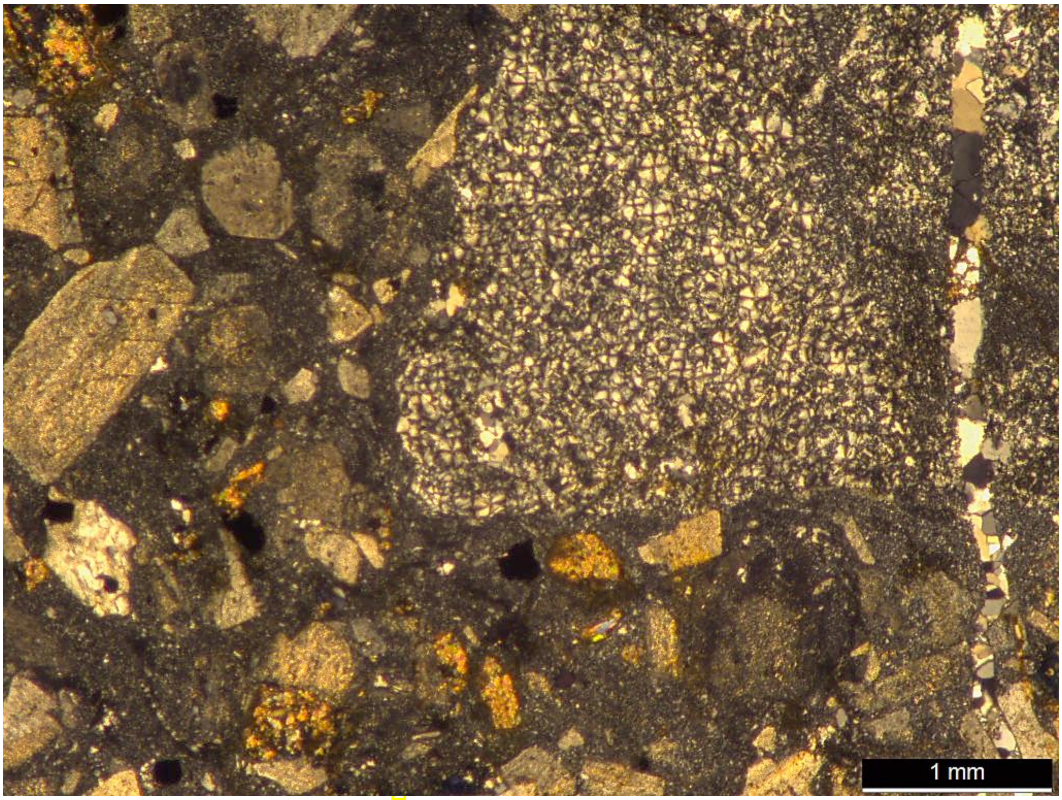


Figure 2.10-2. **Crystal tuff** in the Boojum Rock Tuff (site 10010) with a volcanic **lithic fragment** that has very well developed **microspherulitic texture** with extinction crosses. The orange grains are hornblende. View with crossed polarizers.

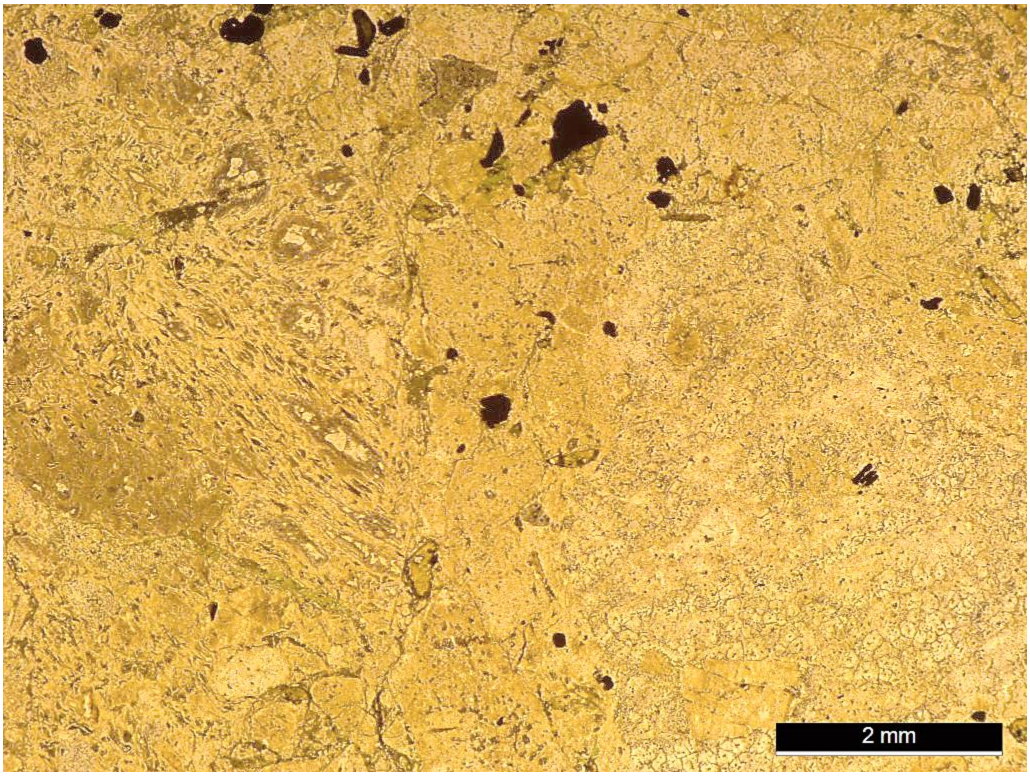
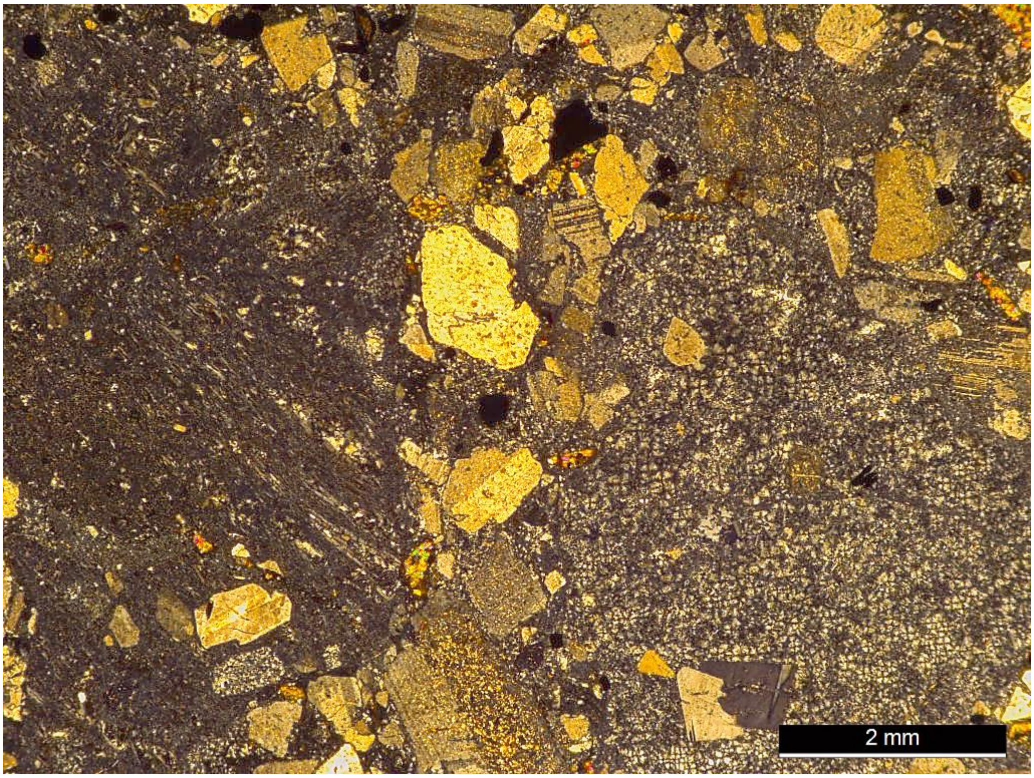


Figure 2.10-3. **Crystal lithic tuff** in the Boojum Rock Tuff (site 10355) with two **lithic fragments** that have **eutaxitic texture** with **pyroclastic banding** (left) and **micro-spherulitic texture** (right). Above: View in plane polarized light in which **microspherulite** outlines are faintly apparent and centers appear as dark spots. Below: Same view with crossed polarizers in which extinction crosses are well developed in micro-spherulites.



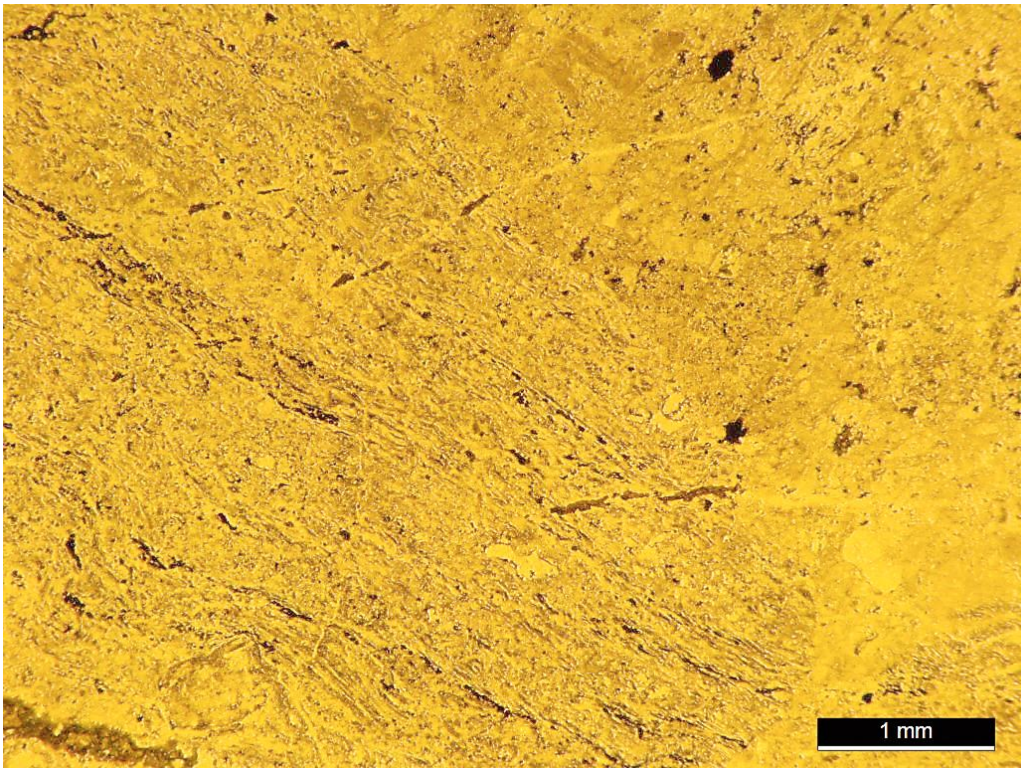
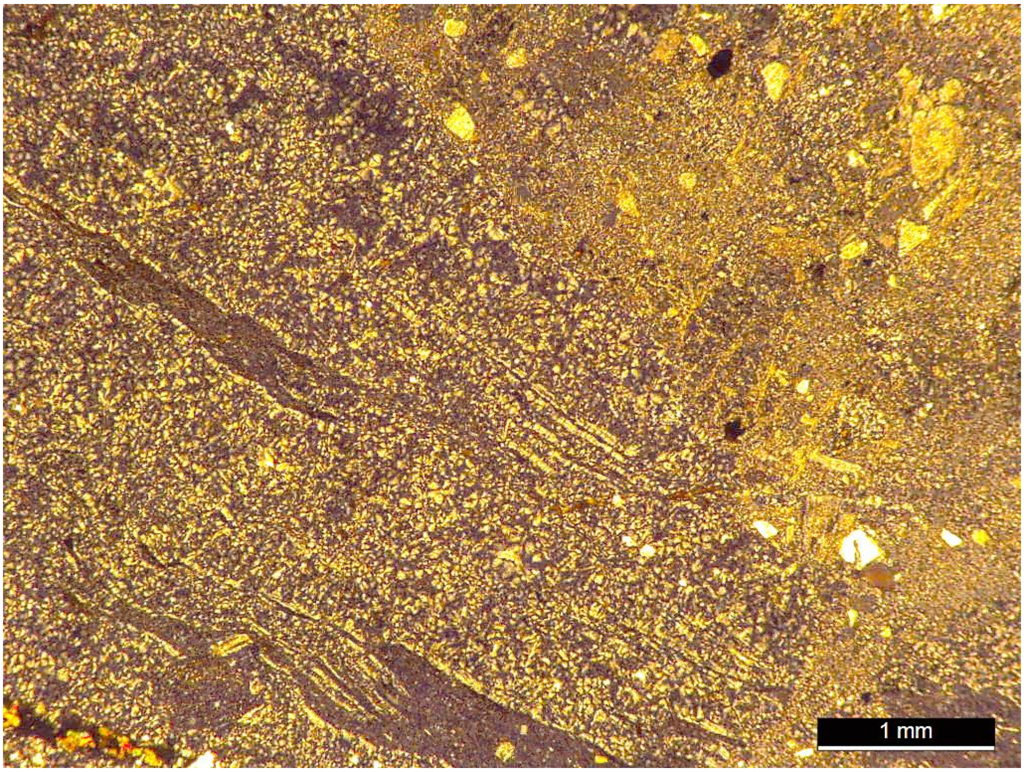


Figure 2.10-4. **Tuff** in the Lynn Volcanic Complex (site 10676) with a **lithic fragment** that has a **eutaxitic texture** and **pyroclastic banding** in plane polarized light while in crossed polarizers it displays **axiolitic strands** (parallel to banding) and **microspherulites** (obscuring banding). Above: View in plane polarized light. Below: Same view with crossed polarizers showing pinched and **flattened pumice fragments** (dark, elongate and pinched blobs with axiolitic rims) that parallel the banding.



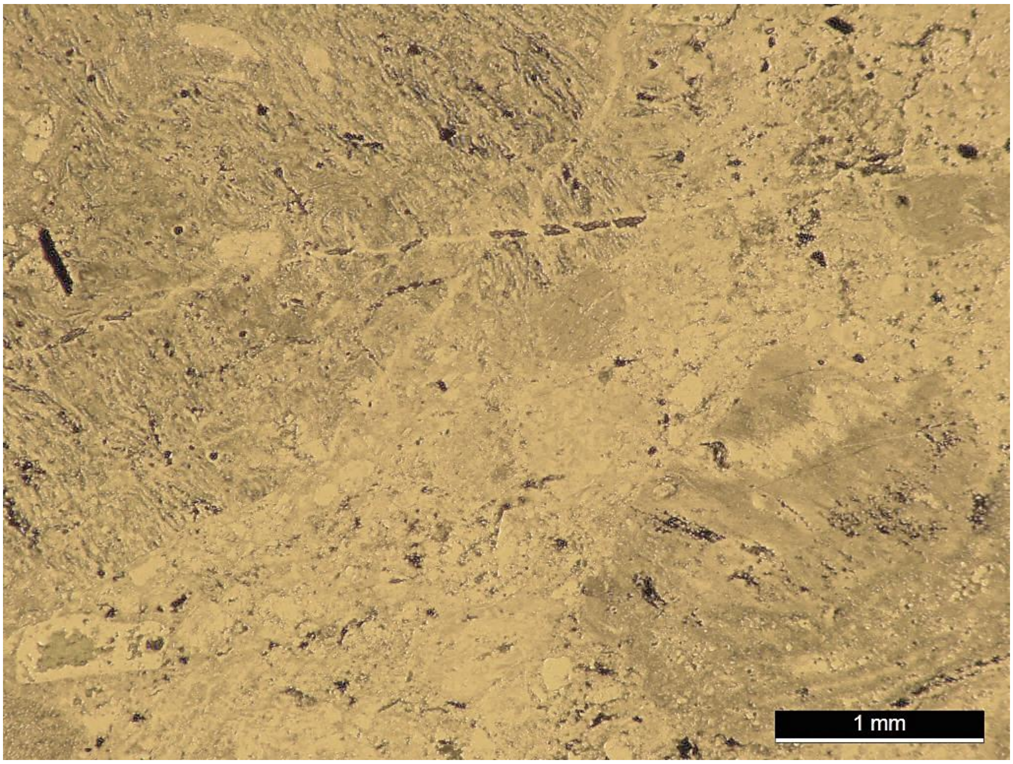
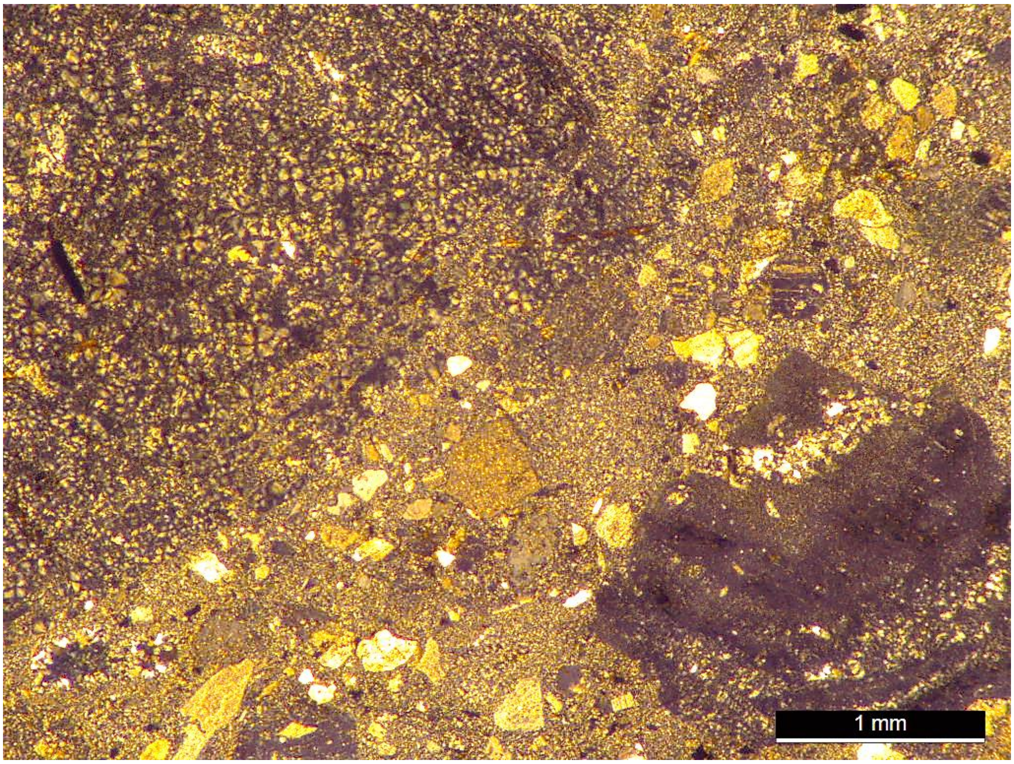


Figure 2.10-5. **Crystal lithic tuff** in the Lynn Volcanic Complex (site 10676) with a volcanic **lithic fragment** (upper left) that has a **eutaxitic texture** and **pyroclastic banding** in plane polarized light, while in crossed polarizers it displays **microspherulites** that obscure banding. In lower right is an ultra-fine volcanic lithic fragment with faint **pyroclastic bands** and an area of **patchy texture**. Above: View in plane polarized light. Below: Same view with crossed polarizers.



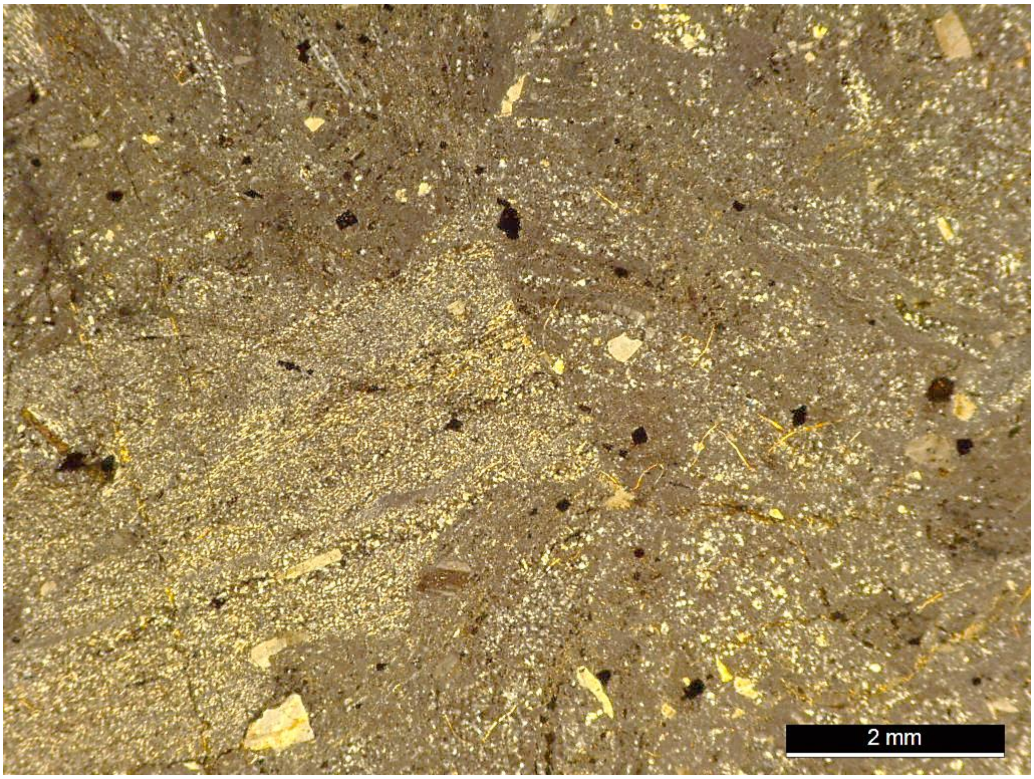


Figure 2.10-6. **Tuff** in the Lynn Volcanic Complex at Boojum Rock (site 10241) with **volcanic lithic fragment** that displays **flow banding**. Matrix displays discontinuous pyroclastic bands. View with crossed polarizers.

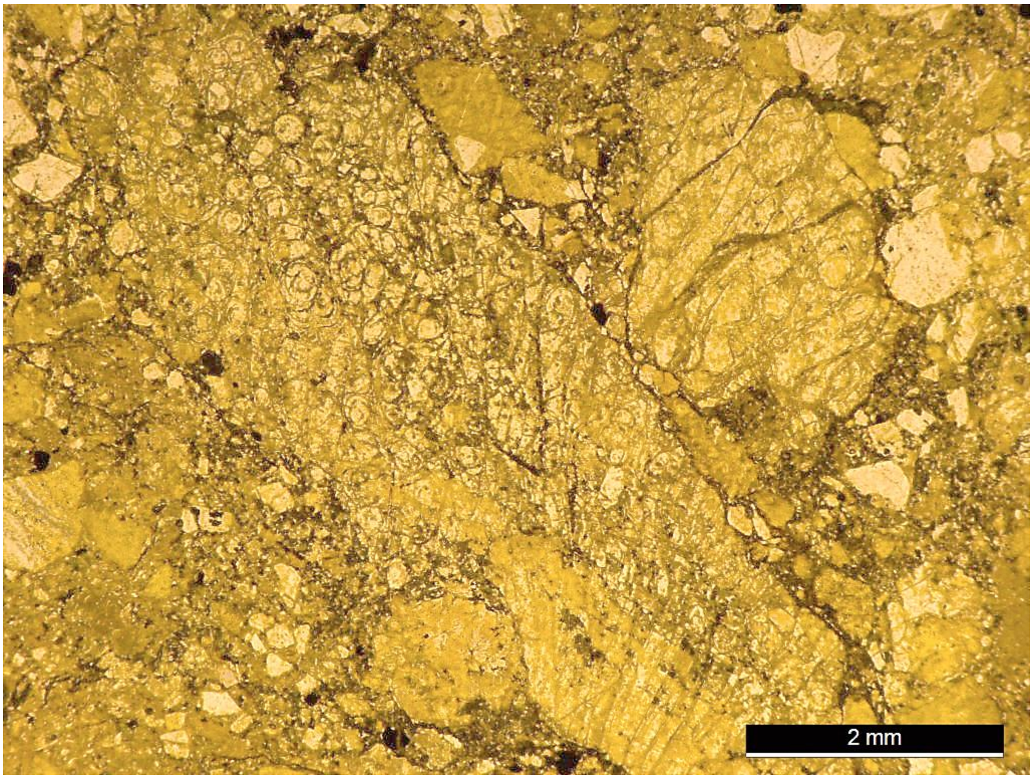


Figure 2.10-7. **Crystal tuff** in the Lynn Volcanic Complex at Boojum Rock (site 10923) with **lithic fragments** that have rarely preserved relict **perlitic texture** (circular outlines). View in plane polarized light.

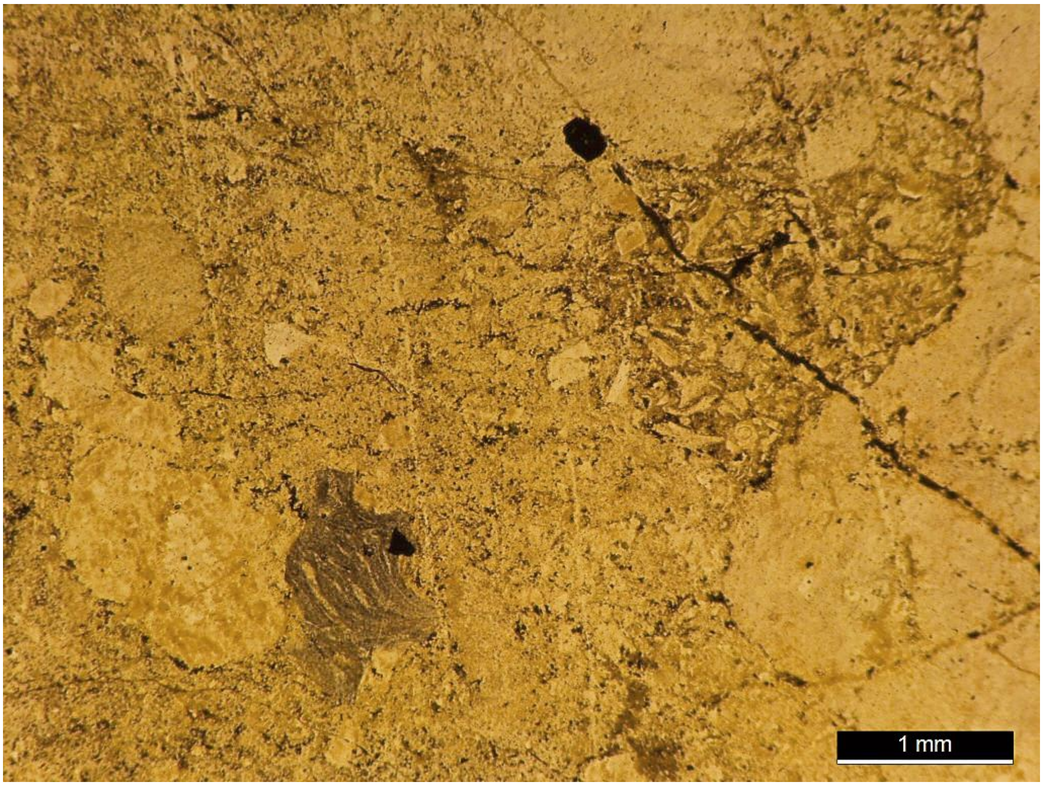


Figure 2.10-8. **Tuff** in the Lynn Volcanic Complex at Boojum Rock (site 10248) with **lithic fragments** that display **hard glass shards** with curved **bubble walls** (upper right) and highly **flattened glass shards** in **eutaxitic texture** (dark fragment in lower left). View in plane polarized light.

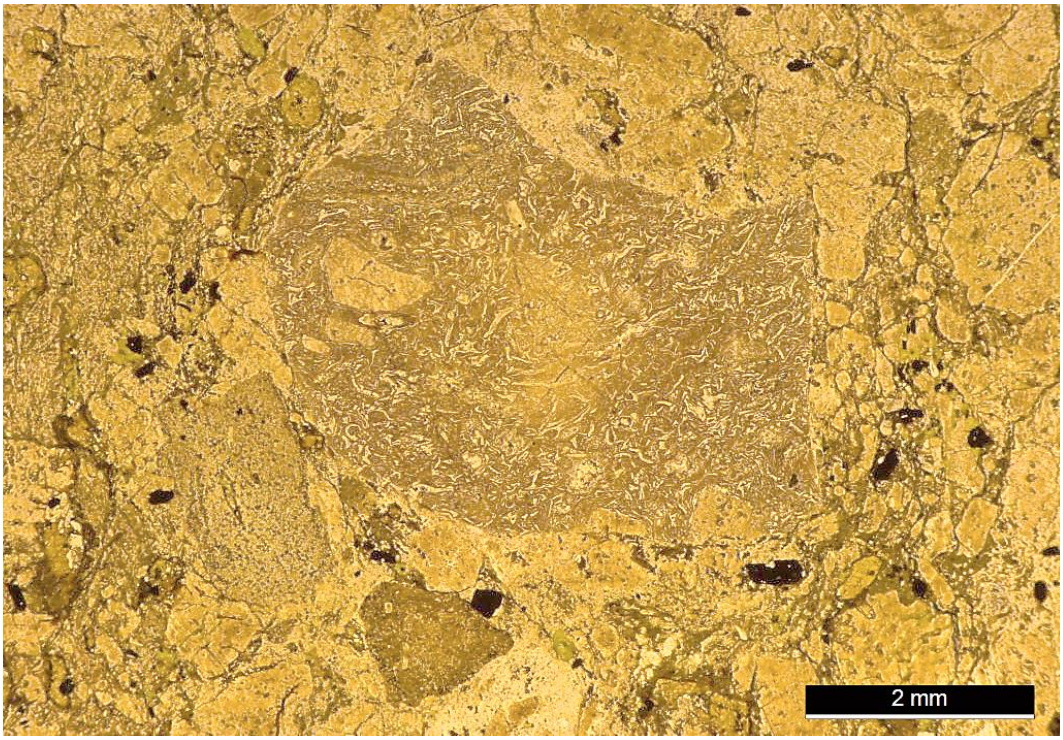


Figure 2.10-9. **Lithic tuff** in Black Rock Tuff (site 10355) with **volcanic lithic fragment** that displays **flattened glass shards** with deformed **bubble walls**. View in plane polarized light.

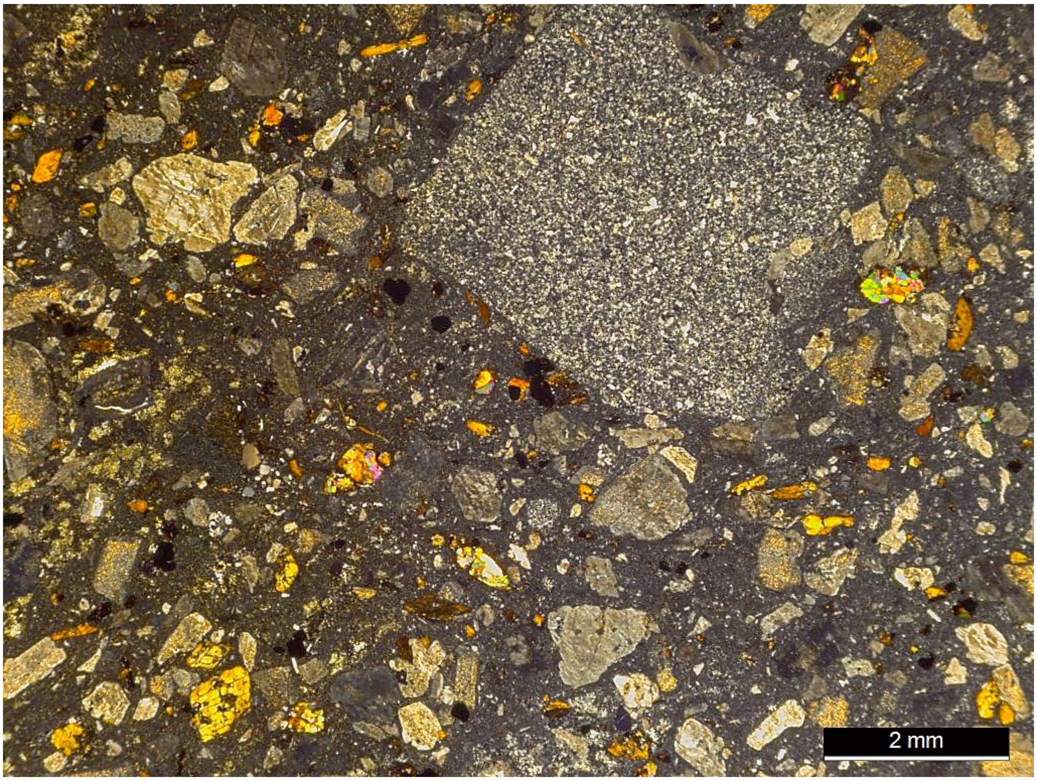


Figure 2.10-10. **Crystal tuff** in the Lynn Volcanic Complex at Boojum Rock (site 10908) with **volcanic lithic fragment** that display a **patchy texture** with sparse **tabular plagioclase crystals**. Note orange hornblende crystals in surrounding matrix partly altered to epidote. View with crossed polarizers.

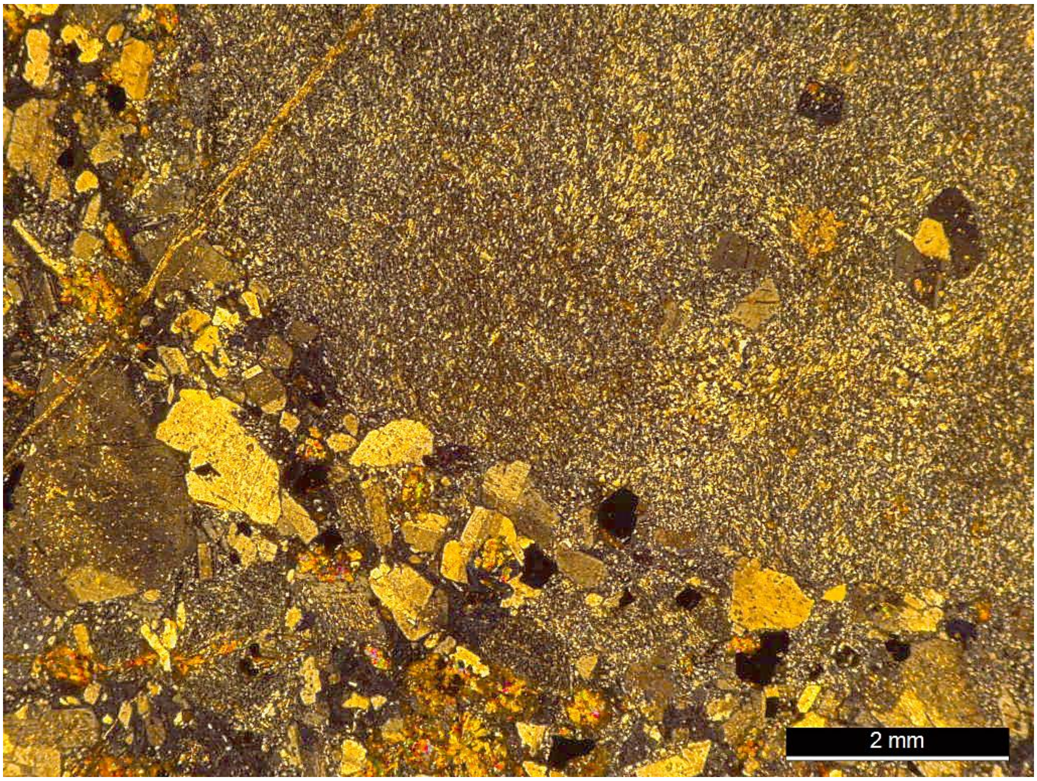


Figure 2.10-11. **Lithic tuff** in the Boojum Rock Tuff (site 10355) with **volcanic lithic fragment** that displays a **felsitic patchy texture** with fine **tabular plagioclase crystals**. View with crossed polarizers.

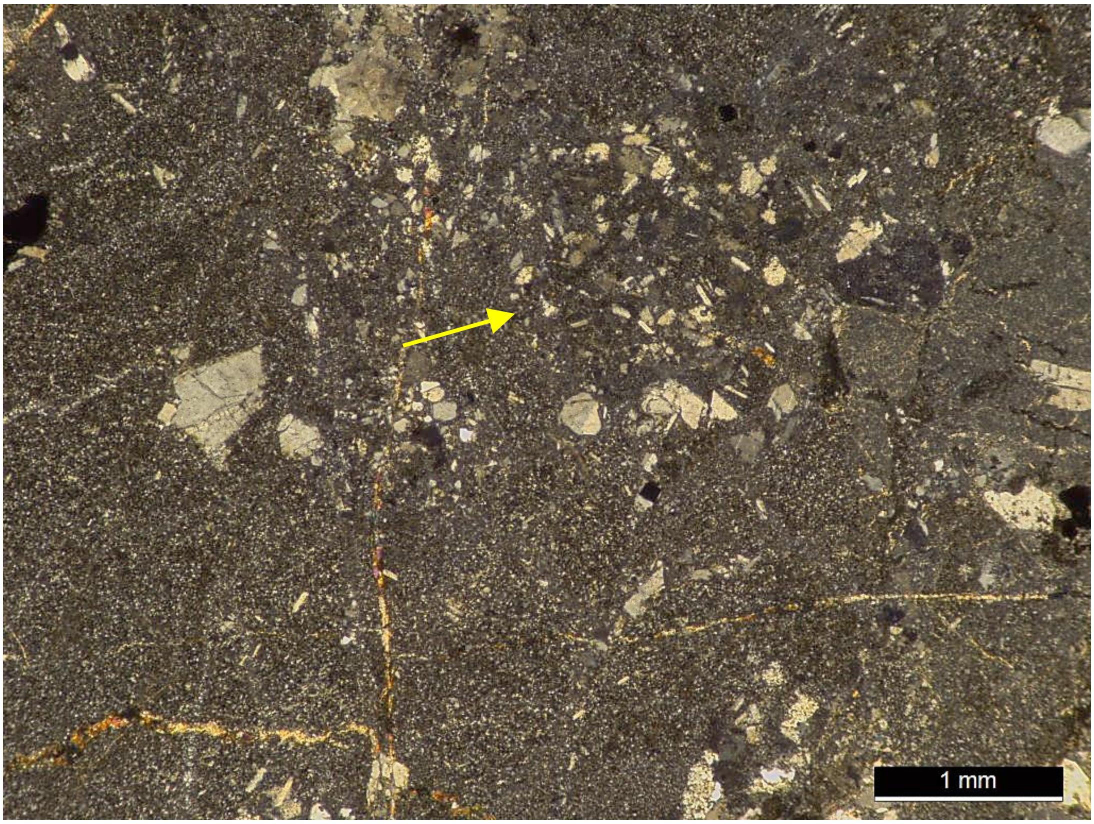


Figure 2.10-12. **Vitric tuff** with **fine patchy texture** in the Lynn Volcanic Complex at Boojum Rock (site 10917). This tuff has a **volcanic lithic fragment** with a fine matrix and **tabular plagioclase phenocrysts** (arrow). View with crossed polarizers.

2.10.2 Accidental Lithic Fragments – Quartzite and Argillite (Hornfels)

Accidental lithic fragments found in the Middlesex Fells are well represented by fragments of argillite and quartzite from the Westboro Formation. Westboro fragments occur in all the volcanic units. These fragments are easily spotted, sometimes with flattened, deformed and sutured quartz grains or sandstone clasts with lightly altered round grains (Figs. 2.10-13 to 19) .

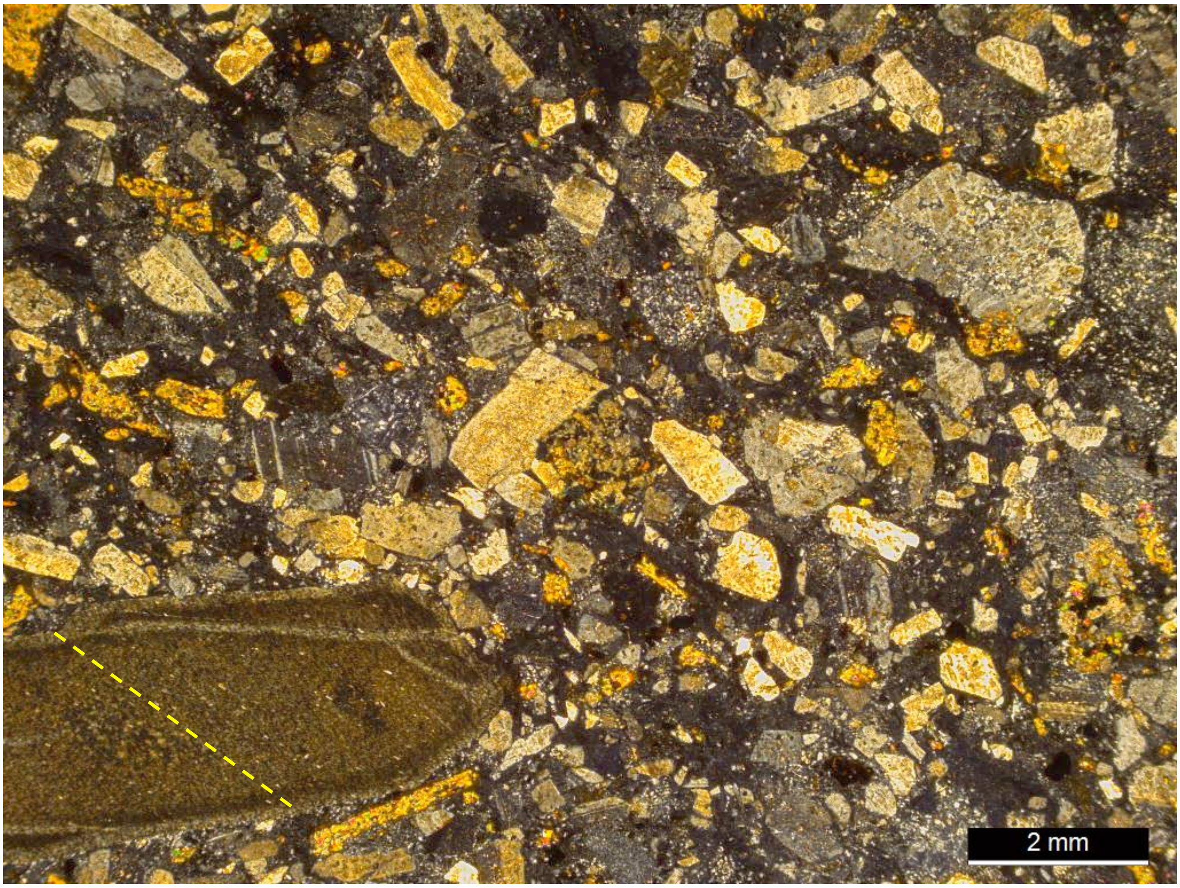


Figure 2.10-13. **Lithic tuff** in Boojum Rock Tuff (site 688BN) with **argillite lithic fragment** from the Westboro Formation. Yellow dashed line indicates foliation in argillite while gray lines and rims are an alteration. Note the extremely high density of broken crystals. View with crossed polarizers.

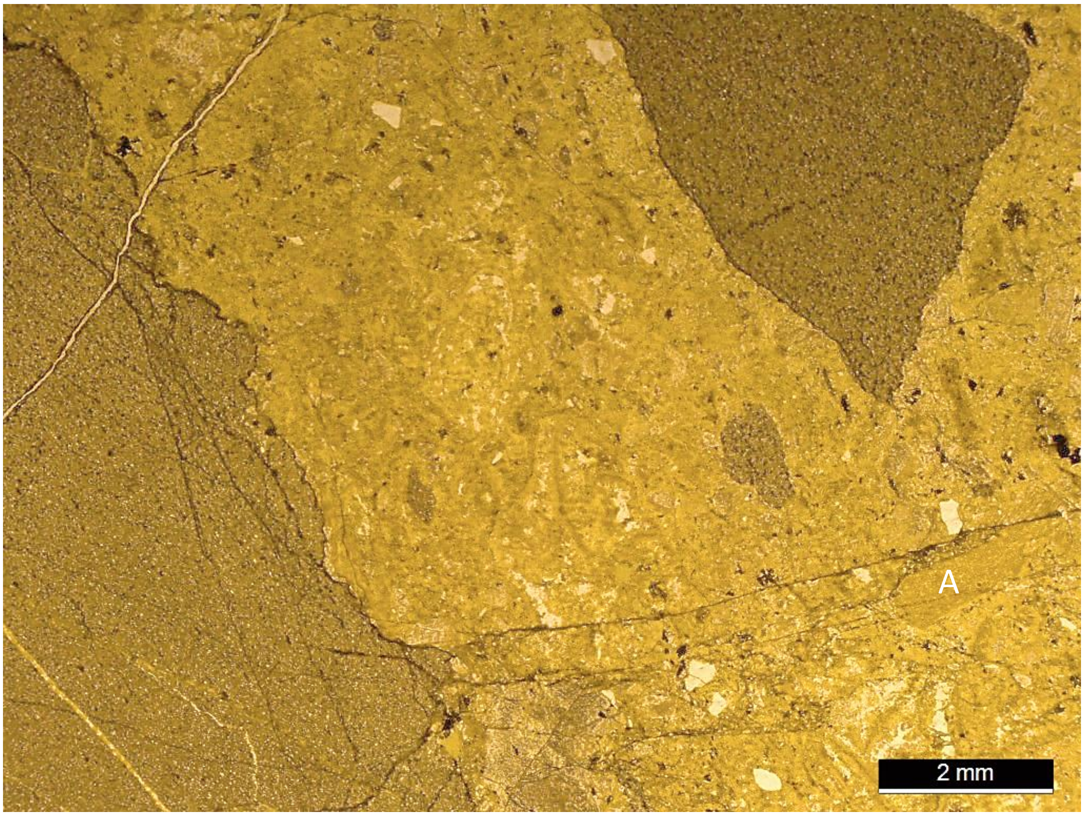
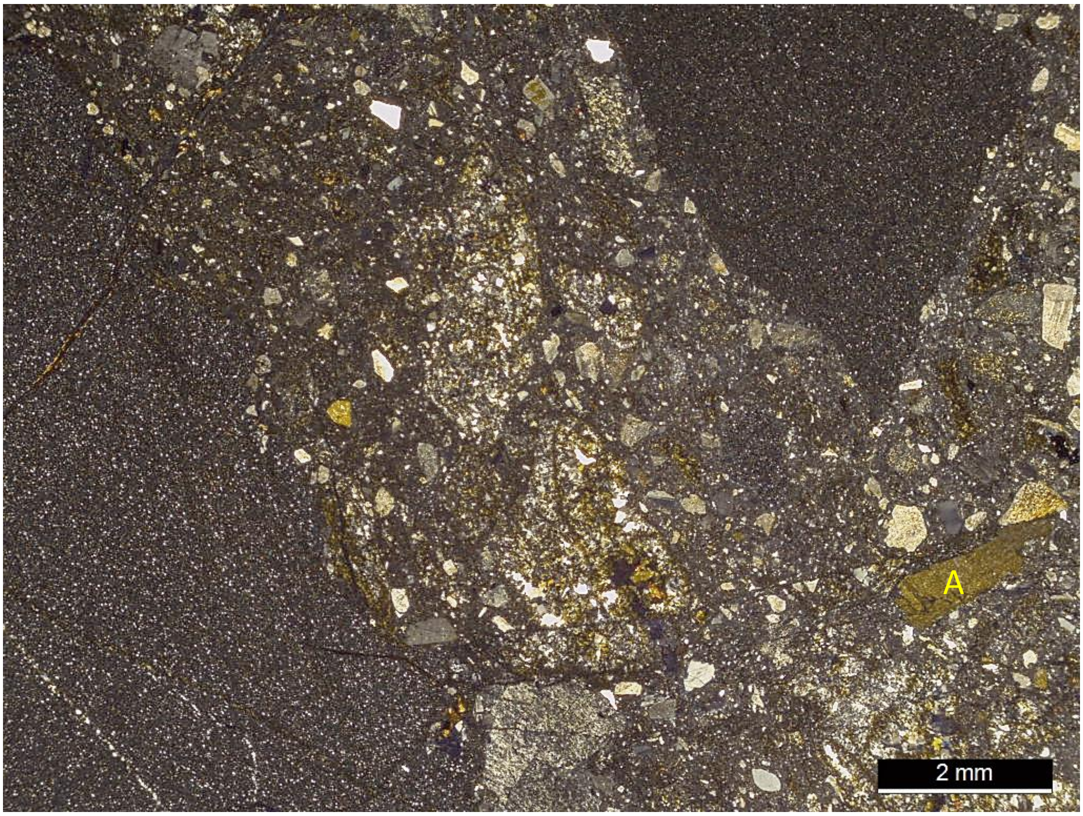


Figure 2.10-14. **Crystal tuff** in the Lynn Volcanic Complex on Whip Hill (site 10376, stained for potassium) in contact with mudstone unit (lower left) and containing **mudstone lithic fragments** (near center and upper right). Tuff has **fine granular and patchy textures.** In the center in the matrix is a lithic fragment with glass shards. In the lower right is an alkali feldspar fragment (A, yellow stain). Above: View in plane polarized light. Below: Same view with crossed polarizers.



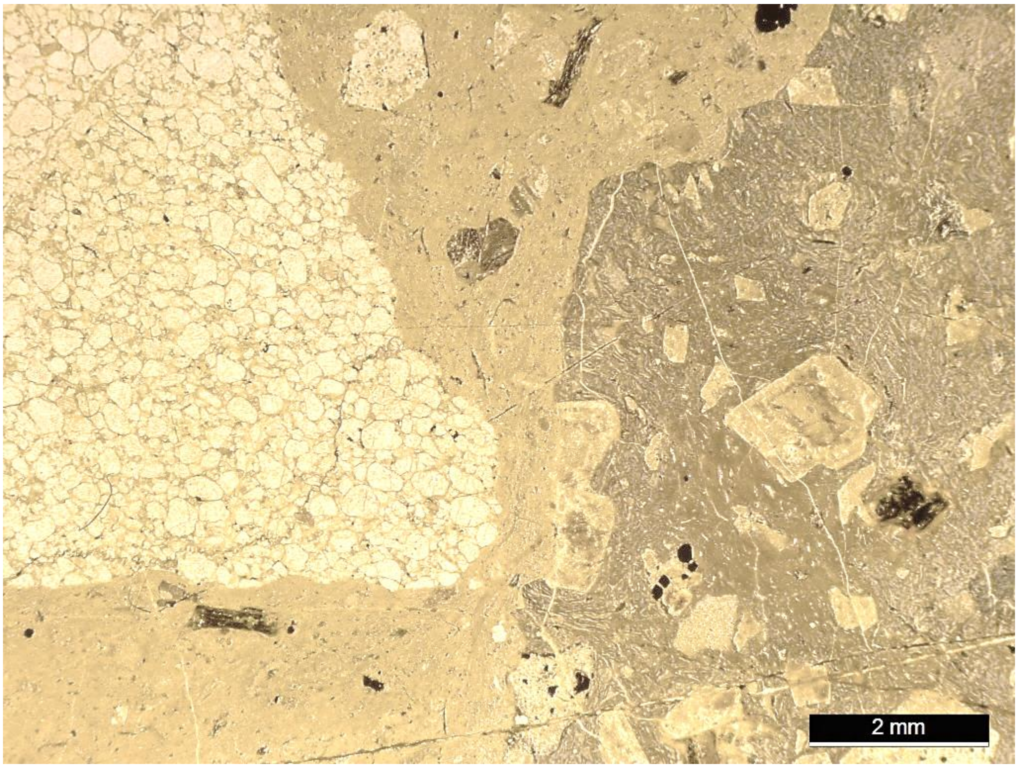
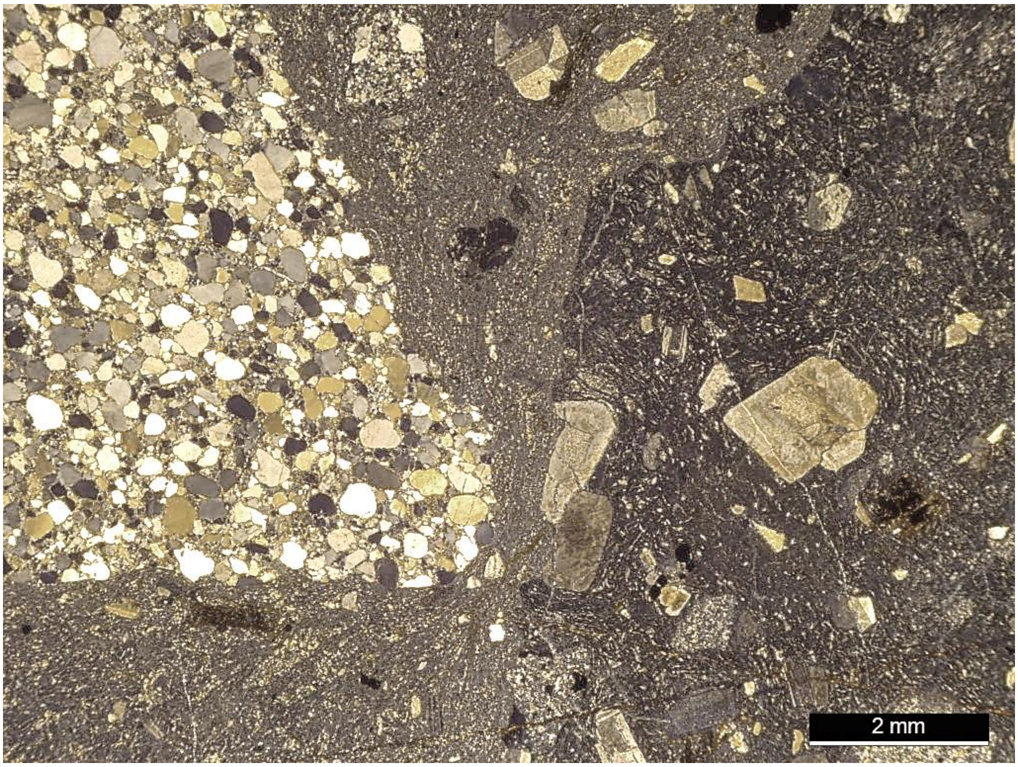


Figure 2.10-15. **Lithic crystal tuff** in the Lynn Volcanic Complex (site 10497, stained for potassium). Tuff separating the fragments has a faint **eutaxitic texture** (wrapping around crystals and lithic fragments), **pyroclastic banding**, and faint **axiolitic texture. Volcanic lithic fragment** on right is crystal tuff with eutaxitic texture wrapping around crystals. Note truncated, zoned crystal on edge of fragment. On the left is a sandstone lithic fragment with barely sutured quartz sand grains. Above: View in plane polarized light. Below: Same view with crossed polarizers.



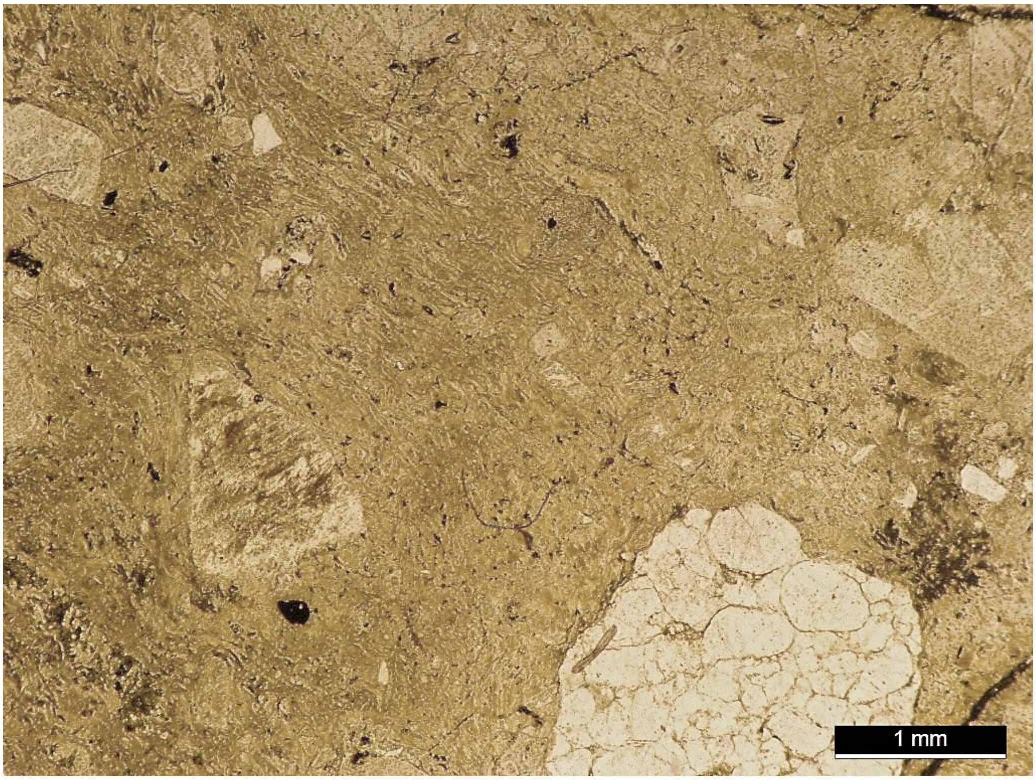
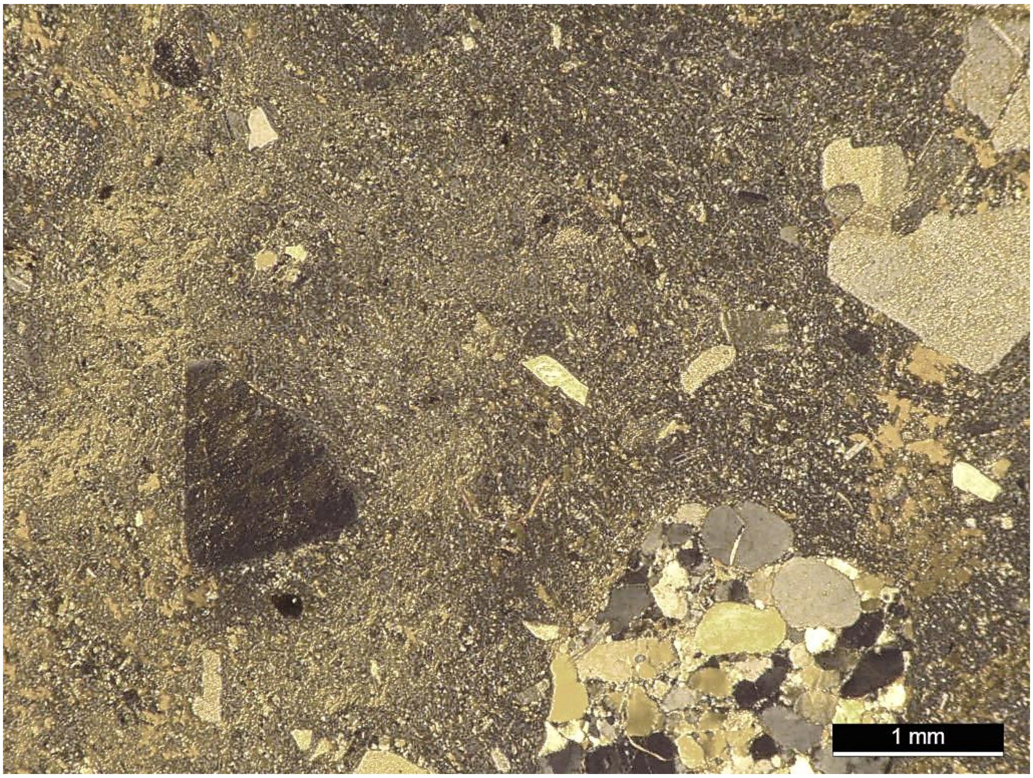


Figure 2.10-16. **Tuff** in the Lynn Volcanic Complex with **eutaxitic texture** and **flattened glass shards** (site 10513, stained for potassium). **Quartzite lithic fragment** in lower right with round sutured quartz grains. Above: View in plane polarized light. Below: Same view with crossed polarizers.



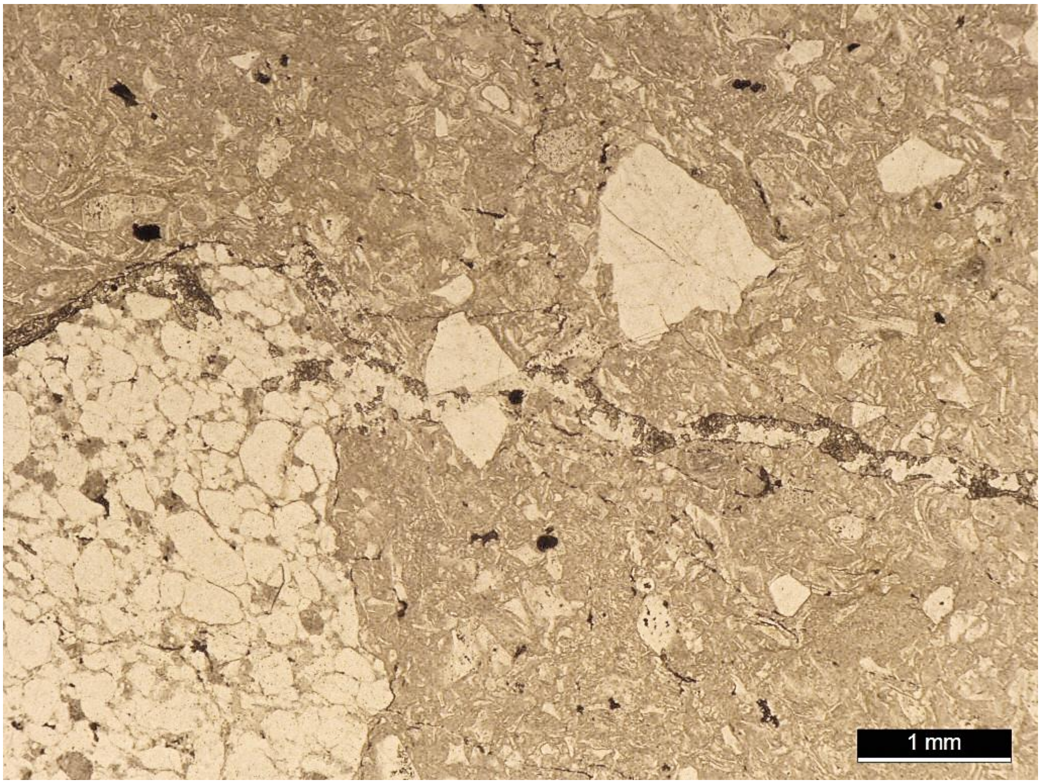
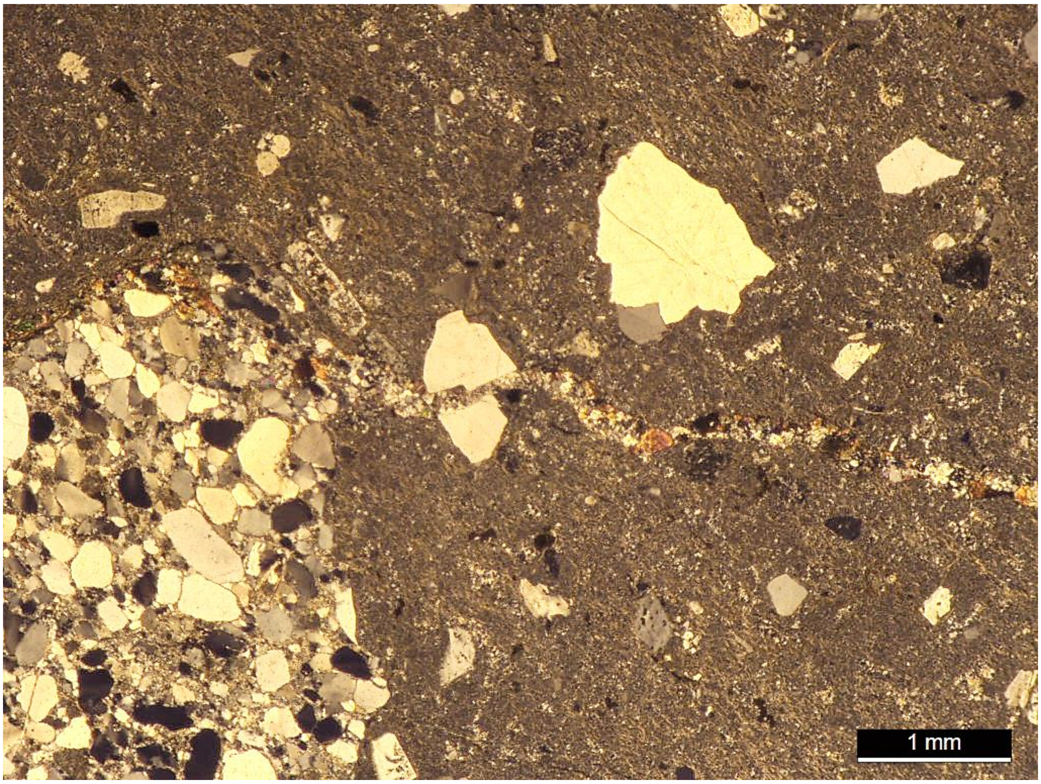


Figure 2.10-17. **Tuff** with **hard glass shards** in the Lynn Volcanic Complex (site 590BN). **Quartzite lithic fragment** in lower left has sutured grains. Large clear grains are quartz from a granitic source. <u>Above</u>: View in plane polarized light. <u>Below</u>: Same view with crossed polarizers.



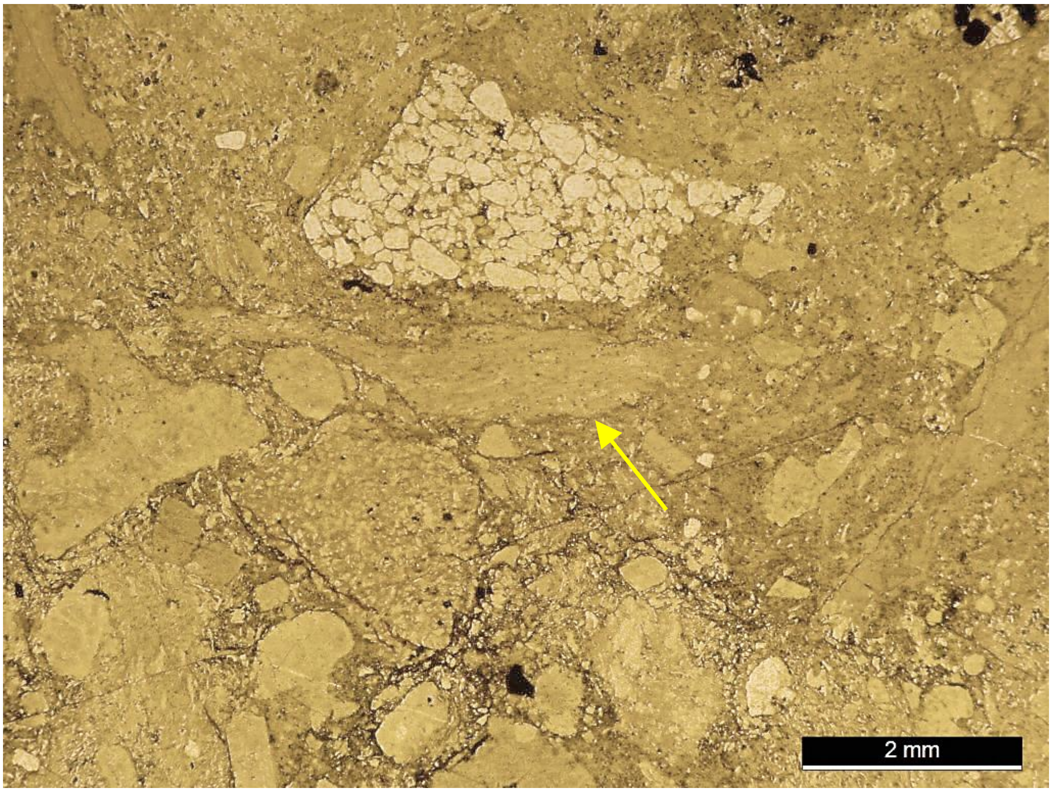
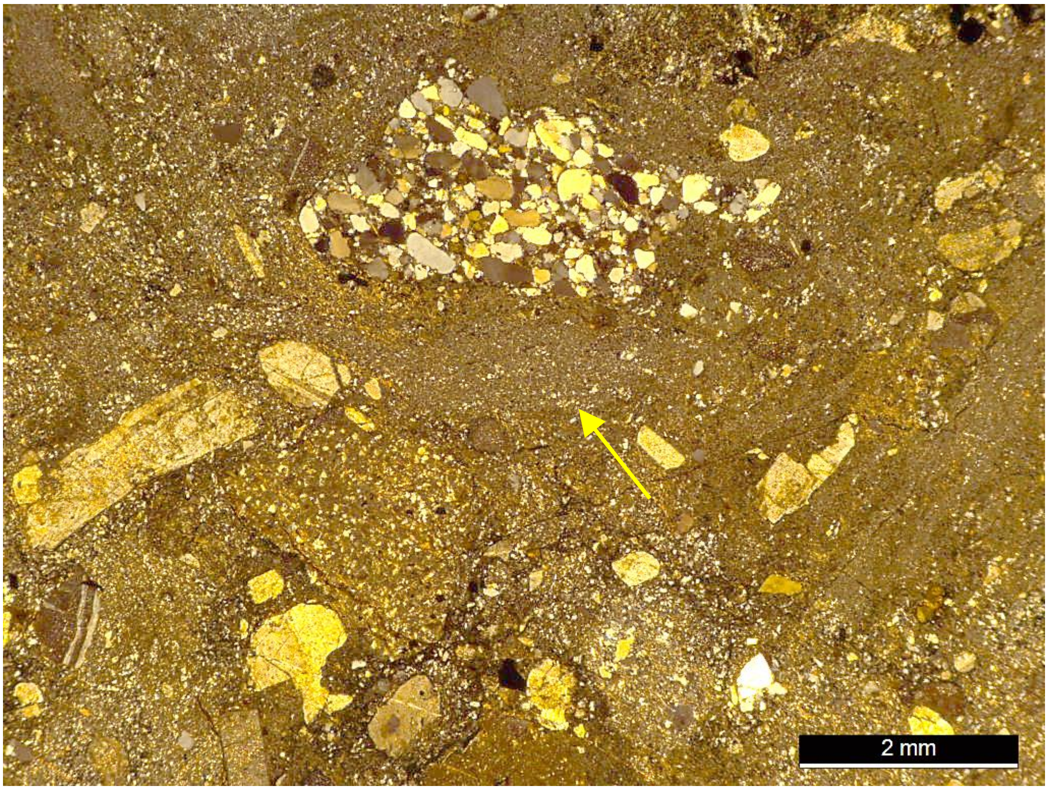


Figure 2.10-18. **Crystal tuff** in the Lynn Volcanic Complex (site 10513, stained for potassium) with **quartzite lithic fragment** from the Westboro Formation (near top) and just beneath it a **flattened eutaxitic tuff fragment** (arrow). Above: View in plane polarized light. Below: Same view with crossed polarizers. Note how volcanic fragments and textures sometimes become invisible in crossed polarizers.



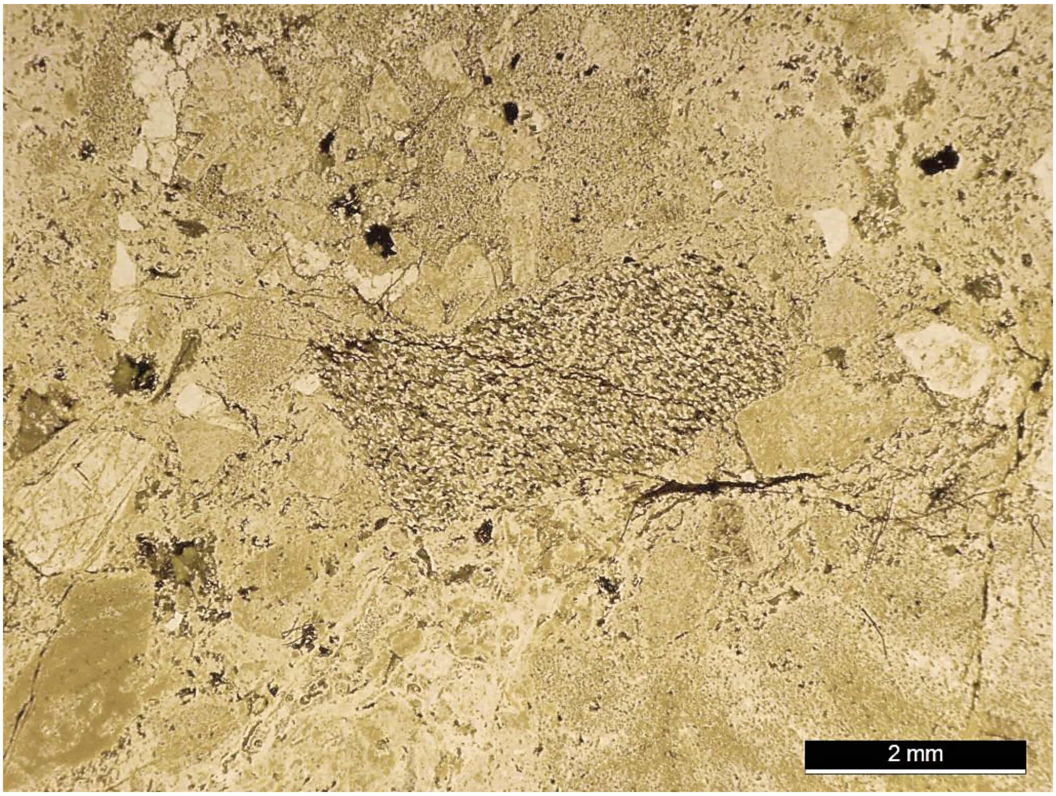
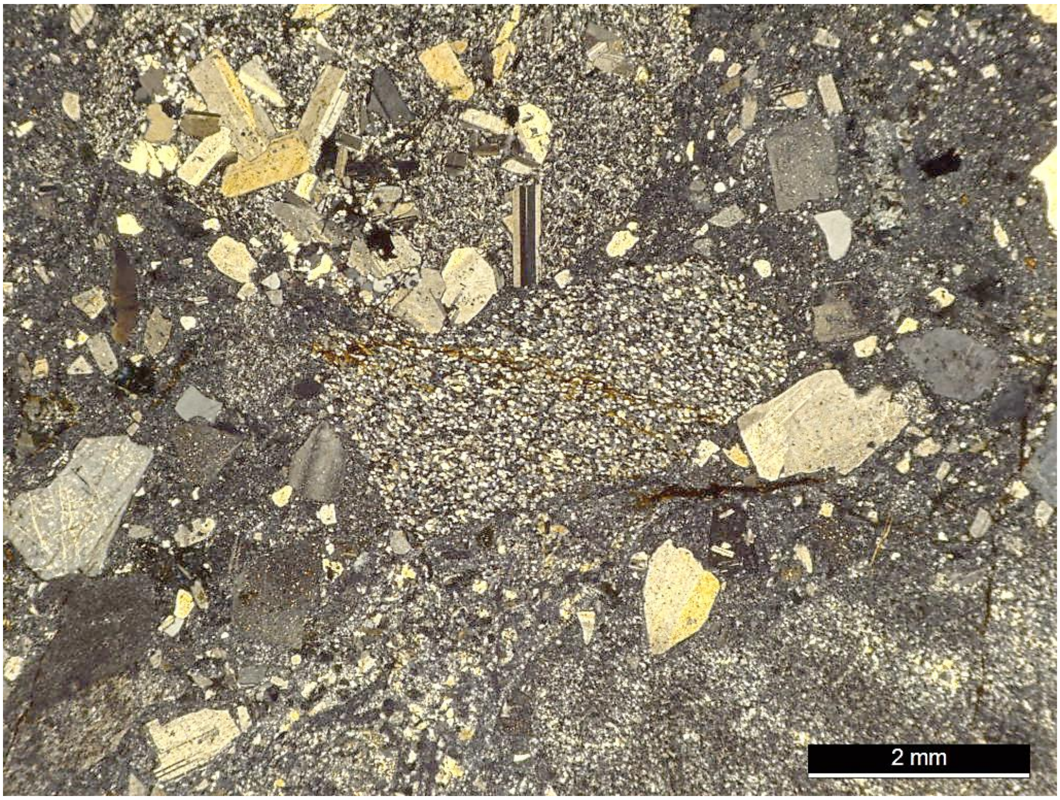


Figure 2.10-19. **Lithic tuff** in the Lynn Volcanic Complex (site 10584, stained for potassium) with very fine **quartzite lithic fragment** from the Westboro Formation (center). At top and in contact with the quartzite fragment is a porphyritic and well crystallized rhyolitic lava fragment with **cumulophyric plagioclase**. Note how euhedral the crystals are in this fragment. In lower right is a patchy textured volcanic fragment. <u>Above</u>: View in plane polarized light. <u>Below</u>: Same view with crossed polarizers.



2.10.3 Accidental Lithic Fragments – Coarse Granitic Rocks

Accidental lithic fragments include sialic plutonic igneous rock types and mineral grains derived from them. These rock types are not only conspicuous components of volcaniclastic rocks in the Fells but are locally abundant in some pyroclastic units. It is seldom possible to see complete multi-mineral fragments of these rock types in thin section since their grain size is very large. However, there are abundant fragments with 2-3 mineral grains from these rocks, mostly adhered quartz and feldspar, that allow an identification of the source rock. Of these grains granodiorite appears to be a major source. Many large single mineral grains are also sourced in these rock units and include large (>2 mm) grains of quartz as well as perthitic alkali feldspar that cannot have a juvenile or cognate volcanic source (Figs. 2.10-20 to 25). This is an important aspect of the composition of the volcanic units that assists in differentiating volcanic units and in determining the relative ages of the pyroclastic units and plutonic bodies.

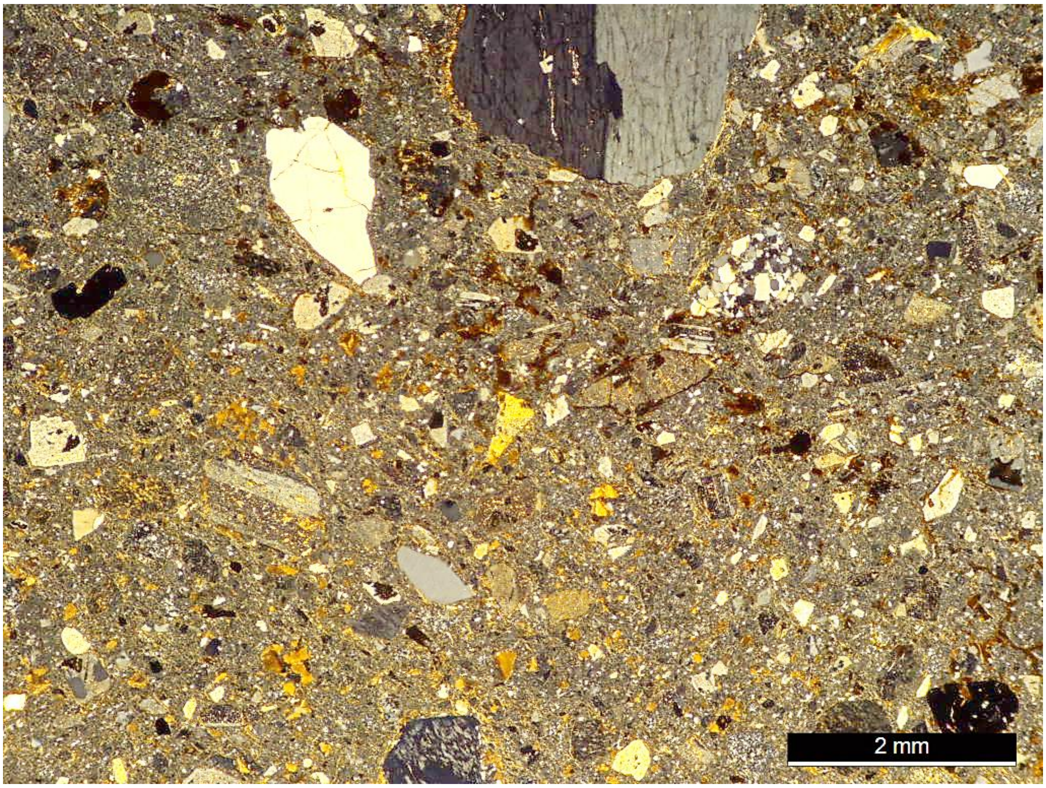


Figure 2.10-20. **Accidental fragments** in **crystal tuff** in the Lynn Volcanic Complex (site 642BN). At the very top of the image is a twinned perthitic alkali feldspar grain and the bright grain to the left is a large quartz fragment likely derived from coarse granodiorite or granite. Below and to the right of the alkali feldspar is a small quartzite lithic fragment with sutured grains. View with crossed polarizers.

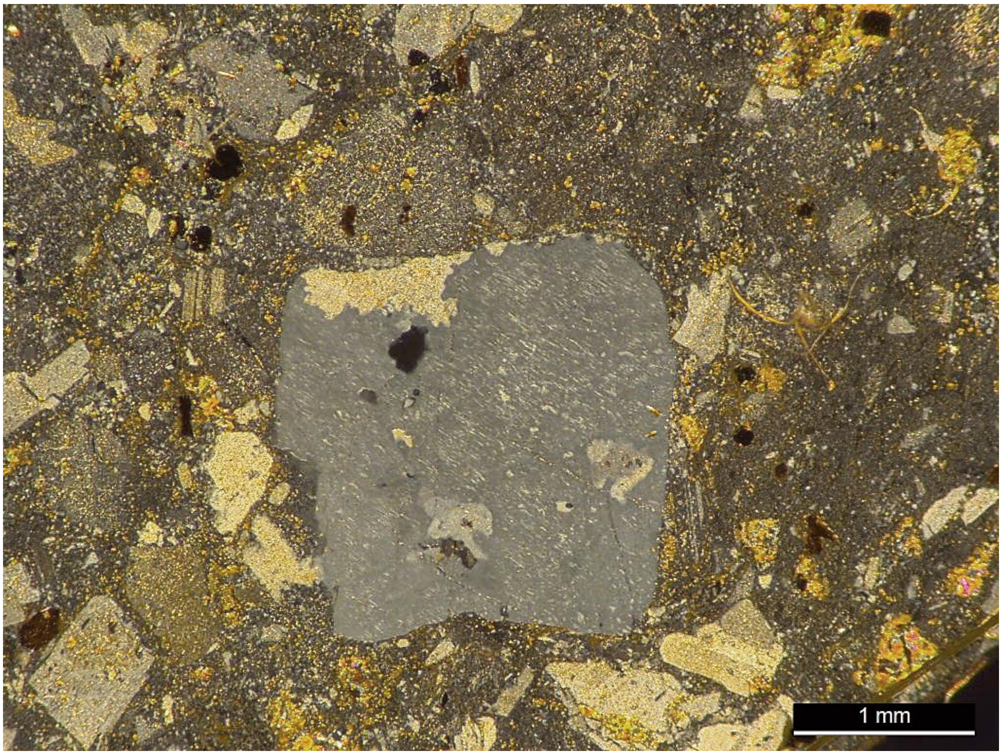


Figure 2.10-21. **Crystal tuff** in the Boojum Rock Tuff (site 10354) with a very rare accidental perthitic alkali feldspar grain. This is the only grain of this type that has been found in this volcanic unit. View with crossed polarizers.

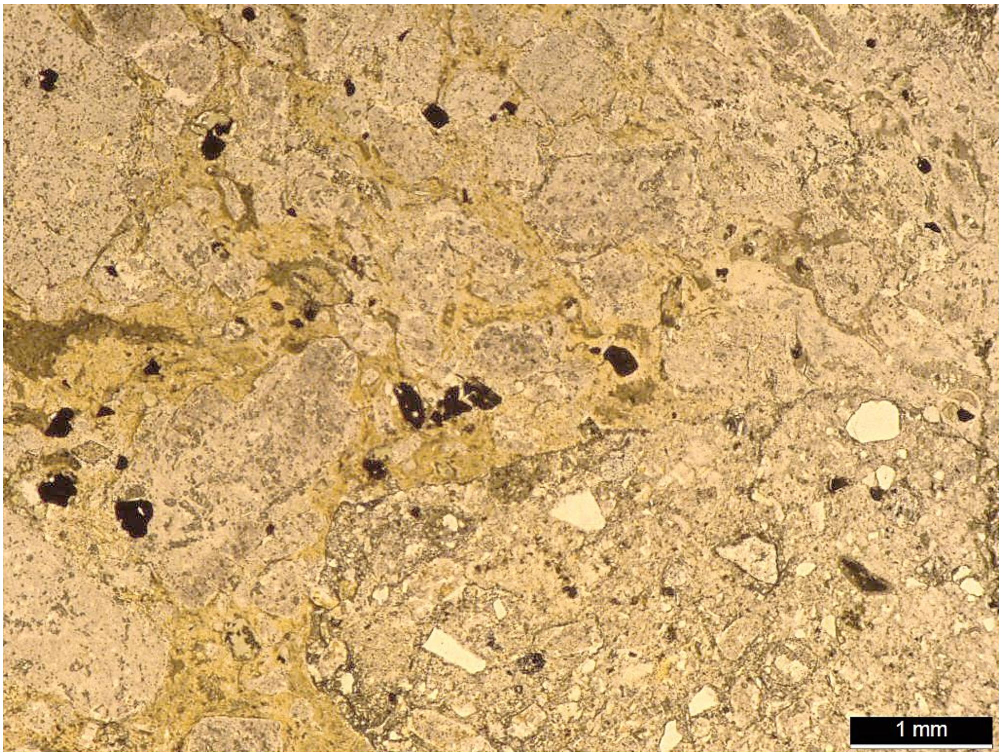


Figure 2.10-22. **Crystal tuff** in the Boojum Rock Tuff (site 10354) with a lithic fragment containing very rare lithic quartz fragments (bright grains). These grains are thought to be accidental and not cognate or juvenile, quartz fragments. Yellow stained areas across center of view may be a flattened and deformed obsidian fragments with axiolitic strands. View in plane polarized light.

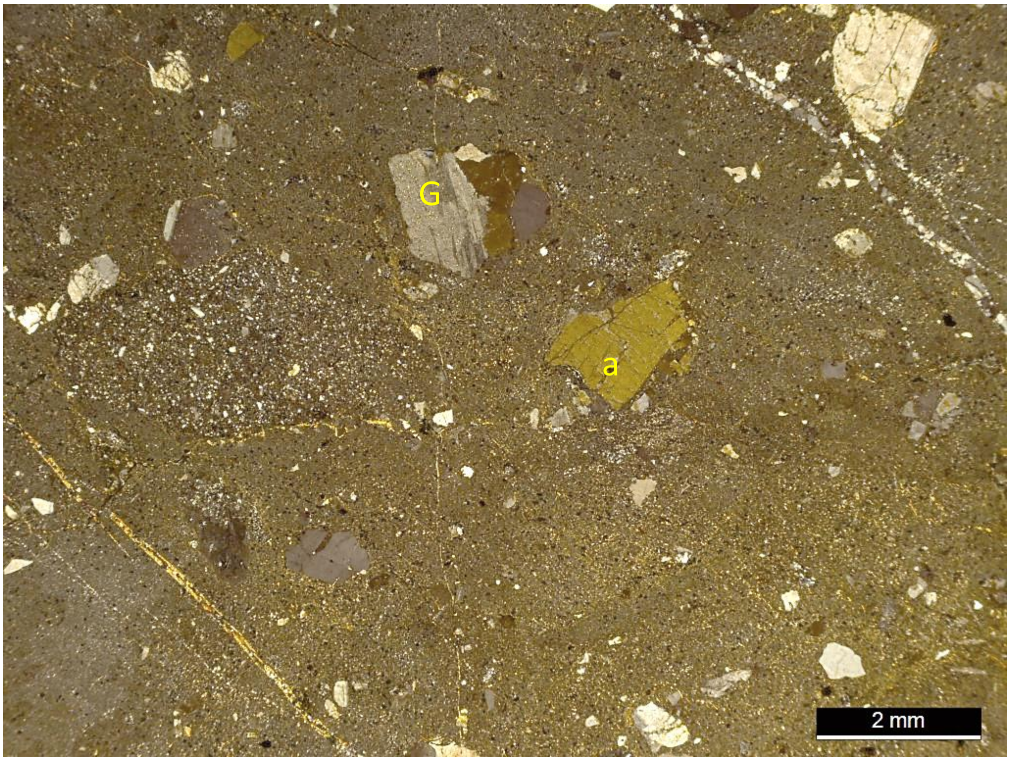


Figure 2.10-23. **Crystal tuff** in the Lynn Volcanic Complex at Boojum Rock (site 10895) with an angular alkali feldspar grain (a) and a multi-mineral granitic grain with quartz and plagioclase (G). On the left side is a lithic volcanic fragment with a **patchy to granular texture**. View with crossed polarizers.

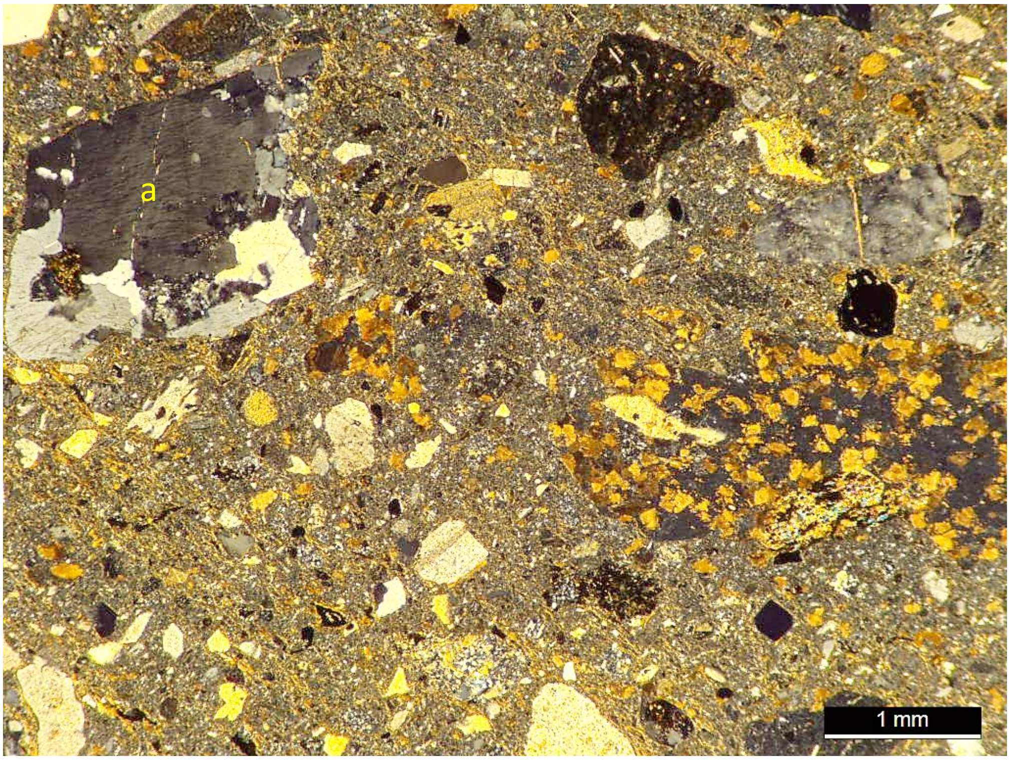


Figure 2.10-24. **Crystal tuff** in the Lynn Volcanic Complex (site 642BN) with a multi-mineral fragment containing alkali feldspar (a) and a lithic fragment of unknown source with orange calcite crystals likely derived from a metasedimentary rock (right side). The rock also contains scattered quartz fragments. View with crossed polarizers.

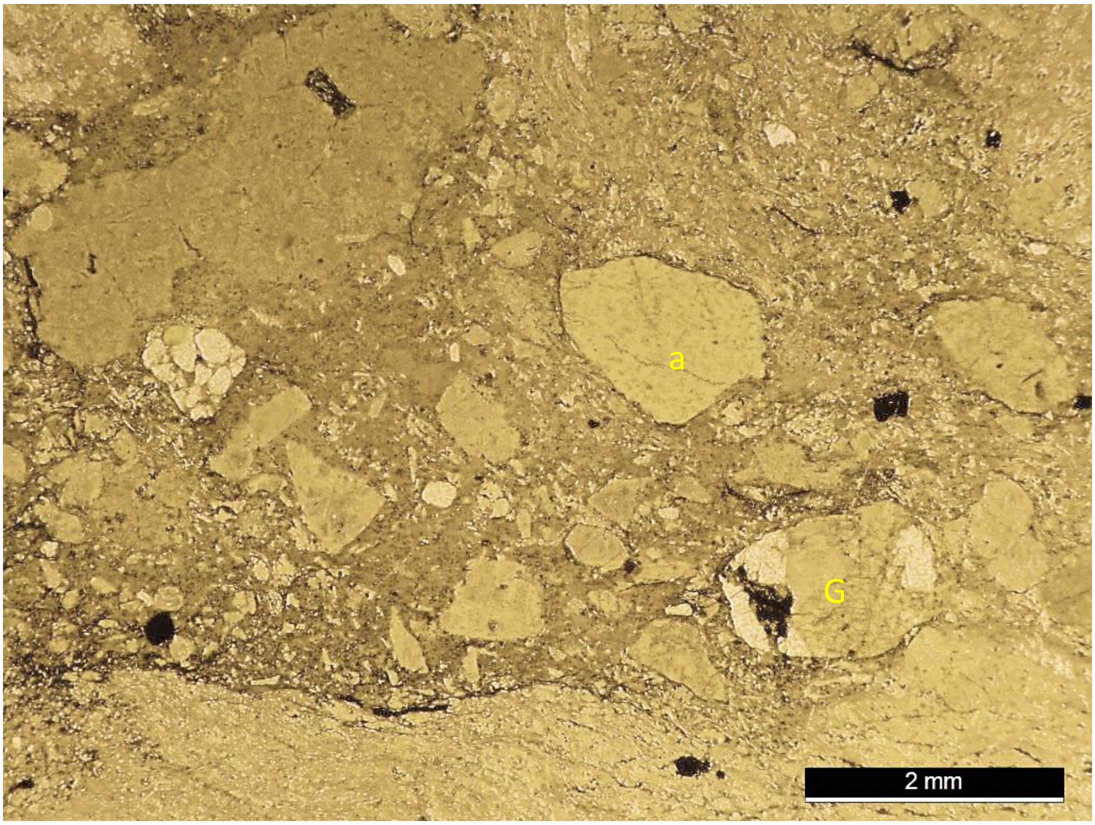
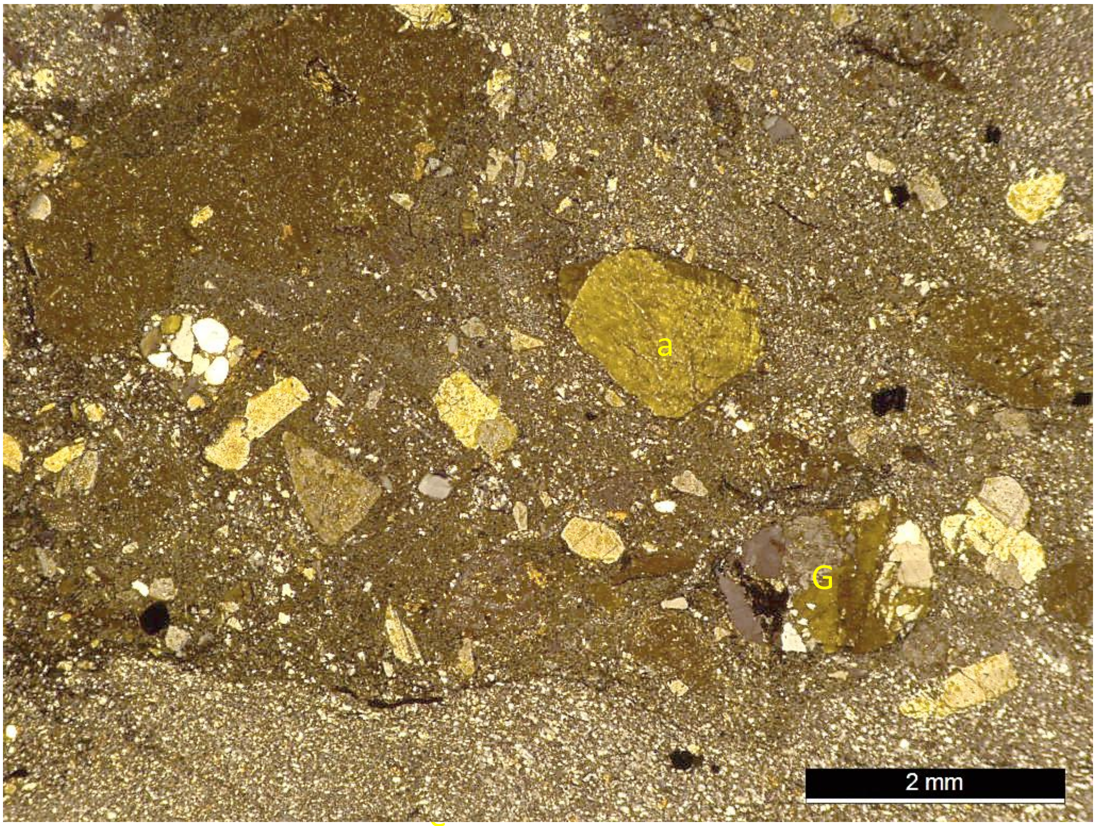


Figure 2.10-25. **Tuff** in the Lynn Volcanic Complex (site 10954) with an **alkali feldspar grain** (a), a multi-mineral granitic clast (G), and a piece of **quartzite** (left side). The matrix has scattered hard glass shards. Above: View with plane polarized light. Below: View with crossed polarizers.



2.10.4 Accidental Lithic Fragments – Granophyre

Although rare in volcanic rock units of the southern Middlesex Fells, fragments of the Lawrence Woods Granophyre (Figs. 2.10-26 to 27) have an important occurrence within one area of the Lynn Volcanic Complex. While in most places the granophyre clearly intrudes the Lynn, granophyre fragments also occur within one area of the Lynn. This relationship is interpreted to indicate that at least one area of the Lynn is slightly younger than the Lawrence Woods Granophyre. These dual field relationships seem to indicate that the Lynn Volcanic Complex and the Lawrence Woods Granophyre are co-magmatic or at least close in age.

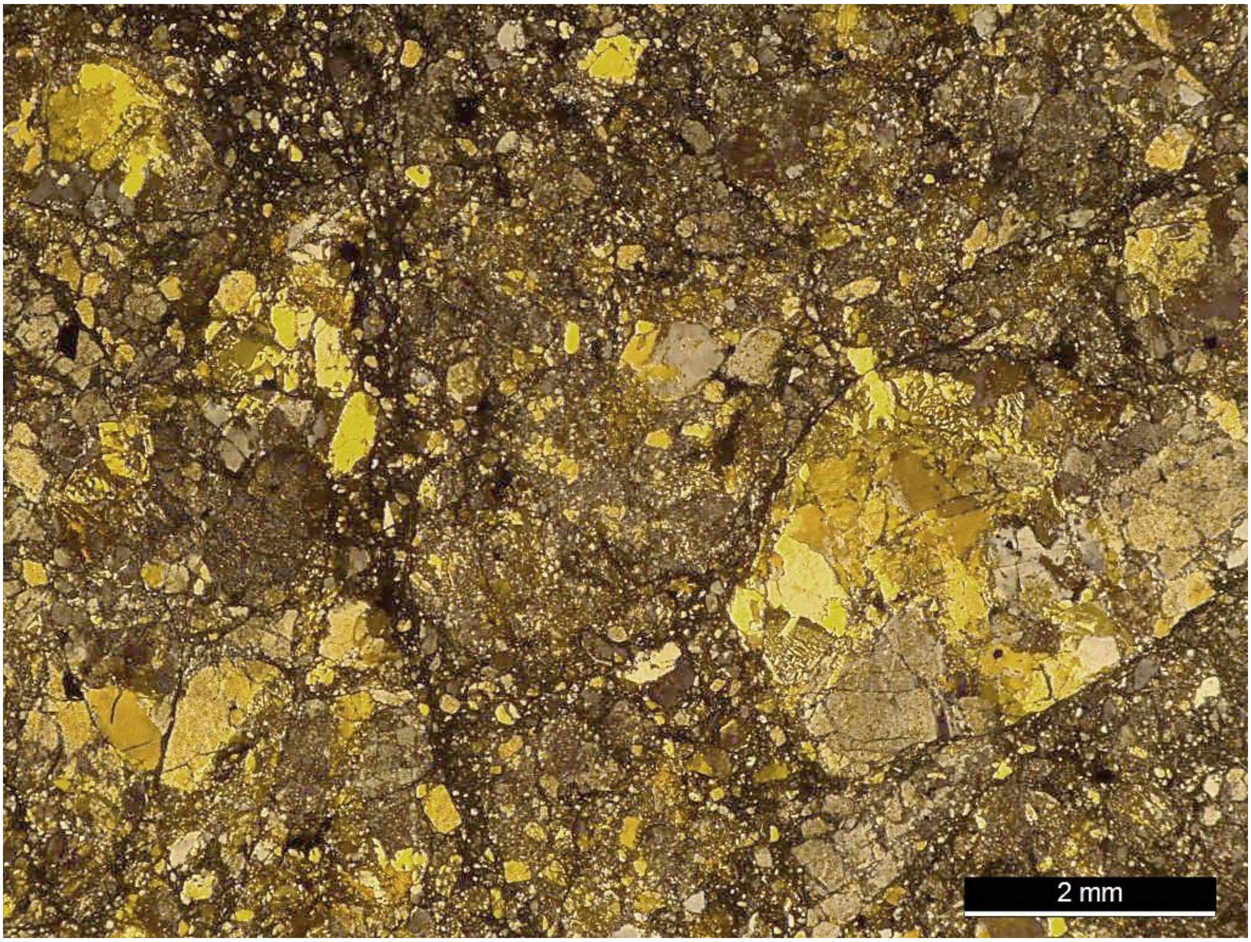


Figure 2.10-26. **Crystal tuff** or possibly **volcaniclastic rock** in the Lynn Volcanic Complex (site 10759) with granophyre lithic fragments from the Lawrence Woods Granophyre. View with crossed polarizers.

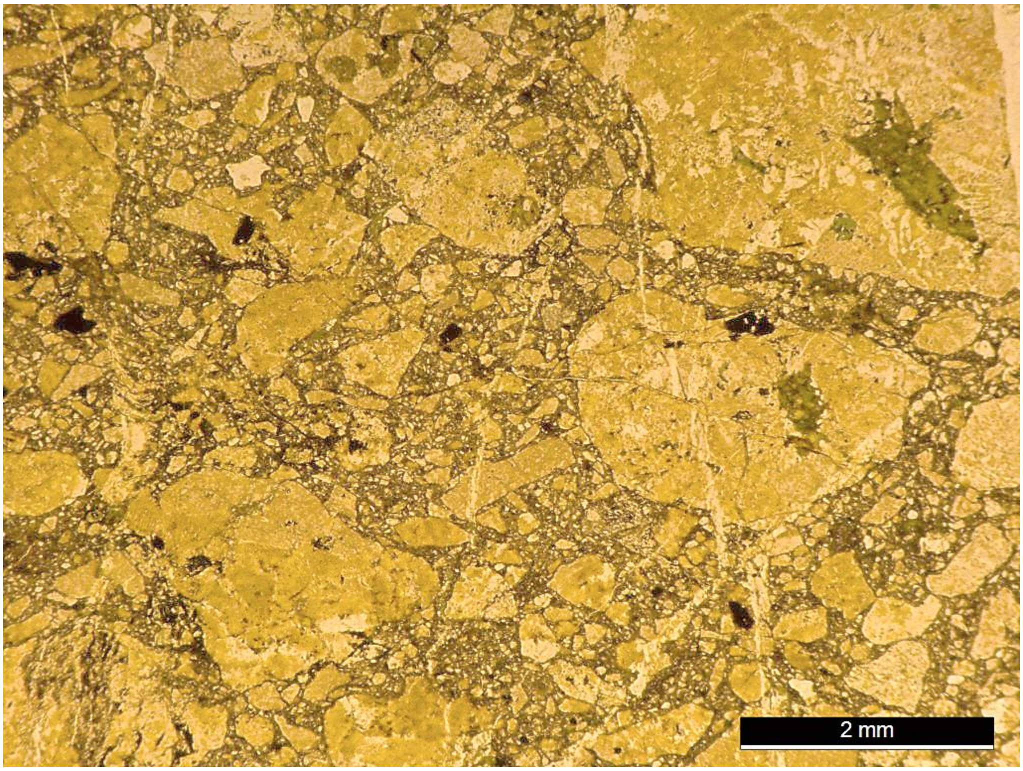
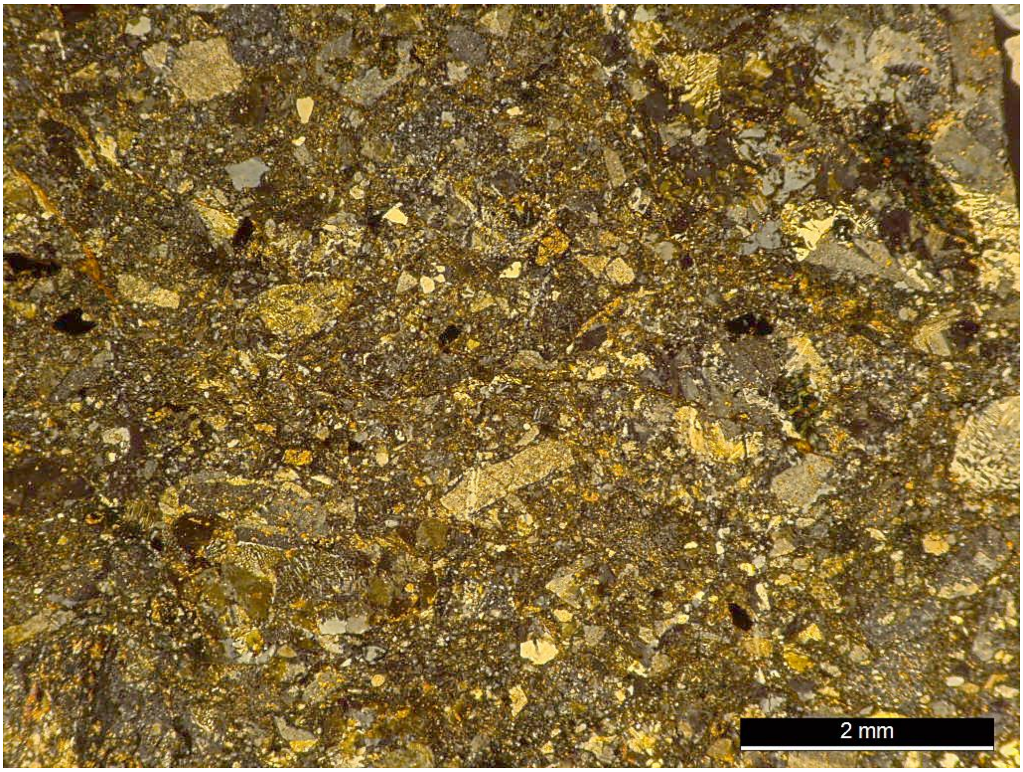


Figure 2.10-27. **Lithic tuff** in the Lynn Volcanic Complex (site 10980) with **lithic fragments** from the **Lawrence Woods Granophyre**. Above: View with plane polarized light. Below: View with crossed polarizers. Compare this image with granophyric clasts in volcaniclastic rocks (section 4), where clasts are more rounded and clast-supported.



3. FELSIC LAVA FLOWS

Lava flows make up a small percentage of the felsic volcanic rocks in the Middlesex Fells, being far less abundant than tuffs. All flows found in the Fells are rhyolitic in composition and generally show a dark yellow staining for potassium. However, they do not contain alkali feldspar phenocrysts and apparently solidified before alkali phenocrysts could crystallize. Instead, radiating **spherulitic or fibrous growths** of alkali feldspar and quartz formed, which occurred either during solidification or shortly after during devitrification. At the north end of Spot Pond in the Straw Point Volcanic Complex, flows have **felsitic micropoikilitic textures** with quartz surrounding much finer feldspar grains. Development of this felsitic texture may have been aided by sustained heating adjacent to a large plutonic intrusion (Stoneham Granodiorite).

Key features to look for when trying to identify rhyolitic lava flows are flow bands that are very continuous and well developed cumulophyric plagioclase feldspar clusters. Intensely folded **lava or flow banding** and other remnant structures such as **auto-brecciation** and **perlitic texture** are conspicuous in outcrops and in cut rocks (Figs. 3-1 to 6). In some cases, lava banding can be obscured or wiped out by devitrification or recrystallization during contact metamorphism near later plutonic bodies.

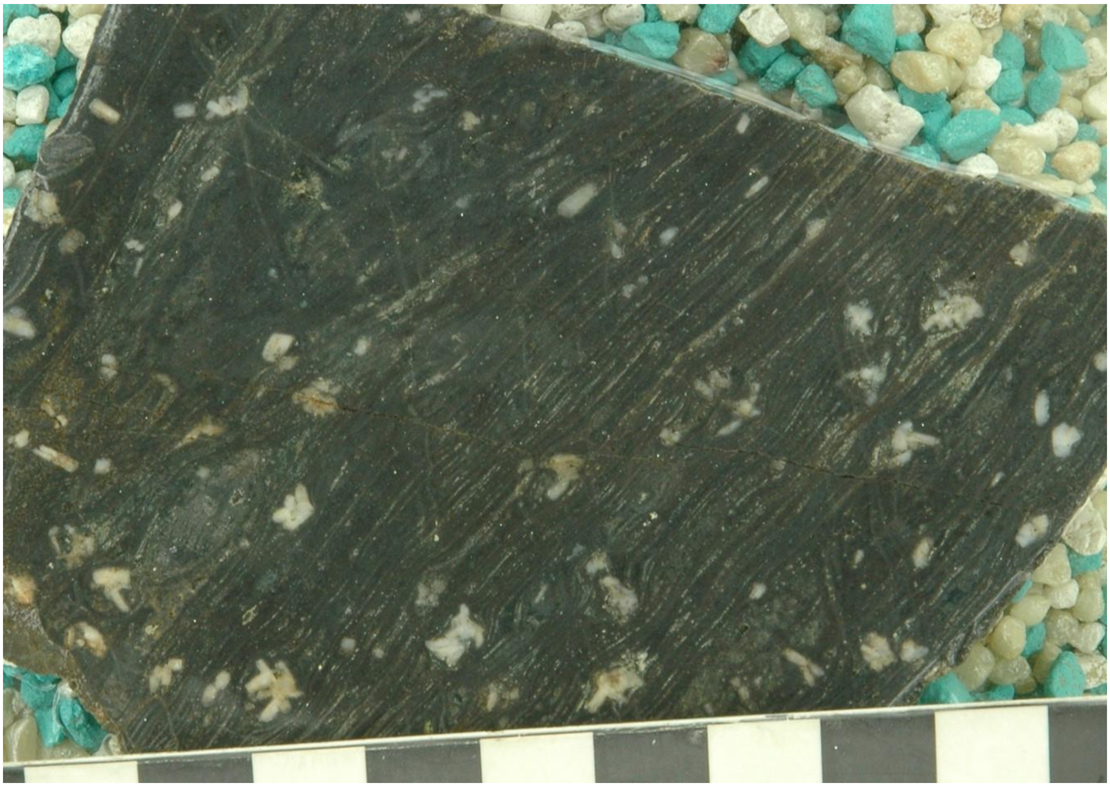


Figure 3-1. **Flow-banded rhyolitic lava** in the Lynn Volcanic Complex (site 10366) with highly euhedral **cumulophyric plagioclase** clusters. Note also the intense folding that occurs in the left side of the image. Cut rock sample.

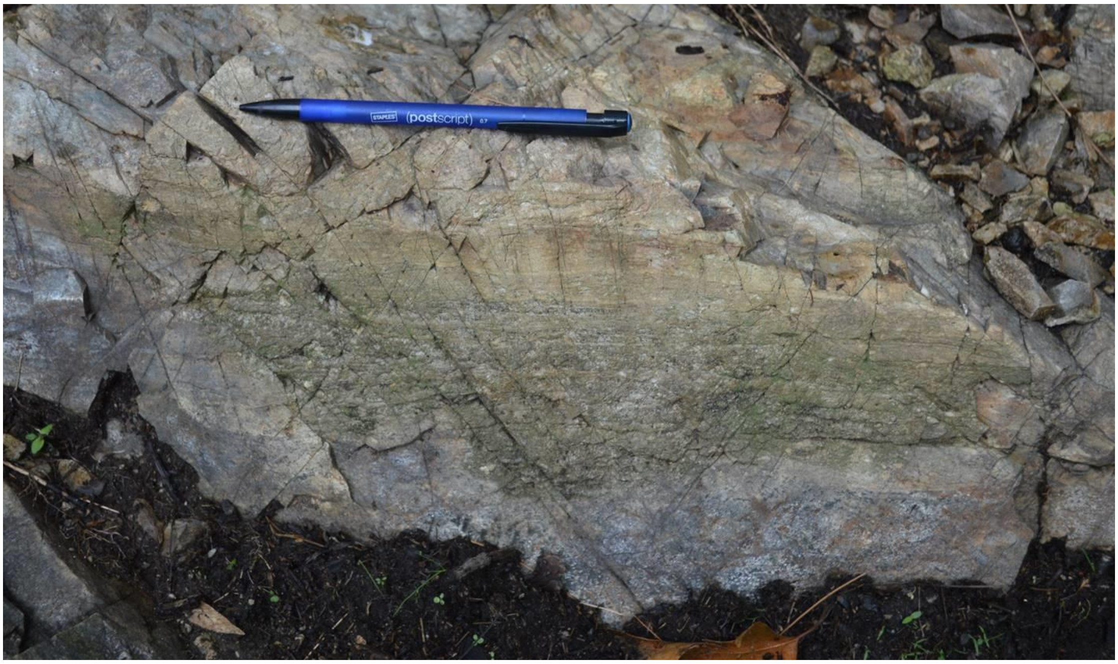


Figure 3-2. **Flow-banded rhyolitic lava** in the Straw Point Volcanic Complex (site 11148) with highly euhedral **cumulophyric clusters** and individual crystals of plagioclase. Weathered outcrop surface.

Figure 3-3. **Flow-banded rhyolitic lava** in the Straw Point Volcanic Complex (site 11138) with highly euhedral **cumulophyric clusters** and single euhedral crystals of plagioclase. The layer below is intensely banded while banding is faint in the unit above.

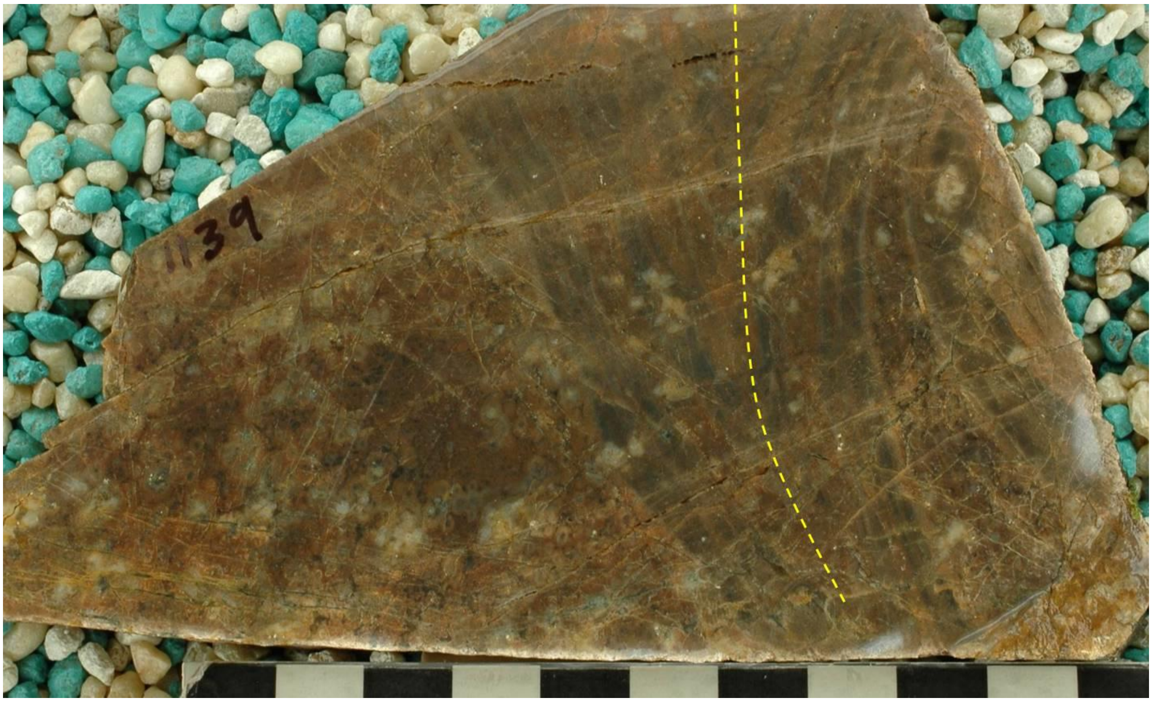


Figure 3-4. **Flow-banded rhyolitic lava** in the Straw Point Volcanic Complex (site 11139) with highly euhedral **cumulophyric clusters** and individual euhedral crystals of plagioclase. Yellow line traces the axis of a fold. Cut rock sample.

Figure 3-5. **Auto-brecciated, flow-banded rhyolitic lava** in the Lynn Volcanic Complex (site 642BN) with breccia clasts surrounded by tuff at the top of a flow unit. Cut rock sample.

Figure 3-6. Remnant **perlitic texture** (circular structures) in **flow-banded rhyolitic lava** in the Lynn Volcanic Complex (site 10398). See section 3.2.5 below. Cut rock sample.

3.1 Pyroclastic-banding in Tuffs vs. Flow-banding in Lava Flows

Sialic lava units often have well developed banding due to flow unless it is obliterated by devitrification. While it is true that many lava flows show spectacular banding, banded volcanic rocks are not always lava flows. Tuffs are also commonly banded. Lava flow-banding can be distinguished from pyroclastic banding in several ways:

1) Bands in lava flows have more delicate and thinner bands, leading to a better-defined structure that is very continuous with bands having a more uniform width. Pyroclastic bands are irregular and discontinuous (pinched) with bands being formed of individual flattened glass fragments, glassy welded zones, and volcanic debris that is distributed heterogeneously.

2) Lava banding is commonly continuous through intricate folds (Fig. 3.1-1). Pyroclastic bands may be folded by rheomorphic deformation of very hot, soft or molten material after it is deposited but this is not as common.

3) Crystals in lava flow banding are euhedral phenocrysts and are not as abundant as in most tuffs. Lava flow crystals are commonly cumulophyric clusters of euhedral plagioclase (Figs. 3.1-2 to 3). The clusters are usually distinguishable in hand specimens (Fig. 3-1 to 8).

4) Banded lava flows have fewer lithic fragments that so far have always been volcanic. Accidental lithic fragments may be present but are rare.

Lava bands are visible in hand specimens and are clearly visible in a microscope. In plane polarized light, flow bands appear as layers with darker and lighter potassium staining. In crossed polarizers, bands are defined as layers of ultra-fine to medium-grained felsitic texture with different crystal sizes and orientations and with the coarser layers often having a darker potassium stain (Fig. 3.1-2 to 6). Some flow bands, instead of a compositional differences, seem to be alternating layers with a **patchy or splotchy felsitic texture** and layers with a patchy texture made of elongate, aligned, and sometimes radiating crystals (Figure 3.1-7 to 8). It appears that the fabric developed during the flow of molten obsidian may influence later crystal growth patterns.

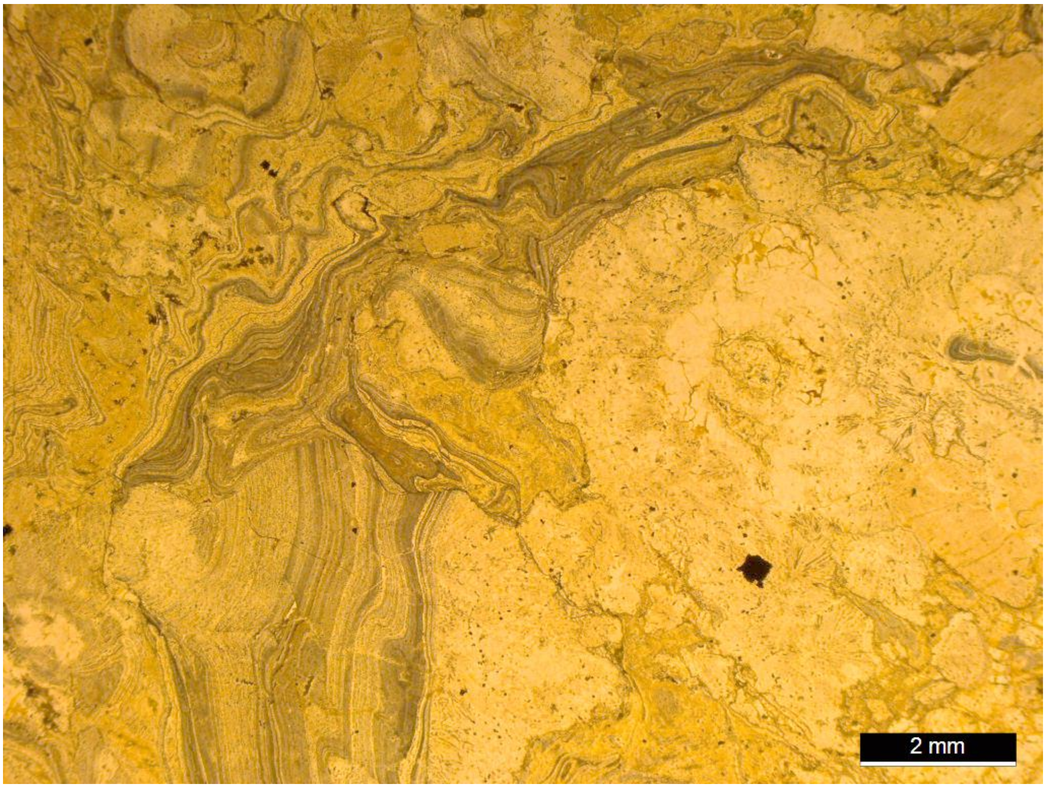
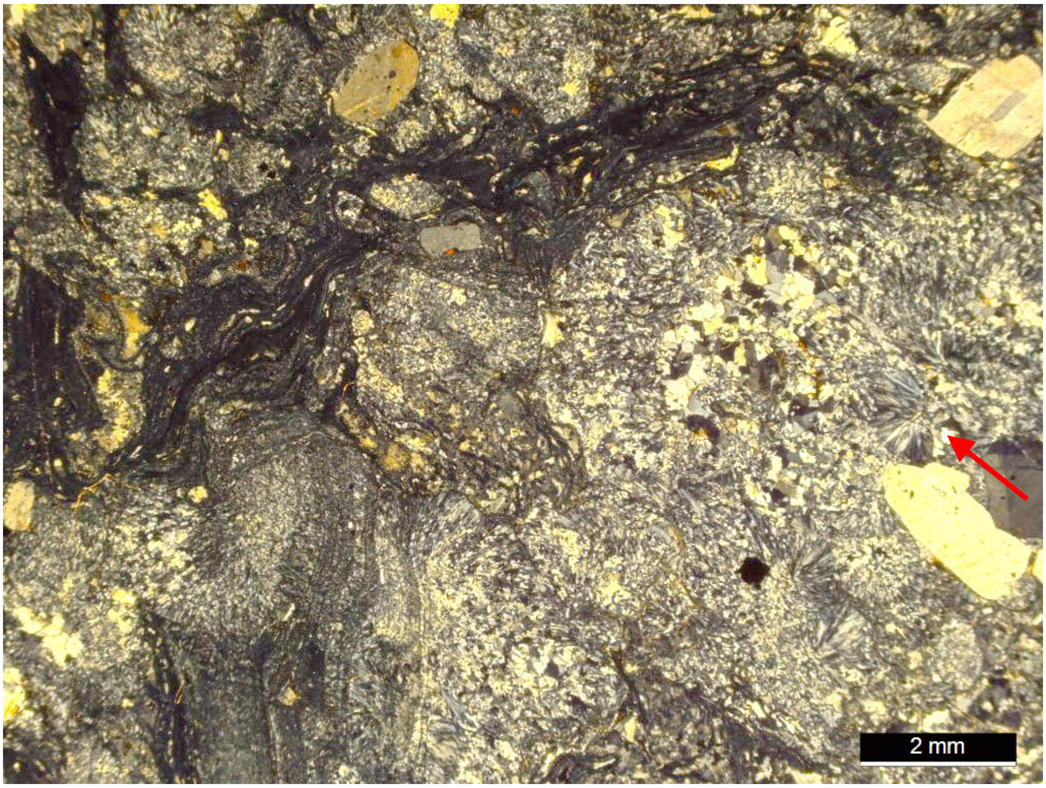


Figure 3.1-1. Thinly **flow-banded rhyolitic lava** in the Lynn Volcanic Complex (site 10398). This is near the surface of a flow with few phenocrysts and ultra-fine matrix crystals, possibly formed during devitrification. Above: View with plane polarized light. Below: View with crossed polarizers. Note radiating spherulitic growths on right side below (arrow shows one example). See Fig 2.7-22 above for spherulitic growths in tuff that are much finer.



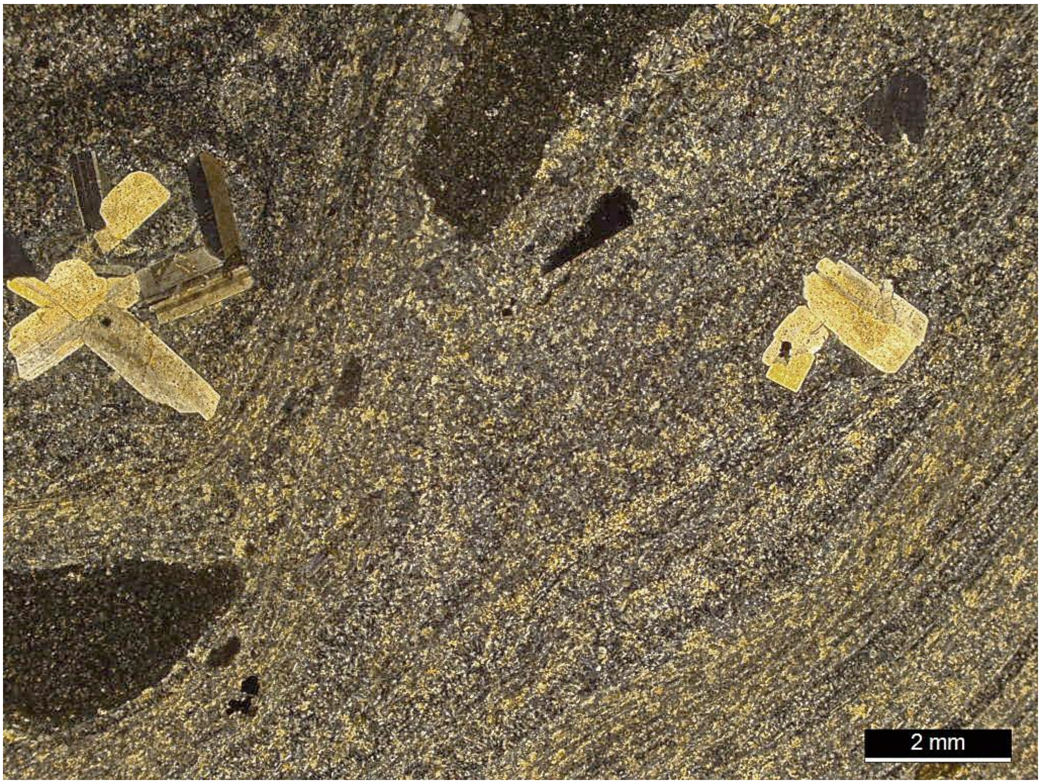


Figure 3.1-2. Thinly **flow-banded rhyolitic lava** in the Lynn Volcanic Complex (site 10346). Note the **cumulophyric clusters** of euhedral plagioclase. Dark splotches have extremely fine **micro-spherulitic texture** that may be auto-brecciated lava fragments. View with crossed polarizers.

Figure 3.1-3. Thinly **flow-banded rhyolitic lava** in the Lynn Volcanic Complex (site 10366) with **cumulophyric plagioclase cluster**. View with crossed polarizers.

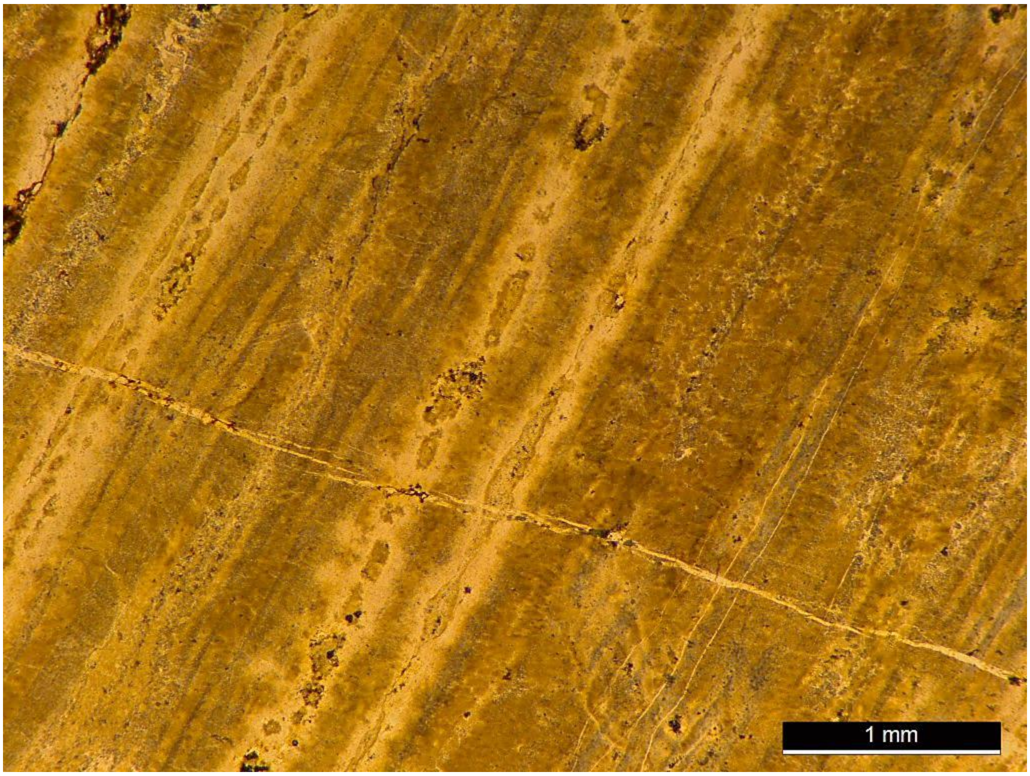
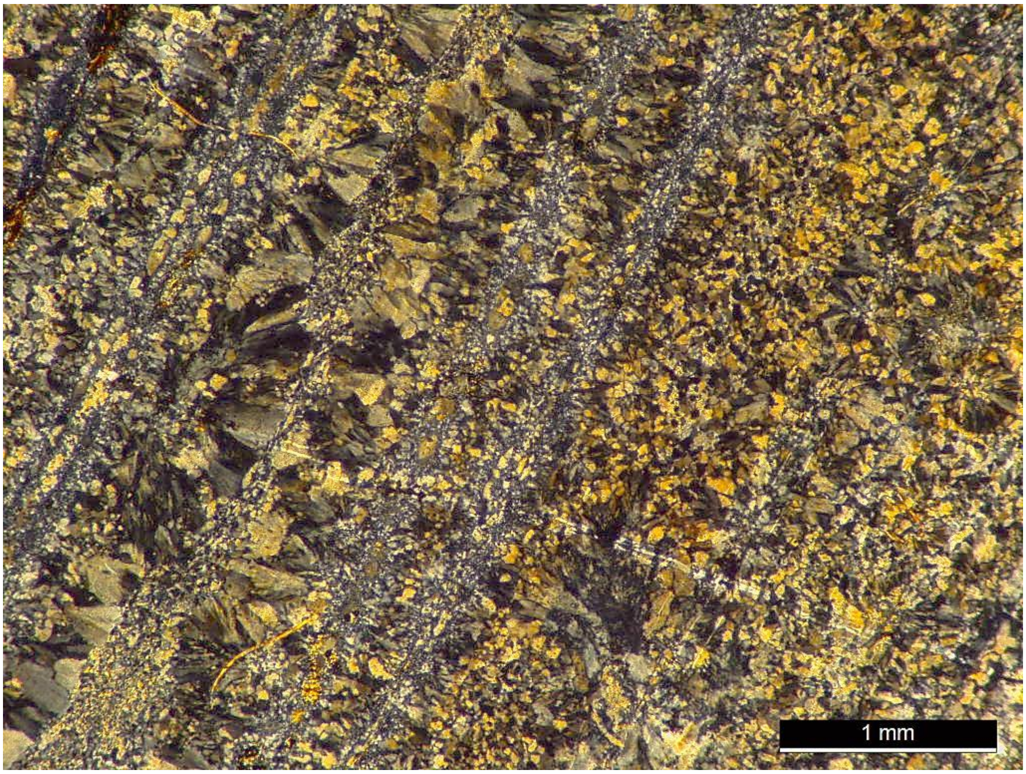


Figure 3.1-4. Thinly **flow-banded rhyolitic lava** in the Lynn Volcanic Complex (site 10366). Above: View in plane polarized light. Note the darker and lighter staining of adjacent bands. Below: View with crossed polarizers. The darker bands (image above) have a coarser grain size with radiating crystals while light bands are fine grained (compare images).



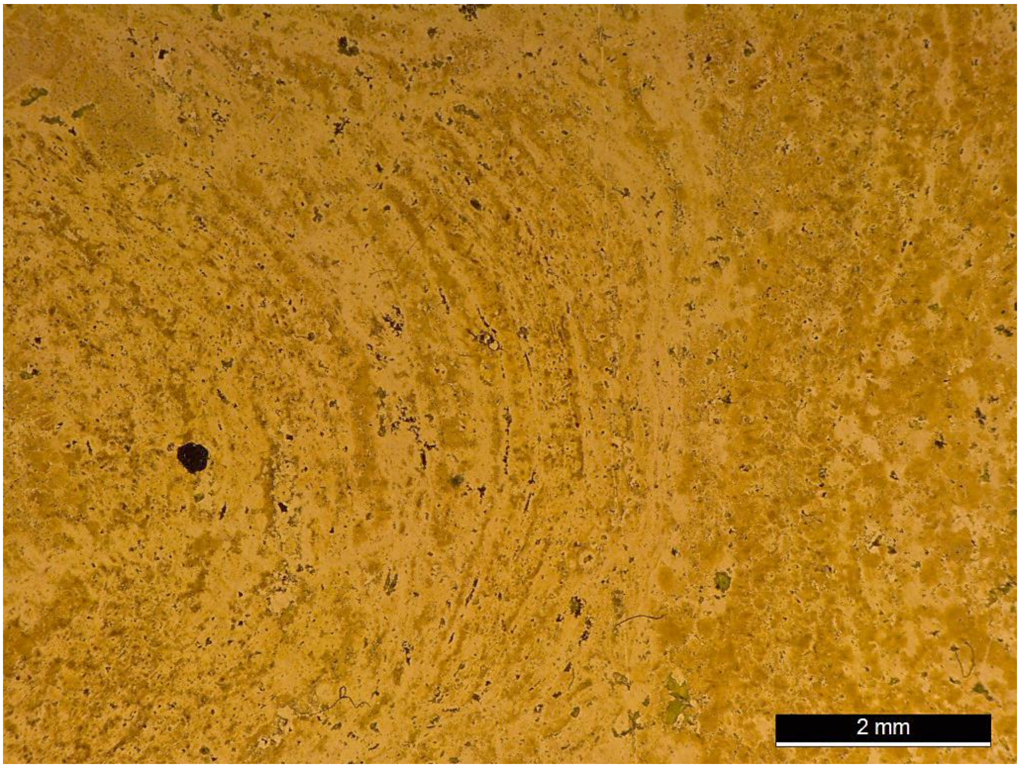
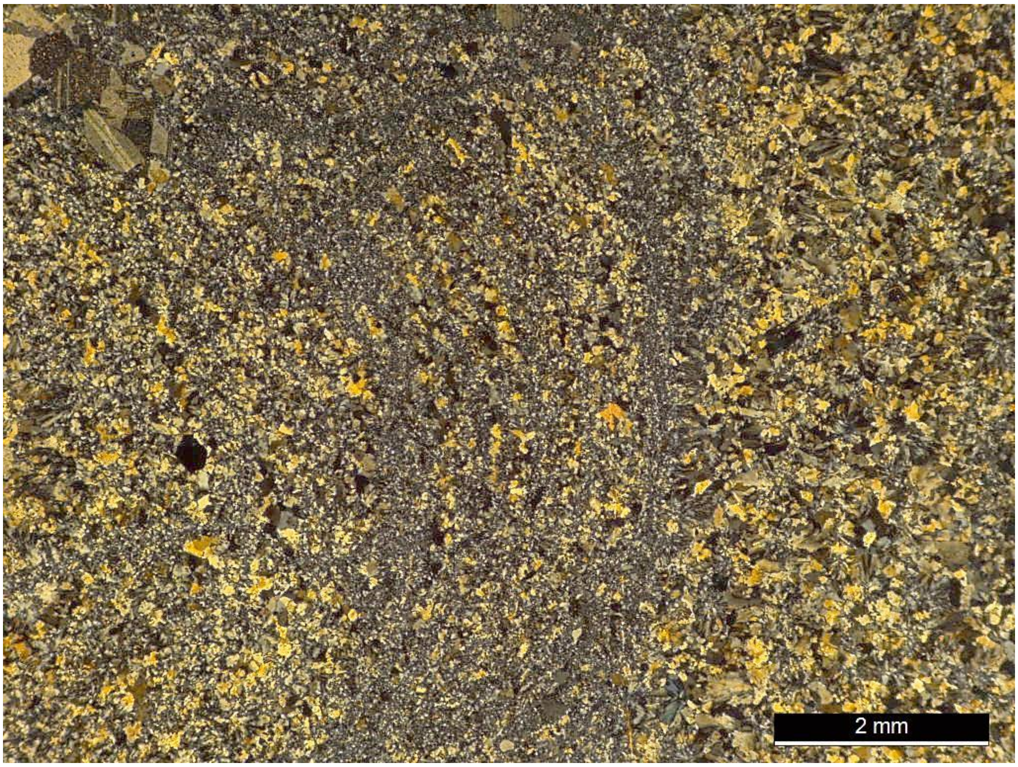


Figure 3.1-5. Thinly **banded rhyolitic lava** in the Lynn Volcanic Complex (site 10345). In upper left is a euhedral **cumulophyric plagioclase cluster** . Above: View in plane polarized light. Note the darker and lighter staining of adjacent bands. Below: View with crossed polarizers. The darker areas have a coarser grain size and lighter layers have axiolitic strands (compare images).



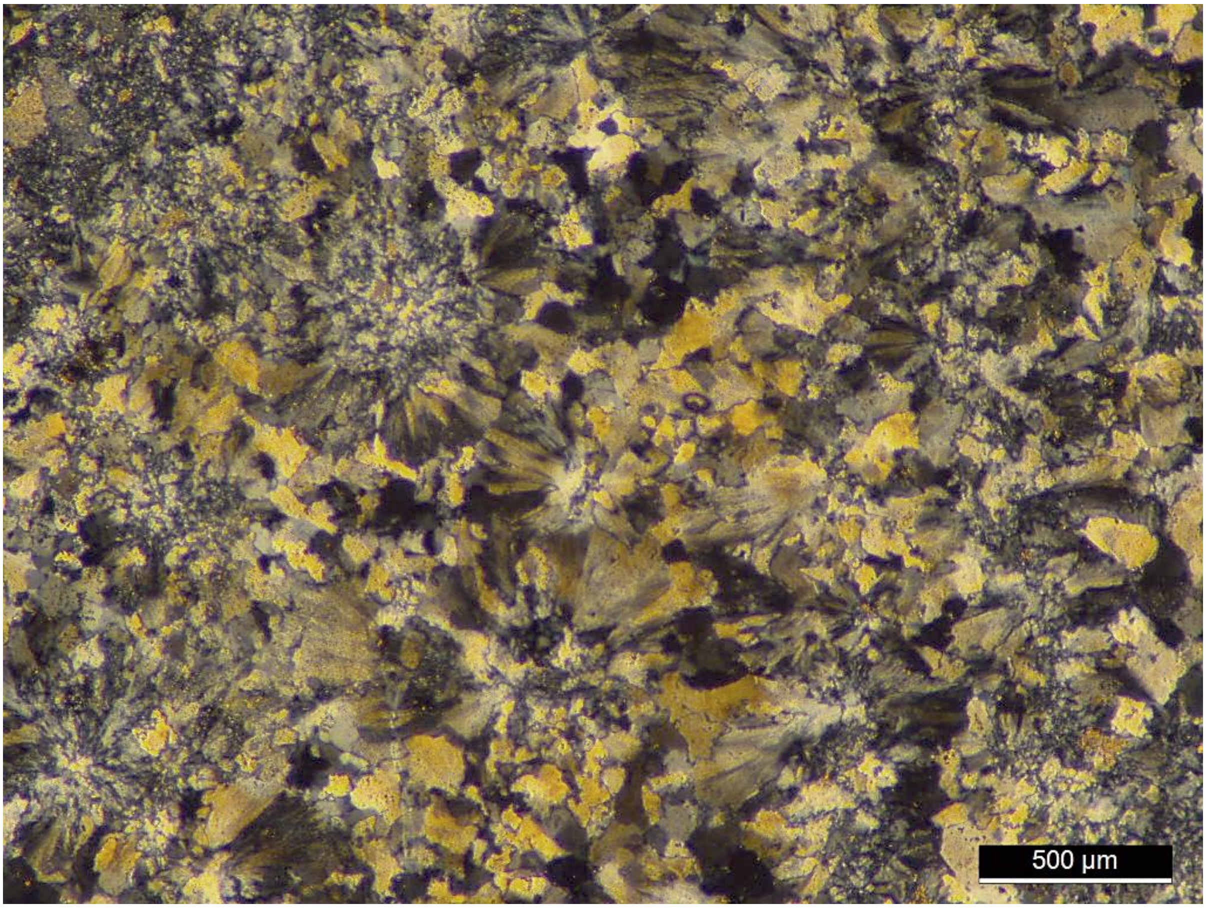


Figure 3.1-6. Close up view of thinly **flow-banded rhyolitic lava** in the Lynn Volcanic Complex (site 10345). Bands have a **felsitic texture** that is a patchwork of radiating crystals and micropoikilitic radiating splotches. **Tabular plagioclase crystals** are rare except in cumulophyric clusters. View with crossed polarizers.

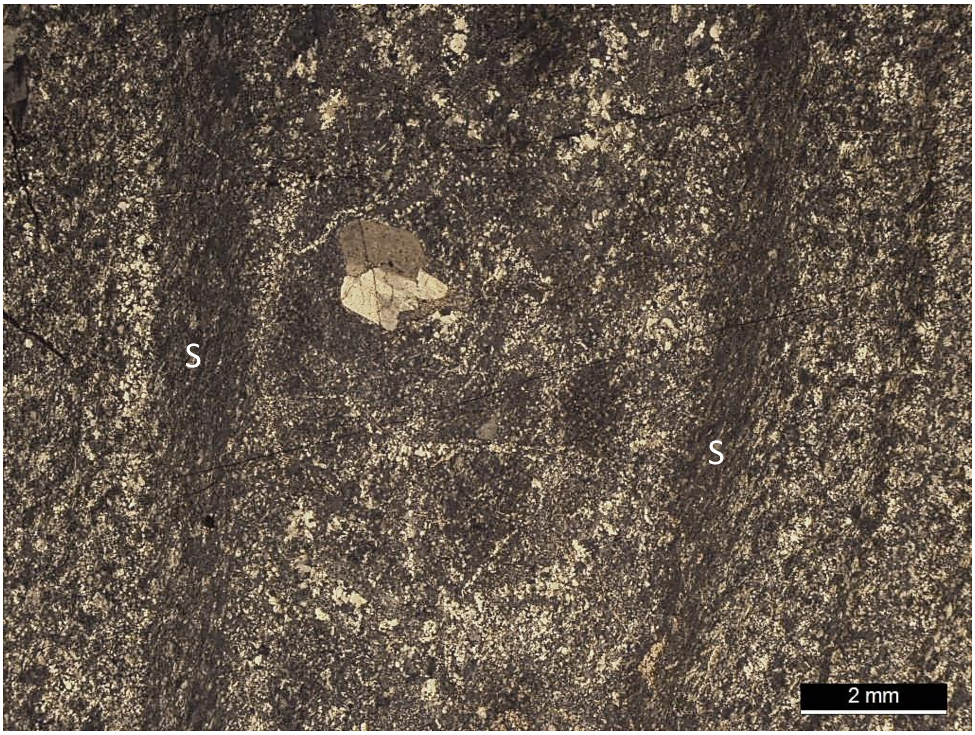


Figure 3.1-7. **Flow-banded rhyolitic lava** in the Straw Point Volcanic Complex at the north end of Middle Reservoir (site 11139). View of fold axis (top to bottom). Bands with a fine **patchy texture** are interlayered with bands that have a **stretched patchy texture (S)**. The interior of the fold has a **splotchy texture** and **cumulophyric plagioclase**. Either the fabric developed in molten glass, stretching of the original obsidian influenced later crystal growth during devitrification, or deformation was occurring during micro-crystal growth. View with crossed polarizers.

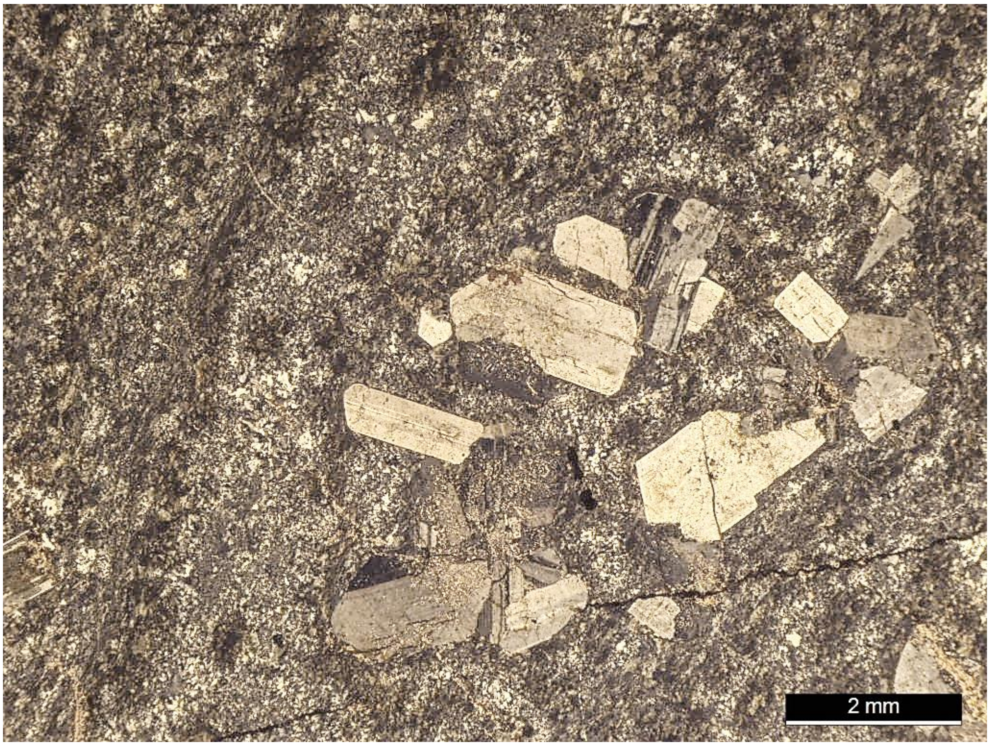


Figure 3.1-8. **Flow-banded rhyolitic lava** in the Straw Point Volcanic Complex at the north end of Middle Reservoir (site 11139). C**umulophyric plagioclase** in a **splotchy felsitic texture**. In upper left are bands with a lightly **stretched patchy texture** and **patchy texture**. View with crossed polarizers.

3.2 Textures and Features of Lava Flows

3.2.1 Highly Flow-Banded Lava Flows

Early crystallization or devitrification in banded flows creates a **felsitic texture** of radiating crystals with **undulatory extinction** (Figs. 3.1-1 to 6) and fibrous **spherulitic growths** (Fig. 3.1-1) in a very clean, impurity-free patchwork of well-defined non-poikilitic crystals. Different bands are defined as layers with different grain sizes. Unlike the microspherulitic textures described for pyroclastic rocks above, **spherulitic growths** in lava flows have not been found as complete spheres but instead arcs that define only partial spheres of radiating crystals in cross section (Figs. 3.1-1 and 3.1-6, see Figs. 2.7-18 to 25 above for comparison in tuffs).

3.2.2 Fine Felsitic-Textured Lava Flows

Not all lava flows have conspicuous banding either in hand specimens or in microscopic views. In some cases, rapid solidification led to the formation of obsidian before crystallization could occur. Devitrification of the obsidian then created a **fine felsitic texture** that obscures the original banding that the rock may have had except in a few isolated places (Figs. 3.2-1 to 4). In the case of lava flows at the north end of Spot Pond in the Straw Point Volcanic Complex, formation of a **felsitic texture** may have been aided by heating during contact metamorphism adjacent to a large plutonic body (Stoneham Granodiorite).

Figure 3.2-1. Outcrop with faintly **flow-banded rhyolitic lava** in the Straw Point Volcanic Complex (site 10605). **Banding** (arrows) has been mostly wiped out by devitrification and later contact metamorphism that produced a **felsitic texture**. This rock contains **euhedral cumulophyric plagioclase clusters**. Weathered outcrop surface.

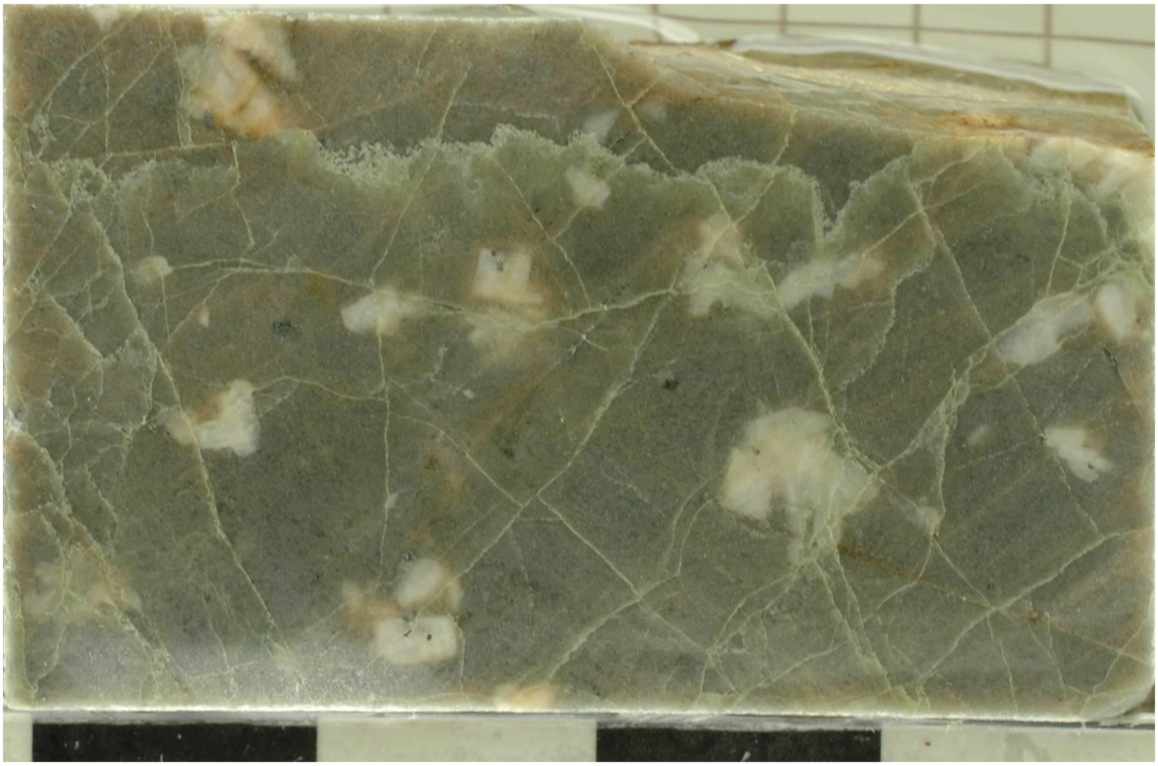


Figure 3.2-2. R**hyolitic lava** in the Straw Point Volcanic Complex (site 10591) with highly **euhedral cumulophyric plagioclase clusters** surrounded by a **very fine felsitic matrix** that obscures banding. Cut rock chip.

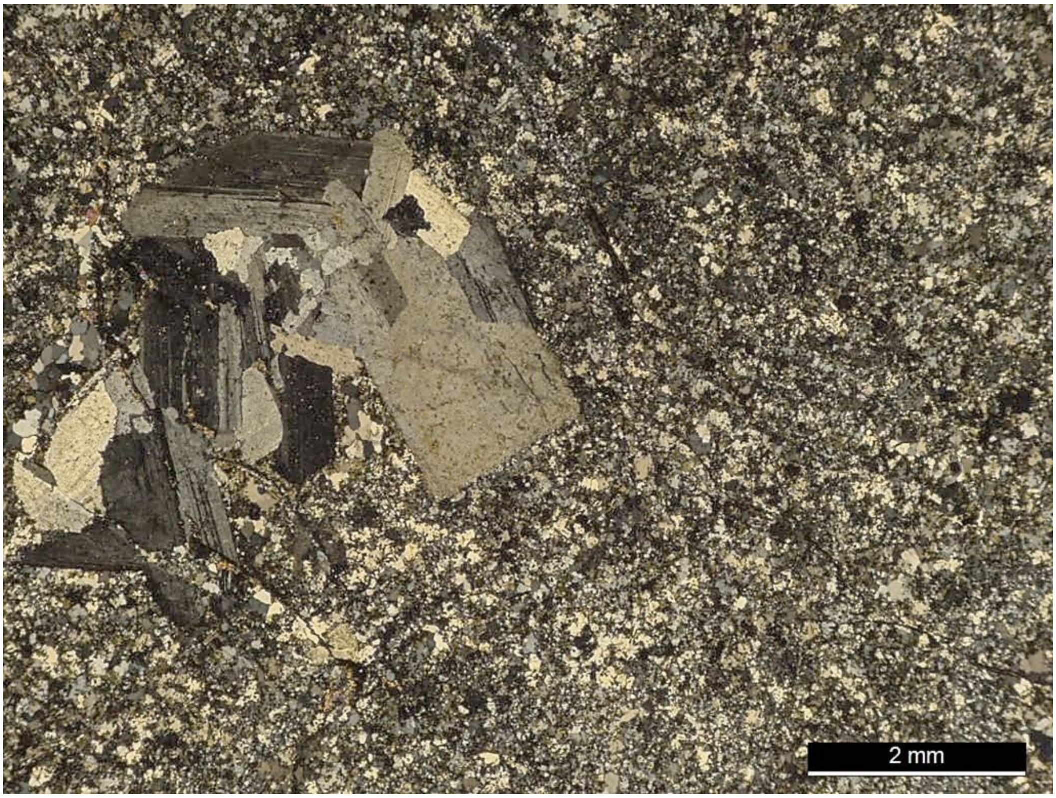


Figure 3.2-3. **Rhyolitic lava** in the Straw Point Volcanic Complex (site 10591) with a **euhedral cumulophyric plagioclase cluster** surrounded by a **fine felsitic patchy** to **micropoikilitic** matrix. View with crossed polarizers.

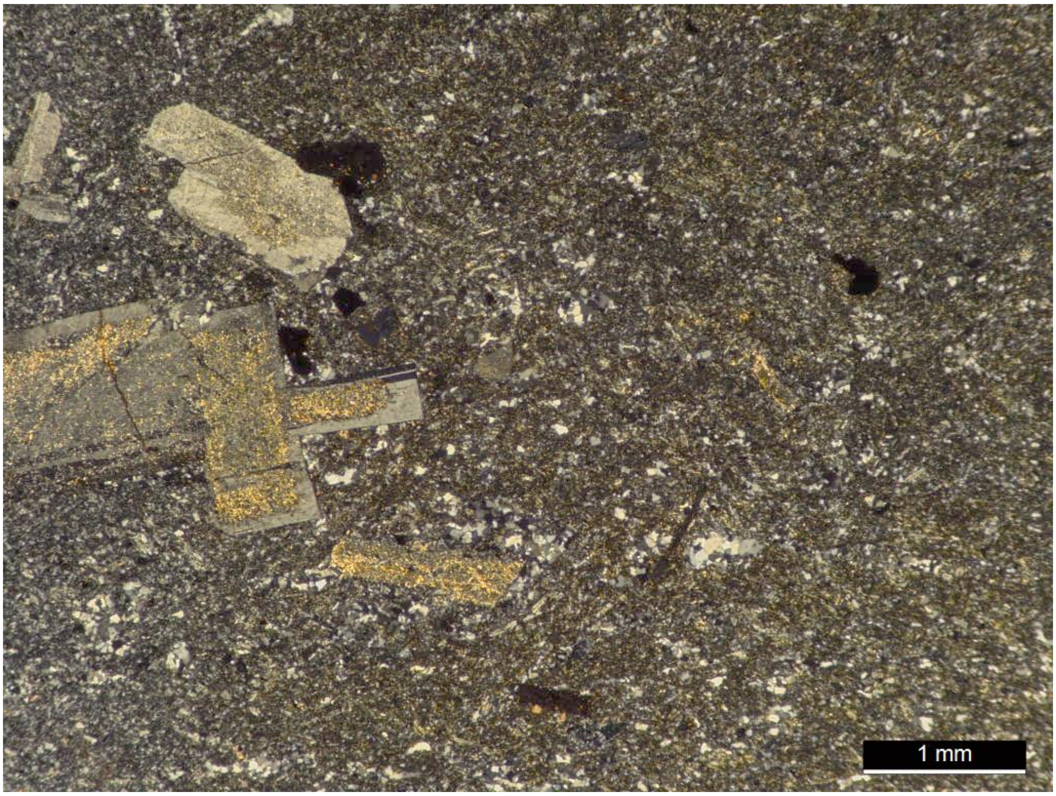


Figure 3.2-4. **Rhyolitic lava** in the Straw Point Volcanic Complex (site 10604) with highly **euhedral plagioclase** surrounded by a **fine felsitic matrix**. View with crossed polarizers.

3.2.3 Micropoikilitic Lava Flows

In rhyolitic lava flows intense devitrification and recrystallization can lead to a **micropoikilitic (“snowflake”) texture** with quartz surrounding much smaller plagioclase and alkali feldspar crystals (Figs. 3.2-5 to 10). The **quartz oikocrysts** are visible in outcrop as small spherical structures, giving weathered surfaces a spotted appearance that at first glance mimics ooids in limestone or spherulites. This texture is prevalent at the northern end of Spot Pond in the Straw Point Volcanic Complex where reheating during contact metamorphism and emplacement of the adjacent Stoneham Granodiorite may have helped recrystallization to a **micropoikilitic texture**.

Figure 3.2-5. **Micropoikilitic rhyolitic lava** in the Straw Point Volcanic Complex (site 10421). Banding has been wiped out by devitrification and later contact metamorphism. The **micropoikilitic texture** gives the rock a spotted appearance. Weathered outcrop surface. Pencil for scale.

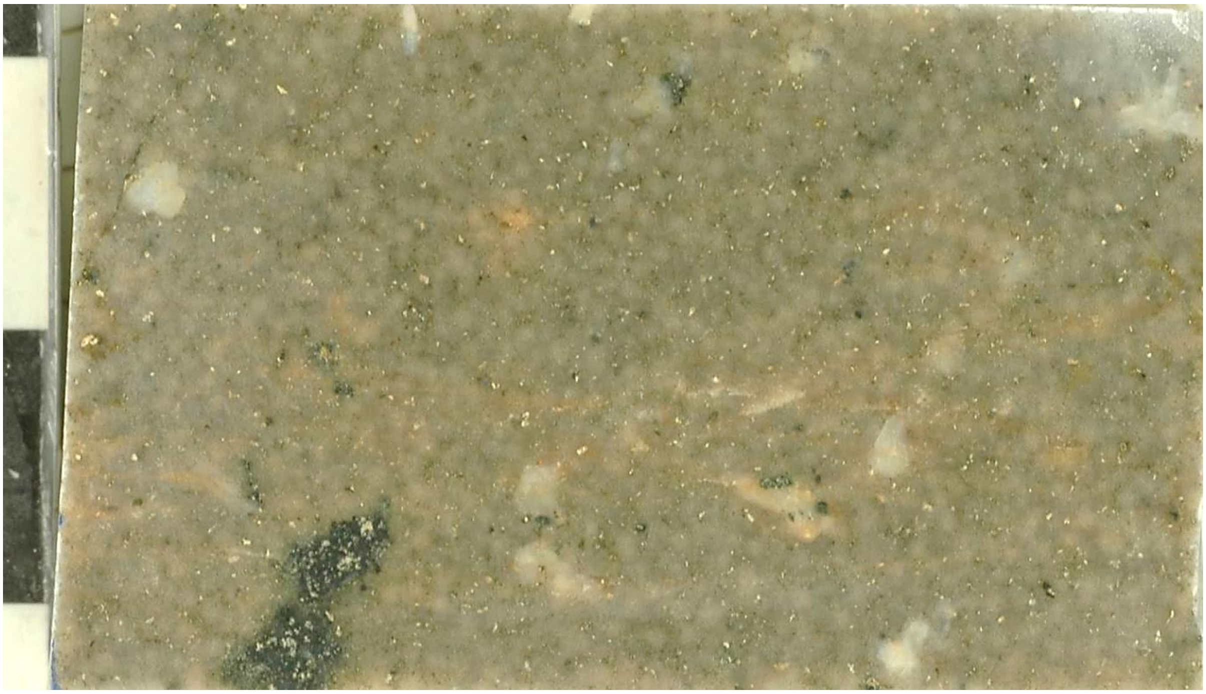


Figure 3.2-6. **Micropoikilitic rhyolitic lava** in the Straw Point Volcanic Complex (site 10425). Banding has been wiped out by devitrification and later contact metamorphism. The **micropoikilitic texture** gives the rock a spotted appearance. View of cut rock chip.

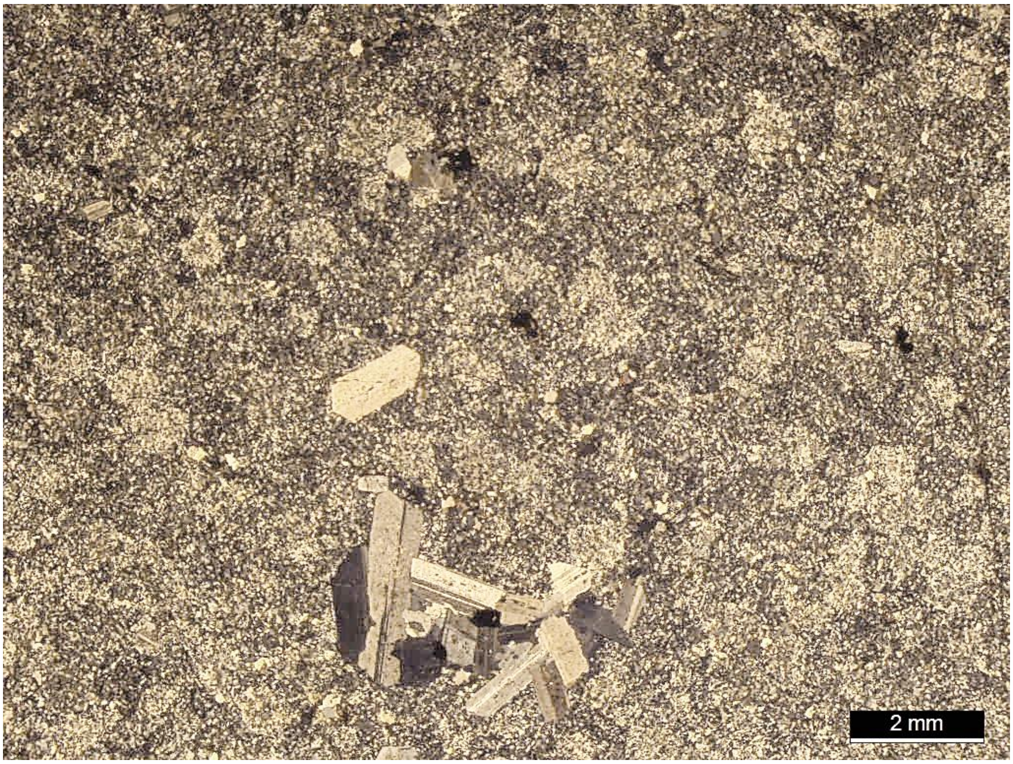


Figure 3.2-7. **Micropoikilitic rhyolitic lava** in the Straw Point Volcanic Complex (site 11244). Banding has been wiped out by devitrification and later contact metamorphism. The **micropoikilitic texture** gives the rock a spotted or “snowflake” texture. Near base is **cumulophyric plagioclase**. View with crossed polarizers.

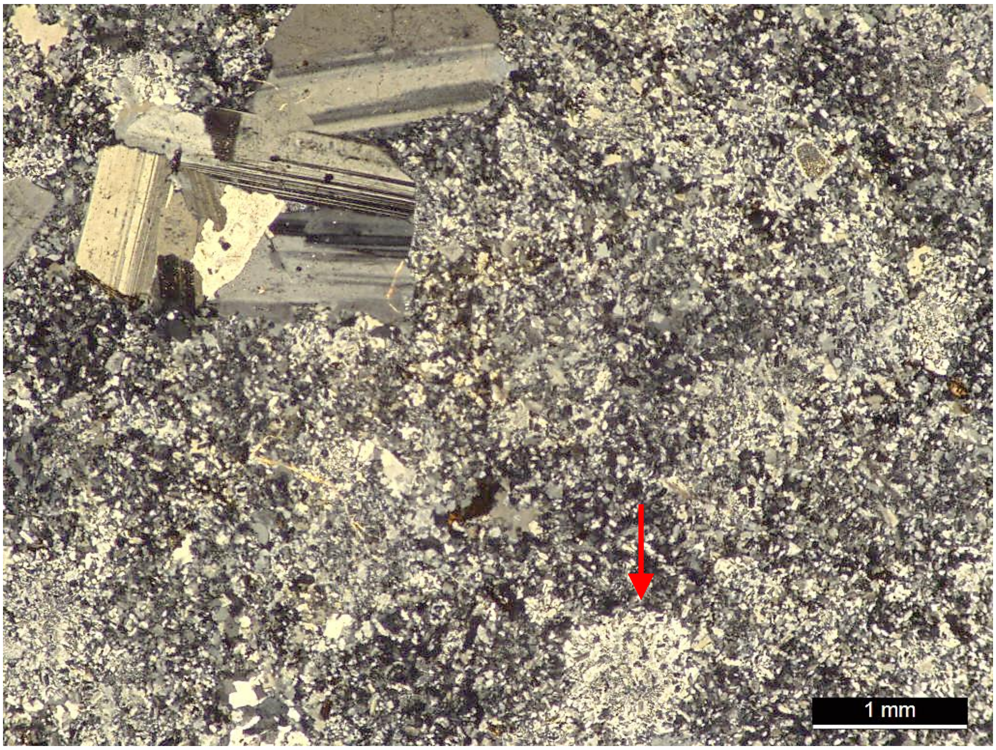


Figure 3.2-8. **Micropoikilitic rhyolitic lava** in the Straw Point Volcanic Complex (site 10425). Banding has been wiped out by devitrification and later contact metamorphism. The **micropoikilitic texture** gives the rock a spotted or “snowflake” texture. Note the prominent white oikocryst of quartz at the bottom center of the image (arrow). In upper left is **cumulophyric plagioclase** showing no alteration. View with crossed polarizers.

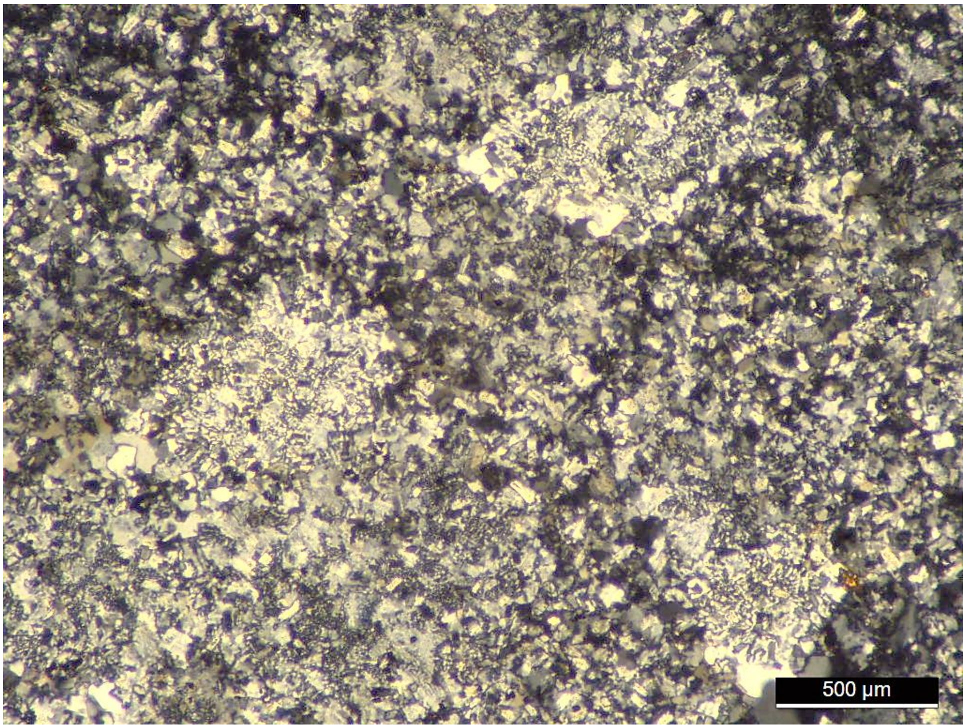


Figure 3.2-9. Close up view of **micropoikilitic rhyolitic lava** in the Straw Point Volcanic Complex (site 10421). Banding has been wiped out by devitrification and later contact metamorphism. The **micropoikilitic texture** gives the rock a spotted or “snowflake” texture. Inside each “snowflake” are tiny myrmikitic growths. View with crossed polarizers.

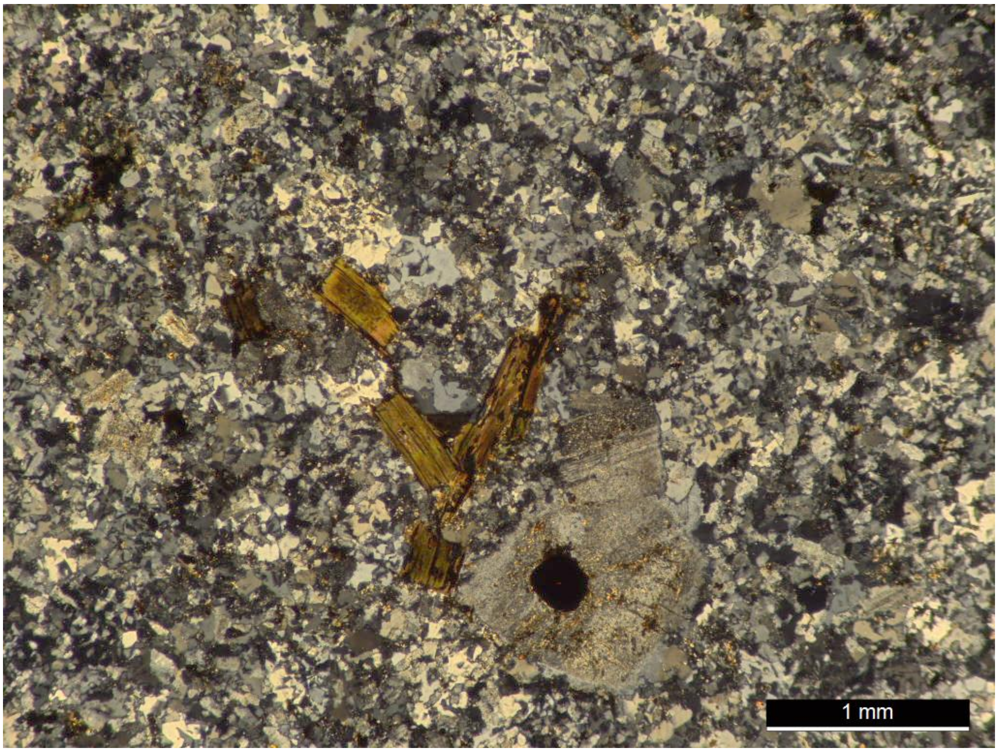


Figure 3.2-10. **Micropoikilitic rhyolitic lava** in the Straw Point Volcanic Complex (site 10442). Banding has been wiped out by devitrification and later contact metamorphism. The **micropoikilitic texture** gives the rock a spotted or “snowflake” texture. Also seen here are **biotite phenocrysts**. View with crossed polarizers.

3.2.4 Auto-brecciated Lava Flows

Lava flow surfaces may also be **auto-brecciated**. Auto-brecciation occurs when a lava surface hardens and then crack into pieces that the get surrounded by liquid. Auto-brecciated fragments have a texture like the enclosing banded lava with subtle grain size differences (Fig. 3.2.10; compare to cut rock view in Fig. 3-5).

3.2.5 Perlitic Textures

The outer surfaces of lava flows may have a relict **perlitic texture** that is associated with intricate folding of fine flow banding (Fig. 3.2.11; compare to cut rock view in Fig. 3-6).

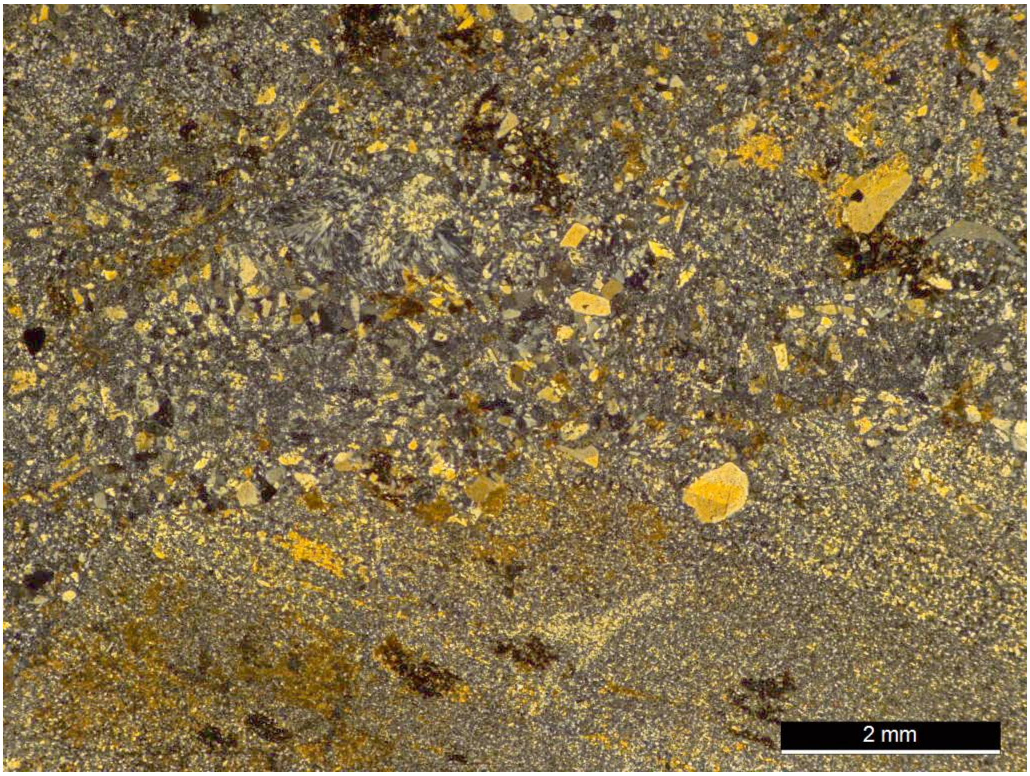


Figure 3.2-10. **Auto-brecciated rhyolitic lava** in the Lynn Volcanic Complex (site 10366). The bottom half of the view is a fine-grained flow-banded lava fragment , while above is coarser enclosing lava. View with crossed polarizers. Compare with cut rock view in Fig. 3-5.

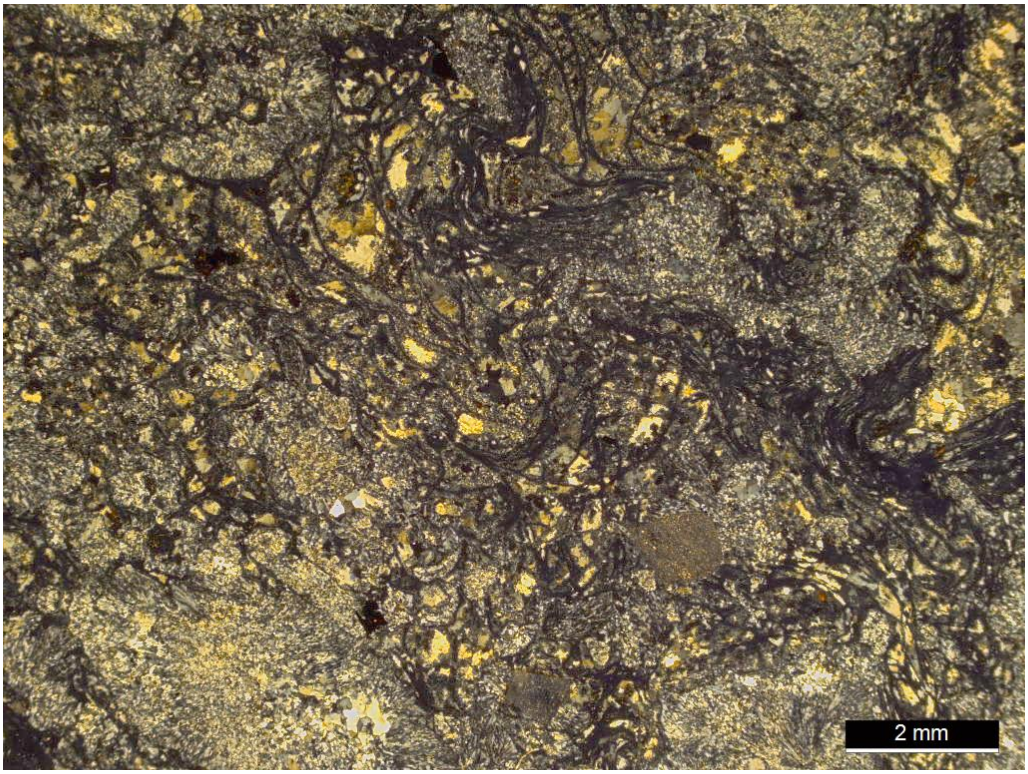


Figure 3.2-11. Surface of **rhyolitic lava** that has a **perlitic texture** in the Lynn Volcanic Complex (site 10398). Curving thin black lines are relict perlitic cracks. View with crossed polarizers. Compare with cut rock view in Fig. 3-6.

4. VOLCANICLASTIC ROCKS

Volcaniclastic rocks are formed by the **remobilization** of volcanic materials by surface erosion processes and later re-deposition by runoff, stream flow, mass movement or glacial activity, which can alter particle shapes. These deposits can have a mixture of clasts from volcanic and other geologic units of different ages or origins. Remobilization may occur very shortly after the original volcanic units were formed. These rocks may be dominated by volcanic particles and can be difficult to distinguish from pyroclastic deposits. Rounding of particles is general better developed in volcaniclastic rocks. There can be extensive mixing of pyroclastic and volcaniclastic units within modern volcanic environments and this is expected in the rocks of the Middlesex Fells.

This publication conservatively interprets rocks as being volcaniclastic only if: 1) particles appear to have shapes modified by surface processes, and 2) the particles include non-volcanic materials from older rock units not associated with the current eruptions (**epiclasts)**. Some of these clasts are from rock formations outside the Middlesex Fells. The operating definition used here is a conservative distinction that does not catch all remobilized volcanic materials. For example, deposits that result from the reworking of just volcanic materials by surface processes are technically volcaniclastic, but they are not included in the definition here unless they have an **epiclast** component.

Volcaniclastic particles are on average more rounded than is typical in pyroclastic units in which crystals have almost exclusively euhedral and broken euhedral shapes and lithic fragments are angular. An additional characteristic of volcaniclastic rocks is that the rounded particles can be well sorted and can be touching each other forming a **clast-supported structure**, which is not as common in tuffs. In tuffs, crystals are usually dominated by one mineral type, are euhedral and broken euhedral, and are not rounded. In tuffs particles are usually separated from each other by finer matrix material in a **matrix-supported structure** although mass movement and glacial activity can also create volcaniclastic deposits that are matrix-supported. Figures 4-1 to 12 show outcrop, hand specimen, and cut rock examples of volcaniclastic conglomerates and breccias.

Figure 4-1. **Polymictic, round pebble, clast-supported volcaniclastic conglomerate** with sandy matrix in the Lynn Volcanic Complex at Boojum Rock (site 365BN). The red sandstone clast (center) is unlike any rock formation in the Fells. This unit resembles parts of the Roxbury Formation or conglomerates associated with the Mattapan Volcanics (Thompson and others, 2014) to the south in Boston. Weathered outcrop surface.

Figure 4-2. **Polymictic, round pebble, clast-supported volcaniclastic conglomerate** with a sandy matrix in the Lynn Volcanic Complex at Boojum Rock (site 365BN). Sample is cut across bedding (upper right to lower left). In this sample is a mixture of volcanic (dark red), quartzite (light to medium gray and greenish-gray) and granitic (pink) clasts. Cut rock sample.

Figure 4-3. **Polymictic, round pebble, clast-supported volcaniclastic conglomerate** with a sandy matrix in the Lynn Volcanic Complex at Boojum Rock (site 365BN). In this sample is a mixture of volcanic (dark red), quartzite (light to medium gray and greenish-gray) and granitic (pink) clasts, including a porphyritic or crystal tuff pebble (arrow). Cut rock chip.

Figure 4-4. **Polymictic, round pebble, clast-supported volcaniclastic conglomerate** with a sandy matrix in the Lynn Volcanic Complex at Boojum Rock (site 364BN). In this sample is a mixture of quartzite (light to medium gray and greenish-gray) and granitic (white and pink) clasts and small volcanic (red) grains. In the lower right is a laminated shale and sandstone pebble with graded beds that is not from any of the rock formations in the Fells. This rock contains alkali feldspar grains as well. Weathered rock surface.

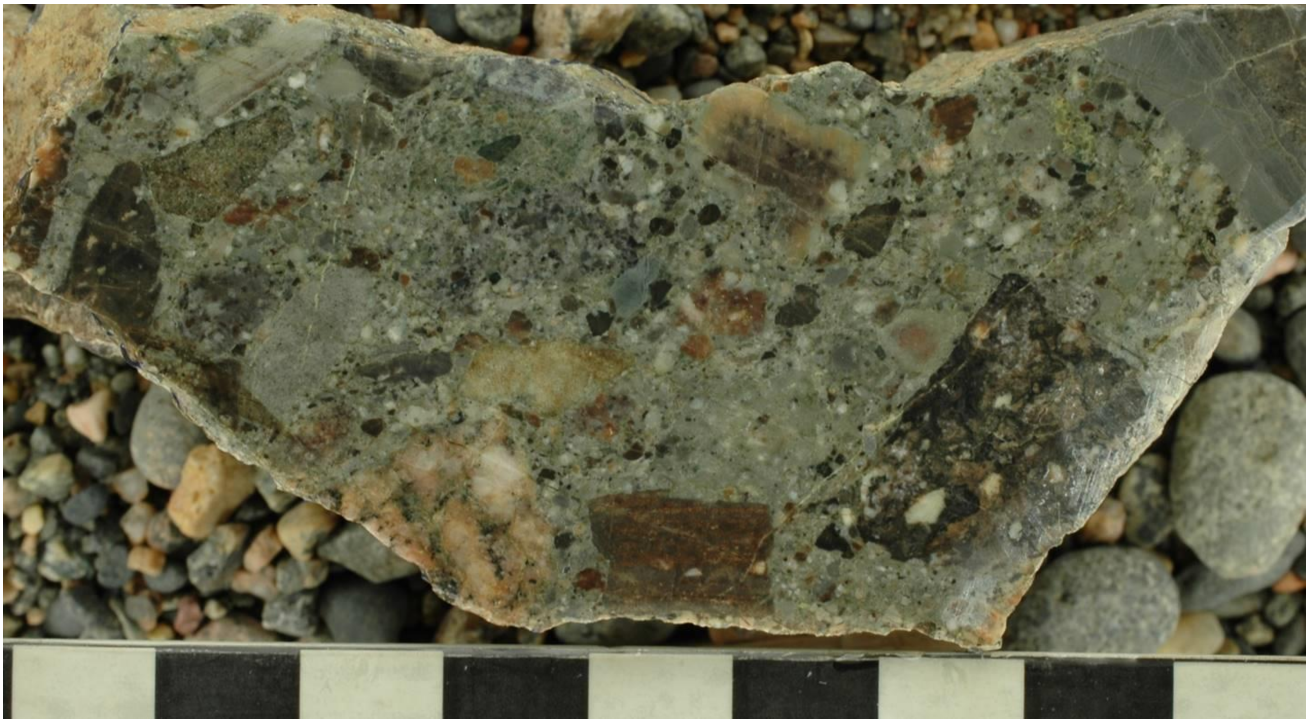


Figure 4-5. **Polymictic volcaniclastic conglomerate** with a sandy matrix in the Lynn Volcanic Complex at Boojum Rock (site 364BN). In this sample is a mixture of volcanic (dark red to almost black), quartzite (light to medium gray, see especially upper right corner) and granitic (lower left center) clasts that are not as rounded as in the examples above (Figs. 4-1 to 4). This rock is also not as well sorted. Cut rock sample.

Figure 4-6. **Polymictic, round pebble volcaniclastic conglomerate** with a sandy matrix in the Lynn Volcanic Complex (site 10687). In this sample is a mixture of quartzite (light to medium gray and greenish-gray), granodiorite (white and rarely pink), and quartz (clear gray) clasts with greenish-gray, finer volcanic material in the matrix and a sandy matrix-supported texture. Cut rock sample.

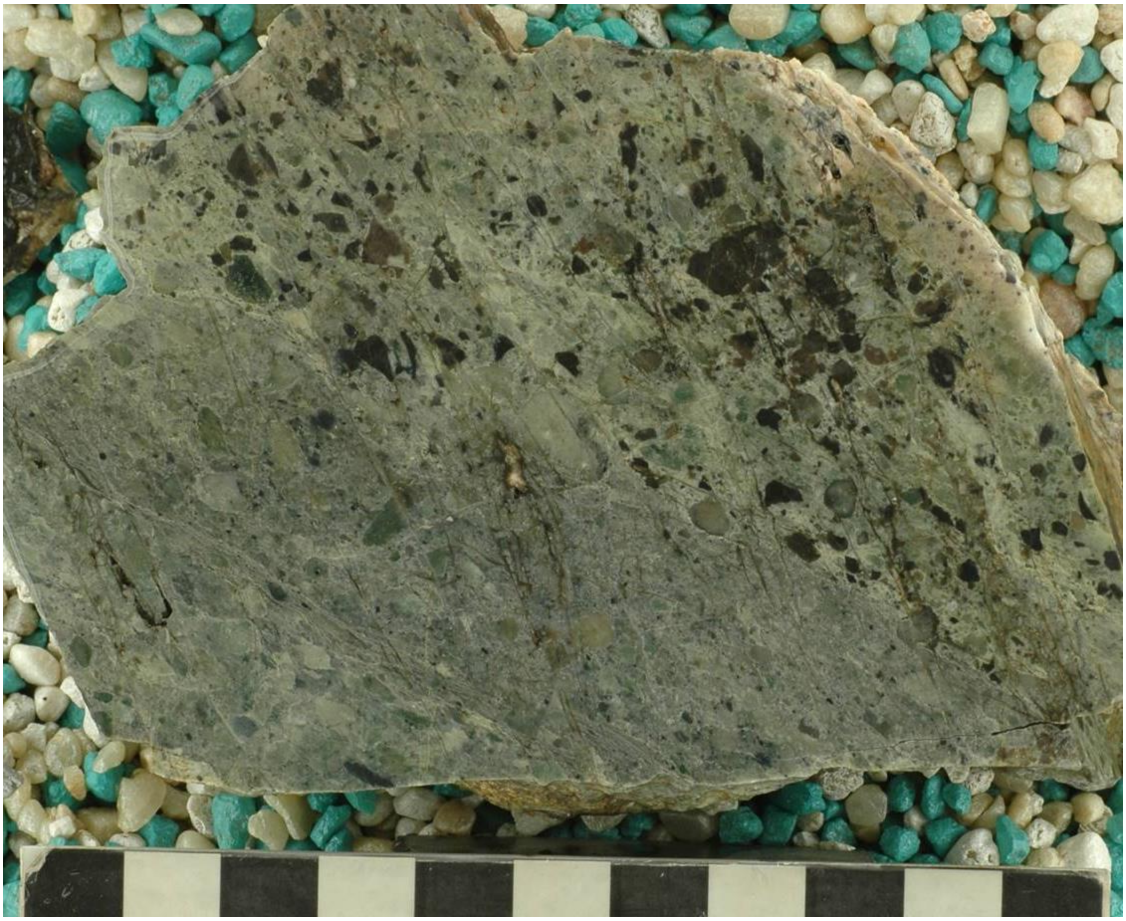


Figure 4-7. **Polymictic, round pebble, clast-supported volcaniclastic conglomerate** with a sandy matrix (bottom) in contact with a more angular **volcaniclastic breccia/conglomerate** composed of mostly dark volcanic clasts (above) in the Lynn Volcanic Complex at Boojum Rock (site 10553). This sample shows the variation of interbedded materials in volcaniclastic rocks. Cut rock sample.

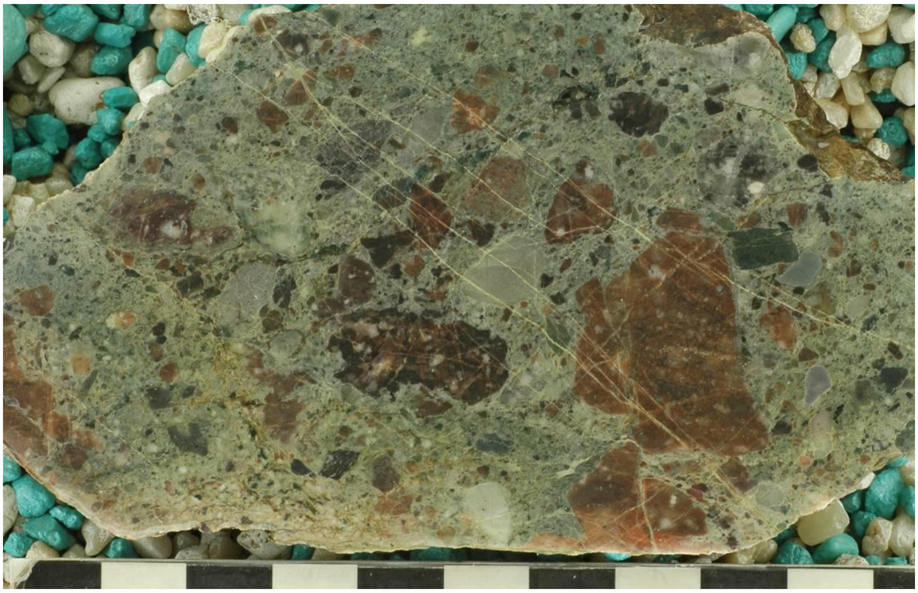


Figure 4-8. **Polymictic volcaniclastic conglomerate** in Lynn Volcanic Complex at Boojum Rock (site 10553). In this sample is a mixture of volcanic (red) and quartzite (light to medium gray) clasts that are less rounded and in a more poorly sorted greenish-gray matrix than in the examples above (Figs. 4-1 to 7). Cut rock sample.

Figure 4-9. **Polymictic and arkosic, clast-supported volcaniclastic conglomerate** in the Lynn Volcanic Complex on Pine Hill (site 10841). This sample has an unusual concentration of granule-size rounded plagioclase grains (white). Weathered rock surface.

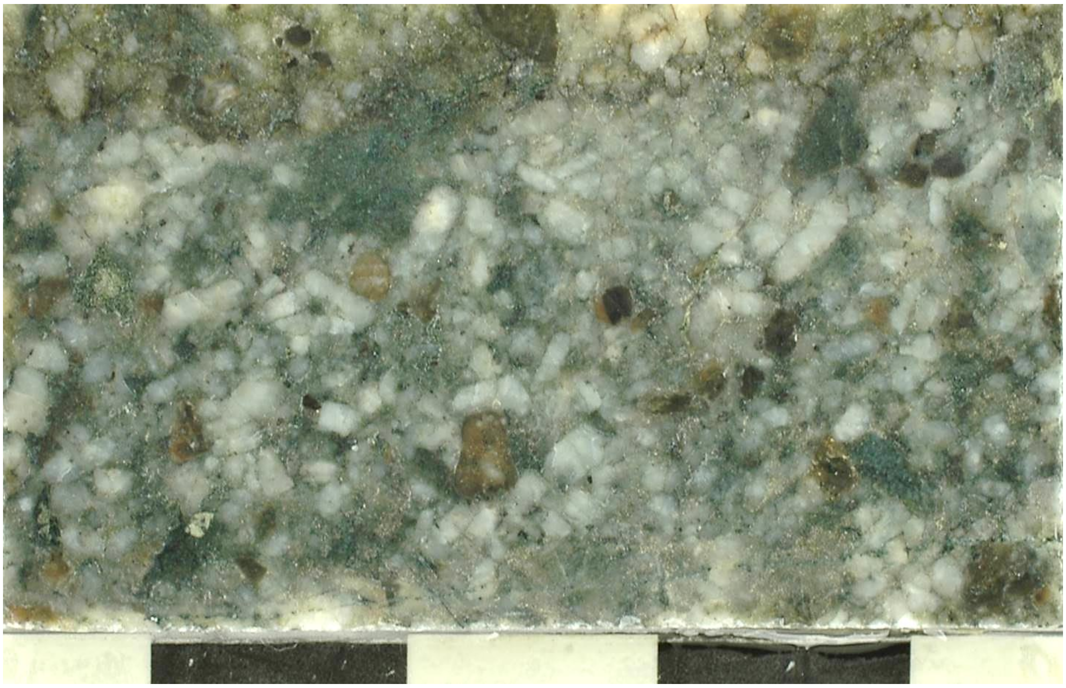


Figure 4-10. **Polymictic and arkosic, clast-supported, round pebble volcaniclastic conglomerate** in the Lynn Volcanic Complex on Pine Hill (site 10841). This sample has an unusual concentration of granule-size, rounded plagioclase grains (white). Cut rock chip.

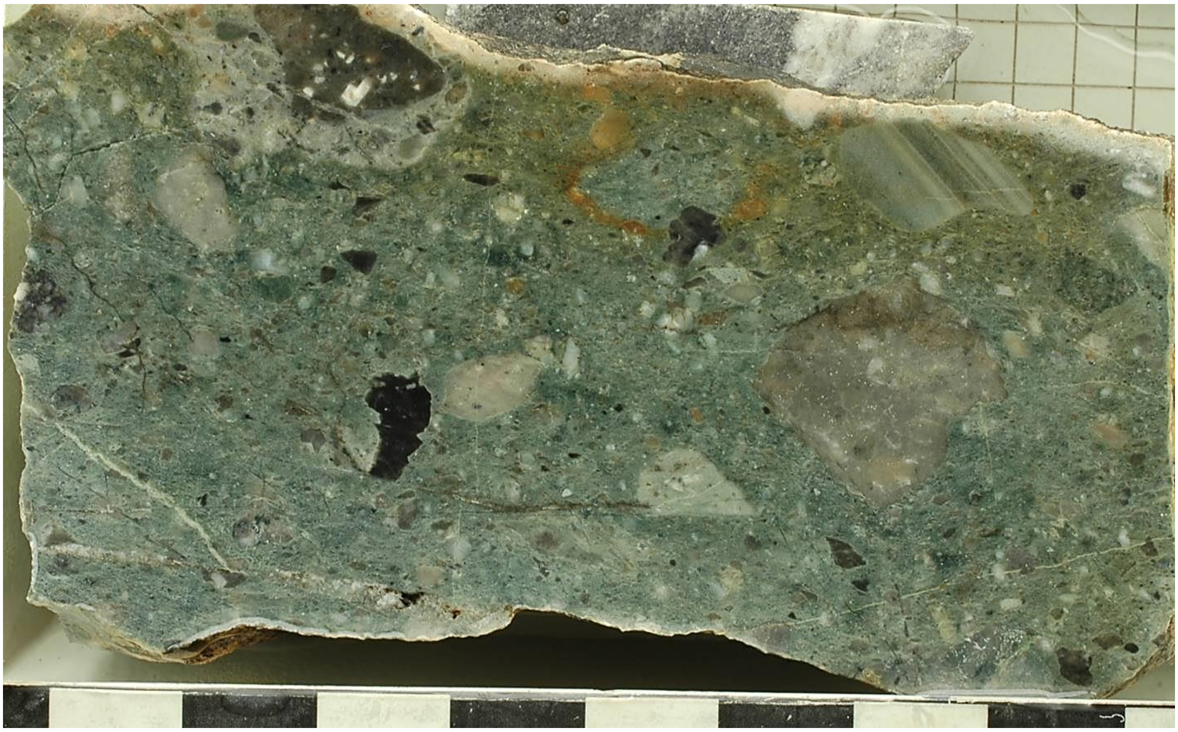


Figure 4-11. **Polymictic, poorly sorted, volcaniclastic conglomerate (diamictite**) in the Lynn Volcanic Complex (site 10626). The grayish-green matrix seen here is common in poorly sorted volcaniclastic rocks of the base of the Lynn Volcanic Complex in the Pine Hill area. Note the rounded laminated quartzite pebble in the upper right. Cut rock sample. I wish I had a coffee table made of this rock.

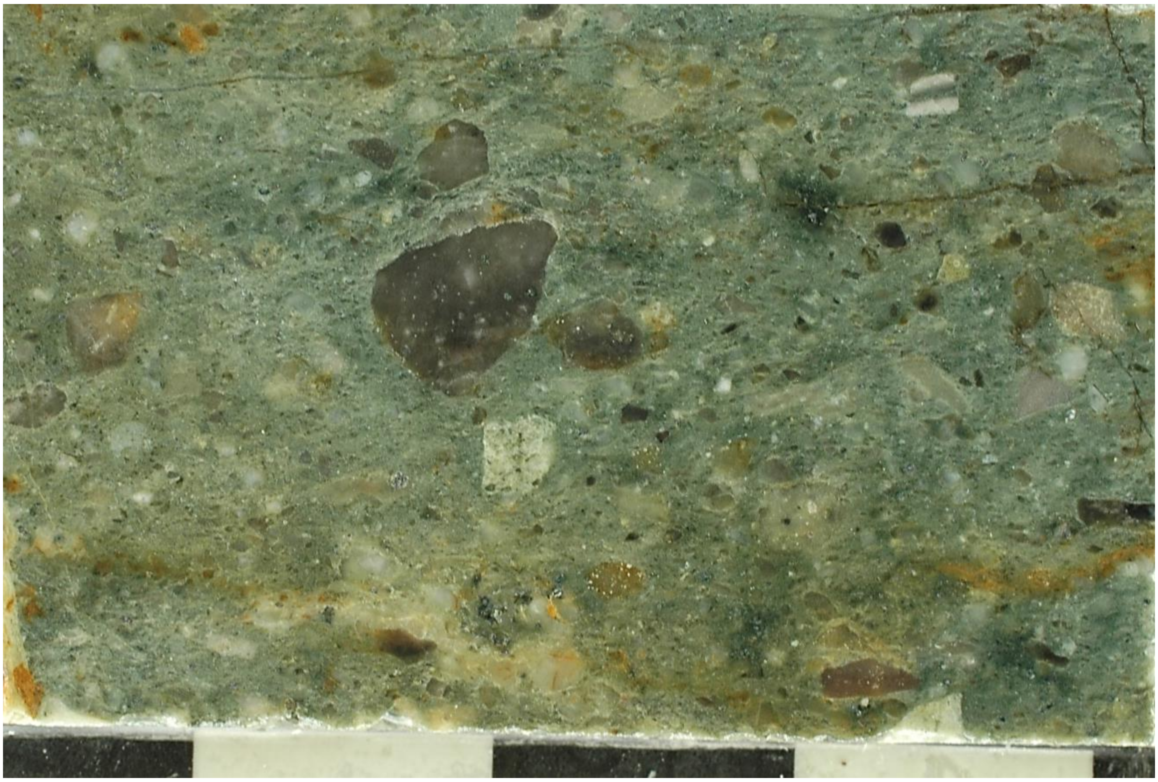


Figure 4-12. **Polymictic, poorly sorted, volcaniclastic conglomerate (diamictite**) in the Lynn Volcanic Complex (site 10626). Dark gray and reddish-gray clasts are volcanic. The grayish-green matrix seen here is common in poorly sorted volcaniclastic rocks of the base of the Lynn Volcanic Complex in the Pine Hill area. Cut rock chip.

In addition to the rounding of particles, volcaniclastic rocks can have matrices that have much better sorting than pyroclastic rocks and are often classified as sandstones and sandy conglomerates. Sand-sized grains tend to be much better sorted than in pyroclastic rocks where crystals tend to have a variety of sizes and fewer mineral types (Figs. 4-13 to 20).

Epiclasts included in the volcaniclastic rocks of the Middlesex Fells are of several major types:

1) Clasts of coarse–grained igneous rock, especially granodiorite and granite, as well as single mineral grains such as quartz, plagioclase, and perthitic alkali feldspar derived from these rocks. Volcaniclastic rocks deposited on the eroded surface of granite or granodiorite have abundant epiclasts of these types. Granophyre clasts occur at only one place in the Lynn Volcanic Complex and are rare.

2) Clasts of quartzite and sandstone that appear to be derived from both the local Westboro Formation but also rock formations not exposed in the Middlesex Fells.

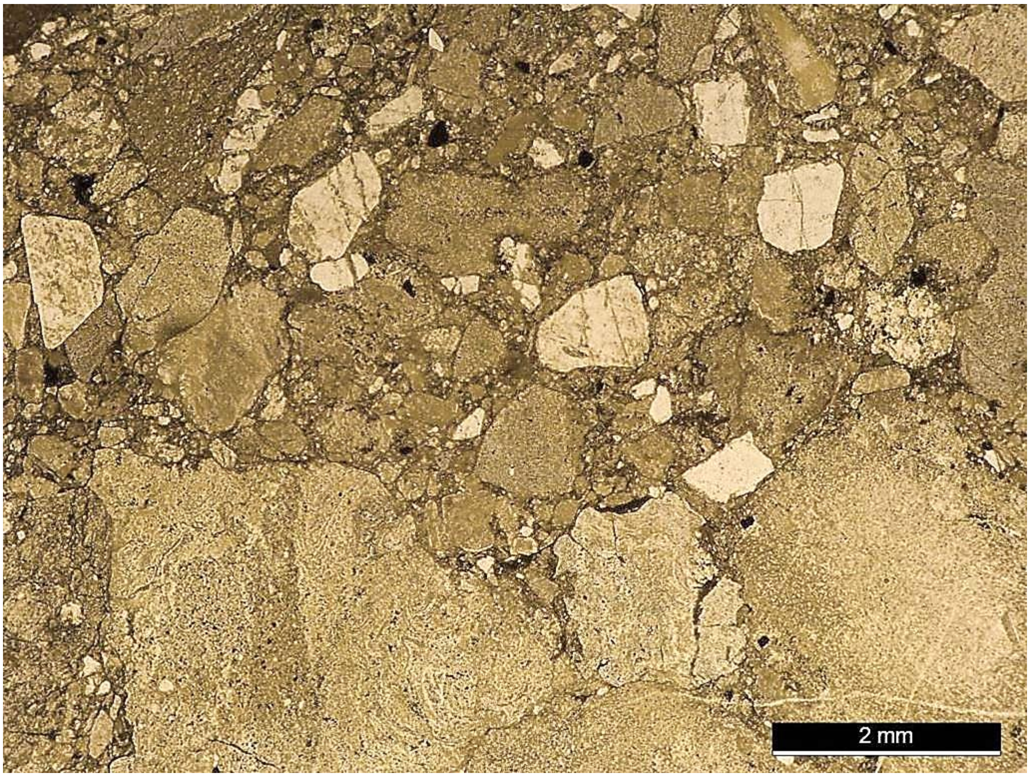


Figure 4-13. **Polymictic, clast-supported volcaniclastic conglomerate** in the Lynn Volcanic Complex at Boojum Rock (site 364BN). Note partial rounding of many particles. View in plane polarized light.

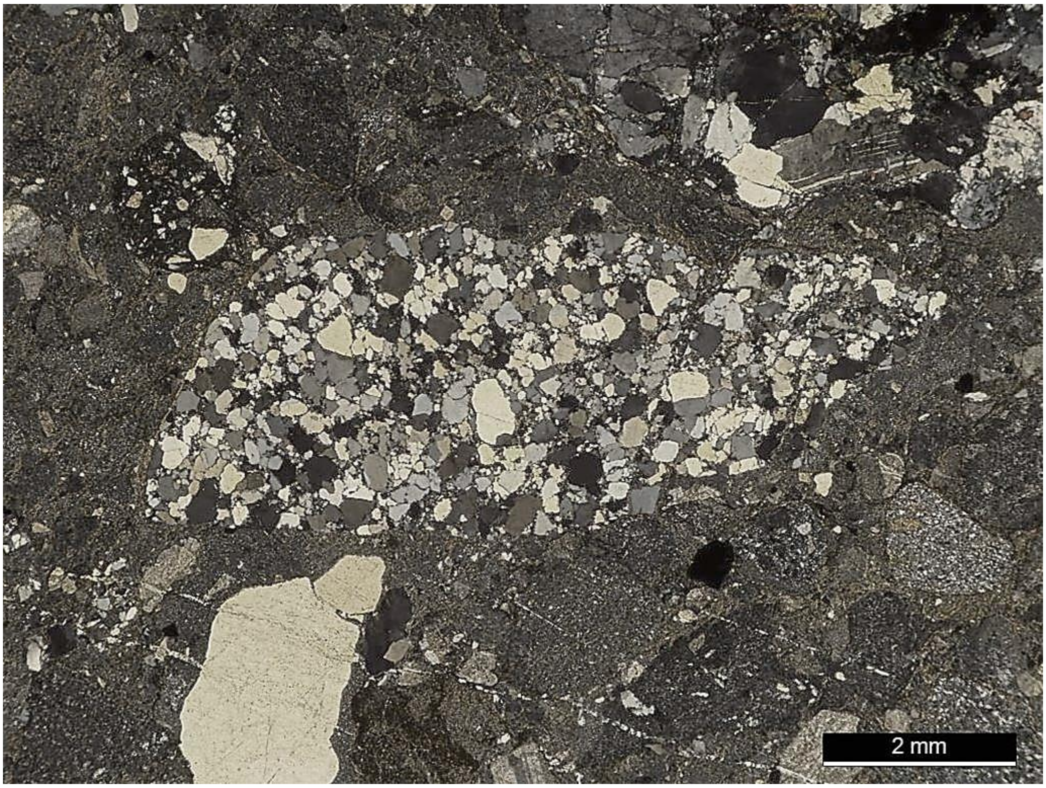


Figure 4-14. **Polymictic**, **clast-supported volcaniclastic conglomerate** in the Lynn Volcanic Complex at Boojum Rock (site 364BN). Large clast in the center is quartzite with sutured grains. In upper right is granodiorite and in lower left is a partly rounded quartz grain likely derived from granodiorite. Note rounding of clasts. View with crossed polarizers.

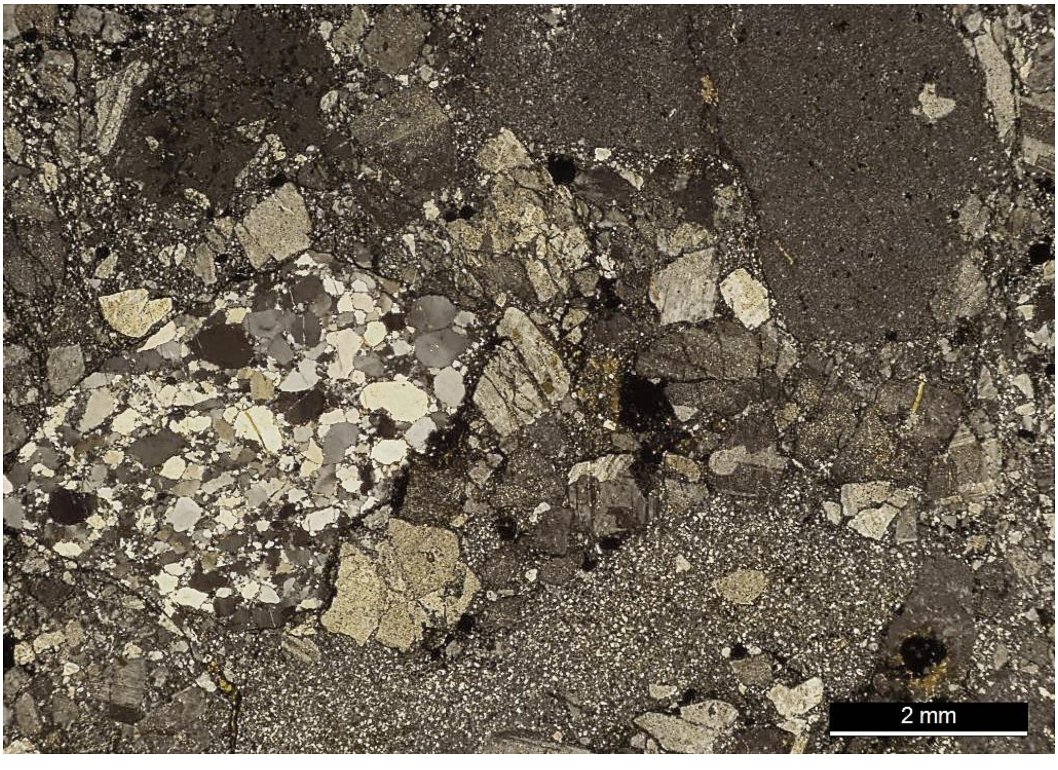


Figure 4-15. **Polymictic**, **clast-supported volcaniclastic conglomerate** in the Lynn Volcanic Complex (site 10514). On the left is a quartzite clast with sutured grains. The speckled area near the bottom is very fine sandy matrix material. View with crossed polarizers.

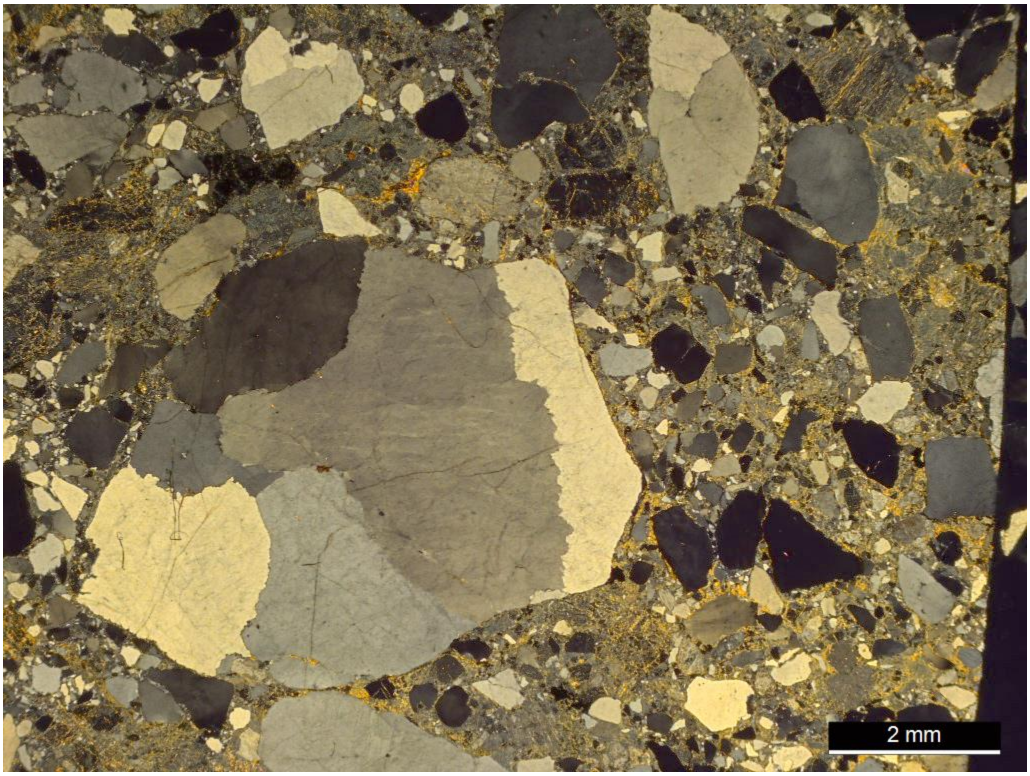


Figure 4-16. Very quartz-rich **clast-supported volcaniclastic conglomerate** in the Lynn Volcanic Complex (site 10602). Large clast in the center is composed of multiple quartz grains from granodiorite. Many grains are rounded. View with crossed polarizers.

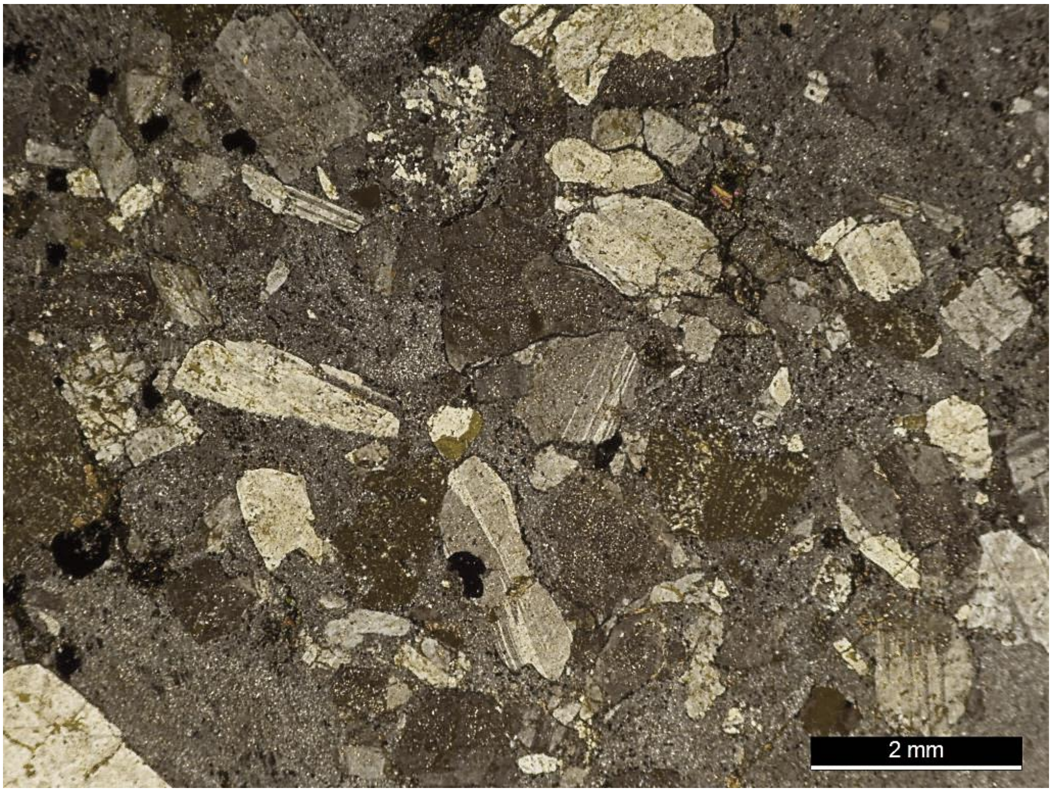


Figure 4-17. Very plagioclase-rich **clast-supported volcaniclastic conglomerate** in the Lynn Volcanic Complex (site 10841). Compare with Figures 4-9 to 10 of the same rock. View with crossed polarizers.

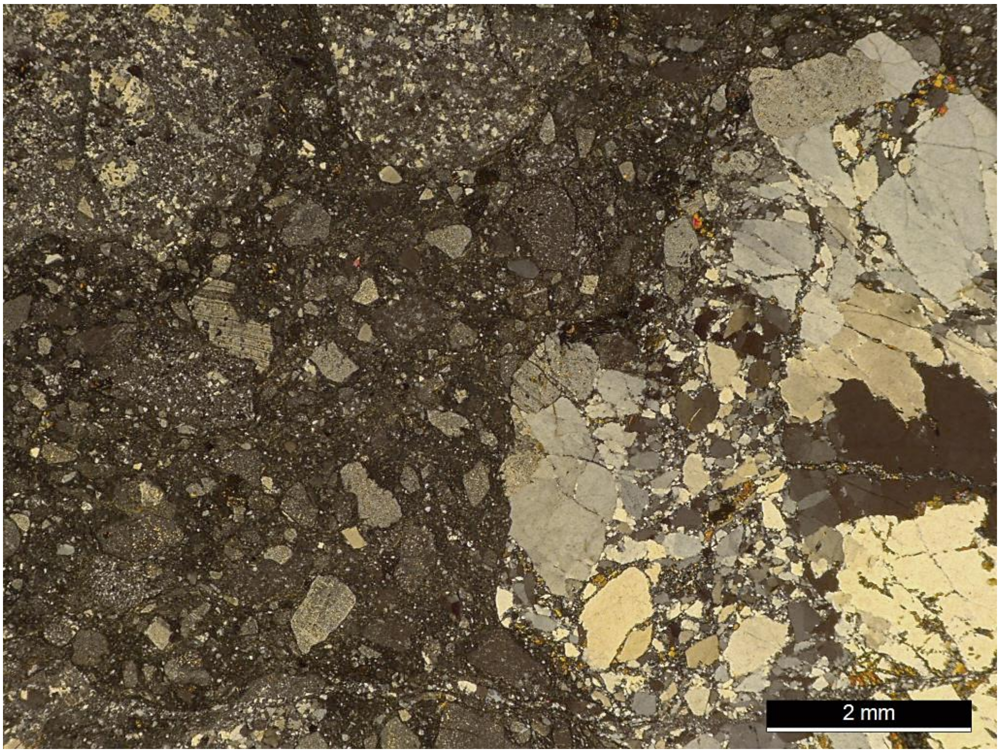


Figure 4-18. **Polymictic**, **matrix-supported, poorly sorted volcaniclastic conglomerate (diamictite**) in the Lynn Volcanic Complex (site 10626). On the right is a brecciated granodiorite clast. In the upper left are two large volcanic clasts with **patchy texture**. View with crossed polarizers. Compare with Figures 4-11 and 12 from the same site.

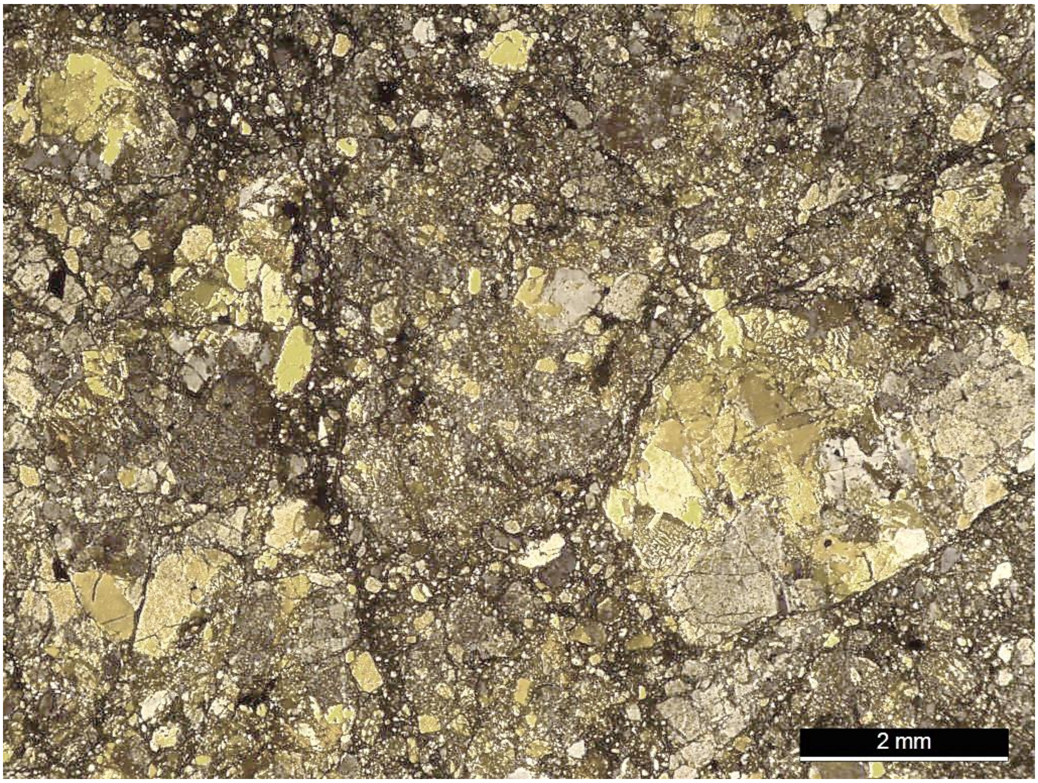


Figure 4-19. **Polymictic volcaniclastic conglomerate** in the Lynn Volcanic Complex (site 10759). This rock is in an isolated area where the rock unit has granophyre clasts. View with crossed polarizers. Yellow color is due to potassium stain.

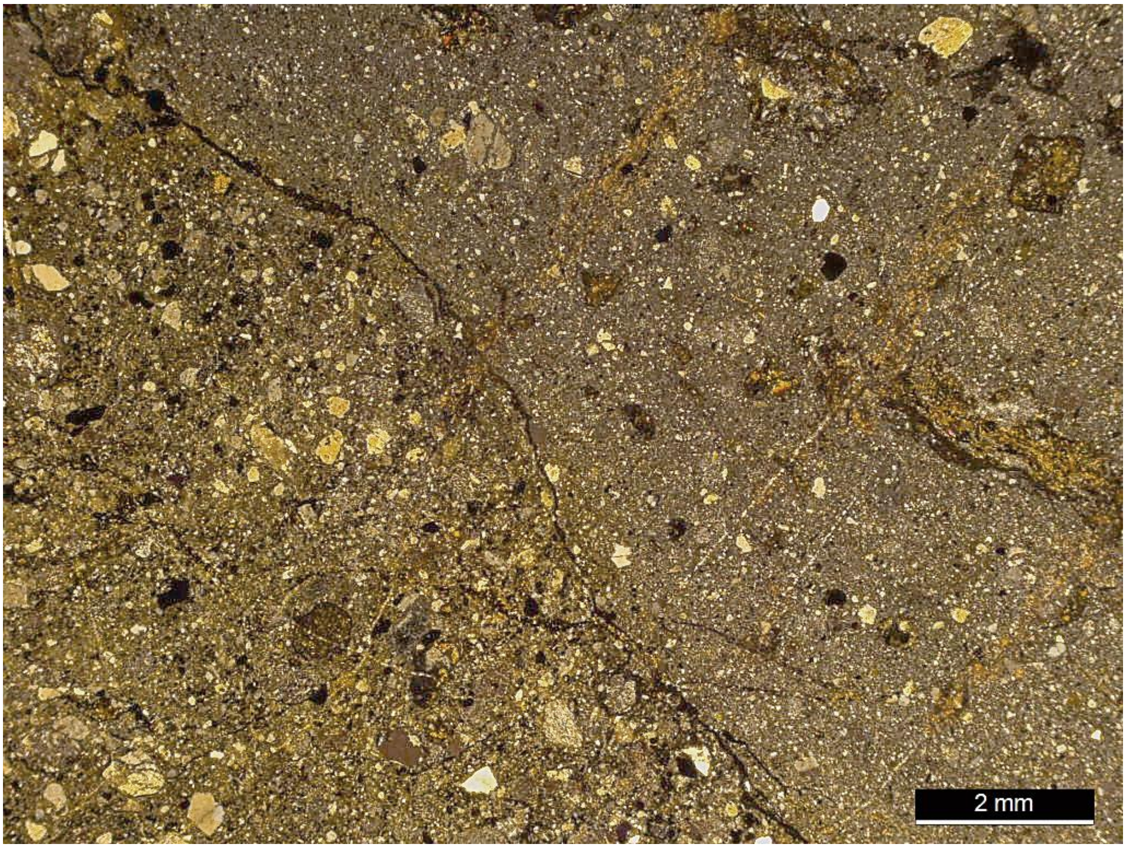


Figure 4-20. **Matrix-supported, poorly sorted volcaniclastic sandstone** in the Lynn Volcanic Complex on Pine Hill (site 10517). A bedding plane in the middle of the view separates areas of different grain size (finer in upper right). Many of the larger grains on both sides are slightly rounded. View with crossed polarizers.

5. FEEDER PIPES

Although dolerite and basalt dikes that could have fed basaltic eruptions are often abundant, preserved passageways for sialic magma escaping to the surface are relatively rare. Perhaps these near surface passageways are seldom preserved or the magma in them explosively expands and produces a pyroclastic eruption, thus evacuating the feeder pipe or blowing it apart near the surface. When sialic pipes are preserved, near surface passageways are generally porphyritic intrusions in near surface rocks, but they can simultaneously have a few textures or features like subvolcanic plutonic rocks at greater depth as well as the volcanic units that they feed at the surface.

The Lynn Volcanic Complex on Boojum Rock provides an opportunity to study what appears to be a large sialic dike or passageway from which expanding magma formed a surface eruption. This body is a porphyry with a wide lenticular shape. It has a non-banded core and along its margins flow banding and accessory volcaniclastic or pyroclastic units. It is thought to represent a passageway or wide conduit opened by an explosive eruption that was later filled by magma. The unit occurs as an intrusion in an older pyroclastic unit, the Boojum Rock Tuff, which has a very different composition (euhedral and broken hornblende and plagioclase crystals, no quartz, no resorbed crystals). The Boojum Rock passageway has a very fine-grained micropoikilitic, banded, or granophyric matrix and rounded and resorbed euhedral quartz phenocrysts. The outer margin of this unit has flow banding and oriented phenocrysts. This unit has a very similar texture to the Lawrence Woods Granophyre, although with a finer-grained matrix, and is thought to be an offshoot from this subvolcanic pluton.

5.1 Passageway – Core Porphyry

The center of a sialic passageway will ideally be an aphanitic porphyry of rhyolite or dacite that does not display conspicuous banding. Crystals in this body will be euhedral and appear to be randomly oriented. There may be areas that are not homogeneous but without well defined zones. The centers of these bodies may have moved as a plug that avoided shearing along the outside of the intrusion (Figs. 5.1-1 to 6).

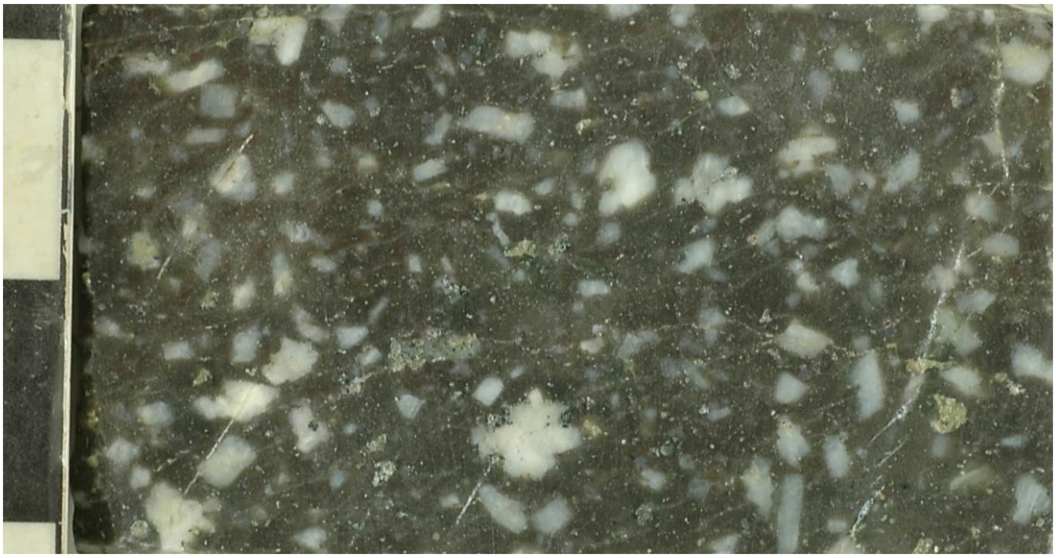


Figure 5.1-1. Dark reddish-gray porphyritic (**cumulophyric**) rhyolite dike or passageway of the Lynn Volcanic Complex at Boojum Rock (site 405BN). Note very euhedral crystals. Cut rock chip.

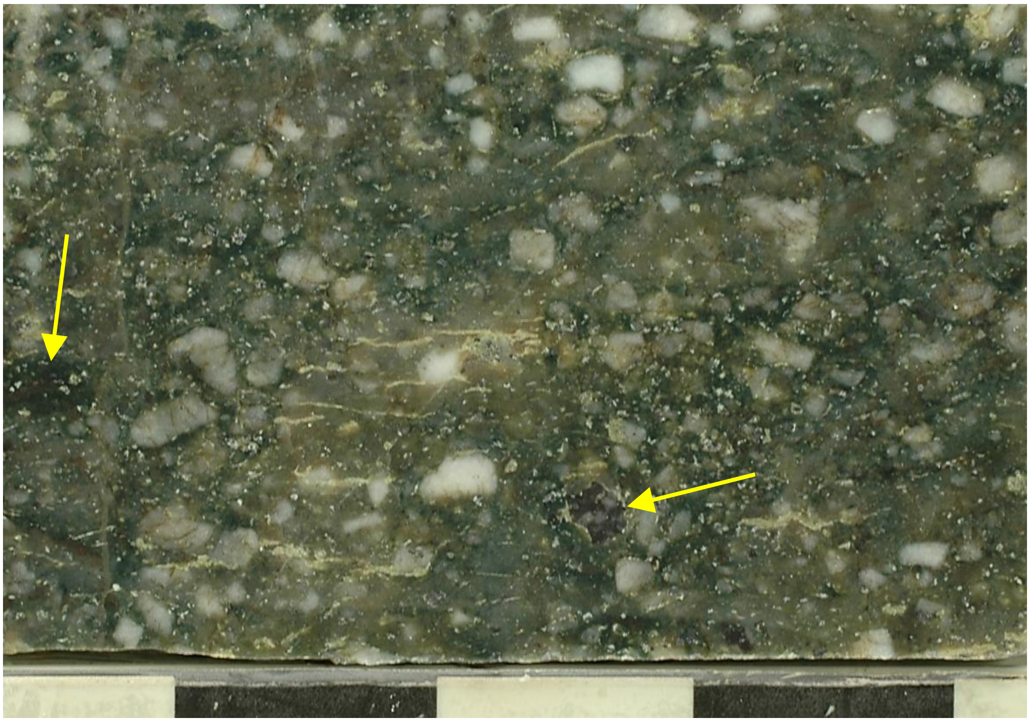


Figure 5.1-2. Dark reddish-gray porphyritic rhyolite dike or passageway of the Lynn Volcanic Complex at Boojum Rock (site 10951). Note the inhomogeneity of this rock and small volcanic xenoliths (arrows). Cut rock chip.

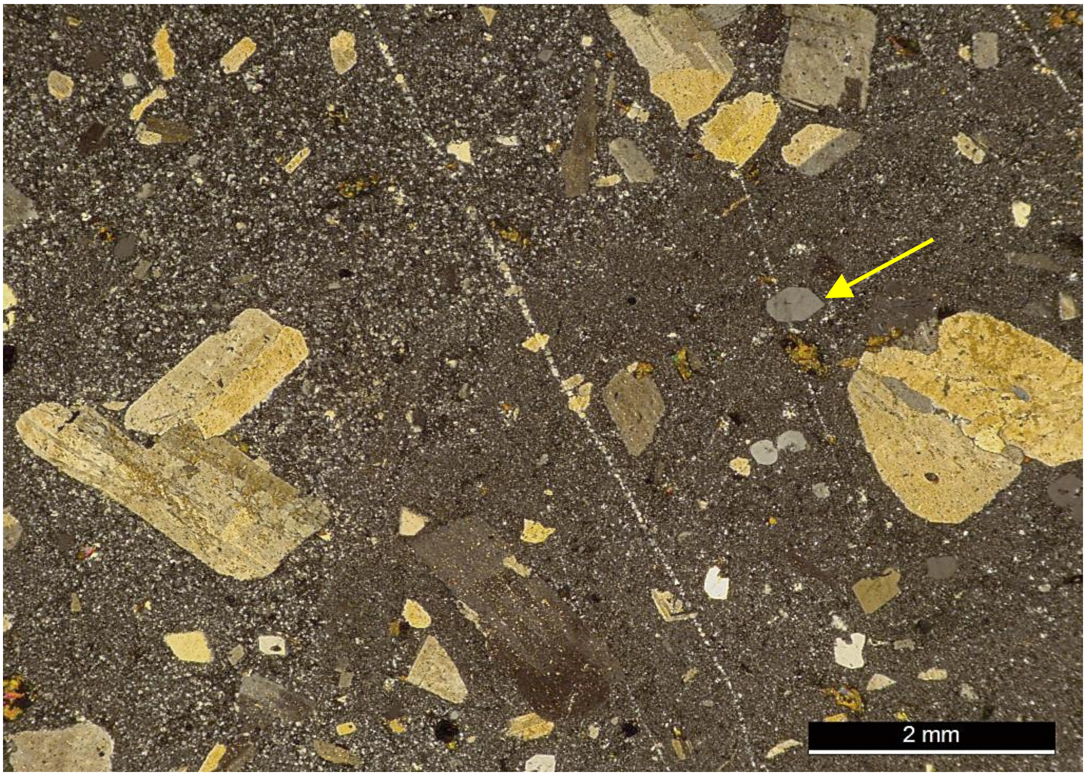


Figure 5.1-3. Porphyritic rhyolite with **cumulophyric plagioclase** in passageway associated with the Lynn Volcanic Complex at Boojum Rock (site 405BN). Note **double dipyramid quartz crystal** (arrow) and rounded and resorbed plagioclase and quartz.

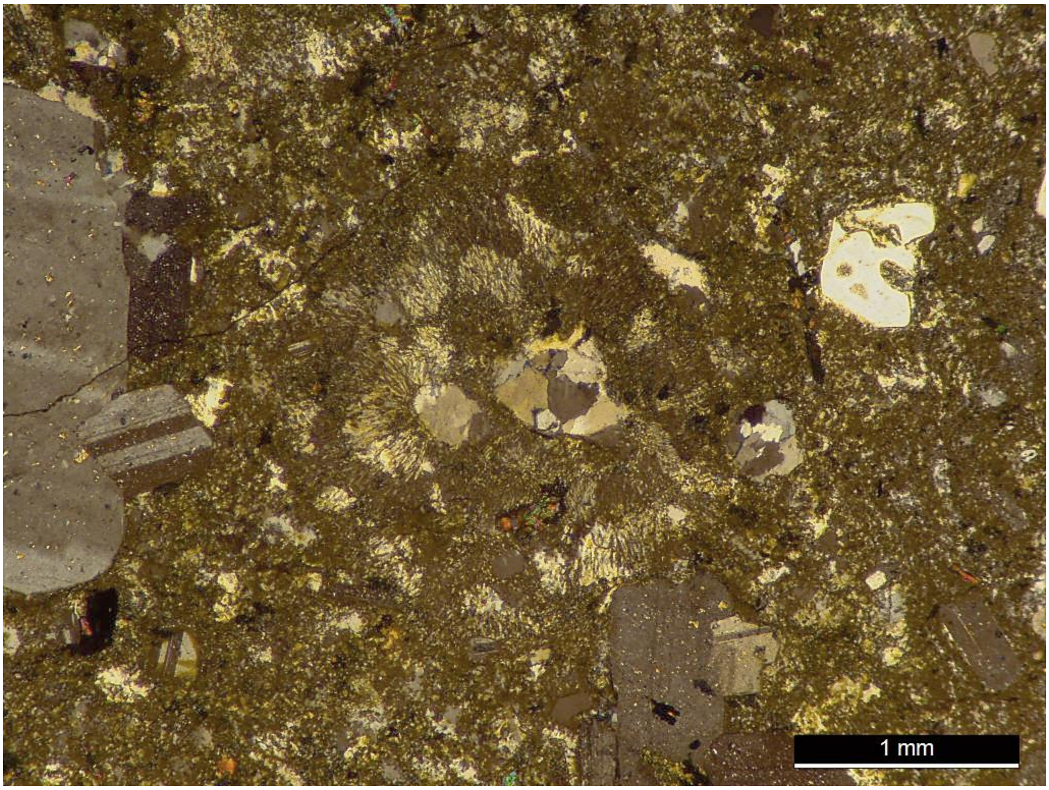


Figure 5.1-4. **Micro-granophyric (myrmikitic)** porphyritic rhyolite with **cumulophyric** plagioclase in passageway associated with the Lynn Volcanic Complex at Boojum Rock (site 10906). Note rounded and **resorbed** plagioclase and quartz crystals.

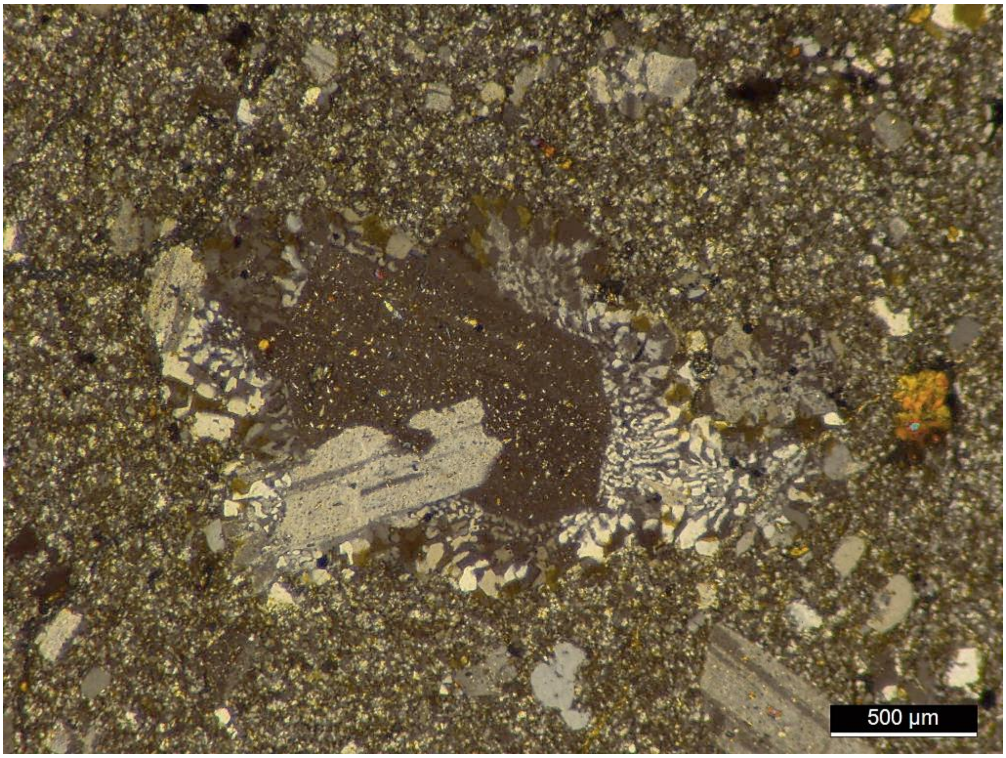


Figure 5.1-5. Porphyritic rhyolite with **myrmikitic growth** on plagioclase in passageway associated with the Lynn Volcanic Complex at Boojum Rock (site 10896). Note small **resorbed quartz** crystals (mostly gray).

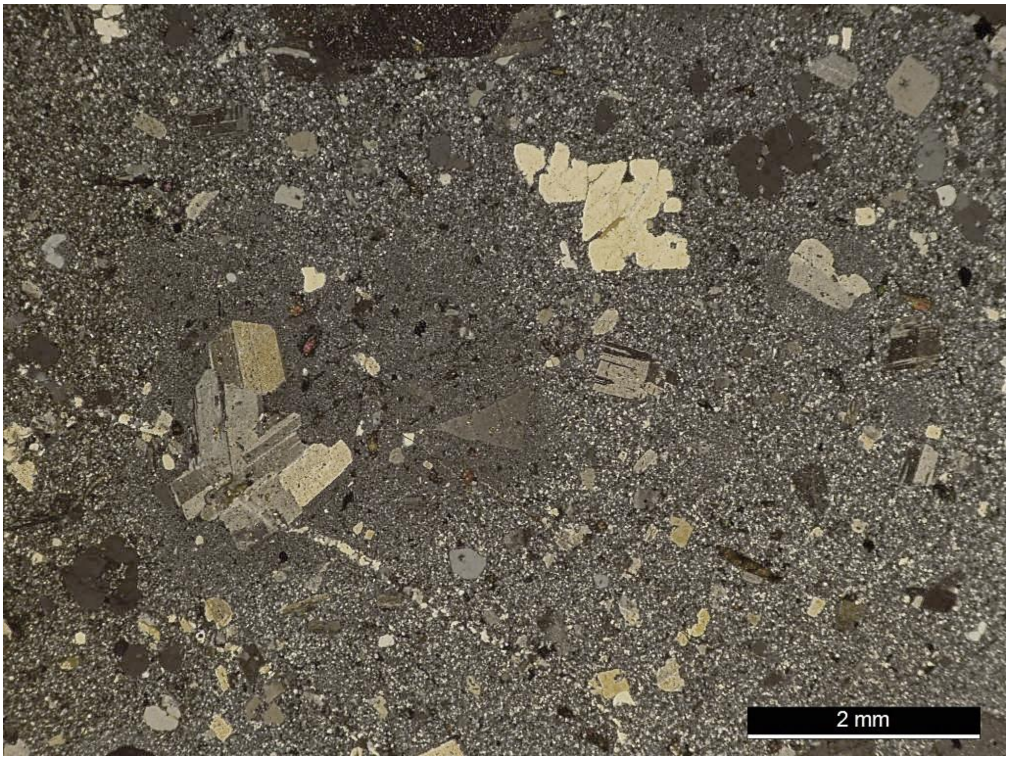


Figure 5.1-6. Porphyritic rhyolite with **cumulophyric** plagioclase in passageway associated with the Lynn Volcanic Complex at Boojum Rock (site 10896). Note fractured, rounded, and **embayed** quartz crystals in upper right.

5.2 Passageway – Flow Banded Margins

In many places the sialic passageway associated with the Lynn Volcanic Complex on Boojum Rock is flow banded with a **banded** structure visible on outcrops along with **oriented phenocrysts**. This area of the intrusion is like the core of the porphyry in almost every way (rounded euhedral plagioclase phenocrysts, **cumulophyric** plagioclase, rounded and **embayed quartz**, and **myrmikitic** and **granophyric** textures), except that it has flow-banding. The banding is believed to be the result of the shearing of magma along the margins of the intrusion. At this point outcrop exposures do not allow an examination of very much of the margins of the intrusion and **flow banding** is often not conspicuous except in thin section, but banding has only been found along the margins (Figs. 5.2-1 to 9).

Figure 5.2-1. **Flow-banded** porphyritic rhyolite associated with the Lynn Volcanic Complex at Boojum Rock (site 10912). Weathered rock surface. Holes are either bubbles or where minerals have weathered out.

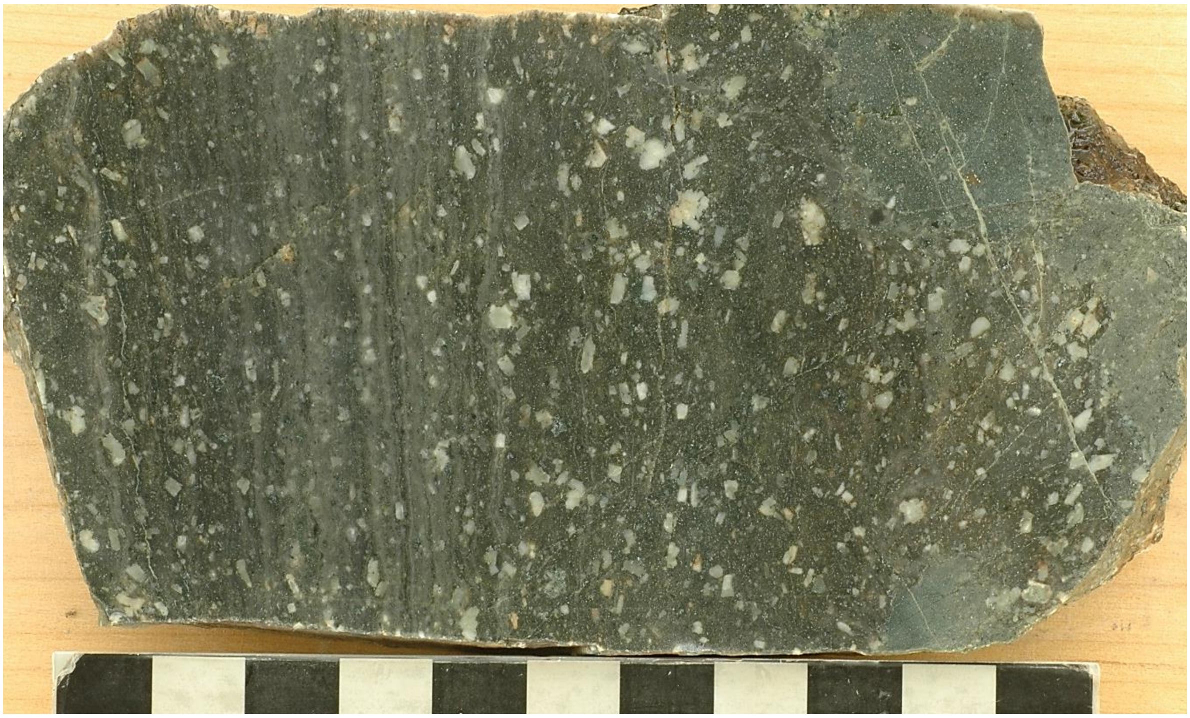


Figure 5.2-2. **Flow-banded** porphyritic rhyolite associated with the Lynn Volcanic Complex at Boojum Rock (site 10912). On right is contact of banded rhyolite with a much finer marginal facies of the intrusion. Note crude preferred alignment of plagioclase crystals parallel to banding. Cut rock surface.

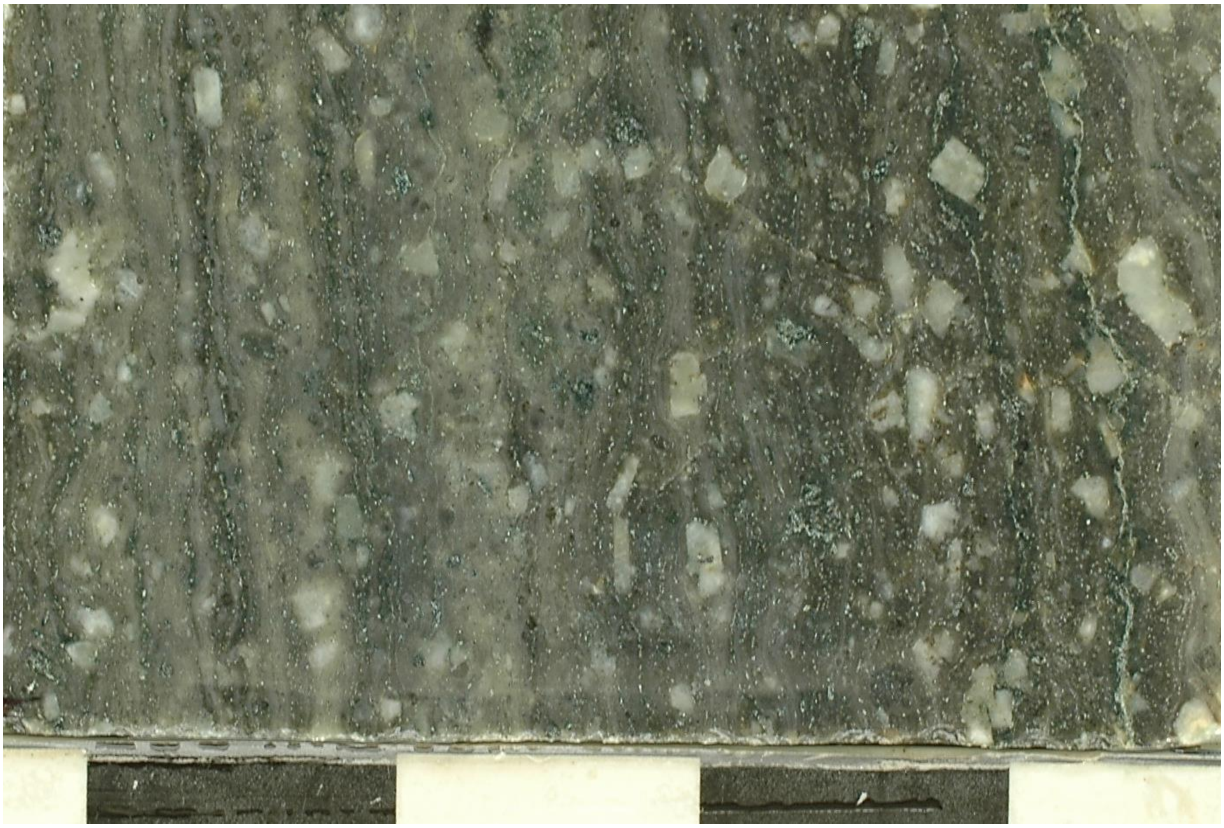


Figure 5.2-3. Flow-banded porphyritic rhyolite associated with the Lynn Volcanic Complex at Boojum Rock (site 10912). Note plagioclase phenocrysts aligned parallel to banding. Close up view of cut rock chip.

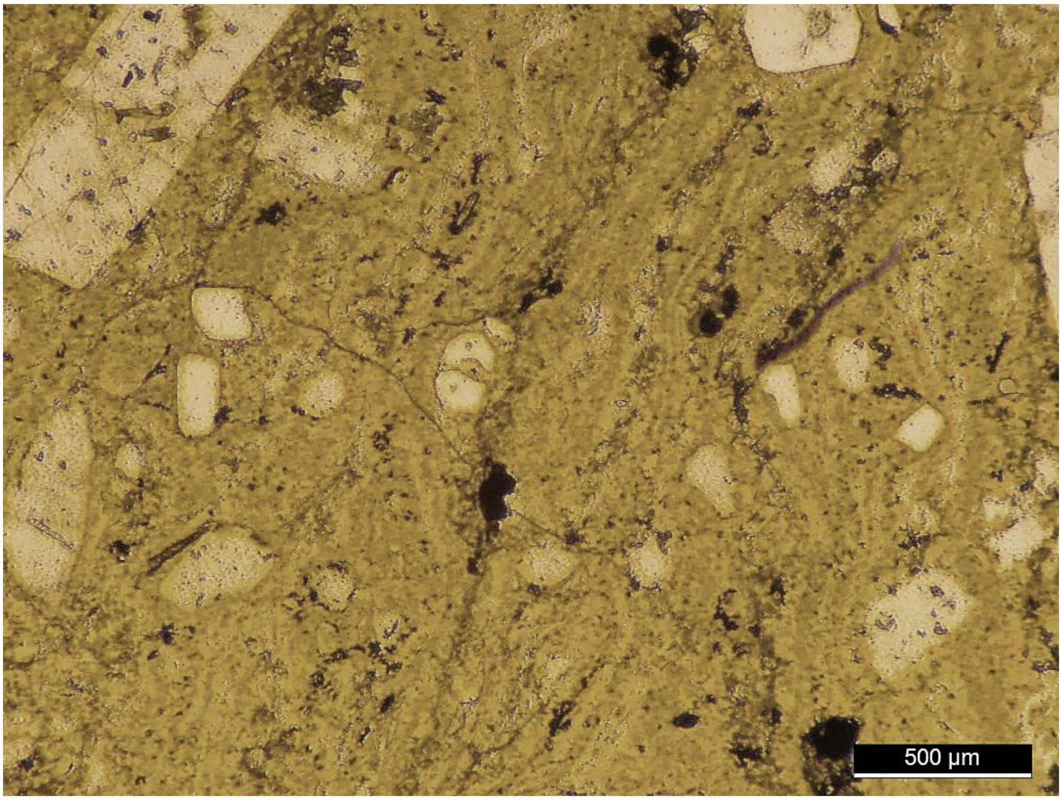
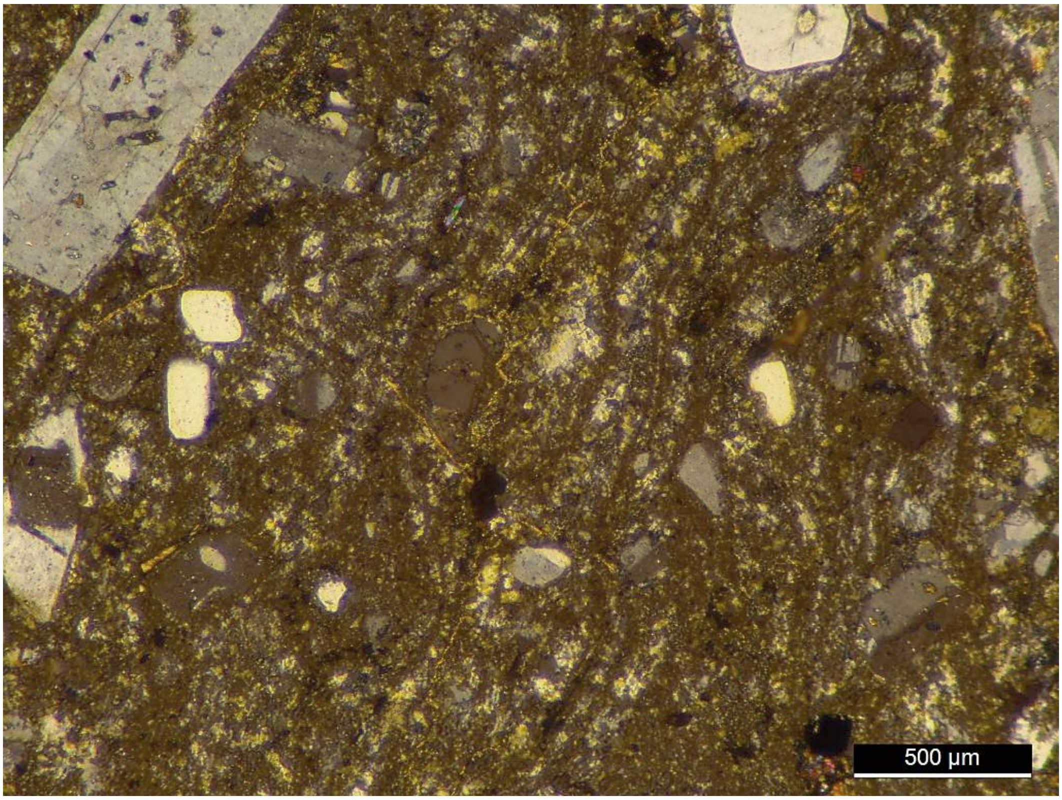


Figure 5.2-4. **Flow-banded** porphyritic rhyolite associated with the Lynn Volcanic Complex at Boojum Rock (site 10906). Note **rounded resorbed quartz** phenocrysts and very euhedral plagioclase (upper left). **Banded matrix** has a very fine **splotchy** to **micropoikilitic texture** with **axiolitic strands**. <u>Above</u>: View in plane polarized light. <u>Below</u>: View with crossed polarizers.



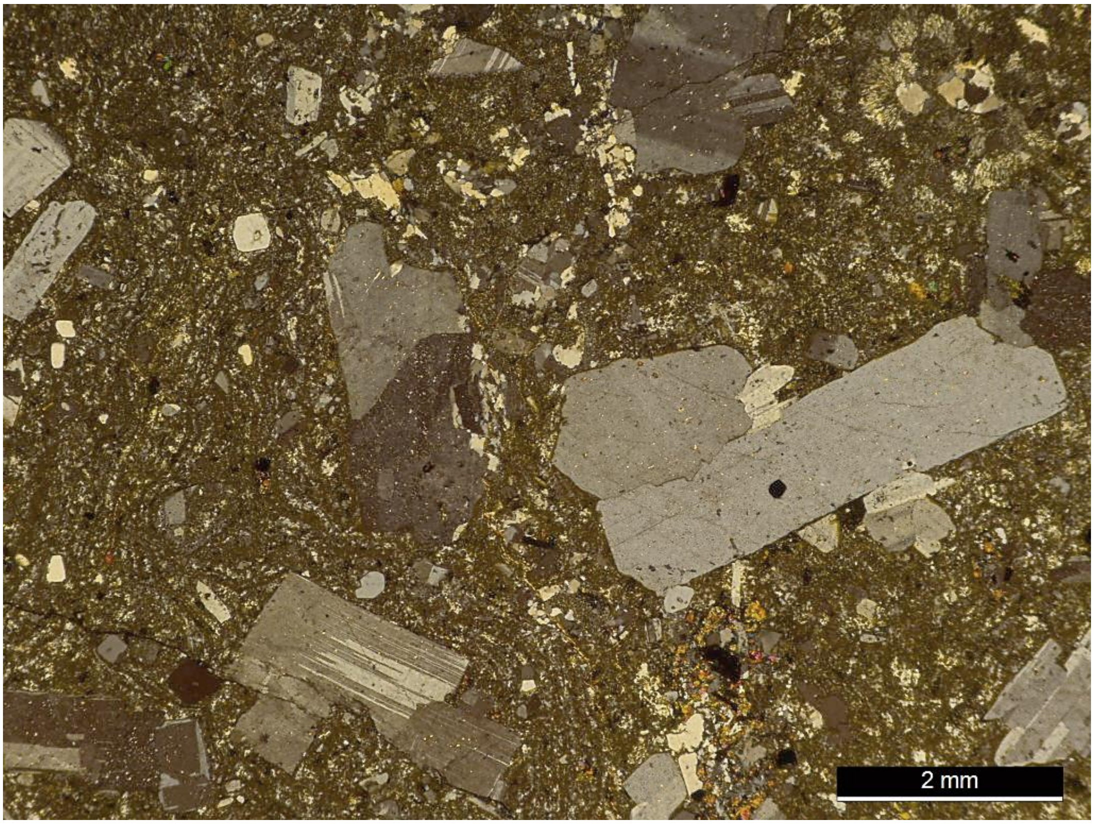


Figure 5.2-5. **Flow-banded** porphyritic rhyolite associated with the Lynn Volcanic Complex at Boojum Rock (site 10906). Note areas between large euhedral plagioclase crystals (right side) with fine **micropoikilitic texture**.

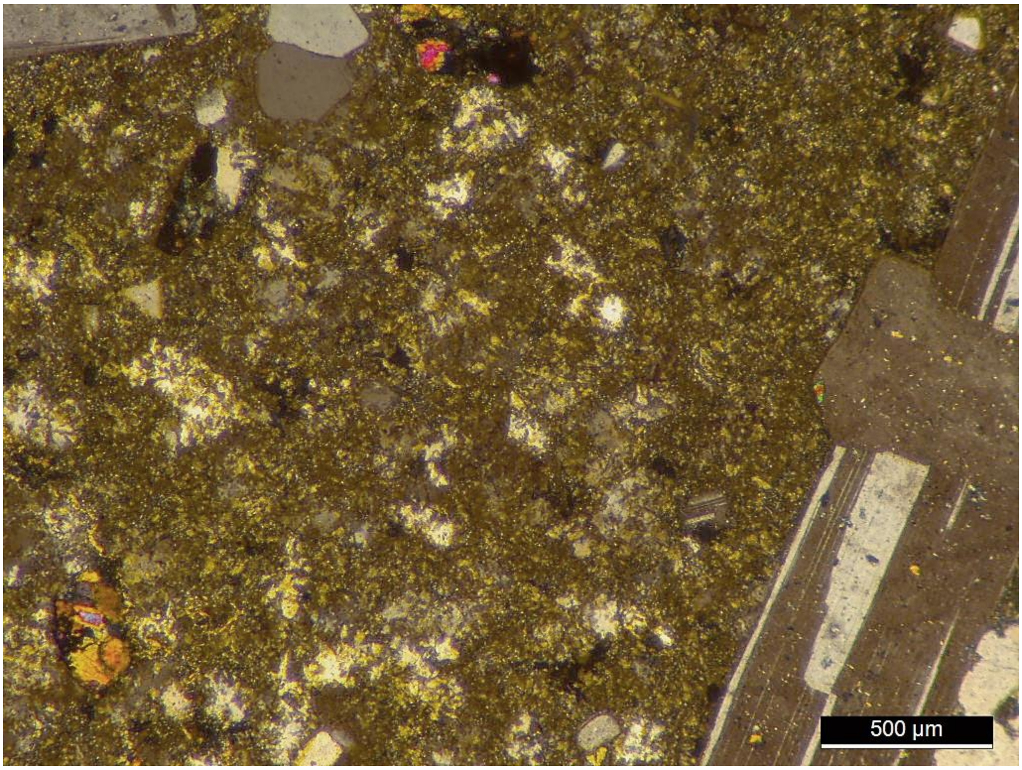


Figure 5.2-6. **Flow-banded** porphyritic rhyolite associated with the Lynn Volcanic Complex at Boojum Rock (site 10906). Close up of **fine micropoikilitic texture** in area between large euhedral plagioclase crystals.

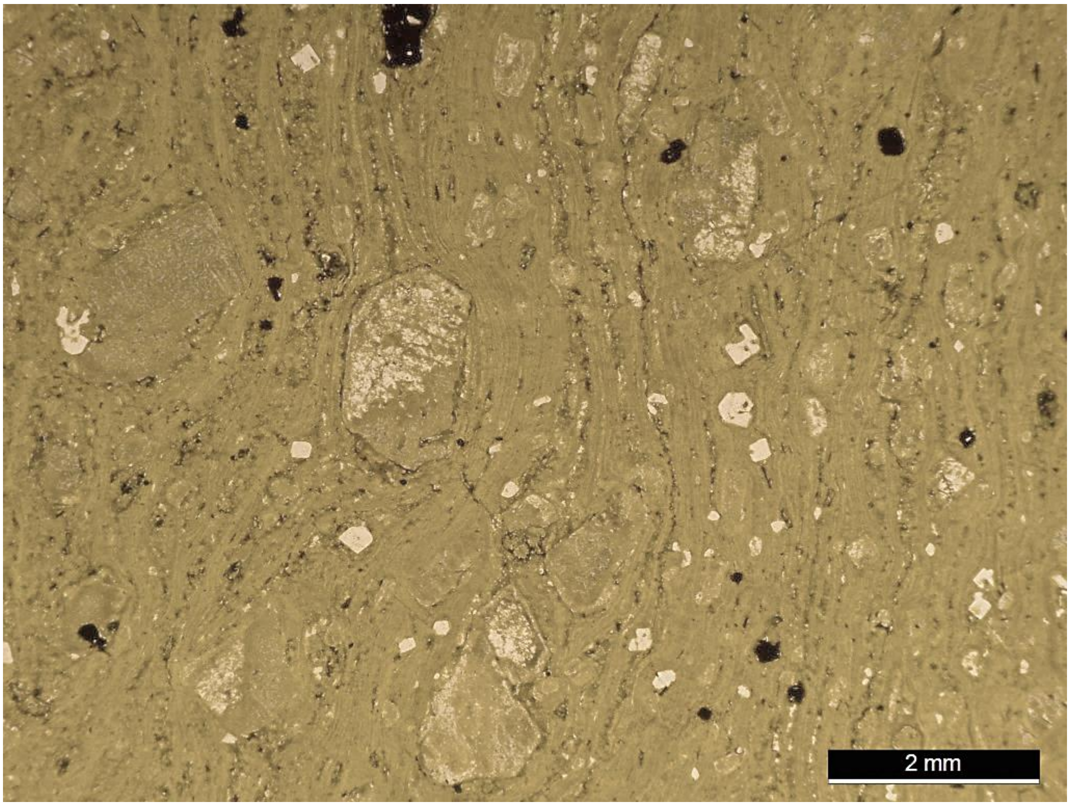
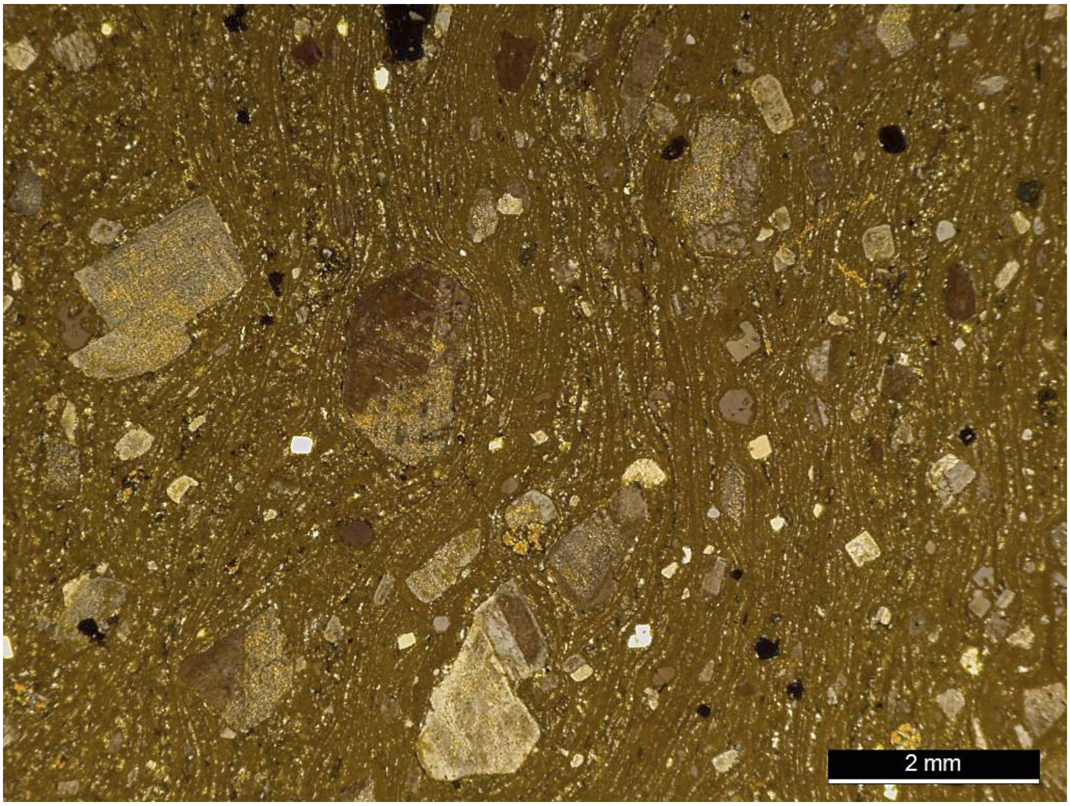


Figure 5.2-7. **Flow-banded** porphyritic rhyolite with **axiolitic strands** associated with the Lynn Volcanic Complex at Boojum Rock (site 10912). This is an area of very prominent banding. Note small **rounded, resorbed quartz** crystals. Above: View in plane polarized light. Below: View with crossed polarizers.



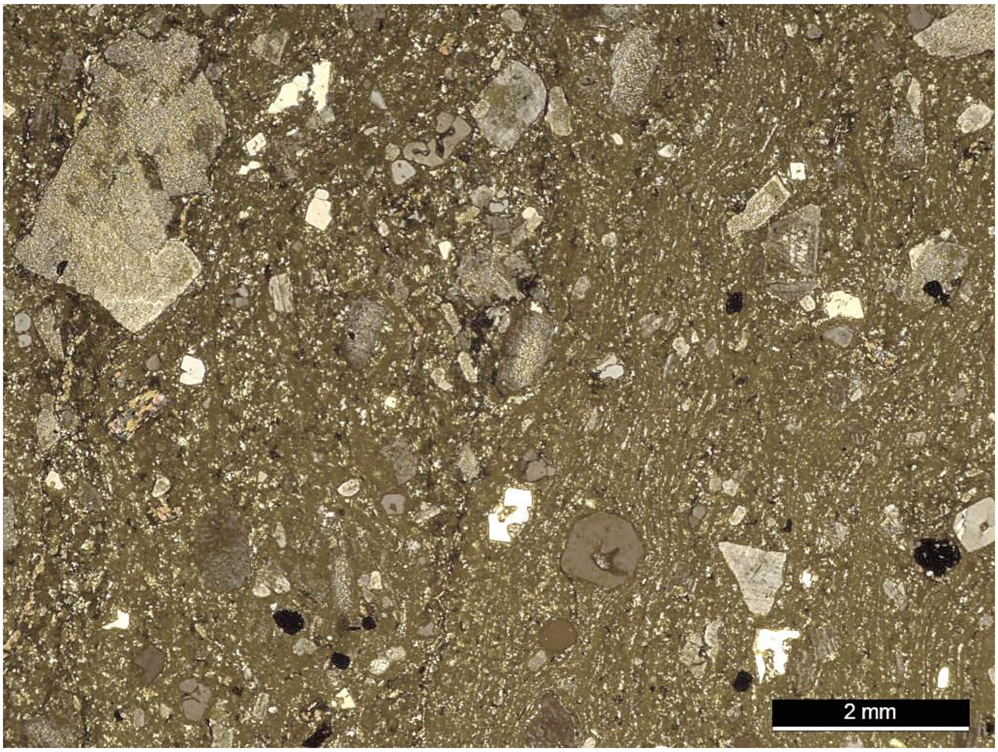


Figure 5.2-8. **Flow-banded** porphyritic rhyolite associated with the Lynn Volcanic Complex at Boojum Rock (site 10912). Note uneven distribution of crystals and very **fine micropoikilitic texture** in areas of higher crystal density (left), while banding (right) occurs in area of lower crystal density. Scattered across view are **rounded and embayed quartz** crystals. View with crossed polarizers.

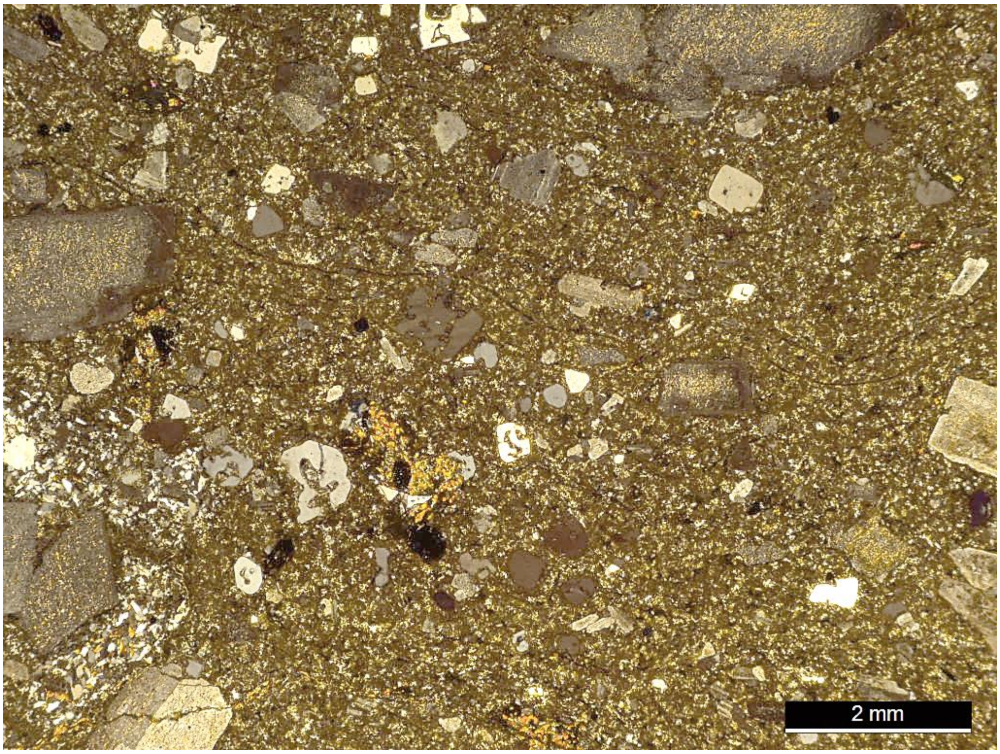


Figure 5.2-9. **Flow-banded** porphyritic rhyolite associated with the Lynn Volcanic Complex at Boojum Rock (site 10912). Area of very **fine micropoikilitic texture** with high crystal concentration and **rounded and embayed quartz** crystals. Faint flow banding occurs from left to right across upper center of image (thin black bands). View with crossed polarizers.

5.3 Passageway – Marginal Pyroclastics or Volcaniclastics

The outer edges of the passageway are bounded by pyroclastic or volcaniclastic units with either a red or green matrix (Figs. 5.3-1 to 7). These units are thin (up to 2 m) and appear to be remnants of pyroclastic or volcaniclastic material preserved along the margin of the porphyritic pipe at Boojum Rock and within the surrounding Boojum Rock Tuff. This suggests that the passageway was open before being filled by magma and may have initially had pyroclastic material. Like the intrusive body the marginal fragmental material has a very different composition from tuff in the adjacent Boojum Rock Tuff.

Figure 5.3-1. Red pyroclastic/volcaniclastic unit (left, contact at yellow arrows) associated with the margin of the rhyolite porphyry (right) of the Lynn Volcanic Complex at Boojum Rock (site 10219). Weathered rock surface.

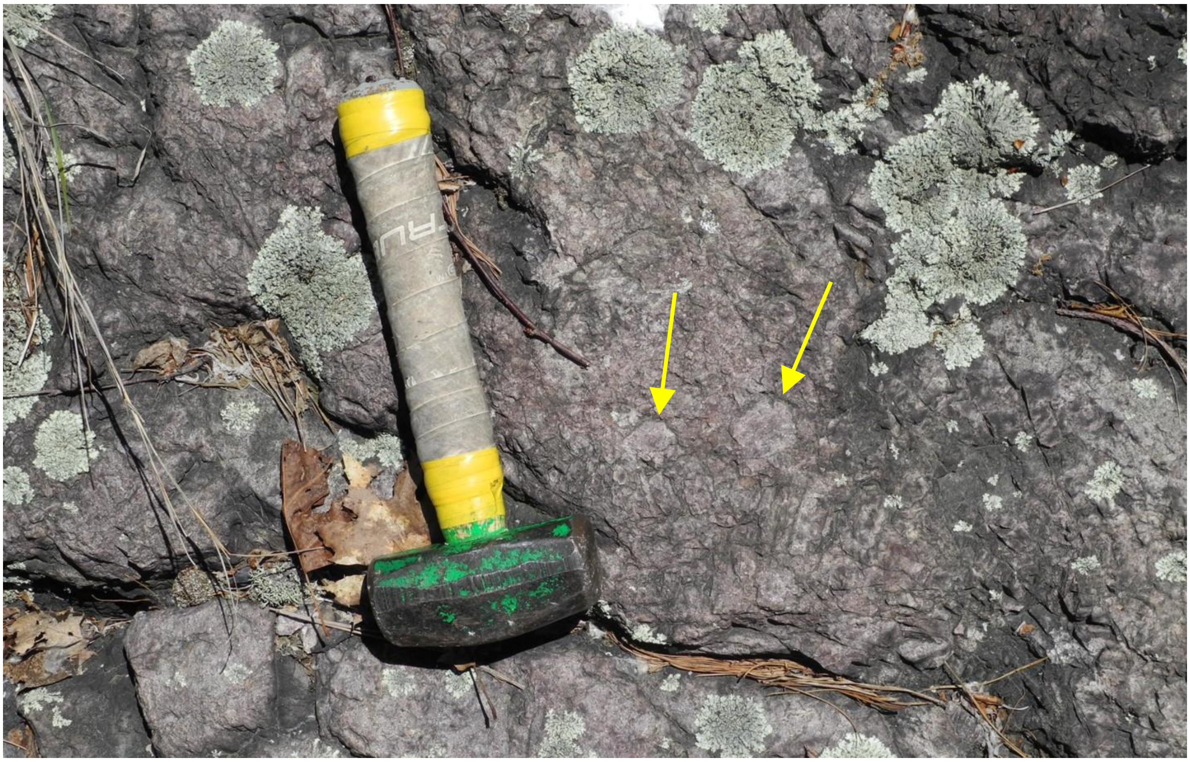


Figure 5.3-2. Clasts (arrows) in red pyroclastic/volcaniclastic unit associated with the margin of rhyolite porphyry of the Lynn Volcanic Complex at Boojum Rock (site 10219). Weathered rock surface.

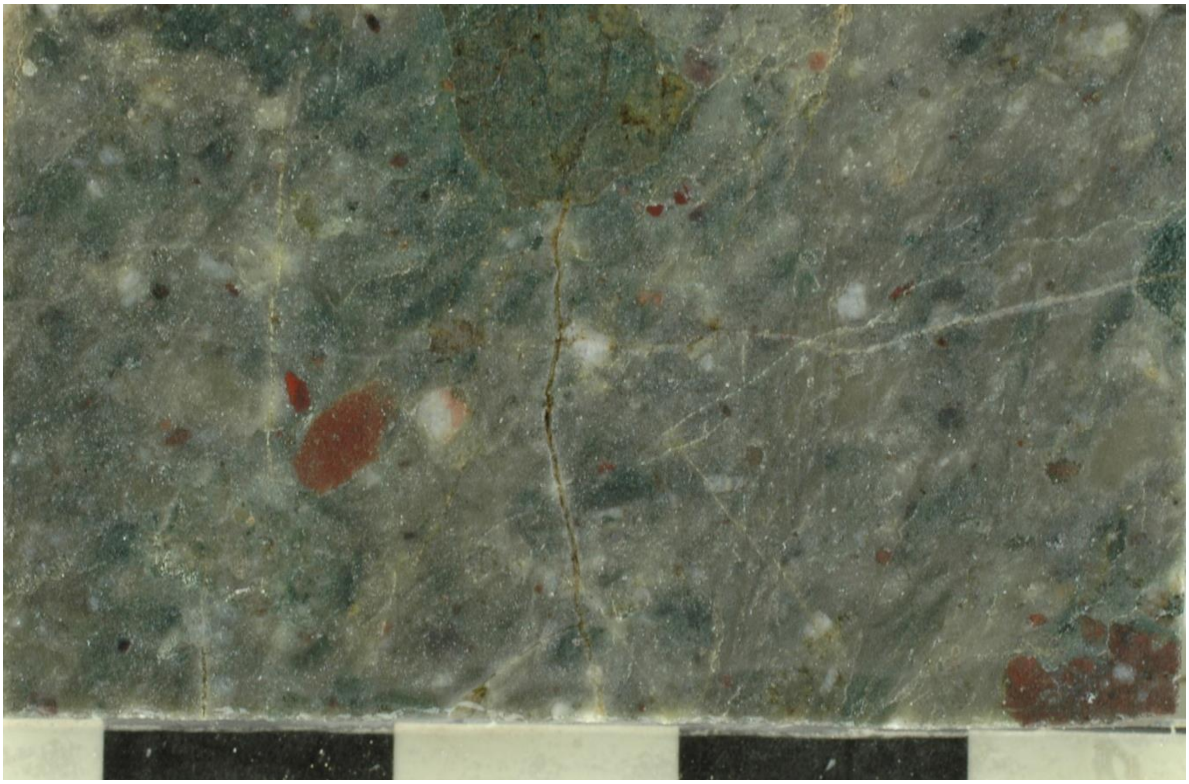


Figure 5.3-3. Green volcaniclastic (?) unit associated with the margin of the rhyolite porphyry of the Lynn Volcanic Complex at Boojum Rock (site 10895). Red clasts are volcanic. Cut rock chip.

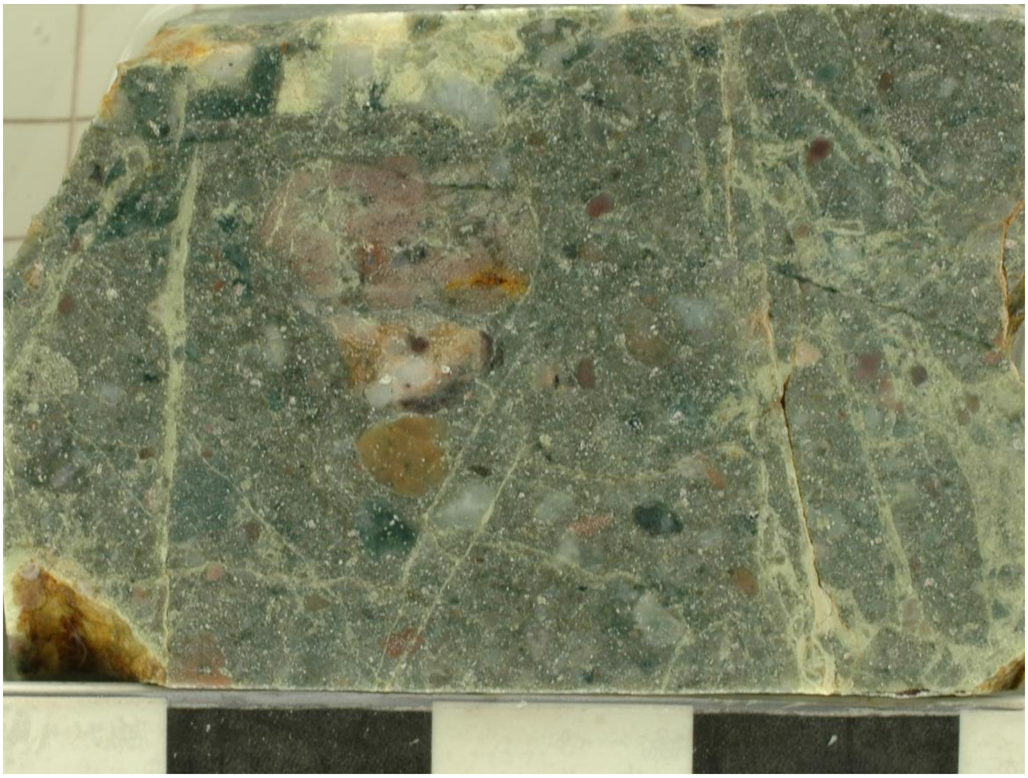


Figure 5.3-4. Green volcaniclastic (?) unit associated with the margin of the rhyolite porphyry of the Lynn Volcanic Complex at Boojum Rock (site 10907). Red and pink clasts are volcanic. Cut rock chip.

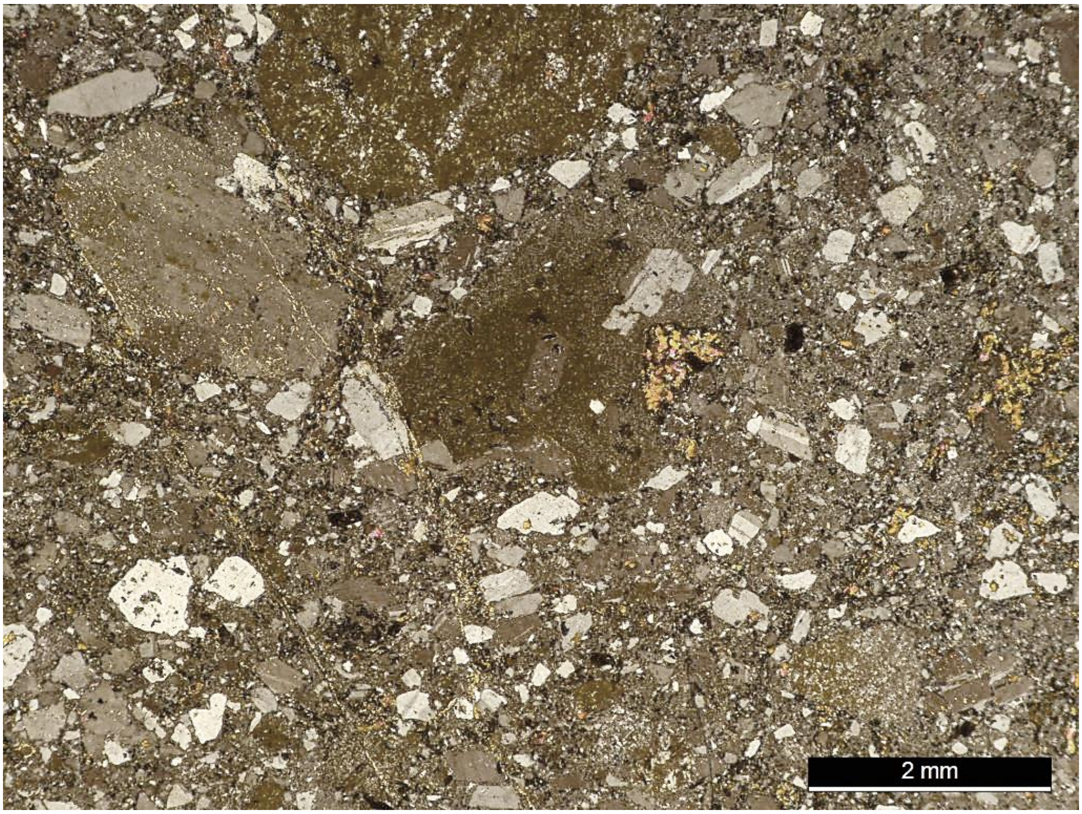


Figure 5.3-5. Green pyroclastic/volcaniclastic unit associated with the margin of rhyolite porphyry of the Lynn Volcanic Complex at Boojum Rock (site 10907). Large fragments are volcanic. This rock has many broken plagioclase and quartz crystals. Quartz crystals are absent in the adjacent Boojum Rock Tuff. View with crossed polarizers.

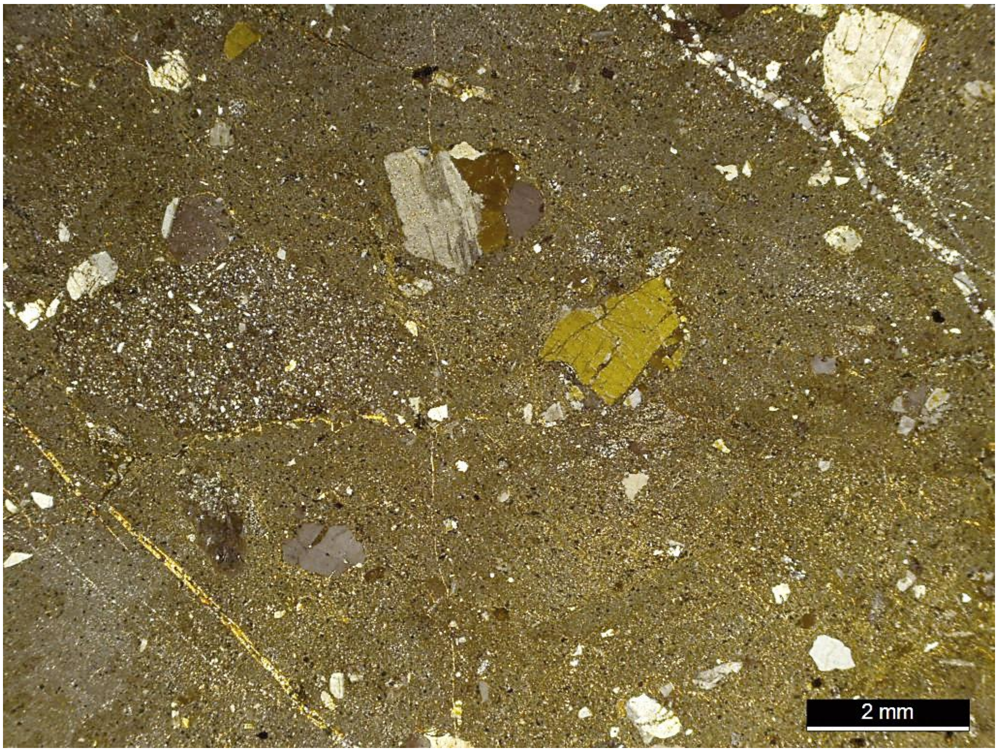


Figure 5.3-6. Green volcaniclastic (?) unit associated with the margin of the rhyolite porphyry of the Lynn Volcanic Complex at Boojum Rock (site 10895). In the center is a granodiorite fragment and an alkali feldspar fragment (stained yellow). On the left is a volcanic fragment with fine **patchy texture**. View with crossed polarizers.

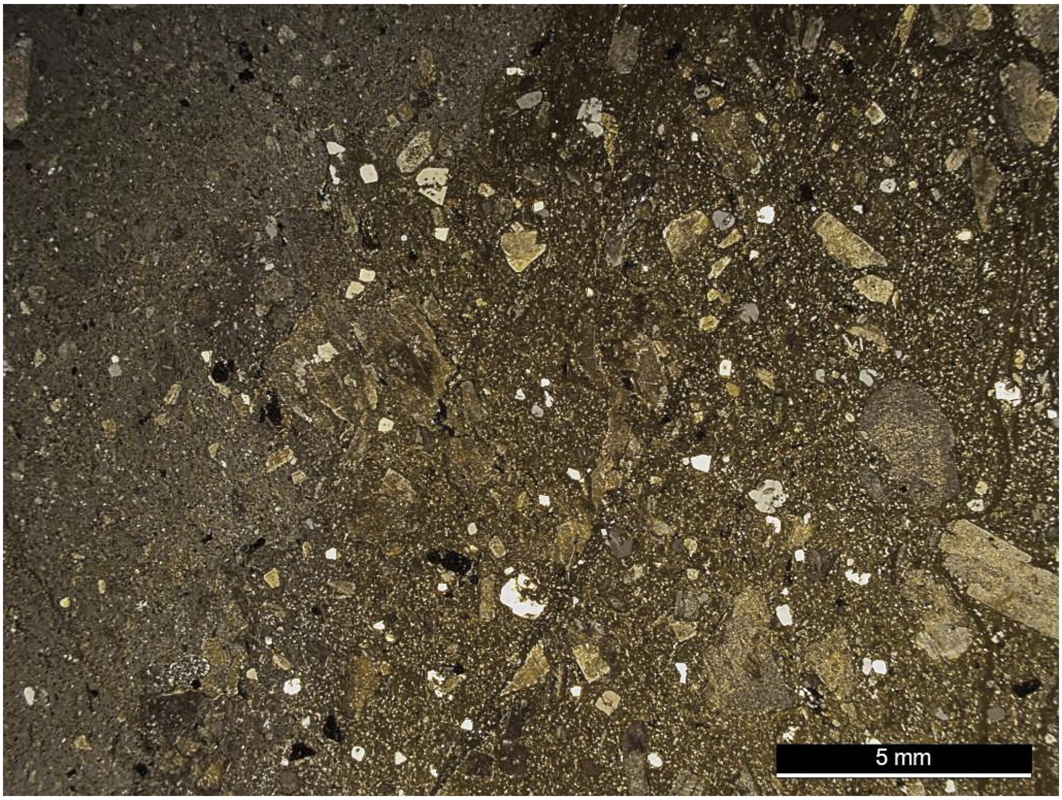


Figure 5.3-7. Contact of rhyolite porphyry of the Lynn Volcanic Complex at Boojum Rock (site 10907) on right and volcaniclastic (?) unit (left). Note banding on right side of view (black line). View with crossed polarizers.

6. RESOURCES

6.1 Publications and References

Bloss, F.D., 1954, Microstylolites in rhyolite porphyry: Journal of Sedimentary petrology, v. 24, no. 4, p. 252-254.

Branney, M.J. and Kokelaar, P., 2002, Pyroclastic Density Currents and the Sedimentation of Ignimbrites: Geological Society (of London) Memoir no. 27, 143 p.

Breitkreuz, C., 2013, Spherulites and lithophysae – 200 years of investigation on high-temperature crystallization domains in silica-rich volcanic rocks: Bulletin of Volcanology, v. 75: 705, 16 p. DOI 10.1007/s00445-013-0705-6

Gifkins, C., Herrmann, W., and Large, R., 2005, Altered Volcanic Rocks, A Guide to Description and Interpretation: ARC Centre of Excellence in Ore Deposits, Univ. of Tasmania, 275 p.

Golding, H.G. and Conolly, J.R., 1962, Stylolites in volcanic rocks: Journal of Sedimentary petrology, v. 32, no. 3, p. 534-538.

McPhie, J., Doyle, M., and Allen, R., 2010, Volcanic Textures, A Guide to the Interpretation of Textures in Volcanic Rocks: ARC Centre of Excellence in Ore Deposits, Univ. of Tasmania, 196 p.

Philpotts, A.R. and Ague, J.J., 2009, Principles of Igneous and Metamorphic Petrology, 2nd edition: Cambridge University Press, New York, 667 p.

Raith, M.M., Raase, P., and Reinhardt, J., 2012, Guide to Thin Section Microscopy (2nd edition), e-book @ http://www.minsocam.org/msa/openaccess_publications/Thin_Sctn_Mcrscpy_2_prnt_eng.pdf

Ridge, J.C., 2022, The Bedrock Geology of the Middlesex Fells Reservation (version: January 2022): Map (scale: 1:4600) and explanation (192 p.) http://sites.tufts.edu/fellsgeology/

Schmincke, H.-U., 2004, Volcanism: Springer-Verlag, Berlin, 324 p.

Thompson, M.D., Ramezani, J., and Crowley, J.L., 2014, U-Pb zircon geochronology of Roxbury Conglomerate, Boston Basin, Massachusetts: Tectono-stratigraphic implications for Avalonia in and beyond SE New England: American Journal of Science, v. 314 (June), p. 1009-1040. DOI 10.2475/06.2014.02

Winter, J.D., 2010, An Introduction to Igneous and Metamorphic Petrology, 2nd edition: Prentice Hall, New York, 702 p.

6.2 Internet

Web site of Alex Strekeisen:
http://www.alexstrekeisen.it/english/index.php