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Petrography as a Cost-Effective Approach to Understanding Geothermal System Evolution

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ABSTRACT

The microscopic study of geothermal well samples (petrography) provides a window into rock composition, mineralogy, and texture that enhances understanding of both primary rock types and their hydrothermal alteration history. Integrating petrographic analysis with other data from wells in 3D geologic models reveals the underlying origins of permeability, its destruction and rejuvenation through time, and the present state of the system. Common assumptions about the correspondence of alteration assemblages and temperature do not always hold, and petrography often clarifies the reasons for such mismatches. Petrography also allows fine-tuning of stratigraphic and structural interpretations, identification of datable units, and clarification of key conceptual model elements.

Examples of important and often neglected geologic details resolved with petrography include: 1) identification of sparse silicic rocks in dominantly andesitic systems that are good candidates for dating and sometimes have high permeability; 2) differentiation of intrusive rocks from thick lavas using textural and mineralogic criteria that help identify near-intrusive margins hosting permeable zones or pointing towards the system upflow location. Important mineralogic observations from petrography include: 1) epidote ± adularia ± quartz is commonly formed at fracture initiation in upflow zones; 2) prehnite, wairakite, and calcite are more commonly formed later and tend to result in permeability loss unless fractures are being reopened or new ones are being formed; 3) in some cases wairakite may be the most reliable indicator of reservoir top and extent; and 4) plagioclase is susceptible to dissolution and replacement by albite and adularia, commonly resulting in secondary microporosity, and movement of Ca^{+2} and Al^{+3} from regions of hot upflow to higher levels of the system.

Detailed studies involving fluid inclusion analysis, SEM, cathodoluminescence, and age dating can be coordinated with petrography and provide more detailed confirmation of mineral compositions and system evolution.

1. Introduction

This paper is an introduction to petrography and its importance in geothermal resource evaluation and conceptual modeling. It highlights recent examples where petrographic study, integrated with other key well data, has improved understanding of primary rock types and stratigraphic sequences, identified the importance of shallow intrusions, and clarified alteration assemblages and vein filling sequences (paragenetic sequence). Petrography can provide unique insights into the geologic causes for temperature and permeability patterns established by other methods, providing added confidence in geologic conceptual models that are grounded in hard (actual rock!) data.

1.1 What is petrography and how is it done?

Petrography is the study of rocks with the polarizing microscope typically using objective lenses of 2x to 100x magnification, combined with additional magnification of 5 to 10x in the microscope oculars. This allows detailed observation of mineralogical and textural relationships at the scale of centimeters to a few microns. It also takes advantage of the optical properties of minerals in plane-polarized and cross-polarized light that aid in their identification.

1.2 How can it help identify common rock types?

Most high-temperature geothermal systems are hosted by volcanic-sedimentary sequences cut by intrusive rocks (Stimac et al., 2015). Fluid flow is focused along interconnected fractures (complex networks) formed by the interplay of magmatic-intrusive, hydrothermal, and regional tectonic processes. Petrography allows rapid characterization of primary rock types based on their original mineral assemblages (or pseudomorphs) and well-established mineral and rock textures. It is true there are a bewildering array of igneous and sedimentary rock textures that may become obscured by hydrothermal alteration, but with training and experience it is relatively easy to spot primary textures, minerals, and their pseudomorphs (outline of original replaced mineral). This allows some "reading through" hydrothermal alteration unless all primary textures have been obliterated. Propylitic alteration tends to preserve and only partially overprint primary textures, whereas phyllic and advanced argillic alteration are more destructive to them.

1.3 What are the common mineral assemblages observed in neutral-pH, magmatic hydrothermal (geothermal) systems?

Many reviews of alteration associated with hydrothermal ore deposits (e.g., Thompson and Thompson, 1996; Simmons et al., 2005; Sillitoe, 2010) and geothermal systems (Bird et al., 1983; Browne, 1978a, b; Reyes, 1990; Moore et al., 2000, 2002) provide a sound basis for interpretation of commonly observed alteration assemblages and paragenetic relationships.

Alteration formed in exploitable geothermal systems with neutral-chloride fluid compositions closely resembles that associated with low-sulfidation epithermal ore deposits, but subordinate high sulfidation alteration is also common (Simmons et al., 2005). The classic alteration assemblages of neutral-chloride (commercial) intrusion-related geothermal systems are propylitic alteration in the reservoir (epidote-chlorite-quartz-pyrite ± wairakite ± prehnite), with an overlying transition zone (mixed-layer clays, chlorite, pyrite) and clay cap (smectite-zeolites-pyrite) that by virtue of its low permeability largely isolates the reservoir from overlying groundwater regime (Reyes, 1990; Stimac et al., 2015). Calcite and anhydrite are also common in all zones, but calcite tends to be more abundant in shallow zones, and anhydrite at deeper levels (Reyes, 1990). Deeper wells in some systems reveal alteration assemblages like those documented from porphyry ore deposits (Sillitoe, 2010). These include potassic, phyllic, and so-called high-T propylitic alteration zones (Reyes, 1990), among others. Thus studies of ore-forming systems provide useful analogs for geothermal systems, with the added advantage that knowledge of ore-forming systems have generally been refined to a greater degree by application of sophisticated analytical methods.

Phyllic alteration (sericite/illite-quartz-pyrite ± anhydrite) is also common in intrusive related geothermal systems, especially if the system is hosted by silicic rocks. Silicic rock composition tends to favor formation of illite and quartz as the main alteration minerals rather than chlorite and epidote which are usually also present in small amounts. Strongly phyllic alteration zones, especially with abundant anhydrite and pyrite and grading locally into advanced argillic zones, tend to have lower permeability and poor fracture interconnection even though temperatures may be high.

1.4 How can petrography help reveal geothermal system evolution and current status?

Minerals and mineral assemblages form (in equilibrium or as the system moves toward a new equilibrium state) in response to fluid composition and temperature, and thus can be used to deduce past and present states of the system. Early minerals and textures occur in older, often deformed, or crosscut veins, and infilled by younger mineral growth. Subhedral to euhedral mineral growth in open space is usually preserved in recently or currently active fracture pathways and reveal the mineral assemblage currently in equilibrium with fluid compositions. Significant permeable zones often produce cuttings with a large percentage of euhedral or subhedral hydrothermal minerals such as epidote, quartz, or wairakite.

1.5 Why is petrography not commonly done nowadays?

Many hallmark scientific studies were done in the first few decades of large-scale geothermal exploitation (e.g., Bird et al., 1983; Browne, 1978a, b; Reyes, 1990, 1991; Moore et al., 1998, 2000, 2004a, b; Hulen et al., 1997, 1999; Simmons and Christenson, 1993). Since the fundamentals have been established, fewer and fewer research studies have been published in recent years. Government funded research has been shifted to the application of new analytical methods and analysis of unconventional systems (e.g., EGS). During the same period much of the conventional geothermal industry has moved to the application of a few simple tools to keep costs of well characterization to a minimum. Still, when petrography has been applied by well-funded or forward-thinking companies or research partners, it has continued to establish key geologic controls on geothermal systems and their evolution. Some notable additions to the literature include alteration studies at Tiwi and Karaha Telaga Bodes (Moore et al., 2000, 2002, 2004a, b, 2008), the Geysers (Jones et al., 2017); Reykjanes (Libbey and William-Jones, 2013, 2015, 2016a, b), Kawerau (Milicich et al., 2018) and Muara Laboh (Stimac et al., 2019), to mention a few.

Wellsite geologic description has remained the relatively cheap and easy standard that is applied to rock type and alteration mineral identification in most geothermal projects. Making thin sections of selected samples for detailed petrographic analysis has a lag-time and additional expense. Rudimentary characterization of the minerals present adds little to wellsite analysis that can’t be gleaned from traditional XRD or a new generation of portable SWIR, XRD and XRF systems.

However these bulk rock data do not provide any textural context such vein filling assemblages and the order vein filling.

Unfortunately as analysis of well data has moved progressively into digital compilation and analysis, fewer and fewer geothermalists are learning the art of petrography, or even what to do with the information it provides.

1.6 Who usually does petrography and why is it not done more widely?

For the uninitiated, petrography of geothermal samples is as much an art as a science. It is true you that one has to learn to identify all the primary and secondary minerals common to geothermal systems, but one also has to be able to recognize primary rock textures, patterns of alteration assemblages, and typical paragenetic sequences. This is not a simple task, and the beginner can quickly become lost. Therefore petrography is done by a small cadre of experts who by some twist of fate, enjoy peering down a tube into the microscopic world. The "10,000-hour rule" applies here as in many other skillsets. However, once one reaches a reasonable level of competency, it is easy to make significant contributions to the understanding of the geology of geothermal systems, both in terms of the primary rock types making up the stratigraphy, and in determining the alteration minerals assemblages present and what they reveal about geologic controls on permeability.

Perhaps the main reason that petrography is not more widely applied is that most geothermal companies do not maintain (are not willing to pay for) the internal expertise to do this work, and hiring an outside expert also requires time, effort, and funds. They must see a direct "payoff" from this investment, rather than receiving a report that is difficult to understand and cannot easily be integrated with other well data without extra effort. Thus making petrographic data more accessible and relevant to answering key questions is critical. Finding an expert who understands how petrographic data can be integrated with other geoscience and reservoir engineering data to build geothermal conceptual models can have a far greater impact on geothermal development decisions (W. Cumming, pers. communication).

2. The Approach of Conceptual Model Integration

The approach advocated here is to make petrographic data more accessible and focused on the issues most relevant to a field developer or manager in the age of 3D model construction. This makes the insights gained more useful to non-experts in establishing reservoir stratigraphy and alteration and permeability patterns through integration with other critical data. Integration of petrography with results from image logs and reservoir engineering interpretation of permeable zones provides a means of better understanding geologic controls on permeability and the reservoir's evolution to its current state. For example, as described in Section 4.2, the top of the permeable geothermal reservoir in SW Muara Laboh is much deeper than the base of the low resistivity cap detected by MT and much deeper than smectite detected using Methylene Blue. The conceptual model for this area was revised based on integration of petrography showing that infilling of early epidote veins that originally did define the top of the reservoir was the underlying cause (see Baroek et al., 2018; Sihotang et al., 2021). It has been proposed that a sector collapse of the nearby Patah Sembilan volcano may have triggered boiling and cooling leading to this condition (Stimac et al., 2019).

The main data that can be collected from petrography are:

1. Sample type and depth;
2. Primary rock type(s), compositions, and primary minerals and characteristic textures;
3. Abundances of alteration minerals;
4. Alteration assemblage(s);
5. Abundance of vein/vug/vesicle filling fragments;
6. Alteration mineral paragenesis and most recently formed mineral(s);
7. Indications of open space and overall sample permeability;
8. Indications of faulting, shearing, and brecciation;
9. Indications of unstable formations; and
10. Sample quality (cuttings size, correct thin section thickness)

Documenting these data in a spreadsheet, with numerical values even if semi-quantitative, is much more useful than narrative descriptions, since depth-referenced tabulated data can be directly input to databases, searched, re-organized, compared with other data, and plotted in graphic logs and in 2D and 3D visualizations using appropriate software. The judicious import of a combination of wellsite and petrographic data to 3D models allows for rapid improvement in stratigraphic and alteration models, and comparison of alteration patterns to measured well temperatures and depths of permeable zones. The ability to map the distribution of alteration mineral assemblages or paragenetic sequences in 3D relative to other key data such as temperature and chemistry can help reveal the underlying reasons for permeability and temperature trends in the system that are fundamental to building the field conceptual model (e.g., Baroek et al., 2018; Mussofan et al., 2019).

Since petrography is a visual science, some documentation of the key takeaways of petrographic analysis should also be made for each sample. This allows quality assurance of the petrographic interpretations, and comparison of key features to other wells. If this data is archived, it can be referred to later when issues arise that may not have been considered at the time of the original work.

Digital photographs can be taken of dominant rock types, textures, alteration minerals and paragenetic relationships that provide the “proof” of the observations assembled in spreadsheets. This is important in case new evidence leads to changes in the interpretations made. For each well, I advocate documenting a “summary and highlights” that provide the key takeaways of petrography, including inferences on well temperature and permeability patterns. In my opinion, the photos are very useful and provide the main evidence for any interpreted rock types and vein filling sequences. They will allow other integrators to make their own interpretations compared to the original petrographer. Photos should be documented in both plane-polarized (PPL) and cross-polarized light (XPL) to make optical aspects of mineral identification clearer.

2.1 Taking Microscopy to the Next Level

While cuttings are the standard well sample, such small fragments do not easily preserve large-scale textures or crosscutting relationships that prove hydrothermal breccias or sheared veins. These features must be “pieced back together” Humpty Dumpty-style by an experienced observer, with some attached uncertainty. Larger-scale textures may be directly observable in core, making this the best approach to unraveling system details. That is why core is the gold standard for paragenetic interpretation. It is worth taking cores at key points in at least one well per pad if total circulation losses are experienced. This is particularly important in the first exploration and development wells, when learning curves are steep and new revelations can have the most profound impact on project plans and directions.

Image-analysis software can be useful in developing more quantitative percentage data for minerals or open space, but this methodology is probably best implemented using SEM images that are more clearly related to mineral composition rather than traditional petrography.

Detailed studies involving fluid inclusion analysis, age dating, SEM or cathodoluminescence can be coordinated with petrography and provide more quantitative confirmation of mineral compositions, paragenesis and system evolution. Integrated studies applying multiple methods provide stronger constraints than petrography alone. Electron microprobe, ion probe, or induced coupled plasma mass spectrometry (ICP-MS) analysis of minerals for major and trace elements, stable isotopes or isotope-based geochronology have all been applied and can reveal details that cannot be determined by other methods. However, these tools are typically applied in the research setting and are not commonly available to industry professionals unless they have established collaborative research relationships. Even further, petrography supports petrophysical studies done on core that illuminate the textural and mineralogic nature of porosity and permeability patterns (e.g, Baroek et al., 2018).

3. Examples of Key Issues

3.1 Primary rock types and mineral assemblages

Recognition of rock types that provide insight into fieldwide permeability patterns and possible heat source locations are particularly important. Here we provide examples of the importance of silicic volcanic formations in dominantly andesitic sequences, as well as the under-recognized importance of intrusive rocks in volcanic packages.

Recognition of silicic rock intervals within dominantly andesitic arc sequences may be a challenge for those unfamiliar with distinctive primary textures such as flow banding and devitrification that are characteristics of such highly viscose magmas. Primary devitrification is the crystallization of glassy erupted material in the presence of magmatic vapor during slow cooling of thick, well insulated deposits such as ash-flow tuffs and lava flows and dome interiors.

Wellsite descriptions commonly mistake more silicic rocks for zones of hydrothermal silicification of the dominant andesitic rock sequence. Petrography can easily differentiate distinctive primary silicic volcanic textures and mineralogies (quartz, biotite, or alkali feldspar phenocrysts, flow banding, spherulitic devitrification, etc.) from hydrothermal silicification, essentially an increase in quartz content through dissolution, reaction, and infilling of vugs and veins.

Two dominantly andesitic fields with interbedded silicic sequences that were first identified by detailed petrography are Bulalo (Vicedo et al., 2008) and Salak (Stimac et al., 2008; Drestanta et al., 2017). In both cases silicic formations are dominated by devitrified lavas/domes and ash-flow tuffs with flattened pumice fragments and glass shards indicating welding (Figure 1 and 2). Spherulites, formed during primary devitrification of silicic volcanic glass are a uniquely identifiable texture. Phenocrysts of quartz and biotite also indicate silicic rock compositions.

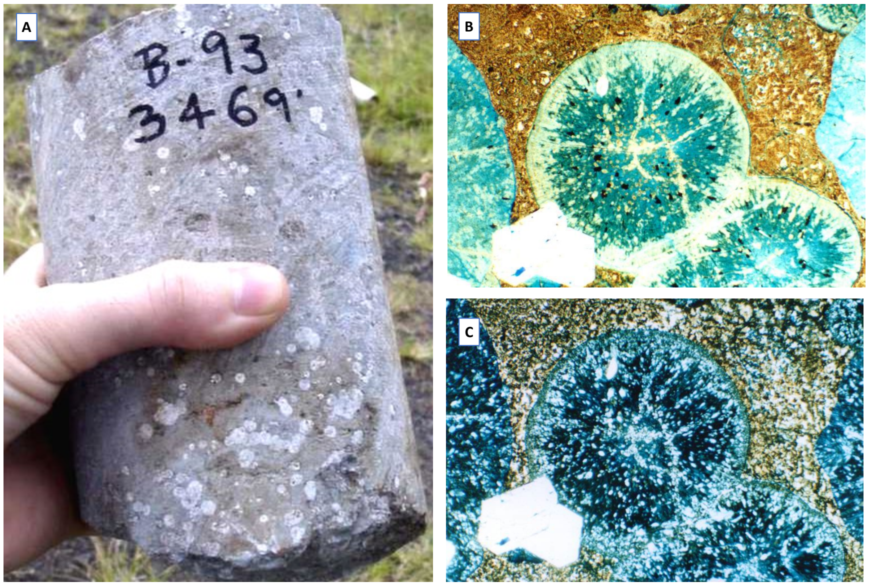
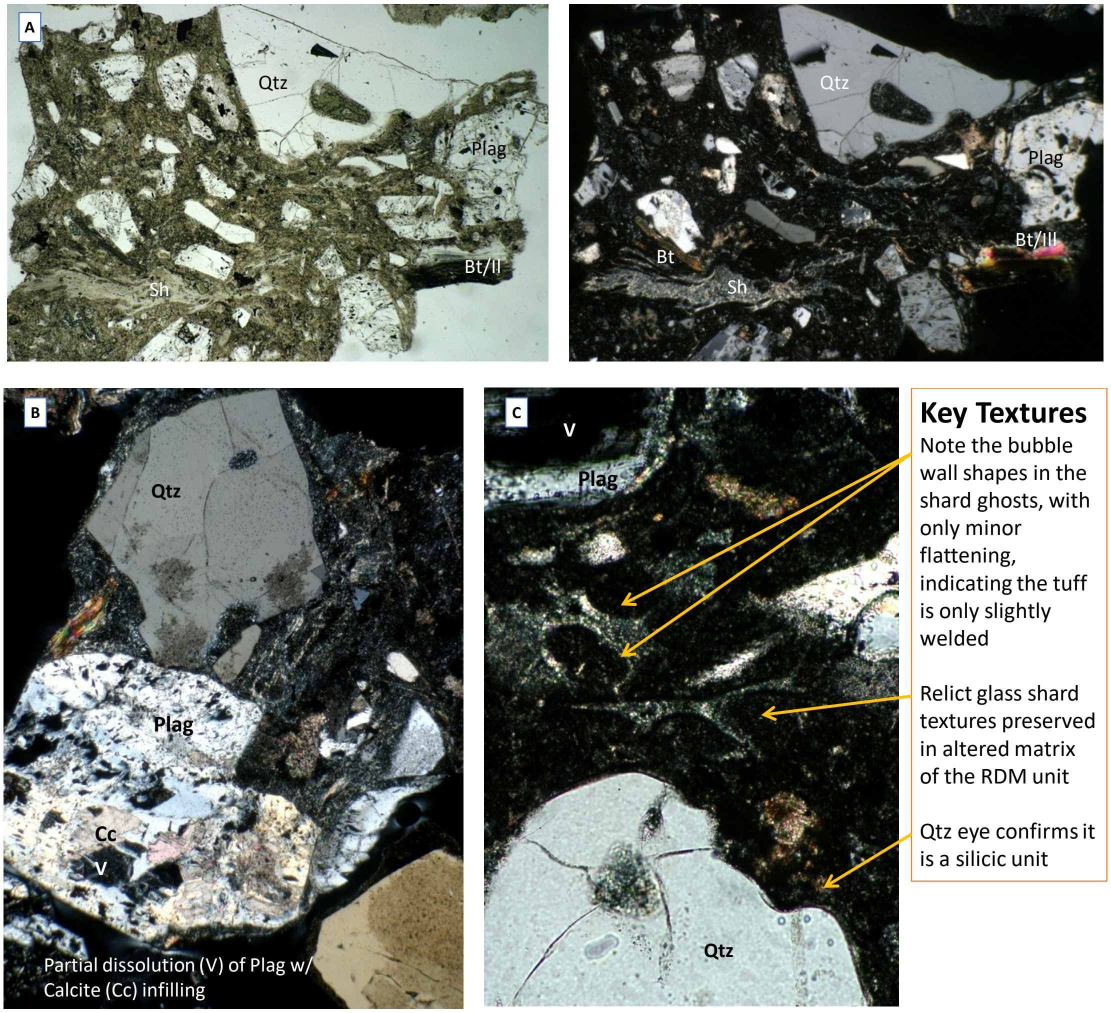


Figure 1: Bulalo Spherulitic Rhyolite Formation. A) Core sample of rhyolite lava with spherulites from Bul-93 (3496 ft MD). B) Spherulites (blue stain indicates microporosity) in plane-polarized light (long dimension about 2 mm), and C) crossed polarized light.

Gamma-ray logs provide further confirmation of these silicic units and allow accurate correlation of them from well to well (Drestanta et al., 2017; Estrella, 2019). It is worth noting that both in Bulalo (SR1 & SR2 units) and Salak (RDM unit) that the silicic packages are relatively high in fracture permeability. Their distribution (moderate thickness and large extent) is consistent with including ignimbrite outflow sheets (Drestanta et al., 2017). Vertical pseudo-columnar jointing of such extensive outflow sheets commonly occurs during cooling and devitrification. Along with their unusual stratigraphic continuity and relatively high strength due to welding, re-activation of such polygonal joint systems may explain why these units behave as aquifers that may channel either hot or cool fluid (e.g., Vicedo et al., 2008; Sunio et al., 2015).

Silicic rock sequences provide evidence of changing magmatic sources, and in some cases may be associated with episodes of caldera collapse that can be used to formulate volcanic facies models. Holocene to Plio-Pleistocene silicic formations are even more prevalent in Sumatra compared to Java, where they are commonly an important component of reservoir geology (Mussofan et al., 2019, 2021). Petrography (along with zircon dating) helps constrain the timing of reservoir rock formation and locations of major stratigraphic discontinuities (Stimac et al., 2019).



Partial dissolution (V) of Plag w/ Calcite (Cc) infilling

Key Textures

Note the bubble wall shapes in the shard ghosts, with only minor flattening, indicating the tuff is only slightly welded

Relict glass shard textures preserved in altered matrix of the RDM unit

Qtz eye confirms it is a silicic unit

Figure 2: The Salak Rhyodacite Marker (RDM). A) Partially welded rhyodacite ash-flow tuff with plagioclase (Plag), biotite (Bt) and quartz (Qtz) phenocrysts in plane-polarized light (PPL, left) and cross-polarized light (XPL, right). Welded flattened glass shards (Sh) are visible. B) Plag partially dissolved (V) and replaced by Cc in XPL, and C) Less welded bubble wall and shard textures in XPL. Long dimension of photos is about 2 mm in A) and B), and 0.5 mm in C).

3.2 Identification of shallow intrusions versus lava flows

Another challenge for wellsite geologists is determining whether relatively coarse crystalline rocks represent thick lava flow sequences or fine-grained hypabyssal intrusives. These rocks have similar textures that may be further obscured by hydrothermal alteration. This applies across the compositional spectrum from basalt (microgabbro) to rhyolite (granitoid). Field geologists know that dikes and sills commonly cut volcanic sequences, especially as the volcanic package thickens over its lifetime, and these rocks have a variety of distinctive textural attributes. Petrography provides information on grain size and microfabric of the rock that addresses this issue more directly than other methods.

Intrusive rocks tend to be holocrystalline (no interstitial glass/devitrification textures), mostly non-fragmental, mostly non-vesicular, and consistently coarser grained than lavas. They also contain late-stage crystallization of trace-phase crystal intergrowths and/or late-stage hydrous mineral crystallization/replacement, and metasomatism by late-stage magmatic fluids. Sometimes mineral exsolution (unmixing) textures may be preserved.

The location and abundance of intrusive rocks is important because they often crosscut formations and may intrude zones of structural weakness that fail repeatedly. Such zones may have enhanced vertical permeability. The youngest generation of intrusives is likely to provide insight into the location of the field's main heat source and identify possible upflow zones.

From detailed petrographic studies of several fields, it is clear that shallow intrusions are more prevalent than commonly assumed based on wellsite geology, and as wells are drilled to progressively greater depth in mature fields, the likelihood of encountering intrusions increases. Some such rocks are strongly altered, but others are relatively fresh, leaving open the possibility that some intrusions post-date the bulk of hydrothermal alteration present in their host rocks, and are associated with the magmatic heat source for the current hydrothermal system. While it cannot always be proven whether a given interval is intrusive or extrusive, the weight of evidence based on common intrusive textures points to young intrusion in many cases (Estrella et al., this volume).

Within the caldera setting at Rantau Dedap, intrusives are very common at or near the bottom of most deep wells (Mussofan et al., 2021). Some are fresh whereas others show extensive alteration. Dating of zircon from intrusions and the hosting volcanics indicates that most intrusions overlap in age with prominent ash-flow tuff sequences.

Petrography on deep samples by Moore (2007) and others, from Darajat (Indonesia) gradually revealed that the reservoir hosted by the "Andesite Lava Complex" likely included abundant microdioritic intrusions (Rejeki et al., 2010) and it was eventually renamed the "Andesite-Intrusive Complex" (Intani et al., 2019). Abundance of matrix amphibole and quartz and lack of fragmental textures were common indicators of microdiorite.

In another example, fine-grained shallow mafic intrusives appear very common in the Fiale section based on F1, F2, and F3 well cuttings, especially below 1400 m depth. These intrusive rocks consist primarily of subpoikilitic intergrowths of plagioclase, pyroxene, rare olivine and FeTiOs variably altered to epidote-amphibole-biotite-adularia-albite-pyrite (Figure 3). Due to their high content of fresh plagioclase (producing lighter color and glassy mineral grains), they may have been mistaken for more silicic volcanics containing quartz in wellsite descriptions. Their coarse-grained holocrystalline texture, and occurrences of spotted hornfels typical of contact metamorphic zones support this interpretation. Weak alteration in many samples interspersed with more altered rocks suggests that some intrusions may be relatively young, post-dating some alteration. The occurrence is consistent with a sheet dike and sill complex.

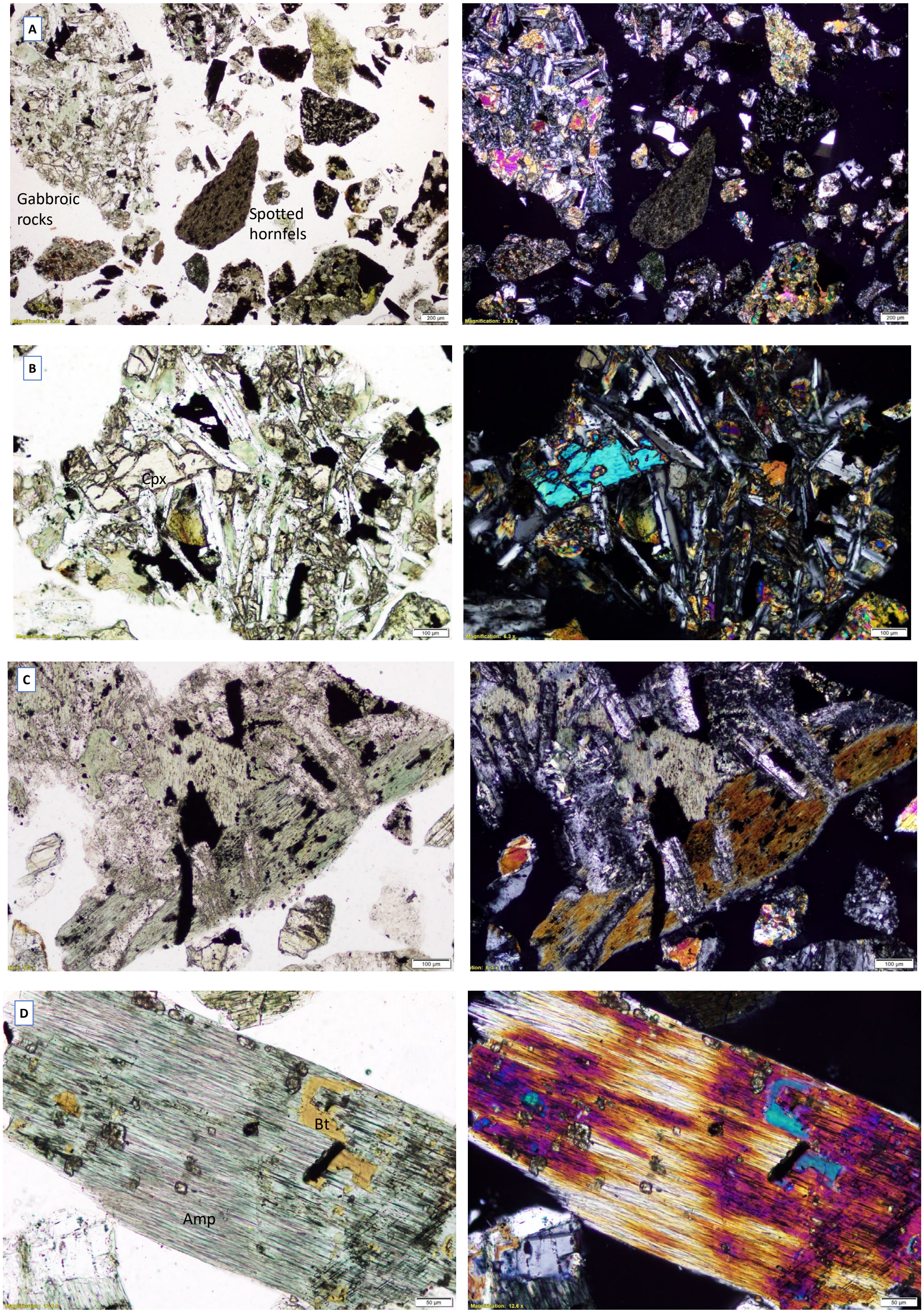

A
Gabbroic rocks
Spotted hornfels
200 µm
Magnification: 2.52 x
200 µm
B
Cpx
100 µm
Magnification: 6.3 x
100 µm
C
100 µm
100 µm
D
Bt
Amp
50 µm
Magnification: 12.6 x
50 µm

Figure 3: Intrusive rocks from Fiale, Djibouti, all in PPL (left) and XPL (right). A) F3 1801 m – Mafic intrusives, possible contact metamorphic rocks (spotted fn. gr. clasts), and basaltic rocks. B) F2 2689 m – Med gr. gabbroic intrusive w/ some fresh Cpx. C) F3 2052 m – Med. gr. deuterically altered gabbroic intrusive with Plag-Amp-FeTiOs; D) F2 2212 m – Fibrous hydrothermal amphibole with late-stage Biotite (Bt).

Knowing the location of intrusions may help in targeting deep wells in established fields. For example, the Geysers is spatially associated with a felsic intrusion (Geysers Plutonic Complex or GPC). This intrusive complex was only recognized through detailed petrography and core samples with chemical analyses (Schriener and Suemnicht, 1981; Hulen and Walters, 1993; Hulen et al., 1997). The dated intrusions are too old to represent the heat source but are spatially associated with permeability in their contact regions and above but more recent underlying intrusion is very likely (Hulen et al., 1997).

Petrography, dating and mineral compositions and textures indicate that at least one phase of the GPC represents a feeder to the adjacent Cobb Mountain silicic volcanics (Hulen et al., 1997; Schmitt et al., 2006). Recent detailed study of zircon trace element and isotopic patterns from both the GPC and Cobb Mountain sequence has confirmed that they formed under similar condition and from a common source magma (Angeles-De La Torre et al., 2023).

Similarly at Larderello (Italy) an extensive deep reservoir zone is associated with NW-SE trending metamorphic high that is probably related to a shallow granitic intrusion (Bertani et al. 2005). Seismic surveys show two seismic reflectors interpreted as the metamorphic contact aureole of the old (2-3 my) granitic intrusion. It normally coincides with the deep reservoir.

3.3 Identification of weak and chemically sensitive formations

Weak or chemically sensitive formations are a major cause of stuck pipe. Recognizing the composition, location and depth of these formations early allows for improving mud programs and drilling practices to reduce the risk of such costly events. The most common cause of drilling problems in volcanic-hosted geothermal fields is clay-rich volcanic and volcaniclastic rocks that were converted to low-temperature clays at or near the surface and have compacted and failed to re-equilibrate during deeper burial. They commonly include mixed-layer clays that are water sensitive and expand unevenly when exposed to water (Figure 4). In thin section, cuttings from weak formations display cracking along clay partings and plucking of grains during the thin section making process.

Chemically sensitive clays tend to swell, disaggregate and slough into the open hole when exposed to water. Fault zones also tend to be weak because they are intensively fractured and rocks are ground to clay-size particles referred to as cataclasite or gouge. Poorly consolidated fault breccias easily shed larger clasts into the hole. Sensitive clay-rich formations also tend to smear into fault zones and add to their instability. At Sorik Marapi wells drilled from one pad experienced many instances of stuck pipe related to formation instability. Review of cuttings from the problematic horizons showed that there was evidence for both clay-rich tuffs and cataclasite related to faulting (Figure 4).

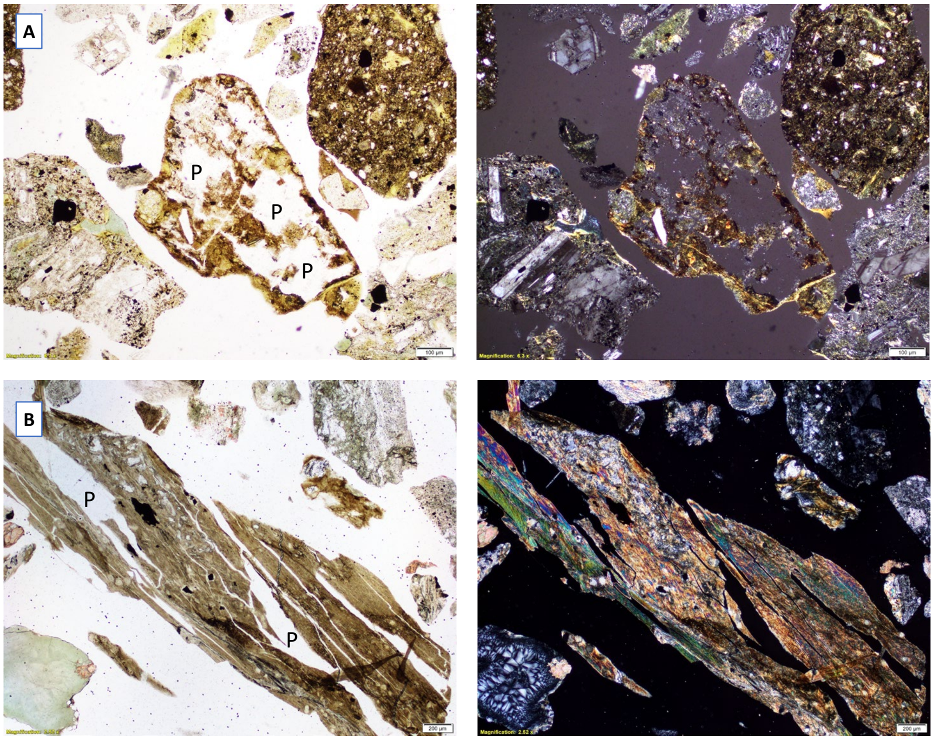


Figure 4. Examples of textures indicating water sensitive formations, in PPL (left) and XPL (right). A) AA-01ST 1971 m. Andesite lava (lower left), fn gr tuff (middle) and volcaniclastic (upper right). Tuff shows some plucking (P) typical of reactive clays which slough off thin section glass during grinding in water. B) AA-EXT-06OH 1813 m – Decrepitating partially welded and sheared tuff coming apart along clay partings.

3.4 Strategy for sampling core for veins

Core samples are ideal for evaluating vein paragenesis and aid with interpretation of heterogeneous lithologies or structures. The most revealing sample is one that exposes an entire vein and its wall rock. If the vein has open space there is a reasonable chance that the fluid was flowing through it or stored within it before sampling. Veins with significant open space and euhedral crystals provide information about the current and recent mineral assemblage growing from reservoir fluid.

Preserving delicate euhedral crystals in open space is difficult, and some destruction of vein mineral textures is common during coring and sampling. Care should be taken to preserve open-space textures. This is best done by flooding the open space with epoxy prior to cutting the thin section blank. First the sample should be photographed and described in the core. Then the sample area should be flooded with epoxy to lock crystals in place and preserve textural relationships. Once this is done, the sample can be safely cut from the core, and shaped to fit on a thin section blank.

Thin sections prepared by typical vendors come in two sizes: 24 x 46 mm (standard) and 2 x 3" (large). The size of the thin section selected depends on the size of the vein textures of interest. Since veins are commonly 0.5 to 2 cm in width, the larger size is warranted. But for thin veinlets <0.5 mm standard thin section may suffice. Large thin sections are also helpful for heterogeneous rock types, contacts, or structural features of interest.

Use of blue epoxy helps with identification and quantification of porosity. For samples impregnated under vacuum at above ambient temperature epoxy typically penetrates even tiny pores that are either interconnected or exposed on the cut face. Staining of calcite aids in quick assessment of the abundance of this mineral and may also help differentiate different carbonate minerals. Staining for alkali feldspar is helpful in identification of adularia, which may be difficult to identify if anhedral or fine-grained.

4. Alteration Assemblages, Paragenesis, and Dissolution

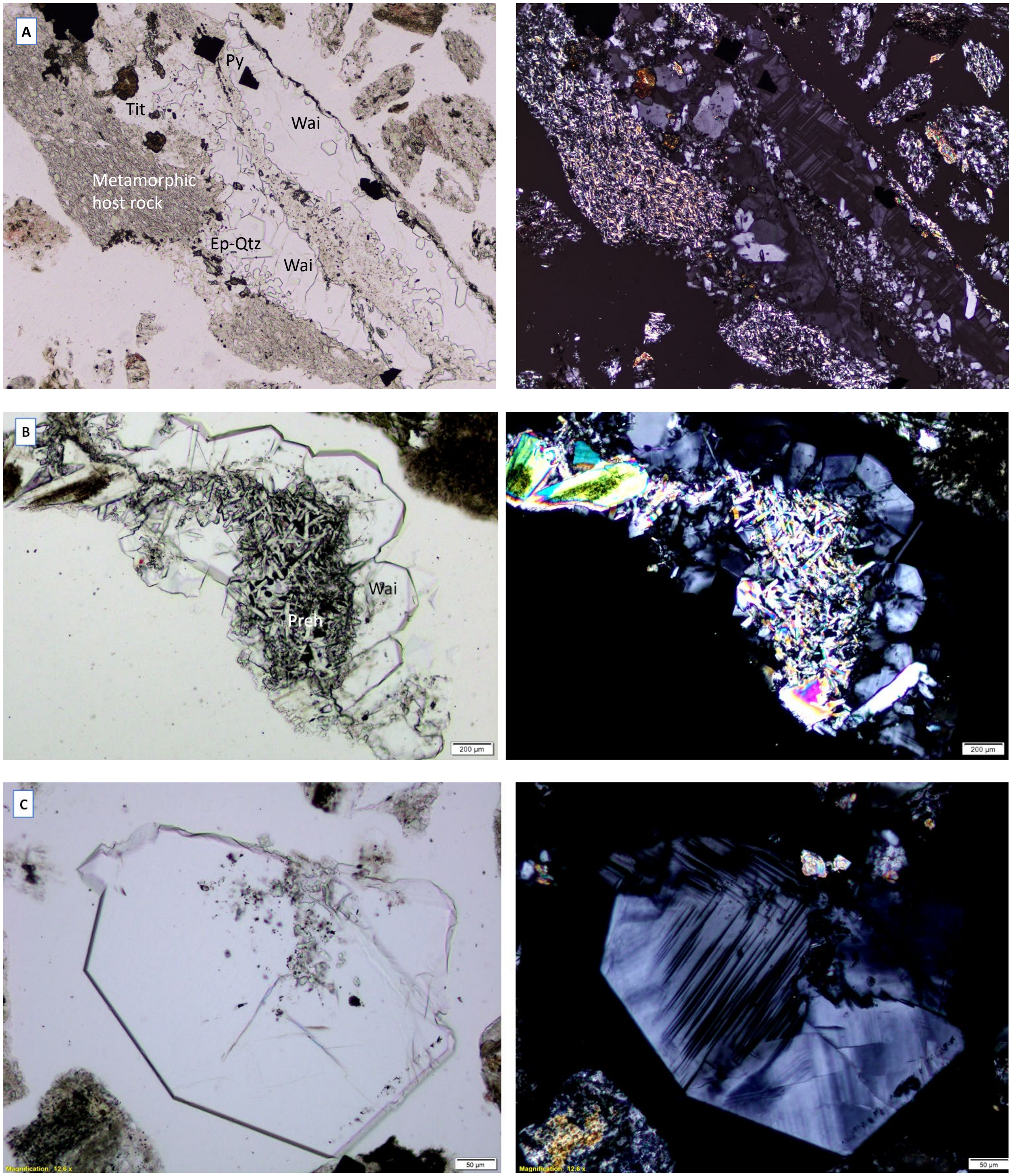
4.1 Common paragenetic sequences

In typical high-temperature neutral-chloride geothermal systems, the first minerals to form upon fracture initiation and upflow of heated meteoric water circulation are epidote ± adularia ± quartz. As temperatures decline, prehnite ± quartz commonly form. Wairakite ± calcite ± anhydrite are more commonly formed later as temperature declines or pH declines due to admixture with steam condensate. Quartz and calcite are commonly the main hydrothermal minerals in lower-temperature systems, and toward the tops of shallow boiling zones in hotter systems. Calcite ± anhydrite may also form from descending peripheral steam-heated waters as system temperatures and pressures wane. Later mineral growth tends to result in permeability loss unless fractures are being reopened or new ones are being formed. Progressive infilling of veins tracks the life of the system, although rejuvenation and repeated paragenetic cycles are possible.

Although epidote is typically used to define high-temperature geothermal reservoir volumes, in some cases wairakite may be the most reliable indicator of the reservoir top and extent. Wairakite is common in high-temperature geothermal systems (>230°C) dominated by propylitic alteration (Moore et al., 2004). They observed wairakite forming after epidote ± prehnite and either before or after later anhydrite ± calcite. They interpret this sequence of deposition to indicate evolution from system initiation and upflow (epidote), minor cooling (prehnite), mixing with descending steam condensates (wairakite), and descent of sulfate and bicarbonate-rich steam heated waters (anhydrite and calcite). This general sequence, or variations on it, is extremely common, especially in the upper portions of geothermal reservoirs. Wairakite is stable at relatively low concentrations of dissolved CO_2. At higher concentrations of CO_2 it is replaced by calcite (Thompson and Thompson, 1996; Moore et al., 2004).

At Sorik Marapi wairakite is commonly the most abundant calc-silicate mineral (Figure 5). It is found partially filling late-stage veins that appear to have formed at or near current system conditions. It is particularly useful in determining the top of the reservoir since epidote is sparse to absent. It sometimes encapsulates needles of earlier formed epidote or prehnite, and it is found in close association with quartz, calcite, and anhydrite. Geochemical data from wells indicate that the Sorik Marapi reservoir fluid is a dilute (TDS ~1500-1900 mg/kg) neutral Na-Cl brine (Hinz et al., 2021) with low non-condensable gas (up to 0.1 wt% total NCG) primarily composed of CO_2, with minor portions of H_2S and trace amounts of NH_3, N_2, CH_4, and H_2. These characteristics are permissive for the main reservoir being connected to a source of steam condensate or mildly acidic descending fluid. However, wairakite is found deeper in the reservoir at high temperature as well as at shallow levels.

Alternating episodes of boiling, rupture, and influx of overlying steam-heated waters might explain the association of wairakite with quartz and bladed calcite or anhydrite. This may be related to the close spatial relationship of the reservoir to active splays of the Great Sumatran Fault system.



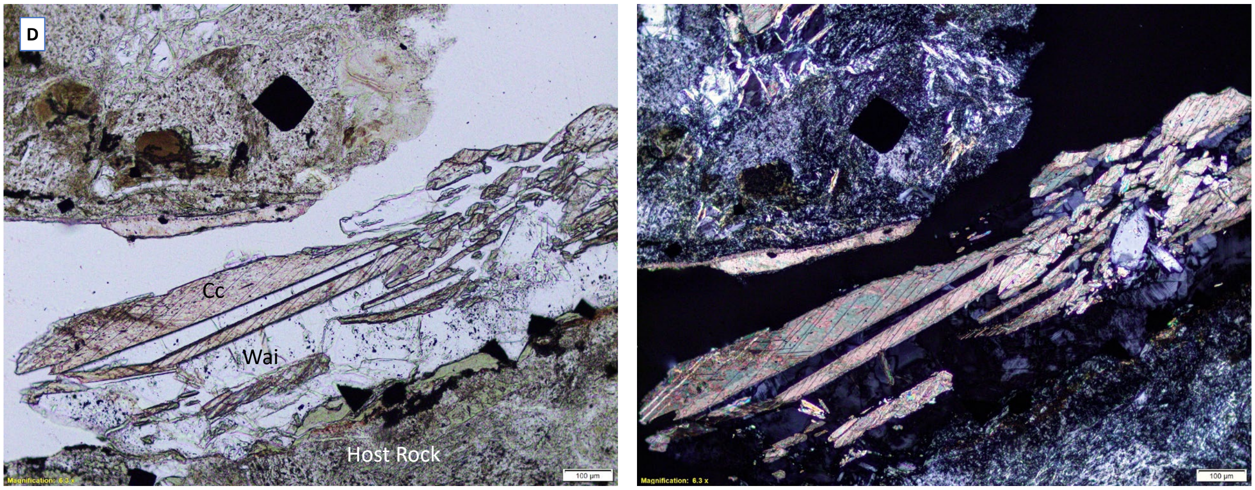


Figure 5. Wairakite at Sorik Marapi. A) Wairakite (Wai) infilling open veins with early quartz (Qtz). B) Wai encapsulating earlier prehnite (Prh). C) Euhedral Wai indicating growth in an open vein, possibly encapsulating minor calcite and epidote. D) Intergrown bladed calcite (Cc) and Wai suggesting boiling conditions.

4.2 Open space textures

Numerous petrographic studies of cuttings and core indicate that well permeability is more likely when open space textures such as euhedral or subhedral intergrowths of common vein minerals are observed. Conversely completely filled vein samples may signal that system permeability has declined in that area. For example, in southwestern Muara Laboh, early epidote at what was expected to be the top of the reservoir is invariably encapsulated in later calcite, prehnite, and quartz. The interval of completely filled veins corresponds with a lack of permeability, and it eventually gives way to highly permeable zones where epidote-adularia-quartz intergrowths with abundant open space are observed. Thus the current top of the permeable reservoir in this area does not match expectations based on either the presence of epidote, resistivity patterns, or smectite based on Methylene Blue. Onset of significant open space in veins and reduction in minerals that are typically late and infilling corresponds with the top of the deep reservoir. Integration of petrographic observations with image log interpretation in this area indicates the association of permeable zones with late silicic dikes that have same trend as one set of major fractures (see Baroek et al., 2018; Stimac et al., 2019).

4.3 Hydrothermal breccias

Hydrothermal breccias are a common feature of geothermal systems that are difficult to identify from cuttings examination under the binocular microscope. With core it is possible to identify such breccias and characterize their textures, mineralogy and likely conditions of formation (Hulen and Nielson, 1988; Hulen et al., 1999).

Sillitoe (1985) described several mechanisms for hydrothermal breccia formation, including release of magmatic-hydrothermal fluids from shallow magma bodies, and magmatic heating and expansion of pore fluids. Such breccias also form at shallow levels coupled fluid overpressure and episodic structural failure that allow decompression and boiling of hydrothermal fluid (Sibson, 1992).

In some porphyry mining districts including some confined to sizable plutons, small volumes of fine-grained porphyritic intrusive rock are temporally, spatially, and probably genetically associated with the brecciation process (Sillitoe, 1985). The intrusive rock may occur as dikes and small bodies, angular breccia fragments, and irregular, partly disaggregated masses within the breccia pipes. The last type of occurrence provides evidence that the magma was still plastic during brecciation.

Most hydrothermal breccias described from geothermal systems contain only hydrothermal minerals, consistent with their shallow source regions. However in rare cases, quenched magma may be observed within the breccia, indicating a deeply rooted magmatic source. Such an example can be seen in Figures 6 to 8, where irregular blobs of chilled hornblende dacite magma are found as clasts in the breccia. Related veins and vuggy parts of the hydrothermal breccia matrix show a paragenesis with initial epidote-garnet-amphibole, followed by prehnite and wairakite, and finally late infillings of calcite in some veins. The breccia texture and mineralogy suggests that brecciation was driven by magma intrusion into an existing hydrothermal system.

In this example the breccia is located at about 5500 ft MD. The well is located near a dacite dome with the same phenocryst assemblage as fragments in the breccia. The dome is too old to be directly associated with a heat source for the system, and the well temperatures indicate the breccia was formed prior to the current thermal regime. There is essentially no open space associated with the breccia and related veins.

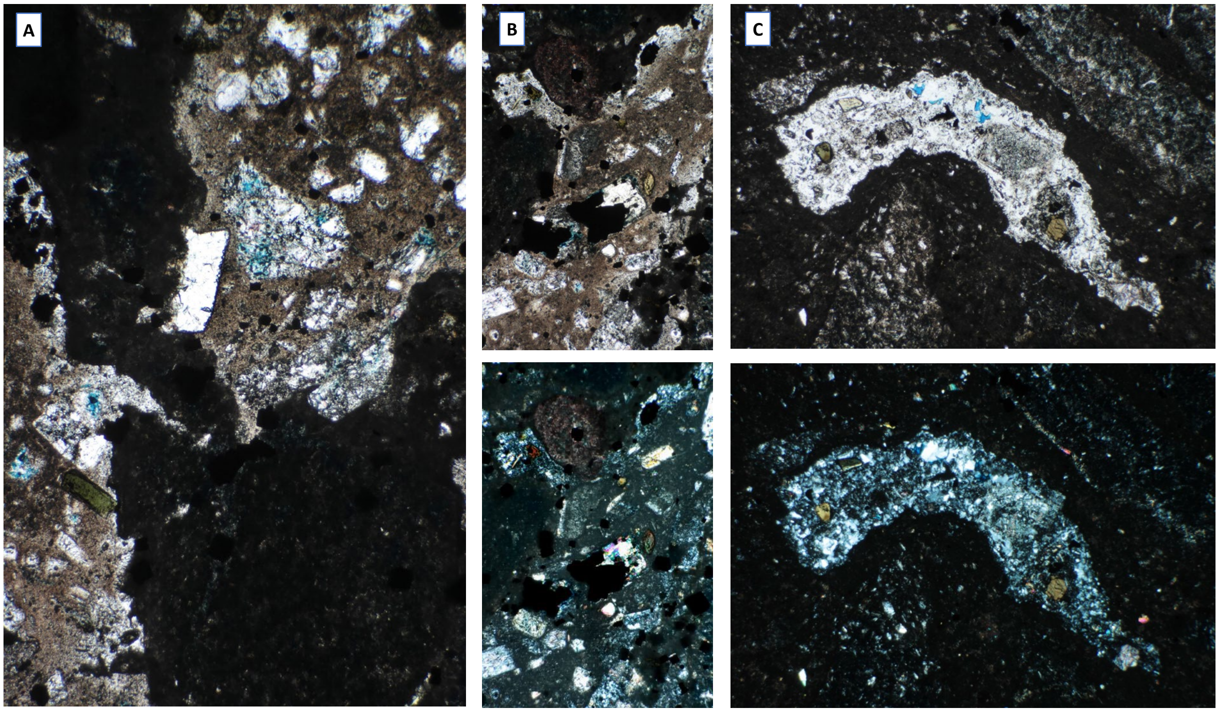


Figure 6. Quenched hornblende dacite magma "enclaves" within rock flour matrix of hydrothermal breccia. A) two adjacent blobs of porphyritic dacite magma with irregular crenulate margins (PPL). B & C) Irregular crenulate blobs of dacite magma in PPL and XPL.

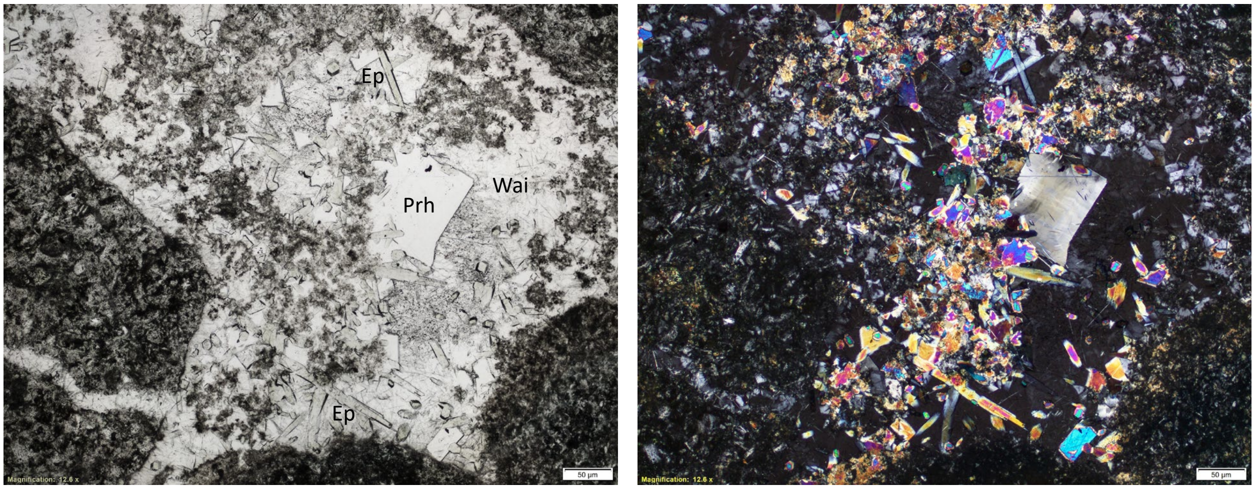


Figure 7. Early vug filling with Ep, followed by Prh, and later infilling of Wai. PPL (left) and XPL (right).

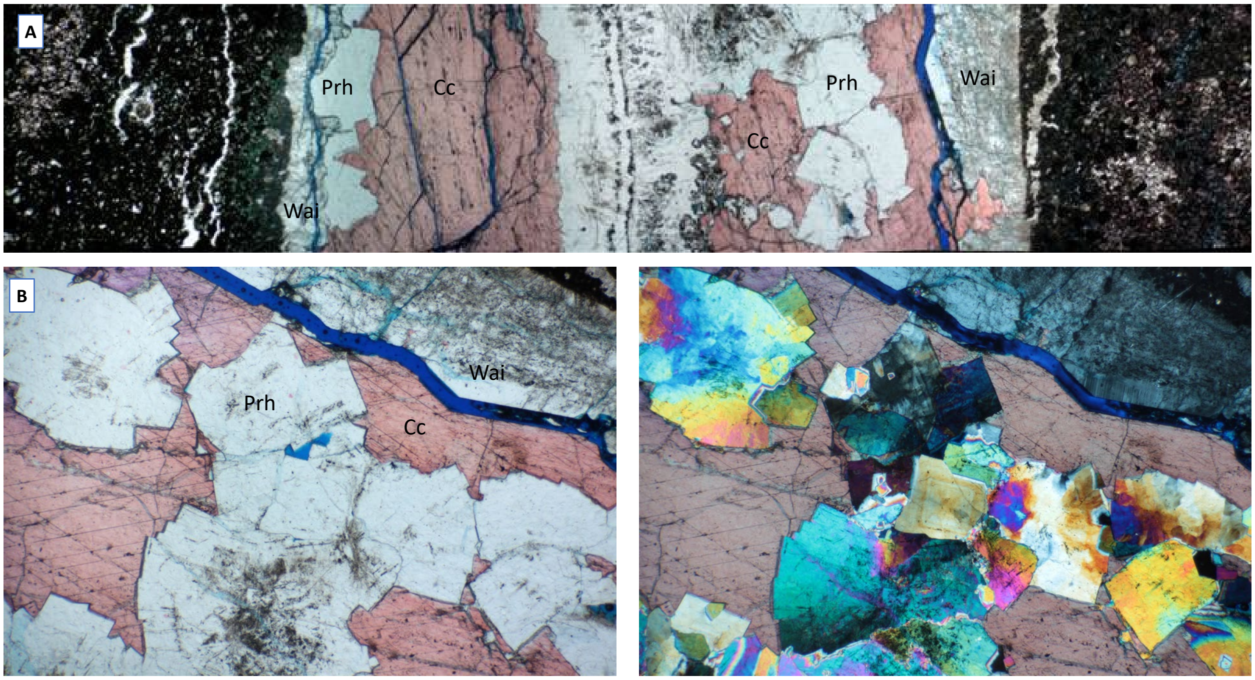
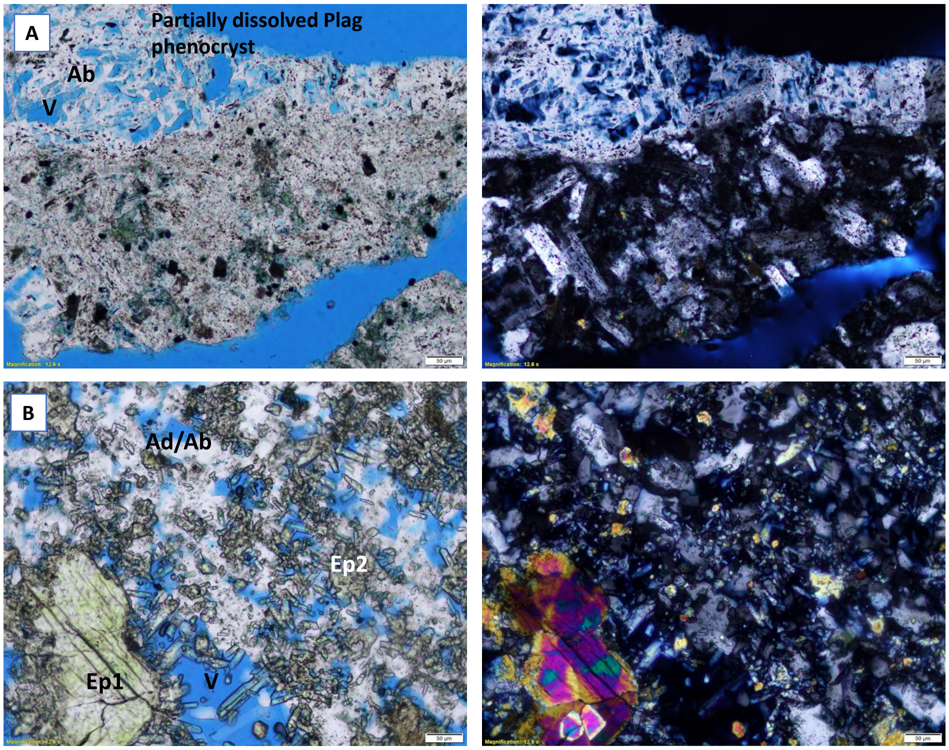


Figure 8. Late vein filled with Prh, Wai, and finally sealed by stained (pink) calcite (Cc). A) full vein and wall rock; vein is about 5 mm wide in PPL. B) Wai and Prh encapsulated in late Cc infilling in PPL (left) and XPL (right); contact between Wai and Cc was opened during sample preparation and filled with blue epoxy.

4.4 Plagioclase dissolution

Mineral dissolution is an underappreciated component of secondary porosity formation and maintenance in the hotter parts of geothermal systems. Perhaps the most important mineral in andesitic volcanic sequences is plagioclase, often comprising 30-60% of the rock. More calcic compositions of this mineral are generally out of equilibrium with hydrothermal fluid compositions and it typically succumbs to dissolution and diffusion mediated reactions to form a variety of Ca-bearing silicates or calcite. Petrographic examination of many samples indicates that there is commonly a net loss of plagioclase by dissolution, with the dissolved cations being transported away by hydrothermal fluid. This is most obvious in parts of the system that could be characterized as upflow based on high temperature but occurs more broadly (e.g., Fig. 2).

For example, the central Bulalo reservoir is well established as the main upflow zone of the system (Clemente and Abrigo, 1993; Estrella et al., this volume). High measured temperatures and the prevalence of epidote and adularia-rich propylitic alteration are consistent with this. Selvages with pronounced plagioclase dissolution around open veins indicate that regions of hot upflow are partially maintained by dissolution of plagioclase, creating vuggy microporosity in and around major fractures. In particular the more calcic cores of plagioclase phenocrysts are susceptible to extensive dissolution and replacement by albite and adularia formed from ascending fluid with more abundant Na^+ and K^+. Based purely on textural observations, this appears to be one of the main sources of secondary porosity in the deeper and hotter parts of volcanic-intrusive sequences in geothermal systems. Dissolution of more calcic plagioclase is consistent with studies of bulk rock composition and mineralogy of the Reykjanes upflow that show Ca^{+2} was preferentially removed from the upflow zone, and, along with other soluble components, is redeposited at shallower levels (Libbey and Williams-Jones, 2015, 2016).



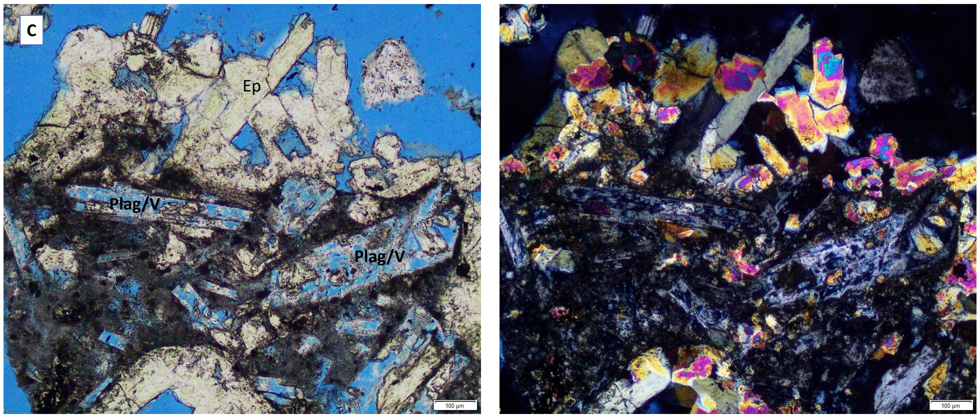


Figure 9. Plagioclase (Plag) dissolution textures in PPL and XPL. A) Bul-115 8400 ft. Fn. gr. porphyritic intrusive with Plag showing extensive dissolution and conversion to albite creating secondary porosity. B) Bul-115 10600 ft. Intergrowth of Ep-Ad-Ab w/abundant open space typical of upflow zones. Two generations of epidote are evident. C) Bul-124 8400 ft. Epidote veins and replacement of andesite lava adjacent to partially dissolved Plag phenocrysts.

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