ANTA 604 Supervised Personal Project

Postgraduate Certificate of Antarctic Studies
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The Formation of Castle Rock
Hut Point Peninsular
Antarctica

Abstract

Castle Rock is situated on Hut Point Peninsula, Ross Island and stands as a steep sided, flat topped monolith 413m above sea level. This distinct shape predominately built from hyaloclastite sequences closely resembles those subglacial volcanoes of Iceland and the Antarctic Peninsula. This study looks into volcanic and sedimentary processes associated with Castle Rock formation in determining possible conditions and stages under which this subglacial eruption formed. It is found that glacier confinement plays a large role in building such a steep sided structure. Structural indicators show periods of rapid and stable glacial melting at each stage of volcanism. Temperature dependant hyaloclastites correlate with these trends and palagonite alteration can be a measure of the amount of available melt water at each stage. This type of formation can be seen as a primary source of information in understanding and characterising paleoenvironemnets in Antarctica.

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1.0 Introduction

Castle rock has an elevation of 413m where it outcrops as a flat topped, steep sided monolith on Hut Point Peninsular, Antarctica. It has a piecemeal architecture mainly consisting of hyaloclastites that reflect the environmental conditions of eruptive stages. Hyaloclastites are products of post eruptive processes, which involve rapid aqueous chilling of basalts to form basaltic glass (sideromelane) which continues to undergo alteration (palagonisation). The water needed for hyaloclastite formation can be either from a submarine, within sea water or glacial, within melt water environment. A submarine origin for Castle Rock has been concluded as untenable for Castle Rock as subsidence rather than uplift appears to be occurring at hut Point Peninsular (Kyle, 1981). Considering this, the evidence found in this project and the close resemblance with other subglacial volcanoes all support a subglacial origin for formation of Castle Rock. Considering this, subglacial eruptions can be a primary source of source of information in understanding the Antarctic cryosphere, which can help to characterise paleoenvironments in Antarctica (Smellie & Skilling, 1994).

This aim of this study is to gain a better insight into volcanic and sedimentary processes associated with the formation and to demonstrate the likely conditions under which this subglacial eruption formed. This is completed by looking at outcrop evidence such as shape and form, structural relationships, lithofacies, lithologies together with the degree of palagonisation within sequences. Both outcrop descriptions and thin section analysis have been undertaken in order to achieve this.

2.0 Background and setting

2.1 Geological and tectonic Setting

Castle Rock is situated on Hut Point Peninsular, Ross Island, and is a part of the McMurdo Volcanic group, a sequence of Cenozoic alkaline igneous rocks that extends around 800km from Cape Adare southwards to the Ross Ice Shelf. Figure 1 demonstrates this volcanic group which follows along the western margin of the Ross Embayment within the West Antarctic Rift System (Cooper *et al.*, 2007; Kyle, 1990). The West Antarctic Rift System is a region of thinned lithosphere 750 to 1000km wide lying between Marie Byrd Land and the East Antarctic craton.

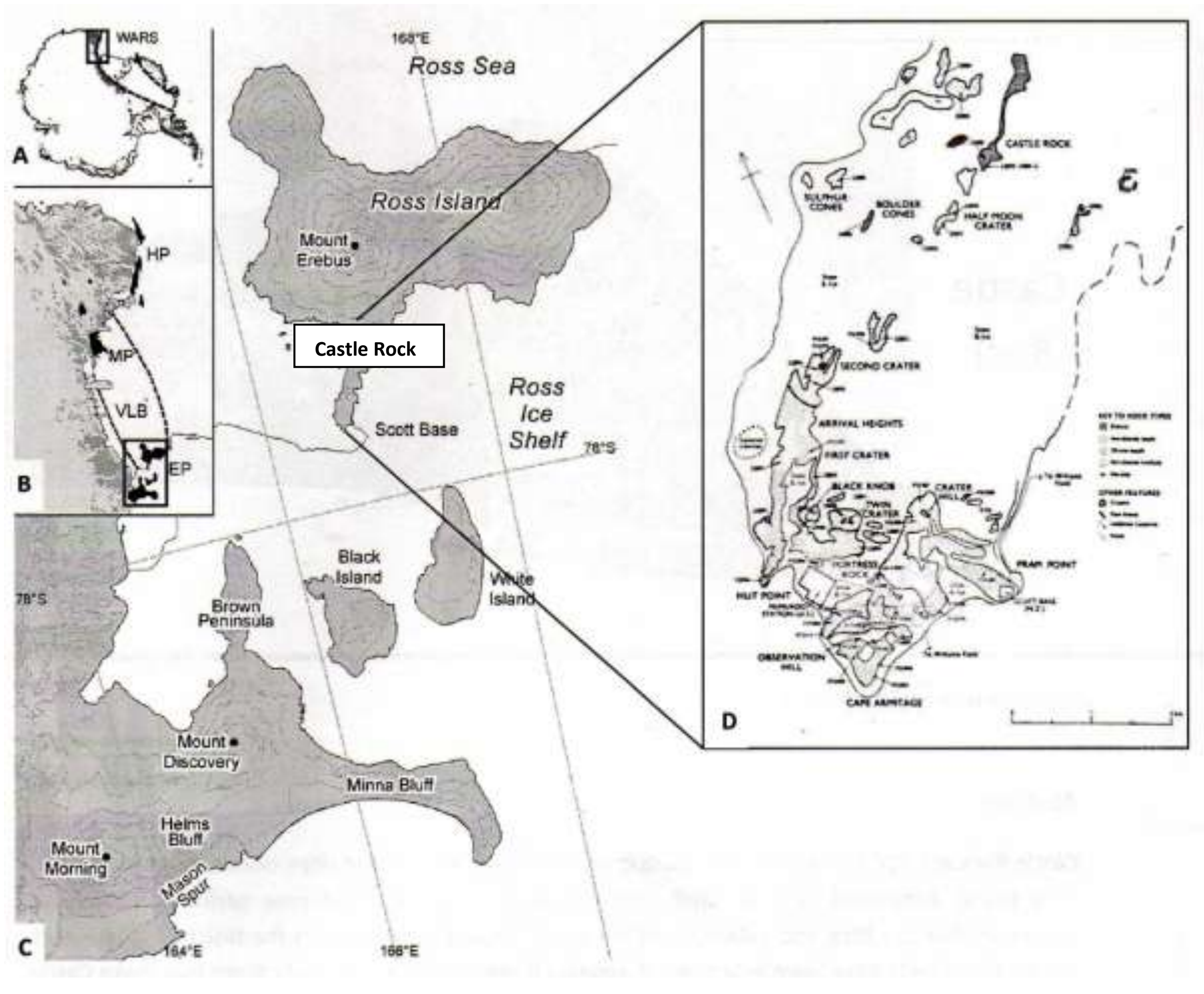


Figure 2.1 Locality map showing: a) the Antarctic continent with bounding faults of the west Antarctic Rift System; b) extensional basin of the Ross Sea; c) detailed map of the provenance of Mt Erebus where Castle Rock is situated on Hut Point Peninsular; d) Castle Rock on Hut Point Peninsular displaying the main volcanic outcrops. (Figure modified from Cole *et al.,* 1971 and Cooper *at al.,* 2007).

Two distinct stages of rifting have been identified for the extension of the Ross Sea (Cooper *et al.*, 2007; Huerta & Harry, 2007). The first stage involved free dispersive extension throughout the Ross Sea starting at the late Cretaceous and carrying into the early Palaeogene time. A series of N-S striking sedimentary basins within the Ross Sea provides a record of extension during this period. The second stage of extension was more strongly focused primarily within the most western basin, the Victoria Land Basin. This stage saw the change to transtensional and strike-slip faulting responsible for the formation of the Terror rift, which is bounded by the rift shoulder of the Transantarctic Mountains to the west. This rifting system has been noted to have ceased extension by the late Palaeogene.

South Victoria Land Basin hosts the southern part of the McMurdo Volcanic Group, where here it is a locus of volcanism indicated as being within the Erebus province (Kyle and Cole, 1974). The Erebus province includes Mt Erebus, on Ross Island and Hut Point peninsular as demonstrated in Figure 1D, consisting of range of alkali basalts, trachyte and phonolite (Kyle & Cole, 1974). The cause of this volcanism has been extensively argued within literature. Views between mantle plume source popular in early literature (Behrendt *et al.,* 1991) versus the more recent theory of plate dynamics of decompression melting (Rocchi *et al.,* 2002).

2.2 Location and geography of research area

Castle Rock (77^{o}48’S, 166^{o}46’E) has an elevation of 413m a.s.l where it stands as a distinctive flat-topped turret-shaped monolith. It is situated around 3.5 km north of Scott Base on Hut Point Peninsular, Ross Island, Western Ross Embayment, south of Victoria land. The surrounding landscape has been extensively glaciated where Castle Rock today stands ice free.

2.3 Hyloclastites and palagonite definitions

Hyloclastites are fragmental and glassy rocks as they are formed during rapid magma quenching in glacial melt water (Frolova *et al*., 2005). Baslatic glass is thermodynamically unstable material, which is sensitive to alteration. This alteration product is referred to as palagonite where palagonite is the alteration material from the hydration and oxidation of the basaltic glass in water (Nayudu, 1964). The early work from Shausen (1851) described palagonite as "a fully transparent wine-yellow to resin-brown mineral of vitreous lustre and hackly concoidal substance being very similar to gum Arabic brown sugar" (from Nayudu, 1964). The colour of palagonite is significant as it can be highly variable, ranging from shades of yellow to shades of orange to brown and is largely temperature dependant (Stroncik & Schmincke, 2002). Palagonite can display varying degrees and levels of alteration. Initally palagonite is the first product of volcanic glass transformation and simply coats glase edges. It can also coat vesicle walls within glass fragments leaving their central parts empty. Palagonite coats gradually grow and fill intergranular spaces forming pore-type cement. Palaganite then subsequently transforms into smectite and vesicles in the glass can become filled (Frolova, 2007).

3.0 Methodology

The initial part of this study involved field work on the 26th of December 2010 around the Castle rock outcrop. The base of Castle Rock above the snow line was covered and the peak was accessed up the NE face. Field methods included measurements of strike and dip of bedding, where possible collection of orientation related rock samples and describing and observing changes in lithofacies was taken. Access to site was by skidoo where the outcrop was traversed by foot.

Among the rock samples obtained, fifteen were selected for analysis that represented the array of variation at the site. These include samples from the following areas:

- Hyaloclastite beds from different areas of change
- Palagonite beds
- Basalt clasts
- Pillow lava from both hyaloclastite and palagonite
- Main vent
- Baked zone around central vent
- Intrusion/Dyke

Thin sections were prepared from the selected hand samples on Logitec equipment. All samples were reduced down to a thickness of 30 µm and mounted using epoxy resin and a cover-slip. Petrographic analysis and optical microscopy was then carried out on all thin-sections using a standard Zeiss monocular microscope, fitted with a horizontal rotating stage.

4.0 Results

4.1 Field sketch

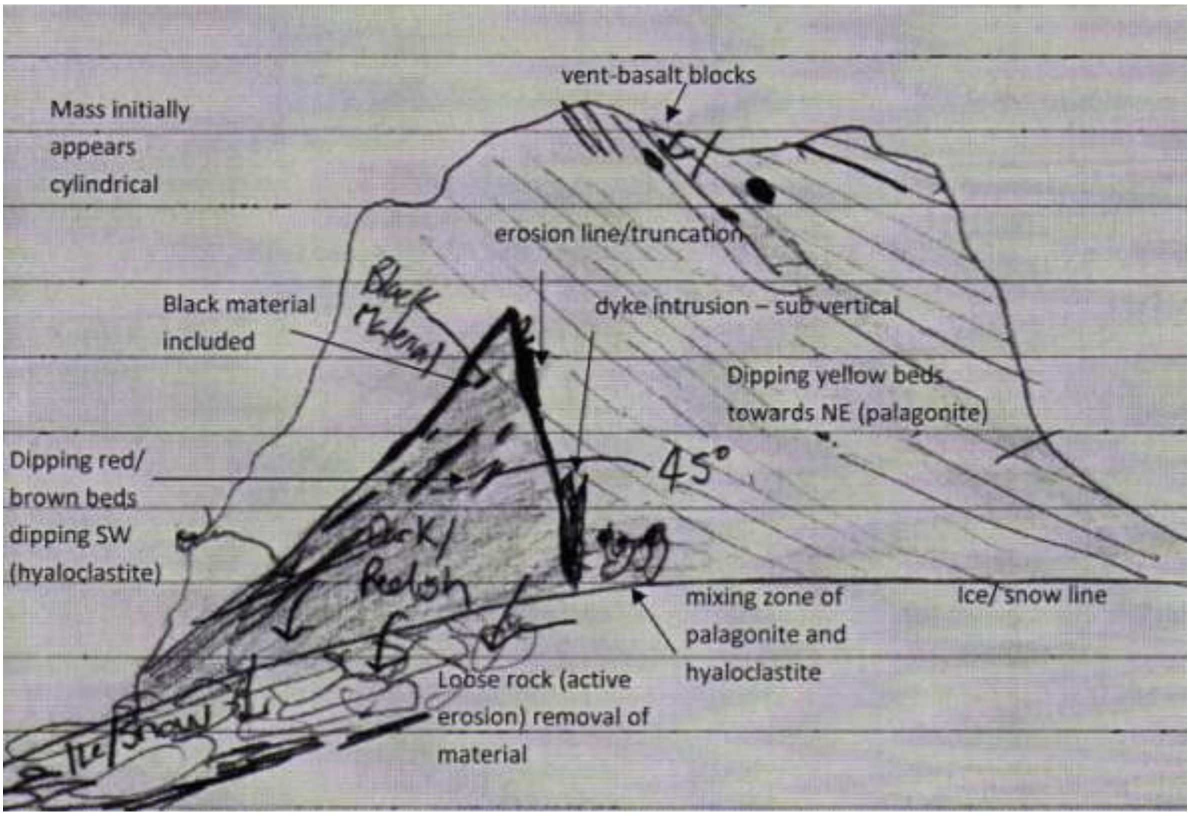
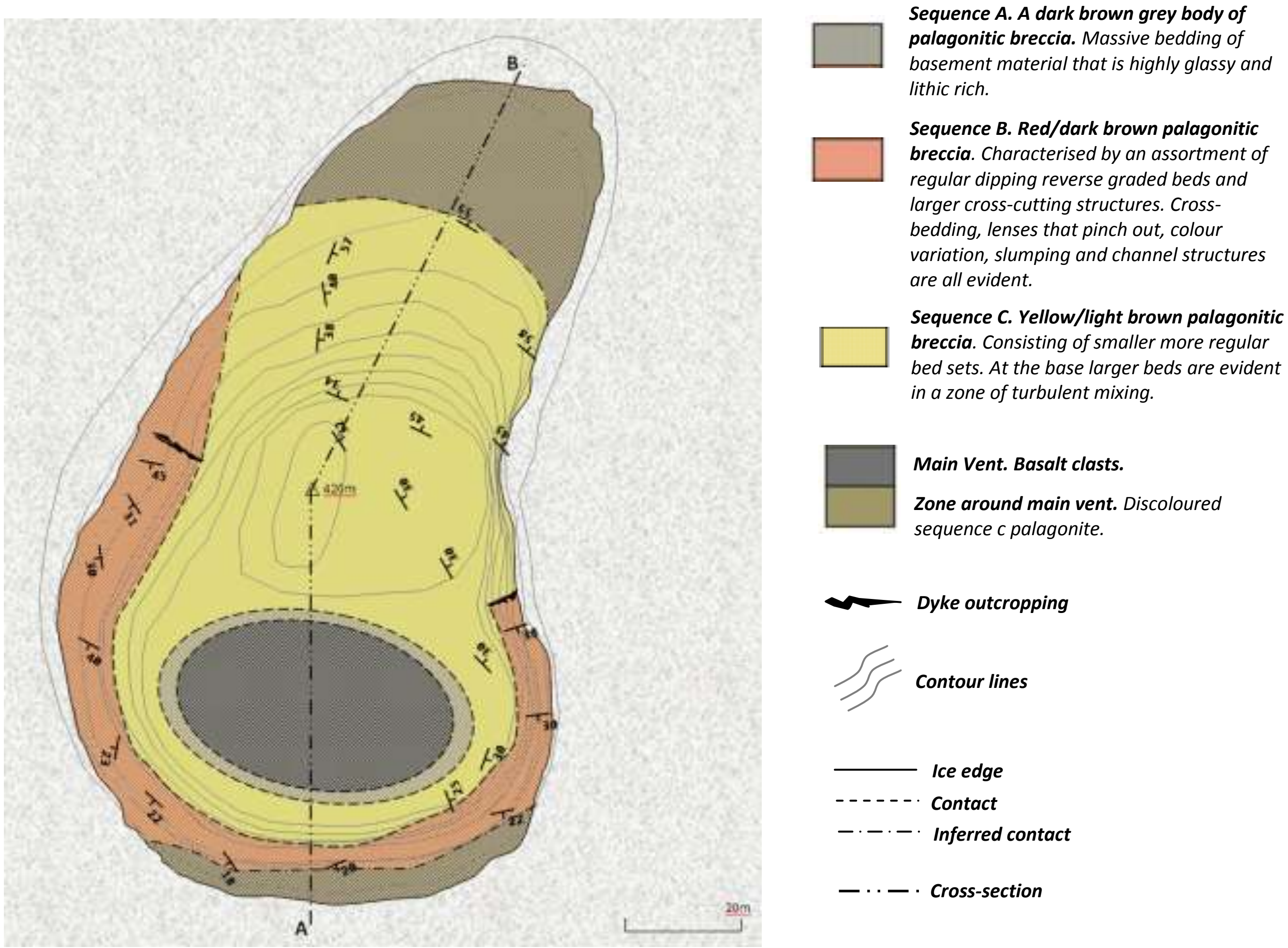


Figure 1. Field sketch Castle Rock looking north west. The distinct flat-topped turret-shaped monolith stands above the snow and ice line consisting of varying dipping sequences.

4.2 Map and schematic cross-section



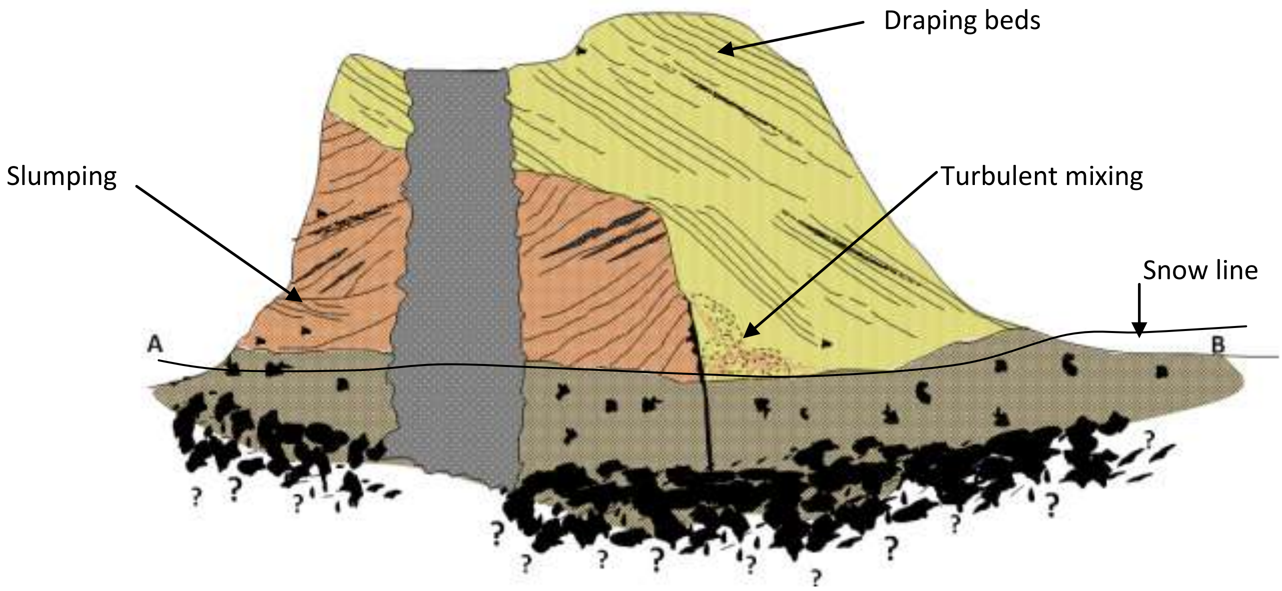


Figure 2. Diagram drawn to represent the different sequences observed at Castle Rock.

4.3 Outcrop descriptions of lithofacies

Sequence A – *A dark brown grey body of palagonitic breccia. Massive bedding of basement material that is highly glassy and lithic rich.*

Sequence A refers to the dark hyaloclastite material found at the base of Castle rock. It outcrops near the snow line at the south beneath sequence B and again in the north beneath sequence C, further extending up the peninsular into other dark hyaloclastite mounds at the surface.

At the south end, this darker material lies as a platform for the above sequence B with a distinct gradational boundary where bedding is poorly evident but tended to follow that of sequence B (Figure 3). Here it is characterised as dark brown grey in colour, highly glassy, poorly sorted clastic rich mass with a medium sized brown glass sand matrix. Clasts are basalt in composition and occur as and partially intact pillows or lava lobes up to 30cm in length or as angular to sub-angular fragments.

Figure 3. South end, dark hyaloclastite/breccia following same trend as above sequence B.

At the north end this sequence is slightly lighter and appears to have a very irregular contact with sequence C, which tends to drape and jig-saw fit into the darker hyloclastic breccia base (Figure C). Here sequence C with its irregular base is largely bedded with a dip to the north with highly variable dip angles. This hyaloclastic material here is clast rich, again with partially intact lava lobes of basalt and angular to sub-angular fragments which are held in place with a dark brown glassy sand matrix.

Overall, this sequence A is a darker lithic rich basement of poorly sorted beds, which are friable to moderately indurated (see supporting appendix). At either end where they outcrop, this sequence tends to be associated with the beds of the sequences that overlie them.

Figure 4. North end, dark hyaloclastite/breccia mixing and pinching up into lighter sequence C.

Sequence B - *Red/dark brown palagonitic breccia. Characterised by an assortment of regular dipping reverse graded beds and larger cross-cutting structures. Cross-bedding, lenses that pinch out, colour variation, slumping and channel structures are all evident.*

Sequence B refers to the wedge shaped red brown hyaloclastite, which outcrops from around the northeast to southwest face (Figure 2). This sequence has a maximum thickness of 25 metres above sequence A. Overall bedding predominantly dips in a southward direction at an angle of 20-30 degrees where the beds typically display reverse grading shown in Figures 4 and 5.

Figure 4. Alternating darker (black) and lighter (red) dipping beds of sequence b towards the west.

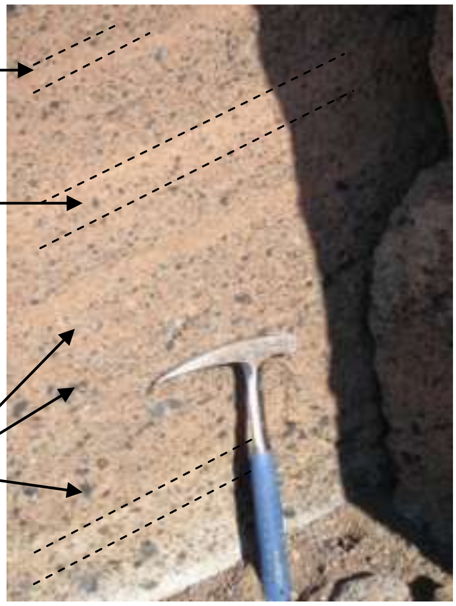


Figure 5. Close up of palagonite dipping beds displaying reverse grading.

There are also areas where there have been inclusions of pillow or lava lobe basalts within the beds (Figure 5). These tend to have fragmented edges with a fine-grained film surrounding the entire clast.

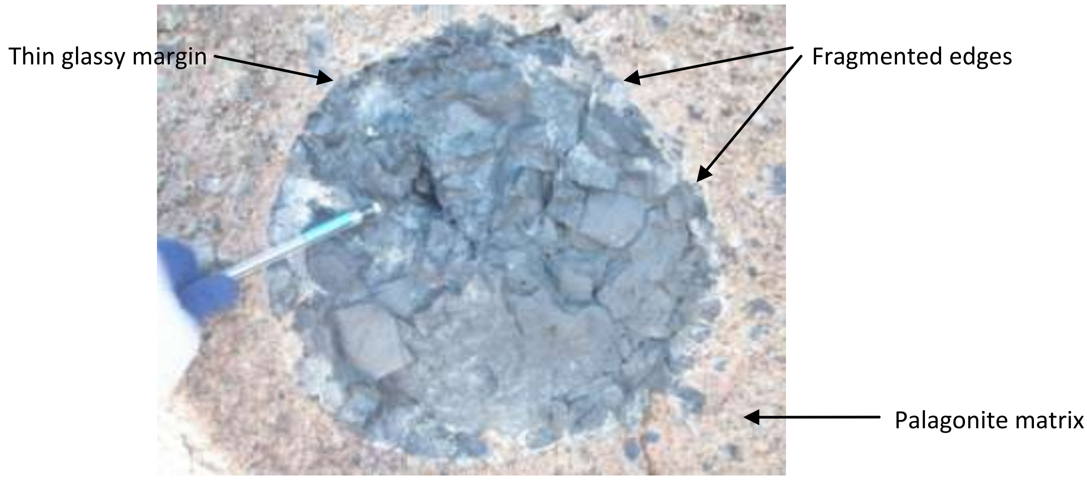


Figure 6. Pillow or lobe within palagonite sediments. A finer grained rim surrounds the glassy lobe.

There is also a high degree of variability within this sequence. Colour, bed thickness, sorting, strike and dip are highly variable. At the south end, cross-cutting, slumping and channel structures are evident (Figure 7). On-lap of beds, horizons or finer grains and lenses of blocky material that pinch out all contribute to the variability within this sequence. Erosional surfaces between beds occur regularly throughout this sequence.

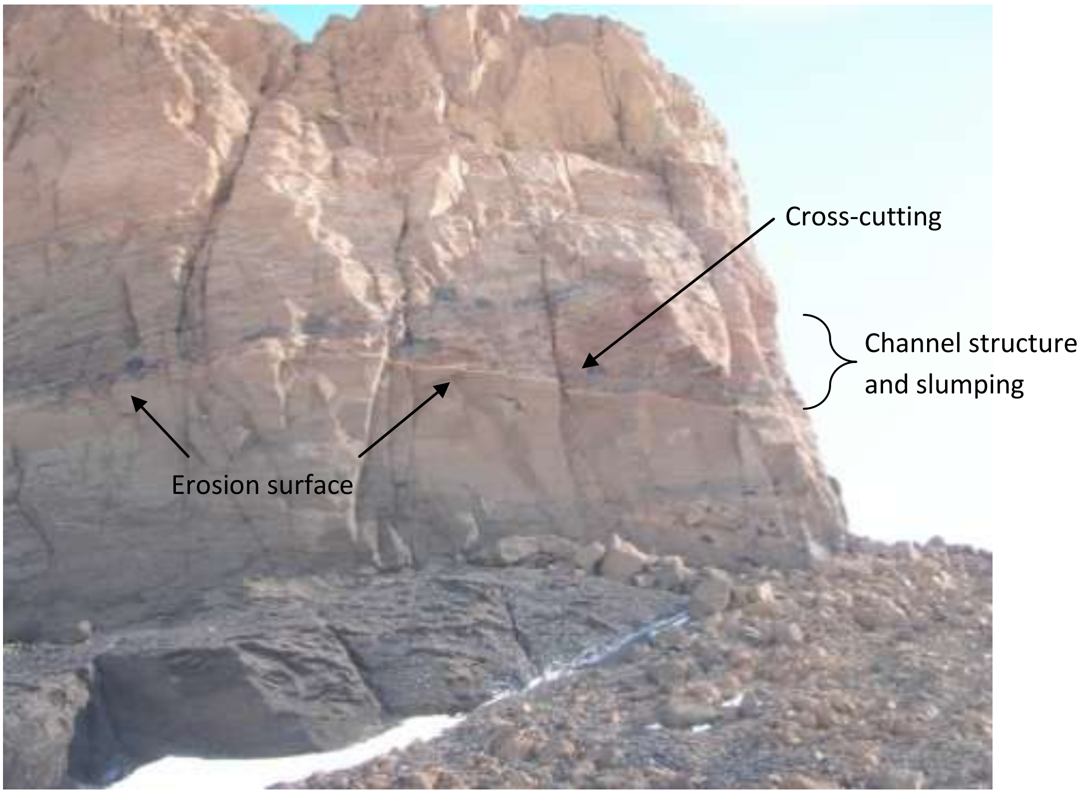


Figure 7. View at south end. Dark basement bed (sequence A) followed by the highly variable sequence structure B. Channel structures, erosional surfaces, cross-cutting and slumping evident.

There are two basaltic squeezes or dyke structures that occur, one at the east face and the other on the west face. Contact surfaces are irregular and are seen pinching out and fingering into the neighbouring beds of this sequence. The dyke on the east face has been truncated by sequence C and resembles an erosional contact between the two sequences. Figure 8 demonstrates the nature of this contact where pieces of the dyke and sediment from sequence B has been mixed and incorporated into the base of sequence C.

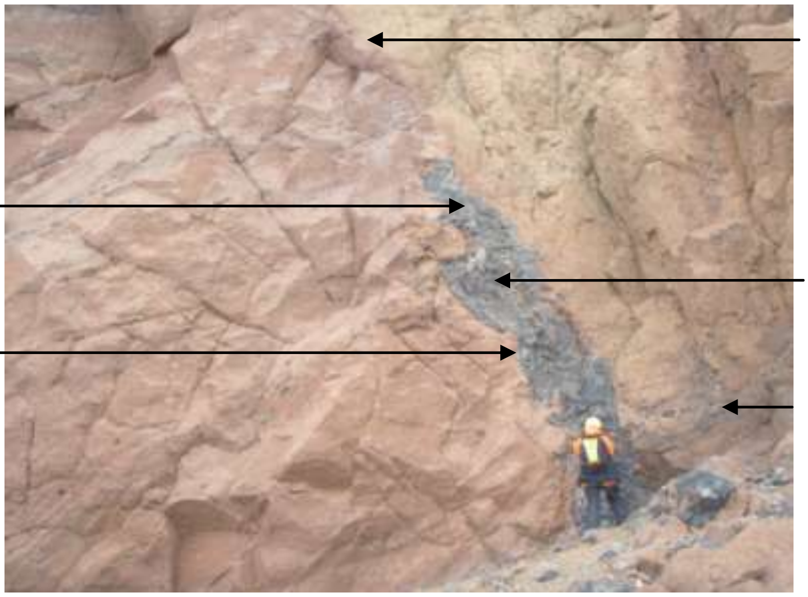


Figure 8. Dyke structure or basaltic squeeze into sequence B. An erosion surface separates sequence c that truncates sequence B.

A second contact between B and C is established on the west face however, this is not as distinguishable and appears to be gradational between the sequences.

Sequence C - *Yellow/light brown palagonitic breccias, consisting of smaller more regular bed sets. At the base larger beds are evident in a zone of turbulent mixing.*

Sequence C is the lighter coloured palagonite breccia compared to other sequences. It occurs as a body that caps castle rock and drapes over the majority of the north side. This is the last of the sequences to occur at castle rock. It consists of dipping beds towards the northeast where dip angle tends to steepen nearer the base. The layers formed are much more uniformed compared to sequence B where overall there is more consistency in the bed structures. Figure 9 demonstrates beds at the top where thickness and grading are uniform. Beds tend to display reverse grading and matrix supported angular clasts and lithics. Finer horizons of pale glassy sand are evident between poorly sorted and graded beds. Figure 10 displays the inclusion of larger basaltic lava lobes or pillow lava are also incorporated into this mass.

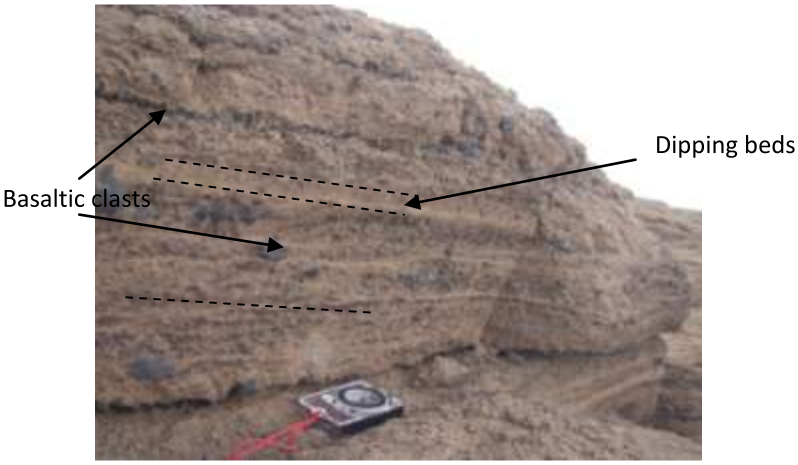


Figure 9. Alternating clast rich and fine sand size dipping palagonite beds, reverse grading evident.

Figure 10. Pillow/lava lobe within fine sand size palagonite.

At the base near the contact massive beds and mixing with sequence B material is apparent where clasts from the dyke seem are to be included. Figure 4 displays a zone of mixing which tends to mix out from the base and pinch up-wards.

At the top of Castle Rock outcrops a large volcanic plug that extends a rough diameter of thirty metres. The vent is characterised by black basaltic clasts with a range of textures. These consist of clasts that display a high degree of vesicles some showing alignment to clasts that are ropey and spindly (Figure 11). Around this vent area is a zone of discolour from a pale yellow to a grey ashy almost burnt appearance. Figure 12 demonstrates the extent of this zone that is incorporated almost mixed into the pale brighter sequence A.

Figure 9. Central vent region with basaltic clasts and blocks at the top of Castle Rock.

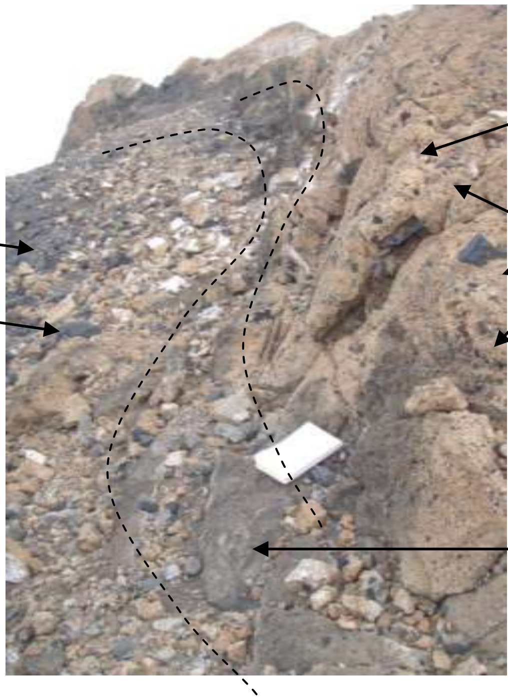


Figure 10. Baked palagonite margin around a central vent area at the top of Castle Rock.

4.4 Mineralogy and Microscopic textures

Palagonite and Basalts

Samples taken from Castle Rock (appendix 1) have been examined under the microscope where various degrees of palagonite tuffs are evident. Palagonite is the alteration product of basaltic glass and occurs when rapid magma quenching in cool water temperatures and hydration and oxidation of the glass can occur (Frolova *et al*., 2005).

Stroncik and Schmincke (2002) explain that the macroscopic appearance of volcanic glass deposits depends on the intensity of alteration, which includes palagonisation and the formation of secondary cements. Two main types of palagonite can be distinguished 1) yellow, isotropic, clear “gel palagonite”. 2) tallow-brown, slightly anisotropic, fibrous palagonite, which developes during more advance steps of palagonite on the outer surface of gel palagonite (Frolova *et al*., 2005.

With this in mind results from these palaganised rocks have been divided into areas that reflect condition of the volcanic glass (sideralomine), the extent of palagonisation and the amount of intact vesicles versus individual shards within each slide. Individual assessments of each slide are in appendix 2. Three levels of palagonisation have been recognised.

Palagonite

<u>Low-level alteration</u>

Less than 15% palagonisation, alteration clays low <5% usually with a high degree of basaltic sand grains.

This is classified as low level as there is a general absence of palagonite gel formation around glass shards and alteration clays are uncommon. Colours under plain polarised light (ppl) appear dull and darker. Basaltic sand grains tends to me most evident in the samples where fresh glass appears to be a progression from a black and dark brown towards a light brown and orange colour. Within this plagioclase, microlites often show alignment and twinning. The overall texture is highly vascular with a bubbly/porous appearance. Skeletal olivine fragments are evident.

Samples: JH018, JH046, JH101

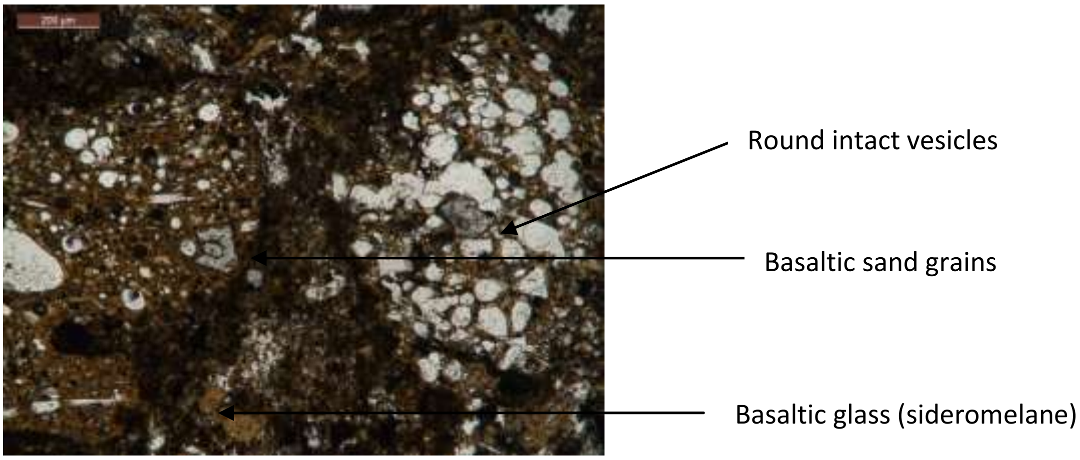


Figure 11. Sample JH001, displaying basaltic sand grain in ppl. This is highly vesicular in areas which are mainly intact. Patches of sideromelane and palagonisation also evident

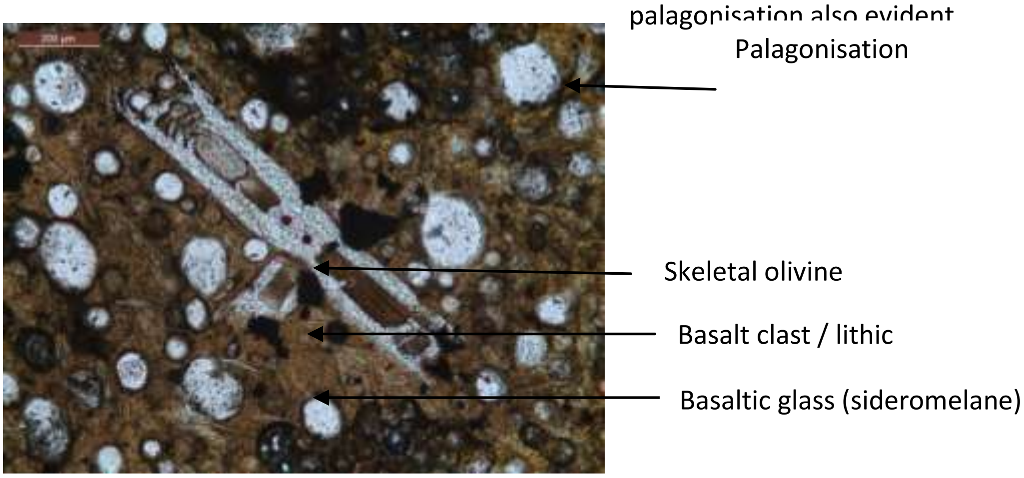


Figure 12. Sample JH001 displaying in ppl a skeletal olivine phenocryst within a groundmass of sideromelane.

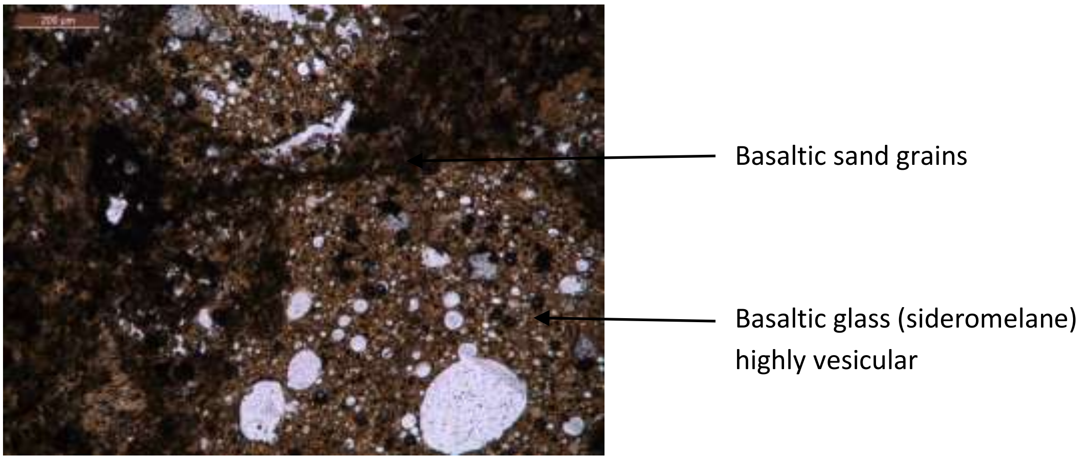


Figure 13. Sample JH018 displaying basaltic sand grain and sideromelane.

<u>Medium level alteration</u>

Around 20% palagonisation, alteration clays low ~5% usually with a moderate degree of basaltic sand grains.

This is classified as medium level alteration as palagonisation has started to occur around sideromelane vesicles in some areas and in patchy areas. Colours under ppl appear moderately brighter and oranger than the low-level. Basaltic sand grains still appear to be dull in colour and are still prominent throughout samples. Sideromelane appears brighter and more extensive. Within sideromelane are plagioclase microlites which also often show alignment and twinning. There is minor evidence of further alteration as some highly-birefringent clays are seen around extremely perished edges. The overall texture is highly vascular with a bubbly/porous appearance. There are more broken grains and individual shards at this level compared to the low-level alteration. Skeletal olivine fragments are evident throughout.

Samples: JH001, JH005, JH045

Sample

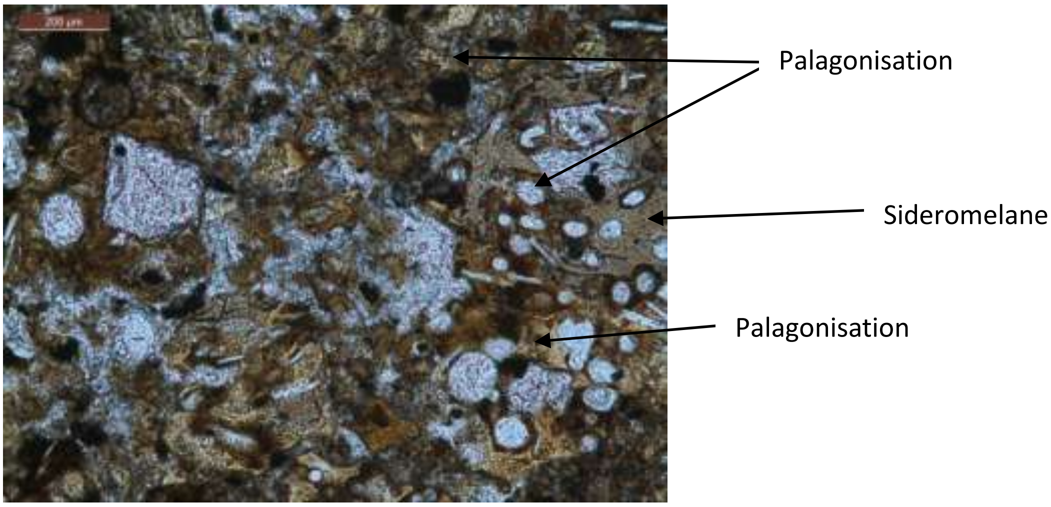


Figure 14. Sample JH005 in ppl shows extensive areas of palagonisation. Coating of vesicles and degradation to shard walls is evident.

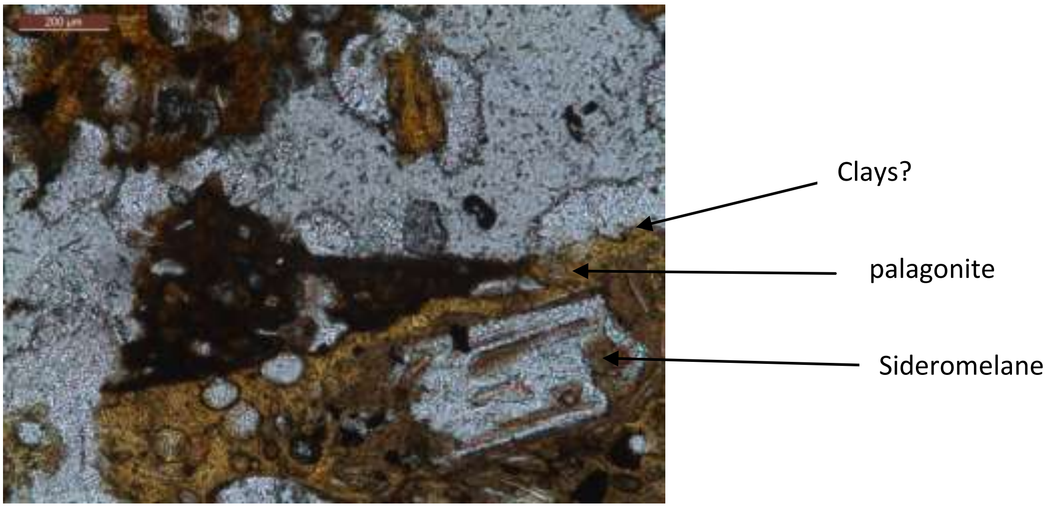


Figure 15. Sample JH045 in ppl shows areas of palagonisation around sideromelane. Edges which are more degraded tend to show evidence of further alteration of clays.

High level alteration

30%> palagonisation, alteration clays high with low presence of basaltic sand grains.

This is classified a high level as palagonisation as palagonite gel coatings or rim banding is extensive around most sideromelane, even within closed vesicles. Colours under ppl appear bright orange to yellow. Basaltic sand grains still appear to be dull in colour and are still evident within sample but do not dominate. Sideromelane appears bright and more extensive. Within the sideromelane are plagioclase microlites which also often show alignment and twinning. There is evidence of further alteration as some high-birefringent clays are seen around extremely perished edges. The overall texture is highly vascular with a bubbly/porous appearance. There are more broken grains and individual shards at this level, with additions of extensive patchy palagonite areas. Skeletal olivine fragments are evident throughout but more fragmented.

Samples: JH017, JH028, JH039

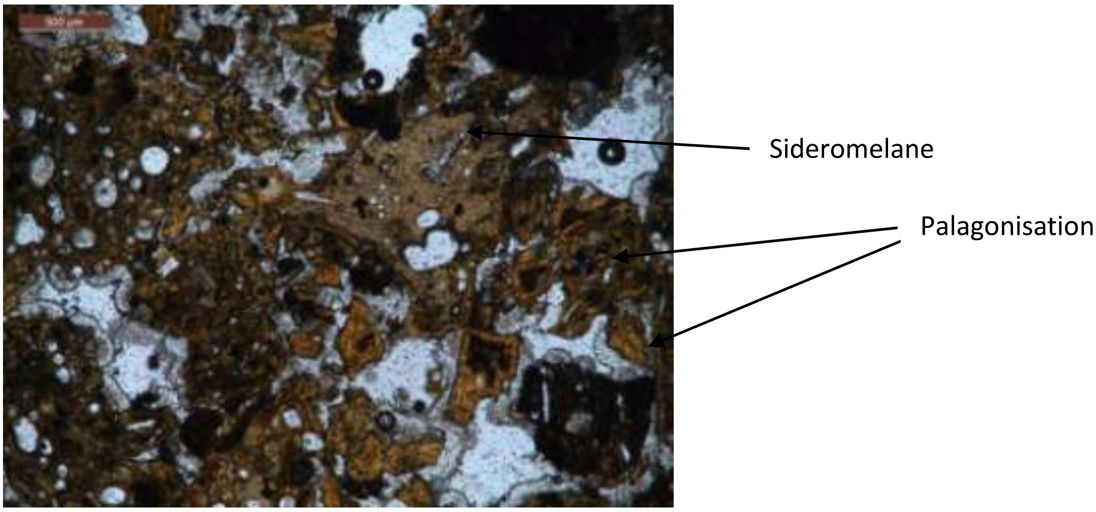


Figure 16. Sample JH017; in ppl shows palagonite gel layers coating edges of sideromelane fragments and individual shards. Areas of alteration clay formation are also evident.

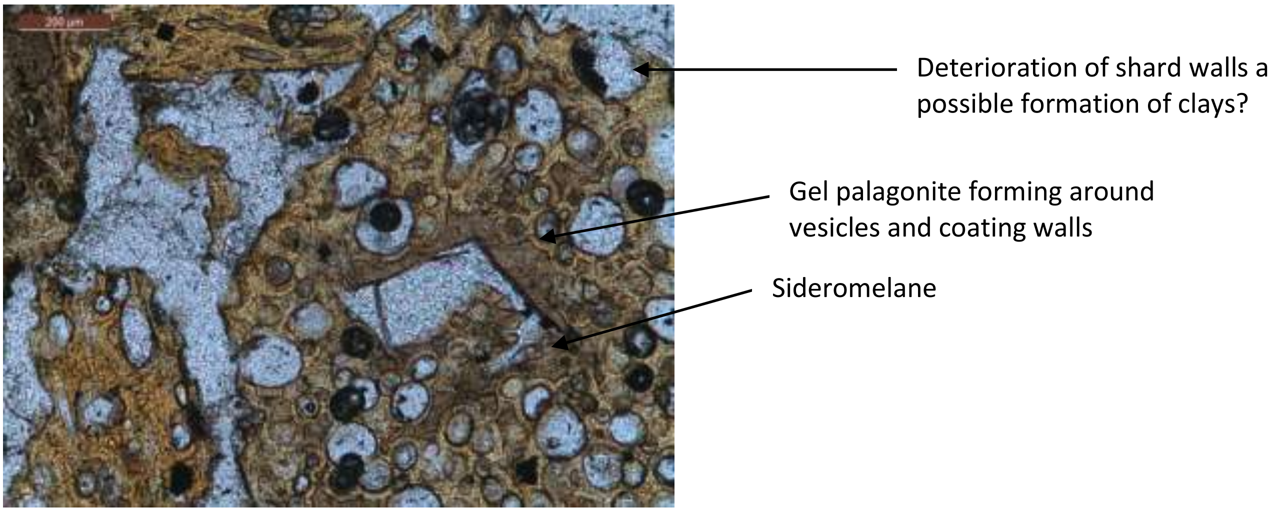


Figure 17. Sample JH028 in ppl: palagonisation is extensive; coating the insides of vesicles is prominent. Alteration clays are evident.

Basalts

Olivine basalts have been identified in many areas of the outcrop. They collectively all appear to have the same composition of olivine, plagioclase and opaques (see appendix 2). Olivine phenocrysts are highly skeletal and lath-shaped plagioclase shows twinning. In some instances the plagioclase appears aligned even with clasts samples found within a palagonite groundmass. A component that is most highly variable within the basalts is the amount of vesicles, how elongated and aligned they are.

5.0 Discussion and Interpretation

The structural associations and lithofaces found at Castle Rock closely resemble those of subglacial volcanoes in Iceland such as the Table Mountains (Kyle, 1981, McPhie *et al*, 1993, Nayudu, 1964 and Smellie, 2007) and volcanic deposits at Brown Bluff, Antarctica (Skilling, 1994 and Smellie & Skilling, 1994). The shape of Castle Rock is very distinctive of a tuya, which have a distinctive shape having formed when lava erupts through a thick glacier or ice sheet. These are typically steep sided, relatively flat or gently domed summit regions with or without a crater and oval or straight sided shapes. Castle Rock exhibits this shape as demonstrated in figure 1 and the cross-section of figure 2. The idea of glacial confinement is an idea responsible for such a steep sided form. Smellie (2007) explains that meltwater created by a polar subglacial eruption will therefore be confined in a vault overlying the vent. Colder temperatures of polar glaciers are stronger and deform much more slowly requiring more energy to bring ice up to melting point. Ice walls of a lake or vault will therefore recede more slowly. Because of this slow rate of reducing walls the formation and build upwards with hyaloclastite sequences and volcanic breccias that can further more act as a buttresses contributing to tall steep sided structures.

Lithological characteristics and sequences structures reflect stages of lake formation, which is critical towards understanding formation. Within the three sequences identified at Castle Rock, all reflect different stages of subglacial and glacial lake progression. Sediment lithofacies indicate current activity and mass flows during each eruptive phase (Smellie & Skilling, 1994). To contribute to that the stages and rates at which walls reduce can be indicated (Smellie, 2007). Interpretation of each sequence is as follows;

> *Sequence A* indicates a relatively early stage in the sequence formation seen as the basement of Castle Rock. Poor bedding, rubble texture, poorly sorted with evidence of partially intact pillows throughout is evident. The limited space and water available is an indication of the lack of bedding and sorting. In structures such as these this is usually referred to as the pillow, or lava lobe building stage however these are seldom observed intact (Tazieff, 1978). It could well mean that this early stage of volcanism incurred

breaking of original pillow basalts then breaking and mixing of these when activity increased and water became available.

Sequence B is the next in sequence and represents a stage where glacial melting and ice wall receding was relatively fast. The formation of being and reverse grading suggests a larger lake and water movement to allow for dipping bedding structures to form downslope and larger clastics to settle out first out of solution. However, there is much more variety of structures. Slumping, cross-cutting and forest beds are created when ice is melted creating more room for material. Essentially what is occurring here is settlement and bedding out of solution in a confined area created by the ice walls, as these widen the unstable in situ hyaloclastite is resedimented downslope (McPhie *et al.,* 1993). Partially intact pillow basalts occur also with the hyalocatistc matrix. These are likely to be remnants from the initial stages of volcanism continuing to be incorporated in to the water slurry mix.

Sequence C is the last of the sequences observed and represents a stage where the glacial lake was at its widest and fullest. This sequence consists predominantly of dipping beds that cap the top and drape down the northeast side of the formation. The dip angle of these beds gets steeper further down slope. Beds are more unformed and more consistently spaced and reverse grading is more prominent compared to sequence B. At this stage ice would have melted all the way to the surface, with a larger lake area. It was likely before this sequence, sequence B experience large scale slumping in the northeast section. The remaining of sequence B would therefore act as a buttress and with a significant area opened up towards the northeast would have catered for the deposition of sequence C. High density turbidity currents would have dominated the earlier stage of this sequence evident from the mixing of both sequences at the base.

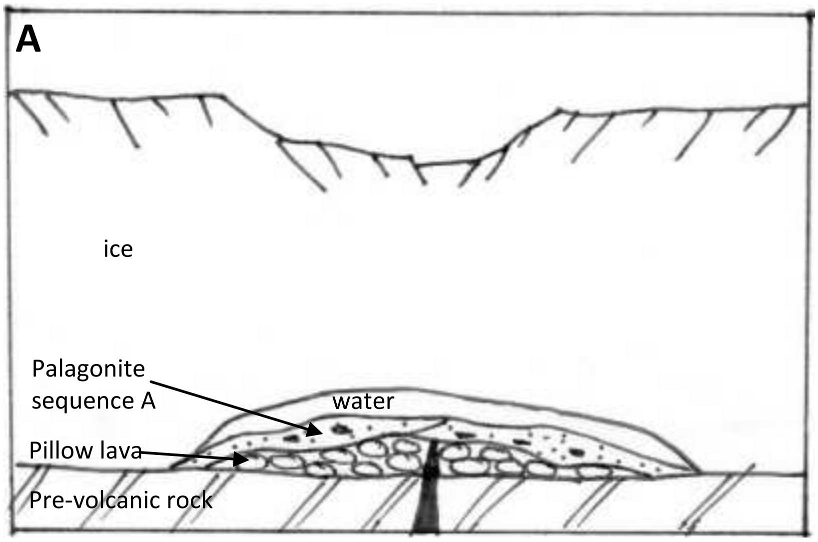
Examination of the lithology of the hyaloclastite of each sequence further supports how ice walls may have responded and how much melt is generated at the time of eruption. Stroncik & Schmincke (2002) explain that dark-brown to red-brown palagonite is formed in elevated temperatures in the vicinity of fumarolic activity. Sequence B has the very distinctive dark-brown to red-brown palagonite colour. The volcanic activity at this stage would have been very hot and gaseous with more thermal energy to melt the surrounding ice walls. This supports evidence of major slumping structures due to widening walls no longer able to support unstable insite beds. In comparison lighter coloured palagonite is formed at lower ambient temperatures (Stroncik & Schmincke, 2002). Sequence C is very much lighter than sequence B, where the lack of slumping structures in the beds and the confided distance material drapes outwards suggests ice wall advance was very slow at this stage.

There is a relationship between the amount of alteration and degree of exposure and temperature to meltwater. Alteration of hyaloclastites to form palagonite involves the hydration and oxidation of volcanic glass through dissolution and precipitation process (Frolova *et al*., 2005 and Nayudu, 1964). This together with basaltic glass being a thermodynamically unstable material is extremely sensitive to reactions and alteration relatively rapidly in cold water (Frolova *et al*., 2005). With the samples examined, a weak correlation between sequences and level of alteration exists. It is found that the level of alteration, the amount of palagonite increases in samples taken from sequence A to C. This supports conclusions about increasing water levels and decreasing temperatures during the eruptive stage of sequence C. Here conditions would have allowed for fast quenching and enough available water to allow alteration to reach advance levels. Samples from sequence C displayed the lowest levels of alteration. This suggests although fast quenching of lavas may have occurred without sufficient amount of melt water generated, the amount of palagonisation that can occur is restricted. Evidence that supports fast quenching in all cases is the skeletal olivine structures and the vesicles within glass fragments and shards.

With evidence found at Castle Rock that further support its subglacial origin, the possibility of using the ice thickness of ice needed for this formation can be used as in indication of previous ice levels. K/Ar dating has been undertaken on the dyke with sequence B giving a K/Ar age of 1.18 ± 0.05 m.y. (Kyle, 1981). This helps constrain a time where Hut Point Peninsular during the formation of Castle Rock was covered by a possible expanded Ross Ice Shelf (Kyle, 1981). The height of Castle Rock at 413m suggests ice thicknesses must have been in excess of this height. Original ice thickness has a major control on the lithofacies which result in the formation of tuyas (Smellie, 2007). Castle Rock lithofaces support ice levels at this height.

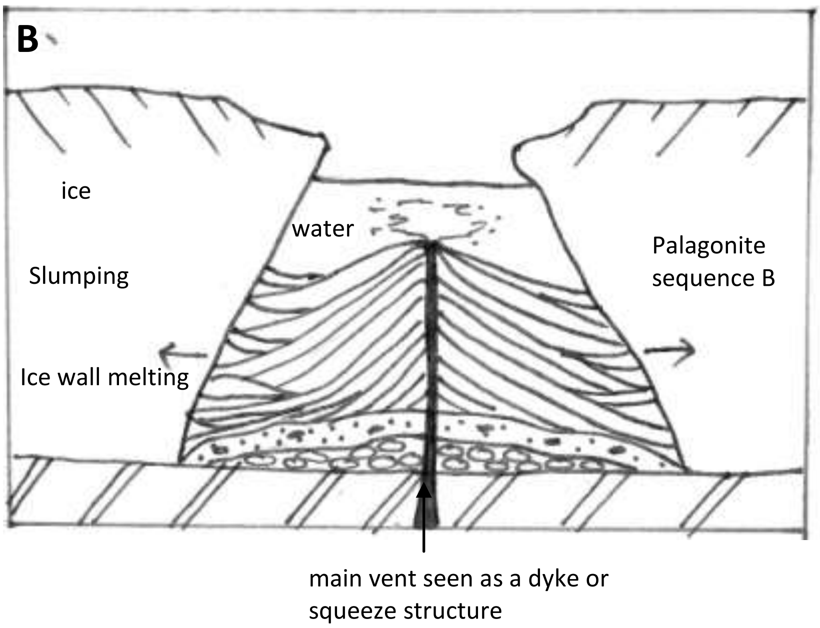
Further work done on dating the sequences at Castle Rock and comparison studies of research of ice thicknesses during the Cenezoic could help indicate when ice was at this thickness. More importantly however, Castle Rock can be used as a primary source of information regarding the Antarctic cryosphere. Volcanic and sedimentary processes associated with such subglacial eruptions can help characterise paleoenvironments in Antarctica.

Interpretation of formation



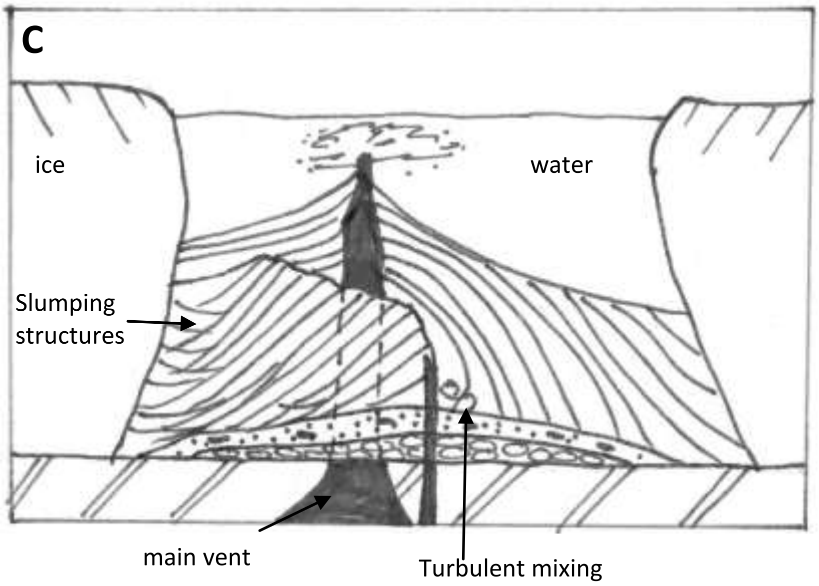
Sequence A – initial volcanic activity of passive effusion of pillow lava and palagonite hyaloclastite. Melt water is created by geothermal heating of basal ice. This creates the start of a water filled vault. Within an ice wall barrier water is constrained. When water starts to accumulate the quenching and then hydration in melt solution occurs producing a palagonite layer. Minimal space and melt produces a weakly altered material that is poorly sorted and poorly bedded.

As volcanism continues and becomes more active with higher thermal energies, the ability to melt the confining ice walls becomes easier.



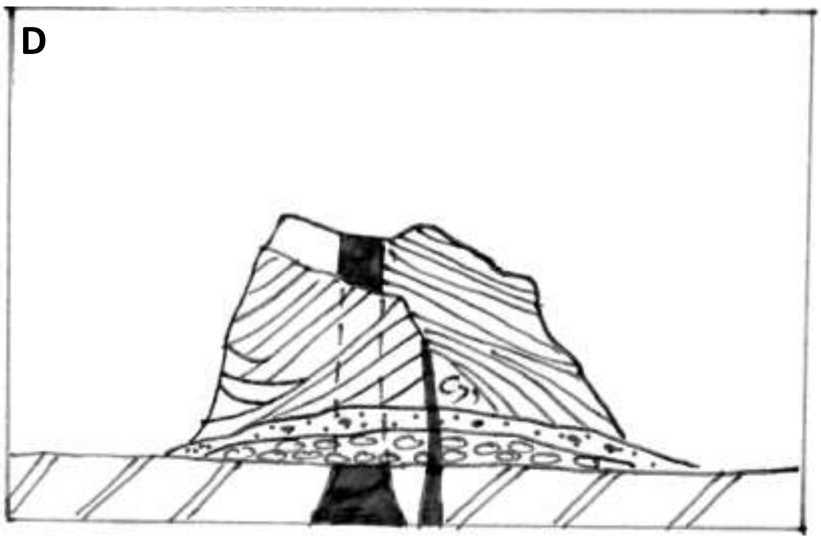
Sequence B – volcanic activity and hyaloclastite produced is constrained by ice wall position. The volcanic activity at this stage is hot and gaseous heating the lake and advancing walls. The red-brown dark colour of these hyaloclastites is typical for elevated temperatures. With more glacial melt and full advancement to the surface palagonite material is able to continue to alter during hydration and settle out forming beds. Slumping structures are evident in these beds due to melting creating more room for material, unstable and unconsolidated in situ palagonite gives way.

Volcanism continues to widen ice walls. Sequence B continues to slump. There appears that a major failure which occurs to the northeast side. Also contributing to this failure is the increasing vent through this sequence. Together this opens up more void space for the deposition of sequence C.



Sequence C – Volcanic activity appears to be in ambient temperatures producing a lighter yellow palagonite sequence. With a large lake area, alteration is more advanced and bedding structures are well formed. This sequence is not constrained by so much by glacier ice walls but of the remaining sequence B that acts as a buttress. Dipping beds that drape from the top to the base, and truncate the erosion surface of the previous vent (basaltic squeeze) is evident. At early stages high turbidity currents cause mixing of the unconsolidated red sequence B with the fresh yellows palagonite at the base.

Eventually volcanism ceases, the glacial lake drains and ice retreats leaving behind a steep sided, flat topped monolith.



Structure seen today - With melt water draining and ice retreat some unconsolidated and unstable material at the edges which were once supported and constrained by the ice walls collapses and is removed leading to the architecture seen at Castle Rock today.

Figure 18. Series of cartoons illustrating possible events involved in the construction of Castle Rock. Not to scale.

6.0 Conclusions

- Castle Rock is a steep sided, flat topped tuya, which is distinctive to having formed when lava erupts through thick stable glacier ice.
- The idea of glacial confinement is responsible from such a shape and hyaloclastic deposits are constrained to the glaciers ice walls.
- Structures within sequences can help indicate vault and lake size. Slumping structures for example represent redistribution to in-situ but unconsolidated beds in times where ices wall expansion may be rapid.
- Colour of palagonite hyaloclastite is representative of temperature of lake. This correlates well times of with ice wall progress, vault opening and times when it remains stable.
- Palagonite alteration reflects amount of water available in the lake. It is found that stages of less available melt water, alteration is at its lowest.
- Evidence at Castle Rock supports a subglacial origin. Together with rock dating, such a landform is a primary indication of a time where the Ross Ice Shelf was thicker and much more expanded.

7.0 Acknowledgements

This project would have not been possible without the help of many people. First and foremost I would like to thank the help and guidance from Dr Yvonne Cook. Her roll in facilitating this project and assistance in the field has been invaluable. Field trainer and safety officer, Sean Brooks, also needs a mention here for assistance with field safety making traversing of steep ice slopes around Castle Rock possible. Dr Jim Cole my geology department supervisor for his expertise, guidance and knowledge in Antarctic geology and petrography work.

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To my class mates and buddies from PCAS 2010 for making this overall experience one I will never forget.

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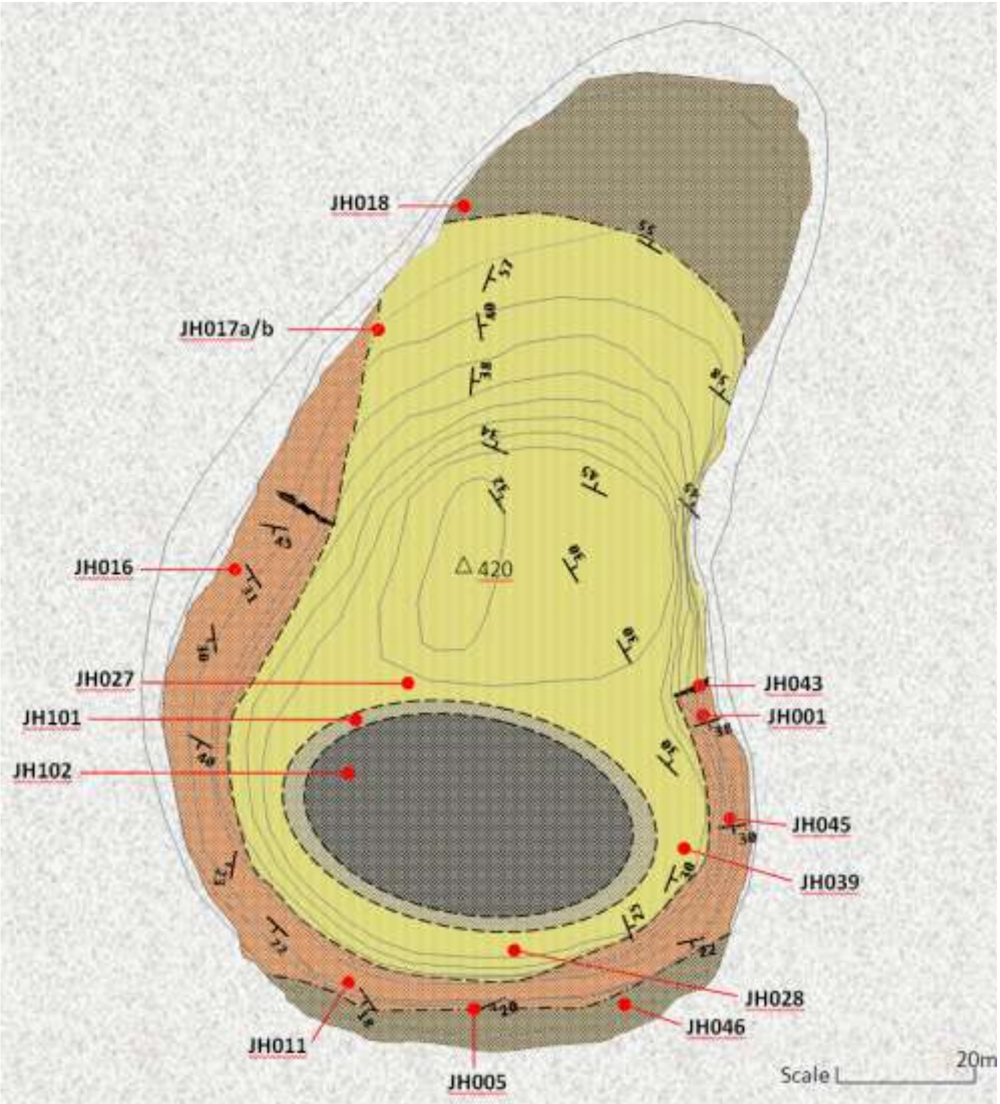
9.0 Appendices

Appendix 1 Sample locations



Appendix 2 Thin section and hand sample descriptions

Sample ID	*Sample location and type*	*Petrographic features and descriptions*
JH001 	**Location:** base of SE face **Type:**	**Modal composition:** Primary - Basaltic sand grains 20%, sideromelane (basltic glass) 20%, palagonization 25%, alteration clays 5% Phenocrysts olivine 5%, opaques 10%. Secondary- Basaltic clasts 15% **Microscope Textures:** Large angular broken basaltic sand grains ~4mm in diameter. These are highly vascular ~20%. Included are phenocrysts of olivine which have euhedral skeletal structures, aligned plagioclase microlites displaying a trachytic texture surrounded by a groundmass made up of very fine grained volcanic glass (hyalopilic texture). Sideromelane covers large areas, which range from large highly vascular pieces to small angular shards. Identified as having smooth surface structures, clear to semi-transparent, isotropic in XPL. Included is highly skeletal olivine and traces of plagioclase. All sideronelane displays palagonization. More intact masses display palagonite rimming of the structures and vesicle coating. Smaller shards occur as extensively and fully altered displaying an intense orange colouring in both PPL and ZPL. Alteration clays surround some areas of palagonization displaying a high birefringence in XPL. Basaltic clasts are highly vascular and range in size, 1-5mm. **Rock Textures (hand specimen):** Poorly sorted, dark red brown, clast rich, matrix supported, friable rubbly texture. Clasts are vesiculated angular to sub-angular basalts and are randomly distributed. This is supported in a medium sand sized red matrix.
JH005 	**Location:** South face at base into discoloured zone **Type:**	**Modal composition:** Primary - Basaltic sand grains 15%, sideromelane (basltic glass) 25%, palagonization 30%, alteration clays 10% Phenocrysts olivine 5%, opaques 10%. Secondary- Basaltic clasts 5% **Microscope Textures:** Slide covers two layers. Area 1-finer grained and better sorted and well distributed broken anhedral sieve and skeletal textured olivine and opaques mixed within broken angular shards of basaltic sandgrains and sideromelane, no full vesicles are intact. High degree of palagonization and rim alteration is evident along with a moderate distribution of high birfringent clays. Area 2- Broken basaltic clasts included with basaltic sand grains and large pieces of palagonized sideromelane and alteration clays. **Rock Textures (hand specimen):** Friable, rubbly texture overall. Sample taken between beds which display different physical grades. The contact between the layers displays a sharp gradational boundary. Top bed is moderately to well sorted, light brown matrix of medium sand size randomly including angular lithics of very coarse sand to granule size. The bottom bed is poorly sorted, dark grey, clast rich with a medium sand light brown matrix. Clasts are broken angular to sub-angular (<25mm) vesiculated.

JH011 	**Location:** SW face **Type:**	**Modal composition:** Olivine 20%, plagioclase (micrphenocrysts) 30%, opaques 15%, glassy matrix 35% **Microscope Textures:** Hypocrystaline, highly vascular ~ 50% ranging in size <2mm and are confined in streams, finegrained glassy groundmass, phenocrysts of plagioclase and olivine. Olivine occurs as subhedral to euhedral shapes with skeletal and sieve structures. Microlites of plagioclase appear as needle like structures (lath-shaped) with simple twinning occurring with minor alignment. **Rock Textures (hand specimen):** Very fine grained, inhomogenous, black basalt pillow lava or lobe 200mm in rough diameter included within the red irregular large bed of moderately sorted hyaloclastite. Internally consists of vertical bands of round to oval vesicles (<2mm) with a denser solid rim.
JH016 	**Location:** West face at snow line **Type:**	**Modal composition:** Primary - Basaltic sand grains (glassy matrix rich) 20%, sideromelane (basaltic glass) 20%, palagonization 25%, alteration clays 5%, phenocrysts olivine 5%, opaques 10%. Secondary- Basaltic clasts 15% **Microscope Textures:** Large angular broken basaltic sand grains ~4mm in diameter. These are highly vascular ~20%. Included are phenocrysts of olivine which have euhedral skeletal structures, aligned plagioclase microlites displaying a trachytic texture surrounded by a groundmass made up of very fine grained volcanic glass (hyalopilic texture). Sideromelane covers large areas, which range from large highly vascular pieces to small angular shards. Identified as having smooth surface structures, clear to semi-transparent, isotropic in XPL. Included is highly skeletal olivine and traces of plagioclase. All sideromelane displays palagonization. More intact masses display palagonite rimming of the structures and vesicle coating. Smaller shards occur as extensively and fully altered displaying an intense orange colouring in both PPL and ZPL. Alteration clays surround some areas of palagonization displaying a high birefringence in XPL. Basaltic clasts are highly vascular and range in size, 1-5mm. **Rock Textures (hand specimen):** Poorly sorted, dark red brown, clast rich, matrix supported, moderately indurated, rubbly texture. Clasts are vesiculated angular to sub-angular basalts and are randomly distributed. This is supported in a medium sand sized red/orange matrix.

JH017a&b  	**Location:** NW face **Type:**	**Modal composition:** Primary - Basaltic sand grains 5%, sideromelane (basaltic glass) 30%, palagonization 35%, alteration clays 15%, phenocrysts olivine 5%, opaques 5%. Secondary- Basaltic clasts 5% Note: possible growth of phillipsite **Microscope Textures:** Highly vascular ~50% throughout and angular glassy shards with high alteration. Included in basaltic sand-grains are phenocrysts of olivine which have euhedral skeletal structures, aligned plagioclase microlites displaying a trachytic texture surrounded by a groundmass made up of very fine grained volcanic glass (hyalopilic texture). Sideromelane covers large areas, which range from large highly vascular pieces to small angular shards. Identified as having smooth surface structures, clear to semi-transparent, isotropic in XPL. Included is highly skeletal olivine and traces of plagioclase. All sideromelane displays palagonization, this is extensive throughout. More intact masses display palagonite rimming of the structures and vesicle coating. Smaller shards occur more altered to fully altered displaying an intense orange colouring in both PPL and ZPL. Alteration clays surround some areas of palagonization displaying a high birefringence in XPL. Possible phillipsite growth in areas. Basaltic clasts are highly vascular. **Rock Textures (hand specimen):** Samples taken above and below a graded contact. Both hand samples display same physical and texture properties. A poorly sorted, porous, moderately indurate, with mustard pale brown matrix supporting sub-rounded basaltic clasts and lithics <5mm in size. Patches of friable, orange fine sand are randomly included throughout.
JH018  	**Location:** North face in discoloured zone **Type:**	**Modal composition:** Primary - Basaltic sand grains 30%, sideromelane (basaltic glass) 30%, palagonization 15%, alteration clays <5%, phenocrysts olivine 10%, opaques 5%. Secondary- Basaltic clasts 5% **Microscope Textures:** Highly vascular ~50% and porous throughout. Included in basaltic sand-grains are phenocrysts of olivine which have euhedral skeletal structures, aligned plagioclase microlites displaying a trachytic in a very fine grained volcanic glass (hyalopilic texture). Sideromelane covers large areas, which range from large highly vascular pieces to small angular shards. Identified as having smooth surface structures, clear to semi-transparent, isotropic in XPL. Included is highly skeletal olivine and traces of plagioclase. All sideromelane displays palagonization, this has restricted distribution being patching and filling space between shards. Palagonite rimming does not occur. of the structures and vesicle coating. Alteration clays have minor distributed throughout. Basaltic clasts are highly vesicular and occur with skeletal olivine and needle plagioclase. **Rock Textures (hand specimen):** Poorly sorted, well indurated, dark grey to dark brown (appears discoloured or baked) matrix supported breccias of angular secondary basaltic clasts and other primary lava fragments sized 1-5mm. Matrix is grey and fine grained

JH027 	**Location:** At summit North of vent **Type:** Pillow basalt or lava lobe clast in palagonized hylaoclastite	**Modal composition:** Olivine 20%, plagioclase (micrphenocrysts) 20%, opaques 10%, glassy matrix 50% **Microscope Textures:** Hypocrystaline, highly vascular ~ 60% ranging in size <1mm and, finegrained glassy matrix, phenocrysts of plagioclase and olivine. Olivine occurs as subhedral to euhedral shapes with skeletal and sieve structures. Microlites of plagioclase appear as needle like and rectangle structures (lath-shaped) with simple twinning, no alignment, randomly distributed with a fine grained groundmass. **Rock Textures (hand specimen):** Very fine grained, black basalt clast, boulder, 250mm in rough diameter included within yellow/mustard well bedded moderately sorted hyaloclastite. Clast has an inhomogenous shape, with a solid rim, internally round vesicles (<2mm in size).
JH028 	**Location:** At summit South side of vent **Type:**	**Modal composition:** Primary - Basaltic sand grains 5%, sideromelane (basltic glass) 35%, palagonization 35%, alteration clays 10%, Phenocrysts olivine 5%, opaques 5%. Secondary- Basaltic clasts 5% Note: possible growth of phillipsite **Microscope Textures:** Highly vascular ~50% throughout. Included in basaltic sand-grains are phenocrysts of olivine which have euhedral skeletal structures, aligned plagioclase microlites displaying a trachytic texture surrounded by a groundmass made up of very fine grained volcanic glass (hyalopilic texture). Sideromelane covers large areas, which range from large highly vascular pieces to small angular shards. Identified as having smooth surface structures, clear to semi-transparent, isotropic in XPL. Included is highly skeletal olivine and traces of plagioclase. All sideronelane displays palagonization, this is extensive throughout. More intact masses display palagonite rimming of the structures and vesicle coating. Smaller shards occur more altered to fully altered displaying an intense orange colouring in both PPL and ZPL. Alteration clays surround some areas of palagonization displaying a high birefringence in XPL. Possible phillipsite growth in areas. Basaltic clasts are highly vascular and range in size, 1-5mm. **Rock Textures (hand specimen):** Poorly sorted, dark red brown, clast rich, matrix supported, moderately to well indurated, rubbly texture, displays a porous texture with vesicles <5mm in size. Clasts are vesiculated angular to sub-angular basalts and are randomly distributed within the sample. This is supported in a medium sand sized red/orange matrix.

JH039 	**Location:** At summit East side of vent **Type:**	**Modal composition:** Primary - Basaltic sand grains 20%, sideromelane (basltic glass) 25%, palagonization 25%, alteration clays 5%, phenocrysts olivine 5%, opaques 10%. Secondary- Basaltic clasts 10% **Microscope Textures:** Broken glass shard and basaltic sand groundmass with patchy palagonization. Finer grained and well distributed. Broken anhedral sieve and skeletal textured olivine and opaques mixed within. sideromelane, some full vesicles are intact palagonization and rim alteration is evident along with a moderate distribution of high birefringent clays. Alteration clays are more commonly scattered and attached to palagonite of smaller shards. **Rock Textures (hand specimen):** A moderately sorted, moderate-well indurated, matrix supported breccia comprised of randomly distributed basaltic lithic clasts (5-25mm). These clasts are very fine grained and vesicular (rounded vesicles <1mm in size). The matrix is porous in areas, comprising of fine sand sized pale orange material moderately sorted with a coarse to very coarse sand sized, rounded basalt lithics.
JH043 	**Location:** SE face 1m from base **Type:** Dyke/squeeze	**Modal composition:** Olivine 20%, plagioclase (micrphenocrysts) 40%, opaques 10%, glassy matrix 30% **Microscope Textures:** Hypocrystaline, highly vascular ~ 60% ranging in size <5mm and, finegrained glassy matrix, phoncrysts of plagioclase and olivine. Olivine occurs as subhedral to euhedral shapes with skeletal and sieve structures. Microlites of plagioclase appear as needle like structures (lath-shaped) with simple twinning, no alignment. **Rock Textures (hand specimen):** Very fine grained, grey basalt with elongated vesicles (<3mm). Apart of the squeeze/dyke into the red hyaloclastite sequence.

JH045  	**Location:** SE face 1m from base **Type:**	**Modal composition:** Groundmass only: Primary - Basaltic sand grains 25%, sideromelane (basaltic glass) 25%, palagonization 30%, alteration clays 5%, phenocrysts olivine 5%, opaques 10%. Secondary- Basaltic clasts 10% **Microscope Textures:** Mixed broken glass shard, palagonite and basaltic sand groundmass. Finer grained and well distributed. Broken anhedral sieve and skeletal textured olivine and opaques mixed within. Sideromelane, some full vesicles are intact palagonization and rim alteration is limited with palagonite as independent shards. Moderate distribution patches of high birefringent clays independent to palagonite shards and patches. No alteration to pillow basalt rim, a straight contact is observed. **Rock Textures (hand specimen):** A well sorted, moderate-well indurated, matrix supporting a large basaltic clast (50mm in size). Clast is very fine grained and vesicular (rounded vesicles <1mm in size). The matrix is porous in areas, comprising of fine sand sized prominent orange material.
JH046  	**Location:** SE face 1m from base **Type:**	**Modal composition:** Primary - Basaltic sand grains (glassy matrix rich)30%, sideromelane (basaltic glass) 30%, palagonization 15%, alteration clays <5%, phenocrysts olivine 10%, opaques 5%. Secondary- Basaltic clasts 5% **Microscope Textures:** Highly vascular ~50% and porous throughout. Included in basaltic sand-grains are phenocrysts of olivine which have euhedral skeletal structures, aligned plagioclase microlites displaying a trachytic in a very fine grained volcanic glass (hyalopilic texture). Sideromelane covers large areas, which range from large highly vascular pieces to small angular shards. Identified as having smooth surface structures, clear to semi-transparent, isotropic in XPL. Included is highly skeletal olivine and traces of plagioclase. All sideromelane displays palagonization, this has restricted distribution being patching and filling space between shards. Palagonite rimming does not occur. Alteration clays have minor distributed throughout. Basaltic clasts are highly vesicular and occur with skeletal olivine and needle plagioclase. **Rock Textures (hand specimen):** A poorly sorted, friable/poorly indurated dark brown/black, rubbly textured breccia comprised of a large range of randomly distributed angular basaltic clasts (<10mm). Larger clasts are seen to be very vesicular. Matrix is dark brown and coarse sand sized. Within the rock finer lighter lenses of material are evident.

JH101 	**Location:** At summit from discoloured boarder to vent **Type:**	**Modal composition:** Primary - Basaltic sand grains (glassy matrix rich)35%, sideromelane (basaltic glass) 30%, palagonization 15%, phenocrysts olivine 10%, opaques 5%. Secondary- Basaltic clasts 5% **Microscope Textures:** Highly vascular ~50% and porous throughout. Included in basaltic sand-grains are phenocrysts of olivine which have euhedral skeletal structures, aligned plagioclase microlites displaying a trachytic in a very fine grained volcanic glass (hyalopilic texture). Sideromelane covers large areas, which range from large highly vascular pieces to small angular shards. Identified as having smooth surface structures, clear to semi-transparent, isotropic in XPL. Included is highly skeletal olivine and traces of plagioclase. Limited palagonization where patching is seen as fine grained filling as groundmass between shards, no alteration rimming is evident. Basaltic clasts are highly vesicular and occur with skeletal olivine and needle plagioclase. **Rock Textures (hand specimen):** Poorly sorted, well indurated, dark grey to dark brown (appears discoloured or baked) matrix supported breccias of angular secondary basaltic clasts and other primary lava fragments sized 1-5mm. Matrix is grey and fine grained.
JH102 	**Location:** Main vent / plug **Type:** Basalt	**Modal composition:** Olivine 20%, plagioclase (microphenocrysts) 30%, opaques 12%, glassy matrix 37% Clinopyroxene <1%. **Microscope Textures:** Hypocrystaline, fine-grained groundmass, phenocrysts of olivine, clinopyroxene and plagioclase. Olivine max size 1mm in size, euhedral-subhedral crystal shape with a skeletal structure. Clinopyroxene displaying twinning. Plagioclase appears as elongated needle lath shaped structures with some larger crystals rectangular in shape, simple twinning is exhibited, overall showing a minor trachytic texture. **Rock Textures (hand specimen):** A very fine grained, well sorted, well indurated, dense black basalt. Some streams/ vascular bands. The same area (main plug) there are a range of basalt clasts that can be scoriaceous, highly vascular or ropey in texture.