Online Materials part I. Rock and mineral characteristics

Based on the rock characteristics and the mineral assemblages, the drill hole GH-3 has the most felsic rocks, trachyte to trachyandesite in all three drills. Drill GH-2 shows the felsic rock on top of the mafic flows. Drill GH-1 just contains mainly mafic rocks. The rocks can be grouped into S1 to S5 five sections based on their petrographic and mineralogical characteristics.

From top to bottom, the petrographic characteristics of five sections are as following:

Section 1, samples 106.2 to UB-1 in GH3, the rocks are mainly trachyte and contain phenocrysts of plagioclase, biotite and pseudomorphic ankerite (Fig. S1). Abundant of apatite and Fe-oxide crystals coexist with biotite in the clusters (Fig. S2).

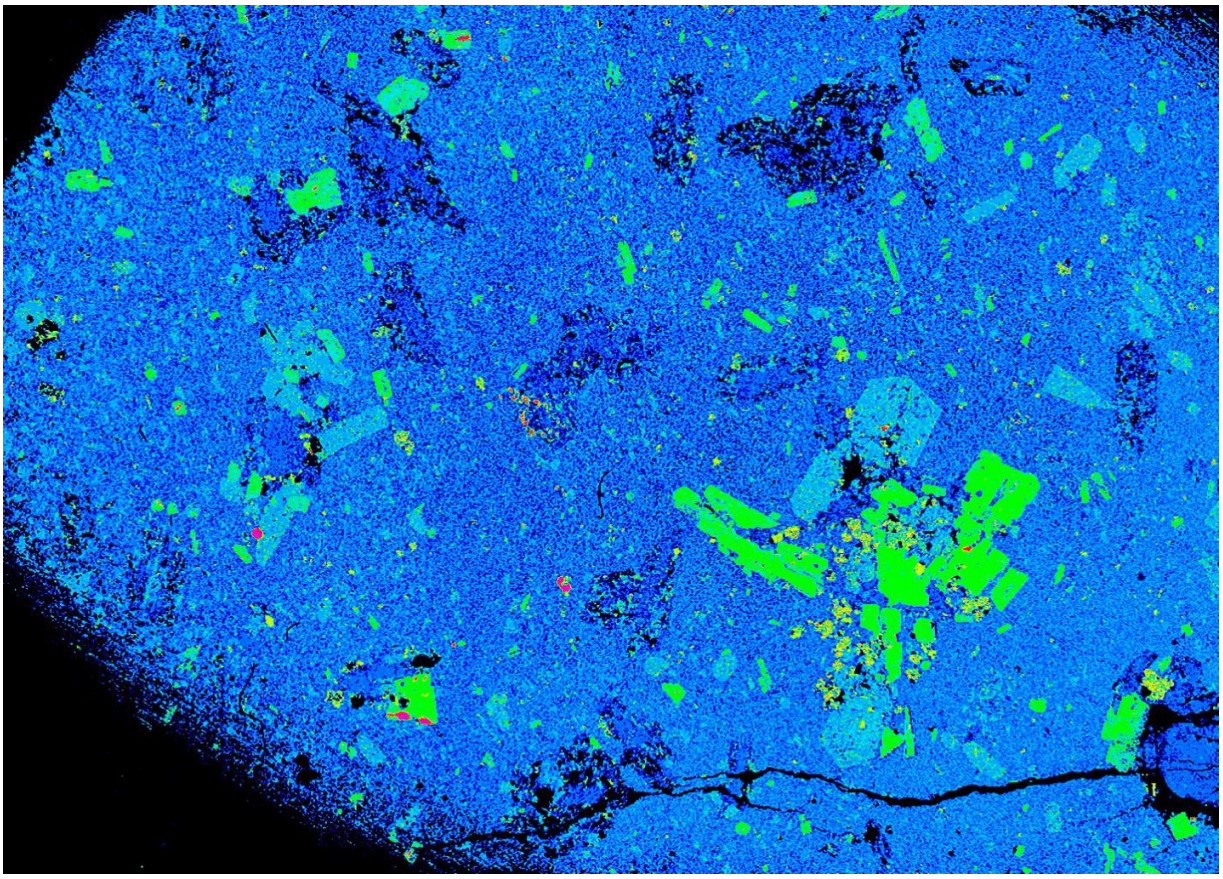

Figure S1, whole-section BSE image of UB-1, biotite-bright green, ankerite-light blue, plagioclase (An ~60)-dark blue. Pseudomorphic ankerite grains and biotite form clusters within microcrystalline matrix.

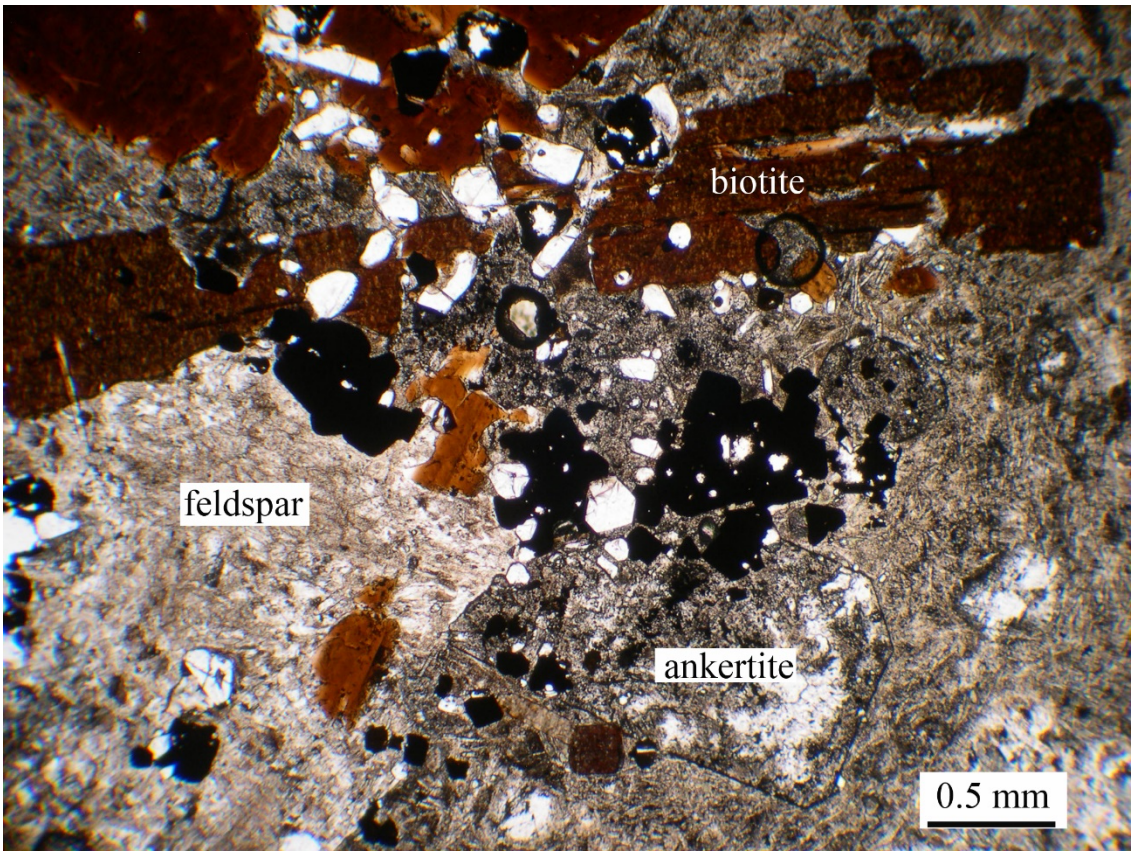

Figure S2, apatite and Fe-oxide crystals coexist with biotite formed the clusters. Apatite and Fe-oxide cut or include in pseudomorphic carbonate grains.

Section 2, samples UB-11 in GH-2 and UB-2 to UB10 in GH-3 are grouped into this section. The rocks are trachyte and mainly contain alkali feldspar (anorthoclase with OR ~50) as phenocrysts. Only small amount of pseudomorphic carbonates exist in these rocks (Fig. S3).

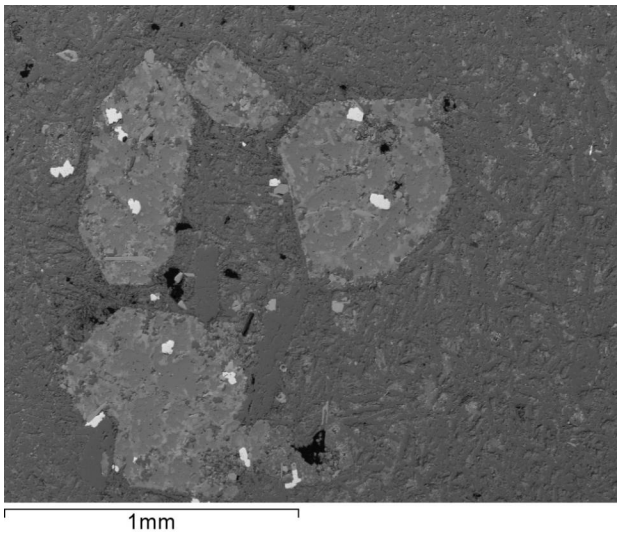

Figure S3. Pseudomorphic carbonate grains in trachyte UB-7.

Section 3, samples UB-12 to UB-14 in GH-2 are obsidians with plagioclase phenocrysts and basalt with gas bubbles, they are like the UB-18 and UB-19 in GH1. There is calcite filling the vesicles in these rocks (Fig. S4).

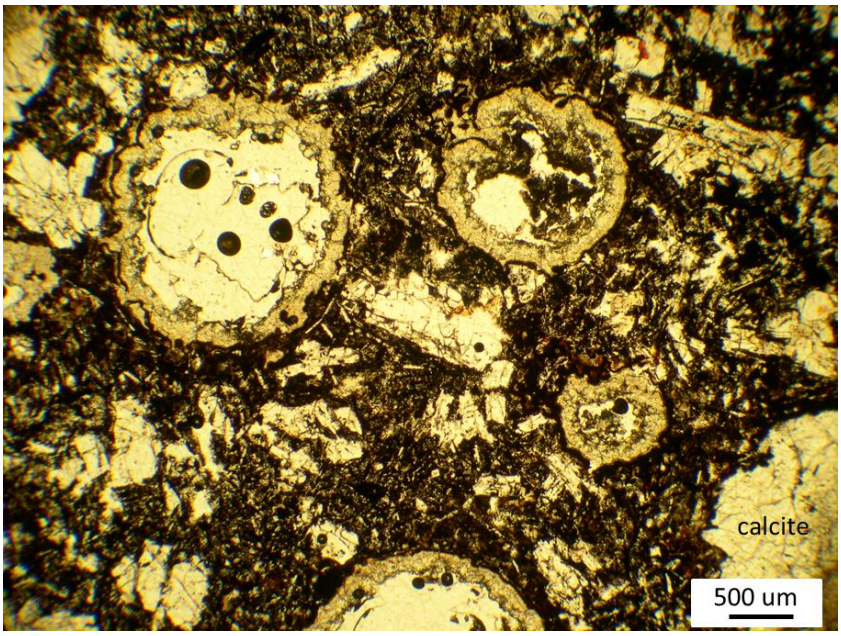

Figure S4. Petrographic image of sample UB13, basaltic rock with gas bubbles. Phenocrysts are mainly plagioclase with a few biotites. Calcite fills gas bubbles.

Section 4, rocks in this section, UB20 to UB22 contain clinopyroxene, feldspar, and oxide phenocrysts. Feldspars are altered to sericite. Sample UB21 is basaltic rock with altered phenocrysts, plagioclase altered to sericite and mafic mineral altered to chlorite with carbonate fills the fractures (Fig. S5). Sample UB-22 in GH-1 is a layer of trachyandesite with sanidine phenocryst with carbonate vein cut the rock.

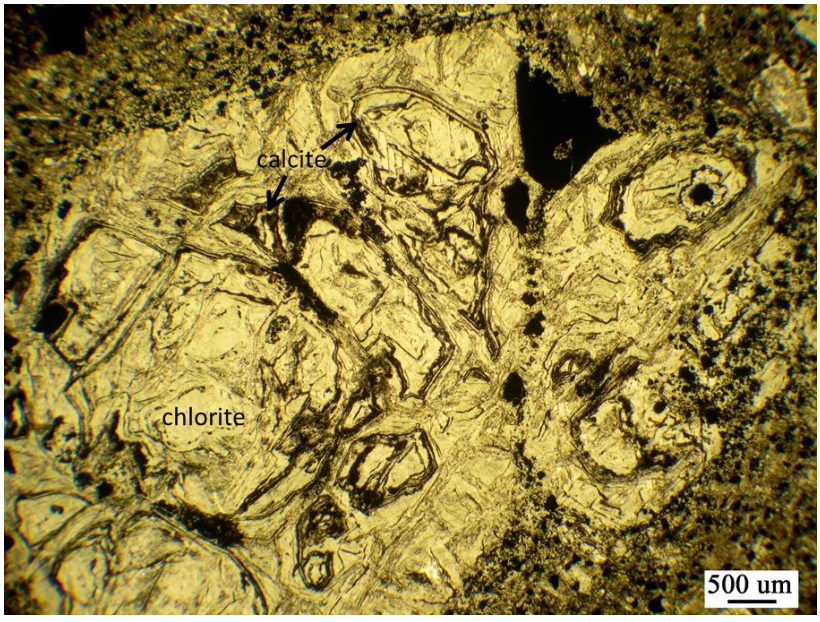

Figure S5. Mafic mineral (possibly pyroxene) altered to chlorite with calcite fills the fractures and forms the ring shapes.

Section 5, samples UB15 and 16 in GH-2 and UB23 to UB40 in GH-1 are trachybasalt containing plagioclase and clinopyroxene phenocrysts. The rocks contain amphibole and pseudomorphic carbonate grains with sharp boundary and colloform texture (Fig. S6, S7). The colloform textures are composed of different carbonates, usually siderite (light gray) and calcite (dark gray), showing zoned feature. Each pseudomorphic grain can contain several centers of periodic precipitation. The matrixes of the rocks contain plagioclase/sanidine. C-O isotopes were collected from sample UB15.

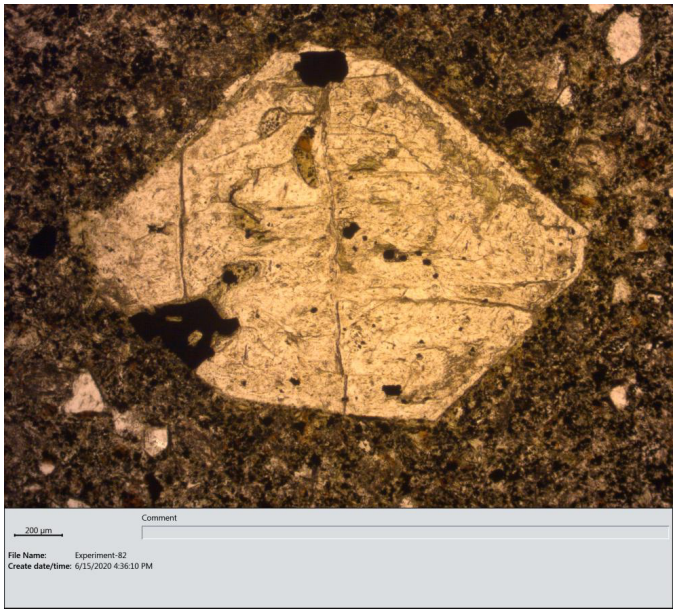

Figure S6. Pseudomorphic carbonate grain with colloform texture, the carbonate minerals are calcite (dark gray) and siderite (light gray). The C-O isotopes of UB15 colloform carbonates have $\delta^{13}C_{VPDB}$ ~ -0.8 to -1.4 and $\delta^{18}O_{SMOW}$ ~ 17.6 to 18.6. The C-O isotopes of these grains match with the texture of these carbonates and indicate a hydrothermal activity in these rocks.

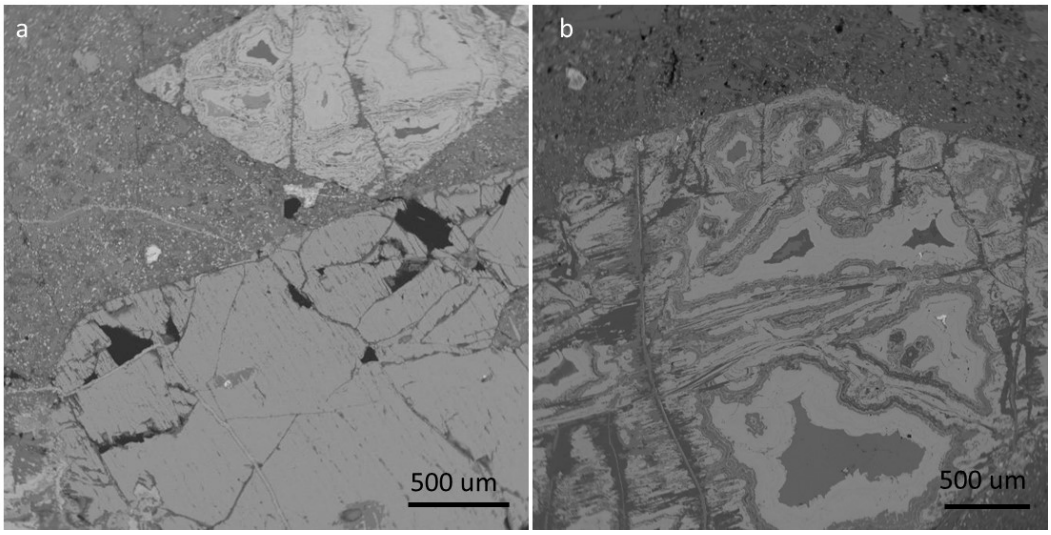

Figure S7. Pseudomorphic carbonate grain (calcite) contains corroded ilmenite and relicts of droplet-shape chlorite, it may form from carbonate replacing clinopyroxene.

Mineral chemistry

Based on the electron microscope analysis (Supplementary II), the geochemical features of studied minerals are plotted in the following diagrams.

The phenocrysts in the sections contain clinopyroxene (Fig. S8), feldspar (Fig. S9), and carbonate minerals (Fig. S10). The carbonate phases in trachytic rocks are mainly ankerite and in trachybasalt are mainly calcite and siderite (Fig. S10). Trachyandesite contains amphibole, which co-exists with cpx. Amphibole shows partial alteration and changes to actinolite (Fig. S11). Biotite only exists in trachytic rocks (Fig. S12).

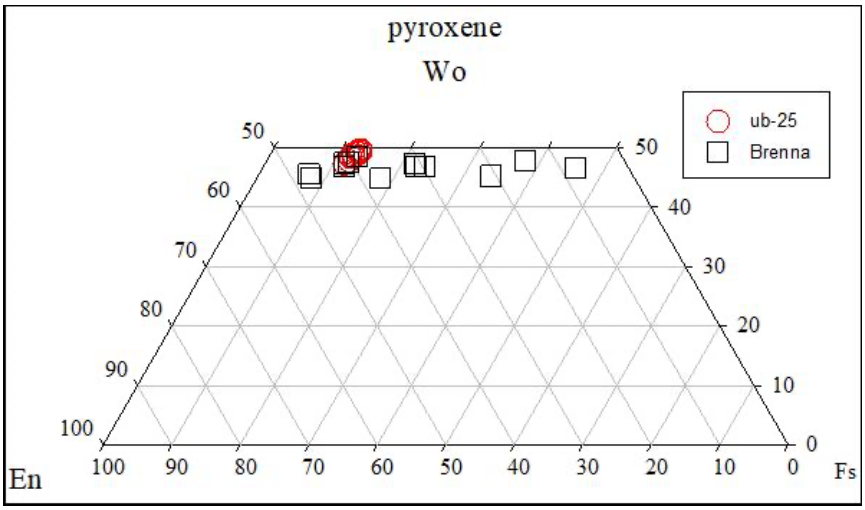

Figure S8, pyroxene composition in Ulleung Island mafic group. The cpx has high Ca content.

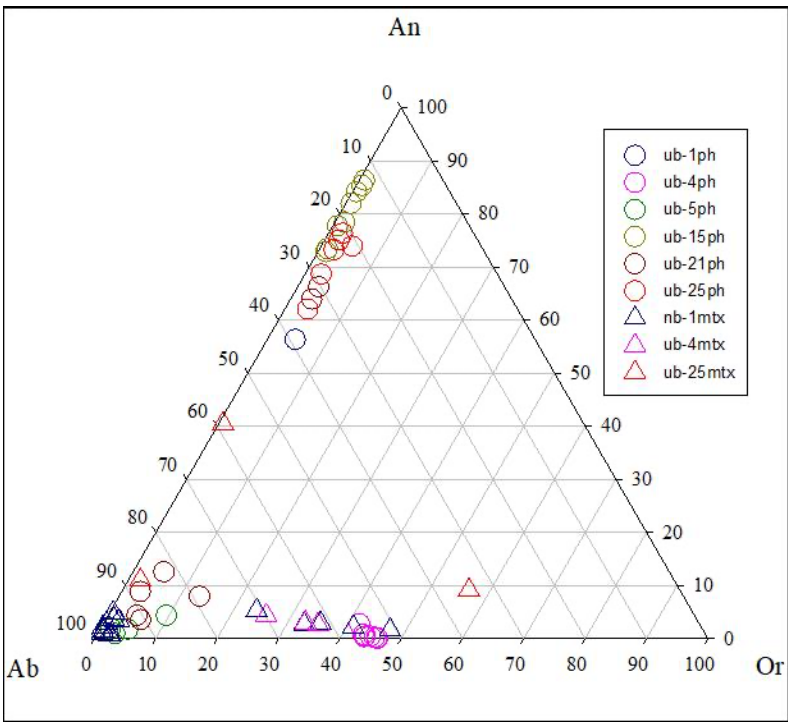

Figure S9, feldspar composition in Ulleung Island volcanic rocks. Felsic trachytic rocks mainly have alkali-feldspar. Mafic trachybasaltic rocks contain plagioclase phenocryst and microcrystalline alkali feldspars in matrix.

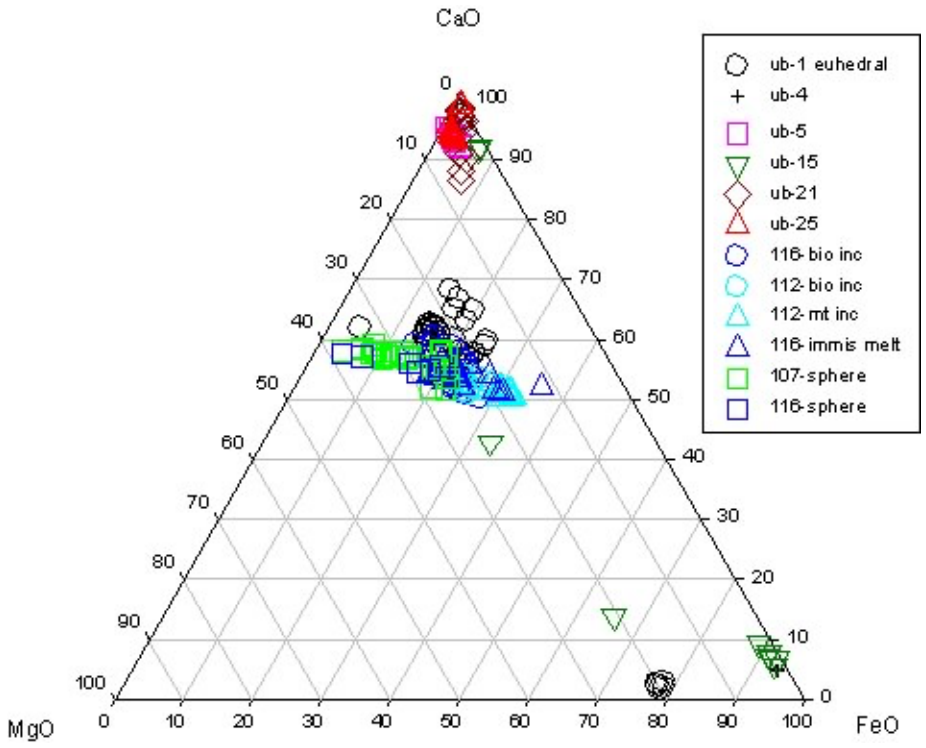

Figure S10, Chemical characteristics of carbonate minerals in the Ulleung Island volcanic rock.

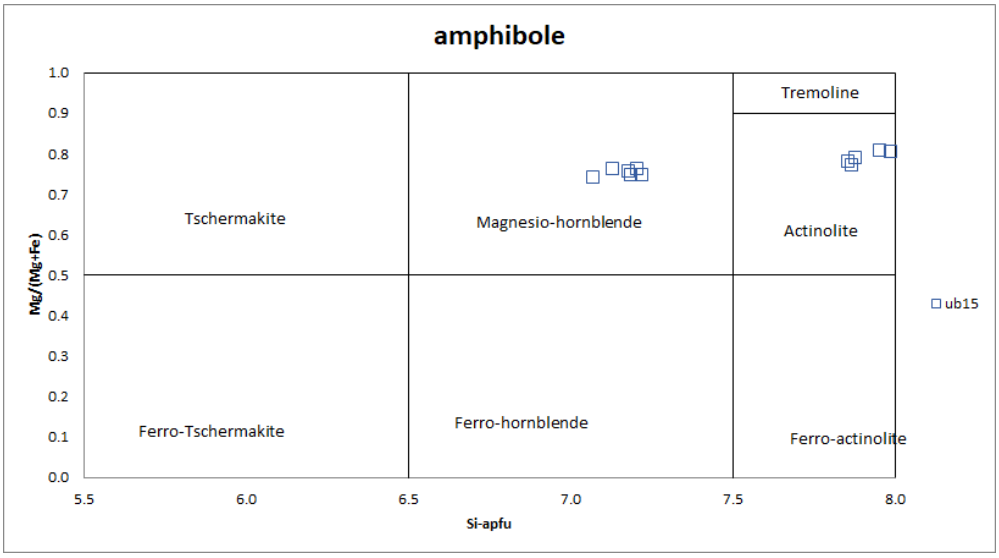

Figure S11. Amphibole composition in Ulleung Island mafic group.

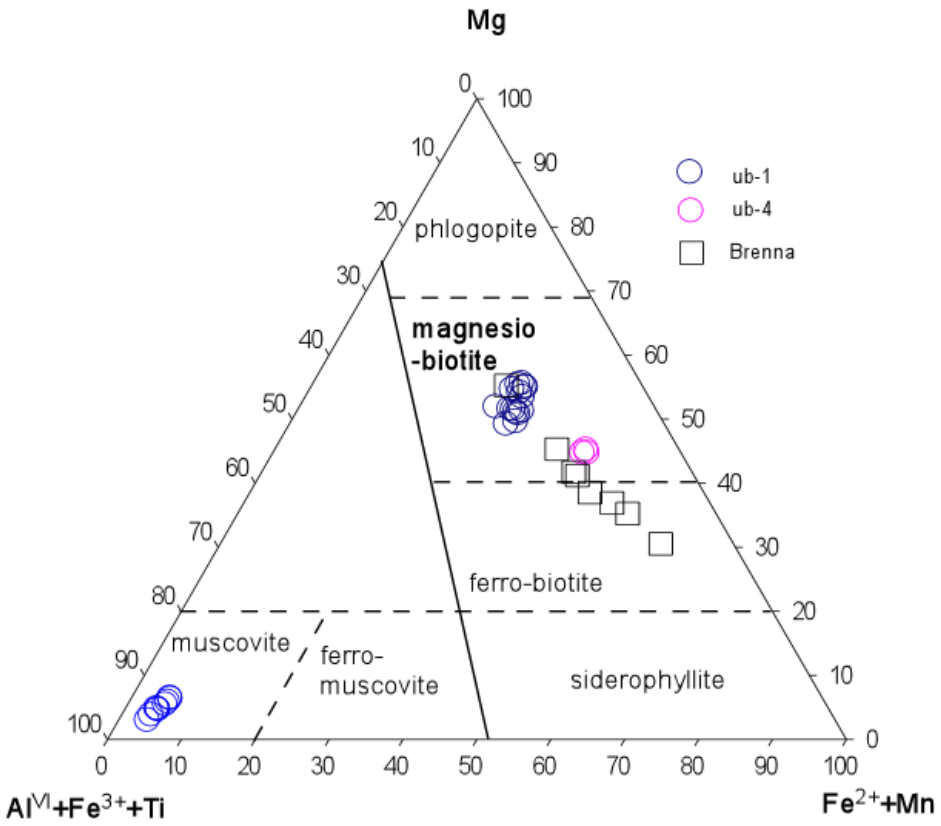

Figure S12. The mafic minerals in trachytic groups (sections S1-S2) are mainly biotite. Biotites have high MgO contain and fill in composition of magnesio-biotite range (Foster 1960) and muscovite could be the alteration product of biotite.