



Stockholm
University

Bachelor Thesis

Degree Project in
Geology 15 hp

A Geochemical Study of Conglomerate Clasts from the Yukon-Koyukuk Basin and Their Tectonic Origin

Charlotte Fredriksson



Stockholm 2017

Department of Geological Sciences
Stockholm University
SE-106 91 Stockholm
Sweden

Table of contents

Abstract	
1. Introduction	4
2. Regional Geologic Setting	5
3. Sampling and Petrography	7
3.1 Sampling	7
3.2 Petrography	7
4. Analytical Methods	8
5. Analytical Results	8
5.1 Major Elements	8
5.2 Rock and Magma Series Classification	8
5.3 Trace Elements	11
6. Discussion	11
7. Conclusions	14
8. Acknowledgements	15
9. References	16

Appendices

A - Sample preparation

B - Thin section descriptions

C - Data tables and plots

D - Sample pictures

Abstract

The Yukon-Koyukuk basin in western central Alaska is a Cretaceous basin filled with sedimentary deposits eroded from its borderlands. Included in these deposits are clast-bearing conglomerates that are believed to originate from the Koyukuk Terrane, a large U-shaped outcrop of Mesozoic igneous rocks located in the interior of the basin. The igneous rocks of the Koyukuk Terrane are interpreted to be remnants of an intra-oceanic arc that collided with the North American continental margin in the Late Jurassic and Early Cretaceous due to a subduction-driven collision. Geochemical studies of igneous rocks from the Koyukuk Terrane exist, but the conglomerate clast correlation is based on inference -there is no data from the conglomerate clasts that can relate them to the ancient intra-oceanic arc. This geochemical investigation of conglomerate clasts from the Yukon-Koyukuk basin evaluates their tectonic origin and their relationship to the remnant arc of the Koyukuk Terrane. Major and trace elements, together with classification and discrimination diagrams, are used to evaluate the petrogenesis of the clasts. The results are compared to geochemical data of igneous rocks from the Koyukuk Terrane and confirm that the conglomerate clasts originate from an island arc-subduction zone environment and that they are likely derived from the Koyukuk Terrane.

1. Introduction

The western and central part of Alaska includes several geologic terranes that together tell an interesting tectonic history of the area and its formation. The area is commonly divided into the oldest Proterozoic and early Paleozoic continental assemblages of the Seward Peninsula in the west, the Ruby Terrane in the east, the Arctic Alaska (Brooks Range) in the north, and the lowland Mesozoic Yukon – Koyukuk province located in the interior (Patton and Box, 1989) (Fig. 1). The Yukon-Koyukuk province includes an outcrop of Jurassic and Lower Cretaceous volcanic and plutonic rocks (Koyukuk Terrane) and a sedimentary basin enclosing it (Yukon-Koyukuk basin). The province is adjacent to Arctic Alaska and the Ruby Terrane and is dissected by an ultramafic to mafic rock assemblage that belongs to the Angayucham Terrane (Fig. 2). Both the Koyukuk and Angayucham terranes differ from their continental surroundings as the former is believed to be remnants of an intra-oceanic arc and the latter old oceanic floor (ophiolite). Both were accreted onto the North American continent due to a convergent plate boundary at where oceanic crust located between the North American continent and the intra oceanic arc was subducted beneath the arc. This finally led to an arc-continent collision in the Late Jurassic and Early Cretaceous (Patton and Box, 1989).

The Yukon-Koyukuk basin covers an area of approximately 118,000 km² and is comprised of several types of lithic sediments, one of these are mafic clast-bearing conglomerates (O'Brien et al., in press). These clasts are believed to have been eroded from the remnant island arc of the Koyukuk terrane and its borderlands (Patton et al, 1989). A detailed geochemical study by Box and Patton (1989) related the igneous rocks of the Koyukuk Terrane to subduction zone magmatism and concluded that these rocks belong to a former intra-oceanic arc. Yet, they haven't done any actual study of the conglomerate clasts to be able to say where they originate from.

This study is a geochemical investigation of conglomerate clasts from the Yukon-Koyukuk basin with the aim to determine their tectonic origin and if they in fact are related to the remnant island arc of the Koyukuk Terrane. Major and trace elements are used together with classification diagrams, triangular plots, multi-element diagrams and other discrimination diagrams, to evaluate the petrogenesis of the clasts. The following steps are taken to pursue this goal:

- 1) Classify the clasts by rock name and identify their magma series.
- 2) Examine whether the clasts display geochemical signatures that can be correlated with their tectonic environment.
- 3) Determine whether the geochemical data from the clasts correlates with the igneous rocks of the Koyukuk Terrane presented in Box and Patton (1989).

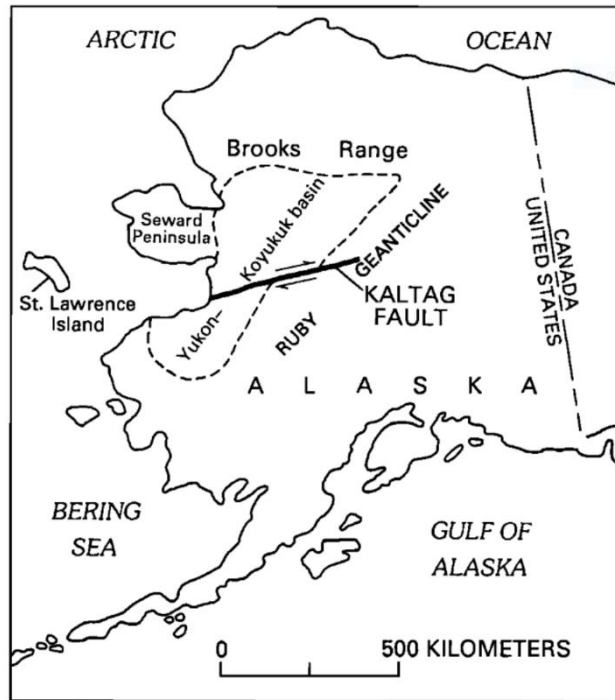


Figure 1. Map after Patton and Box (1989) of Alaska and the location of the Yukon-Koyukuk basin and its borderlands (Seward Peninsula, Brooks Range and

2. Regional Geologic Setting

The Yukon- Koyukuk province located in the interior of the western Alaska includes the U-shaped Koyukuk Terrane, an arcuate outcrop of Cretaceous and older volcanic rocks that is surrounded by Cretaceous sedimentary basins (Yukon-Koyukuk basin) on its northern, eastern and southern sides (Box and Patton, 1989). The outcrop of the Koyukuk Terrane comprises two exposures of sedimentary deposits. Based on these exposures O'Brien et al. (in press) divided the Yukon-Koyukuk basin into two sub- basins, the Kobuk-Koyukuk sub-basin north of the Koyukuk Terrane and the Lower Yukon sub-basin to the south. However, due to the Cenozoic Kaltag fault with dextral motion, the lower part of the Kobuk-Koyukuk sub-basin is now exposed south of the Koyukuk Terrane (Fig 2) (Box and Patton, 1989). The crust underlying the Yukon-Koyukuk basin is still unknown and its nature is debated by several authors (see O'Brien et al., in press).

The Yukon-Koyukuk province is surrounded by regionally metamorphosed continental rocks of mainly pelitic schists, carbonate rocks, quartzites and orthogenisses. The majority of these assemblages are metamorphosed to greenschist facies but there are also exposures of higher grade metamorphism such as amphibolite and even blueschist facies (Box and Patton, 1989). These regional metamorphic facies of the continental borderlands are believed to have developed during the arc-continental collision that began in the Late Jurassic (Patton and Box, 1989).

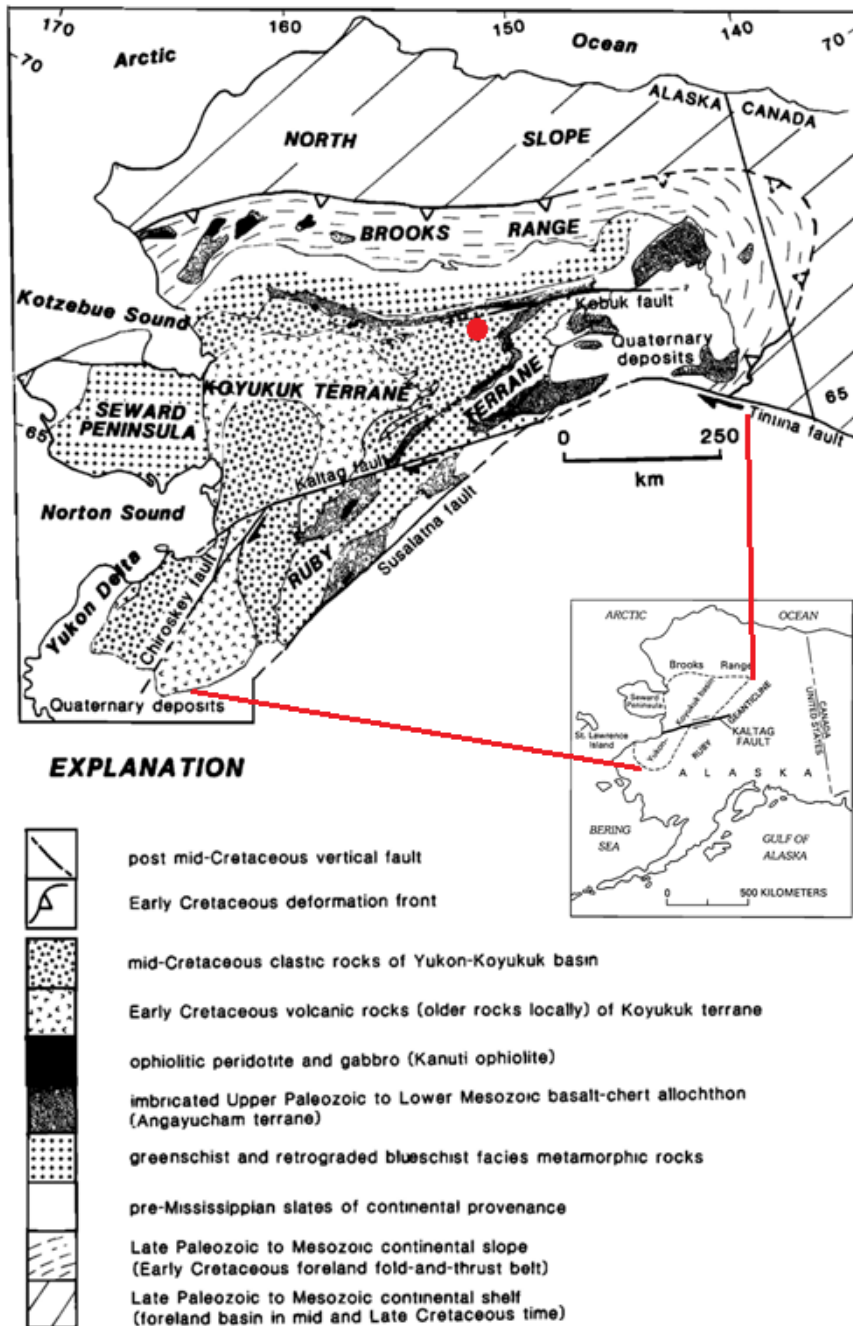


Figure 2. Regional tectonic map of North western part of central Alaska from Box and Patton (1989) showing the general regional setting of the Yukon-Koyukuk basin and the Koyukuk terrane including the borderlands. The small map of Alaska is taken Patton et al (1989). Shown in both maps is the Kaltag fault which displaces the northern Yukon-Koyukuk basin from its southern part.

3. Sampling and Petrography

3.1 Sampling

The conglomerate clasts used in this study were collected from the north-eastern Kobuk-Koyukuk sub-basin close to the Brooks Range (Fig 2). A total of 31 clasts were collected and 11 of these were provided for this study. Following 11 samples were analysed: VP16-23g, VP16-24a, VP16-24b, VP16-24c, VP16-24d, VP16-24e, VP16-24f, VP16-25a, VP16-25b, VP16-25c and VP16-25d. All clasts were collected from the same area close to the John River located north of the village Bettles. The sample location is marked with a red circle in Fig 2. All samples were weathered. Photographs in the appendix show the clasts and their relative sizes.

3.2 Petrography

Thin sections were made of the clasts and studied under the petrographic microscope. All samples show evidence of low-grade hydrothermal alteration with secondary minerals such as chlorite, calcite, epidote/clinozoisite, prehnite, serpentine and sericite present. Calcite- and quartz-filled veins and vesicles are common. VP16-25b and VP16-25c have high LOIs between 6-9 %, whereas the other samples have LOIs between 1-4 % (Table 1). The high LOIs for VP16-25b and VP16-25c may imply that these samples have been more affected by hydrothermal alteration than the others. Evidence for this can be seen in thin section where these two samples have a high abundance of secondary hydrous minerals such as calcite, chlorite, sericite and serpentine. In VP16-25c there are mineral grains, probably olivine, that are totally serpentinized.

The overall mineralogy of the samples is dominated by plagioclase feldspar but minerals such as amphibole, pyroxene and oxides are also common. Samples VP16-24a, VP16-24b, VP16-24d, VP16-24e and VP16-24f have trachytic texture with plagioclase laths and flow oriented plagioclase crystals typical of lava flows. All volcanic and hypabyssal samples have amphibole in their mineralogy, some are unaltered and others are being replaced by chlorite. The hypabyssal samples have a coarser texture with large and well developed plagioclase grains indicating slower cooling in the shallow crust. Samples VP16-25a and VP16-25d both display interlocking plutonic texture in thin section. The plutonic samples were not as altered as the volcanic ones but still had secondary minerals such as calcite and chlorite present.

Samples VP16-25b and VP16-24c have enclaves with mineralogy distinct from the groundmass indicating that they might represent mixing of magmas. Sample VP16-23g had a 10mm volcanic xenolith with trachytic texture in a plutonic interlocking groundmass. Consequently, samples VP16-23g, VP16-24c and VP16-25b show indications of being mixtures of rocks/magmas and because their geochemical signatures do not represent a single composition they are not used during the geochemical interpretations in this report. They will however be plotted but in pale colours and for comparison only. Thin section descriptions for each sample are provided in the appendix.

4. Analytical Methods

The geochemical analyses of the eleven samples was obtained using two techniques, X-ray Fluorescence (XRF) and Laser Ablation Inductively Coupled Plasma Mass Spectrometry (LA-ICP-MS). Both the XRF and the ICP analyses were performed at the Department of Geological Sciences, Stockholm University, Sweden. The XRF was used for analysing the major and minor elements measured in weight percent oxide (wt.%). The following oxides were analysed by XRF: SiO₂, Al₂O₃, CaO, MgO, MnO, P₂O₅, Fe₂O₃, Na₂O, K₂O and TiO₂. Note that only Fe₂O₃ is mentioned as all FeO was oxidized to Fe₂O₃ during Loss On Ignition (LOI) determination when the samples were heated to 1000 °C for several hours. In plots where FeO is needed, the Fe₂O₃ was converted using the oxide multiplication factor 0.899 (Winter, 2014). The LA-ICP-MS was used to analyse 32 trace elements, measured in parts per million (ppm). Table 1 presents all measured oxides and trace element data from the XRF and ICP-MS, as well as the LOI %. Elements below the detection limit (LOD) are not plotted and are marked in Table 1 with '<' before the abundance. Further information on the sample preparation and the instrumentation used is provided in the appendix.

5. Analytical Results

5.1 Major Elements

The samples show a wide range in silica (SiO₂) content from 45 - 69 wt.%. The alumina (Al₂O₃) content varies between 14-20 wt.%. Concentrations of titanium oxide (TiO₂) are lower than 1 wt.% for all samples except for VP16: 24b, 24e and 24f that have concentrations just above 1 wt.%. Differentiation trends are shown in the major elements by decreasing MgO, FeO*, and CaO with increasing SiO₂ content. The differentiation trend for TiO₂ is a bit scattered but still shows a decrease with increasing SiO₂ content; the trend for Al₂O₃ is similar but with a less pronounced decrease. For the alkalis, Na₂O increases with increasing SiO₂ but K₂O is scattered. Bivariate plots of major oxide versus silica content is provided in the appendix.

5.2 Rock and Magma Series Classification

All eleven samples were plotted on a "total alkali versus silica" (TAS) classification scheme based on their measured geochemistry (Fig 3). The mafic samples with a silica content between 45-57 wt.% (VP16- 24a, 24b, 24d, 24e, 24f and VP16-25c) plot in the basalt and basaltic andesite fields except sample VP16-24c that plots in the trachy-basalt field. Sample VP16-25b with an intermediate silica content of 60.8 wt.% SiO₂ plots in the andesite field. The more felsic samples with silica contents between 65 – 70 wt.% SiO₂ (VP16-25b, 25d and VP16-23g) plots in the dacite field. All samples plot in the sub-alkaline field except VP16-24c and VP16-25c that both plot in the alkaline field. The sub-alkaline samples were further plotted in an AFM ternary diagram to distinguish between the calc-alkaline and tholeiitic magma series (Fig 4). Majority of the samples are calc-alkaline, with the exception of sample VP16-24a that lies just above the division line in the tholeiitic field.

Table 1. Major and trace element analyses of conglomerate clasts from the Kobuk-Koyukuk Basin (Alaska).

Sample ID	VP16-23g	VP16-24a	VP16-24b	VP16-24c	VP16-24d	VP16-24e	VP16-24f	VP16-25a	VP16-25b	VP16-25c	VP16-25d
Type	Xenolith	Hypabyssal	Hypabyssal	Mixed	Volcanic	Volcanic	Hypabyssal	Plutonic	Mixed	Porphyritic	Plutonic
<i>Major Elements (wt.%)</i>											
SiO ₂	69.8	51.2	56.5	50.6	51.3	51.0	52.6	67.2	60.8	45.3	69.7
Al ₂ O ₃	14.7	17.1	15.0	16.4	16.1	18.5	15.7	17.4	14.6	19.8	16.5
CaO	4.78	10.6	5.87	8.46	10.9	6.83	8.84	4.93	8.43	8.34	2.97
MgO	1.46	6.47	4.41	6.07	7.67	8.14	6.40	0.86	2.98	9.89	1.10
MnO	0.138	0.190	0.227	0.224	0.186	0.215	0.215	0.121	0.216	0.24	0.053
P ₂ O ₅	0.102	0.056	0.088	0.124	0.046	0.108	0.073	0.048	0.091	0.069	0.039
Fe ₂ O ₃	3.49	10.2	11.4	11.9	8.73	8.95	10.6	3.76	6.08	12.6	2.76
Na ₂ O	4.31	2.49	4.21	4.64	2.32	4.71	3.43	4.32	5.76	2.16	5.68
K ₂ O	0.797	0.755	1.27	0.705	2.14	0.313	1.02	1.07	0.401	0.858	0.838
TiO ₂	0.438	0.968	1.08	0.815	0.603	1.28	1.15	0.3	0.627	0.741	0.281
dry T	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
LOI%	3.0	4.0	1.5	3.3	3.2	3.1	3.8	1.6	8.1	6.3	1.5
<i>Trace Elements (ppm)</i>											
Ba	81.7	312	552	146	790	175	386	336	81.5	155.1	382
Cr	156	133	57.6	101	176	191	126	174	65.2	468	173
Cs	0.192	0.3	0.368	0.127	0.473	2.81	0.529	0.202	0.134	<0.194	0.175
Cu	15.2	48.3	15.9	131	96.7	71.7	74.4	9.72	11.3	61.5	97
Ga	12.2	14.8	14.5	17.0	11.1	17.6	14.3	14.9	9.48	14.5	15.7
Hf	3.87	1.29	2.20	1.55	0.963	2.75	1.99	3.44	2.38	1.08	3.24
Nb	1.99	1.23	2.43	1.56	1.53	1.76	2.21	3.1	1.79	0.46	10.3
Ni	25.2	48.4	17.9	37.3	58.8	108	39.4	12.8	13.6	191	21.6
Pb	1.43	1.14	0.669	2.39	1.29	1.99	0.901	2.15	1.35	1.55	2.63
Rb	14.1	16.9	25.9	9.87	44.9	4.32	<21.7	29.8	9.93	11.2	20.4
Sc	15.7	40.3	35.5	43.8	39.9	34.3	42.1	7.11	21.3	38.3	8.13
Sr	267	373	410	1363	430	196	402	612	124	323	566
Ta	0.145	0.08	0.162	0.095	0.0777	0.137	0.138	0.191	0.126	0.0323	0.747
Th	1.57	0.464	1.17	0.991	0.56	0.296	0.503	1.49	0.940	0.246	5.52
U	0.620	0.189	0.403	0.527	0.146	0.281	0.181	0.76	0.657	0.183	2.29
V	99.7	271	284	332	191	240	270	45.3	130	229	59.7
Y	24.2	16.5	24.5	16.8	12.0	27.5	23.6	15.1	16.7	15.8	10.0
Zr	142	46.4	80.9	54.1	36.6	114	73.7	144	87.7	37.6	135
La	8.89	4.37	7.03	9.15	4.76	4.89	5.27	13.2	4.79	5.32	19.0
Ce	19.3	9.81	15.6	19.6	9.75	13.6	12.3	26.0	9.83	11.2	30.6
Pr	2.96	1.48	2.29	2.88	1.36	2.28	1.90	3.51	1.87	1.83	3.28
Nd	13.7	7.48	11.2	14.0	6.57	11.7	9.90	15.1	9.47	9.66	12.0
Sm	3.68	<2.41	3.50	3.65	1.91	4.06	3.21	3.18	2.80	2.84	2.3
Eu	1.10	0.964	1.12	1.29	0.733	1.46	1.20	1.09	0.782	1.01	0.773
Gd	3.85	2.64	3.8	3.53	2.08	4.28	3.76	2.77	2.71	2.99	2.02
Tb	0.589	0.436	0.649	0.509	0.339	0.728	0.622	0.412	0.436	0.458	0.285
Dy	3.98	3.03	4.33	3.17	2.17	4.91	4.36	2.50	2.96	3	1.63
Ho	0.833	0.655	0.915	0.663	0.452	1.05	0.927	0.527	0.658	0.628	0.329
Er	2.48	1.91	2.84	1.81	1.33	3.17	2.8	1.61	1.96	1.76	0.992
Tm	0.357	0.271	0.423	0.270	0.177	0.468	0.437	0.241	0.300	0.242	0.147
Yb	2.72	1.80	2.72	1.82	1.28	3.21	2.67	1.91	2.13	1.71	1.13
Lu	0.421	0.245	0.419	0.255	0.181	0.443	0.381	0.313	0.305	0.24	0.169

Notes - All analyses were made at the Department of Geological Sciences at Stockholm University (Sweden). Major and minor elements were determined by XRF on fused whole-rock powders and measured in wt.% oxide. International reference standards gave accuracy for the major oxides that was better than 2% except for P₂O₅ that had accuracy better than 5%. Trace elements were analysed by LA-ICP-MS and measured in parts per million (ppm). Abundances preceded by '<' are values below the detection limit. The standard error for the trace elements were generally between 3 – 10%, with Ta showing overall higher standard errors between 8-27% for all the samples. Structurally bound H₂O was determined by loss on ignition analysis (LOI).

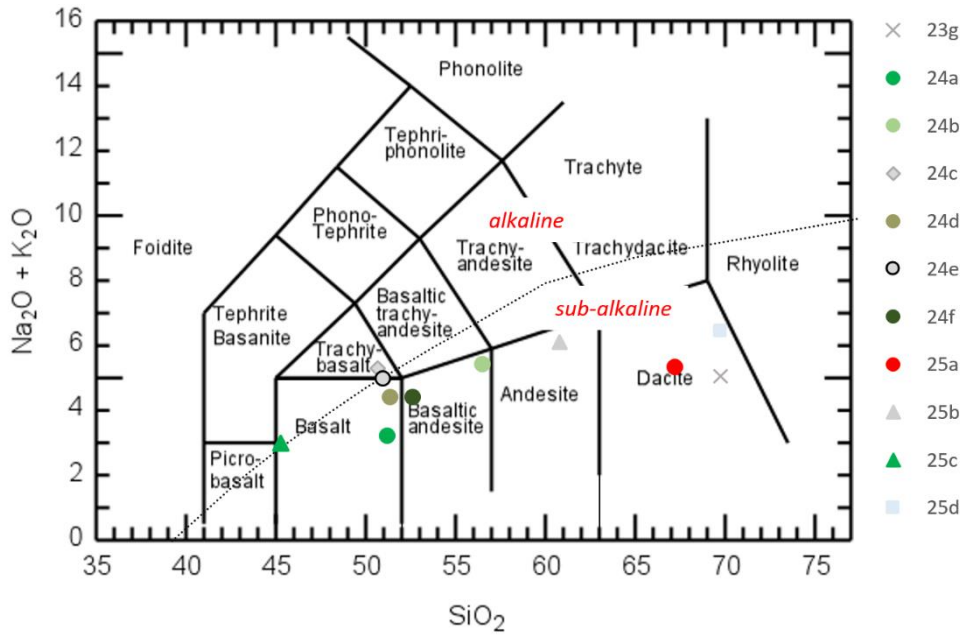


Figure 3. All eleven samples plotted on a TAS classification scheme including the division of alkaline versus sub-alkaline fields. The division line was drawn using values after Irvine and Baragar (1971).

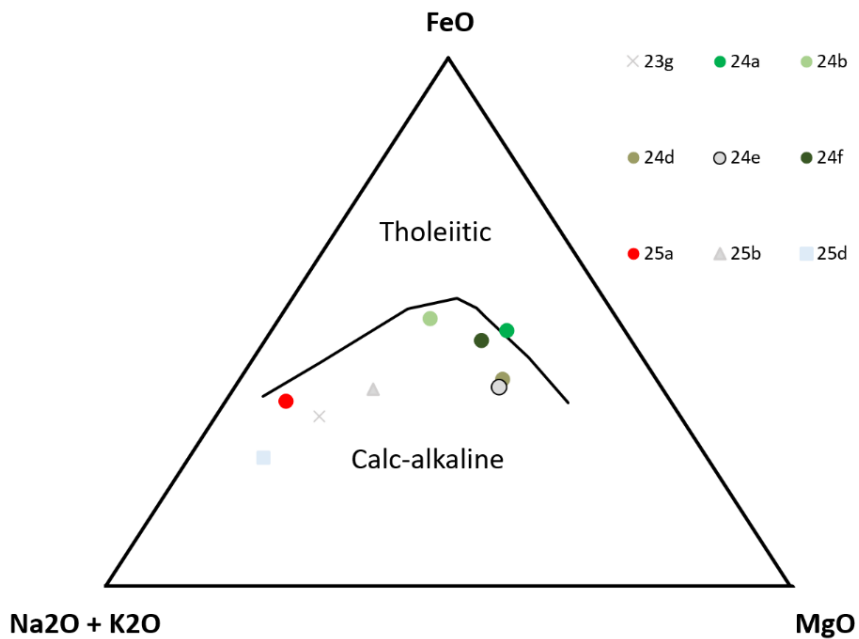


Figure 4. AFM diagram that further separates the sub-alkaline samples into either the calc-alkaline or tholeiitic magma series. The division line was drawn using values after Irvine and Baragar (1971).

5.3 Trace Elements

The geochemical data is shown in multi-element diagrams normalized to N-MORB (Fig. 5a). All samples show a 1-2 order of magnitude enrichment relative to N-MORB in the large ion lithophile elements (LILs) which are also enriched relative to Ce (a light REE). All samples show a 2-3 order of magnitude depletion of the high field strength elements (HFS) Ta and Nb relative to Ce, except sample VP16-25d (outlier) that shows no notable change of Ta and Nb relative to Ce. Samples VP16-25a and 25d display less than 1 order of magnitude negative P and Ti anomalies. The samples are light REE (LREE) enriched by about 1 order of magnitude relative to N-MORB (Fig. 5b). All samples except VP16-24e show a minor depletion, less than 1 order of magnitude, in the heavy REE (HREE) relative to N-MORB. N-MORB normalized ($_N$) REE patterns ($[La/Lu]_N$) for the samples vary between 2–8.

In figure 5c, the data are compared to that of Box and Patton (1989). Samples with evidence of mixing and outliers (VP16-23g, -24c, -25b and -25d) are omitted and data from the Units 3b, 3c and 3d of Box and Patton (1989) are indicated. Sample VP16-25a and Unit 3d show the steepest REE pattern ($[La/Lu]_N = 7-9$). The flattest REE pattern ($[La/Lu]_N = 2-3$) is represented by VP16-24e, VP16-24f and Unit 3c. VP16-24a, -24b, -24d, -25c and Unit 3b (both samples) have an intermediate sloping REE pattern ($[La/Lu]_N = 3-4$). A table with the $(La/Lu)_N$ and $(La/Sm)_N$ ratios is given in the appendix.

6. Discussion

Most of the samples studied are mafic basalts and basaltic andesite (Fig. 3). The samples define a sub-alkaline magma series, with the exception of VP16-25c that plot just into the alkaline field (Fig. 3). Since VP16-25c was one of the high LOI samples, its total alkali content might be an artefact of alteration and this sample might well belong to the sub-alkaline series. Matching N-MORB normalized REE patterns between VP16-25c and the sub-alkaline samples (Fig. 5b) suggests that this is likely the case. The samples are also predominantly calc-alkaline (Fig. 4), with the exception of the transitional tholeiite (VP16-24a).

Basalts and andesites are common rock types associated with volcanic island arcs, whereas continental volcanic arcs generally contain more intermediate to felsic rock types due to partial melting of already more evolved continental crust (Winter, 2014). Calc-alkaline samples can be indicators of subduction-related magmatism since this magma series is commonly restricted to subduction zones where hydrous magmas are produced by devolatilization of the down going slab (Winter, 2014). The tholeiitic sample VP16-24a is on the division line of Irvine and Baragar (1971) and must be regarded as 'transitional': another criteria (e.g., the division line of Kuno, 1968), places this sample in the calc-alkaline field. Nevertheless, both the calc-alkaline and tholeiitic series are common in arc magmatism where the former is commonly more evolved and the latter is often associated with immature island arcs (Winter, 2014). The trace elements display patterns characteristic of subduction zone magmatism (Fig. 5) in which Nb and Ta (HFS) depletion and high concentration of LIL's (K, Rb, Ba, Sr and Th) relative to the LREE and Ce is diagnostic. These characteristics, combined with a lack of more evolved rock types, favours an island arc setting.

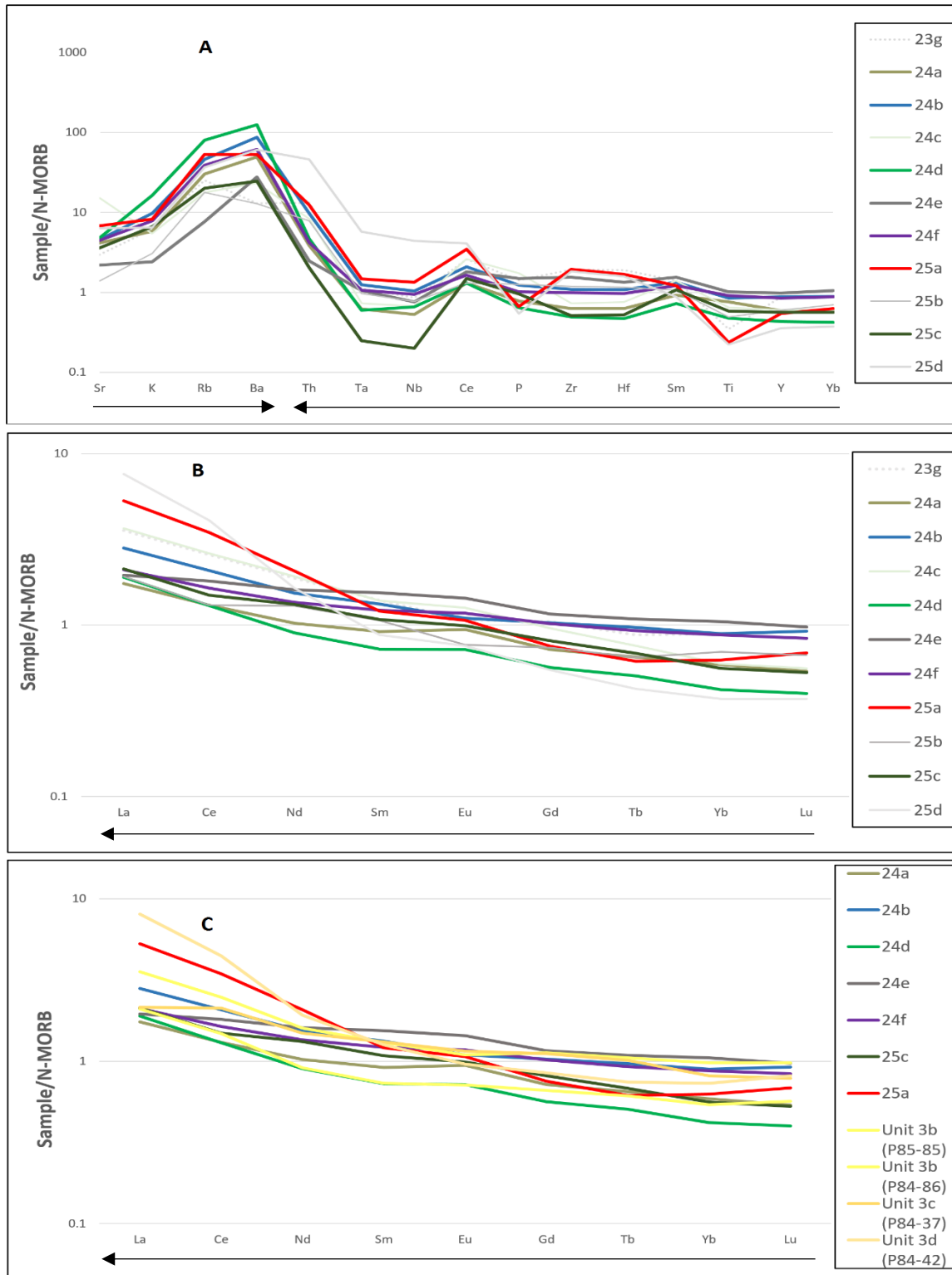


Figure 5. Variation diagrams with samples normalized to N-MORB and E-MORB. **A)** Multi-element plot normalized to N-MORB (values from Pearce and Parkinson, 1993). **B)** REE plot normalized to N-MORB. **C)** REE plot normalized to N-MORB comparing samples VP16-24a, -24b, -24d, -24e, -24f and -25a with Units 3b, 3c and 3d of Box and Patton (1989). N-MORB normalizing values for Figs. 5b and 5c are from Sun and McDonough (1989). Black arrows show direction of increasing element incompatibility.

To confirm an island arc setting, isotopic studies such as Nd or Pb would be necessary (Sinha, Whalen and Hogan, 1997). Most of the samples exhibit subduction related signatures, however, VP16-25d lacks the depletion of Nb and Ta relative to Ce. Perhaps this clast relates to the Angayucham ophiolite and a sea floor rather than subduction zone environment? This would be an interesting avenue of future investigation.

The REE patterns ($[La/Lu]_N$) of these samples, when compared with the volcanic rock units from Box and Patton (1989), are most similar to units 3b, 3c and 3d (Fig. 5c). From this comparison, sample VP16-25a correlates well with unit 3d. The other samples have patterns similar to units 3b and 3c. This similarity is also clear when comparing immobile elements (which are unaffected by low-grade alteration) (Fig. 6). The La vs Ta diagram (Fig. 6a) documents the same correlation between the samples and the units of Box and Patton (1989) as seen in the REEs (Fig. 5c). VP16-25a correlates with unit 3d and the remaining samples plot correlate with units 3a, 3b and 3c. This implies that the conglomerate clasts could originate from the Koyukuk Terrane. This could be additionally verified through geochronological analysis to determine if their ages are the same as the volcanic rocks in the Box and Patton (1989) investigation.

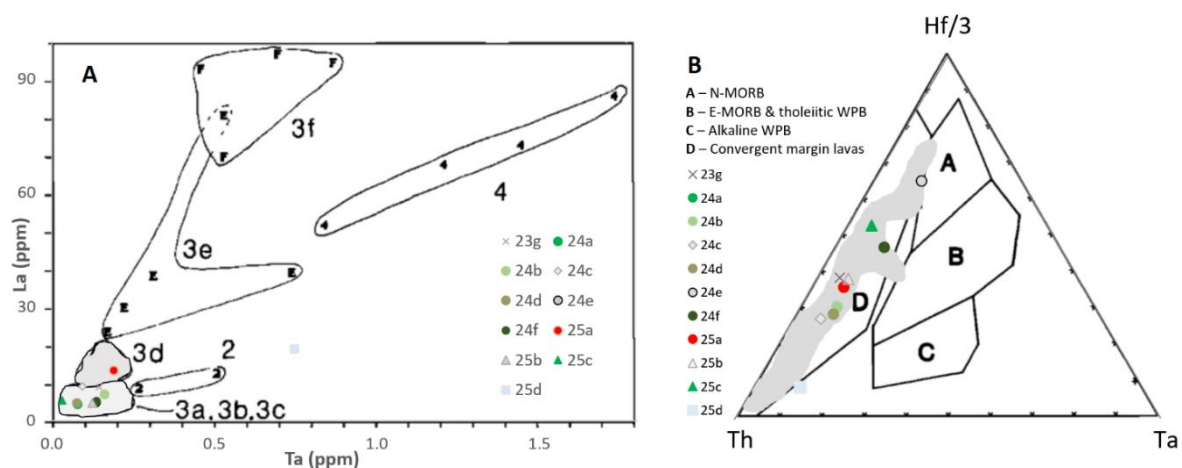


Figure 6. Comparison to the volcanic rocks of the Koyukuk Terrane. **A)** La vs Ta of the samples relative to the data of Box and Patton (1989). **B)** Hf-Th-Ta discrimination diagram showing the data relative to the data of Box and Patton (1989). Note the field D represents convergent margin lavas. Grey areas represent the original data fields from the igneous rocks of the Koyukuk Terrane (after Box and Patton, 1989).

In the Th-Hf-Ta discrimination diagram (Fig. 6b) all samples plot in the D field of convergent margin lavas. This, together with the subduction related signatures from the multi-element plot (Fig 5a,) emphasize the high likelihood that the samples originated from a volcanic arc.

The clasts have the geochemical indicators of being arc related, but does this mean that they all come from the same magma source or the same arc? The most appropriate elements to investigate this are the REEs, since they are generally immobile and unaffected by alteration except under the most extreme conditions. Co-genetic magmas should have similar REE patterns with increasing SiO_2 (Winter, 2014). This is however based on crystal fractionation in a closed system at crystal-melt equilibrium (Lipman, 1987). This type of variation can be seen

to some extent in VP16-24a and -25c and might indicate that these samples evolved from the same parent magma. Several of the samples show similar enrichments for the light REEs, but show variable degrees of enrichment in the middle to heavy REEs. Volcanic arcs are complicated settings in terms of magmatism and both magma mixing and crustal assimilation are common. Arc rocks might therefore not show these co-genetic REE trends since other processes such as different degrees of partial melting, magma mixing and or crustal assimilation will have affected them (Murphy, 2007). Yet the patterns and trends seen in both the REE plots and the multi-element plots for these samples are very similar and even though their REE patterns vary they never differ from each other by more than 1 order of magnitude. This is consistent with the clasts originating from the same arc with their parent magmas being affected by variable differentiation processes before cooling.

7. Conclusions

This study presents a geochemical analysis of conglomerate clasts from the Alaska Yukon-Koyukuk basin with the aim to determine the tectonic origin of the clasts and to investigate their relationship to the remnant arc of the Koyukuk Terrane. From the results of this investigation, the following conclusions can be made:

- The conglomerate clasts vary in silica content but are mainly volcanic to hypabyssal basalts- basaltic andesites, rock types that typically dominate intra-oceanic arcs created by subduction of oceanic plates.
- All samples except one display the typical HFS depleted and LIL enriched signatures characteristic of subduction related magmatism, implying that these clasts originate from an arc environment.
- The geochemistry of the samples correlate well to the volcanic rocks (Units 3b, 3c and 3d) of Box and Patton (1989) and indicates that the conglomerate clasts can be derived from the Koyukuk Terrane.
- Further investigation using isotopic analysis would help to constrain the subduction environment (intra-oceanic or continental), as well as to confirm the clast ages, thus confirming their correlation with the Koyukuk Terrane.
- The overall similarity of trace element patterns indicate that the clasts may originate from the same arc. Individual differences are likely due to the complexity of the arc setting and the diversity of processes that can affect magma evolution.

8. Acknowledgements

I would like to thank following people for helping me accomplish this thesis: Victoria Pease for being a cheering and supportive supervisor; Dan Zetterberg, Curt Broman and Emelie Axelsson for taking their time helping me in an educational way to prepare and run my samples for the geochemical analyses.

9. References

- Box, S. and Patton, W. (1989). Igneous history of the Koyukuk Terrane, western Alaska: Constraints on the origin, evolution, and ultimate collision of an accreted island arc terrane. *Journal of Geophysical Research: Solid Earth*, 94(B11), pp.15843-15867.
- Lipman, P. (1987). Rare-Earth-Element Compositions of Cenozoic Volcanic Rocks in the Southern Rocky Mountains and Adjacent Areas. *Bulletin*; 1668. [online] U.S. G.P.O. Available at: <https://pubs.usgs.gov/bul/1668/report.pdf> [Accessed 12 May 2017].
- Murphy, B. (2007). Arc Magmatism II: Geo-chemical and Isotopic Characteristics. *Journal of The Geological Association of Canada*, 34(1).
- O'Brien, T.M., Miller, E.L., Pease, V., Hayden, L.A., Fisher, C.M., Hourigan, J.K., and Vervoort, J.D., In Press. Provenance, U-Pb detrital zircon geochronology, Hf isotopic analyses, and Cr-spinel geochemistry of the northeast Yukon Koyukuk Basin, AK: Implication for Alaska interior basin development, *Geological Society of American Bulletin*.
- Patton, W. and Box, S. (1989). Tectonic setting of the Yukon-Koyukuk Basin and its borderlands, western Alaska. *Journal of Geophysical Research: Solid Earth*, 94(B11), pp.15807-15820.
- Sinha, A., Whalen, J. and Hogan, J. (1997). *Nature of magmatism in the Appalachian orogen*. Boulder, CO: Geological Society of America, p.345.
- Winter, J. (2014). *Principles of Igneous and Metamorphic Petrology*. 2nd ed. Edinburgh Gate: Pearson Education Limited, pp.160-163.

Maps and Figures

- Irvine, T. N., and W. R. A. Baragar., 1971. A guide to the chemical classification of the common volcanic rocks, *Can. J. Earth Sci.*, 8, 523-548.
- Kuno, H. (1968). Differentiation of basalt magmas. In: Hess H.H. and Poldervaart A. (eds.), *Basalts: The Poldervaart treatise on rocks of basaltic composition, Vol 2*. Interscience , New York, pp. 623-688.
- Pearce, J.A. and Parkinson, I.J., 1993. Trace element models for mantle melting: application to volcanic arc petrogenesis; in Prichard, H.M., Alabaster, T., Harris, N.B.W., and Neary, C.R., eds., *Magmatic Processes and Plate Tectonics*, Geological Society Special Publications, no. 76, 373-403.
- Sun, S.S. and McDonough, W.F., 1989. Chemical and isotopic systematics of oceanic basalts; implications for mantle composition and processes. In: *Magmatism in the ocean basins*. Saunders, A.D. and Norry, M.J. (Editors), Geological Society of London, London, no. 42, 313-345.

Appendix

A - Sample preparation

B - Thin section descriptions

C - Data tables and plots

D - Sample pictures

A. Sample preparation for geochemical analyses

Geochemical analyses of the samples were obtained using three analytical methods: LOI (loss on ignition), XRF for the major elements, and ICP for the trace elements. The samples were prepared in several steps before analyses. First step of preparation was to remove any weathering from the surfaces of the clasts. This was done by using a diamond saw blade made with zinc and copper alloy. After sawing, each sample was polished using a polishing wheel with silicon carbide (SiC) grit number 180. This removed metal contamination from the saw blade left of the cut edge of the samples. Each sample was then cleaned of dust or powder and split with a geological hammer into small pieces of <9mm. These pieces were then pulverised using a Retsch RS 200 Vibratory disk mill.

After all samples had been powdered, the LOI analysis was performed to determine the volatile content of each rock sample and to remove structurally bound water (water in hydrous mineral phases). This was done by putting 5 grams of sample into a crucible. Crucible weight and crucible + sample weight was noted. The samples in crucibles were put into an oven where they were heated to 1000°C for 10 hours. When the samples were finished devolatilizing, each was weighed again with their crucibles and their “dry weight” noted. To calculate the LOI formula 1 was used.

Formula 1. $LOI = 100 * (a - c)/(a - b)$

a = Crucible + sample “wet weight”

b = Crucible weight

c = Crucible + sample “dry weight” after heated to 1000°C

After the LOIs were calculated the dry samples were prepared for the XRF. First each sample was ground to a fine powder in an agate mortar. Then 5.0000 g +/- 0.0002 g of sample was weighed and put into a Pt beaker. Each Pt beaker has a specific number that was written down in the lab book together with the sample number and its weight. 2.0000 g +/- 0.0002 g of Lithium meta borate flux was then added to the Pt beaker + sample powder. Both components were carefully and well mixed. When all samples were made they were, 4 at the time, put into the holders of the autofuser (Phoenix M/VFD 4000) together with 4 moulds. The heating and fusion of the samples plus flux was performed using a pre-programmed formula and all samples were processed in an identical manner. When all samples were melted to glass, poured into their moulds, and cooled, they were labelled with their sample number. After labelling the discs were stored in plastic bags, one for each sample disc. The samples were then processed by the XRF.

Once the XRF analyses were finished and quality control of the data had been made, the glass discs were prepared for LA-ICP-analysis. This was done by crushing each sample disc with a geological hammer into small pieces (still in the plastic bag). One small glass piece (approximately 3 mm) of each sample was mounted on a thick glass disc with tape. Two glass discs were used for the 11 samples and a map of the location of each sample was drawn of

each glass disc. To further stabilize the samples for LA-ICP-analysis epoxy was poured over the sample fragments. The epoxy was made by carefully mixing 15 ml of Epofix Resin with 2 ml of Epofix hardener. The samples were then left for 36 hours for the epoxy to dry. They were then polished before being analysed via LA-ICP-MS.

B. Thin section descriptions

VP16-23g

LOI: 3.11 %

Hand specimen: mesocratic, phaneritic medium grained (intrusive?), both light yellow-greenish and dark greenish minerals giving the rock an overall green colour. Volcanic xenolith in the plutonic matrix.

Major minerals: quartz, calcite, chlorite, sericite, plagioclase, epidote/clinozoisite, amphibole

Accessory minerals: titanite.

Textures: the host rock have a plutonic intergranular and interlocking texture. The xenolith has a trachytic texture (lava flow).

Reactions: seritization of plagioclase feldspars (hydrothermal alteration).

Notes: plutonic rock with a volcanic xenolith of approximately 10 mm. The xenolith has a small grained trachytic texture. Lots of cracks filled with calcite, quartz and chlorite.

VP16-24a

LOI: 4.22%

Hand specimen: melanocratic and fine grained phaneritic texture.

Major minerals: calcite, amphiboles, plagioclase, chlorite, sericite, pyroxene, epidote

Accessory minerals: opaques (oxides)

Texture: equigranular and trachytic texture.

Reactions: chlorite are starting to replace pyroxenes. Actinolite starts to replace hornblende.

Notes: volcanic (hypabyssal?). Trachytic texture indicates lava flow while the coarser trachytic texture indicate solidification in the shallower crust (hypabyssal).

VP16-24b

LOI: 1.47%

Hand specimen: melanocratic. Fine grained phaneritic. Yellowish green in colour.

Major minerals: plagioclase feldspars, amphibole (hornblende?), sericite, chlorite.

Accessory minerals: opaques (oxides).

Texture: equigranular and trachytic.

Reactions: seritization of plagioclase grains.

Notes: volcanic (hypabyssal?). Not as altered as the other ones. Not sure if the amphiboles are hornblende or actinolite but their strong pleochroism indicates that they might be hornblende. The hornblendes are started to be replaced by a lighter green mineral growing on the edges (actinolite replacement?). The amphiboles are small and subhedral and some expose simple twinning.

VP16-24c**LOI: 3.36%**

Hand specimen: melanocratic. Fine grained porphyritic with light grey microphenocrysts. Groundmass is greenish grey in colour.

Major minerals: feldspars, plagioclase, sericite, chlorite, amphiboles, pyroxene, quartz, epidote, devitrified glass.

Accessory minerals: opaques (oxides)

Texture: microporphyritic with phenocrysts of pyroxenes, alliotriomorphic (mostly anhedral grains), devitrified glass pockets. Probably a volcanogenic sediment since the rock has angular fragments of mineral grains. Doesn't look like either a volcanic rock or plutonic rock.

Reactions: seritization of feldspar grains (hydrothermal alteration).

Notes: volcanic mixture? Porphyritic rock with calcite veins. The pyroxenes are fractured and doesn't look happy but they are not altered which indicates no eruption into the ocean. Some amphiboles have simple twinning. Looks like epidote and chlorite replaces the amphiboles. Tiny quartz grains in the groundmass. Probably explosive eruption rock, have some evidence of mixing where there looks like crystals has been fractured and ended up in blobs of lava.

VP16-24d**LOI: 3.26%**

Hand specimen: melanocratic and very fine grained (almost aphanitic). Green-yellowish grey in colour.

Major minerals: amphibole, chlorite, calcite, quartz, epidote, pyroxene, prehnite, sericite.

Accessory minerals: opaues (oxides).

Texture: subhedral-anhedral amphibole crystals. Trachytic and intergranular texture.

Reactions: majority of the plagioclase feldspars have been altered to sericite (hydrothermal alteration).

Notes: volcanic rock. Dark green fibrous mineral, same birefringence as biotite but fibrous and dark green in PPL, probably chlorite. The amphibole crystals are commonly browner in the central part and becomes lighter greenish in the edges which could be replacement of hornblendes by actinolite.

VP16-24e**LOI: 3.17%**

Hand specimen: melanocratic and aphanitic.

Major minerals: plagioclase, amphiboles, chlorite, epidote/clinozoisite, opaques, sericite, pyroxene.

Accessory minerals:

Textures: trachytic and microlithic texture indicating a fast cooling lava flow.

Reactions: seritization of feldspars. Breakdown of amphiboles and pyroxenes.

Notes: volcanic rock with abundant tiny opaque grains. Veins with some 3rd order birefringence mineral, too tiny to identify but looks like epidote.

VP16-24f

LOI: 3.89%

Hand specimen: phaneritic medium grained melanocratic. Some darker grey minerals together with dark greenish minerals.

Major minerals: calcite, pyroxene, feldspars, sericite, chlorite, amphibole (hornblende and actinolite?)

Accessory minerals: opaques (oxides)

Textures: trachytic texture, calcite grains and pyroxenes mantled by chlorite. Looks like actinolite/chlorite starts to replace hornblende but also chlorite replacement of pyroxene

Reactions: Chloritization.

Notes: volcanic (hypabyssal?). Calcite veins present. Looks like amphibole (hornblende) is growing around pyroxene grains which are also mantled by chlorite and calcite.

VP16-25a

LOI: 1.67 %

Hand specimen: mesocratic and phaneritic medium grained (plutonic), large quartz grains and some yellowish green minerals giving the rock an olive-green colour.

Major minerals: quartz, chlorite, clinozoisite/epidote, plagioclase, prehnite, sericite, amphibole.

Accessory minerals:

Texture: plagioclase grains having sieve texture.

Reactions: seritization of plagioclase grains (hydrothermal alteration)

Notes: plutonic rock, not as altered as the other samples.

VP16-25b

LOI: 8.79%

Hand specimen: melanocratic, porphyritic texture with light pinkish grey phenocrysts (1-5 mm) in a darkish grey coloured matrix.

Major minerals: calcite, Quartz, Chlorite, Sericite, devitrified glass (anisotropic, dark in XPL light green in PPL).

Accessory minerals: opaques (oxides)

Texture: porphyritic and inequigranular. Glomerophenocrysts of plagioclase feldspars. Tiny quartz grain making up the groundmass.

Reactions: seritization of euhedral to subhedral plagioclase grains.

Notes: volcanic mixture of two magmas? Looks very unhappy, secondary calcite grains together with very fine grained quartz grains making up the groundmass in bubbles together with devitrified glass around the calcite. The secondary calcites could be due to eruption in ocean water (rich in carbonates). Looks like the sample has blobs of other solidified magma (trachytic texture) in it. Overall it has a felsic mineral composition.

VP16-25c**LOI: 6.75%**

Hand specimen: melanocratic, porphyritic with light green yellowish and dark grey phenocrysts (1-5 mm) in a grey coloured matrix.

Major minerals: serpentine, chlorite, sericite, pyroxene, prehnite, epidote.

Accessory minerals: opaques, titanite.

Textures: Inequigranular texture, porphyritic (larger olivine? and pyroxene grains in a fine-grained matrix of sericite altered plagioclase grains. Trachytic texture.

Reactions: seritization of plagioclase and serpentinization of olivine and partly of pyroxene (hydrothermal alteration).

Notes: volcanic with porphyritic-aphanitic texture. Olivine and pyroxene grains remarkable larger (phenocrysts) and very fractured. The pyroxenes are having first to lower second order birefringence colours. Some larger olivine grains have been totally replaced by serpentine.

VP16-25d**LOI: 1.52%**

Hand specimen: leucocratic – mesocratic, phaneritic medium grained (plutonic rock?). Some light greenish-yellow minerals together with quartz grains and a darker grey mineral.

Major minerals: plagioclase, amphibole, quartz, calcite, chlorite, prehnite, epidote/ clinozoisite, sericite, opaques, pyroxene.

Accessory minerals: titanite.

Textures: inclusions of prehnite grains in larger feldspars (Sieve texture?)

Reactions: plutonic rock. Breakdown of amphibole by oxides. Fractured pyroxene grains that are started to be broken down by chlorite.

Notes: polybaric rock, that has gone from high P/T to lower P/T shallower crust. The amphiboles with oxides looks out of equilibrium.

C. Data tables and plots

Table 3.1. Analytical conditions for the LA-ICP-MS.

laser energy density:	7.3 J/cm ²
spot size:	150 μm
frequency:	10 Hz
additional N ₂ :	1.1 ml/min
5 analyses per sample	
external standard:	NIST-612
secondary standards:	BCR-2 / SARM-1
internal standard:	Si
20 seconds background, 40 seconds laser-on, 10 seconds wash-out	

Table 3.2. REE ratios of units 3b, 3c and 3d from Box and Patton (1989) together with ratios of the VP16 samples. La/Lu represents light REE to heavy REE ratio. La/Sm represents light REE to intermediate REE ratio.

	3b (P85-85)	3b (P84-86)	3c (P84-37)	3d (P84-42)	VP16-24a	VP16-24b	VP16-24d	VP16-24e	VP16-24f	VP16-25a	VP16-25c
La/Lu	3.6	3.7	2.7	9.9	3.8	3.2	4.8	2.0	2.5	7.7	4.0
La/Sm	2.7	2.9	1.6	6.4	1.9	2.1	2.6	1.3	1.7	4.4	2.0

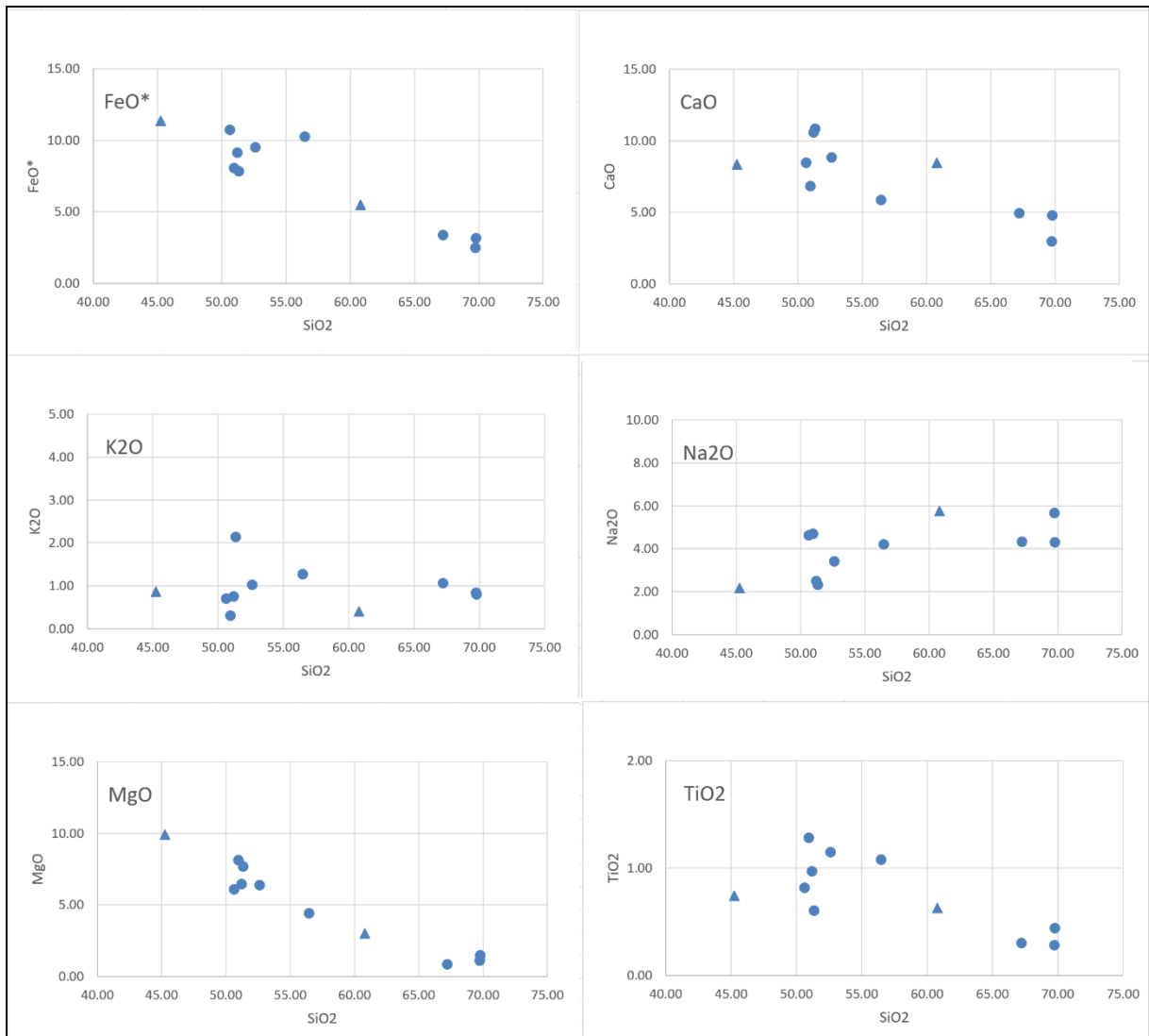


Figure 3.1. Major oxides versus silica content for all samples. All oxides are plotted in wt.%. High LOI samples are plotted with a triangle.

D. Sample pictures

- I) Pictures of all clasts taken before the geochemical analysis preparation.
- II) Pictures of thin section slides and pieces of un-weathered samples.

