

PROVENANCE AND ALTERATION OF GLACIAL SEDIMENTS IN KING GEORGE ISLAND, ANTARCTICA

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Received on 3 February 2019

Received in revised form on 30 March 2019

Accepted on 31 March 2019

Editor: Mauro Geraldine, Universidade do Estado do Rio de Janeiro

Citation:

Rangel, C.V.G.T., Orlando, M.T.A., Jardim, H.A., Almeida, I.C.C., Mendonça, E.S., Teixeira, D.B., Thomazini, A., Schaefer, C.E., 2019. Provenance and alteration of glacial sediments in King George Island, Antarctica. *Journal of Sedimentary Environments*, 4 (1): 124-142.

Abstract

Mineralogical and geochemical data of glacial sediments of Low Head, King George Island, Antarctica, are presented to approach its provenance and alterations aspects. Mineralogical analyses were performed using petrography and an x-ray diffraction method, while the geochemistry was performed by x-ray fluorescence. Comparisons using major elements in the sediments with possible source areas, suggested that they are closer to the King George Island parent rocks, with no contribution of rocks from Antarctic Peninsula. The gravel and sand fractions demonstrate that the till is composed of basaltic and andesitic rock fragments, plagioclase, pyroxene and amphibole, typical of active immature volcanic arc. The mud fraction indicates chemical characteristics consistent with calc-alkaline to tolleitic and metalluminous affinity of source rock of the till and the presence of secondary mineral phases, such as laumontite,

brucite and saponite. The values of alteration indices, such as the chemical index of alteration (CIA) and the $\text{SiO}_2/\text{Al}_2\text{O}_3$ ratio, in the regional rocks and sediments reflect a remarkable degree of alteration, possibly due to hydrothermal activity, exemplified by the presence of laumontite. In addition, bivariate chemical diagrams suggest slight weathering compared to the South Shetland Islands, which may have been responsible for the formation of brucite and saponite. The results suggest that although there are secondary mineral products, some grade of weathering could have acted in the till during sedimentary cycles or the till was strongly influenced by components of local weathered basalts.

Keywords: Sediment provenance. Alteration. Glaciogenic sediments. Mineralogy. Geochemistry.

1. Introduction

On King George Island, Maritime Antarctica, the warming that has taken place during the last several decades have been accompanied by rapid glacial retreat and considerable ice wastage (Cook et al., 2005; Rückamp et al., 2011). This process has exposed large rock outcrops and

deposited glaciogenic sediments (till) in the shore regions, forming large proglacial plains.

These plains are a good laboratory to understand the structural, textural and compositional nature of till in Antarctica. Although many studies have described the

regolithic material on King George Island, these studies have focused on soil formation and soil properties (for example, Michel et al., 2006; Schaefer et al., 2008; Simas et al., 2008).

The till compositional characteristics at different locations on King George Island have been attributed to the specific local parent volcanic materials (Monien et al., 2011), which are mainly basalts, andesites and its pyroclastic products. On the other hand, some source rocks from Antarctic Peninsula are suggested during Oligocene to Miocene times (Birkenmajer, 1980, 1992a, 1992b; Dingle and Lavelle, 1998).

Chemical characteristics of Mesozoic to Cenozoic parental rocks of South Shetlands indicate predominantly a calc-alkaline to tholeiitic affinity in an active magmatic arc (Birkenmajer et al., 1991, 1994; Yeo et al., 2004; Machado et al., 2005). To the northern Antarctic Peninsula, the Jurassic to Late Cretaceous, acid to intermediate magmatism indicate predominantly a calc-alkaline affinity,

in a mature arc, similar to the western South America (Saunders et al., 1980; Birkenmajer, 1994).

In the point of view of weathering, Robert and Kennet (1997), based on clay content and oxygen isotope identified slight chemical weathering in Antarctica, during Eocene-Oligocene times. Santos et al. (2007) analyzed the coastal sediments in Admiralty Bay, King George Island and demonstrated that no significant alteration due to the weathering occurred in the sedimentary environment. Mineralogical studies carried out on continental shelf sediments collected from the South Shetland Islands (Jeong et al., 2001, 2004) and a core obtained from Maxwell Bay on King George Island (Monien et al., 2011) suggest that the presence of clay minerals reflects hydrothermal alteration of volcanic bedrock. Mineralogical and geochemical studies of the till of Low Head, King George Island (Fig. 1), were performed. The purpose of this work is to characterize the composition of the till and provide more information on its provenance and alteration.

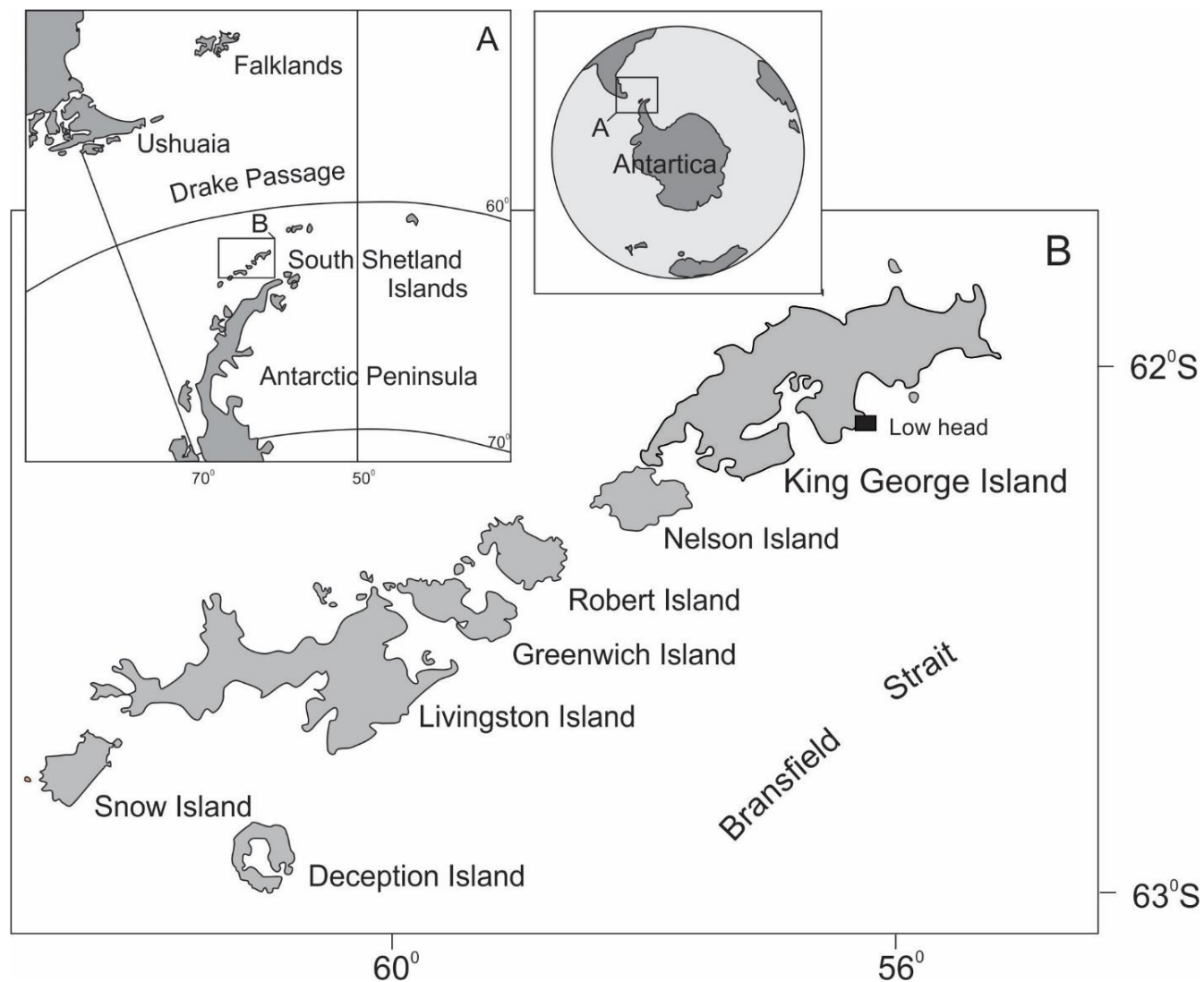


Fig. 1. Location of the South Shetland Islands archipelago and Antarctic Peninsula (A) and the Low Head area at King George Island (B).

1.1 Geological overview

The Antarctic Peninsula is associated with domains that represent the amalgamation of some suspect terranes (Vaughan and Storey, 2000), although most of them are parautochthonous. They are related to turbiditic sequences in an accretionary wedge (the Trinity Peninsula Group and Le May Group; Birkenmajer, 2001; Hervé et al., 2006); low grade metamorphic complex (the Scotia Complex); Jurassic to Lower Cretaceous basaltic and andesitic lavas (the Antarctic Peninsula Volcanic Group) and their hypabyssal to plutonic correlated (Gledhill et al., 1982); Cretaceous calc-alkaline granitoids (the Andean Intrusive Suite; Hawkes, 1961; Barton, 1965). These units have their correspondent in the Patagonian and Fuegian segments of the Andes (Hervé et al., 2006), representing the continuity of the orogenic process in the west margin of Gondwana in the Paleozoic/Mesozoic times, before the breakup (Dalziel, 1984; Trouw et al., 1997).

The Trinity Peninsula Group was deposited during the Permian-Triassic, in the fore-arc region, as a turbiditic association of pelites and wackes, with associated pillows and hyaloclastites, metamorphosed in prehnite-pumpellyite facies (Hyden and Tanner, 1981; Hervé et al., 2006). In the back-arc region, during the Middle to Upper Jurassic, on the erosive discontinuity of the Trinity Peninsula Group, lacustrine and alluvial sedimentary beds of Mount Flora Formation were deposited. In the Middle Jurassic-Early Cretaceous, this crustal section was affected by the calc-alkaline, intermediate to acid magmatism of the Antarctic Peninsula Volcanic Group (Birkenmajer, 1994, 2001).

During the Mid to Upper-Cretaceous, the plutons of the Andean Intrusive Suite intrudes the previous units, while the subduction process evolves, and the magmatic arc shift to the west, beginning the formation of the South Shetlands arc, extended through the Miocene age (Birkenmajer, 1994; Hervé et al., 2006). This migration induces in the Oligocene-Recent, an extensional regime into the lithosphere, between the inner magmatic arc (Antarctic Peninsula) and the Shetland Arc, opening the Bransfield Rift (Birkenmajer, 1992a, 1994).

The tectonic scenery of the opening of the Bransfield back-arc and the counterclockwise rotation of the Antarctic continent during the Tertiary, induces to a terrestrial and submarine volcanic activity and the establishment of a set of strike-slip faults in the South Shetland. The chemical signature of the magmatism is predominantly calc-alkaline and tholeiitic (Birkenmajer, 1994, 2001). Based on this hypothesis, the King George Island inherits a framework dominated by tectonic blocks separated by shear zones (Fig. 2A). These blocks are predominantly made up of basaltic to andesitic lava flows with minor amounts of plugs, dikes, sills and pyroclastic deposits.

In the Early Oligocene, the largest Tertiary glaciation on King George Island was established and a large ice platform

was formed, transporting sediments from the Antarctic Peninsula to the South Shetland, depositing the glaciogenic sediments of Polonez Cove Formation (Birkenmajer, 1992a, 1992b; Dingle and Lavelle, 1998).

The region of Wesele Cove, Low Head and Lions Cove, Krakov Block, a set of effusive, pyroclastic, intrusive rocks and correlated sedimentary products were formed during Eocene to Miocene, including the Polonez Cove Formation. These rocks are intruded by Miocene basalts of the Cape Syrezol Group (Birkenmajer, 1989) (Fig. 2B and 2C). The chemical signature in these areas is predominantly calc-alkaline, metaluminous (Birkenmajer et al., 1991).

2. Materials and Methods

The field works were carried out in the retreat zone of Wyspianski icefall in the Low Head area (Antarctic Peninsula, South Shetland Islands archipelago, King George Island; Fig. 1), during the 29th Brazilian Antarctic Expedition.

About 500 grams of sediments were collected 30 cm depth, in the retreat zone of glacial plain. The sampling points were chosen based on distinct till deposits, as frontal moraines, lateral moraines, etc (Figure 2C). In the laboratory, samples were dried and sieved. For each sample, the sand and granule fragments were separated, attached with epoxy resin and prepared as thin sections for petrographic analyses, which were performed using transmitted light polarizer microscope. The fine silt and clay fractions were prepared for X-ray diffraction analysis, scanning electron microscopy and geochemical analysis of the major elements by X-ray fluorescence spectrometry.

The X-ray powder diffraction analyses were performed at the Laboratory of Photonic Nanometry, Federal University of Espírito Santo, Brazil, with RIGAKU conventional equipment, model Ultima IV, using Cu K alpha radiation (average length $\lambda = 0.15419$ nm) using the Theta/2Theta Bragg-Bretano geometry. A 100-micrometer sieve was used to prepare the sediment powder samples for X-ray diffraction measurements. NIST standard reference materials were used for calibration and setup (SRM 640d code- Silicon Powder (Si); SRM 660b code- Lanthanum Hexaboride (LaB₆)) (Martinez et al., 2014).

To obtain the scanning electron microscope (SEM) images, the samples were coated with a fine gold film. The images of the mud fractions were obtained using a Shimadzu microscope, model SSX-550, at the Department of Physics, Federal University of Espírito Santo, Brazil.

To perform X-ray fluorescence spectrometry, 8 to 10 grams of each sample were mixed with 16 grams of organic binder material and pressed to make 35-mm tablets. The analyses were performed at the Laboratory of Geochemistry, Department of Geology, Federal University of Espírito Santo, Brazil, with the S8 TIGER spectrometer with a lithium fluoride (LiF) 200 standard analyzer crystal.

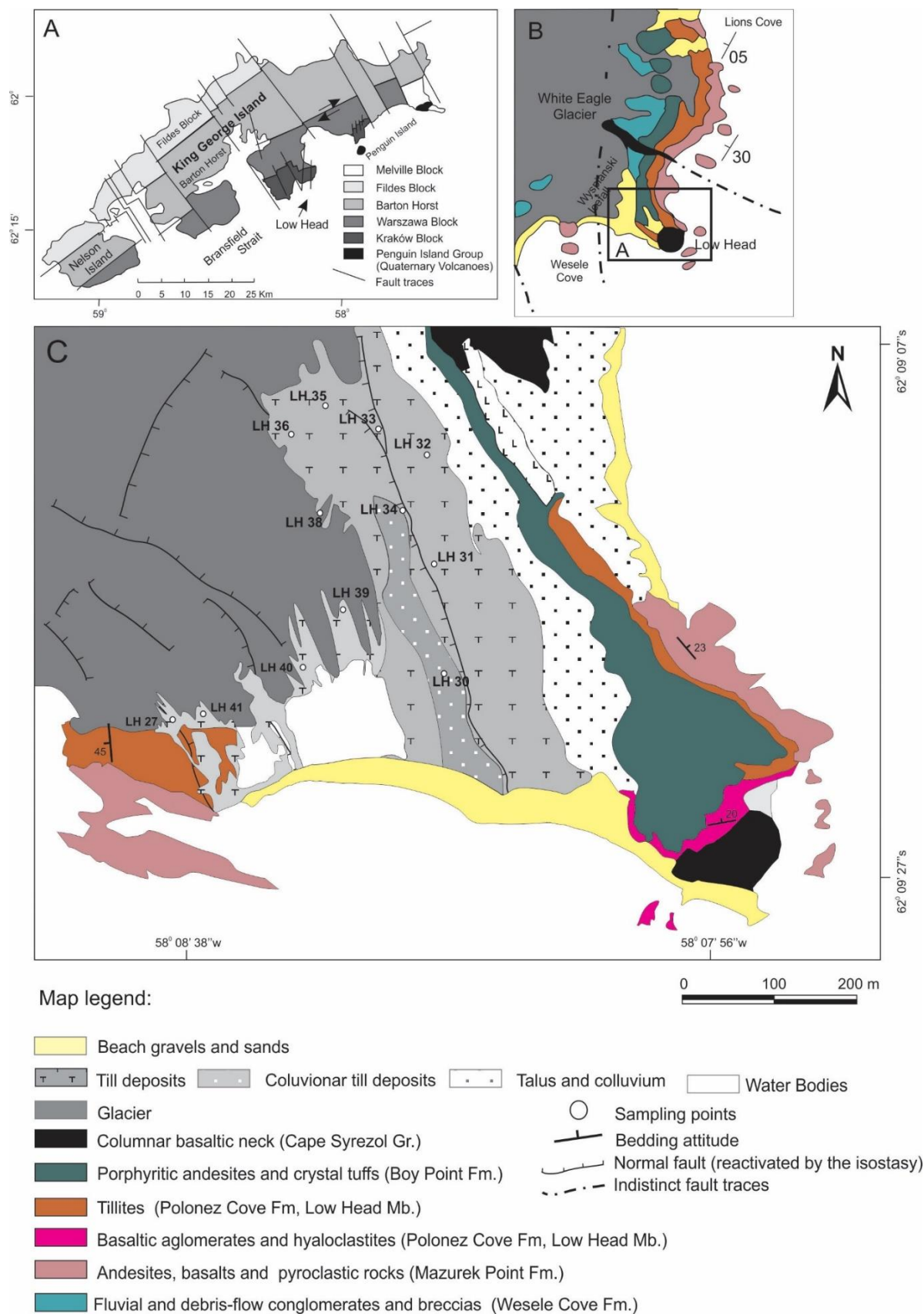


Fig. 2. A) tectonostratigraphic compartmentalization of King George Island. Modified from Birkenmajer (1983). (B) Geological sketch of Low Head, Wesele Cove and Lions Cove region, Krakow Block. Modified from Birkenmajer (2001). (C) Geological map in detail of Low Head.

Major elements are expressed in weight percentage for oxides. Iron contents are expressed as the total iron (Fe_2O_{3t}).

Glacial sediments were compared with parental rocks of South Shetland Islands utilizing data from Machado et al. (2005) (Livingstone, Greenwich, Robert and King George islands), Yeo et al. (2004) (Barton and Weaver peninsulas, King George Island) and Birkenmajer et al. (1991) (King George Island). The parental rocks dataset of Antarctic Peninsula is based on Saunders et al. (1980).

Simple correlation matrices were determined using the statistical mode of Libre Office, to test the degree of association among major elements in the sediments and rocks.

3. Results

3.1 Petrography of the coarse fractions

The sand and gravel size fractions in the till are composed mainly of rock fragments, including fragments of effusive, volcanoclastic and minor epiclastic rocks, as well as fragments of minerals, such as pyroxene, amphiboles and plagioclase (Table 1). Rock fragments are present mainly in the moraine deposits, whereas mineral fragments are common in the outwash deposits (Table 1; Figure 2C, sample LH 39).

Basalts and andesites are the main effusive rock fragments and generally make up more than 40% of the grains (Table 1). A range of textures, including porphyritic, trachytic, glomeroporphyritic and intersertal, were observed (Figs. 3A and 3B). In the outwash deposits, the percentage of effusive rock fragments decreases to about 25%, whereas the proportion of mineral fragments increases (Table 1).

Pyroclastic rock fragments are represented by basaltic to andesitic tuffs and lapilli tuffs (Fig. 3C), which make up 25% to 41% of the grains (Table 1). Arkoses and lithic sandstones are the main constituents of the epiclastic rocks. Other clasts include quartz, microcline, carbonate and minor pyroxene and amphiboles (Fig. 5d), which make up between 1% and 10% of the grains (Table 1).

In the mineralogical grain assemblage of the sediments, plagioclase is the main constituent (6%-28%), followed by pyroxene (0% to 13.8%) and amphiboles (0% to 3.7%) (Table 1). Trace minerals include quartz, carbonate, olivine, zircon and biotite.

3.2 Chemical and mineralogical composition of the mud fractions

The mud chemical composition shows that SiO_2 ranges

from 51.4% to 59.2%, whereas Fe_2O_{3t} (total iron oxides) varies from 7.9% to 12.8%. The Ca_2O varies from 6.6% to 9.1%, and MgO ranges from 3.8% to 6.3% (Table 2).

Compared to the possible source areas, the chemical signature of till suggests more similarities with the South Shetland rocks than Antarctic Peninsula. In the chemical classification diagrams of magmatic series and rocks, used in this work to provenance purposes, the sedimentary till samples are clustered in the more concise field of South Shetland rocks, while the Antarctic Peninsula forms a more extended cluster (Fig. 4).

General chemical characteristics of parental rocks and derived sediments suggest basaltic and andesitic compositions in a calc-alkaline to tholeiitic series and metaluminous series (Fig. 4). On the other hand, the Antarctic Peninsula rocks has strictly calc-alkaline signature in a metaluminous to peraluminous series. The main geotectonic chemical signature indicates an orogenic background and a minor oceanic crust affinity (reflecting a spreading centre and oceanic ridge and floor) (Fig. 4).

The correlation matrices (Table 3A and 3B) of chemical data from rocks from King George, Livingstone, Greenwich Islands and Antarctic Peninsula (Appendix 1), indicated correlations among SiO_2 and Al_2O_3 , Fe_2O_{3t} , CaO , MgO , TiO_2 , P_2O_5 and MnO . It could suggest fractionation of primary silicates, such as pyroxenes, amphiboles, Ca-plagioclases and olivine. The correlations of Al_2O_3 with respect to Fe_2O_{3t} , TiO_2 , P_2O_5 and MnO could be associated with primary oxides, such as ilmenite, magnetite, hematite and phosphates such as apatite and minor monazite. The Na_2O anomalies are probably due to the enrichment in Na-plagioclase over Ca-plagioclase. The relationship between CaO , Na_2O and K_2O could be associated mainly with the occurrence of feldspars.

In the till, the correlation coefficients (Table 3C) show that Fe_2O_{3t} and CaO remain negatively correlated with SiO_2 , which likely reflects the main primary mineral phases, such as pyroxene, amphibole and plagioclase. The negative correlations with TiO_2 are explained by the retention of detrital heavy minerals, such as ilmenite and (or) rutile, whereas the positive correlations with Na_2O are related to its mobility in the surface environment.

The positive correlation between Al_2O_3 and K_2O could be related to the presence of clay minerals, zeolites or K-feldspars. The negative correlations of CaO with Na_2O and K_2O suggest its presence in plagioclase. Similar behavior of Na_2O and K_2O in the surface probably reflects the presence of clay or other secondary minerals in the sediments. All the correlations associated with P_2O_5 could be mainly related to apatite and minor relations with monazite clastic primary phases.

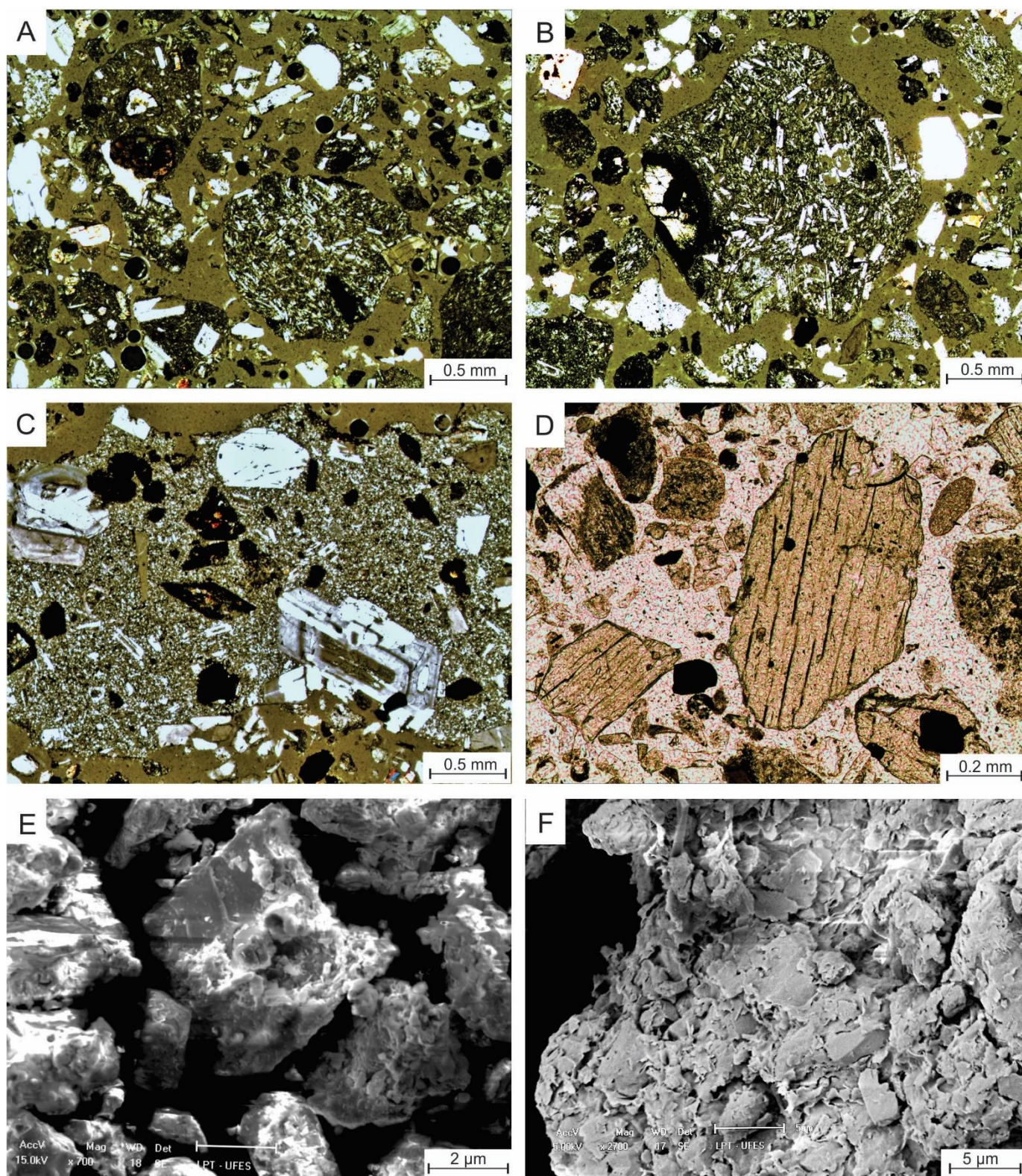


Fig. 3. A. Effusive basaltic and andesitic rock fragments exhibiting porphyritic and intersertal textures. Crossed polarizers. B. Detail of a basaltic grain with intersertal texture. Crossed polarizers. C. Pyroclastic rock fragments composed of crystalline lapilli in a microlitic and vitric ash matrix. Crossed polarizers. D. Detail of amphibole grains. Parallel polarizers. E. Image of an amphibole crystal under SEM in the mud size fractions. F. Image of detrital clay in SEM covering the surface of the grains.

Tab. 1. Modal counting (%) of the main sand and gravel size fraction constituents.

<i>Grain type</i>	LH 30	LH 31	LH 38	LH 27	LH 32	LH 33	LH 34	LH 41	LH 35	LH 36	LH 40	LH 39	Average
<i>Effusive volcanic rock fragments</i>	45.9	40.7	35.6	44.7	45.3	45.4	53.6	39.14	34.2	47.7	50.2	25.1	42.3
<i>Pyroclastic rock fragments</i>	28.1	38.0	26.7	23.2	30.2	30.6	25.4	39.75	41.6	25.4	27.7	27.3	30.3
<i>Sedimentary epiclastic rock fragments</i>	2.4	2.8	2.5	1.2	5.4	9.9	3.5	8.40	7.1	5.4	10.1	1.3	5.0
<i>Plagioclase</i>	12.2	12.2	16.0	14.2	12.2	9.2	16.5	6.91	14.6	15.7	11.9	28.6	14.2
<i>Pyroxene</i>	0.0	6.0	13.8	13.0	5.5	0.7	0.7	5.43	2.5	5.8	0.0	9.0	5.2
<i>Amphibole</i>	0.5	0.4	5.3	3.7	1.4	0.2	0.1	0.37	0.0	0.0	0.0	1.8	1.1
<i>Others (carbonate, uartz, olivine, etc)</i>	10.8	0.0	0.0	0.0	0.0	4.0	0.1	0.0	0.0	0.0	0.0	6.9	1.8

According to the X-ray diffractometric patterns (Fig. 5), the silt and clay fractions followed the indicated composition of the gravel and sand fractions. The primary mineralogical components include pyroxene, amphibole, plagioclase and quartz, which are typical of andesite and basalt compositions. Secondary products are indicated by brucite, saponite (a smectite-like clay) and laumontite, a common secondary hydrothermal zeolite in basaltic and andesitic rocks.

Well-defined crystals of amphibole and sheets of detrital clays that show broken edges and irregular distributions were detected using the SEM (Fig. 3E and 3F).

4. Discussion

The observed prevalence of feldspar and volcanic lithic fragments, rather than quartz and other stable grains, indicates a tectonically active source area. The provenance parameters of Dickinson et al. (1983) suggest that an undissected magmatic arc was the source area (Fig. 6A). This statement agrees with the compositional characteristics of an immature magmatic arc in the natural tectonic setting of the South Shetland Islands, instead of a more mature arc, related to the Antarctic Peninsula. This characteristic is supported by chemical data, which show that the inner arc of the Antarctic Peninsula has more extensive chemical characteristics, ranging from metaluminous to peraluminous, evidencing crustal recycling.

In volcanic rocks, glass and feldspar are very important in the weathering process, and they provide Ca, Na and K to aqueous solutions. The Al_2O_3 is retained, and the feldspars change to clay minerals. In this sense, the chemical index of alteration (CIA) defined by Nesbitt and

Young (1982), indicates the parameters of some altered materials. CIA values ranging from 30 to 45 are associated with fresh basalts. On the other hand, CIA values between 45 and 55 are associated with fresh granites and granodiorites. Pleistocene till has CIA values of approximately 52, whereas these values in Pleistocene glacial clays range from 60 to 65. The general CIA values for clays are 75-80 for illite, whereas kaolinite and chlorite have values closer to 100 (Nesbitt and Young, 1982).

Both the volcanic rocks of King George, Livingstone, Greenwich islands, Antarctic Peninsula and the till of Low Head exhibit CIA values that range from 52 to 66 (Table 2 and 3). This range, which contains values that are higher than those of fresh basalts and acid rocks, demonstrates that these rocks suffered some degree of alteration, probably caused by hydrothermal alteration as described in previous works (Jeong et al., 2001, 2004; Simas et al., 2008; Monien et al., 2011). Canile (2010) identified an alteration process in some levels of the basalt sequence of the Mazurek Point Formation in Low Head, attributing to a chemical weathering process that acted during Eocene times. The similar values of CIA encountered in the sedimentary counterparts (till) of the regional rocks, could indicate the heritage of this alteration process.

The SiO_2/Al_2O_3 ratio is a useful parameter in sediment maturity studies. It is sensitive to recycling and weathering processes. The average values of this parameter range from 3.0 in basic rocks to 5.0 in acidic rocks, whereas values from 5.0 to 6.0 or higher are typical of sediments, indicating progressive maturity (Dingle and Lavelle, 1998).

Clearly, ratios lower than the average values of rocks demonstrate SiO_2 leaching and alteration, while greater values in sediments reflect increased compositional maturity due to the removal of aluminous mineral phases such as micas, plagioclase and clays.

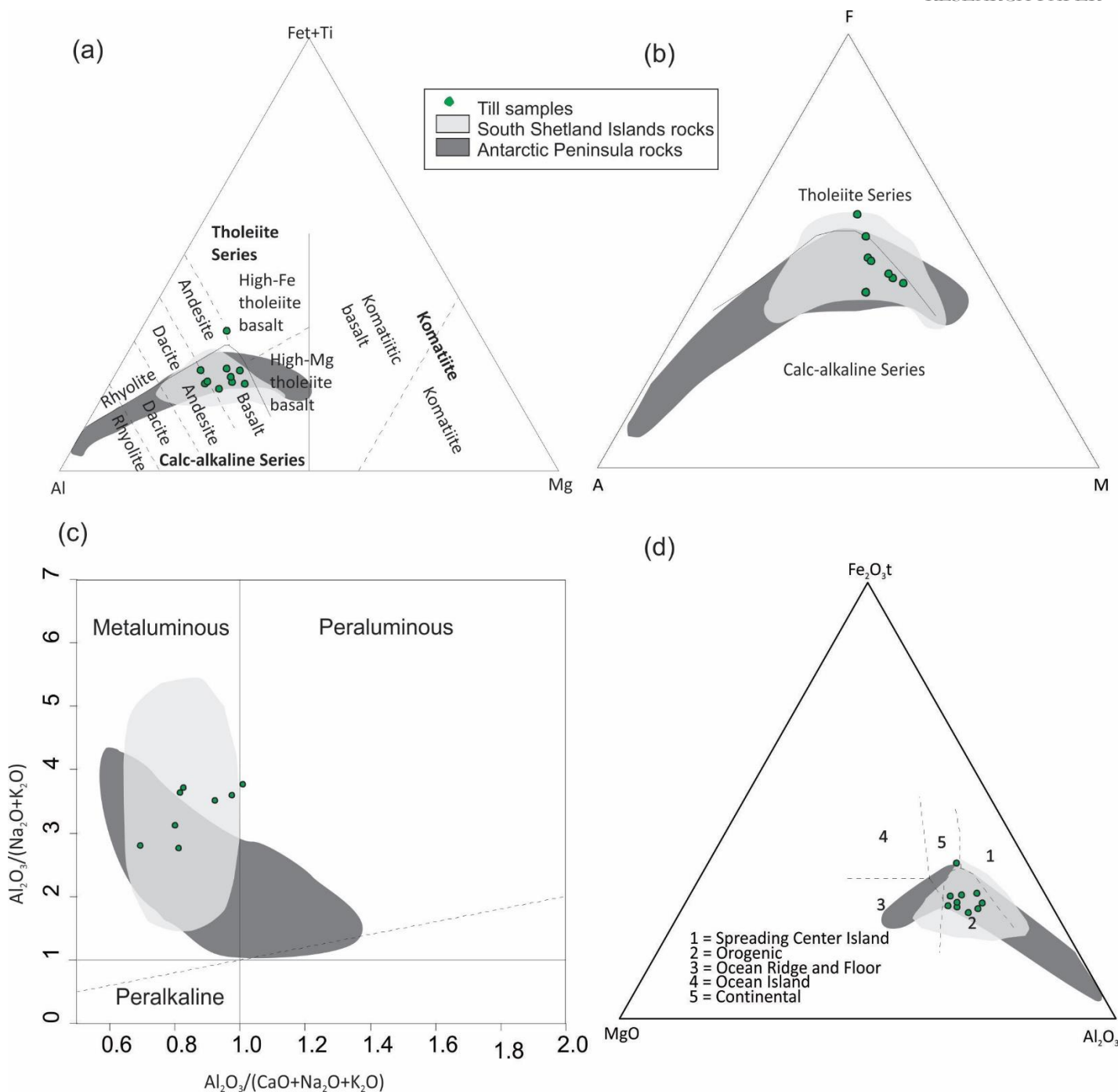


Fig. 4. Diagrams for comparison between parent rocks and glacial sediments: (a) Chemical classification of igneous rocks (Jensen, 1976) defining basaltic to andesitic parental rocks in the South Shetland Islands and basaltic to rhyolitic parental rocks in the Antarctic Peninsula. Fet is the total iron. (b) Diagram of magmatic series (Irvine and Baragar, 1971) defining a calc-alkaline to tholeiitic series for the rocks of the South Shetland Islands and Antarctic Peninsula. A: alkalis, F: Iron, M: Magnesium (c) Ratio diagram displaying aluminum against alkalis (Maniar and Piccoli, 1989) that defines a metaluminous series for the rocks of the South Shetland Islands and Metaluminous to peraluminous to the Antarctic Peninsula. (d) Tectonic discrimination diagram (Pearce et al., 1977) that defines mainly an orogenic context for the South Shetland Islands and till sediments. Fe_2O_3t is the total iron. Observe that the general characteristics of the lithotypes in the South Shetland Islands are maintained in the till sediments, demonstrating the same regional provenance, while the rocks of Antarctic Peninsula exhibit more expanded characteristics.

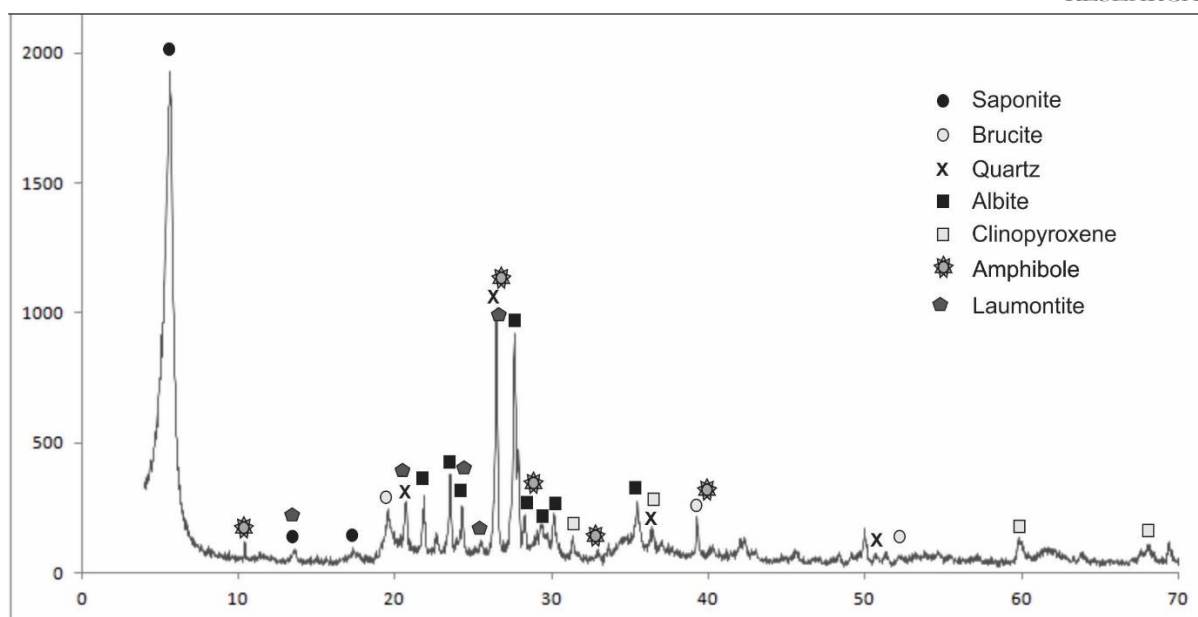


Fig. 5. Diffraction diagram (CuK α , $\langle\lambda\rangle=0.15419$ nm) exhibiting the peaks corresponding to the main mineral phases present in mud fractions of the till deposits of Low Head, King George Island.

Tab. 2. Chemical analyses (% Wt), chemical index of alteration (CIA) values and SiO₂/Al₂O₃ ratios of till from Low Head, King George Island, Maritime Antarctic. Fe₂O_{3t} represents total iron.

Sample	SiO ₂	Al ₂ O ₃	Fe ₂ O _{3t}	CaO	MgO	Na ₂ O	K ₂ O	TiO ₂	P ₂ O ₅	MnO	CIA	SiO ₂ /Al ₂ O ₃
LH - 30	58.07	16.42	8.98	8.25	3.89	2.12	0.81	0.93	0.21	0.16	59.49	3.54
LH - 31	59.24	15.94	9.07	6.74	4.94	1.57	1.00	0.90	0.22	0.23	63.13	3.72
LH - 32	57.18	16.36	8.82	6.64	6.34	2.02	1.13	0.86	0.25	0.21	62.56	3.50
LH - 33	58.69	17.26	8.34	6.91	4.19	1.88	1.31	0.86	0.20	0.17	63.08	3.40
LH - 35	57.72	16.41	8.43	7.10	5.68	2.10	1.08	0.84	0.22	0.18	61.48	3.52
LH - 36	56.43	15.95	8.59	8.84	5.39	2.29	1.00	0.91	0.18	0.19	56.80	3.54
LH - 38	55.82	16.08	9.34	7.96	5.92	2.31	1.11	0.85	0.20	0.19	58.56	3.47
LH - 39	51.44	16.15	12.87	8.88	4.58	2.82	0.98	1.50	0.19	0.25	56.02	3.19
LH - 40	55.94	17.34	7.99	8.09	5.23	2.88	1.20	0.81	0.14	0.16	58.76	3.23
LH - 41	54.80	18.03	8.58	9.12	4.58	2.25	1.09	0.90	0.20	0.15	59.13	3.04

The values of the SiO₂/Al₂O₃ ratio, which fall between 1.8 and 3.8 in the set of rocks of South Shetland (Appendix 1), are lower or slightly higher than the basic rock pattern, demonstrating alteration of the fresh members. Regarding the sediments, the values of this ratio range from 3.0 to 3.7 (Table 2) demonstrating no substantial leaching of the material. Their chemical characteristics indicate mafic/intermediate parent rocks, as well as some level of Al₂O₃ removal, probably by the elimination of clay mineral phases. The Antarctic Peninsula rocks have SiO₂/Al₂O₃ ratio values predominantly between 3.0 to 5.0, higher than in sediments, indicating basic to acid fresh rocks, although some members have values higher than 5.0, which could

indicate the presence of secondary mineral phases and Al₂O₃ removal.

The presence of secondary products such as saponite ((Mg, Fe)₃(Al, Si)₄O₁₀(OH)₂(Ca, Na)_{0.3}*4H₂O) and laumontite ((Ca, Na, K) Al₂Si₄O₁₂*4H₂O) in the till might explain the behavior of Na₂O, K₂O, CaO and Al₂O₃ in the correlation matrix (Table 3), as well as in the CIA and SiO₂/Al₂O₃ ratios.

The SiO₂ and Al₂O₃ bivariate correlation diagrams, which compare the rocks (grey-shaded areas) and the till (Fig. 7), indicates overlapping for almost all elements, except to Al₂O₃ (that exhibit a distinct trend to the Antarctic Peninsula) and Na₂O.

Tab. 3. Coefficients of correlation for major elements of magmatic volcanic and plutonic rocks from King George, Livingstone and Greenwich islands (a), Antarctic Peninsula (b) and till from Low Head, King George Island (c). Data from Machado et al., (2005), Yeo et al. (2004), Birkenmajer et al. (1991) and Saunders et al. (1980). Bold values in 6a are significant for α : 0.01 (n=106). Critical coefficients are 0.230 (α : 0.01) and 0.164 (α : 0.05). Bold values in 6b are significant for α : 0.01 (n=21). Critical coefficients are 0.492 (α : 0.01) and 0.378 (α : 0.05). Bold values in 6c are significant for α : 0.05 (n=10). Critical coefficients are 0.715 (α : 0.01) and 0.549 (α : 0.05). Fe_2O_{3t} represents total iron.

A.	SiO_2	Al_2O_3	Fe_2O_{3t}	CaO	MgO	Na_2O	K_2O	TiO_2	P_2O_5	MnO
SiO_2	1.000									
Al_2O_3	-0.442	1.000								
Fe_2O_{3t}	-0.576	-0.162	1.000							
CaO	-0.81	0.494	0.336	1.000						
MgO	-0.613	0.013	0.279	0.564	1.000					
Na_2O	0.596	-0.318	-0.111	-0.695	-0.492	1.000				
K_2O	0.439	-0.259	-0.205	-0.608	-0.37	0.123	1.000			
TiO_2	0.058	-0.483	0.615	-0.254	-0.086	0.373	0.162	1.000		
P_2O_5	0.367	-0.556	0.173	-0.555	-0.305	0.429	0.391	0.715	1.000	
MnO	-0.061	-0.102	0.372	-0.032	0.045	0.153	-0.001	0.369	0.242	1.000

B.	SiO_2	Al_2O_3	Fe_2O_{3t}	CaO	MgO	Na_2O	K_2O	TiO_2	P_2O_5	MnO
SiO_2	1.000									
Al_2O_3	-0.73	1.000								
Fe_2O_{3t}	-0.98	0.719	1.000							
CaO	-0.95	0.648	0.931	1.000						
MgO	-0.92	0.474	0.86	0.89	1.000					
Na_2O	0.299	-0.14	-0.282	-0.309	-0.46	1.000				
K_2O	0.874	-0.757	-0.849	-0.908	-0.735	0.046	1.000			
TiO_2	-0.86	0.707	0.89	0.756	0.693	0.018	-0.753	1.000		
P_2O_5	-0.69	0.622	0.679	0.571	0.55	0.238	-0.656	0.894	1.000	
MnO	-0.85	0.669	0.889	0.82	0.691	0.027	-0.823	0.893	0.811	1.000

C.	SiO_2	Al_2O_3	Fe_2O_{3t}	CaO	MgO	Na_2O	K_2O	TiO_2	P_2O_5	MnO
SiO_2	1.000									
Al_2O_3	-0.084	1.000								
Fe_2O_{3t}	-0.735	-0.379	1.000							
CaO	-0.721	0.217	0.343	1.000						
MgO	0.006	-0.345	-0.173	-0.327	1.000					
Na_2O	-0.805	0.184	0.391	0.661	0.025	1.000				
K_2O	0.110	0.493	-0.369	-0.376	0.266	0.016	1.000			
TiO_2	-0.757	-0.254	0.968	0.434	-0.308	0.447	-0.362	1.000		
P_2O_5	0.365	-0.314	0.028	-0.564	0.247	-0.714	-0.179	-0.078	1.000	
MnO	-0.300	-0.696	0.741	-0.183	0.230	-0.034	-0.222	0.658	0.298	1.000

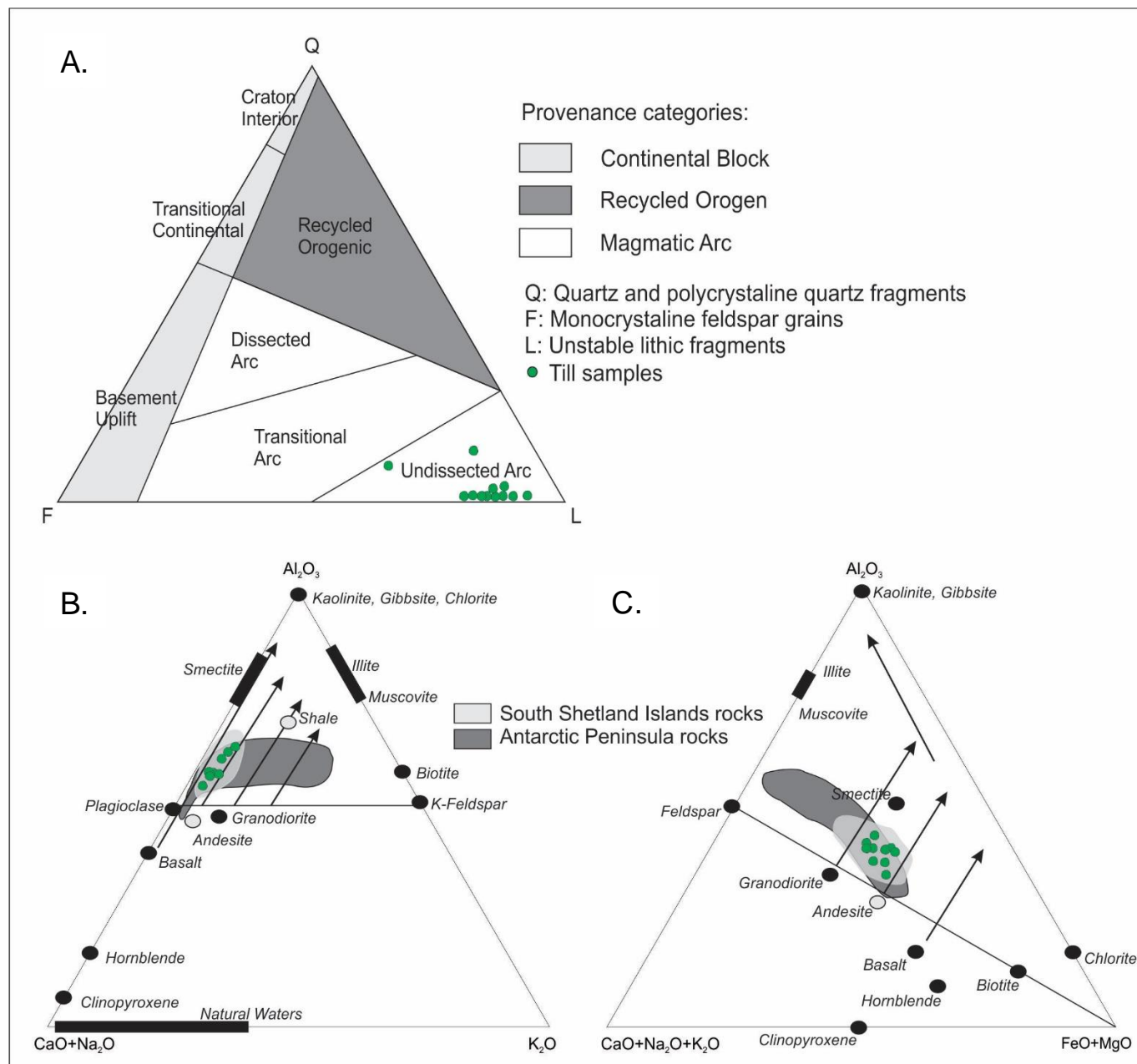
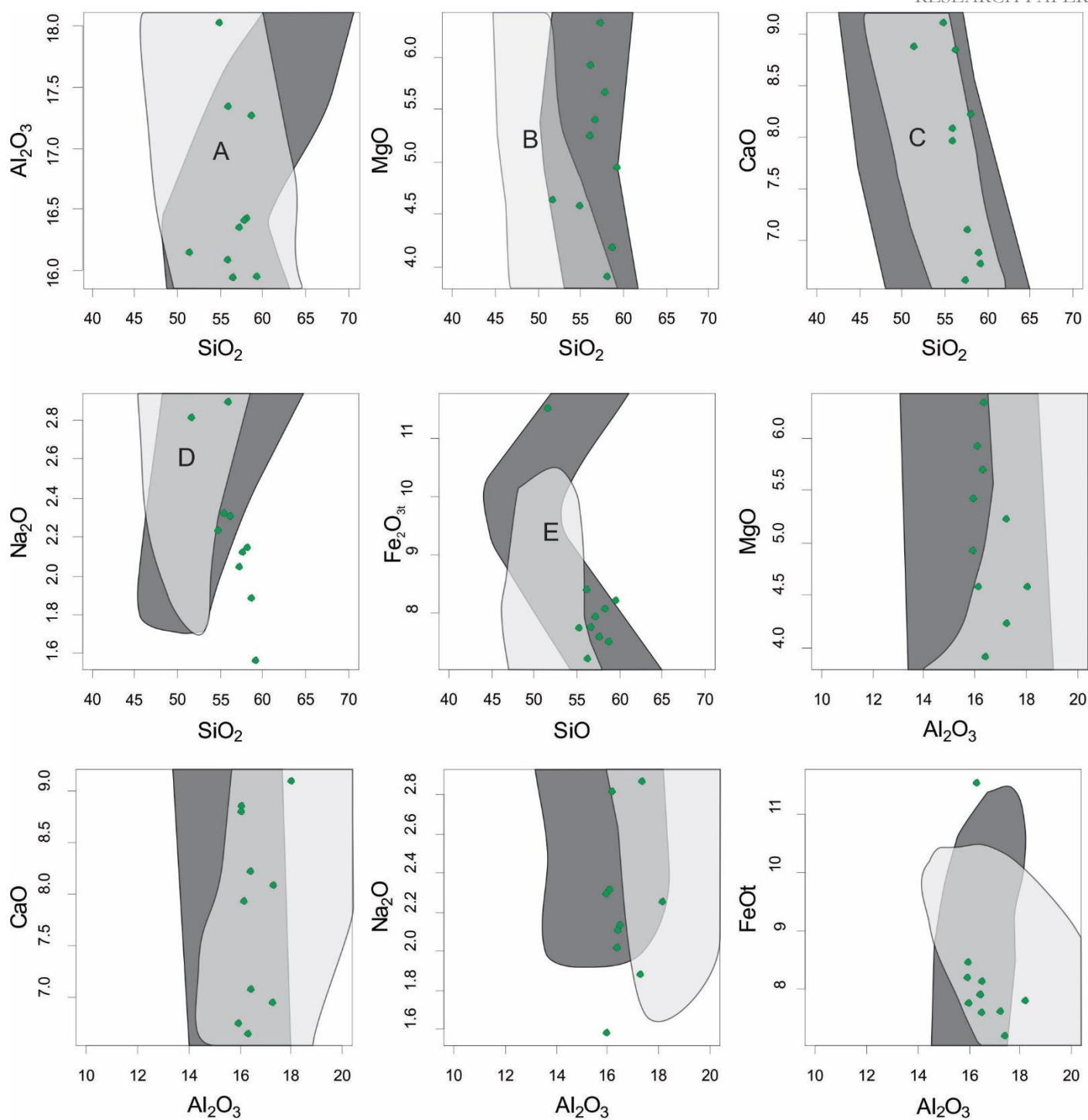


Fig. 6. A. Ternary plots of provenance from Dickinson et al. (1983). B. and C.: plots of weathering of McLennan et al. (1993), showing trends of the till sediments from Low Head. Observe in B. a trend above the andesite and plagioclase fields, toward the smectite field and clays vertex. In C., the samples exhibit a cluster between andesite and granodiorite, toward the smectite.

The behavior of Al_2O_3 corroborates the discrimination diagrams of series of Maniar and Piccoli (1989) (Fig. 4) and with the SiO_2/Al_2O_3 ratio (Appendix 1), suggesting that the parental rocks of King George Island could be associated strictly to the South Shetland, with none or few contributions of the Antarctic Peninsula.

Considering the possible parental rocks from South Shetland, the behavior of MgO , Na_2O and Fe_2O_3 in the till,

outside the corresponding domain, suggest some mobility, which could be associated with the presence of the secondary mineral phases (Fig. 7). This result indicates that, although regional rocks demonstrate some degree of hydrothermal alteration, including the formation of laumontite, the till sediments may have suffered some small degree of weathering, leading to the formation of clay and hydroxide minerals.



Legend:

- A: Clinopyroxene + Plagioclase
- B: Clinopyroxene + Clinoamphibole±Olivine
- C: Plagioclase+Clinopyroxene+ Amphibole
- D: Clinopyroxene+Plagioclase
- E: Clinopyroxene+Olivine+Amphibole

- Till samples
- South Shetland Islands rocks
- Antarctic Peninsula rocks

Fig. 7. Bivariate correlation diagrams comparing the rocks (grey-shaded areas) and till sediments from Low Head, King George Island. Observe the behavior of Al_2O_3 , CaO , MgO , Na_2O and Fe_2O_{3t} (total iron oxides), which fall outside of the domain of the South Shetland Island rocks.

Ternary plots of weathering (McLennan et al., 1993) also confirm that the till and South Shetland rocks suffered some level of alteration. In the alkalis and aluminum plot, the samples tend to plot above the andesite and plagioclase fields, towards the smectite field and the clays vertex. In the alkalis and Fe_2O_3 plus MgO diagram, the samples tend to plot between the andesite and granodiorite, towards the smectite area (Fig. 6B and 6C). The trends of Antarctic Peninsula rocks indicate a series of fresh rocks, from more basic to acid alkaline members (Fig. 6B and 6C).

Conclusion

The predominance of effusive and pyroclastic rock fragments over epiclastic and grains of minerals, such as plagioclase and clinopyroxene, indicate that these sediments are derived from the immature magmatic arc rocks. The geochemical characteristics of the possible provenance areas suggest that the till sediments of Low Head have more similarities with the South Shetland Island than the Antarctic Peninsula. Although Birkenmajer (1980) had described an influence of parental rocks from the Antarctic Peninsula in the Krakowiak Glacier Member, Polonez Cove Formation. Additionally, the calc-alkaline and metaluminous chemical signatures of these rocks, which were produced in an orogenic context, were maintained in the sediments.

The main chemical differences between the parental rocks and sediments were detected in the correlation matrices among SiO_2 and Al_2O_3 with Na_2O , K_2O , MnO , and Fe_2O_3 , suggesting the presence of secondary mineral phases. On the bivariate plots, these differences are clearly demonstrated by the fields where the samples were plotted (MgO , Na_2O and Fe_2O_3), which lie slightly outside the areas defined by the South Shetland rocks. The CIA index of Nesbit and Young (1982) and the $\text{SiO}_2/\text{Al}_2\text{O}_3$ ratios indicate the effects of some alteration or weathering in the rocks of the source area and their sedimentary counterparts. The ternary plots of weathering also suggest trends of clay development towards smectite. The presence of secondary mineral phases, such as laumontite, saponite and brucite, was confirmed by X-ray diffractometry. SEM images demonstrated that the clays in the till suffered some level of transportation.

The results indicate that probably the saponite and brucite may have developed in some instance of the sedimentary cycle with further transportation of the material or were derived from Eocene weathered basalts, while the laumontite likely formed due to hydrothermal alteration of parental rocks.

Although sediments in this study represent a specific locality in King George Island, they have an important significance to understand the regional development of retreat zones and the provenance of the till, showing

general similarities and congruencies with regional rocks of South Shetland Islands and the alteration processes suffered by them.

Acknowledgment

This paper is dedicated to the memory to all who have lost their lives in the Comandante Ferraz Station, in the 2012 fire. The field data presented here are the legacy of two campaigns carried out in 2011 and 2012. Owing to the fire and complete destruction of the Comandante Ferraz Antarctic station, all the work and samples of 2012, regarding the Ecology and Baranowski glaciers were lost. The authors also would like to thank the Brazilian Antarctic Program/ CNPq (PROANTAR), the Brazilian Navy and the Brazilian Air Force for providing material resources and logistical support during the field work and research.

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Appendix 1. Major element chemical analyses (% Wt), chemical index of alteration (CIA) values and SiO₂/Al₂O₃ ratios of magmatic volcanic and plutonic rocks from King George, Livingstone and Greenwich Islands and Antarctic Peninsula. Data from Machado et al. (2005), Yeo et al. (2004), Birkenmajer et al. (1991) and Saunders et al. (1980). Fe₂O_{3t} represents total iron.

	Sample	SiO ₂	Al ₂ O ₃	Fe ₂ O _{3t}	CaO	MgO	Na ₂ O	K ₂ O	TiO ₂	P ₂ O ₅	MnO	CIA	SiO ₂ /Al ₂ O ₃
Machado et al., 2005	101	46.91	23.15	7.83	11.00	4.61	2.66	0.51	0.62	0.09	0.16	62.03	2.03
	102	49.80	18.68	9.04	11.70	5.85	2.46	0.58	0.75	0.22	0.17	55.89	2.67
	103	50.19	19.89	9.64	9.97	4.31	3.31	0.57	0.84	0.13	0.18	58.95	2.52
	104	50.34	20.56	7.59	10.90	6.15	2.16	0.79	0.45	0.09	0.12	59.75	2.45
	105	50.50	19.70	10.28	9.78	4.33	3.14	0.48	0.84	0.13	0.17	59.52	2.56
	106	50.98	19.05	9.06	10.73	5.08	2.90	0.30	0.78	0.16	0.15	57.76	2.68
	107	52.03	18.73	9.20	8.10	3.91	3.58	1.34	1.06	0.26	0.20	58.99	2.78
	108	52.14	17.96	10.05	7.79	3.73	3.58	0.67	0.85	0.15	0.18	59.87	2.90
	109	52.30	18.85	9.03	7.76	4.75	3.89	0.92	0.84	0.19	0.11	59.99	2.77
	110	52.64	20.64	7.96	10.39	4.25	1.84	0.40	0.71	0.12	0.14	62.04	2.55
	111	53.22	17.18	8.22	8.35	4.68	3.18	1.03	0.88	0.14	0.14	57.77	3.10
	112	54.16	19.08	8.03	8.48	3.70	3.14	0.91	0.78	0.21	0.20	60.36	2.84
	113	54.89	18.57	7.99	8.49	3.72	3.51	0.80	0.78	0.20	0.15	59.20	2.96
	114	55.39	19.19	8.81	7.34	2.90	4.06	0.92	0.70	0.22	0.16	60.90	2.89
	115	57.16	17.34	8.03	7.15	3.13	4.30	0.81	0.96	0.27	0.29	58.58	3.30
	116	60.92	16.81	6.58	5.25	2.85	3.46	1.02	0.97	0.31	0.16	63.34	3.62
	117	51.73	18.15	9.06	9.92	5.35	2.91	0.52	0.80	0.16	0.16	57.62	2.85
	118	53.78	17.14	9.78	7.53	4.89	3.03	0.77	0.98	0.22	0.15	60.20	3.14
	119	55.72	17.05	8.34	7.55	4.14	3.13	0.92	0.91	0.21	0.14	59.51	3.27
	120	47.47	25.74	8.67	9.33	3.06	3.23	0.45	0.83	0.04	0.12	66.43	1.84
	121	53.95	18.87	8.49	9.20	4.57	2.95	0.20	0.78	0.11	0.16	60.44	2.86
	122	55.99	17.40	7.46	7.26	3.89	3.67	1.05	0.61	0.13	0.14	59.22	3.22
	123	48.09	16.93	9.50	10.03	8.86	2.66	0.58	0.97	0.35	0.14	56.06	2.84
	124	49.13	17.64	9.38	9.65	7.76	3.17	0.68	0.95	0.26	0.16	56.65	2.79
	125	49.21	18.20	9.56	10.31	7.47	2.58	0.28	0.91	0.14	0.16	58.02	2.70
	126	49.31	17.50	9.60	10.82	8.00	2.51	0.21	0.89	0.15	0.17	56.38	2.82
	127	49.40	18.30	8.90	10.54	7.33	2.64	0.30	0.79	0.13	0.14	57.58	2.70
	128	48.41	20.51	9.55	12.29	4.73	2.47	0.28	1.11	0.17	0.14	57.69	2.36
	129	48.40	18.29	9.24	11.51	7.59	2.37	0.42	0.91	0.18	0.16	56.12	2.65
	130	49.50	15.90	12.80	9.30	4.20	3.60	0.62	1.42	0.21	0.18	54.04	3.11
	131	49.60	17.30	11.60	9.30	4.10	3.90	0.33	1.31	0.28	0.18	56.11	2.87
	132	50.40	16.00	10.30	11.20	6.20	3.10	0.26	0.97	0.16	0.14	52.36	3.15
	133	50.54	17.03	9.57	9.65	8.01	2.88	0.19	1.10	0.23	0.18	57.24	2.97
	134	50.70	15.90	11.40	9.40	5.20	3.70	0.81	1.18	0.19	0.16	53.34	3.19
	135	53.07	16.93	9.23	10.30	6.45	2.66	0.50	0.70	0.08	0.17	55.71	3.13
	136	53.60	15.90	11.30	7.50	3.09	4.10	1.35	1.63	0.44	0.17	55.11	3.37
	137	53.88	19.63	8.34	8.80	2.79	3.97	0.96	1.02	0.13	0.13	58.84	2.74
	138	54.00	16.00	10.10	7.00	2.60	4.40	0.68	1.57	0.60	0.21	56.98	3.38
	139	55.46	15.27	11.02	7.24	3.59	3.99	1.05	1.35	0.27	0.19	55.43	3.63
	140	56.73	17.42	7.55	6.27	3.08	4.15	1.03	0.74	0.24	0.20	60.34	3.26

	Sample	SiO ₂	Al ₂ O ₃	Fe ₂ O _{3t}	CaO	MgO	Na ₂ O	K ₂ O	TiO ₂	P ₂ O ₅	MnO	CIA	SiO ₂ /Al ₂ O ₃
Yeo et al., 2004	141	57.96	15.07	9.46	6.42	2.36	3.72	0.66	1.31	0.39	0.19	58.25	3.85
	142	60.90	16.77	6.49	5.45	2.46	4.31	1.04	0.80	0.27	0.19	60.83	3.63
	143	60.98	16.69	6.43	5.44	2.42	4.24	1.03	0.80	0.26	0.19	60.91	3.65
	2201	47.46	21.23	8.40	14.53	6.77	0.99	0.06	0.47	0.07	0.16	57.67	2.24
	2202	46.04	17.94	9.21	10.51	6.04	1.86	0.09	0.68	0.13	0.14	59.01	2.57
	2203	49.79	19.42	8.82	10.96	5.50	2.76	0.28	0.74	0.13	0.16	58.11	2.56
	2204	50.87	22.47	7.70	11.43	3.89	2.31	0.33	0.70	0.12	0.19	61.49	2.26
	2205	51.39	20.51	8.50	8.90	5.22	3.93	0.53	0.83	0.14	0.16	60.56	2.51
	2206	50.60	20.82	8.06	9.37	4.44	3.43	0.41	0.70	0.11	0.19	61.18	2.43
	2207	49.00	18.44	8.25	12.55	3.70	2.05	0.16	0.61	0.11	0.11	55.54	2.66
	2208	50.51	19.02	9.23	9.81	5.22	2.92	0.21	0.72	0.13	0.15	59.51	2.66
	2209	50.18	20.80	7.19	9.77	4.80	2.93	0.54	0.58	0.13	0.11	61.10	2.41
	2210	49.41	19.33	7.49	8.38	4.65	3.41	0.37	0.61	0.14	0.12	61.38	2.56
	2211	49.79	18.10	8.74	8.51	4.52	3.08	0.25	0.73	0.14	0.14	60.45	2.75
	2212	51.57	18.90	8.38	8.26	4.76	3.37	0.52	0.73	0.22	0.18	60.87	2.73
	2213	50.04	17.31	9.07	7.68	3.62	2.76	2.16	0.69	0.16	0.18	57.87	2.89
	2214	51.56	16.78	10.35	8.04	4.09	3.87	0.15	0.94	0.18	0.18	58.18	3.07
	2215	53.02	18.74	8.88	8.43	4.41	3.32	0.67	0.76	0.20	0.16	60.14	2.83
	2216	54.22	17.73	9.46	8.21	4.18	4.34	0.24	0.94	0.19	0.20	58.09	3.06
	2217	54.23	19.05	8.87	8.97	4.10	3.10	0.21	0.75	0.17	0.16	60.80	2.85
	2218	52.41	18.02	7.82	8.42	3.96	3.32	1.30	0.68	0.17	0.13	58.02	2.91
	2219	53.42	18.46	8.63	8.20	4.31	3.17	0.45	0.73	0.20	0.16	60.96	2.89
	2220	54.20	18.75	8.64	8.42	4.41	3.26	0.26	0.76	0.19	0.14	61.09	2.89
	2221	55.22	19.50	6.90	8.59	4.12	3.83	0.28	0.61	0.13	0.17	60.56	2.83
	2222	55.69	19.08	6.99	9.51	4.05	3.07	0.19	0.68	0.17	0.14	59.91	2.92
	2223	56.06	18.94	7.85	7.12	3.15	3.88	1.66	0.99	0.31	0.16	59.94	2.96
	2224	52.88	18.03	8.36	8.15	4.55	3.35	1.06	0.78	0.26	0.15	58.94	2.93
	2225	53.40	18.03	8.69	8.25	4.38	3.25	1.13	0.75	0.22	0.13	58.81	2.96
	2226	53.10	17.06	8.11	8.13	4.76	2.74	1.52	0.75	0.24	0.12	57.93	3.11
	2227	53.14	18.24	8.97	7.22	3.37	3.39	0.97	0.82	0.27	0.12	61.17	2.91
	2228	53.67	17.91	7.95	8.26	4.17	2.79	0.22	0.70	0.20	0.16	61.38	3.00
	2229	54.55	17.72	7.71	8.31	4.29	2.76	1.16	0.73	0.21	0.14	59.17	3.08
	2230	54.84	17.97	7.68	8.24	3.46	2.77	1.06	0.70	0.19	0.15	59.82	3.05
	2231	54.25	17.60	7.47	8.26	2.65	3.26	0.74	0.83	0.27	0.13	58.94	3.08
	2232	54.90	17.64	7.96	6.96	3.36	3.38	1.13	0.78	0.25	0.13	60.60	3.11
	2233	55.37	14.48	7.94	8.03	4.07	2.81	1.75	0.76	0.21	0.13	53.49	3.82
	2234	55.06	17.21	7.33	6.25	2.74	3.41	1.75	0.82	0.31	0.12	60.13	3.20
	2235	57.22	15.84	8.21	5.27	3.19	3.45	2.73	1.04	0.42	0.15	58.04	3.61
	2236	57.65	15.77	8.33	5.17	3.00	3.96	2.29	1.03	0.41	0.14	58.00	3.66
	2237	58.60	16.73	6.67	5.25	2.19	3.68	2.49	0.85	0.37	0.12	59.43	3.50
	2238	56.70	16.10	9.96	6.92	3.48	3.97	1.96	1.44	0.46	0.19	55.61	3.52
	2239	54.76	15.67	9.53	7.51	3.93	3.08	1.77	1.39	0.43	0.17	55.90	3.49
	2240	55.89	15.84	9.65	6.80	3.95	3.20	1.65	1.40	0.44	0.18	57.62	3.53

	Sample	SiO ₂	Al ₂ O ₃	Fe ₂ O _{3t}	CaO	MgO	Na ₂ O	K ₂ O	TiO ₂	P ₂ O ₅	MnO	CIA	SiO ₂ /Al ₂ O ₃
Birkenmajer et al., 1991	2241	55.18	18.45	8.19	6.74	3.47	4.40	0.37	1.12	0.27	0.15	61.58	2.99
	2242	55.90	17.68	7.93	6.53	3.11	4.60	1.11	1.08	0.32	0.21	59.09	3.16
	2243	56.46	17.99	7.33	7.26	3.07	3.95	1.21	0.91	0.27	0.16	59.16	3.14
	3301	48.80	17.40	8.82	9.34	10.40	3.27	0.51	1.00	0.31	0.17	57.01	2.80
	3302	48.80	17.60	9.24	9.32	9.33	3.34	0.61	1.19	0.35	0.17	57.01	2.77
	3303	49.83	16.60	8.37	8.53	12.53	2.73	0.38	0.77	0.05	0.15	58.78	3.00
	3304	51.52	19.28	9.29	6.79	4.66	1.94	5.09	0.94	0.20	0.24	58.25	2.67
	3305	51.85	18.10	9.85	9.30	6.11	3.15	0.28	0.83	0.25	0.26	58.71	2.86
	3306	52.32	16.42	8.76	9.18	9.33	2.62	0.21	0.80	0.11	0.19	57.76	3.19
	3307	52.62	20.52	7.98	9.72	4.12	3.26	0.69	0.78	0.11	0.14	60.02	2.56
	3308	53.11	18.23	8.08	9.11	6.34	3.29	0.71	0.83	0.06	0.15	58.17	2.91
	3309	53.94	19.82	7.68	8.89	3.92	3.72	0.84	0.76	0.18	0.15	59.57	2.72
	3310	55.06	18.63	8.28	6.37	3.07	2.55	4.59	0.94	0.28	0.16	57.97	2.96
	3311	56.59	17.90	7.60	7.72	4.12	3.56	1.27	0.77	0.27	0.12	58.78	3.16
	3312	56.63	17.41	6.22	9.74	5.09	3.21	0.72	0.70	0.06	0.14	56.02	3.25
	3313	58.04	17.13	6.55	7.77	5.34	3.31	0.93	0.67	0.08	0.12	58.79	3.39
	3314	58.21	17.44	7.48	6.67	3.80	3.42	1.79	0.81	0.18	0.13	59.48	3.34
	3315	59.06	18.09	6.98	6.75	3.10	4.45	0.45	0.77	0.17	0.13	60.83	3.26
	3316	61.94	16.47	6.70	5.16	2.42	3.85	2.30	0.79	0.20	0.11	59.29	3.76
	3317	62.57	16.68	6.27	6.50	2.47	3.43	0.81	0.82	0.26	0.12	60.83	3.75
	3318	57.33	17.93	6.83	7.41	4.01	4.10	1.36	0.70	0.13	0.16	58.21	3.20
	3319	60.54	17.51	6.07	5.59	3.13	4.14	2.28	0.69	0.24	0.12	59.32	3.46
	3320	62.17	16.72	5.79	5.09	2.68	4.25	2.53	0.74	0.23	0.12	58.48	3.72
Saunders et al., 1980	7	49.63	15.46	8.81	11.91	10.87	2.00	0.34	0.68	0.1	0.15	52.04	3.21
	8	53.51	16.64	10.96	8.22	4.13	3.31	1.15	1.51	0.28	0.17	56.75	3.22
	9	59.96	16.09	6.93	5.84	2.97	5.24	1.13	1.51	0.66	0.22	56.86	3.73
	10	66.33	14.62	3.92	3.04	1.25	4.54	3.11	0.6	0.19	0.1	57.76	4.54
	11	49.23	16.36	10.71	9.77	8.47	3.8	0.54	1.43	0.39	0.23	53.69	3.01
	12	58.47	15.23	8.15	7.6	5.38	3.53	0.66	0.78	0.19	0.16	56.37	3.84
	13	68.09	14.7	3.63	2.95	1.37	4.59	2.75	0.52	0.11	0.07	58.82	4.63
	14	74	13.57	1.61	0.34	0.15	3.67	4.83	0.13	0.04	0.03	60.55	5.45
	15	50.05	16.59	10.37	6.73	8.38	3.56	1.87	1.54	0.54	0.16	57.70	3.02
	16	56.85	17.52	7.93	5.76	4.43	2.47	2.18	0.98	0.22	0.14	62.73	3.24
	17	66.19	15.49	4.93	4.4	1.64	3.36	2.26	0.56	0.18	0.1	60.72	4.27
	18	73.37	14.5	2.67	0.48	0.92	2.57	5.21	0.21	0.06	0.07	63.71	5.06
	19	52.76	15.65	9.26	10.37	7.47	2.96	0.76	0.61	0.13	0.16	52.62	3.37
	20	58.99	16.24	6.22	5.6	3.61	3.5	2.56	0.83	0.19	0.09	58.21	3.63
	21	62.76	16.93	5.95	3.51	1.68	4.52	1.42	0.79	0.28	0.13	64.18	3.71
	22	73.28	13.81	2.19	1.44	0.37	3.99	4.36	0.19	0.08	0.06	58.52	5.31
	23	75.51	13.45	1.18	0.86	0.19	3.43	5.56	0.16	0.04	0.02	57.73	5.61
	24	48.46	15.42	9.17	9.85	11.77	2.15	0.37	1.07	0.32	0.13	55.49	3.14
	25	65.43	17.35	3.78	4.96	1.52	3.82	1.23	0.45	0.21	0.07	63.41	3.77
	26	69.89	14.59	3.56	2.68	1.18	3.62	3.5	0.44	0.12	0.07	59.82	4.79

	Sample	SiO₂	Al₂O₃	Fe₂O_{3t}	CaO	MgO	Na₂O	K₂O	TiO₂	P₂O₅	MnO	CIA	SiO₂/Al₂O₃
	27	76.04	12.7	1.09	0.57	0.12	4.32	4.53	0.16	0.04	0.03	57.41	5.99