Compositional Characteristics of Middle to Upper Tertiary Volcanic Rocks of the Bolivian Altiplano

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By Edward A. du Bray, Steve Ludington, William E. Brooks, Bruce M. Gamble, James C. Ratté, Donald H. Richter, *and* Eduardo Soria-Escalante

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CONTENTS

Abstract........ 1
Introduction........ 1
Petrography........ 4
Geochemistry........ 4
    Analytical Methods........ 4
    Unaltered Rocks........ 4
    Altered Rocks........ 18
Discussion and Conclusions........ 20
    Unaltered Rocks........ 20
    Altered Rocks........ 21
References Cited........ 21
Appendixes—Brief Descriptions of Samples........ 23

FIGURES

1. Maps showing volcanic features and sample locations, Altiplano and Cordillera........ 2
2. Total alkali–silica variation diagram showing analyses of volcanic rock samples........ 5
3. Histogram of SiO_2 contents........ 16
4. Variation diagrams showing abundances of major oxides........ 17
5. Variation diagram showing rubidium and strontium abundances........ 18
6. Histogram of rubidium-strontium ratios........ 18
7. Ternary variation diagram showing the relative proportions of rubidium, potassium, and strontium........ 19
8. Trace element–tectonic setting discrimination variation diagrams........ 19
9. Ternary AFM variation diagram........ 20

TABLES

1. Chemical compositions of unaltered volcanic rock samples from the Bolivian Altiplano........ 6
2. Chemical compositions of altered volcanic rock samples from the Bolivian Altiplano........ 14

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ABSTRACT

Middle to upper Tertiary lava flows, hypabyssal flow domes, and ash-flow tuffs of the Bolivian Altiplano, including those genetically associated with polymetallic vein deposits, are composed dominantly of metaluminous dacite. Major oxide and trace element compositions of these rocks, which contain variable combinations and abundances of plagioclase, biotite, hornblende, clinopyroxene, quartz, and potassium feldspar, are similar to those of continental margin, volcanic arc rocks throughout the world. Abundances of Al_2O_3, total iron, MgO, CaO, and TiO_2 decrease with increasing SiO_2, whereas K_2O abundances increase with increasing SiO_2. Compositional variation trends defined by these rocks primarily reflect crustal contamination of primitive, asthenospheric, mantle-derived partial melts that have undergone subsequent evolution involving varying amounts of crystal fractionation. Alumina saturation indices of the Altiplano volcanic rocks average 0.958, a value that precludes any significant involvement of sedimentary rock in the crustal assimilation assemblage. These observations are consistent with the genesis of these I-type rocks in the archetypal continental volcanic arc.

Samples of volcanic rock genetically related to polymetallic vein deposits have distinctive compositions that reflect hydrothermal alteration. Most of the altered Altiplano volcanic rocks have low Na_2O and CaO contents and high K_2O and loss on ignition (LOI) contents, all of which reflect sericitic alteration. A smaller number of altered samples, which also contain secondary quartz, have high SiO_2 abundances, which reflect silicification.

INTRODUCTION

The U.S. Geological Survey and the Servicio Geológico de Bolivia (1992) conducted a mineral resource assessment of the Altiplano and Cordillera Occidental in southwestern Bolivia during 1990–91. During fieldwork for the assessment, field parties visited many Cenozoic volcanic centers (fig. 1), particularly those with associated mineral deposits, and the volcanic rocks were sampled. Geochemical and petrographic data were obtained to aid in the characterization of these rocks and in the interpretation of the geologic setting of the associated mineral deposits. Data and interpretations presented here are byproducts of the mineral resource assessment.

Mesozoic and Cenozoic igneous rocks of the Andes in western South America have long been recognized as the products of archetypal continental margin, subduction-related volcanic arc magmatism (Mitchell and Reading, 1969; Dewey and Bird, 1970). Volcanoes in the western part of the South American arc have been more extensively studied (see, for example, Harmon and Rapela, 1991) than those of the Altiplano, primarily because they are the locus of ongoing igneous activity within the arc.

A detailed review of central Andean geology is beyond the scope of this study and would be redundant in light of already published reports. Richter and others (1992) provided a synopsis of southwestern Bolivian geology, and references cited therein present current concepts concerning the geologic evolution of the Altiplano. One of the world's archetypal continental volcanic arcs, the Andean arc, whose origin is related to subduction of the Nazca plate beneath the western edge of the South American continental plate, trends northerly through southwestern Bolivia. The Andean arc has been divided into northern, central, and southern volcanic zones (Thorpe and others, 1982); the area of the Bolivian Cordillera Occidental (the western of the two Andean mountain chains extending through the length of Bolivia) and Altiplano is within the central volcanic zone (see Richter and others, 1992, fig. 2). In Bolivia, the central volcanic zone is composed of western and eastern limbs separated by the Altiplano; the two limbs merge to a single arc in southernmost Bolivia. Igneous centers, principally ash-flow calderas and lava flow and dome complexes of intermediate composition, along the east edge of the Altiplano segment of the central volcanic zone were active during the Oligocene and

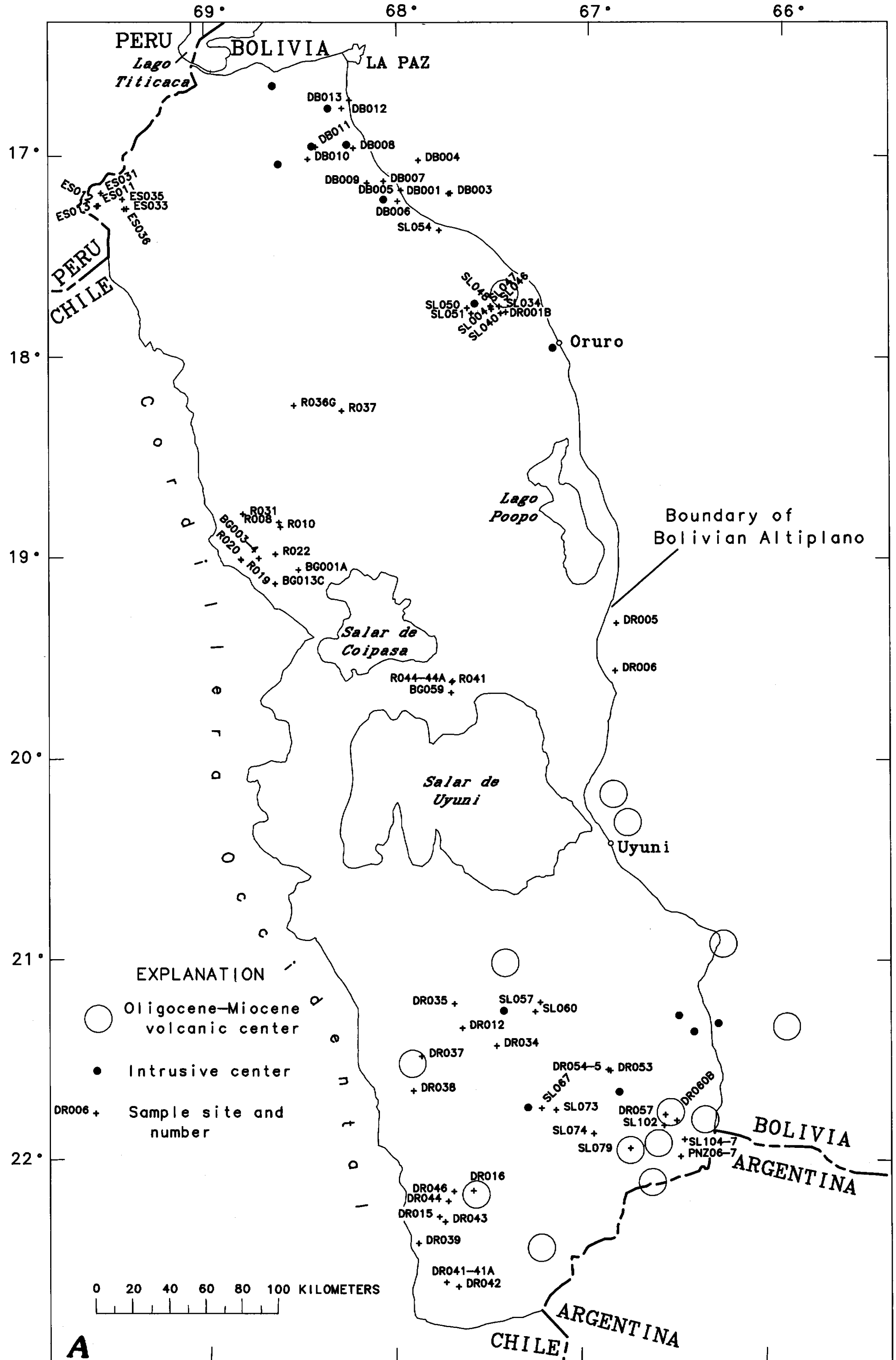
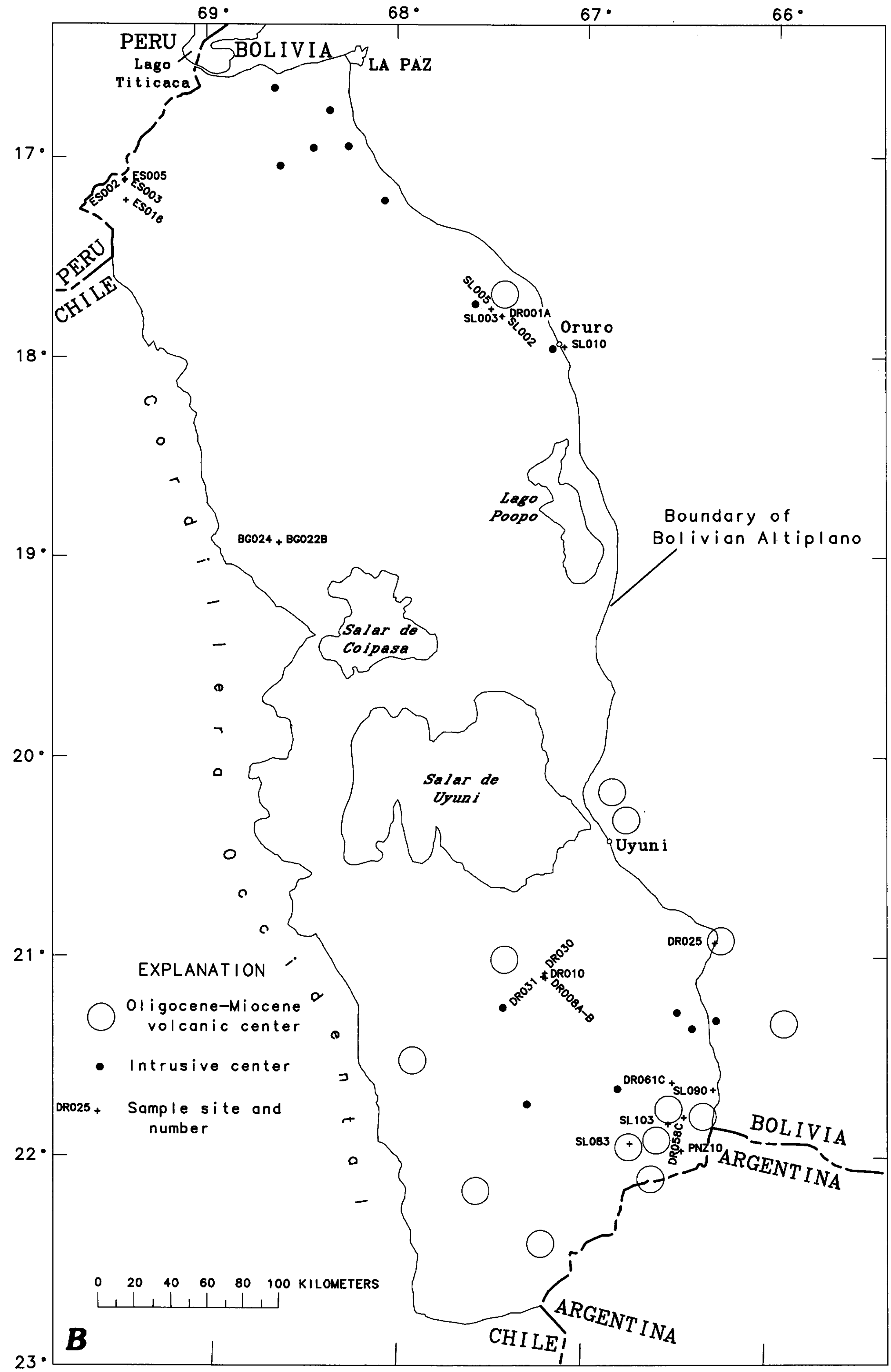


Figure 1 (above and facing page). Maps showing middle to upper Tertiary volcanic features and sample locations, Altiplano and Cordillera Occidental, Bolivia. All sample numbers are prefixed by 90B. Modified from Richter and others (1992). *A*, Unaltered volcanic rocks. *B*, Altered volcanic rocks.


69°
68°
67°
66°
17°
18°
19°
20°
21°
22°
23°
PERU
BOLIVIA
Lago
Titicaca
LA PAZ
ES005
ES002
ES003
ES016
PERU
CHILE
SL005
DR001A
SL003
SL002
Oruro
SL010
Cordillera Occidental
Lago
Poopo
Boundary of
Bolivian Altiplano
BG024
BG022B
Salar de
Coipasa
Salar de
Uyuni
Uyuni
DR025
DR030
DR010
DR031
DR008A-B
EXPLANATION
Oligocene-Miocene
volcanic center
Intrusive center
DR025
Sample site and
number
DR061C
SL090
SL103
SL083
DR058C
PNZ10
BOLIVIA
ARGENTINA
0 20 40 60 80 100 KILOMETERS
B
ARGENTINA
CHILE

Miocene. Igneous centers, principally stratovolcanoes, in the Cordillera Occidental became active during the Miocene and are the locus of ongoing arc magmatism. Exceptionally thick (as much as 70 km) continental crust (James, 1971) beneath both limbs of the central volcanic zone in Bolivia developed during Oligocene and Miocene time by thin-skinned tectonic processes (Sempere and others, 1990). The Altiplano region is considered to represent a series of contiguous, intermontane foreland basins; sediment deposited in these basins was shed from fold and thrust belt uplifts that developed in response to crustal shortening and thickening (Richter and others, 1992).

Middle to upper Tertiary volcanic rocks on the Altiplano that are associated with the majority of the Bolivian polymetallic vein deposits have been relatively little studied. Kussmaul and others (1977) provided an excellent description of the geologic framework of southwestern Bolivia. They presented major oxide and trace element data for 26 samples of volcanic rocks that they combined with analyses from Fernandez and others (1973) to infer five major cycles of magmatic activity during which magmas formed by partial melting at different crustal levels were erupted as lavas and ash-flow tuffs. Baker and Francis (1978) showed that the ages of major eruptive centers are highly variable in different parts of the central volcanic zone. Davidson and others (1991), de Silva (1991), and Davidson and de Silva (1992) offered modern interpretations of the plate tectonic and magmatic processes that have influenced the petrogenesis of volcanic rocks of the central volcanic zone.

Acknowledgments.—The mineral resource assessment of the Bolivian Altiplano (U.S. Geological Survey and Servicio Geológico de Bolivia, 1992), of which this report is an outgrowth, was carried out with the able assistance of many people. The acknowledgments section in the assessment report is equally applicable to this one. We would also like to thank G.B. Sidder and D.J. Bove for their thoughtful and helpful reviews.

PETROGRAPHY

Most middle to upper Tertiary volcanic rocks of the Altiplano are petrographically similar. They are chiefly porphyritic dacite that contains variable proportions of plagioclase, biotite, hornblende, pyroxene, quartz, and potassium feldspar phenocrysts in a very fine grained groundmass that befits its hypabyssal to extrusive nature. Combinations of opaque oxide minerals, apatite, titanite, and zircon are present as accessory minerals. Ash-flow tuffs have well-developed vitroclastic textures, display various degrees of welding, are moderately pumiceous, and have variably devitrified glassy groundmass textures.

Some Altiplano volcanic rocks studied exhibit varying degrees of propylitic or sericitic alteration. Feldspars, plagioclase in particular, in most of the intensely hydrothermally altered Altiplano volcanic rocks have been replaced by fine-grained intergrowths of white mica. Six samples of altered volcanic rocks that have anomalously high SiO_2 contents contain secondary silica.

GEOCHEMISTRY

Geochemical analyses were obtained for 105 igneous rock samples. Of these samples, 82 are considered to represent unaltered igneous compositions. They include 53 lava flows (including hypabyssal intrusions and flow domes), 24 ash-flow tuffs, 2 plutonic rocks, 2 dikes, and 1 mafic enclave (table 1).

The compositions of the remaining 23 samples (table 2) reflect various types and intensities of hydrothermal alteration. These rocks were altered by cogenetic hydrothermal fluids that are responsible for genesis of associated mineral deposits. Some of these samples were collected to determine the mobility of certain oxides and elements during hydrothermal alteration and to determine whether particular oxide or element abundances experienced relative gains or losses. Some weak alteration, not recognized at the time of sample collection, became apparent during data analysis; compositions atypical of common igneous rocks were identified as suspicious. Hand specimen or microscopic examination subsequently confirmed the altered nature of these samples.

ANALYTICAL METHODS

All of the geochemical data presented here were determined in analytical laboratories of the U.S. Geological Survey in Denver, Colorado. Major oxide analyses were performed (analysts, J.E. Taggart and D.F. Siems) using X-ray fluorescence techniques (Taggart and others, 1987); FeO, CO_2, F, and Cl were determined by wet chemistry (analysts, C.S. Papp, T.R. Peacock, J.D. Sharkey, and K.J. Curry) (Jackson and others, 1987). Fe^{2+} to total iron as Fe^{2+} ratios were adjusted to 0.80 and major oxide abundances recalculated to 100 percent, on an anhydrous basis. Trace element abundances were determined (by E.A. du Bray) by energy-dispersive X-ray fluorescence spectroscopy (Elsass and du Bray, 1982) using ^{109}Cd and ^{241}Am radioisotope excitation sources; the accuracy of this type of data is discussed by Sawyer and Sargent (1989).

UNALTERED ROCKS

Middle to upper Tertiary Altiplano volcanic rocks were classified following the system of the International Union of Geological Sciences (Le Bas and others, 1986); however, the alkaline-subalkaline subdivision of Irvine and Baragar (1971) was used to classify the alkalinity of these

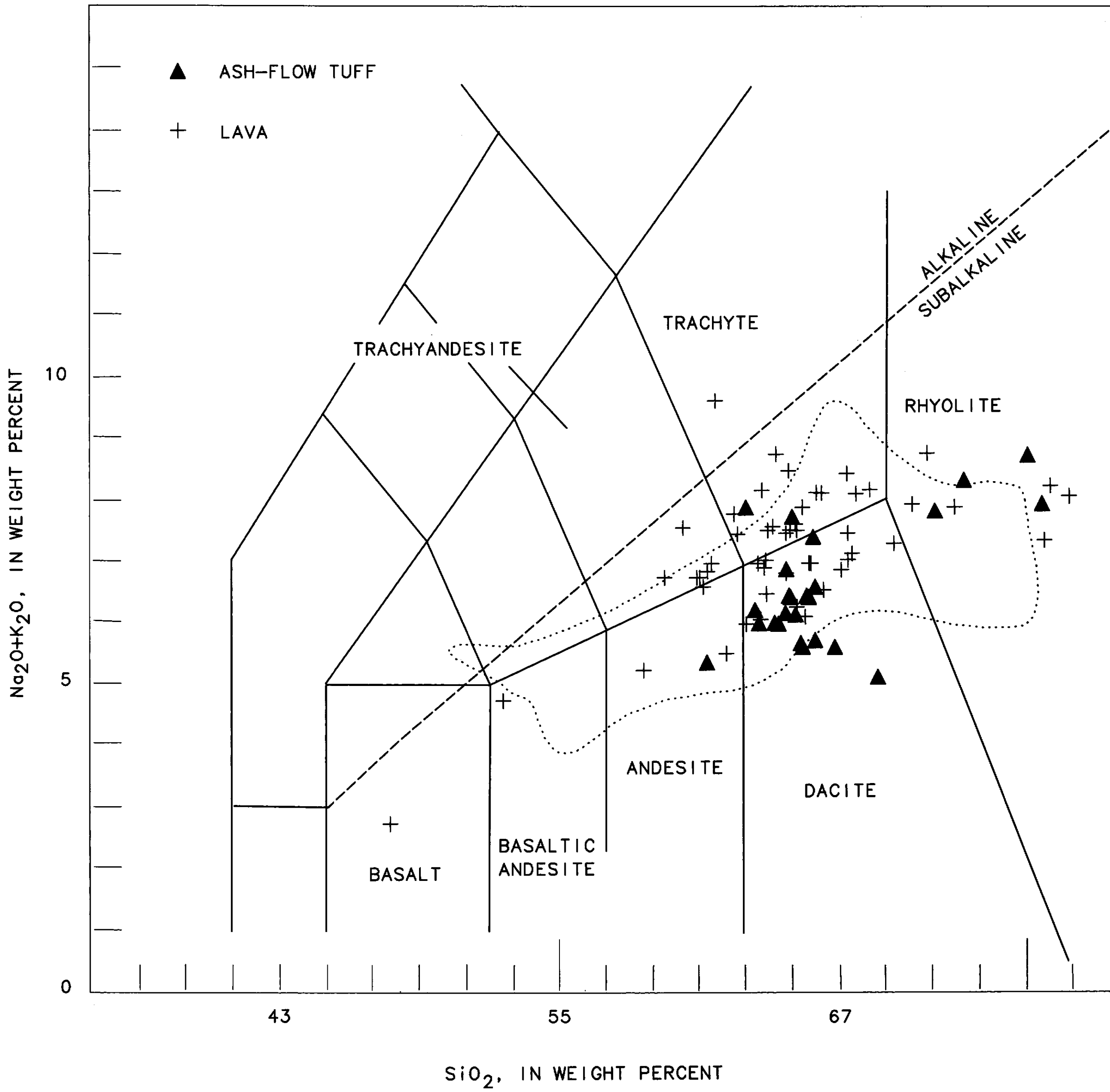


Figure 2. Total alkali–silica variation diagram with IUGS classification grid (Le Bas and others, 1986) showing analyses of volcanic rock samples from the Bolivian Altiplano. Alkaline-subalkaline division is that of Irvine and Baragar (1971). Dotted line outlines the area in which data for the 59 samples of Altiplano volcanic rock of Fernandez and others (1973) and Kussmaul and others (1977) plot.

rocks. All but one of these rocks are subalkaline, and most cluster in the dacite and trachyte-trachydacite fields (fig. 2); andesitic-trachyandesitic and rhyolitic compositions are each represented by about 10 samples, one sample is composed of basaltic andesite, and one sample is composed of basalt.

Geochemical variation among the middle to upper Tertiary volcanic rocks of the Altiplano is similar to that of most continental volcanic arc calc-alkaline igneous rocks (table 1). SiO_2 contents of the analyzed samples display a well-defined mode at about 65 weight percent (fig. 3). Al_2O_3, FeO*(total iron expressed as FeO), MgO, CaO, and TiO_2 abundances decrease with increasing SiO_2, whereas K_2O abundances increase with increasing SiO_2; Na_2O, MnO, and P_2O_5 abundances display no consistent relationship to SiO_2 abundances (fig. 4). K_2O abundances in most of these samples plot in the high-potassium calc-alkaline series of Ewart (1982), and Na_2O to K_2O ratios are approximately normally distributed about an average of 0.88 at an average SiO_2 content of about 65 weight percent.

Compositions of the analyzed samples are metaluminous to weakly peraluminous. The alumina saturation index (ASI), the molar ratio of $Al_2O_3/(CaO+K_2O+Na_2O)$, for the average of the 82 unaltered samples is 0.958. This value is a

Table 1. Chemical compositions of unaltered volcanic rock samples from the Bolivian Altiplano.
[Sample numbers prefixed by 90B. Major oxide data (weight percent) normalized to 100 percent, volatile free. FeO/FeO*(total iron as FeO) recalculated to 0.80. FeO_a, ferrous iron content by wet chemistry. H_2O+, chemically bound water; H_2O-, adsorbed water. Trace element data in parts per million. Sum_i, prenormalization total with total iron as Fe_2O_3. LOI, loss on ignition. bdl, below detection limit]

Sample	DR001B Lava	DR005 Lava	DR006 Tuff	DR012 Tuff	DR015 Tuff	DR016 Tuff	DR034 Tuff	DR035 Lava	DR037 Lava	DR038 Lava	DR039 Lava
Lat °S.	17.7828	19.3314	19.5678	21.3541	22.2985	22.1678	21.4433	21.2317	21.4950	21.6669	22.4300
Long °W	67.4290	66.8404	66.8446	67.6469	67.7679	67.5866	67.4633	67.6900	67.8633	67.9077	67.8800
SiO_2	65.31	63.64	65.98	64.96	61.44	64.49	66.06	63.89	61.20	63.91	62.96
Al_2O_3	15.68	16.60	17.11	16.63	18.05	16.40	16.90	17.83	17.23	16.67	16.30
Fe_2O_3	1.00	0.93	0.72	1.03	1.20	1.06	0.96	0.99	1.17	1.10	1.18
FeO	3.61	3.34	2.58	3.71	4.33	3.83	3.45	3.55	4.19	3.96	4.25
MgO	2.23	2.29	1.35	1.18	2.84	2.28	1.00	1.68	2.97	2.63	2.82
CaO	3.44	4.73	3.51	4.98	5.68	4.93	4.10	4.11	5.43	4.16	5.16
Na_2O	3.27	2.71	2.56	3.22	2.97	2.78	2.99	3.67	3.25	3.22	2.42
K_2O	4.23	4.21	4.79	3.19	2.42	3.20	3.57	3.24	3.28	3.25	3.77
TiO_2	0.86	1.10	0.86	0.75	0.83	0.78	0.73	0.66	0.94	0.85	0.87
P_2O_5	0.30	0.39	0.52	0.29	0.13	0.17	0.19	0.31	0.26	0.17	0.18
MnO	0.06	0.06	0.04	0.06	0.08	0.07	0.07	0.08	0.07	0.07	0.07
LOI	2.90	1.45	2.41	1.74	1.53	0.37	2.08	1.70	1.10	1.17	1.51
Sum_i	99.59	99.39	99.69	99.58	99.49	99.57	99.88	99.13	100.25	99.39	99.49
FeO_a	0.37	2.90	1.53	0.10	2.84	2.36	0.04	1.71	3.77	0.82	2.69
H_2O+	2.17	1.02	1.77	1.12	1.30	0.32	0.70	1.37	0.88	0.76	1.44
H_2O-	0.39	0.34	0.41	0.48	0.39	0.14	1.24	0.49	0.32	0.42	0.26
CO_2	bdl	bdl	0.01	0.02	bdl	bdl	bdl	bdl	bdl	bdl	bdl
CL	0.18	0.04	0.04	0.02	0.02	0.02	0.01	0.05	0.04	bdl	0.03
F	0.04	0.04	0.06	0.03	0.01	0.02	0.02	0.02	0.03	0.02	0.02
Rb	127	148	294	129	101	151	142	86	114	136	142
Sr	509	514	456	348	406	310	307	729	531	406	384
Y	10	18	17	13	24	29	23	30	17	11	22
Zr	205	268	190	130	153	160	121	210	183	154	158
Nb	13	18	21	11	10	12	9	21	13	13	12
Pb	24	11	44	43	28	bdl	101	bdl	16	34	7
Th	19	17	bdl	bdl	16	12	bdl	bdl	bdl	12	21
Ba	1,179	1,400	1,015	724	609	588	606	1,303	817	801	607
La	55	66	68	34	26	39	31	48	46	13	31
Ce	111	142	66	59	77	71	71	97	76	70	68
Nd	46	58	65	31	34	33	23	45	32	16	24

Table 1. Chemical compositions of unaltered volcanic rock samples from the Bolivian Altiplano—Continued.

Sample	DR041 Lava	DR041A Lava	DR042 Tuff	DR043 Lava	DR044 Tuff	DR046 Tuff	DR053 Lava	DR054 Lava	DR055 Lava	DR057 Lava	DR060B Lava
Lat °S	22.6217	22.6217	22.6450	22.3233	22.2217	22.1717	21.5650	21.5600	21.5600	21.7800	21.8100
Long °W	67.7300	67.7300	67.6633	67.7367	67.7200	67.6900	66.8550	66.8667	66.8667	66.5600	66.4983
SiO_2	65.30	62.16	65.79	63.69	65.70	63.64	63.46	52.61	76.20	66.42	65.62
Al_2O_3	16.33	16.79	16.22	16.87	15.74	16.59	16.66	18.22	13.45	15.94	16.40
Fe_2O_3	0.97	1.31	0.95	1.02	0.98	1.15	1.21	1.94	0.14	0.86	1.00
FeO	3.48	4.70	3.44	3.67	3.53	4.14	4.35	6.98	0.51	3.10	3.59
MgO	2.21	2.98	1.81	2.44	2.09	2.50	2.22	3.54	0.19	1.58	2.79
CaO	4.56	5.30	4.51	5.27	4.56	4.93	4.81	10.10	1.11	4.56	3.34
Na_2O	3.06	2.77	3.20	2.91	2.75	2.82	3.20	2.88	3.31	2.15	2.50
K_2O	3.15	2.69	3.19	3.13	3.63	3.12	2.96	1.82	4.89	4.38	3.59
TiO_2	0.69	0.96	0.66	0.74	0.76	0.84	0.76	1.42	0.06	0.70	0.75
P_2O_5	0.18	0.24	0.15	0.18	0.18	0.19	0.25	0.34	0.07	0.28	0.29
MnO	0.07	0.09	0.06	0.07	0.07	0.08	0.11	0.15	0.06	0.03	0.12
LOI	1.94	1.74	0.42	1.34	0.31	0.35	1.76	1.41	0.40	4.56	2.46
Sum_i	99.71	99.90	100.06	99.56	99.17	99.64	99.46	99.87	98.62	98.98	99.16
FeO_a	2.83	3.56	1.91	3.19	2.56	2.11	1.88	3.78	0.27	1.51	0.21
H_2O+	1.71	1.57	0.45	1.25	0.18	0.35	1.68	0.37	0.19	1.69	1.63
H_2O-	0.33	0.43	0.14	0.23	0.16	0.11	0.37	0.23	0.20	1.17	1.03
CO_2	bdl	bdl	bdl	bdl	0.14	bdl	0.04	1.28	0.04	2.14	0.25
CL	0.03	0.02	0.02	0.02	0.04	0.02	0.05	0.01	bdl	0.03	0.04
F	0.02	0.02	0.01	0.02	0.01	0.02	0.02	0.03	bdl	0.02	0.03
Rb	130	108	142	121	158	145	117	55	201	168	220
Sr	321	351	318	365	271	315	477	473	132	304	534
Y	22	30	17	29	24	30	23	32	32	24	23
Zr	133	194	127	159	162	174	156	154	65	149	171
Nb	7	6	11	10	16	7	22	14	41	20	24
Pb	bdl	29	22	41	48	24	27	bdl	7	27	132
Th	bdl	18	bdl	19	40	16	bdl	bdl	bdl	21	23
Ba	597	585	508	678	630	588	767	385	410	813	936
La	25	26	27	25	30	35	30	23	11	49	53
Ce	72	78	62	79	79	77	62	51	27	95	79
Nd	28	26	13	26	25	35	19	23	6	33	27

Table 1. Chemical compositions of unaltered volcanic rock samples from the Bolivian Altiplano—Continued.

Sample	BG001A Pluton	BG003 Lava	BG004 Lava	BG013C Lava	BG059 Dike	R008 Lava	R010 Tuff	R019 Lava	R020 Lava	R022 Tuff	R031 Tuff
Lat °S	19.0680	19.0105	19.0105	19.1364	19.6781	18.8318	18.8548	19.0185	19.0156	18.9898	18.7893
Long °W	68.5158	68.7248	68.7248	68.6379	67.7099	68.6181	68.6103	68.8162	68.8186	68.6367	68.8066
SiO_2	70.84	75.94	76.96	62.87	61.27	59.51	72.40	60.32	66.14	75.21	75.85
Al_2O_3	14.60	13.64	13.61	17.22	17.36	18.43	14.75	16.40	16.28	13.52	13.52
Fe_2O_3	0.71	0.16	0.08	1.04	1.14	1.44	0.44	1.28	0.79	0.25	0.26
FeO	2.54	0.59	0.29	3.74	4.10	5.17	1.57	4.61	2.85	0.91	0.93
MgO	0.62	0.26	0.17	1.87	2.25	0.95	0.92	2.88	1.47	0.25	0.62
CaO	1.21	1.91	0.74	4.80	4.19	6.53	1.24	5.13	3.36	0.97	0.68
Na_2O	3.88	2.13	3.30	3.76	4.48	4.16	2.04	4.32	4.40	3.68	2.66
K_2O	4.88	5.22	4.74	3.27	3.79	2.54	6.25	3.20	3.67	5.03	5.27
TiO_2	0.52	0.15	0.11	0.96	0.90	0.81	0.31	1.18	0.70	0.18	0.18
P_2O_5	0.12	bdl	bdl	0.41	0.40	0.39	bdl	0.58	0.28	bdl	bdl
MnO	0.07	bdl	bdl	0.05	0.11	0.07	0.08	0.09	0.07	bdl	0.03
LOI	0.75	5.89	0.90	3.30	1.94	1.67	3.30	0.14	1.90	0.38	2.14
Sum_i	98.99	99.05	98.65	98.33	99.17	99.35	99.05	99.45	99.28	98.87	99.14
FeO_a	0.01	0.14	0.07	1.50	2.36	1.07	bdl	2.35	1.59	0.12	0.08
H_2O+	0.71	2.44	0.72	1.76	1.86	0.51	1.26	0.14	1.82	0.36	0.93
H_2O-	bdl	3.19	0.23	1.07	0.08	0.18	1.55	0.16	0.18	bdl	1.23
CO_2	bdl	bdl	bdl	bdl	0.30	1.08	bdl	bdl	bdl	0.03	bdl
CL	bdl	0.01	bdl	0.06	0.01	0.01	0.30	0.03	0.10	bdl	bdl
F	0.03	0.01	0.02	0.03	0.03	0.03	0.02	0.03	0.02	bdl	0.03
Rb	167	146	162	96	92	41	155	63	109	106	181
Sr	123	235	98	759	644	712	176	1209	717	176	71
Y	33	21	10	30	31	16	19	19	15	9	40
Zr	259	84	88	227	298	213	205	250	208	105	147
Nb	6	9	12	14	25	18	17	17	14	14	12
Pb	47	9	23	22	47	22	7	25	45	31	19
Th	bdl	12	22	bdl	bdl	bdl	bdl	bdl	bdl	9	22
Ba	1,021	1,118	1,160	1,141	1,278	1,069	1,262	1,467	1,422	575	648
La	36	38	40	48	58	31	35	68	43	39	41
Ce	71	75	64	99	100	66	66	126	105	96	79
Nd	29	8	15	59	29	40	20	37	45	16	20

Table 1. Chemical compositions of unaltered volcanic rock samples from the Bolivian Altiplano—Continued.

Sample	R036G Lava	R037 Tuff	R041 Lava	R044 Lava	R044A Lava	PNZ01 Tuff	PNZ03 Tuff	PNZ05 Tuff	PNZ06 Tuff	PNZ07 Tuff	SL004 Lava
Lat °S	18.2497	18.2753	19.6252	19.6200	19.6200	unk	unk	unk	21.9919	21.9919	17.7687
Long °W	68.5370	68.2868	67.7074	67.7019	67.7019	unk	unk	unk	66.4735	66.4735	67.5047
SiO_2	64.94	71.18	47.78	66.33	67.50	65.14	65.52	65.48	66.10	64.87	67.36
Al_2O_3	17.60	14.52	14.41	15.86	15.80	16.46	16.22	16.14	16.01	17.29	15.40
Fe_2O_3	0.80	0.57	2.94	0.91	0.87	1.06	1.13	1.13	1.16	0.96	0.84
FeO	2.89	2.05	10.59	3.28	3.12	3.80	4.07	4.05	4.16	3.47	3.04
MgO	0.93	1.10	7.22	1.51	1.72	1.97	2.04	2.04	1.89	1.76	2.18
CaO	2.97	2.04	11.61	2.64	2.31	4.04	4.08	4.22	3.64	4.24	1.78
Na_2O	4.31	3.89	2.57	4.30	3.70	2.01	1.77	1.80	1.77	2.08	4.54
K_2O	4.13	3.92	0.12	3.80	3.72	4.12	3.83	3.82	3.92	4.07	3.87
TiO_2	1.06	0.51	2.27	0.86	0.82	1.02	1.00	0.99	1.03	0.90	0.69
P_2O_5	0.37	0.18	0.25	0.46	0.43	0.32	0.28	0.28	0.27	0.31	0.26
MnO	bdl	0.05	0.23	0.04	0.03	0.06	0.06	0.05	0.06	0.05	0.04
LOI	1.22	0.82	0.71	1.96	3.64	0.90	2.65	2.62	3.22	1.35	2.10
Sum_i	98.70	98.83	98.33	98.80	98.93	99.72	99.86	99.72	99.88	99.46	97.88
FeO_a	0.56	0.06	1.17	0.47	0.34	3.17	2.30	2.37	1.96	2.85	1.20
H_2O+	0.96	0.68	0.55	0.72	1.21	0.52	0.98	0.93	1.14	1.21	1.85
H_2O-	0.29	0.10	0.27	1.45	2.38	0.35	1.33	1.28	1.57	0.26	0.29
CO_2	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	0.86
CL	0.02	0.02	0.02	bdl	bdl	0.03	0.03	0.03	0.03	0.05	0.03
F	0.05	0.02	0.03	0.03	0.03	0.03	0.02	0.02	0.02	0.02	0.04
Rb	115	83	76	90	89	168	137	145	153	166	102
Sr	1,076	593	1,345	1,101	973	326	307	309	284	342	275
Y	25	7	16	11	10	29	22	18	26	25	19
Zr	364	120	229	186	194	233	174	179	191	196	162
Nb	25	16	25	20	21	13	19	13	10	15	12
Pb	24	bdl	11	7	bdl	34	14	26	22	26	14
Th	bdl	bdl	bdl	bdl	bdl	13	9	bdl	15	bdl	10
Ba	1,744	1,201	1,185	1,183	1,191	855	739	743	780	748	1,285
La	77	31	55	63	55	58	45	41	28	46	31
Ce	137	81	111	94	85	111	81	89	89	95	90
Nd	71	33	57	37	36	53	33	36	35	38	25

Table 1. Chemical compositions of unaltered volcanic rock samples from the Bolivian Altiplano—Continued.

Sample	SL034 Enclave	SL040 Lava	SL046 Lava	SL047 Lava	SL048 Lava	SL050 Lava	SL051 Tuff	SL054 Lava	SL057 Pluton	SL060 Dike	SL067 Lava
Lat °S	17.7568	17.7888	17.7577	17.7588	17.7549	17.7645	17.7889	17.3788	21.2240	21.2707	21.7536
Long °W	67.4632	67.4539	67.4623	67.5069	67.5090	67.6300	67.6106	67.7776	67.2317	67.2589	67.2218
SiO_2	61.38	63.74	65.89	64.37	65.53	71.97	70.17	65.86	61.77	64.80	69.39
Al_2O_3	16.53	15.31	16.00	15.02	15.35	16.13	14.67	15.17	16.95	17.39	15.61
Fe_2O_3	1.19	1.07	0.89	1.07	0.97	0.25	0.58	0.88	1.23	0.77	0.55
FeO	4.27	3.85	3.21	3.86	3.51	0.92	2.10	3.18	4.44	2.76	1.99
MgO	2.51	2.70	1.53	2.78	2.73	0.42	1.25	2.28	2.04	0.47	1.08
CaO	6.05	3.92	4.60	2.79	2.86	1.81	2.58	4.00	2.69	6.06	3.17
Na_2O	3.66	3.77	3.44	3.79	3.80	3.90	3.82	3.17	7.17	3.26	2.51
K_2O	3.19	4.35	3.50	4.95	4.05	3.95	4.11	4.32	2.42	3.51	4.74
TiO_2	0.84	0.80	0.65	0.80	0.71	0.53	0.45	0.76	0.77	0.61	0.71
P_2O_5	0.25	0.36	0.21	0.28	0.26	0.12	0.20	0.30	0.43	0.32	0.23
MnO	0.12	0.13	0.06	0.29	0.22	bdl	0.05	0.07	0.10	0.05	bdl
LOI	4.19	3.39	3.56	2.85	1.71	2.16	1.80	4.55	1.01	2.31	1.14
Sum_i	99.62	99.18	99.51	99.11	99.14	98.97	98.79	99.17	99.44	99.21	99.35
FeO_a	3.09	2.12	1.43	1.93	2.12	0.08	0.43	2.12	2.17	1.09	1.75
H_2O+	1.48	1.45	1.34	1.35	1.05	1.08	1.52	1.43	0.80	0.68	0.58
H_2O-	0.19	0.27	0.40	0.24	0.29	0.40	0.27	0.34	0.15	0.26	0.33
CO_2	2.84	1.77	1.88	1.43	0.58	bdl	0.01	3.06	bdl	1.31	0.19
CL	0.02	0.02	0.01	0.04	0.06	0.01	0.03	0.02	0.15	0.04	0.04
F	0.02	0.04	0.02	0.03	0.02	0.06	0.02	0.03	0.03	0.02	0.02
Rb	95	162	126	181	135	126	129	127	47	73	202
Sr	531	528	398	254	599	535	495	451	310	531	272
Y	23	23	22	15	21	bdl	11	12	23	22	15
Zr	130	203	145	161	157	172	159	183	268	205	185
Nb	19	8	14	13	14	16	11	14	14	10	15
Pb	bdl	138	10	214	117	21	23	7	bdl	13	31
Th	bdl	bdl	10	bdl	bdl	15	12	bdl	bdl	bdl	bdl
Ba	1,062	1,725	1,212	1,400	1,513	1,017	1,056	1,215	1,127	1,111	781
La	32	67	36	53	49	26	35	68	40	30	35
Ce	76	122	81	88	89	71	64	111	96	82	84
Nd	27	63	26	55	33	27	28	45	38	30	41

Table 1. Chemical compositions of unaltered volcanic rock samples from the Bolivian Altiplano—Continued.

Sample	SL073 Lava	SL074 Lava	SL079 Tuff	SL102 Lava	SL104 Tuff	SL105 Tuff	SL106 Tuff	SL107 Tuff	DB001 Lava	DB003 Lava	DB004 Lava
Lat °S	21.7622	21.8795	21.9504	21.8372	21.9034	21.9034	21.9033	21.9033	17.1963	17.1939	17.0297
Long °W	67.1441	66.9410	66.7462	66.5638	66.4549	66.4542	66.4533	66.4524	67.7270	67.7180	67.8853
SiO_2	58.64	63.08	66.89	67.69	68.67	65.09	64.35	64.82	66.61	65.83	64.85
Al_2O_3	18.82	16.03	15.69	14.88	15.21	16.40	16.80	16.47	15.70	15.36	16.11
Fe_2O_3	1.25	1.16	0.83	0.81	0.79	0.88	0.97	0.95	0.93	0.97	1.02
FeO	4.50	4.18	2.97	2.92	2.85	3.15	3.51	3.41	3.34	3.51	3.68
MgO	2.73	3.53	1.55	2.05	2.16	1.96	2.55	2.40	1.83	2.35	1.88
CaO	8.03	4.81	5.67	3.61	4.34	3.83	4.78	4.08	2.77	3.74	3.61
Na_2O	3.09	2.60	2.72	2.37	2.05	2.45	2.75	2.95	3.42	3.12	3.42
K_2O	2.14	3.37	2.85	4.71	3.07	5.26	3.24	3.88	4.19	3.79	4.02
TiO_2	0.50	0.84	0.60	0.66	0.60	0.67	0.73	0.70	0.89	0.89	0.89
P_2O_5	0.23	0.28	0.19	0.27	0.24	0.28	0.30	0.29	0.30	0.30	0.47
MnO	0.07	0.13	0.04	0.04	0.02	0.04	0.03	0.04	0.03	0.13	0.05
LOI	3.00	2.25	4.18	2.01	5.68	1.33	4.44	3.61	2.04	3.28	1.41
Sum_i	99.66	99.41	99.43	99.09	99.32	99.23	99.45	99.31	99.23	99.35	99.27
FeO_a	2.82	2.86	0.98	1.82	0.86	0.13	0.25	0.98	0.36	3.44	1.49
H_2O+	0.67	1.50	1.32	0.93	2.43	0.53	2.09	1.81	0.71	1.96	0.56
H_2O-	0.42	0.33	0.58	0.19	2.61	0.55	1.88	1.43	1.19	0.17	0.84
CO_2	2.15	0.44	2.21	1.08	bdl	0.01	0.02	0.03	bdl	1.88	bdl
CL	0.02	0.13	0.02	0.04	0.04	0.16	0.06	0.05	bdl	bdl	0.03
F	0.01	0.02	0.02	0.02	0.02	0.01	0.02	0.02	0.03	0.04	0.03
Rb	77	124	119	209	140	194	146	167	159	126	141
Sr	758	499	392	405	651	530	689	636	505	488	643
Y	10	16	18	17	22	16	20	21	18	13	16
Zr	79	136	137	170	125	146	158	159	221	225	225
Nb	8	13	7	20	14	18	16	17	15	16	29
Pb	11	30	29	318	25	5	12	23	21	6	bdl
Th	bdl	13	16	bdl	bdl	20	20	16	13	bdl	12
Ba	746	910	572	777	821	881	933	896	1,019	958	1,333
La	11	38	34	50	52	50	50	63	51	33	65
Ce	49	74	74	91	76	86	93	106	104	97	122
Nd	12	28	34	32	41	28	32	33	34	24	67

Table 1. Chemical compositions of unaltered volcanic rock samples from the Bolivian Altiplano—Continued.

Sample	DB005 Lava	DB006 Lava	DB007 Lava	DB008 Lava	DB009 Lava	DB010 Lava	DB011 Lava	DB012 Lava	DB013 Lava	ES011 Tuff	ES012 Lava
Lat °S	17.1774	17.2272	17.1341	16.9689	17.1427	17.0245	16.9631	16.7677	16.7326	17.2512	17.2527
Long °W	67.9806	67.9988	68.0668	68.2242	68.1526	68.4602	68.4193	68.2839	68.2450	69.5522	69.5614
SiO_2	63.92	61.05	67.48	67.82	67.25	65.05	61.59	68.38	62.69	63.06	62.55
Al_2O_3	16.01	16.21	16.20	15.00	16.20	18.03	17.79	15.39	15.05	16.69	17.34
Fe_2O_3	1.06	1.36	0.93	0.75	0.91	0.99	1.14	0.68	1.30	1.14	1.00
FeO	3.81	4.89	3.34	2.69	3.28	3.55	4.09	2.44	4.69	4.12	3.61
MgO	2.25	2.68	1.38	0.76	1.13	0.66	1.54	1.35	2.79	1.57	2.24
CaO	4.75	5.52	2.40	3.76	3.32	3.48	5.69	2.69	4.30	4.24	4.25
Na_2O	3.18	3.26	3.08	3.53	3.54	2.73	4.14	4.08	3.49	4.25	4.29
K_2O	3.79	3.44	3.94	4.54	3.29	4.77	2.79	4.09	3.93	3.62	3.49
TiO_2	0.75	1.00	0.62	0.76	0.60	0.48	0.68	0.65	1.20	0.90	0.84
P_2O_5	0.37	0.46	0.54	0.37	0.44	0.22	0.37	0.28	0.49	0.31	0.32
MnO	0.11	0.12	0.09	0.02	0.04	0.04	0.18	bdl	0.06	0.10	0.06
LOI	4.08	0.76	1.50	4.28	1.57	1.51	0.46	0.85	1.93	0.94	2.08
Sum_i	99.44	99.41	99.37	99.23	99.48	99.52	99.30	99.25	99.42	99.07	99.35
FeO_a	2.31	1.99	1.33	0.62	0.06	0.83	2.36	0.34	0.76	0.09	2.08
H_2O+	0.74	0.62	1.20	1.20	0.60	1.16	0.42	0.41	0.68	0.35	1.66
H_2O-	0.68	0.34	0.36	0.46	0.49	0.23	bdl	0.22	0.88	0.19	0.51
CO_2	2.83	bdl	bdl	2.03	bdl	bdl	0.03	bdl	bdl	bdl	bdl
CL	0.02	0.06	0.02	0.01	0.02	0.04	0.07	0.02	0.03	0.02	0.12
F	0.03	0.02	0.02	0.07	0.02	0.03	0.02	0.02	0.03	0.03	0.02
Rb	135	127	132	113	119	264	101	116	111	92	86
Sr	671	711	457	929	621	800	916	799	928	1,089	1,256
Y	22	33	23	12	20	27	27	11	35	18	17
Zr	194	213	155	241	209	264	206	172	234	183	174
Nb	28	29	22	15	22	20	26	8	19	8	11
Pb	23	17	16	25	40	bdl	5	34	11	bdl	17
Th	16	18	bdl	9	13	bdl	bdl	bdl	bdl	bdl	12
Ba	945	916	826	1,500	1,109	1,695	1,488	1,440	1,444	1,468	1,482
La	45	53	42	87	43	41	43	50	60	57	68
Ce	99	100	91	108	89	108	109	91	129	98	104
Nd	44	42	37	46	29	44	44	28	44	28	62

Table 1. Chemical compositions of unaltered volcanic rock samples from the Bolivian Altiplano—Continued.

Sample	ES013 Lava	ES031 Lava	ES033 Lava	ES035 Lava	ES036 Lava	Lava average	Tuff average	Lava average	Tuff average
Lat °S	17.2546	17.1881	17.2675	17.2200	17.2683	n=53	n=24	F and K[1]	F and K[1]
Long °W	69.5594	69.5386	69.4058	69.4264	69.4181				
SiO_2	64.63	60.99	64.01	64.18	62.13	64.47±4.73	66.72±3.72	63.84±4.39	67.99±3.32
Al_2O_3	16.18	17.16	16.43	15.99	16.75	16.17±1.15	16.05±1.18	16.27±0.63	15.83±1.41
Fe_2O_3	0.89	1.26	1.04	1.03	1.17	1.01±0.42	0.88±0.28	1.15±0.36	0.77±0.18
FeO	3.19	4.52	3.74	3.72	4.19	3.62±1.50	3.17±1.00	4.15±1.29	2.76±0.64
MgO	1.95	2.36	1.95	2.11	2.18	2.06±1.09	1.71±0.65	2.58±1.87	1.41±0.49
CaO	3.83	5.57	4.25	4.32	4.63	4.20±1.89	3.89±1.42	4.53±1.59	3.51±0.87
Na_2O	4.42	3.83	3.93	3.79	4.00	3.40±0.63	2.74±0.68	2.84±0.61	2.91±0.52
K_2O	3.81	2.89	3.56	3.75	3.61	3.67±0.86	3.86±0.92	3.44±1.12	3.92±0.55
TiO_2	0.76	1.00	0.73	0.70	0.87	0.80±0.32	0.70±0.24	0.91±0.27	0.67±0.19
P_2O_5	0.29	0.34	0.29	0.32	0.38	0.30±0.12	0.22±0.12	0.21±0.09	0.17±0.08
MnO	0.05	0.08	0.07	0.08	0.09	0.08±0.06	0.06±0.03	0.08±0.04	0.06±0.03
LOI	1.45	1.56	0.36	1.31	0.43	2.01±1.22	2.00±1.48	1.00±0.54	1.36±0.81
Sum_i	99.43	99.94	99.35	99.62	99.40				
FeO_a	1.81	2.12	1.73	1.88	0.82	1.61±1.04	1.35±1.11		
H_2O+	1.32	1.44	0.28	1.36	0.28	1.10±0.55	1.01±0.60		
H_2O-	0.17	0.40	0.34	0.33	0.28	0.51±0.55	0.75±0.71		
CO_2	bdl	bdl	bdl	bdl	bdl	0.47±0.84	0.10±0.45		
CL	0.13	0.07	0.02	0.07	0.01	0.04±0.04	0.05±0.06		
F	0.02	0.02	0.02	0.02	0.04	0.03±0.01	0.02±0.01		
Rb	88	76	99	111	78	125± 43	148± 41		
Sr	1,191	692	825	946	1,196	638±304	401±190		
Y	8	9	23	17	16	19±8	21±8		
Zr	180	151	169	167	191	184± 50	161± 32		
Nb	13	12	8	12	11	16±7	14±4		
Pb	39	10	28	21	25	34± 55	26± 21		
Th	bdl	bdl	bdl	bdl	bdl	6±8	10±0		
Ba	1,503	1,036	1,228	1,261	1,465	1117±334	811±248		
La	51	35	32	54	55	45± 16	41± 12		
Ce	95	55	77	97	117	91± 23	82± 15		
Nd	50	24	54	31	41	37± 15	33± 11		

[1]Fernandez and others (1973), 20 lavas and 13 tuffs; and Kussmaul and others (1977), 18 lavas and 8 tuffs.

Table 2. Chemical compositions of altered volcanic rock samples from the Bolivian Altiplano.

[Sample numbers prefixed by 90B. Major oxide analyses (weight percent) normalized to 100 percent, volatile free. FeO/FeO*(total iron as FeO) recalculated to 0.80. Trace element data in parts per million. Sum_i, prenormalization total with total iron as Fe_2O_3. LOI, loss on ignition. bdl, below detection limit]

Sample	DR001A	DR008A	DR008B	DR010	DR025	DR030	DR031	DR058C	DR061C	BG022B	BG024
Lat °S	17.8029	21.1167	21.1167	21.1100	20.9364	21.0929	21.1100	21.8100	21.6368	18.9387	18.9387
Long °W	67.4485	67.2000	67.2000	67.2133	66.2913	67.2032	67.2133	66.4483	66.5147	68.6274	68.6274
SiO_2	86.79	68.64	66.93	64.61	65.22	64.19	62.48	64.20	67.74	75.16	80.88
Al_2O_3	8.36	16.62	16.13	15.86	16.23	18.35	19.04	15.46	16.21	13.13	12.03
Fe_2O_3	0.25	0.41	0.89	1.40	0.95	0.60	0.88	2.21	0.54	0.28	0.07
FeO	0.89	1.46	3.19	5.04	3.42	2.15	3.15	7.96	1.95	1.02	0.24
MgO	0.37	0.65	0.61	0.92	1.85	0.48	0.54	1.08	0.51	bdl	0.10
CaO	0.03	0.39	0.35	0.64	3.78	1.91	0.90	0.58	0.41	0.11	0.18
Na_2O	bdl	2.05	1.54	1.09	2.78	2.66	1.07	0.34	0.74	1.20	1.66
K_2O	2.57	8.96	9.61	9.50	4.48	8.76	10.52	5.87	11.15	8.84	4.72
TiO_2	0.68	0.47	0.45	0.45	0.88	0.63	0.92	0.72	0.50	0.20	0.13
P_2O_5	0.06	0.23	0.22	0.22	0.27	0.29	0.42	0.28	0.25	0.06	bdl
MnO	bdl	0.13	0.07	0.25	0.16	bdl	0.09	1.29	bdl	bdl	bdl
LOI	2.75	1.89	1.79	2.83	4.33	1.10	3.77	5.07	1.69	1.46	1.71
Sum_i	99.40	99.52	98.20	98.55	98.98	98.86	99.18	99.04	98.74	98.30	98.18
Rb	91	228	208	186	233	267	307	276	650	325	160
Sr	22	72	200	233	223	632	111	39	110	95	48
Y	20	26	15	18	15	18	12	15	47	18	15
Zr	164	193	190	193	175	181	232	160	137	177	107
Nb	12	16	17	17	10	20	21	15	11	18	14
Pb	85	56	178	346	24	28	253	70	45	2243	33
Th	bdl	bdl	bdl	bdl	bdl	bdl	bdl	11	30	bdl	13
Ba	528	1,535	5,003	4,072	927	1,224	1,776	538	1,012	1,075	1,066
La	29	26	31	30	51	31	61	56	29	39	48
Ce	106	50	46	52	80	67	82	89	69	68	68
Nd	12	47	48	44	22	40	53	31	54	30	11

close approximation to the mean ASI (0.985) of 1,074 I-type granites from the Lachlan Fold Belt of Australia, which suggests that the Altiplano volcanic rocks were derived from an igneous (mantle) source (Chappell and White, 1992).

Ferrous-ferric iron data for volcanic rocks are notorious for being unrepresentative of magmatic oxidation levels; late-stage volcanic processes including outgassing and devitrification cause many volcanic rocks to become significantly more oxidized than their associated magma. Use of this type of data in petrologic studies, including computation of normative mineralogy, can lead to erroneous conclusions (Middlemost, 1989). Review of ferrous and ferric iron data for middle to upper Tertiary volcanic rocks of the Altiplano indicates that these samples have also experienced varying amounts of posteruption oxidation (table 1). Values of FeO/FeO* for these samples are randomly distributed between 0 and 0.8 but converge on a maximum, unoxidized value between 0.75 and 0.80, which is similar to the iron oxidation value of 0.74 suggested by Middlemost (1989) for dacitic compositions. Consequently, FeO/FeO* values for all of the samples described here have been adjusted to a value of 0.80 (table 1).

Major oxide compositions of ash-flow tuffs and lavas of the Bolivian Altiplano display slight, but significant differences (table 1). The average composition of 24 ash-flow tuff samples is more evolved than that of 54 lava flow samples. Relative to abundances in lava samples, abundances of SiO_2 and K_2O are high in ash-flow tuff samples and those of FeO*, MgO, CaO, Na_2O, TiO_2, and P_2O_5 are low. Despite the differences between average compositions for the ash-flow tuffs and lava flows, their compositional data form colinear arrays or overlapping fields on variation diagrams (figs. 2, 4).

Trace element abundances of the Altiplano ash-flow tuffs are also distinctly more evolved than those of the lava flows (table 1, fig. 4). Rubidium abundances in the ash-flow tuffs are slightly higher, relative to those of the lava flows, whereas abundances of strontium, zirconium, and barium are lower. As was the case for the major oxides, trace element abundances for the ash-flow tuffs and

Table 2. Chemical compositions of altered volcanic rock samples from the Bolivian Altiplano—Continued.

Sample	PNZ10	SL002	SL003	SL005	SL010	SL083	SL090	SL103	ES002	ES003	ES005	ES016
Lat °S	21.9919	17.8030	17.8004	17.7674	17.9538	21.9414	21.6706	21.8392	17.1214	17.1184	17.1158	17.2197
Long °W	66.4735	67.4494	67.4496	67.5070	67.1192	66.7407	66.2923	66.5367	69.4333	69.4342	69 4303	69.4261
SiO_2	70.58	78.55	89.52	71.93	70.35	65.62	67.27	64.67	66.12	67.88	68.06	73.20
Al_2O_3	15.44	12.10	6.69	13.26	15.22	16.35	15.76	16.11	17.80	17.16	18.70	17.10
Fe_2O_3	0.56	1.05	0.18	1.65	2.15	0.96	0.73	1.04	1.62	0.99	1.30	0.56
FeO	2.03	3.77	0.64	5.95	7.75	3.47	2.63	3.76	5.83	3.57	4.69	2.01
MgO	1.36	0.37	0.27	0.90	0.55	0.89	1.63	2.02	0.88	1.01	0.53	0.35
CaO	0.42	bdl	0.04	0.20	0.04	1.74	1.30	6.15	0.31	1.58	0.13	0.11
Na_2O	0.18	bdl	bdl	0.19	bdl	1.63	2.03	0.39	1.90	3.10	1.20	0.77
K_2O	8.81	3.55	1.96	4.29	3.05	8.23	7.72	4.75	4.24	3.60	3.93	4.80
TiO_2	0.44	0.61	0.64	1.14	0.72	0.76	0.59	0.77	1.00	1.02	1.03	0.86
P_2O_5	0.19	bdl	0.05	0.48	0.17	0.29	0.23	0.29	0.29	0.10	0.43	0.24
MnO	bdl	bdl	bdl	bdl	bdl	0.06	0.12	0.06	bdl	bdl	bdl	bdl
LOI	2.67	4.71	3.89	8.59	7.19	1.61	2.08	8.38	6.48	5.28	8.16	7.24
Sum_i	99.38	99.31	98.91	98.16	98.66	99.21	99.44	99.37	99.19	98.91	99.00	99.25
Rb	428	153	77	224	144	341	364	163	75	72	88	128
Sr	25	17	20	1,173	111	343	197	133	634	755	797	873
Y	21	16	14	23	18	19	21	22	18	19	12	10
Zr	125	153	174	231	146	160	157	150	207	205	216	173
Nb	9	13	15	21	20	17	15	10	15	11	13	16
Pb	22	26	11	111	46	102	28	34	40	24	40	31
Th	11	11	bdl	bdl	bdl	bdl	16	10	bdl	bdl	bdl	bdl
Ba	1,376	292	225	1,267	534	949	1747	648	1,608	1,616	1,485	1,342
La	38	36	52	95	43	34	36	51	44	61	65	43
Ce	58	79	76	176	65	63	57	99	95	103	116	79
Nd	31	23	23	87	39	40	49	25	46	44	67	43

lava flows form colinear and mostly overlapping fields on variation diagrams (figs. 5, 7, 8).

Compositional data for unaltered Altiplano volcanic rocks are characterized by groups of oxides and elements whose abundances show mutual covariation. These covariant relations suggest that compositional variation was controlled by a distinct mineral assemblage, in accord with the fact that the compositions of Altiplano volcanic rocks form linear arrays on many variation diagrams. The minerals inferred to have influenced Altiplano volcanic rock compositional variation are present as phenocrysts therein. These minerals influenced compositional variation by their occurrence in the partial melting residuum or in crystal fractionation assemblages.

The oxides whose abundances are most highly correlated are FeO*, CaO, MgO, TiO_2, and MnO. Correlation coefficients (r^2) between FeO and CaO, MgO, and TiO_2 are all greater than 0.85; within this group, mutual correlation coefficients exceed 0.7. FeO* and MgO abundance variations are also correlated with those of MnO; correlation coefficients values are more than 0.6. Mutual abundance covariations involving these oxides indicate hornblende or clinopyroxene as minerals influencing the compositional variation of the Altiplano volcanic rocks. The lack of a significant correlation between K_2O abundances and those of this group of oxides indicates that biotite was not important in the geochemical evolution of the Altiplano volcanic rocks.

Abundance variations of SiO_2 and K_2O have a correlation coefficient of 0.78, whereas those of K_2O and rubidium have an correlation coefficient of 0.60. These abundance covariations indicate potassium feldspar as another phase that influenced Altiplano volcanic rock compositional variation. Additional significant abundance covariations were not identified within the major oxides.

Abundance covariations principally involving trace elements identify three accessory minerals that may have influenced Altiplano volcanic rock compositional variation. Significant abundance covariations involving P_2O_5, Sr, La, Ce, and Nd; CaO and TiO_2; and Zr, La, Ce, and Nd indicate apatite, titanite, and zircon, respectively, as additional phases that probably influenced compositional variation within the Altiplano volcanic rocks.

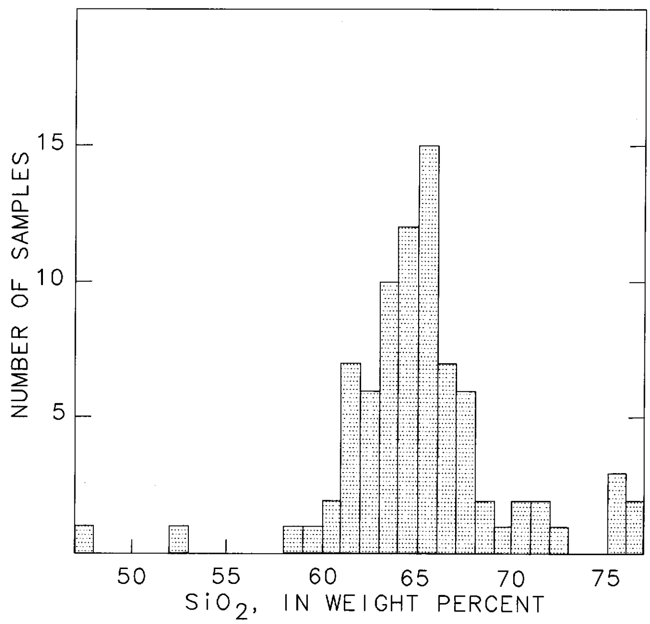


Figure 3. Histogram showing SiO_2 of volcanic rock samples from the Bolivian Altiplano.

Compositions of Altiplano volcanic rocks can be compared to data of Macdonald and others (1992), which provides the best compendium of volcanic rock compositions versus tectonic setting relations. Their compilation is of obsidian compositions and thus is biased toward more evolved, rhyolitic compositions. Although their database is not entirely compatible with that for the majority of middle to upper Tertiary Altiplano volcanic rocks, the average composition of subduction-related obsidian from a continental margin setting (Macdonald and others, 1992) is grossly similar to that of the Altiplano volcanic rocks.

The major oxide abundances of most of the Altiplano volcanic rocks are considerably less evolved than those of the average obsidian from continental margin, subduction-related settings (Macdonald and others, 1992). In particular, SiO_2 and total alkalis are lower in the Altiplano rocks, whereas abundances of Al_2O_3, FeO*, MgO, CaO, and TiO_2 are higher. The halogen contents of middle to upper Tertiary Altiplano volcanic rocks are slightly lower than those of the average obsidian from continental margin subduction-related settings (Macdonald and others, 1992). Fluorine contents in the Altiplano rocks are approximately normally distributed around a mean value of 0.03 weight percent, whereas the average fluorine content of subduction-related obsidian is about 0.05 weight percent. Chlorine contents in the Altiplano rocks are approximately normally distributed, though slightly skewed to higher abundances, around a mean value of 0.04 weight percent, whereas the average chlorine content of subduction-related obsidian is about 0.07 weight percent. Many of the major oxide and halogen abundance differences between the Altiplano rocks and the subduction-related obsidian of Macdonald and others (1992) may principally reflect the intrinsic bias toward rhyolitic, more evolved compositions characteristic of the latter. Trace element abundances (including Rb, Zr, Nb, Y, La, Ce, and Nd) in middle to upper Tertiary volcanic rocks of the Altiplano are similar to those of the average obsidian from continental margin subduction-related settings (Macdonald and others, 1992) in many respects. The average abundances of barium and strontium, 1,027 and 558 ppm, respectively, in the Altiplano samples are considerably greater, however, than those in the continental margin, subduction-related rocks (730 and 120 ppm, respectively) and may again relate to a sampling bias, toward rhyolitic compositions, in the latter. Barium and strontium abundances in the Altiplano rocks are also high relative to their abundances in granite (600 and 285 ppm, respectively) or the crust (425 and 375 ppm, respectively) (Krauskopf, 1967).

The average zirconium abundance of the unaltered Altiplano samples is 180 ppm, similar to the value for obsidian from continental margin, subduction-related settings (Macdonald and others, 1992) and approximates the experimentally determined (Watson and Harrison, 1983) zirconium saturation threshold (several hundred parts per million) for subalkaline rocks. Because the zirconium threshold increases to values greater than 180 ppm in peralkaline liquids and at temperature greater than about 860°C, we can infer that magmas represented by the Altiplano volcanic rocks did not equilibrate with peralkaline liquids or at unusually high temperatures.

The average rubidium abundances of the Altiplano volcanic rocks and obsidian from continental margin, subduction-related settings, 130 and 135 ppm (Macdonald and others, 1992), respectively, are remarkably similar. Rubidium abundances of the Altiplano volcanic rocks decrease systematically with increasing strontium abundances (fig. 5), a relationship observed for most igneous rocks (Macdonald and others, 1992). The average rubidium-strontium ratio for the Altiplano rocks, 0.23, is significantly lower than the average value of 1.1 for obsidian from continental margin, subduction-related settings, however. The disparity between these two rubidium-strontium ratios emphasizes the disparity between strontium abundances in volcanic rocks of the Altiplano and those in obsidian from continental margin,

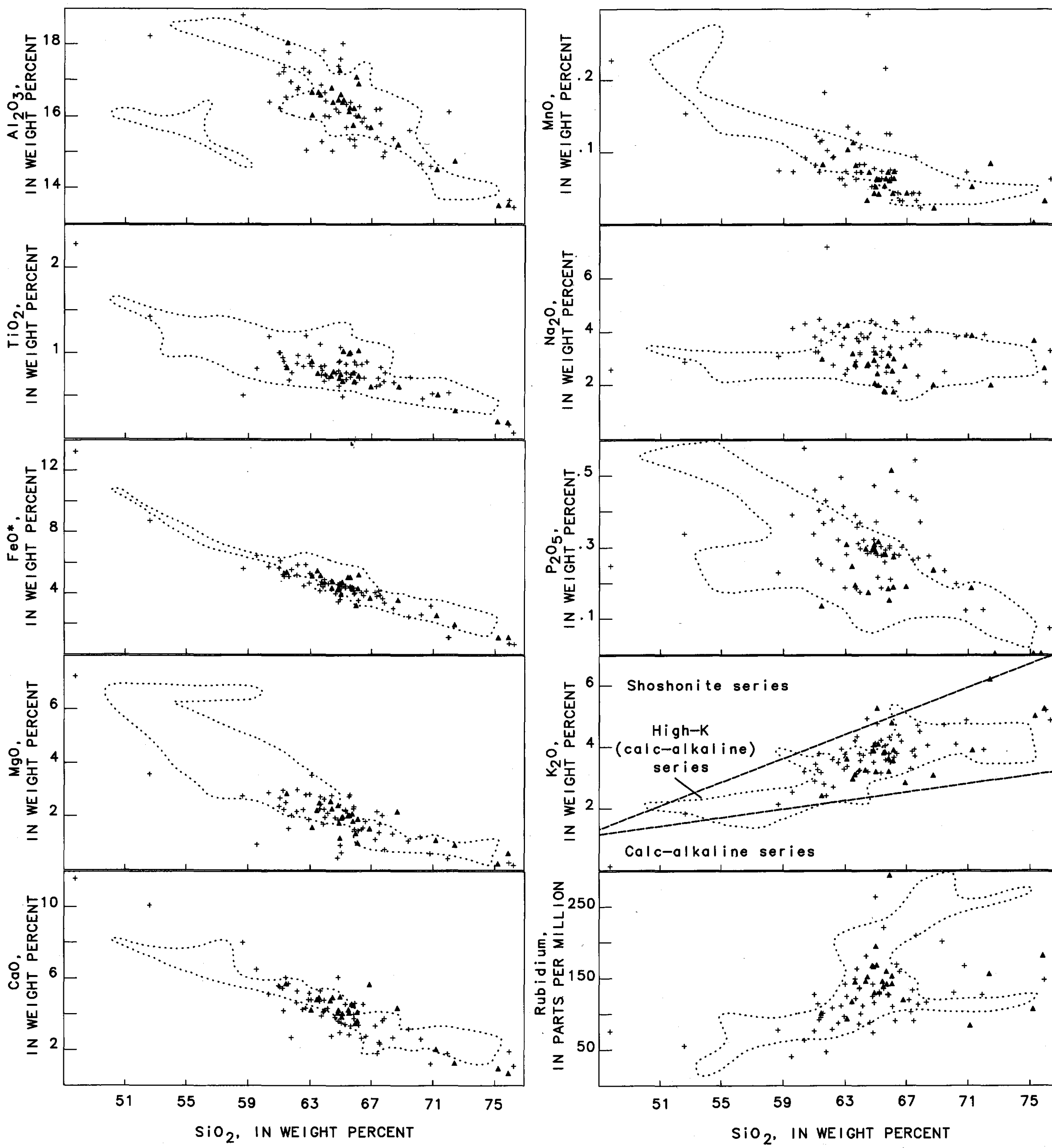


Figure 4. Variation diagrams showing abundances (table 1) of major oxides, normalized to 100 percent volatile free, in volcanic rock samples from the Bolivian Altiplano. Data for lava flows and ash-flow tuffs are shown by pluses and triangles, respectively. Dashed discriminant lines on K_2O versus SiO_2 diagram are from Ewart (1982). Dotted line outlines the area in which data for the 59 samples of Altiplano volcanic rock of Fernandez and others (1973) and Kussmaul and others (1977) plot.

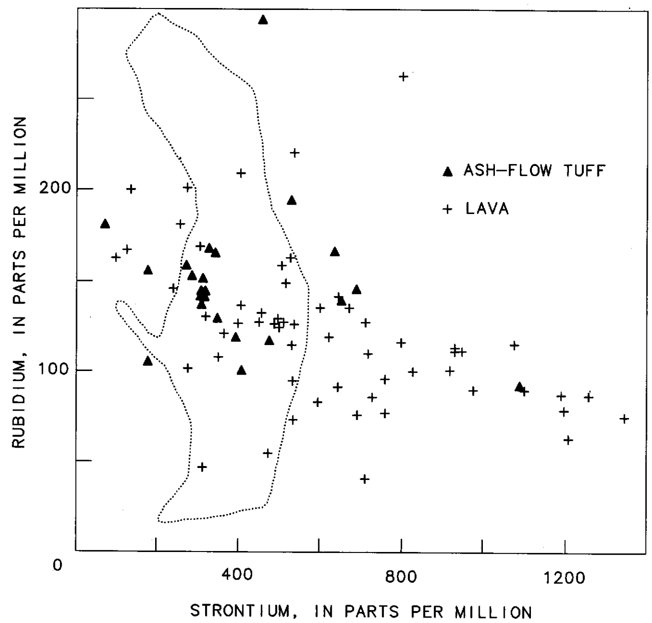


Figure 5. Variation diagram showing rubidium and strontium abundances (table 1) in volcanic rock samples from the Bolivian Altiplano. Dotted line outlines the area in which data for the 59 samples of Altiplano volcanic rock of Fernandez and others (1973) and Kussmaul and others (1977) plot.

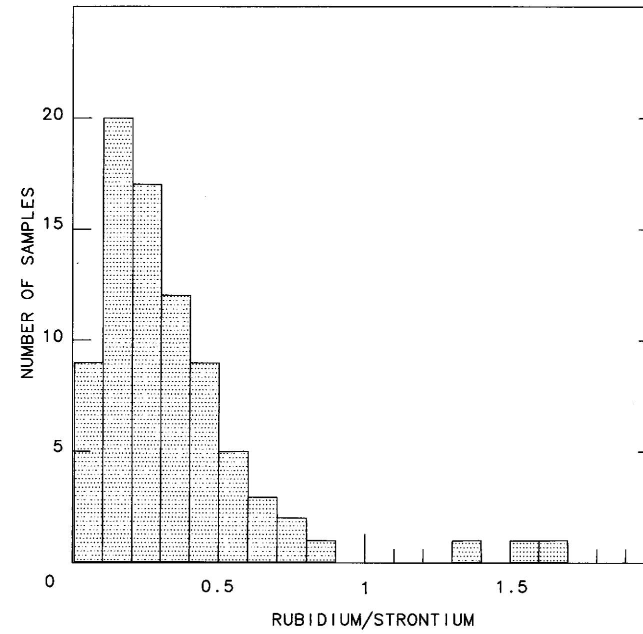


Figure 6. Histogram showing rubidium-strontium ratios for volcanic rock samples from the Bolivian Altiplano.

subduction-related settings. Rubidium-strontium ratios in most of the Altiplano volcanic rocks are between 0.1 and 0.9 and are approximately normally distributed, though slightly skewed toward higher values, about the mean value (fig. 6).

The degree of magmatic evolution displayed by volcanic rocks of the Altiplano is depicted by their relative rubidium, potassium, and strontium abundances (fig. 7). Abundances of these elements are principally controlled by feldspar (Hanson, 1978); abundances of strontium and rubidium are most and least, respectively, depleted by feldspar fractionation. Thus, as feldspar fractionation and differentiation proceed, potassium and, to an even greater extent, rubidium are concentrated in the residual liquid relative to strontium. Compositions plotting nearest the strontium apex of the rubidium-potassium/100-strontium ternary diagram represent the least evolved magmas. Volcanic rocks of the Altiplano are very slightly less evolved than middle Tertiary, subduction-related ash-flow tuffs of southern Nevada (for instance, du Bray, in press) and are significantly less evolved than strongly rubidium-enriched, within-plate igneous rocks (for instance, du Bray and others, 1988).

Pearce and others (1984) recognized that intrusive rocks generated in various tectonic settings have distinctive geochemical signatures, and they developed trace element discriminant diagrams from which tectonic setting can be inferred. Trace element abundance variations in coeval volcanic and plutonic rocks generated in a given terrane should be similar. Consequently, compositions of the Altiplano volcanic rocks can be compared to the tectonic setting–trace element grids developed by Pearce and others (1984). Trace element data for nearly all of these samples plot in the volcanic arc field on these diagrams (fig. 8). Gill (1981) indicated that barium-niobium ratios of modern arc rocks are greater than 26; negative niobium anomalies on extended trace element diagrams are a diagnostic geochemical characteristic of continental volcanic arc rocks. The average barium to niobium ratio for the Altiplano volcanic rocks is 66, and negative niobium anomalies are a ubiquitous feature of the Altiplano volcanic rocks. Barium to niobium ratios for the Altiplano volcanic rocks range from 10 to 192 and are approximately normally distributed around the mean; only two samples have ratios less than 30, and only six samples have ratios greater than 130. In addition, major oxide compositions for the Altiplano volcanic rocks follow a calc-alkaline trend parallel to but displaced below the Cascade trend on an AFM (Na_2O+K_2O, FeO*, MgO) diagram (fig. 9). These compositional features support the observation that middle to upper Tertiary Altiplano volcanic rocks are subduction-related, continental volcanic arc magmas and corroborate the utility of this type of diagram in tectonic discriminant analysis.

ALTERED ROCKS

The abundances of a number of the major oxides in 23 altered volcanic rock samples are atypical of the average composition of the Altiplano volcanic rocks in particular and igneous rocks in general; the anomalous compositions of

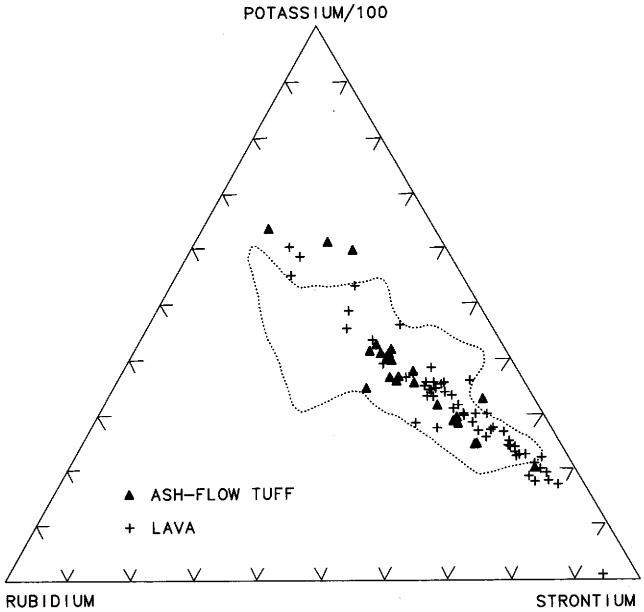


Figure 7. Ternary variation diagram showing the relative proportions of rubidium, potassium, and strontium (table 1) in volcanic rock samples from the Bolivian Altiplano. Dotted line outlines the area in which data for the 59 samples of Altiplano volcanic rock of Fernandez and others (1973) and Kussmaul and others (1977) plot.

these samples probably result from geochemical remobilization caused by hydrothermal alteration (table 2). In most of the altered Altiplano volcanic samples, Na_2O abundances are low to very low (average, 1.41 weight percent) and K_2O abundances are high (average, 6.91 weight percent) relative to average Altiplano volcanic rocks and to other calc-alkaline igneous rocks; most of these samples also have unusually low to very low CaO (average, 1.21 weight percent) contents and high LOI values (average, 4.22 weight percent).

SiO_2 abundances in several samples (DR001A, BG024, and SL003) exceed 78 weight percent, the maximum value for normal igneous rocks. In addition, SiO_2 abundances in several other samples (PNZ10, SL002, and ES016), which similar to the previous three samples were identified as dacite during field investigations, are high relative those characteristic of Altiplano dacites. The compositions of these six samples are similar, with regard to low Na_2O and CaO and high K_2O abundances, to those of samples described in the preceding paragraph except they also have high SiO_2 abundances. LOI values in most of these same samples are high, relative to the value of 2 weight percent characteristic of unaltered Altiplano volcanic rocks, and are as high as more than 7 weight percent.

Abundances of a number of the trace elements in the altered rocks are systematically different from those of the average Altiplano volcanic rock. As befits their spatial association with mineralized rock related to polymetallic mineral deposits, many of the 23 altered samples contain variously elevated abundances of combinations of arsenic, lead,

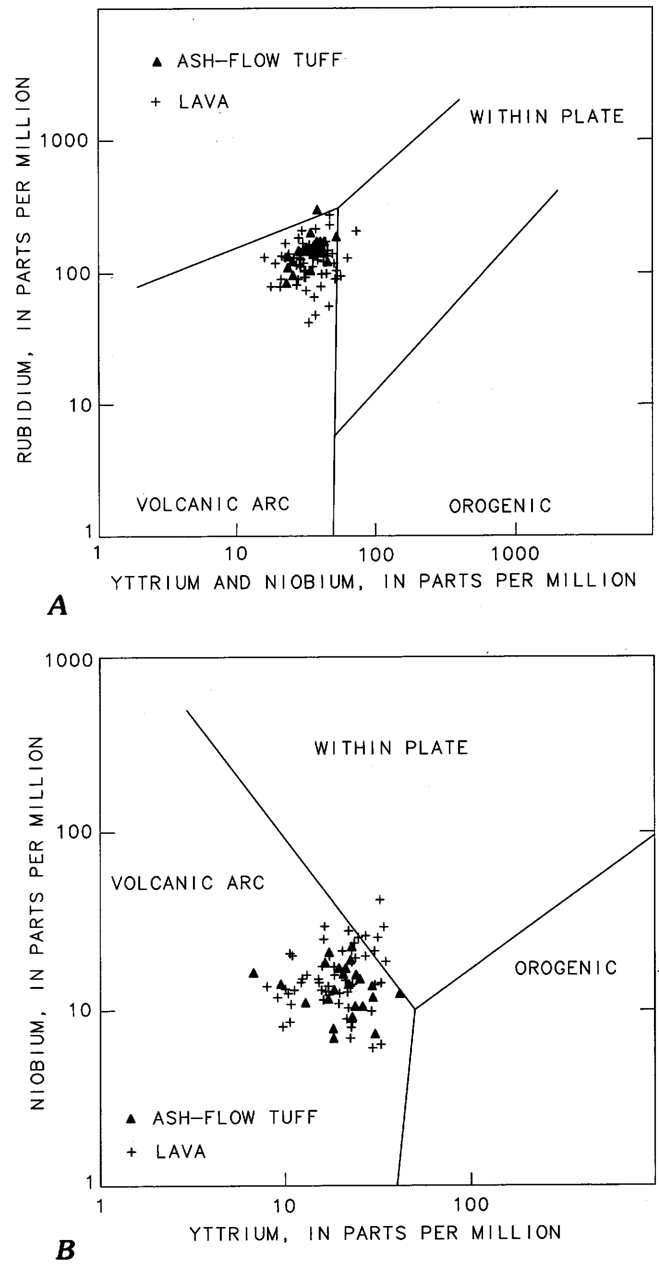


Figure 8. Trace element–tectonic setting discrimination variation diagrams showing compositions (table 1) volcanic rock samples from the Bolivian Altiplano. Tectonic setting–composition boundaries are from Pearce and others (1984). *A*, Rubidium versus yttrium and niobium. *B*, Niobium versus yttrium.

antimony, tin, and zinc (U.S. Geological Survey and Servicio Geológico de Bolivia, 1992). In addition, rubidium abundances in the altered rocks are high relative to the average Altiplano volcanic rock (table 1), whereas strontium abundances are depleted. Barium abundances are erratically distributed; some of the altered samples are characterized by dramatically elevated barium abundances, whereas others have depleted abundances. Most altered samples having high SiO_2 abundances have slightly high tin abundances

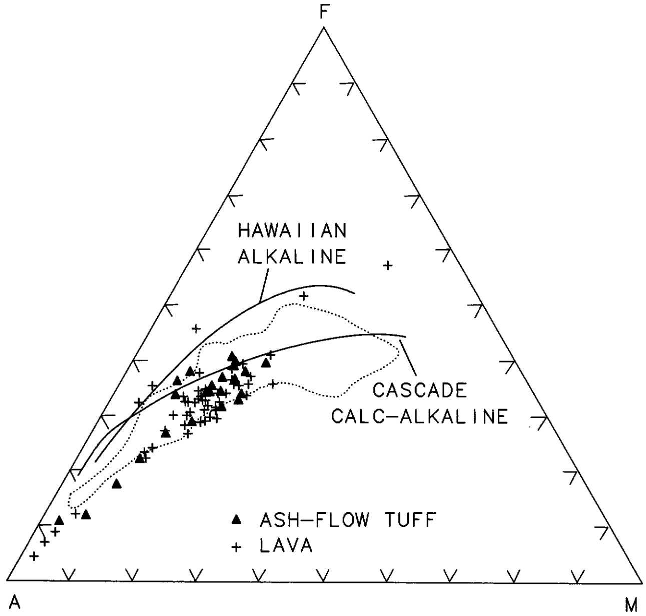


Figure 9. Ternary AFM (Na_2O+K_2O, FeO*, MgO) diagram showing compositions of volcanic rock samples from the Bolivian Altiplano. Cascade calc-alkaline trend line from Irvine and Baragar (1971). Dotted line outlines the area in which data for the 59 samples of Altiplano volcanic rock of Fernandez and others (1973) and Kussmaul and others (1977) plot.

relative to the average Altiplano volcanic rock and to the other altered Altiplano samples. Abundances of yttrium, zirconium, niobium, and the light rare earth elements in the altered samples are virtually indistinguishable from those of the average Altiplano volcanic rock, supporting the observation that these elements are relatively immobile during weathering and alteration processes.

DISCUSSION AND CONCLUSIONS

UNALTERED ROCKS

The most primitive (baseline composition) volcanic rocks of the western South America continental margin volcanic arc are compositionally distinct relative to those erupted from intraoceanic volcanic arcs (Davidson and others, 1991). Initially, baseline compositions of central volcanic zone magmas were thought to be inherited from subcontinental mantle lithosphere, but Davidson and others (1991) rejected the hypothesis because isotopic data (especially oxygen) for the central volcanic zone magmas do not support their derivation from that source. Hildreth and Moorbath (1988) and Davidson and others (1991) suggested that the compositional distinctiveness of the Andean arc magmas resulted from extensive interaction between these magmas, probably mostly mantle derived, and crustal material during magma ascent through exceptionally thick continental crust beneath the Andean arc; the primary, mantle magmas experienced major chemical modification through crustal interaction. This interpretation suggests that the predominantly dacitic composition of middle to upper Tertiary volcanic rocks of the Bolivian Altiplano reflects, in part, considerable modification of primitive asthenospheric mantle-derived melts by assimilation of crustal material, including partial melts, along their ascent paths. Alumina saturation indices of the Altiplano volcanic rocks (average, 0.958), however, preclude the involvement of significant amounts of sedimentary rock in the crustal assimilation–partial melting assemblage (Chappell and White, 1992), which suggests that the assimilated crustal component was mostly igneous.

Linear arrays on some variation diagrams (fig. 4) are consistent with geochemical evolution involving, via restite unmixing or crystal fractionation, the phenocryst assemblage observed in dacitic rocks of the Altiplano; however, the relative importances of crystal fractionation versus restite unmixing involving this mineral assemblage are uncertain. These data arrays are also characterized by very low correlation coefficients (large amounts of data scatter), which probably result from assimilation of varying amounts of compositionally diverse crustal materials. The importance of these various processes is probably highly variable among the volcanic centers of the Altiplano. Primary, asthenospheric mantle-derived basaltic partial melts and their differentiates probably represent baseline compositions from which more evolved (dacitic to rhyolitic) magmas were derived by assimilation and fractional crystallization.

Kussmaul and others (1977) considered the K-h relationship (increasing K_2O content of arc-derived volcanic rocks with increasing distance above their Benioff zone) of Dickinson and Hatherton (1967) and concluded that such a relation does not exist for middle to upper Tertiary volcanic rocks of the Bolivian Altiplano. As Kussmaul and others (1977) indicated, south of lat 20° S. the Peru-Chile trench strikes approximately north. Consequently, assuming that the inclination of the Benioff zone does not vary beneath the southern Altiplano, the K-h relationship can be evaluated by considering K_2O content of volcanic rocks as a function of longitude.

Our data suggest that K_2O contents of middle to upper Tertiary volcanic rocks of the Bolivian Altiplano are weakly correlated with longitude; that is, with distance above the Benioff zone. Of the 82 unaltered samples collected as part of this study, 39 are from sites south of lat 20° S., where the trench strikes approximately north. The mean and standard deviation (number of samples for each average given in parentheses) of K_2O content of samples collected in four 0.5°-wide longitude strips between long 68° and 66° W. are 3.30±0.59 (13), 3.28±1.04 (5), 3.57±1.05 (8), and 3.86±0.72 (7), respectively. Although these average values are indistinguishable in light of their associated standard deviations, the averages, 3.30-3.28-3.57-3.86 increase to the east, with increasing distance above the Benioff zone, and the overall trend of K_2O abundances for the 39 samples also increases to the east. The average K_{65} value (Dickinson and Hatherton, 1967) for the four longitude-based samples groups, about 3.5 percent K_2O, indicates a depth to Benioff zone of 250±100 km (Dickinson, 1970). This depth estimate is in accord with the estimate of Barazangi and Isacks (1976), determined by considering the spatial distribution of subduction-related earthquake hypocenters, for depth to the modern Benioff zone below the Altiplano at approximately lat 20° S. Consequently, assuming that the inclination of the Oligocene-Miocene Benioff zone beneath the Altiplano region was similar to its present-day inclination, it is likely that the petrogenetic factors that have caused K_2O abundances in volcanic rocks to be correlated with distance above Benioff zones in many other subduction-related volcanic arcs (Dickinson, 1970) may also have influenced the K_2O content of Andean arc Altiplano volcanic rocks.

Feeley (1993) noted similar systematic, across-arc geochemical trends in Quaternary volcanic rocks of the southern Salar de Uyuni region. Specifically, he suggested that systematic variations in strontium, rubidium, and K_2O abundances are related to the subduction process itself and reflect extensive lower crust hybridization by interaction with primary basaltic magmas beneath the active volcanic front. Magmas ascending somewhat inboard of the active volcanic front will be contaminated by less hybridized lower crust and will consequently contain higher abundances of rubidium and K_2O and lower abundances of strontium.

ALTERED ROCKS

The largest group of altered Altiplano volcanic rocks are those having low Na_2O and CaO contents and high K_2O and LOI contents; these rocks have been affected by varying degrees of sericitic alteration. The distinctive major oxide compositions of these rocks are entirely a function of sericitic alteration that caused feldspar replacement by potassium- and hydroxyl-rich sericite. In this replacement process, Na_2O and CaO were mobilized out of these rocks by circulating hydrothermal fluids. In order for plagioclase to be replaced by sericite, the altering fluid must have been potassium rich. Elevated K_2O abundances in these samples do not represent closed-system, relative K_2O enrichment caused by Na_2O and CaO depletion because the abundances of the other oxides are not proportionally elevated. Consequently, the absolute abundances of K_2O in these samples have been enhanced by the hydrothermal fluids responsible for sericitic alteration. Alteration proceeding elsewhere in these systems must have involved the breakdown of potassium-rich minerals such as potassium feldspar and biotite and the subsequent partitioning of potassium into the hydrothermal fluid. High rubidium abundances, low strontium abundances, and highly erratic barium abundances in these rocks probably reflect the growth of sericite at the expense of plagioclase because plagioclase is a principal mineralogic site for strontium and barium (to a lesser extent), whereas micas such as sericite are a principal mineralogic site of rubidium and barium. Sericitic alteration, inferred on the basis of compositional data, is borne out by petrographic identification of sericite replacing feldspar. Similarly, elevated K_2O and rubidium abundances have been noted in mineralized volcanic rocks of the Julcani district in Peru (Scherkenbach and Noble, 1984).

Similarly, silicification inferred on the basis of compositional data is in accord with petrographic identification of secondary silica in half a dozen samples. These six Altiplano dacite samples have high SiO_2 contents and have been silicified to varying degrees. In addition, similar to the rocks described previously, the major oxide abundances of these samples suggest sericitic alteration of feldspars, especially plagioclase.

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APPENDIXES

Appendix 1. Brief descriptions of unaltered samples collected as part of this study.
[Percentages of indicated minerals are estimates made by examination of thin sections]

Sample no.	Description
90BDR001B	Escantaque. Dacite lava. 2–5 percent fresh biotite, 1–3 percent fresh plagioclase, and 1–3 percent fresh hornblende in glassy pumiceous matrix . Redwood and Macintyre (1989) presented K-Ar (biotite) ages of 5.4±0.2 and 5.7±0.2 Ma for the uppermost Escantaque flow.
90BDR005	Cerro Gordo. Dacite porphyry dome. 3–5 percent fine-grained plagioclase and 2–4 percent hornblende with altered rims in cryptocrystalline matrix.
90BDR006	Los Frailes. Dacite ash-flow tuff. 8–10 percent fine-grained, broken, resorbed quartz, 5–10 percent plagioclase, 3–6 percent fresh biotite, and pumice clasts.
90BDR012	Sora Puncu. Dacite tuff of Ignimbrite Formation. 5–10 percent plagioclase, 2–4 percent red hornblende and 1–2 percent resorbed quartz, with rims of opaque oxide minerals, and 1 percent biotite in a densely welded glassy matrix. Baker and Francis (1978) presented a K-Ar (biotite) age of 3.2±0.2 Ma for an ignimbrite (possibly the same one represented by 90BDR012) 2 km southwest of Sora Punca.
90BDR015	Cerro Pabellon. Andesite tuff of Ignimbrite Formation. 5–8 percent broken plagioclase, 3–5 percent green hornblende, 1–2 percent fresh biotite, trace to 2 percent orthopyroxene, trace to 1 percent clinopyroxene, and pumice in a dense glassy matrix. Baker and Francis (1978) presented a K-Ar (hornblende) age of 1.7±0.5 Ma for an ignimbrite (possibly the same one represented by 90BDR015) 4 km north of Cerro Pabellon.
90BDR016	Cerro Panizos. Dacite tuff of Ignimbrite Formation. 5–10 percent plagioclase, 5–6 percent clinopyroxene and possible orthopyroxene, in a densely welded cryptocrystalline matrix.
90BDR034	San Francisco mine. Crystal-rich dacite ash-flow tuff. 20–25 percent plagioclase, 2–3 percent rounded quartz, 2–5 percent fresh biotite, 1–2 percent altered hornblende, and pumice in glassy matrix.
90BDR035	Mina Eskapa. Dacite porphyry flow or intrusion. 5–8 percent plagioclase and 2–5 percent fresh biotite in trachytic matrix of plagioclase and biotite microlites and cryptocrystalline material. U.S. Geological Survey and Servicio Geologico de Bolivia (1992) presented a K-Ar (biotite) age of 6.3±0.1 Ma.
90BDR037	Cerro Caquella. Andesite porphyry flow. 5–10 percent plagioclase, 3–5 percent orthopyroxene, and 1–2 percent fresh clinopyroxene in cryptocrystalline matrix.
90BDR038	Cerro Cachi Laguna. Dacite porphyry flow. 10–15 percent plagioclase, 1–3 percent fractured quartz, 1–2 percent completely altered hornblende, 1–2 percent completely altered biotite, and trace? clinopyroxene in trachytic matrix containing plagioclase microcrystallites and cryptocrystalline material.
90BDR039	Cerro Apacheta. Andesite porphyry flow. 10–15 percent plagioclase, 2–3 percent fresh biotite, 1–2 percent quartz, 1–2 percent fresh hornblende, trace to 1 percent orthopyroxene, and trace clinopyroxene in cryptocrystalline matrix.
90BDR041	Cerro Amarillo. Dacite porphyry flow.
90BDR041A	Cerro Poderosa. Andesite porphyry flow.
90BDR042	Rio Chunchillerito. Crystal-rich dacite ash-flow tuff. 10–15 percent broken plagioclase, 2–5 percent rounded quartz, 2–5 percent biotite, and 1–2 percent hornblende in nonflattened pumice matrix.
90BDR043	Cerro Pabellon. Dacite porphyry flow. 5–10 percent plagioclase, 1–3 percent orthopyroxene, 1–2 percent fresh hornblende, and xenocryst clots in cryptocrystalline matrix.
90BDR044	Cerro Panizos. Dacite ash-flow tuff. 10–15 percent plagioclase, 2–3 percent clinopyroxene, 1–2 percent orthopyroxene, 1 percent hornblende, 1 percent biotite, and xenocrysts in densely welded glassy matrix.
90BDR046	Cerro Panizos. Dacite ash-flow tuff. 8–12 percent plagioclase, 3–5 percent orthopyroxene, 3–5 percent highly altered hornblende and biotite, 2–3 percent clinopyroxene, and trace quartz in a cryptocrystalline matrix.

Appendix 1. Brief descriptions of unaltered samples collected as part of this study—Continued.

Sample no.	Description
90BDR053	Mina Escala. Dacite porphyry debris flow. Clasts of densely welded ash-flow tuff. 10–20 percent plagioclase, 1–3 percent fresh hornblende, 1–3 percent fresh biotite, and 1–2 percent rounded quartz in glassy matrix. U.S. Geological Survey and Servicio Geologico de Bolivia (1992) presented a K-Ar (biotite) age of 18.2±0.3 Ma.
90BDR054	Mina Rosario. Basalt flow. 10–15 percent plagioclase, 5–8 percent clinopyroxene in rounded clots, and 1–3 percent opaque oxide minerals in intergranular matrix of plagioclase and clinopyroxene.
90BDR055	Mina Escala. Rhyolite porphyry intrusion. 3–5 percent plagioclase, 2–3 percent rounded quartz, 1–2 percent fresh biotite, and 1–2 percent opaque oxide minerals in cryptocrystalline matrix. U.S. Geological Survey and Servicio Geologico de Bolivia (1992) presented a K-Ar (biotite) age of 18.0±0.2 Ma.
90BDR057	Cerro Aguilar. Dacite porphyry flow. 5–10 percent saussuritized plagioclase, 2–3 percent fresh to altered biotite, 1–2 percent opaque oxide minerals, 1 percent altered hornblende, and trace to 1 percent rounded quartz in cryptocrystalline matrix.
90BDR060B	Bolivar mine. Dacite porphyry dome. 10–15 percent fresh plagioclase, 2–5 percent fresh to locally altered biotite, and 1–2 percent embayed quartz in cryptocrystalline matrix.
90BG001A	Several low hills about 7 km north of Cerro Tata Sabaya. Undeformed, reddish, fine- to medium-grained, seriate (monzo?) granite. Slightly more quartz than plagioclase and slightly more plagioclase than alkali feldspar; accessory zircon and thulite. Graphic intergrowths common. About 8 percent brick-red altered unknown mafic silicate minerals.
90BG003	Todos Santos. Rhyolite dome. Brown vitrophyre breccia. Vitrophyre about 30 m thick. Clasts are angular, silicified flow-banded rhyolite; matrix is brown glass with ≤1 percent small biotite phenocrysts. U.S. Geological Survey and Servicio Geologico de Bolivia (1992) presented a K-Ar (biotite) age of 6.1±0.2 Ma for sample 90BR004 (no chemistry), a sample collected near 90BG003, of rhyodacite from Todos Santos.
90BG004	Todos Santos. Rhyolite dome. White, flow-banded with <<1 percent biotite and sparse quartz and sanidine phenocrysts. U.S. Geological Survey and Servicio Geologico de Bolivia (1992) presented a K-Ar (biotite) age of 6.1±0.2 Ma for sample 90BR004 (no chemistry), a sample collected near 90BG004, of rhyodacite from Todos Santos.
90BG013C	Saca Sacani. Andesite flow. Collected as float; assumed to be host rock to native sulfur prospects on Cerro Saca Sacani. Most rocks near here strongly altered by some combination of argillization, iron oxide staining, alunitization, and secondary gypsum deposition.
90BG059	Cerro Husachata, Salinas de Garci Mendoza. Andesite porphyry dike (N. 10° E., vertical) in andesite breccia near Guadalupe mine. 20 percent feldspar phenocrysts as long as 4 mm, and <1 percent fine mafic silicate minerals (including biotite).
90BR008	About 1.5 km west of Negrillos. Andesite breccia. Gray plagioclase-phyric, fine-grained flank flows from a stratovolcano west of Negrillos but could be part of Carangas volcanic sequence.
90BR010	About 2.5 km south of Negrillos. Rhyolite ash-flow tuff. 10–15 percent phenocrysts, mainly plagioclase and biotite and minor sanidine and opaque oxide minerals, in reddish-brown vitroclastic matrix. U.S. Geological Survey and Servicio Geologico de Bolivia (1992) presented a K-Ar (biotite) age of 21.7±0.7 Ma.
90BR019	South flank of Cerro Curumaya, about 10 km west of Todos Santos. Andesite lava. Flow-aligned plagioclase and hornblende in a very fine grained matrix of plagioclase microlites and cryptocrystalline, subvitreous mesostasis.
90BR020	Middle-lower slopes on south side of Cerro Curumaya. Dacite lava. Frothy, glassy, light-gray porphyritic flow interlayered with dark hornblende andesite or dacite flows represented by 90BR019. 30–35 percent phenocrysts, microphenocrysts, and crystal fragments in a nearly colorless glass with some perlitic fractures. Phenocrysts of mainly zoned plagioclase, euhedral hornblende, clinopyroxene, and biotite and accessory apatite, zircon, and opaque oxide minerals. Biotite >hornblende~clinopyroxene.

Appendix 1. Brief descriptions of unaltered samples collected as part of this study—Continued.

Sample no.	Description
90BR022	North of La Rivera, about 10 km(?) east of Todos Santos. Rhyolite ash-flow tuff. Very light gray. 5–10 percent fine-grained phenocrysts of quartz, sanidine, biotite, and hornblende. Phenocrysts similar to those in tuff of the Mauri Formation from west of Turco (90BR037), but not as abundant; "La Rivera" tuff contains less titanite than the tuff west of Turco.
90BR031	Estancia Jarumani. Pink rhyolite ash-flow tuff. 5–10 percent fine-grained phenocrysts: quartz≈sanidine>> plagioclase; sparse biotite. Accessory opaque oxide minerals, tiny zircon; rare lithic fragments.
90BR036G	About 1 km south of Cerro Phasa Willkhi. Fine-grained hornblende dacite breccia.
90BR037	Pumiri Loma, about 15 km southwest of Turco. Rhyolite ash-flow tuff. Nearly white, crystal-rich tuff. Identified on Turco 1:100,000-scale geologic map as tuff of the Mauri Formation but looks like Perez Tuff. Distinctive bipyramidal quartz, sanidine, plagioclase, orangish biotite, red-brown hornblende. Apatite present; zircon not identified. Abundance of euhedral titanite conspicuous. Rare small lithic fragments.
90BR041	Salinas de Garci Mendoza. Porphyritic basalt intrusion. Large 1–2 cm feldspar phenocrysts; plagioclase>> orthoclase. Mafic phenocrysts of hornblende and biotite.
90BR044	Salinas de Garci Mendoza. Dacite porphyry intrusive(?) or dome northwest of 90BR041. Rock essentially the same as 90BR041 but contains fine clay alteration that obscures much of matrix. Large 1–2 cm feldspar phenocrysts; plagioclase>>orthoclase. Mafic phenocrysts, hornblende, and biotite, quite oxidized.
90BR044A	Salinas de Garci Mendoza. Weakly altered dacite porphyry intrusive(?) similar to 90BR044.
90BPNZ01	Panizos caldera. Dacite ash flow tuff.
90BPNZ03	Panizos caldera. Dacite ash flow tuff.
90BPNZ05	Panizos caldera. Dacite ash flow tuff.
90BPNZ06	Panizos caldera. Dacite ash flow tuff.
90BPNZ07	Panizos caldera. Dacite ash flow tuff.
90BSL004	La Joya. Dacite porphyry; about 20 percent crystals. Phenocrysts are 10 percent plagioclase (moderately altered to sericite), 3 percent biotite (altered to chlorite), and 2 percent embayed quartz in a cryptocrystalline matrix; accessory zircon and trace pyrite. Redwood and Macintyre (1989) presented a K-Ar (biotite) age of 14.3±0.4 Ma.
90BSL034	La Barca. Holocrystalline mafic enclave in La Barca dacite. About 20 percent phenocrysts composed of oxidized mafic silicates (probably mostly biotite but including some hornblende) and occasional plagioclase phenocrysts; accessory zircon. Groundmass principally fine-grained plagioclase and interstitial chlorite. Redwood and Macintyre (1989) presented a K-Ar (biotite) age of 14.3±0.4 Ma.
90BSL040	Llallagua. Dacite porphyry; about 15 percent crystals. Phenocrysts are 5 percent hornblende (altered to chlorite, biotite, and opaque oxide minerals), 4 percent biotite (altered to chlorite and opaque oxide minerals) 4 percent plagioclase (moderately altered to sericite), 1 percent opaque oxide minerals, and 1 percent embayed quartz in a cryptocrystalline matrix; accessory apatite. Redwood and Macintyre (1989) presented a K-Ar (biotite) age of 14.3±0.4 Ma.
90BSL046	Llallagua. Dacite porphyry; about 20 percent crystals. Phenocrysts are 10 percent oxidized biotite, 5 percent plagioclase (weakly sericitized), 3 percent quartz, and 2 percent potassium feldspar in a devitrified cryptocrystalline sericitized matrix; accessory apatite, zircon, opaque oxide minerals. Redwood and Macintyre (1989) presented a K-Ar (biotite) age of 14.3±0.4 Ma.
90BSL047	La Joya. Dacite porphyry; about 25 percent crystals. Phenocrysts are 12 percent oxidized biotite, 5 percent plagioclase (weakly sericitized), 3 percent quartz, 3 percent altered hornblende, and 2 percent potassium feldspar (weakly sericitized) in a devitrified cryptocrystalline sericitized matrix; accessory apatite, zircon, opaque oxide minerals. Secondary calcite and chlorite. Redwood and Macintyre (1989) presented a K-Ar (biotite) age of 14.3±0.4 Ma.

Appendix 1. Brief descriptions of unaltered samples collected as part of this study—Continued.

Sample no.	Description
90BSL048	La Joya. Dacite porphyry; about 30 percent crystals. Phenocrysts are 12 percent oxidized biotite, 11 percent plagioclase (weakly altered to sericite), 5 percent hornblende, 4 percent potassium feldspar, and 3 percent quartz in a devitrified cryptocrystalline matrix altered to sericite; accessory apatite, titanite, zircon, opaque oxide minerals, and clinopyroxene. Redwood and Macintyre (1989) presented a K-Ar (biotite) age of 14.3±0.4 Ma.
90BSL050	Cerro Llallagua. Rhyolite porphyry; about 30 percent crystals. Phenocrysts are 14 percent plagioclase, 14 percent potassium feldspar, 1 percent embayed quartz, and 1 percent oxidized biotite; accessory zircon and opaque oxide minerals. Redwood and Macintyre (1989) presented a K-Ar (biotite) age of 14.3±0.4 Ma.
90BSL051	Cerro Quimsa Chata. Weakly welded, porphyritic rhyolite ash-flow tuff; about 15 percent crystals. Phenocrysts are 6 percent biotite, 4 percent plagioclase, 3 percent potassium feldspar, 1 percent quartz, and 1 percent hornblende in incipiently devitrified matrix of pumice shards; accessory titanite, zircon, apatite, and opaque oxide minerals. Redwood and Macintyre (1989) presented a K-Ar (biotite) age of 8.8±0.3 Ma.
90BSL054	Laurani. Dacite porphyry; about 20 percent crystals. Phenocrysts are 8 percent oxidized biotite, 7 percent feldspar (altered to sericite and calcite), 3 percent embayed quartz, and 2 percent altered hornblende in devitrified cryptocrystalline matrix; accessory apatite and titanite. Some feldspar megacrysts as large as 3 cm. Redwood and Macintyre (1989) presented a K-Ar (biotite) age of 8.8±0.3 Ma.
90BSL057	Condor Huasi. Fine grained, porphyritic, hypidiomorphic granular granodiorite with abundant amphibolite xenoliths. Phenocrysts are 10 percent completely sericitized plagioclase, 7 percent hornblende, 3 percent opaque oxide minerals, and 1 percent quartz in completely sericitized matrix; accessory apatite.
90BSL060	Condor Huasi. Dacite porphyry dike; about 20 percent crystals. Phenocrysts are 12 percent plagioclase, 4 percent potassium feldspar, 3 percent biotite, 1 percent quartz, and 1 percent opaque oxide minerals in devitrified cryptocrystalline matrix; accessory zircon.
90BSL067	Todos Santos. Porphyritic dacite; phenocrysts are biotite, plagioclase, and quartz.
90BSL073	Todos Santos. Porphyritic andesite; phenocrysts are hornblende, plagioclase, and quartz.
90BSL074	San Antonio de Lipez. Porphyritic dacite; phenocrysts are biotite, plagioclase, and quartz.
90BSL079	Jaquega. Dacite ash-flow tuff; about 30 percent crystals. Phenocrysts are 10 percent biotite, 8 percent plagioclase, 6 percent potassium feldspar, 5 percent quartz, and 1 percent opaque oxide minerals in devitrified cryptocrystalline matrix; accessory zircon. Occasional unflattened pumice blocks and lithic fragments. Groundmass extensively replaced by secondary calcite.
90BSL102	Morokho. Porphyritic dacite; phenocrysts are biotite, plagioclase, and quartz.
90BSL104	Loma Grande. Eutaxitic dacite ash-flow tuff with about 15 percent crystals; sample from near top of tuff. Crystals are 7 percent biotite, 4 percent plagioclase, 3 percent potassium feldspar, and 1 percent opaque oxide minerals in a partially devitrified cryptocrystalline matrix of glass shards; accessory apatite, zircon, and quartz. Abundant weakly flattened pumice blocks.
90BSL105	Loma Grande. Eutaxitic dacite ash-flow tuff; about 20 percent crystals; sample from stratigraphically lower (relative to previous sample) position in tuff. Crystals are 7 percent plagioclase, 5 percent variably oxidized biotite, 5 percent potassium feldspar, 2 percent quartz, and 1 percent opaque oxide minerals in partially devitrified cryptocrystalline matrix of glass shards; accessory apatite and zircon. Abundant unflattened pumice blocks.
90BSL106	Loma Grande. Eutaxitic dacite ash-flow tuff with about 20 percent crystals; sample from stratigraphically lower (relative to previous sample) position in tuff. Crystals are 7 percent variably oxidized biotite, 6 percent plagioclase, 5 percent potassium feldspar, 1 percent quartz, and 1 percent opaque oxide minerals in partially devitrified cryptocrystalline matrix of glass shards; accessory apatite and zircon. Abundant unflattened pumice blocks.
90BSL107	Loma Grande. Eutaxitic dacite ash-flow tuff; about 15 percent crystals; sample from near base of tuff represented by previous three samples. Crystals are 5 percent plagioclase, 4 percent biotite, 4 percent potassium feldspar, 1 percent quartz, and 1 percent opaque oxide minerals in partially devitrified cryptocrystalline matrix of glass shards; accessory apatite and zircon. Abundant weakly flattened pumice blocks and some secondary calcite.

Appendix 1. Brief descriptions of unaltered samples collected as part of this study—Continued.

Sample no.	Description
90BDB001	Sica Sica. Dacite porphyry; about 15 percent crystals. Phenocrysts are 10 percent plagioclase, 2 percent oxidized biotite, and 1 percent each of hornblende, quartz, and opaque oxide minerals in cryptocrystalline matrix of devitrified glass; accessory titanite. Redwood and Macintyre (1989) presented a K-Ar (biotite) age of 10.1±0.4 Ma.
90BDB003	Sica Sica. Dacite porphyry; about 10 percent crystals. Weakly trachytically layered phenocrysts are 8 percent plagioclase, 1 percent oxidized biotite, 1 percent quartz, and trace hornblende in cryptocrystalline matrix of devitrified glass. Rock is weakly propylitically altered and contains chlorite. Redwood and Macintyre (1989) presented a K-Ar (biotite) age of 10.1±0.4 Ma.
90BDB004	Viscachani. Dacite porphyry; about 25 percent crystals. Phenocrysts are 15 percent plagioclase as large as 1 cm, 5 percent hornblende, 3 percent biotite, 1 percent embayed quartz, and 1 percent opaque oxide minerals in cryptocrystalline matrix of devitrified glass; accessory titanite and apatite. Redwood and Macintyre (1989) presented a K-Ar (biotite) age of 11.1±0.3 Ma.
90BDB005	Viscachani. Dacite porphyry; about 20 percent crystals. Phenocrysts are 15 percent plagioclase, 4 percent biotite, 1 percent opaque oxide minerals, and trace quartz in cryptocrystalline matrix; accessory titanite and apatite. Secondary calcite. Redwood and Macintyre (1989) presented a K-Ar (biotite) age of 11.1±0.3 Ma.
90BDB006	Viscachani. Andesite porphyry; about 20 percent crystals. Phenocrysts are 15 percent plagioclase, 3 percent oxidized biotite, and 2 percent oxidized hornblende in cryptocrystalline matrix with plagioclase microlites. Secondary epidote. Redwood and Macintyre (1989) presented a K-Ar (biotite) age of 11.1±0.3 Ma.
90BDB007	Viscachani. Dacite porphyry; about 25 percent crystals. Phenocrysts are 15 percent plagioclase, 5 percent biotite, and 4 percent embayed quartz in cryptocrystalline matrix; accessory apatite. Redwood and Macintyre (1989) presented a K-Ar (biotite) age of 12.4±0.4 Ma.
90BDB008	Colquencha. Dacite porphyry; about 30 percent crystals. Phenocrysts are 17 percent plagioclase, 10 percent oxidized biotite, and 3 percent quartz in devitrified cryptocrystalline matrix; accessory apatite. Occasional potassium feldspar phenocrysts as large as 1 cm. Redwood and Macintyre (1989) presented a K-Ar (biotite) age of 16.6±0.4 Ma.
90BDB009	Viscachani. Dacite porphyry; about 25 percent crystals. Phenocrysts are 12 percent plagioclase, 7 percent oxyhornblende, 4 percent biotite, 1 percent opaque oxide minerals, 1 percent quartz, and trace potassium feldspar in devitrified cryptocrystalline matrix with plagioclase microlites; accessory apatite. Phenocrysts are trachytically layered.
90BDB010	Miriquiri. Dacite porphyry; about 20 percent crystals. Phenocrysts are 12 percent plagioclase, 5 percent potassium feldspar, 1 percent biotite, 1 percent opaque oxide minerals, and 1 percent embayed quartz in oxidized devitrified cryptocrystalline matrix.
90BDB011	Comanche. Andesite porphyry. Fine- to medium-grained hypabyssal intrusion with hypidiomorphic granular texture. Phenocrysts are 30 percent strongly zoned plagioclase and 5 percent hornblende in fine-grained matrix of plagioclase, opaque oxide minerals, and hornblende. Accessory titanite and apatite. McBride (1977) presented a K-Ar (biotite) age of 17.9±1.0 Ma.
90BDB012	Viacha. Dacite porphyry; about 15 percent crystals. Phenocrysts are 7 percent plagioclase, 7 percent oxidized biotite, and 1 percent quartz in oxidized devitrified cryptocrystalline matrix with plagioclase microlites. Accessory apatite, zircon, and titanite; occasional potassium feldspar phenocrysts. Redwood and Macintyre (1989) presented a K-Ar (biotite) age of 15.8±0.4 Ma.
90BDB013	Viacha. Columnar-jointed andesite porphyry; about 25 percent crystals. Phenocrysts are 10 percent plagioclase, 10 percent oxidized biotite, 4 percent hornblende, and 1 percent clinopyroxene in devitrified cryptocrystalline matrix with plagioclase microlites. Accessory apatite.
90BES011	La Espanola. Dacitic ash-flow tuff.
90BES012	La Espanola. Andesite lava.
90BES013	La Espanola. Dacite lava.

Appendix 1. Brief descriptions of unaltered samples collected as part of this study—Continued.

Sample no.	Description
90BES031	La Espanola. Andesite lava.
90BES033	Golden Hill. Dacite lava.
90BES035	Golden Hill. Dacite lava.
90BES036	Golden Hill. Andesite lava.

Appendix 2. Brief descriptions of altered samples collected as part of this study.
[Percentages of indicated minerals are estimates made by examination of thin sections]

Sample no.	Description
90BDR001A	Cerro La Joya. Dacite porphyry intrusion. 3–6 percent altered biotite, 2–5 percent saussuritized plagioclase, possibly some altered hornblende, minor opaque oxide minerals, and one large resorbed quartz in cryptocrystalline matrix. Redwood and Macintyre (1989) presented K-Ar (biotite) age of 14.3±0.4 Ma.
90BDR008A	Los Toldos mine. Dacite porphyry intrusion. <5 percent saussuritized plagioclase, 2–3 percent fresh and altered biotite, and 1–2 percent opaque oxide minerals in altered cryptocrystalline matrix. U.S. Geological Survey and Servicio Geologico de Bolivia (1992) presented a K-Ar (biotite) age of 8.5±0.3 Ma for sample 90BR010, a sample collected near 90BR008A.
90BDR008B	Inca mine. Dacite porphyry intrusion. <5 percent saussuritized plagioclase, 3 percent highly altered hornblende, and 1 percent green biotite in altered cryptocrystalline matrix. U.S. Geological Survey and Servicio Geologico de Bolivia (1992) presented a K-Ar (biotite) age of 8.5±0.3 Ma for sample 90BR010, a sample collected near 90BR008B.
90BDR010	Los Toldos mine. Dacite porphyry intrusion. 3–5 percent saussuritized plagioclase, 3–4 percent altered hornblende, 1 percent fresh biotite, and abundant zoisite in cryptocrystalline matrix. U.S. Geological Survey and Servicio Geologico de Bolivia (1992) presented a K-Ar (biotite) age of 8.5±0.3 Ma.
90BDR025	Chocaya mines. Ash-flow tuff.
90BDR030	San Cristobal. Ash-flow tuff. Crystal-rich dacite tuff. 15–20 percent plagioclase, 2–3 percent fresh biotite, 1–2 percent(?) potassium feldspar, 1 percent resorbed quartz, and pumice in glassy matrix. U.S. Geological Survey and Servicio Geologico de Bolivia (1992) presented a K-Ar (biotite) age of 8.0±0.1 Ma.
90BDR031	San Cristobal. Andesite porphyry intrusion. Highly altered; relicts of hornblende and saussuritized plagioclase. U.S. Geological Survey and Servicio Geologico de Bolivia (1992) presented a K-Ar (biotite) age of 8.0±0.1 Ma for sample 90BR030, a sample collected near 90BR031.
90BDR058C	Salvadora mine. Dacite porphyry dome. 1–2 percent quartz; all other phenocrysts (plagioclase, hornblende, ?) completely altered.
90BDR061C	Candelaria mine. Dacite porphyry intrusion. About 1 percent quartz, and highly altered plagioclase, biotite, and hornblende.
90BG022B	Cerro Espiritu Santos, Carangas. Rhyolite clast in hydrothermal breccia. Sparse quartz and sanidine phenocrysts in a white, siliceous groundmass. U.S. Geological Survey and Servicio Geologico de Bolivia (1992) presented a K-Ar (biotite) age of 15.4±0.5 Ma for sample 90BG024, a sample collected near 90BG022B.
90BG024	Cerro Espiritu Santos, Carangas. Rhyolite "dike" (tabular body). Biotite-quartz-sanidine rhyolite; same rock as clasts in breccia (90BG022B). Flow banding parallels dike orientation. U.S. Geological Survey and Servicio Geologico de Bolivia (1992) presented a K-Ar (biotite) age of 15.4±0.5 Ma.
90BPNZ10	Panizos caldera. Altered ash-flow tuff.

Appendix 2. Brief descriptions of altered samples collected as part of this study—Continued.

Sample no.	Description
90BSL002	Kori Kollo. Silicified and sericitized dacite ash-flow tuff; abundant secondary quartz. About 5 percent embayed and broken quartz crystals and some plagioclase pseudomorphs in a weakly eutaxitic matrix; abundant pyrite. Pumice blocks abundant.
90BSL003	Kori Kollo. Silicified dacite ash-flow tuff; about 13 percent crystals. Phenocrysts are 10 percent embayed and broken quartz and 3 percent biotite (altered to sericite) in a eutaxitic matrix. Weakly welded; pumice blocks essentially unflattened.
90BSL005	La Joya. Altered aplite. Very fine grained and flow-banded dike; extensively altered to very fine grained sericite. Redwood and Macintyre (1989) presented K-Ar (biotite) age of 14.3±0.4 Ma.
90BSL010	San Jose. Altered dacite porphyry intrusion; about 15 percent crystals. Phenocrysts are 5 percent completely sericitized feldspar, 5 percent embayed quartz, and 5 percent biotite (completely altered to sericite) in microcrystalline sericitized matrix; abundant pyrite and galena.
90BSL083	Jaquega. Altered flow-laminated dacite porphyry; about 20 percent crystals. Phenocrysts are 10 percent variably oxidized biotite, 4 percent plagioclase, 4 percent hornblende (replaced by hematite and quartz) pseudomorphs, and 2 percent potassium feldspar in devitrified cryptocrystalline matrix; accessory apatite.
90BSL090	Esmoraca. Altered dacite porphyry; about 15 percent crystals. Phenocrysts are 7 percent biotite (altered to chlorite and minor epidote), 5 percent feldspar (mostly altered to sericite), 2 percent opaque oxide minerals and sulfides, and 1 percent rounded quartz in microcrystalline matrix composed of quartz, feldspar, and sericite; accessory apatite and zircon.
90BSL103	Morokho. Altered ash-flow tuff; about 25 percent crystals. Phenocrysts are 10 percent biotite, 9 percent feldspar (mostly replaced by calcite), 5 percent quartz, and 1 percent opaque oxide minerals in devitrified microcrystalline matrix; accessory zircon.
90BES002	El Norteno. Altered volcanic rock.
90BES003	El Norteno. Silicified lava.
90BES005	El Norteno. Silicified volcanic rock.
90BES016	Golden Hill. Silicified lava.

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