



GEOSCIENCES

Chemical classification of common volcanic rocks based on degree of silica saturation and CaO/K₂O ratio

JOÃO O.S. SANTOS & LÉO A. HARTMANN

Abstract: Modal classifications of common volcanic rocks are expensive, difficult, or impossible to attain. As a consequence, these rocks are classified using the chemical composition. However, existing classificatory diagrams are unable to identify all 16 families of common volcanic rocks; the most used is the total alkali-silica (TAS) diagram that identifies six families. Rocks not in the TAS diagram are misclassified with other rock names; their names are evolving to extinction, e.g. latite and rhyodacite. Some diagrams use Na₂O, which is a complicating element rather than discriminant. Na₂O is present both in alkali feldspar and plagioclase making difficult the separation of the amount associated to either feldspar. Silicon, potassium, and calcium are the three major elements with highest variations among volcanic rocks. They are selected for use in two new diagrams confronting CaO/K₂O ratio with K₂O content (KCK diagrams). One diagram is designed for saturated (intermediate) rocks (quartz <5 vol.%) and the other for oversaturated (acid) volcanic rocks (quartz >5%). These diagrams are tested using compositions of volcanic rocks from Uatumã magmatism in the Amazon Craton and also by plotting compositions of rocks from type-localities and the world averages. The proposed limits between rock families agree with plotted rock compositions. The KCK diagrams are an alternative to existing diagrams to classify volcanic rocks.

Key words: Chemical classification, volcanic rocks, silica saturation, Uatumã volcanism.

INTRODUCTION

The classification of volcanic rocks is a challenge where the optical identification of their minerals is often not possible considering the presence of very fine crystals (<0.125 mm) or even glassy matrix. Common volcanic rocks (not including ultrabasic effusive, foidite, lamprophyre, carbonatite, and melilite) are classified and named based on their degree of silica saturation and their proportion of K-feldspar and plagioclase (Shand 1913, Rittmann 1952, Streckeisen 1978). Modal compositions, however, are difficult and expensive to obtain even using modern Scanning Electron Microscopes. In addition, the examined volume in one thin

section is insignificant compared with the volume of the whole rock used in chemical analysis. Another difficulty encountered in modal analyses is the determination of the correct compositional variation of feldspars. Knowing the ratio of perthites in orthoclase, sanidine, or microcline (rare in volcanic rocks) is critical to know the amount of albite (and Na₂O) related to either alkali feldspar or plagioclase. The difficulty increases when sub-microscopic cryptoperthites are present (Brown & Willaime 1974, Yund & Chapple 1980). Volcanic plagioclase typically develops compositional zoning during growth where the core was formed at higher temperature and the rim at lower temperature (Haase et al. 1980). The core has less sodium

(proportion of albite) and more calcium (proportion of anorthite). For example, andesite commonly has plagioclase phenocrysts composed of labradorite core and andesine rim (Gill 1981, Izbekov et al. 2002). Reverse zoning is also a limiting factor by which calcic plagioclase surrounds a sodic core, as in many andesites (Gill 1981, Wada 1985).

Considering these difficulties, modal classifications are often replaced by diagrams based on chemical composition. These classifications are widely used based in several diagrams. Common volcanic rocks are organized in 16 families of rocks: alkali feldspar rhyolite (2), rhyolite (3a), rhyodacite (3b), dacite (4 and 5), quartz alkali feldspar trachyte (6*), alkali feldspar trachyte (6), trachyte (7), quartz trachyte (7*), latite (8), quartz latite (8*), trachyandesite (9), quartz trachyandesite (9*), andesite and basalt (10), quartz andesite and quartz basalt (10*). This naming and numbering are the same as the QAP diagram of Streckeisen (1979), except for quartz andesite and quartz basalt, included by Streckeisen (1979) and IUGS (Le Maitre et al. 2002) in basalt and andesite. These 16 families of rocks have direct correspondence to their plutonic equivalents: e.g. andesite is the volcanic equivalent of diorite and latite is the volcanic equivalent of monzonite. The existing and widely used diagrams of chemical classification of volcanic rocks are unable to identify the 16 major families of common volcanic rocks. They also fail to maintain correspondence between names of volcanic and equivalent plutonic rocks. Some common volcanic rocks are disappearing from the literature and moving to extinction, and this is because the diagrams do not identify the rocks. This is the case of latite and rhyodacite, two major rock types.

Nearly all diagrams based on major elements include sodium or Na_2O (Jensen 1976, Cox et al. 1979, De La Roche et al. 1980, Debon & Lefort

1983, Middlemost 1985). This element (or sodium oxide) is present in either plagioclase or alkali feldspar; sodium complicates the classification rather than clarifying. Using Irvine & Baragar (1971) as an example, all sodium (normative albite) is associated with plagioclase. Some or much Na_2O is actually either in the structure of K-feldspar (perthite) or pure albite. An alkali feldspar rhyolite or rhyolite with either perthite or pure albite is misclassified as dacite.

We propose two new diagrams ($\text{KCK} = \text{CaO}/\text{K}_2\text{O}$ versus K_2O) to classify common volcanic rocks. They are based on several sets of data, including the composition of Uatumã volcanic rocks from the Amazon Craton, rocks from type localities (Tröger 1935), and world averages from Nockolds (1954) and Le Maitre (1976). Chemical data from pyroclastic rocks are not included; they represent about 25 vol.% of Uatumã volcanism. We use older datasets because most published volcanic names after the early 1980's were based on the TAS (Total Alkali-Silica - Cox et al. 1979, Le Bas et al. 1986, Le Maitre et al. 2002) diagram, which recognizes six out of the existing 16 families of volcanic rocks.

MATERIALS AND METHODS

Chemical compositions (major and minor elements) of volcanic rocks from the of Amazon Craton were selected for this study. Analyses and classifications are from the 1970 decade and are pre-TAS as required for our testing. Data are from published and unpublished reports of Brazilian Government institutions (Table I). A large number ($n = 218$) of analyses (Table II) were selected from samples of calc-alkaline volcanic rocks related to the Uatumã Supergroup (Albuquerque 1922, Ferreira 1959, Ramgrab & Santos 1974, Santos 1984).

Analyses in Table I were performed at the Laboratory of Chemical Analyses of Minerals and Rocks of Geosciences Institute of UFRGS (Federal University of Rio Grande do Sul, Porto Alegre, Brazil) and in LAMIN (Mineralogical Laboratory of CPRM, Rio de Janeiro, Brazil).

Sample preparation and data processing

Several procedures are suggested in the classification of volcanic rocks. These steps or most of them are useful for classifications. The adopted sequence of procedures in this study is the following:

- Select fresh and representative samples;
- Avoid samples with veins, xenoliths, and hydrothermal minerals;
- Observe thin sections for mineralogy and texture of the rock;
- Perform chemical analyses of major and trace elements, including H₂O, SO₂ and CO₂;
- Only select data with totals ranging from 98% to 102%. Normalize to 100 wt.%;
- Correct the Fe₂O₃/FeO ratio following Coombs (1963) and Chayes (1966);
- Calculate the normative composition (CIPW, Cross et al. 1902);
- Separate normative olivine- and nepheline-rich rocks (ultrabasic and alkaline);
- Calculate the NCI (Normative Colour Index: $hy+di+ol+mt+il+hm$);
- Calculate the NPC (Normative Plagioclase Composition): $[100An / (An+Ab+5/3Ne)]$;
- Plot the NPC (Normative Composition of Plagioclase versus the NCI (Normative Colour Index, Irvine & Baragar 1971) to separate basaltic from andesitic rocks;
- Group the data other than basalt in three sets according to their normative quartz (0-5 vol.%, saturated; 5-20%, moderately oversaturated and >20%, oversaturated). Rocks with Nqtz = zero and having normative

Table I. Sources of chemical analysis of volcanic rocks, from government reports.

Source	Project	Location	Unit	Age-Ma	n	reference	
DNPM-RADAM	RADAM	NA.20-NB.20	Surumu	1985	10	34	Montalvão et al. (1975)
		SA.21	Iricoumé	1860	14		Araújo et al. (1976)
		NA.21	Surumu	1985	10		Oliveira et al. (1975)
DNPM-CPRM	Jamanxim	SB.21-X-C	Iri	1870	12	58	Pessoa et al. (1977)
	Sulfetos Uatumã	SA.21-V	Iricoumé	1860	28		Veiga Jr et al. (1979)
	Molibdênio Roraima	NB.20-Z-D	Surumu	1985	12		Melo et al. (1978)
	Tajajós-Sucunduri	SB.20-Z SB.21-Y	Iri	1870	6		Bizzinella et al. (1980)
SUDAM-GEOMITEC	Tapajós-Maués	SB.21	Iri	1870	6	126	SUDAM-GEOMITEC (1976)
	Tapajós-Jamanxim	SB.21-X-C	Iri	1870	55		SUDAM-GEOMINERAÇÃO (1972)
			Iri	1870	65		SUDAM-GEOMITEC (1972)

DNPM=National Department of Mineral Production. RADAM=Radar in the Amazon. CPRM=Brazilian Geological Survey. SUDAM=Superintendence for the Amazon Development. GEOMITEC=Geologia e Mineração, Trabalhos Técnicos Ltda. Reports are available at: <http://geosgb.cprm.gov.br/> (CPRM); <https://biblioteca.ibge.gov.br/> (RADAM); and <http://www.sudam.gov.br/> (SUDAM).

nepheline are undersaturated, not present in Uatumã volcanism.

- m) Plot the data on the two $K_2O \times CaO/K_2O$ diagrams, one designed for oversaturated (acid) and the other for saturated (intermediate) rocks.

GEOLOGICAL CONTEXT

The Amazon Craton is the largest craton of South America (Fig. 1) with 5,200,000 km² (Santos 2003). To the west, southwest and northwest the craton is limited by the Phanerozoic Andean Belt. To the east and southeast the craton is bordered by collisional belts of the Brazilian Orogen (dominantly Ediacaran). The Amazon Craton is partially covered by extensive Phanerozoic basins, particularly in the west. The craton is organized in seven main provinces (Santos 2003) where Carajás is Archean, Sunsás is Mesoproterozoic, and five (Rio Negro, Rondônia-Juruena, Tapajós-Parima, Trans-Amazon, and Central Amazon) are Paleoproterozoic (Fig. 1).

The Uatumã calc-alkaline volcanism was generated during the Orosirian as the most extensive volcanic tract in South America. Successive Andean-type magmatic arcs are present within the Tapajós-Parima Province (2030-1880 Ma; Santos et al. 2004) covering part of northern Brazil (Amazonas, Pará and Roraima States), southeastern Venezuela (Cuchivero Group and Caicara Formation; Rios 1972), SW Guyana (Burro-Burro and Kuyuwini Groups, Berrangé 1977), and West Suriname (Dalbana Formation; Bosma et al. 1983). The sampled volcanic rocks correspond to three formations: Surumu (NE Roraima State of Brazil, SE Venezuela, W Guyana), Iricoumé (SE Roraima, NW Pará, NE Amazonas states of Brazil), and Iriri (SE Amazon and west Pará states) formed at 1985-1860 Ma (Fig. 1). Two units previously included in the Uatumã magmatism (Ramgrab & Santos 1974, Santos 1984) are not part of this study. The Sobreiro Formation of Carajás Province is older (Rhyacian to Siderian; Vasquez & Costa 2008) and the Colíder Group (Tarelow Neto et al. 2017) from the Rondônia-Juruena Province is younger,

Table II. Major elements of Uatumã volcanic rocks.

	group	n	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	K ₂ O	TiO ₂	P ₂ O ₅	H ₂ O	Total
Supersaturated NQz = >20%	quartz-rich rhyolitoid	4	80.35	11.40	1.44	0.86	0.07	0.22	0.28	1.23	3.33	0.18	n.a.	n.a.	99.36
	AF rhyolite	15	72.84	13.21	1.26	1.82	0.09	0.33	0.19	3.26	5.72	0.53	0.07	0.13	99.45
	Rhyolite	34	72.34	13.25	1.77	1.03	0.09	0.35	0.89	3.96	4.89	0.27	0.15	0.24	99.23
	Rhyodacite	43	68.88	15.71	2.17	1.14	0.09	0.77	1.89	3.88	3.88	0.41	0.22	0.11	99.15
	Dacite	27	66.65	16.12	2.92	1.61	0.10	1.48	3.33	3.65	2.75	0.50	0.12	0.10	99.33
NQz = 5-20%	Quartz AF trachyte	6	68.16	14.52	1.22	2.17	0.11	0.65	0.90	3.84	6.66	0.55	0.21	0.15	99.14
	Quartz trachyte	11	67.51	15.32	1.32	3.08	0.17	0.79	1.58	4.10	5.28	0.47	0.11	0.13	99.86
	Quartz latite	14	65.05	15.44	2.28	2.32	0.13	1.58	3.11	4.12	3.75	0.44	0.23	0.24	98.69
Saturated NQz = 0-5%	AF trachyte	8	65.97	14.46	0.77	2.84	0.18	1.11	1.66	4.75	6.40	0.63	0.13	0.14	99.04
	Trachyte	17	63.01	15.89	1.10	3.86	0.17	2.35	2.83	3.76	4.92	0.43	0.19	0.28	98.79
	Latite	19	59.32	16.20	4.59	3.08	0.17	2.87	4.28	3.64	3.87	0.78	0.24	0.28	99.32
	Andesite	21	55.13	16.80	3.63	5.35	0.19	4.22	6.11	3.73	2.19	0.44	0.21	0.15	98.15

n=number of analysis; AF=Alkali Feldspar; n.a.=not analysed.

Statherian, 1760-1780 Ma (Barros et al. 2009) than Uatumã.

RESULTS

The degree of silica saturation

The fundamental classification concept is the determination of the amount of free silica or feldspathoid in the rock. To circumvent the difficulty and cost of determining quartz (eventually tridymite or chalcedony), we choose the effectiveness of using normative quartz (Nqtz) in place of modal quartz (Mqtz). We compared both attributes from classical type localities of volcanic rocks and of plutonic rocks (Fig. 2 and Table III). The chemical and modal compositions of the rocks are from Tröger (1935) whereas the normative compositions are here calculated from the chemical data of Tröger (1935).

Figure 2 displays positive correlation between modal and normative quartz allowing the use of normative values of quartz to determine the degree of silica saturation of volcanic rocks. Following Shand (1913) and Rittmann (1952), rocks are oversaturated that have excess of SiO_2 over the other oxides, generating either silica minerals in the mode or quartz in the norm. Saturated volcanic rocks are neither oversaturated nor undersaturated with respect to silica, i.e., they have small amounts of either silica minerals or feldspathoids in the mode or norm. Undersaturated rocks with respect to silica, i.e. lack quartz and have feldspathoid (foid) or Mg-olivine in the mode or norm. The fundamental concept of silica saturation and the understanding of the subdivision of acid, intermediate, basic, and ultrabasic rocks was misinterpreted by the IUGS (International Union for Geological Sciences) who supported the use

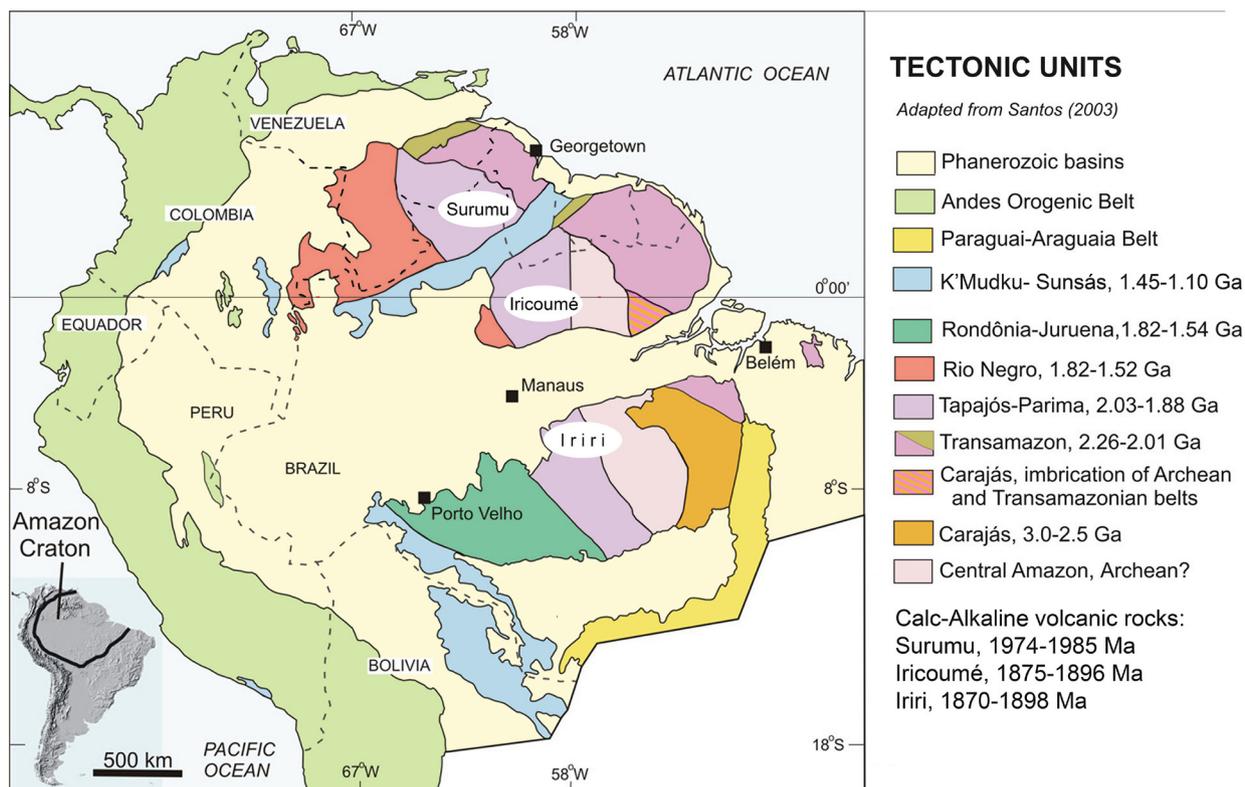


Figure 1. The Amazon Craton in Northern South America subdivided into provinces (Santos 2003). Volcanic rocks of this study are from the Tapajós-Parima Province (2030-1880 Ma) - Surumu, Iricoumé, and Iriri Groups.

of the TAS diagram. Le Bas et al. (1986) and Le Maitre et al. (2002), based on Cox et al. (1979), assumed that the degree of silica saturation is determined by the content of SiO₂ of the rock. But the controls are different. The book “Igneous Rocks” by Le Maitre et al. (2002) empirically defined (pages 49, 52, and 93) that an acid rock has more than 63 wt.% SiO₂; an intermediate rock has between 52% and 63% SiO₂, a basic rock has less than 52% SiO₂ and more than 45% SiO₂, and finally, an ultrabasic rock has < 45% SiO₂. However, the names acid, intermediate, basic, and ultrabasic, by definition (Shand 1913), are related to the degree of SiO₂ saturation and not to the SiO₂ content.

Some examples of misclassification using the content of SiO₂ to separate the four major groups of rocks are the following:

- Olivine-rich basalts, composed by olivine (29.5-42.7% SiO₂), clinopyroxene (48% SiO₂), and bytownite (48% SiO₂) may have SiO₂ < 45% (see alkalic olivine basalt from Hawaii, sample C168 of MacDonald 1968). They are basic, not ultrabasic rocks.
- Lherzolites may have more than 45 wt.% SiO₂ (McDonough & Rudnick 1998; Table

1, p. 145) and they are not basic, but ultrabasic rocks.

- Peridotites may have more SiO₂ than 45% (McDonough & Rudnick 1998; their Table 9, page 155), and are ultrabasic, not basic rocks.
- Basalts may have more than 52% SiO₂ and they are not intermediate rocks, but basic. See samples 11, 21, 40, 41, and 42 of Jensen (1976), Tables 1-2, pages 18-19.
- Trachyandesites, which are intermediate rocks, may have less than 45% silica and they are not ultrabasic rocks. See sample C183 from MacDonald (1968), Table 5, page 496.
- Hawaiiites, which are alkalic andesites, are intermediate rocks, and have average of 47.9% SiO₂ (MacDonald, 1968, Table 8, page 502; Nekvasil et al. 2004, Table 1). Using the TAS diagram hawaiiite would be basic, not intermediate rock.
- Trachytes are formed by alkali feldspar (65-67 wt.% SiO₂) and commonly have more than 63 wt.% SiO₂ (e.g. Sial et al. 1987, Renzului et al. 2002, Nekvasil et al. 2004, Hagos et al. 2010, Martel et al. 2013). Also,

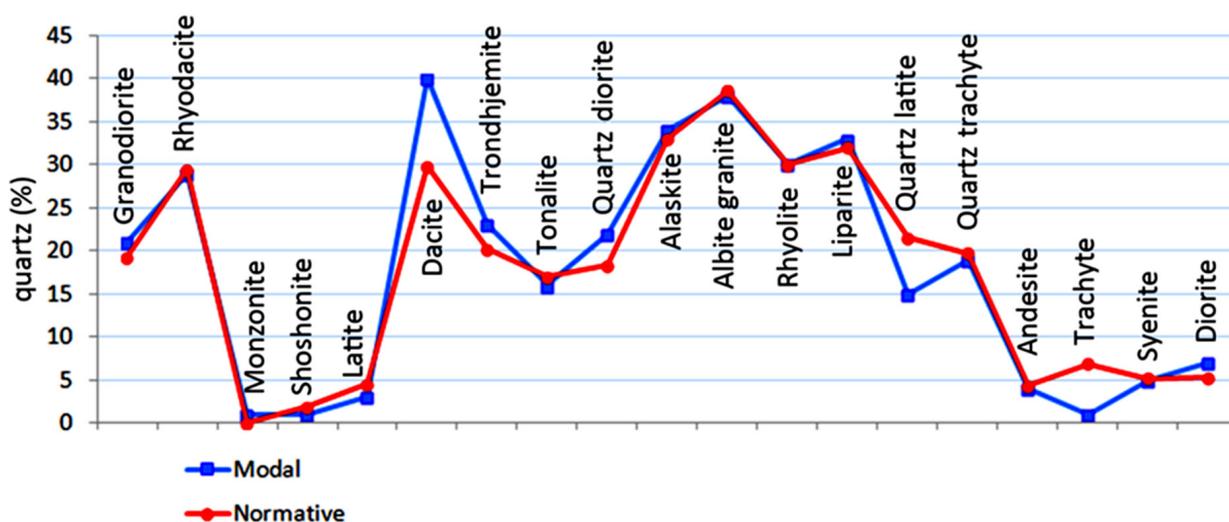


Figure 2. Modal and normative amount (vol.%) of quartz in rocks from type localities. Chemical and modal compositions from Tröger (1935). Normative compositions as calculated in this work.

the upper limit of SiO₂ for intermediate rocks of Cox et al. (1979) in the TAS diagram is high (69 wt.%) representing the presence of quartz (modal and normative) above 5 vol.%, therefore quartz trachytes, which are not intermediate, but acid rocks. This positions most trachytes as acid rocks instead of intermediate rocks.

- Clinopyroxenite, websterite, and particularly orthopyroxenite have >45 wt.% SiO₂ (e.g., Mukasa & Shervais 1999,

Maaløe 2005) and may have >52% SiO₂ (e.g. Ahmadipour et al. 2003, Anbarasu et al. 2011, Maier et al. 2015). However, they are neither intermediate nor basic rocks, but ultrabasic.

- Hornblendites, composed by >90 vol.% hornblende (hornblende has 51 wt.% SiO₂) may have >45 wt.% SiO₂ (e.g. Holub, 2004, Mendes et al. 2004) and they are not basic rocks, but ultrabasic.

Table III. Comparison of Modal and Normative quartz of magmatic rocks from type localities.

Rock	Type locality	Mqtz %	Nqtz %
Alaskite	South Alaska, USA	34	33.08
Albite-granite	Lapland, Sweden	38	38.61
Diorite	West Finland	7	5.31
Farsundite	South Norway	25	30.74
Granodiorite	NW Sacramento, California	21	19.3
Monzonite	South Tirol, Germany	1	0.00
Opdalite	Trondhjem, Norway	16	12.86
Quartz diorite	Yellowstone, USA	22	18.28
Syenite	Dresden, Germany	5	5.19
Tonalite	South Tirol, Germany	16	17.03
Trondhjemite	Trondhjem, Norway	23	20.15
Andesite	Catamarca, Argentina	4	4.31
Basalt	Dresden, Germany	0	2.41
Basanite	Bohemian Mountains, Czech Republic	0	0.00
Dacite	Romenia	40	29.82
Dellenite	Halsingland, Sweden	glassy	23.58
Latite	SW Rome, Italy	3	4.48
Liparite	Lipari Island, Italy	33	32.02
Phonolite	Bohemian Mountains, Czech Republic	0	0.00
Quartz latite	SW Nevada, USA	15	21.47
Quartz trachyte	SW Colorado, USA	19	19.76
Rhyodacite	Marysville, Australia	29	29.41
Rhyolite	North Flagstaff, Arizona, USA	30	30.00
Shoshonite	Yellowstone, USA	1	1.82
Trachyte	SE of Bonn, Germany	1	6.87

Modal quartz (Mqtz) from Tröger (1935). Normative quartz (Nqtz) from this work.

The degree of silica saturation depends on the mineralogical composition of the rock. Some rock forming minerals contain higher and others lower SiO₂ (Table IV). From this table, for example, an ultrabasic rock composed by dominant orthopyroxene (52-60% wt. SiO₂) will have >52% SiO₂ and would be erroneously classified as an intermediate rock using the TAS diagram.

The separation of ultrabasic and basic rocks

The limit between ultrabasic and basic rocks was placed at 45 wt.% SiO₂ (Le Bas et al. 1986). However, SiO₂ is not a discriminant oxide because there are basic rocks with less than 45% SiO₂ (MacDonald 1968) and ultrabasic rocks with more than 45% SiO₂ (McDonough & Rudnick 1998). Pyroxene-rich rocks such as lherzolite, harzburgite, wehrlite, and websterite have dominantly SiO₂ content >45 wt.%. This is

because pyroxenes (clino- and ortho-) have 54-60 wt.% SiO₂ (Table IV).

Is the mantle formed by basic or ultrabasic rocks? Seven models for mantle composition have more than 45% silica (Table V). According to the 45% SiO₂ upper limit for ultrabasic rocks (Cox et al. 1979, Le Bas et al. 1986) Earth's mantle would be composed by basic rocks.

This is sufficient reason to abandon the use of silica content alone to separate ultrabasic from basic rocks. Al, Ca, and Mg are more important major elements than Si to separate basic and ultrabasic rocks. Ultrabasic rocks are characterized by absence of free SiO₂ (Mqtz or Nqtz), high MgO content (>20%), plus low amounts of plagioclase (up to 10 vol.%), Al₂O₃ (<12%), and CaO (<12%). Most ultrabasic rocks are coarse grained and classified according to their mineralogical composition (modal classification). Fine-grained ultrabasic lavas are present in Archean (e.g. Sun & Nesbit 1978) and Paleoproterozoic (Nalivkina 2012, Park 2015) greenstone belts. A chemical approach may be necessary to separate these lavas from basalts considering that ultrabasic rocks have less calcium and aluminium, and more magnesium than basalts. Jensen's (1976) Fe-Ti/Al/Mg cation diagram is useful in spite of lack of calcium.

The classification of Irvine & Baragar (1971)

Some chemical approaches were proposed in the past to classify volcanic rocks where the possible best example is the system of Irvine & Baragar (1971) based on the normative composition (CIPW) and normative colour index of rocks. However, the normative composition-based classifications failed because they are incapable to perform an accurate distribution of the normative Ab between alkali feldspar and plagioclase. Albite (modal) is alkali feldspar commonly present in many felsic volcanic rocks as individual grains or as perthite intergrowths

Table IV. SiO₂ content of rock-forming minerals.

Mineral	SiO ₂ % (%)
Olivine (fayalite)	29.50
Olivine (forsterite)	42.70
Plagioclase (anorthite)	44.40
Amphibole (Fe-hornblende)	44.50
Clinopyroxene (augite)	48.00
Amphibole (Mg-hornblende)	51.00
Orthopyroxene (hypersthene)	52.00
Plagioclase (labradorite)	53.00
Clinopyroxene (pigeonite)	54.70
Clinopyroxene (diopside)	55.50
Plagioclase (andesine)	58.00
Orthopyroxene (enstatite)	60.00
Plagioclase (oligoclase)	63.50
Alkali feldspar (orthoclase)	65.00
Alkali feldspar (albite)	67.00
Alkali feldspar (anorthoclase)	67.70

Source: IMA (International Mineralogical Association). <https://www.ima-mineralogy.org>.

Table V. SiO₂ content of Earth's mantle.

Model	CI Chondrite	CI LOSIMAG	PYROLITE	PRIMA		CI Carb Chondrite	PYROLITE
Source	Hart & Zindler (1986)	Hart & Zindler (1986)	McDonough & Sun (1995)	Allègre et al. (1995)	Jagoutz et al. (1979)	Taylor & McLennan (1985)	Ringwood (1979)
SiO ₂	49.52	45.96	45.00	46.52	45.15	49.9	45.1

in K-feldspar (orthoclase, sanidine, rarely microcline). Albite also occurs as solid solution with sanidine in high- temperature alkalic volcanic rocks forming anorthoclase (Deer et al. 2013), which is dominated by albite (Na 64-90%) molecules over sanidine (K 10-36%; Deer et al. 2013). This feldspar is confined to volcanic, not plutonic rocks (Gill 2010) being more common in trachytes, alkali trachytes (e.g. Johnson et al. 1989, Gill 2010), and alkali rhyolites (e.g. Coats et al. 1968). Alkali feldspar trachyte with anorthoclase may have up to 10 vol.% Na-plagioclase (albite, oligoclase) and anorthoclase-bearing trachyte may have up to 30% Na-plagioclase. How to distribute the amount of Na₂O from the chemical analysis between plagioclase and anorthoclase? The diagram of Irvine & Baragar (1971, their Figure 11) allocated all Na₂O (normative albite) to plagioclase lowering the actual NCP-Normative Composition of Plagioclase. These attributes show that the amount of analysed Na₂O of a volcanic rock may be originated either from plagioclase or from alkali feldspar. Because Na₂O is present in two different and alternative minerals used for rock classification (plagioclase and alkali feldspar), the Na₂O content and the modal and normative albite generate questionable results when used in classificatory diagrams. The common procedure of summing up Ab and An in normative analyses to establish the value of P (plagioclase) produces imprecise

results by exaggerating total P (see Irvine & Baragar 1971, Fig. 7, p. 538).

Irvine & Baragar (1971) adequately classify rocks with remarkably high or low feldspar ratios (P/K). Plagioclase-rich rocks (andesites and basalts) and alkali feldspar-rich rocks (rhyolites [*stricto sensu*] and trachytes) are adequately classified. However, the majority of common volcanic rocks (those between plagioclase-rich and alkali feldspar-rich rocks) may have albite distributed in the two feldspars (plagioclase and K-feldspar). Rhyolite may be misclassified as dacite whereas latite may be misclassified as andesite (see Fig. 7 of Irvine & Baragar 1971). The NCI x NCP diagrams only classify 5 (plus 1 subfamily, icelandite) of the 16 families of common volcanic rocks, see Fig. 3 (for rhyolite, dacite, andesite, and basalt) and Fig. 11 of Irvine & Baragar (1971) for trachyte.

The NCI x NCP diagram is useful to discriminate basalt and andesite. The NCI x NCP diagram passed in the test made with andesites. Andesites from the type-locality and andesite averages plot within the field of andesite. Another test using quartz basalt and quartz andesite from the Eastern Carpathians in Romania (data from Jurje et al. 2014) separates the two groups of rocks (Fig. 3).

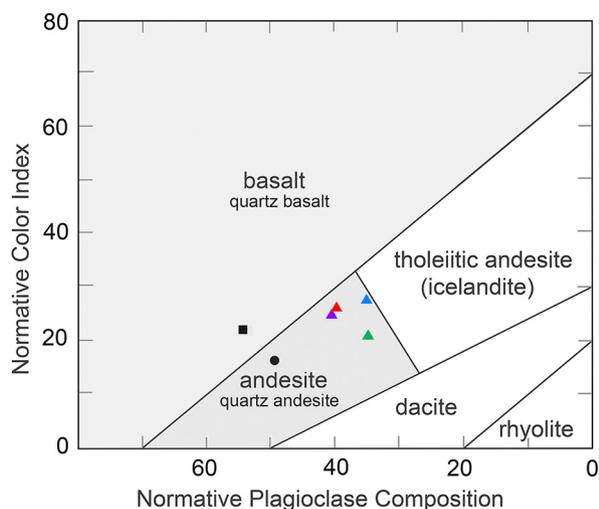


Figure 3. Reproduction of Figure 7 of Irvine & Baragar (1971), recommended for separation of basalt + quartz basalt from andesite + quartz andesite based on the normative plagioclase composition and normative colour index. Also, useful to identify tholeiitic andesites (icelandites), which have lower NPC and higher NCI compared to calc-alkaline andesites. Triangles symbology: red, Uatumã andesites (Santos 2012); purple, andesite type-locality, La Hoyada, Catamarca, Argentina (Becke 1899, from Tröger 1935); blue, andesite world average (n=49; Nockolds 1954), and green, andesite world average (n=2600; Le Maitre 1976); ● = average of five quartz andesites from Eastern Carpathians, Romania; ■ = average of 20 quartz basalts (data from Jurje et al. 2014); NPC=[100An/(An+Ab+5/3Ne)]; NCI=di+hem+hy+ilm+mag+ol.

Reinstating the names quartz andesite and quartz basalt

Our classification keeps the names quartz andesite and quartz basalt (see Fig. 4), which are rocks moderately oversaturated in SiO₂, with 5-20% Nqtz and less than 10% alkali feldspar. Separation between quartz andesite and quartz basalt is made using NCI (Normative Colour Index) and NPC (normative plagioclase composition) indexes. Rocks with NPC <50% (normative andesine) are quartz andesites and rocks with NPC >50% (normative labradorite or bytownite) are quartz basalts, following the Irvine & Baragar (1971) proposition to discriminate andesite and basalt (Fig. 3). This disagrees with

the TAS classification where these names are omitted and included as basalt and andesite. The TAS diagram (Fig. 2.11, p. 31 of Le Maitre et al. 2002) even extended the field of basalt and andesite to 20% quartz. The result is that basalt (a basic rock by definition) and andesite (an intermediate rock by definition) may be acid rocks with up to 20% quartz. So, according to IUGS, basalt is no longer an exclusively basic rock, but includes acid rocks. We reaffirm the use of quartz andesite and quartz basalt as used by researchers such as Turner (1895), Bartrum (1937), Bowen (1954), Rittmann (1952, 1973), Negendank (1973), Allen (1986), Zhigang (1990), Potts & West (2000), Berbeleac et al. (2004), Huang et al. (2012), Santos (2012), and Jurje et al. (2014). The names of basalt and andesite are restricted here for rocks with up to 5% Mqtz or 5% Nqtz following worldwide pre-TAS understanding.

Testing the TAS diagram

There are 16 major families of volcanic rocks that are neither ultrabasic nor feldspathoid-bearing: basalt, quartz basalt, andesite, quartz andesite, trachyandesite, quartz trachyandesite, latite, quartz latite, trachyte, quartz trachyte, alkali feldspar quartz trachyte, alkali feldspar trachyte, dacite, rhyodacite, rhyolite, and alkali feldspar rhyolite. These are shown in QAP (Quartz-Alkali feldspar-Plagioclase) diagram of Fig. 4 (adapted from Streckeisen 1978). Here the volcanic equivalent for the plutonic rocks of 60-90 vol.% quartz (quartz-rich granitoid) has a suggested name of "quartz-rich rhyolitoid" (Field 1 of Fig. 4).

The alkali versus silica diagram was not designed to classify rocks, but to discriminate between either alkaline or tholeiitic suites of volcanic rocks (MacDonald & Katsura 1964, Fig. 1, p. 87; MacDonald 1968, Fig. 7, p. 514) or alkaline and subalkaline rocks (Irvine & Baragar 1971; Fig. 3, p. 532). A single diagram using K, Na, and Si is unable to classify common magmatic rocks

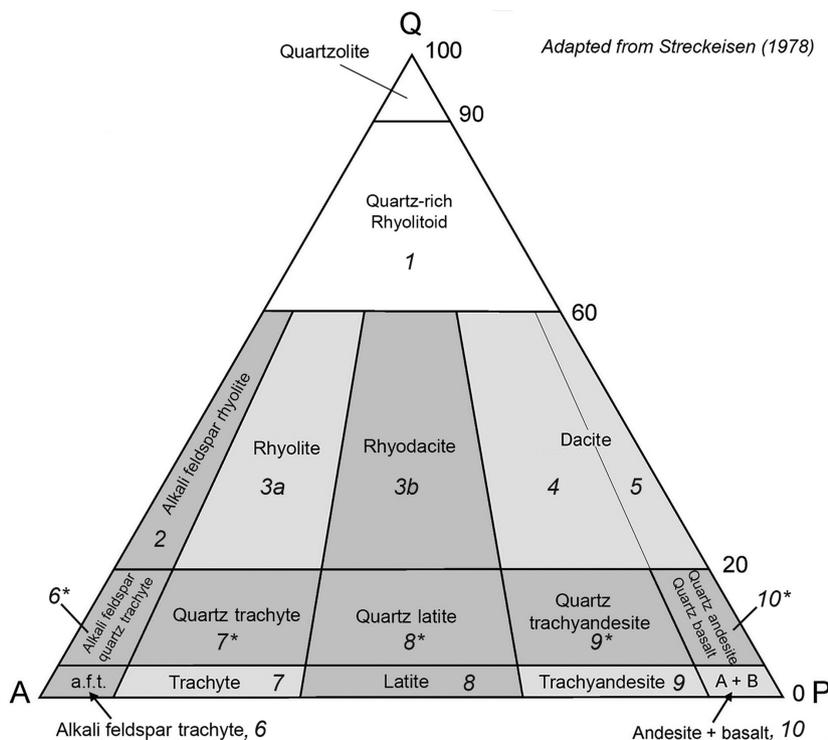


Figure 4. Q (Quartz) – A (Alkali feldspar) – P (Plagioclase) diagram adapted from Streckeisen (1978) with 16 major families of common volcanic rocks. The TAS diagram is able to classify six of them (light grey) and unable to classify 10 of them (dark grey). Name of quartz-rich rhyolitoid (1) is here introduced in analogy of quartz-rich granitoid for plutonic rocks (Streckeisen 1976).

because one mandatory element is missing, and this is calcium. The TAS diagram was tested by plotting rock data from the Amazon Craton, from classic world average compositions (Nockolds 1954 and Le Maitre 1976) and from type-localities (Tröger 1935) – Fig. 5.

The original TAS diagram of Cox et al. (1979), modified by Le Bas et al. (1986) is able to classify 6 of the existing 16 families of common volcanic rocks. The main problem is that the ten missing families are misclassified among the other six families. The following is a list of the main misclassifications:

- All latites are misclassified as andesite, trachyandesite, or as basaltic trachyandesite.
- Most of andesites plot outside the field “andesite”. They are misclassified as basaltic trachyandesite, trachyandesite, and basaltic andesite.
- All quartz latites are misclassified as dacite or trachyte.

- All quartz trachytes are misclassified as trachyte.
- Some trachytes are misclassified as trachyandesite.
- All rhyodacites (arguably the most common felsic volcanic rock on Earth) are misclassified as rhyolite and dacite.
- All dellenites are misclassified as rhyolite.
- Alkali feldspar trachytes are misclassified as trachyte and rhyolite.
- Alkali feldspar rhyolite is misclassified as rhyolite.

The classification of magmatic rocks should maintain the worldwide- accepted correlation between the names of plutonic and volcanic rocks that have similar chemical and modal compositions. For example, the volcanic equivalent of diorite is andesite; latite corresponds to monzonite. This equivalency is lost in the TAS misclassification because most volcanic names lose their correlation with plutonic equivalents. Examples in the TAS diagram:

- The plutonic correspondent of monzonite is andesite (instead of latite).
- The volcanic correspondent of monzogranite is dacite (instead of rhyodacite).
- The plutonic correspondent of quartz trachyte is granite (instead of quartz syenite).

- The volcanic equivalent of quartz monzonite is dacite (instead of quartz latite).

In sum, the Le Bas et al. (1986) – modified from Cox et al. (1979) – diagram generates (generic) classifications of volcanic rocks. This procedure is leading to the artificial extinction of several existing families, some of them among the most common felsic volcanic rocks on Earth such as rhyodacite and latite.

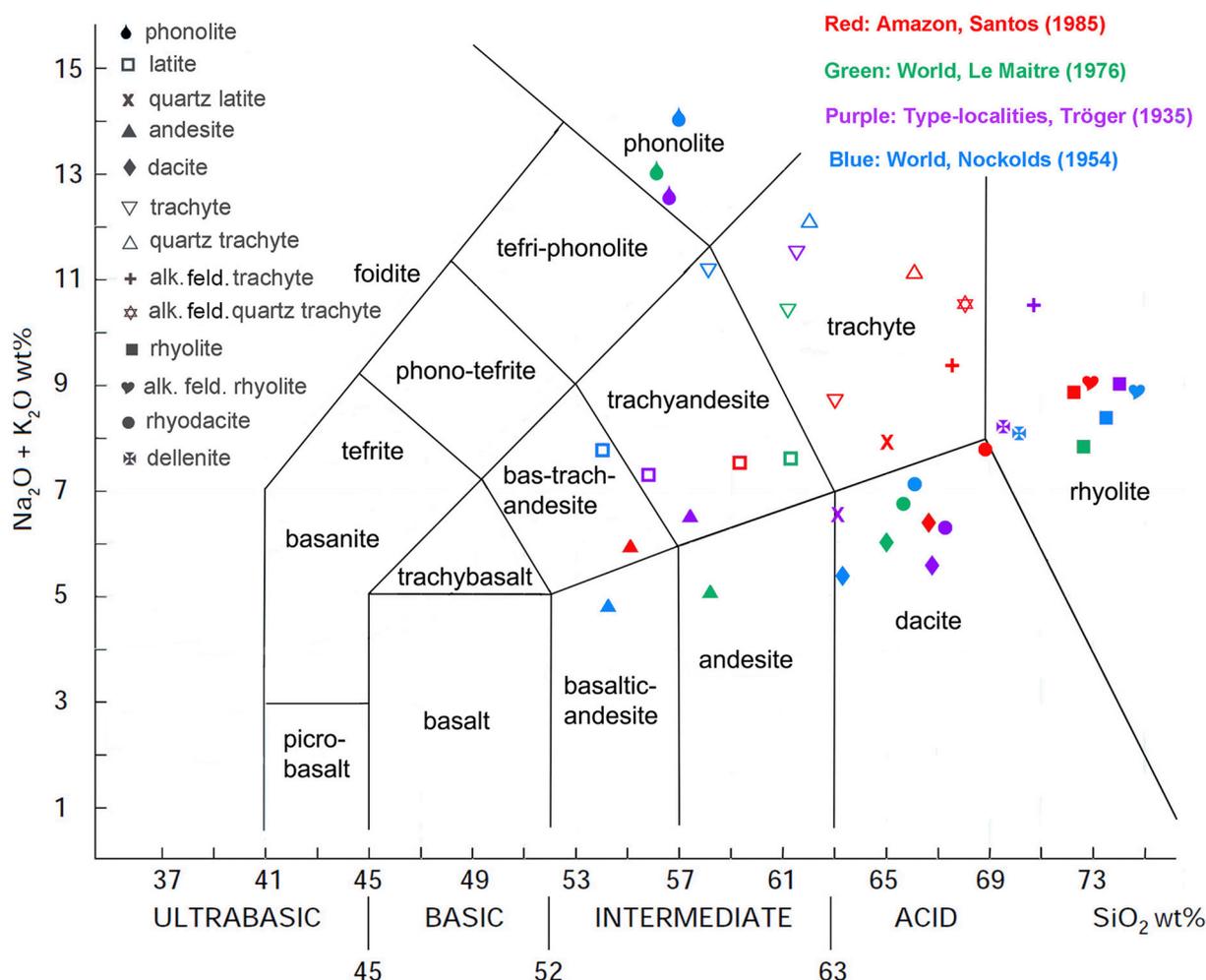


Figure 5. Test of TAS (Total Alkali-Silica) diagram (Le Maitre et al. 2002) to classify rocks from type localities (Tröger 1935), from the Amazon Craton (Santos 1985), and world average compositions (Nockolds 1954, Le Maitre 1976). Data are from Amazon (red), type-localities (purple) and world average compositions (green = Le Maitre 1976; blue = Nockolds 1954). Symbols for rock names are in upper left corner. The result of this plot indicates several misclassifications as summarized in the text. The SiO_2 -based incorrect limits between ultrabasic-basic (45 %), basic-intermediate (52 %), and intermediate-acid (63 %) rocks also shown.

The KCK Classification (CaO/K₂O versus K₂O)

The KCK diagrams are simple, robust, and capable of classifying all 16 families of common volcanic rocks. The diagrams use the three major elements with the largest variation among volcanic rocks (Si-K-Ca), from less- to more- evolved types. Here we plot the CaO/K₂O ratio against the K₂O content where CaO reflects the plagioclase content and K₂O reflects the K-feldspar content. Of the two diagrams, one is for saturated (intermediate) rocks and the other for oversaturated (acid) rocks. The diagrams display the compositions of 218 volcanic rocks from the Amazon Craton combined with compositions of other rocks from known localities, world averages, and type-localities. Compositions from type localities and world averages are used to test the proposed limits among types of rocks.

The proposed classification of volcanic rocks is based on two major parameters:

a) Degree of silica saturation (Shand 1913) – four groups are defined (limits of degrees of saturation are from Shand 1913, Rittmann 1952, Streckeisen 1976):

- Qtz = 0-5 vol.% (saturated rocks)

- Qtz = 5-20% (moderately oversaturated rocks)
- Qtz = 20-60% (oversaturated rocks)
- Qtz = 0%, either normative olivine or feldspathoid = 0-5% (undersaturated)

The undersaturated rocks are basic-ultrabasic and feldspathoid-bearing alkaline rocks; the saturated are named intermediate rocks and the oversaturated acid rocks following Shand (1947) and Yoder & Tilley (1962). We reinforce that the degree of silica saturation is not measured by the SiO₂ content of the rock but by the presence or absence of modal or normative quartz, feldspathoid, or olivine.

b) The feldspar ratio (proportion between plagioclase and alkali feldspar); five groups are recognized:

- Plagioclase-rich rocks (alkali feldspar is <10 vol.%): andesite, quartz andesite, dacite.
- Alkali feldspar-rich rocks (plagioclase is <10%): alkali feldspar rhyolite, quartz alkali feldspar trachyte and alkali feldspar trachyte.
- Rocks dominated by plagioclase (plagioclase >2/3 of feldspars): andesite,

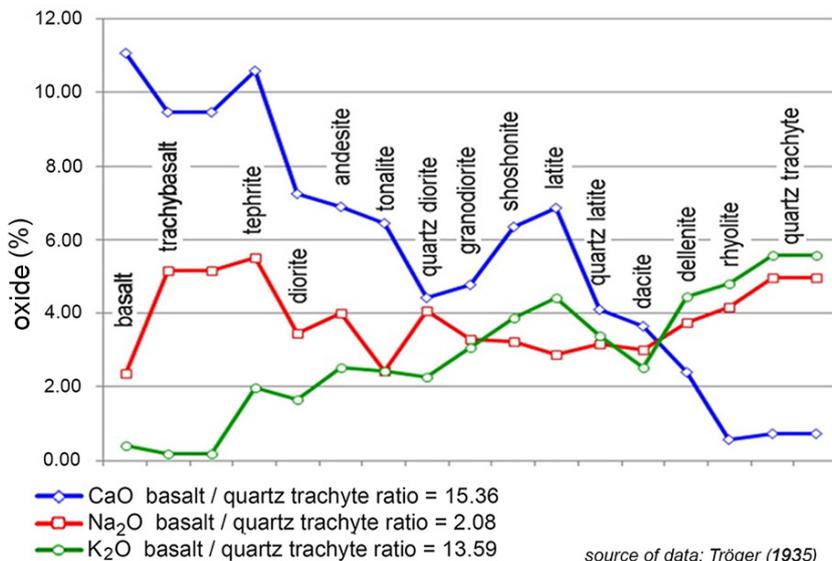
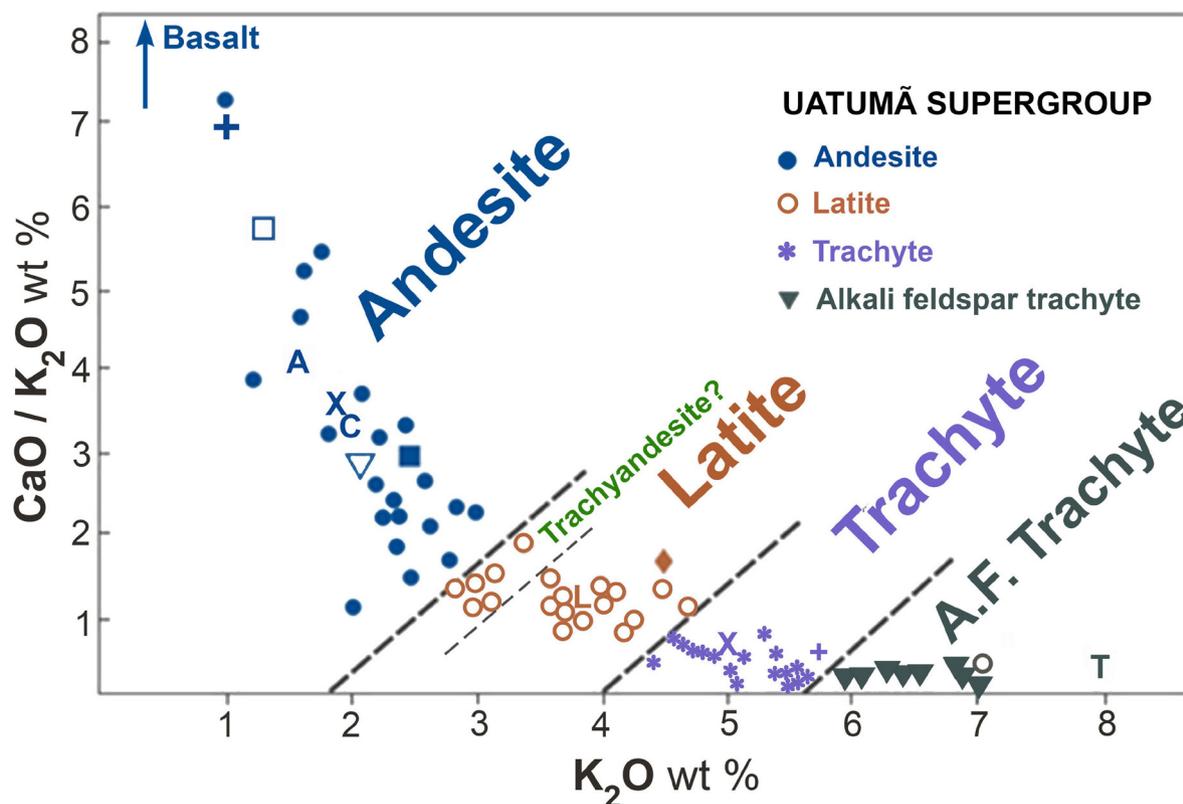


Figure 6. Distribution of Na₂O, CaO, and K₂O of magmatic rocks from less evolved on the left to more evolved on the right. Data from type-localities from Tröger (1935).

- quartz andesite, dacite, basalt, quartz basalt.
- Rocks dominated by alkali feldspar (alkali feldspar >2/3 of feldspars): rhyolite, quartz trachyte, and trachyte.

- Rocks with ± equivalent content (plagioclase and alkali feldspar between 1/3 and 2/3): rhyodacite, quartz latite, latite.

Considering the chemical variations of K₂O, CaO, and Na₂O (Fig. 6) of 17 rock-types, from less



- + 15 andesites, Mount Pelée, Martinica, Roobol & Schmit (1978)
- A 2600 andesites, Le Maitre (1976)
- X 10 andesites, Andes, Gunn et al. (1974)
- C Andesites, Cascades, USA, Irvine & Baragar (1971)
- Andesites, Fidji, Jakes & White (1972)
- ▽ Andesite world average, Daly (1933)
- Andesite, type-locality, Catamarca, Argentina, Becke (1899)
- ◆ Latite, type-locality, Italy, Washington (1906)
- L 198 latites, Le Maitre (1976)
- X 554 trachytes, Le Maitre (1976)
- + 48 trachytes, Daly (1933)
- T Trachyte, Tröger (1935)
- Trachytes, Tristão da Cunha, Irvine & Baragar (1971)

Figure 7. KCK diagram for intermediate rocks with distribution of Uatumã volcanic rocks (legend in upper right). Thirteen known rock compositions and world averages (listed below the graph) are used to test the diagram.

evolved basalt to more evolved quartz trachyte (compositions from Tröger 1935) there are strong variations in the K_2O and CaO contents and little variation in Na_2O . Rhyolite has 11.75 times more K_2O (average = 4.82%) than basalt (average = 0.41%) and 19.75 times less CaO (0.56%) than basalt (11.06%). The difference in the Na_2O content of the end members basalt (2.38%) and quartz trachyte (4.18%) is 1.76%. The Na_2O content of andesite and rhyolite is similar, around 4%. We observe that Na_2O is not a discriminating oxide and therefore is not significant for the classification of volcanic rocks.

CaO and K_2O have negative correlation. CaO contents decrease from less evolved to more evolved rocks, but K_2O increases. CaO diminishes 15 times (1,500%) from basalt to quartz trachyte whereas K_2O increases more than 13 times (1,300%). These two elements are adequate for a classification scheme. The CaO/K_2O ratio enhances the differences in the behaviour of the two elements and is the selected ratio for use against the K_2O content, forming KCK diagrams.

The first diagram is dedicated to the intermediate volcanic rocks (alkali feldspar trachyte, trachyte, latite, andesite, trachyandesite, basalt), namely rocks with <5% Nqtz. Undersaturated alkaline rocks carrying normative nepheline (0-5%) are not included in the diagram, such as alkali feldspar trachyte, trachyte, latite, and andesite (all feldspathoid bearing). Sixty-five out of 218 analysed samples have <5% Nqtz. These compositions were tested in the Irvine & Baragar (1971) diagram (Fig. 4) to check for the presence of basaltic rocks. None was detected, in agreement with the absence of basalts in the Uatumã magmatism. The KCK diagram lacks a field for basalt because this rock type has high CaO/K_2O ratio and plots above the upper limit for andesite at about 8. The CaO/K_2O ratios of world average compositions of basalt are 12.71 (Nockolds 1954) and 22.9 (Le

Maitre 1976). Representative basalt of Tröger (1935) has $CaO/K_2O = 27$. Basalts are identified and separated from andesites using the Irvine & Baragar (1971) NCI x NPC diagram (Fig. 4).

The distribution of sixty-five points in the KCK diagram for intermediate rocks follows a cubic parabolic curve from the richest CaO andesite to the alkali feldspar trachyte with higher K_2O content. Five groups are separated according to their contents of K_2O and $CaO/K_2O =$ andesite, trachyandesite, latite, trachyte, and alkali feldspar trachyte.

Fig. 7 shows the presence of more latite and trachyte than considered before using classifications based on thin sections (SUDAM-GEOMINERAÇÃO 1972, SUDAM-GEOMITEC 1972, Montalvão et al. 1975, Oliveira et al. 1975, Araújo et al. 1976, SUDAM-GEOMITEC 1976, Pessoa et al. 1977, Veiga Jr et al. 1979, Melo et al. 1978, Bizzinella et al. 1980).

About 40% of Uatumã rocks previously interpreted as andesite, are latite and also trachyandesite. Some andesites and high-K andesites (Gill 1981) have excess K_2O (>3.5 wt.%) and actually are latites. Other “andesites” have low CaO (low plagioclase) and are therefore trachyandesites.

After plotting the data of Uatumã volcanic rocks (Fig. 7), the diagram was tested using 13 known rock compositions from the literature. The data lack alkali feldspar trachytes because the sources were published prior to mid-1970. The name alkali feldspar trachyte was introduced in 1978 by Streckeisen. The alkali feldspar trachytes of Fig. 7 were originally classified as “trachytes”. This field is presently subdivided into two, which are separated by the content of K_2O at around 6 wt.%. All trachytes have small amounts of CaO (<1 wt.%) and K_2O from 4.2% to 8%. Trachytes with higher K_2O (from 6% to 8%) and CaO <0.5% are from the alkali feldspar trachyte family.

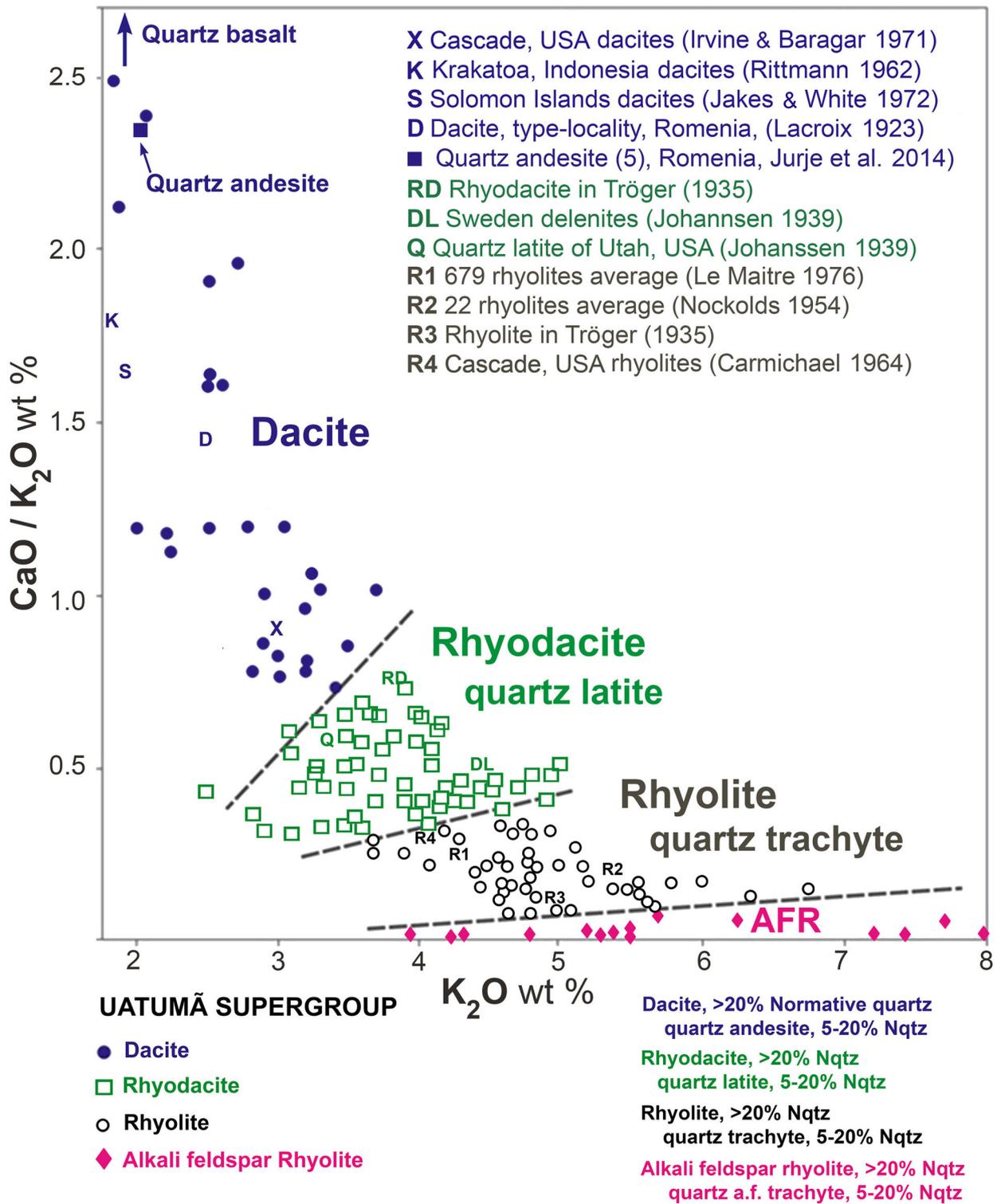


Figure 8. KCK diagram for acid (oversaturated) rocks with distribution of Uatumã volcanic rocks (legend in lower left). Twelve known rock compositions and world averages used to test the diagram are listed in the upper part of the graph.

The second proposed diagram is dedicated to acid volcanic rocks (alkali feldspar rhyolite, quartz alkali feldspar rhyolite, rhyolite, quartz trachyte, rhyodacite, quartz latite, dacite, quartz andesite, quartz basalt), that is rocks with > 5% Nqtz. Distribution of points ($n = 153$) also follows a cubic parabola (Fig. 8) similar to Fig. 7, from less evolved andesite ($\text{CaO}/\text{K}_2\text{O} = 2.5$) to more evolved alkali feldspar trachyte with 8% K_2O . Quartz basalt and quartz andesite (oversaturated rocks) are separated from basalt and andesite (saturated rocks) using the 5% modal and normative quartz limit. The scarcity of consistent data about quartz basalt in the literature restrains the definition of a field for this type of volcanic rock. Based on the $\text{CaO}/\text{K}_2\text{O}$ ratios of basalts, we consider that quartz basalts have $\text{CaO}/\text{K}_2\text{O}$ ratio well above 2.5 which is the highest value for dacites plotted in Fig. 8. The average of 20 Neogene quartz basalts from the Carpathians (Jurje et al. 2014) has $\text{CaO}/\text{K}_2\text{O}$ ratio of 3.95 (at 1.75 wt.% K_2O), plotting above the upper limit of Fig. 8. Quartz andesites also have high $\text{CaO}/\text{K}_2\text{O}$ ratio, in the same range as andesite (2.1 to 7.2, see Fig. 7). One example of quartz andesite (average of five samples) from the eastern Carpathians, Romania (Jurje et al. 2014) has $\text{CaO}/\text{K}_2\text{O}$ ratio of 2.40 (filled quadrangle of Fig. 8).

The limits between dacite (quartz andesite) – rhyodacite (quartz latite) – rhyolite (quartz trachyte) – alkali feldspar rhyolite (quartz alkali feldspar trachyte), were established based on Uatumã rock types. These limits were tested using 12 known rock compositions, type locality compositions, and world average compositions.

DISCUSSION

Common volcanic rocks are broadly grouped into four major categories according to the degree of

silica saturation understood as the availability of silica (generally quartz), feldspathoid, or olivine: acid, intermediate, basic, and ultrabasic rocks (Shand 1947, Yoder & Tilley 1962). The limits between categories are associated to the mineralogical composition because some minerals are more and others less saturated in SiO_2 . Therefore, a rock with higher SiO_2 (weight %) may be less saturated than a rock with lower SiO_2 in chemical composition; and *vice versa*.

Three major elements have wide variation among volcanic rocks, from the less evolved (basalt) to the more evolved (rhyolite, trachyte): silica, calcium and potassium. Sodium or Na_2O has little variation among common volcanic rocks and is not a discriminating element. Besides that, sodium is present in the structure of both plagioclase and alkali feldspar, causing difficulty in the determination of the proportion of Na in the two minerals. Several diagrams from the literature lack proper allocation of sodium among feldspars and, consequently, have strong potential for misclassification of the rocks.

Presence of Ca or CaO is mandatory for any diagram using major elements. Without this oxide/element the proportion of alkali feldspar and plagioclase cannot be established, and the result will be an incorrect classification. The best example of a diagram which is ineffective because of lack of CaO is the TAS diagram.

Some classification diagrams are based in immobile elements such as zirconium, titanium, and yttrium (Winchester & Floyd 1977, Pearce 1996) or thorium and hafnium (Wood et al. 1980). Zircon and zirconium are the notorious and most commonly inherited mineral and element in magmatic systems.

Inherited zircon was formed in different magmatic and tectonic settings in relation to the zircon of the target rock (Pidgeon et al. 1996). Other HFS (high field strength) elements may be also inherited such as Ti (titanite; Pidgeon

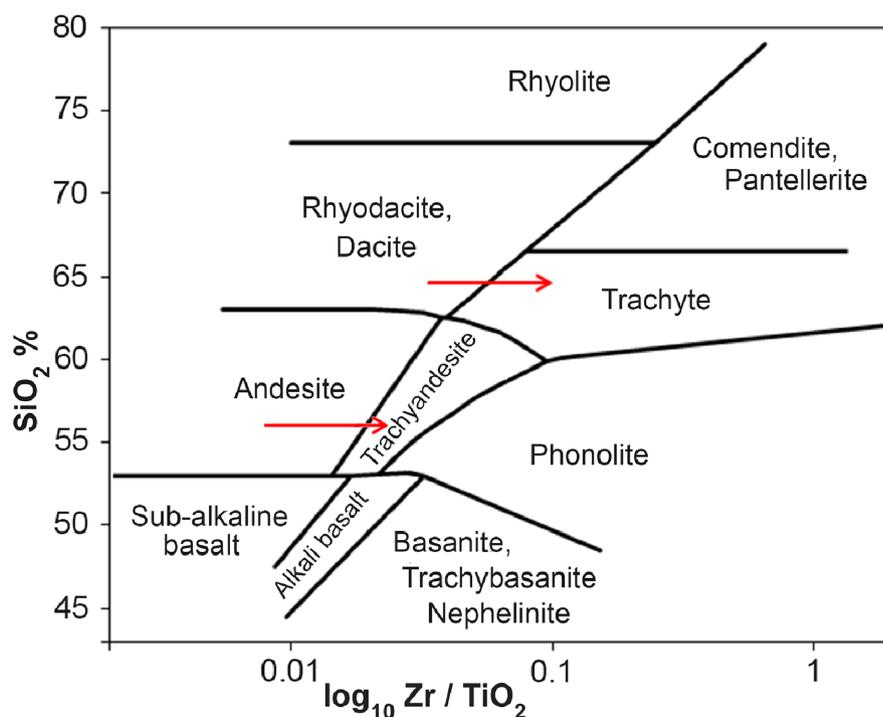


Figure 9. Silica versus $\log_{10} \text{Zr} / \text{TiO}_2$ diagram of Winchester & Floyd (1977). Common presence of inherited zircon and zirconium adds excess Zr to the diagram, causing “trachytization” of rhyodacite, dacite, and andesite.

et al. 1996), Th (monazite, Imayama & Suzuki 2013), Y (xenotime, Miller et al. 1992), and Hf (follows inheritance of zircon). These elements cannot be used or used with great caution in classificatory diagrams because they derive from zircon, xenotime, monazite and titanite, minerals which frequently or occasionally are inherited. Most volcanic rocks have both magmatic zircon and inherited zircon producing an excess of zirconium, which leads to the misclassification of the rock. The common effect of the excess Zr (magmatic plus inherited) is moving the points plotted on SiO_2 versus $\log_{10} \text{Zr} / \text{TiO}_2$ diagram (Winchester & Floyd 1977) to the right causing the artificial trachytization of rhyodacite, dacite, and andesite (Fig. 9).

Some examples of misclassifications using TAS

Several compositions and names based on TAS diagram are broadly incorrect because they include a number of misclassifications. For example, some published andesites are in fact latite (e.g. Eocene “andesites” of Nevada,

samples 49 and 154 of Ryskamp et al. 2008). Those samples have high K_2O (3.86% and 4.23%) corresponding to excess K-feldspar to be andesite. The contents are even higher than the maximum (3.4% K_2O for andesites with 60% SiO_2) considered for high-K andesites (Gill 1981). Other number of “andesites” in fact are quartz andesites because they are oversaturated rocks with normative quartz greater than 5%. Examples are from the Cainozoic Kermadec Island, New Zealand (Kemner et al. 2015): 22GTV-5 (15% Nqtz), 22GTV-4 (11% Nqtz), and 29GTV-1 (16% Nqtz). Large numbers of “rhyolites” have more than 2.6% CaO (e.g. Peate et al. 1992), which results in excess normative plagioclase (from 23% to 34%) to be true rhyolites. All rhyolites of Peate et al. 1999 (table 3, p. 124), from the Lower Cretaceous [Valanginian] Paraná LIP, Brazil, 134-135 Ma according to Pinto et al. (2011), are quartz latite, rhyodacite and dacite. Several dacites (adakites) with Na-plagioclase (oligoclase) are confused with trachytes (e.g. Guo et al. 2007; Miocene, Tibetan Plateau). Twelve trachyandesites of

northern Iran (Davidson et al. 2004) have high K_2O content (average = 4.39%) representing excess sanidine ($A = 35\%$ on QAP diagram). They are all latite, not trachyandesite. Literature has many of these and other misclassifications.

CONCLUSIONS

The studied Uatumã volcanic rocks are from three regions and have a dominance (about 70%) of acid over intermediate (30%) rocks. This contrasts with the pre-Uatumã volcanic rocks of Carajás Province (Sobreiro Formation) which are dominated by intermediate rocks (andesite, basaltic andesite, trachyandesite; Ferreira & Lamarão 2013). On the other hand, intermediate rocks are scarce among the post-Uatumã volcanics (1780-1760 Ma) of Colíder Group of South Amazon Craton, which is mainly composed by rhyolite and ignimbrite (Santos et al. 2019).

The presented KCK diagrams are more effective to classify common volcanic rocks than several diagrams from the literature. The application of these two diagrams is to be tested using large datasets and volcanic rocks from different ages and tectonic environments.

The use of a single classificatory diagram to name both saturated (six families) and oversaturated (ten families) volcanic rocks has limitations. Geological literature lacks any diagram capable of classify all rocks correctly. The first step to chemically classify volcanic rocks is to apply the values of normative quartz (N_{qtz}) to determine the degree of silica saturation and separate the four major groups of rocks: undersaturated, saturated, moderately oversaturated, and oversaturated. Additionally, the return is essential to the classical definition of degree of saturation thus abandoning the proposition (sponsored by the IUGS) which

defines the groups of acid, intermediate, basic, and ultrabasic rocks accordingly to their fixed contents of SiO_2 at 63%, 52% and 45%.

Several thousand rocks from worldwide published articles from 1980 to present day, all classified using the TAS diagram, need to be checked and part of them reclassified using for example the two proposed KCK diagrams. This is necessary considering that the TAS diagram is not able to identify or classify ten among 16 families of volcanic rocks. The artificial extinction of several volcanic rock-types can thus be avoided, including quartz trachyandesite, latite, quartz latite, quartz trachyte, quartz andesite, quartz basalt, alkali feldspar rhyolite, alkali feldspar trachyte, and rhyodacite, which artificially disappeared to a large extent from the literature.

Acknowledgments

The Geological Survey of Brazil kindly allowed the use of published and unpublished analytical data from Uatumã volcanic rocks. We are grateful to geologists from the Geological Survey of Brazil regarding extended and deep discussions on the theme, particularly Hilton T. Costi, Josafá R. Oliveira, Manoel R. Pessoa[†], Wilson Wildner, and Sandoval S. Pinheiro[†].

List of abbreviations

- CD-ROM**, compact disc read-only memory.
- CIPW**, Cross, Iddings, Pirsson, and Washington.
- CPRM**, Geological Survey of Brazil.
- DNPM**, Departamento Nacional de Produção Mineral.
- DOI**, Digital Object Identifier.
- GEOMITEC**, Geologia e Mineração, Trabalhos Técnicos Ltda.
- GSA**, Geological Society of America.
- IMA**, International Mineralogical Association.
- ISBN**, International Standard Book Number.
- ISSN**, International Standard Serial Number.
- IUGS**, International Union of Geological Sciences.
- KCK**, K_2O versus CaO/K_2O ratio.
- LAMIN**, Mineralogical Laboratory of CPRM.

LOSIMAG, Low Si and Mg (mantle model).
Mqtz, modal quartz.
MTS, MagnetoTelluric Sounding.
NCI, Normative Colour Index.
NPC, Normative Plagioclase Composition.
Nqtz, normative quartz.
ORCID, Open Researcher and Contributor ID.
PRIMA, Primitive Mantle.
PYROLITE, PYROXenes and OLIVINE (Upper mantle model).
QAP, quartz, alkali feldspar, plagioclase.
RADAM, Radar na Amazônia.
SUDAM, Superintendência para o Desenvolvimento da Amazônia.
TAS, total alkali-silica.
UEA, Universidade do Estado do Amazonas.
UFRGS, Federal University of Rio Grande do Sul.

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How to cite

SANTOS JOS & HARTMANN LA. 2021. Chemical classification of common volcanic rocks based on degree of silica saturation and CaO/K₂O ratio. An Acad Bras Cienc 93: e20201202. DOI 10.1590/0001-3765202120201202.

*Manuscript received on August 8, 2020;
accepted for publication on February 28, 2021*

JOÃO O.S. SANTOS¹

<https://orcid.org/0000-0001-5524-7949>

LÉO A. HARTMANN²

<https://orcid.org/0000-0001-7863-5071>

¹Universidade do Estado do Amazonas(UEA), Fundação Universitatis de Estudos Amazônicos, Av. Djalma Batista, 3694, Flores, 69050-010 Manaus, AM, Brazil

²Universidade Federal do Rio Grande do Sul, Instituto de Geociências, Av. Bento Gonçalves, 9500, 91501-970 Porto Alegre, RS, Brazil

Correspondence to: **João Orestes Schneider Santos**
E-mail: orestes1@uol.com.br

Author contributions

João Orestes S. Santos developed concepts, revised literature, gathered data, made drawings and diagrams and wrote the article. Léo A. Hartmann participated in conceptualization, literature review, revision of figures and text, some writing.

