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A revised CIPW norm

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Abstract

The CIPW norm proposed one hundred years ago is still a useful scheme because abundances of normative minerals are required for a proper rock classification such as that recommended by the IUGS. However, a standard methodology for CIPW norm computation is required. This paper presents a detailed step-by-step procedure for a Standard Igneous Norm (SIN). Our proposal is based on mass-balance principles involving the concept of variable molecular weights, free or unused parameters such as oxygen, CO_2 and other oxides, and silica deficiency. This SIN is capable of providing highly consistent results, with differences between CIPW norm sums and bulk chemical analyses generally smaller than 0.002.

Keywords: CIPW norm, geochemistry, igneous rocks, rock classification, mass-balance.

1. Introduction

The CIPW norm calculation scheme proposed by W. Cross, J. P. Iddings, L. V. Pirsson, and H. S. Washington at the beginning of the twentieth century (Cross et al., 1902) was designed for estimation of standard mineral assemblages for igneous rocks, through a pre-established, standard calculation procedure. They also stressed that such a calculation of standard minerals is "warranted because of the impossibility of determining the minerals in a great number of rocks in which they are too small, and because of the incomplete crystallization of all more or less glassy rocks". This scheme has been modified, clarified or reproduced in several occasions (e.g. Johannsen, 1931; Kelsey, 1965; Hutchison, 1974; Cox et al., 1979; Le Maitre, 1982; Ragland, 1989; Rollinson, 1993). A major amendment was provided by Kelsey (1965) who presented modifications of the rules for computer programming, thus enabling CIPW norm computations for undersaturated rocks. Although Cross et al. (1902) included hydrous minerals such as amphiboles and micas, they were not considered by Kelsey (1965) nor by other more recent calculation schemes. Such hydrous minerals are not actually required by a modern rock classification scheme for volcanic rocks such as that proposed by the IUGS. Therefore, CIPW norm computations on an anhydrous basis and considering only end-member compositions of solid-solutions of common rock-forming minerals should be sufficient for this purpose. On the other hand, Rittmann norm scheme is available to handle hydrous minerals as well as solid solutions of common minerals (Rittmann, 1973). If the IUGS decides to use these hydrous minerals and solid solutions of common silicate minerals for a new volcanic rock classification system, it would then be useful to incorporate them in an adequate computational scheme.

The IUGS Subcommission on the Systematics of Igneous Rocks (Le Maitre, 1984; Le Bas et al., 1986) emphasized that modal contents cannot be accurately determined in many cases because of the fine grain size or presence of glassy material. Hence, they proposed a chemical classification using simple chemical parameters, namely total alkalis and silica (TAS classification), as done by several previous workers (e.g. Irvine and Baragar, 1971; Cox et al., 1979; Middlemost, 1972, 1980). For ultrabasic rocks, the Subcommission (Le Bas et al., 1986) recommended the use of a future study (published later by Le Bas, 1989) for basanitic and nephelinitic rocks based on CIPW normative mineral contents (Cross et al., 1902). Le Maitre et al. (1989) also presented an excellent summary on the classification of igneous rocks and glossary of terms. Recently, the IUGS Subcommission on the Systematics of Igneous Rocks

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(Le Bas, 2000) made a series of recommendations for rock classification dealing with high-Mg and picritic volcanic rocks that require a special classification, prior to the TAS scheme of Le Bas et al. (1986).

Middlemost (1989) pointed out an urgent need for a standard igneous norm (SIN) calculation scheme because the existing schemes and computer programs produced many erroneous, and in some examples even bizarre, norms. Importantly, the TAS classification is supplemented by CIPW normative minerals for certain sub-root names to be assigned (Le Bas et al., 1986; Le Bas, 1989, 2000). We believe that this need of standardization in the CIPW norm calculation has resulted in a limited use of normative minerals by the petrological community. This unfortunate situation might explain also a lack of interest in using rock classification schemes, in which normative minerals have to be taken into account, such as the TAS classification proposed by the IUGS Subcommission on the Systematics of Igneous Rocks (Le Maitre, 1984; Le Bas et al., 1986; Le Bas, 2000).

This paper presents a system with a substantially modified CIPW norm computation procedure, termed Standard Igneous Norm (SIN), following the suggestions of Middlemost (1989). The fundamental principles of an anhydrous mineral assemblage put forth by Cross et al. (1902) are still followed, but the present procedure is a significant modification of the available CIPW reports (e.g. Kelsey, 1965; Rollinson, 1993) in many respects. Important modifications in the SIN scheme presented in this paper are:

(i) In addition to the eleven major elements, an optional use of minor and trace elements in the norm computation.
(ii) A prior adjustment of chemical analyses to 100% on an anhydrous basis.
(iii) Correction of the mineral formula and/or molecular weight for apatite, and recognition of the need of two different formulae for this mineral. This error from Cross et al. (1902) has persisted in Kelsey (1965), in classical petrology books such as Cox et al. (1979), and even in recent text books such as Rollinson (1993). For example, the molecular weight of "310" quoted by Cross et al. (1902) and Rollinson (1993) seems to be in error because it differs significantly from any of the two values for apatite computed in Table 4 of this paper (336.2016575 or 328.8691887). Similarly, the mineral formula $3CaO \cdot P_2O_5 \cdot {}^1/_3CaF$ quoted by Kelsey (1965) must be $3CaO \cdot P_2O_5 \cdot {}^1/_3CaF_2$. Because apatite calculation will affect the amount of CaO from the very beginning of norm computation, any error in this mineral will be critical for the calculation of important calcium-bearing minerals.
(iv) Implementation of the most accurate atomic weights for oxides and subsequent precise mineral molecular weight calculations. Precise atomic and molecular weights, based on IUPAC Commission on Atomic Weights and Isotopic Abundances (Vocke, 1999), are used for the norm computations (Table 1).
(v) Concept of variable molecular weights incorporated throughout into the present procedure, considering the concentration of certain elements that may substitute for some mineral-forming major elements. For example, because strontium may substitute calcium in the chemical formula of calcium-bearing minerals, the proportion of Sr should be taken into account when calculating the molecular weight of respective normative minerals.
(vi) Keeping track of unused mass throughout the computation, resulting in the calculation of free oxygen, free or unused oxides including CO_2, and unbalanced silica deficiency.
(vii) Continuous testing of remaining oxides in each step until all undersaturated minerals are formed.
(viii) Achievement of highly consistent results, comparing the sum of normative minerals with the bulk chemical composition.

In spite of all these improvements, we recognize that there are still some concepts that could eventually be included, particularly as user options, in a future version of the norm procedure. These options would allow: (1) the incorporation of minor amounts of Fe_2O_3 in clinopyroxenes; (2) inclusion of Zr in pyroxenes rather than the calculation of normative zircon, especially in mafic rocks; (3) substitution of Ti-tschermaks into clinopyroxene, especially in mafic rocks containing Ti-augite phenocrysts; (4) calculation of a monticellite component ($CaMgSiO_4$); (5) formation of normative Mg-chromite for Cr-rich rocks; (6) calculation of hydrated minerals, when appropriate; (7) handling of other elements such as TiO_2 and ZrO_2 in minor oxide combinations, as is done for oxides such as MnO, BaO, NiO, and SrO; (8) incorporation of alternative ways for handling the free oxygen parameter defined in this norm procedure. Furthermore, the sequence of calculations could be changed as an option depending on the geological system that the user is investigating.

2. Adjustment of Iron-Oxidation Ratio

Since Fe_2O_3 and FeO are rarely separately determined, several authors have pointed out the need for the adjustment of Fe_2O_3/FeO ratio in igneous rocks, before any classification or CIPW norm computations (e.g. Irvine and Baragar, 1971). Even in those cases in which the concentrations of Fe_2O_3 and FeO are reported separately, often they do not really represent those for the actual magmas (Middlemost, 1989) for several reasons, such as weathering induced oxidation or compositional changes during grinding of rock samples as discussed by Washington (1930).

Irvine and Baragar (1971) recommended adjusting this ratio if it appears to have been changed, because it can appreciably affect the norm (e.g. Coombs, 1963; Middlemost, 1989), and therefore the rock classification. Irvine and Baragar (1971) also pointed out that this readjustment would necessarily be somewhat arbitrary but essential to be done before CIPW norm computations, particularly for basic and ultrabasic rocks, which are crucial for understanding the mantle and crustal evolution. They proposed an upper limit on Fe_2O_3 to be set according to the following equation:

$$Fe_2O_3 = TiO_2 + 1.5 \quad (1)$$

where Fe_2O_3 and TiO_2 are expressed in % m/m[1]. But if the analysis value of Fe_2O_3 is less than this (equation 1), no changes are made. However, if it is greater, the excess Fe is converted to FeO. This procedure was criticized by Le Maitre (1976) because it only sets an upper limit, and in those rocks in which only total Fe has been determined (being a rather common analytical practice today) the recommended Fe_2O_3/FeO ratio becomes unrealistically high.

Brooks (1976) proposed a standardized Fe_2O_3/FeO ratio of 0.15, and Hughes and Hussey (1976, 1979) advocated that 0.25 or 0.20 should be adopted for basaltic rocks. On the other hand, Basaltic Volcanism Study Project (1981) used a number of different methods to adjust the raw Fe^{3+} values.

Le Bas et al. (1986), in their chemical classification, stated that the ratio of Fe_2O_3 to FeO is taken as given by the analyst, and if none is stated, a standard iron-oxidation ratio is calculated following the method of Le Maitre (1976), who presented the following equation (all chemical parameters are in % m/m):

$$FeO/(FeO+Fe_2O_3) = 0.93 - 0.0042 \times SiO_2 - 0.022(Na_2O+K_2O) \quad (2)$$

Middlemost (1989) presented detailed arguments to show that neither the raw iron-oxidation ratios nor the Le Maitre (1976) method should be used, because they often produced spurious normative mineral concentrations and therefore dis-

[1] % m/m – mass/mass unit expressed in % – equivalent to the familiar wt%, is now recommended to be used for this purpose.

Table 1 Oxides and elements with their molecular or atomic weights to be used in SIN (CIPW) computations*.

Oxide symbol (% m/m or wt%)	Molecular weight (MW_{Oxide}) (AMU)§	Approximate molecular weight (AMU)	Element name	Atomic weight (MW_{Elem}) (AMU)
SiO_2	60.0843	60.1	F	18.9984032 (5)
TiO_2	79.8658	79.9	Cl	35.4527 (9)
Al_2O_3	101.961276	102.0	S	32.066 (6)
Fe_2O_3	159.6882	159.7	Ni	58.6934 (2)
FeO	71.8444	71.8	Co	58.933200 (9)
MnO	70.937449	70.9	Sr	87.62 (1)
MgO	40.3044	40.3	Ba	137.327 (7)
CaO	56.0774	56.1	Rb	85.4678 (3)
Na_2O	61.97894	62.0	Cs	132.90545 (2)
K_2O	94.1960	94.2	Li	6.941 (2)
P_2O_5	141.944522	141.9	Zr	91.224 (2)
CO_2	44.0095	44.0	Cr	51.9961 (6)
			V	50.9415 (1)
SO_3	80.0642	80.1	O	15.9994 (3)

* Atomic weights are the exact values recommended by IUPAC (Vocke, 1999); the analytical uncertainty quoted in parentheses refers to the last digit reported for each element.

§ AMU = Atomic Mass Unit.

Table 2 Elements with the oxide molecular weights and respective formulae to be used in the SIN (CIPW) computations.

Element name	Oxide symbol	Oxide Molecular Weight (AMU)	Conversion formula
F	–	–	$C_F \times 10^{-4}$
Cl	–	–	$C_{Cl} \times 10^{-4}$
S	–	–	$C_S \times 10^{-4}$
Ni	NiO	74.6928	$(MW_{NiO}/AW_{Ni}) \times C_{Ni} \times 10^{-4}$
Co	CoO	74.9326	$(MW_{CoO}/AW_{Co}) \times C_{Co} \times 10^{-4}$
Sr	SrO	103.6194	$(MW_{SrO}/AW_{Sr}) \times C_{Sr} \times 10^{-4}$
Ba	BaO	153.3264	$(MW_{BaO}/AW_{Ba}) \times C_{Ba} \times 10^{-4}$
Rb	Rb_2O	186.935	$(MW_{Rb2O}/(2 \times AW_{Rb})) \times C_{Rb} \times 10^{-4}$
Cs	Cs_2O	281.8103	$(MW_{Cs2O}/(2 \times AW_{Cs})) \times C_{Cs} \times 10^{-4}$
Li	Li_2O	29.8814	$(MW_{Li2O}/(2 \times AW_{Li})) \times C_{Li} \times 10^{-4}$
Zr	ZrO_2	123.2228	$(MW_{ZrO2}/AW_{Zr}) \times C_{Zr} \times 10^{-4}$
Cr	Cr_2O_3	151.9904	$(MW_{Cr2O3}/(2 \times AW_{Cr})) \times C_{Cr} \times 10^{-4}$
V	V_2O_3	149.8812	$(MW_{V2O3}/(2 \times AW_{V})) \times C_{V} \times 10^{-4}$

The abbreviations used are: MW_{Oxide} is oxide molecular weight (e.g., MW_{NiO} is the molecular weight of NiO); AW_{Elem} is element atomic weight (e.g., AW_{Ni} is the atomic weight of Ni); C_{Elem} refers to the concentration of an element in a sample (e.g., C_{Ni} is the concentration of Ni). × denotes multiplication.

torted rock classifications that use norms. It appears that acmite is the only anhydrous normative silicate mineral that contains Fe_2O_3 (Fe^{3+}), besides, of course, purely iron minerals hematite (Fe_2O_3) and magnetite ($FeO \cdot Fe_2O_3$). Other clinopyroxenes may also contain minor amounts of Fe_2O_3, but as proposed in the CIPW norm procedure, these other pyroxenes are considered here as containing solely FeO (see Table 4). Therefore, changes in the Fe_2O_3/FeO ratio introduce changes in the amount of FeO available to form normative minerals (note that initial steps of normative calculations use FeO; Kelsey, 1965), and will change the concentration, or even the species of normative minerals being produced. Based on an extensive compilation of chemical analyses of volcanic rocks, Middlemost (1989) proposed the use of different Fe_2O_3 to FeO ratios depending on the type of rock. This approach has the advantage that the iron-oxidation ratio chosen is probably that of the fresh sample.

Thus, there are at least three different ways to estimate the iron-oxidation ratio: (a) the Middlemost (1989) proposal to adjust the Fe_2O_3/FeO ratios of rocks depending on rock type; (b) the Le Maitre's equation based on the SiO_2 and Na_2O+K_2O contents of the samples (Equation 2 above); (c) the actually measured ratios if available. Any of them could be used consistently throughout the SIN calculations.

3. Standard Igneous Norm (SIN)

This work presents a norm calculation procedure considerably modified after Kelsey (1965), following a rigorous use of the mass-balance concept. The development of SIN requires new rules that are summarized here. Several errors, some of them quite serious, and limitations detected in Kelsey's (1965) procedure are corrected in this version. One such limitation is that unusually undersaturated rocks seem to result in highly inconsistent normative mineral concentrations. This is due to an omission in the last step in Kelsey's scheme, which does not provide a solution for those cases in which the silica deficiency does not reach zero – a requirement of the norm procedure based on mass-balance concepts. These cases present a problem following Kelsey's (1965) procedure, even after the final undersaturated minerals (kaliophilite and leucite) are formed. This error has been corrected in our procedure.

In the next paragraphs, the complete CIPW norm (SIN) calculation procedure is explained here in 39 steps. In this procedure, we explicitly present the equations so as to be understandable to anyone not very familiar with the chemical principles.

1. Input data for standard igneous norm: The oxide data are expressed in % m/m (also known as wt.% or wt%), and trace elements are in μg/g (or mg/kg; also known as

ppm in geochemistry). Although Till (1977) listed some of these elements as oxides, inputting them as elements should be preferred because they are actually better measured in μg/g using methods most suitable for trace element determinations.

When either Fe_2O_3 or FeO is reported, it should be total Fe expressed as one of the two oxidation-forms; otherwise both should be reported. On the other hand, sulfur concentration when available is reported as either SO_3 (% m/m) or S (μg/g); however, sometimes both are reported, in which case their separate identity should be maintained. Many trace elements included in the list of Table 1 can also be used for norm computation. More elements could be added to this list, but it should suffice to use the more important ones (Table 1).

Two options to process the norm of a sample are possible. These are: (option A) to use only the major oxide data (11 oxides, from SiO_2 to P_2O_5 only, see Table 1), go to step 4; and (option B) to use all major (11 oxides), minor (CO_2 and SO_3), and trace elements (F to V listed in Table 1), go to step 2 (CO_2 handling options).

2. CO_2 handling options: If CO_2 is to be used in the norm, it is important to define the manner this measured concentration will be handled for each sample. If the concentration of $CO_2 > 0$, the % modal cancrinite or primary calcite present in the sample is to be indicated. Otherwise, CO_2 will be excluded from the norm computations and reported as "Free-CO_2" along with the normative minerals (see step 17 below). This would be the case when secondary calcite or other carbonate is found in the mode, or no such modal mineral (cancrinite or calcite) could be specified.

3. Conversion of units (element μg/g to oxide % m/m): Trace element data (μg/g) are converted to corresponding oxides (% m/m), using the molecular weights and formulae listed in Table 2. The first three elements are simply changed for their units from μg/g to % m/m, whereas the others are converted from element forms to oxides (% m/m).

4. Adjustment of Fe-oxidation ratio and 100% sum as well as computation of some petrogenetically useful parameters: The oxide data (11 oxides, from SiO_2 to P_2O_5 only; Table 1) are first recalculated to 100% on an anhydrous basis. It is important to mention that the adjusted data before their use in the norm and other computations should be rounded using the three rounding rules given by Bevington (1969). This could be done to three digits after the decimal point (one more digit after the decimal point than the input data which are normally stated to two digits after the decimal point) in order to keep their sum as close to 100 as possible. This would also make the rounding procedure consistent with the error propagation theory. Using these rounded, adjusted data, the rock types are now determined after Le Bas et al. (1986), Le Bas (1989), and Le Bas (2000), and Fe-oxidation ratio adjustment is done according to the recommendations of Middlemost (1989), or Le Maitre (1976), or else the measured Fe_2O_3/FeO ratios are maintained. The magma types (Ultrabasic for $SiO_2 \leq 45\%$, Basic for $45\% < SiO_2 \leq 52\%$, Intermediate for $52\% < SiO_2 \leq 63\%$, and Acid for $SiO_2 > 63\%$; Le Bas et al., 1986) can also be determined as well.

At this stage, several petrogenetically useful parameters can be computed from these adjusted data as explained below.

$$FeO^t/MgO = ((2\times71.8444/159.6882)\times Fe_2O_3 + FeO) / MgO \quad (3)$$

$$S.I. = 100\times MgO / (MgO + FeO + Fe_2O_3 + Na_2O + K_2O) \quad (4)$$

$$A.R. = (Al_2O_3 + CaO + Na_2O + K_2O) / (Al_2O_3 + CaO - Na_2O - K_2O) \quad (5)$$

However, if $SiO_2 > 50.0\%$ and $1.0 < (K_2O/Na_2O) < 2.5$, then

$$A.R. = (Al_2O_3 + CaO + 2Na_2O) / (Al_2O_3 + CaO - 2Na_2O) \quad (6)$$

$$Mg\# = 100\times Mg^{2+} / (Mg^{2+} + Fe^{2+}) \quad (7)$$

where FeO^t is total iron in % m/m expressed as FeO; S.I. = solidification index (Kuno, 1959; Hutchison, 1974); A.R. = alkalinity ratio (Wright 1969); Mg# = magnesium number, where Mg^{2+} and Fe^{2+} are in atomic units (Ragland, 1989; Rollinson, 1993).

These parameters are then reported as rounded to three digits after the decimal point. If the user-option is (A) to use only the eleven major oxides in the norm, go to step 6.

5. A second 100% adjustment: If the user opts for (B) incorporating minor and trace elements in the norm (i.e., elements besides those from SiO_2 to P_2O_5; Table 1), this step is called for. After the conversion of all concentration data to % m/m, the new sum of ad-

Table 3 Mole types and corrected molecular weight formulae to be used in the SIN (CIPW) computations.

Mole type	Equation for computing the "Corrected" molecular weight $(MW_{Oxide})_{corr}$
FeO	$(MW_{FeO})_{corr} = (x_{MnO} \times MW_{MnO}) + (x_{FeO} \times MW_{FeO})$
FeO	$(MW_{FeO})_{corr} = (x_{MnO} \times MW_{MnO}) + (x_{NiO} \times MW_{NiO}) + (x_{CoO} \times MW_{CoO}) + (x_{FeO} \times MW_{FeO})$
CaO	$(MW_{CaO})_{corr} = (x_{BaO} \times MW_{BaO}) + (x_{SrO} \times MW_{SrO}) + (x_{CaO} \times MW_{CaO})$
K_2O	$(MW_{K2O})_{corr} = (x_{Rb2O} \times MW_{Rb2O}) + (x_{Cs2O} \times MW_{Cs2O}) + (x_{K2O} \times MW_{K2O})$
Na_2O	$(MW_{Na2O})_{corr} = (x_{Li2O} \times MW_{Li2O}) + (x_{Na2O} \times MW_{Na2O})$
Cr_2O_3	$(MW_{Cr2O3})_{corr} = (x_{V2O3} \times MW_{V2O3}) + (x_{Cr2O3} \times MW_{Cr2O3})$

Note the first FeO equation is for the user-option of using only the eleven major oxides. All the other equations apply for the option of using the major as well as minor oxides and elements in the norm computations.

Table 4 Corrected molecular weights used in the SIN (CIPW) computations.

Normative mineral name (abbreviation)	Mineral formula	"Constant" molecular weight (AMU)	Required corrected term(s) (m_{corr})	"Corrected" molecular weight † (AMU)
Anorthite (an)	$CaO \cdot Al_2O_3 \cdot 2SiO_2$	278.207276	$(MW_{CaO})_{corr}$	$m_{corr} + 222.129876$
Diopside (di)-Mg *[Clinoenstatite]*	$CaO \cdot MgO \cdot 2SiO_2$	216.5504	$(MW_{CaO})_{corr}$	$m_{corr} + 160.4730$
Wollastonite (wo)	$CaO \cdot SiO_2$	116.1617	$(MW_{CaO})_{corr}$	$m_{corr} + 60.0843$
Dicalcium silicate (cs)	$2CaO \cdot SiO_2$	172.2391	$(MW_{CaO})_{corr}$	$2m_{corr} + 60.0843$
Sphene (tn)	$CaO \cdot TiO_2 \cdot SiO_2$	196.0275	$(MW_{CaO})_{corr}$	$m_{corr} + 139.9501$
Perovskite (pf)	$CaO \cdot TiO_2$	135.9432	$(MW_{CaO})_{corr}$	$m_{corr} + 79.8558$
Apatite (ap)-CaF_2	$3CaO \cdot P_2O_5 \cdot (1/3)CaF_2$	336.2016575	$(MW_{CaO})_{corr}$ *	$M_{corr} + 154.6101241$
Apatite (ap)-CaO	$3CaO \cdot P_2O_5 \cdot (1/3)CaO$	328.8691887	$(MW_{CaO})_{corr}$	$(10/3)m_{corr} + 141.944522$
Calcite (cc)	$CaO \cdot CO_2$	100.0869	$(MW_{CaO})_{corr}$	$m_{corr} + 44.0095$
Hypersthene (hy)-Fe *[Ferrosilite]*	$FeO \cdot SiO_2$	–§	$(MW_{FeO})_{corr}$	$m_{corr} + 60.0843$
Olivine (ol)-Fe *[Fayalite]*	$2FeO \cdot SiO_2$	–§	$(MW_{FeO})_{corr}$	$2m_{corr} + 60.0843$
Magnetite (mt)	$FeO \cdot Fe_2O_3$	–§	$(MW_{FeO})_{corr}$	$m_{corr} + 159.6882$
Ilmenite (il)	$FeO \cdot TiO_2$	–§	$(MW_{FeO})_{corr}$	$m_{corr} + 79.8658$
Albite (ab)	$Na_2O \cdot Al_2O_3 \cdot 6SiO_2$	524.446016	$(MW_{Na2O})_{corr}$	$m_{corr} + 462.467076$
Nepheline (ne)	$Na_2O \cdot Al_2O_3 \cdot 2SiO_2$	284.108816	$(MW_{Na2O})_{corr}$	$m_{corr} + 222.129876$
Thenardite (th)	$Na_2O \cdot SO_3$	142.04314	$(MW_{Na2O})_{corr}$	$m_{corr} + 80.0642$
Sodium carbonate (nc)	$Na_2O \cdot CO_2$	105.98844	$(MW_{Na2O})_{corr}$	$m_{corr} + 44.0095$
Acmite (ac)	$Na_2O \cdot Fe_2O_3 \cdot 4SiO_2$	462.00434	$(MW_{Na2O})_{corr}$	$m_{corr} + 400.0254$
Sodium metasilicate (ns)	$Na_2O \cdot SiO_2$	122.06324	$(MW_{Na2O})_{corr}$	$m_{corr} + 60.0843$
Orthoclase (or)	$K_2O \cdot Al_2O_3 \cdot 6SiO_2$	556.663076	$(MW_{K2O})_{corr}$	$m_{corr} + 462.467076$
Leucite (lc)	$K_2O \cdot Al_2O_3 \cdot 4SiO_2$	436.494476	$(MW_{K2O})_{corr}$	$m_{corr} + 342.298476$
Kaliophilite (kp)	$K_2O \cdot Al_2O_3 \cdot 2SiO_2$	316.325876	$(MW_{K2O})_{corr}$	$m_{corr} + 222.129876$
Potassium metasilicate (ks)	$K_2O \cdot SiO_2$	154.2803	$(MW_{K2O})_{corr}$	$m_{corr} + 60.0843$
Diopside (di)-Fe *[Clinoferrosilite]*	$CaO \cdot FeO \cdot 2SiO_2$	–§	$(MW_{FeO})_{corr}$	$m_{corr} + 176.2460$
Diopside (di)-Fe *[Clinoferrosilite]*	$CaO \cdot FeO \cdot 2SiO_2$	248.0904	$(MW_{CaO})_{corr} + (MW_{FeO})_{corr}$	$m_{corr} + 120.1686$
Chromite (cr)	$FeO \cdot Cr_2O_3$	223.8348	$(MW_{FeO})_{corr} + (MW_{Cr2O3})_{corr}$	m_{corr}
Halite (hl)	NaCl	58.44247	$(MW_{Na})_{corr}$ **	$M_{corr} + 35.4527$
Fluorite (fr)	CaF_2	78.0748064	$(MW_{Ca})_{corr}$ ***	$M_{corr} + 37.9968064$
Pyrite (pr)	FeS_2	119.977	$(MW_{Fe})_{corr}$ ****	$M_{corr} + 64.132$

§ Corrected molecular weights are used for these five cases when the user-option is to use only the eleven major oxides (SiO_2 to P_2O_5) in the norm computations (Option A).

† It is also important to note that the other user-option requires the use of corrected molecular weights for all normative minerals included in this table (Option B).

*, **, ***, **** See explanation of step 9 in the text.

justed major elements from step 4 above and of other minor oxides and trace elements is once again adjusted to 100% (see Table 1 for their list). All elements, except O, can be specified (Table 1). This is done by excluding H_2O^+ and H_2O^-, or loss on ignition (LOI), irrespective of whichever has been reported. All data without rounding are used in the norm computations. Further, the minor or trace oxides are reported without any rounding procedure (as originally input values), whereas the adjusted major oxides are sent to output with three digits after the decimal point from the step 4 above.

6. Mole computations: The concentrations (all in % m/m) of the oxides and elements present (results of step 4 or 5 depending on the user-option (A) or (B)) are converted to moles (molecular and atomic) by dividing the % m/m by the respective molecular or atomic weights. Note the identity of both SO_3 and S is maintained. These new mole units (n_{Oxide} or n_{Elem}) are used in the following calculations.

7. Minor oxide combinations: If the user-option is (A) to use in the norm only the eleven oxides from SiO_2 to P_2O_5, add the moles (n_{Oxide}) as follows: n_{MnO} to n_{FeO} (i.e. MnO must be used in the computations), go to step 8.

Otherwise, if the user opts for (B) to use all major as well as minor oxides and trace elements, add the moles as follows: ($n_{MnO}+n_{NiO}+n_{CoO}$) to n_{FeO}; ($n_{BaO}+n_{SrO}$) to n_{CaO}; add ($n_{Rb2O}+ n_{Cs2O}$) to n_{K2O}; add n_{Li2O} to n_{Na2O}; add n_{V2O3} to n_{Cr2O3}.

8. Corrected oxide molecular weight computations: It is necessary to compute the corrected molecular weights for all those oxides, to which other minor oxides are to be added. This is because the molecular weight of a combined oxide will depend on the proportion of the individual oxides (x_{Oxide}) and their respective molecular weights (MW_{Oxide}). As an example, one can formulate for FeO the following equations according to the user-option. For the user-option (A), MnO concentration was added to FeO and therefore,

$$n_{MnO}+n_{FeO} = (n_{FeO})_{corr} \quad (8)$$
$$x_{MnO} = n_{MnO}/(n_{FeO})_{corr} \quad (9)$$
$$x_{FeO} = n_{FeO}/(n_{FeO})_{corr} \quad (10)$$

Where the proportions are constrained by the following equation

$$x_{MnO}+ x_{FeO} = 1 \quad (11)$$

On the other hand, for a user-option (B), the computations are as follows:

$$n_{MnO}+n_{NiO}+n_{CoO}+n_{FeO} = (n_{FeO})_{corr} \quad (12)$$
$$x_{MnO} = n_{MnO}/(n_{FeO})_{corr} \quad (13)$$
$$x_{NiO} = n_{NiO}/(n_{FeO})_{corr} \quad (14)$$
$$x_{CoO} = n_{CoO}/(n_{FeO})_{corr} \quad (15)$$
$$x_{FeO} = n_{FeO}/(n_{FeO})_{corr} \quad (16)$$

Where the proportions are constrained by the following equation

$$x_{MnO}+x_{NiO}+x_{CoO}+x_{FeO} = 1 \quad (17)$$

The required computations are included in Table 3.

9. Corrected normative mineral molecular weight computations: The corrected oxide molecular weights are now used in the computation of the corrected molecular weights of several normative minerals as shown in Table 4.

Although most corrections indicated in Table 4 are straight forward, those marked by *, **, ***, **** are more complicated. The computations of corrected molecular weights for these four normative minerals (apatite, halite, fluorite, and pyrite) are therefore explained here. $(MW_{Elem})_{corr}$ and $(MW_{Oxide})_{corr}$ are used arbitrarily to express respectively corrected atomic and molecular weights based on oxide-corrections. For "variable" molecular weights, M_{corr} is the term to be added to a fixed value as shown below (see also Table 4).

* The corrected molecular weight of apatite [(ap)–CaF_2; $3CaO{\cdot}P_2O_5{\cdot}(1/3)CaF_2$] can be computed from the following equations:

$$(MW_{Ca})_{corr} = (MW_{CaO})_{corr} - (AW_O) = (MW_{CaO})_{corr} - 15.9994 \quad (18)$$

$$(MW_{Ap-CaF2})_{corr} = 3\times(MW_{CaO})_{corr} + (MW_{P2O5}) + (1/3)\times\{(MW_{Ca})_{corr} + (2\times AW_F)\} \quad (19)$$

$$(MW_{Ap-CaF2})_{corr} = 3\times(MW_{CaO})_{corr} + 141.944522 + (1/3)\times(MW_{Ca})_{corr} + (1/3)\times 2 \times 18.9984032 \quad (20)$$

$$(MW_{Ap-CaF2})_{corr} = 3\times(MW_{CaO})_{corr} + (1/3)\times(MW_{Ca})_{corr} + 154.6101241 \quad (21)$$

where AW_{Elem} stands for the atomic weight of element $_{Elem}$.

**Similarly, the corrected molecular weight of halite (NaCl) will be computed as follows:

$$(MW_{Na})_{corr} = \{(MW_{Na2O})_{corr} - (AW_O)\}/2 = \{(MW_{Na2O})_{corr} - 15.9994\}/2 \quad (22)$$

$$(MW_{NaCl})_{corr} = (MW_{Na})_{corr} + (AW_{Cl}) = (MW_{Na})_{corr} + 35.4527 \quad (23)$$

***For fluorite (CaF_2), this is done as follows:

$$(MW_{Ca})_{corr} = (MW_{CaO})_{corr} - (AW_O) = (MW_{CaO})_{corr} - 15.9994 \quad (24)$$

$$(MW_{CaF2})_{corr} = (MW_{Ca})_{corr} + (2\times AW_F) = (MW_{Ca})_{corr} + (2\times 18.9984032) \quad (25)$$

****For pyrite (FeS_2), the computations are:

$$(MW_{Fe})_{corr} = (MW_{FeO})_{corr} - (AW_O) = (MW_{FeO})_{corr} - 15.9994 \quad (26)$$

$$(MW_{FeS2})_{corr} = (MW_{Fe})_{corr} + (2\times AW_S) = (MW_{Fe})_{corr} + (2\times 32.066) \quad (27)$$

These corrected molecular weights (Table 4) are used in the final conversion of moles of normative minerals (n_{nm}) to % m/m units (see step 37 below).

10. Molecular weights of other normative minerals: "Constant" molecular weights used for other normative minerals are given in Table 5 for an easy reference. These values are used when only eleven major oxides (SiO_2 to P_2O_5) are used for norm computations. But note that for five FeO-bearing normative minerals, i.e., hypersthene (hy)-Fe, olivine (ol)-Fe, magnetite (mt), ilmenite (il), and diopside (di)-Fe (see minerals identified by § in Table 4) the final conversion (step 37) is done using the corrected molecular weight $(MW_{FeO})_{corr}$ because, as explained in steps 7 and 8 above, n_{MnO} is to be added to n_{FeO}.

Note that in the following the notation n_{Oxide} is used to denote moles of each Oxide.

11. Normative zircon ($ZrO_2{\cdot}SiO_2$): Set $z = n_{ZrO2}$; set $Y = z$, where Y denotes silica requirements to make normative minerals. On the other hand, it is implicitly assumed that $n_{SiO2} > n_{ZrO2}$.

Table 5 "Constant" molecular weights to be used in the SIN (CIPW) computations.

Normative mineral name (abbreviation)	Mineral formula	"Constant" molecular weight (AMU)
Quartz (q)	SiO_2	60.0843
Corundum (c)	Al_2O_3	101.961276
Zircon (z)	$ZrO_2{\cdot}SiO_2$	183.3071
Hypersthene (hy)-Mg *[Enstatite]*	$MgO{\cdot}SiO_2$	100.3887
Olivine (ol)-Mg *[Forsterite]*	$2MgO{\cdot}SiO_2$	140.6931
Hematite (hm)	Fe_2O_3	159.6882
Rutile (ru)	TiO_2	79.8658

12. Normative apatite ($3CaO{\cdot}P_2O_5{\cdot}(1/3)CaO$ or $3CaO{\cdot}P_2O_5{\cdot}(1/3)CaF_2$): (i) If $n_{CaO} \geq (3+1/3)n_{P2O5}$, set *ap* = n_{P2O5}; subtract an amount equal to $(3+1/3)$*ap* from n_{CaO} [use Apatite (ap)-CaO type mol. wt. for final conversion in step 37 below]; there is no further P_2O_5 available. If, on the other hand, $n_{CaO} < (3+1/3)n_{P2O5}$, set *ap* = $n_{CaO}/(3+1/3)$; subtract an amount equal to *ap* from n_{P2O5}. There is no further CaO available to form other normative minerals. The remaining P_2O_5 is assigned as free or unused oxide FREE_P2O5.

However, if F is present [use Apatite (ap)-CaF_2 type mol. wt. in option (ii) and both in option (iii) for step 37]. For these two options, one must first calculate the amount of *ap* in the above mentioned step and then carry out the following calculations: (ii) if $n_F \geq (2/3)$*ap*, substract an amount equal to $(2/3)$*ap* from n_F; (iii) if $n_F < (2/3)$*ap*, all the fluorine is used up to make *ap* and both types of apatite will be formed as follows:

$$N_{(ap)\text{–}CaF2} = 1.5 \times n_F \quad (28)$$

$$N_{(ap)\text{–}CaO} = n_{P2O5} - (1.5 \times n_F) \quad (29)$$

Where

$$ap = n_{(ap)\text{–}CaF2} + n_{(ap)\text{–}CaO} \quad (30)$$

Therefore, total amount of apatite formed is same as n_{P2O5}, but it is of two types.

In this step (options ii and iii), there will be free or unused O from n_{CaO}, because the apatite formula includes $(1/3)CaF_2$. This "free-O" is assigned to different variables depending upon the step in which it is released, because this parameter is subject to variable atomic weight for final conversion in step 37. For example, this free-O in step 12(ii), assigned to variable *FREEO_12b* will be $(1/3)$*ap* for option (ii). Similarly, in step 12(iii) *FREEO_12c* will be $n_F/2$ for option (iii).

13. Normative fluorite (CaF_2): If $n_{CaO} \geq n_F/2$, set *fr* = $n_F/2$; subtract an amount equal to *fr* from n_{CaO}; add an amount equal to *fr* to *FREEO_13*. But if $n_{CaO} < n_F/2$, set *fr* = n_{CaO}; subtract an amount equal to 2*fr* from n_F; add an amount equal to *fr* to *FREEO_13*. There is no further CaO available to form other normative minerals, but there will be unused F (FREE_F) in this option.

14. Normative halite (NaCl): If $n_{Na2O} \geq 2n_{Cl}$, set *hl* = n_{Cl}; subtract an amount equal to *hl*/2 from n_{Na2O}; add an amount equal to *hl*/2 to *FREEO_14*. However, if $n_{Na2O} < 2n_{Cl}$, set *hl* = $(n_{Na2O})/2$; subtract an amount equal to *hl* from n_{Cl}. This will be unused Cl (FREE_Cl). Add an amount equal to *hl*/2 to *FREEO_14*. There is no further Na_2O available to form other normative minerals.

15. Normative thenardite ($Na_2O{\cdot}SO_3$): If SO_3 is to present, and if $n_{Na2O} \geq n_{SO3}$, set *th* = n_{SO3}; subtract an amount equal to *th* from n_{Na2O}. However, if $n_{Na2O} < n_{SO3}$, set *th* = n_{Na2O}; subtract an amount equal to *th* from n_{SO3}. This will be unused SO_3 (FREE_SO3). There is no further Na_2O available to form other normative minerals.

16. Normative pyrite (FeS_2): If S is present, and if $n_{FeO} \geq 2n_S$, set *pr* = $n_S/2$; subtract an amount equal to *pr* from n_{FeO}; add an amount equal to *pr* to *FREEO_16*. However, if $n_{FeO} < 2n_S$, set *pr* = n_{FeO}; subtract an amount equal to 2*pr* from n_{FeO}; the remaining n_{FeO} is unused S (FREE_S); add an amount equal to *pr* to *FREEO_16*. There is no further FeO available to form other normative minerals.

17. Normative sodium carbonate ($Na_2O.CO_2$) **or calcite** ($CaO{\cdot}CO_2$):

(a) If the rock contains modal cancrinite, normative sodium carbonate will be calculated. If $n_{CO2} > 0$, then continue this step; otherwise go to step 18. If $n_{Na2O} \geq n_{CO2}$, put *nc* = n_{CO2}; subtract an amount equal to *nc* from n_{Na2O}. However, if $n_{Na2O} < n_{CO2}$, put *nc* = n_{Na2O}; subtract an amount equal to *nc* from n_{CO2}; there is no further Na_2O available to form other normative minerals but there will be free or unused CO_2 available; this is stored in the normative array as "free-CO_2" (variable *FREECO2* = n_{CO2}) and should be reconverted to CO_2 % m/m in step 37.

(b) If the rock contains modal calcite, normative calcite will be calculated. If $n_{CaO} \geq n_{CO2}$, put $cc = n_{CO2}$; subtract an amount equal to *cc* from n_{CaO}. However, if $n_{CaO} < n_{CO2}$, put $cc = n_{CaO}$; subtract an amount equal to *cc* from n_{CO2}. There is no further CaO available to form other normative minerals but there will be free or unused CO_2 (FREECO2) available.

(c) If none of the above two options is possible because modal cancrinite was not present or modal calcite was secondary or from associated limestone, it is not included in the norm. This means that unused CO_2 (FREECO2) will be available (if $n_{CO2} > 0.0$).

18. Normative chromite ($FeO{\cdot}Cr_2O_3$): If $n_{Cr2O3} > 0$ and if $n_{FeO} \geq n_{Cr2O3}$, set $cm = n_{Cr2O3}$; subtract an amount equal to *cm* from n_{FeO}. However, if $n_{FeO} < n_{Cr2O3}$, set $cm = n_{FeO}$; subtract an amount equal to *cm* from n_{Cr2O3}. This will be unused Cr_2O_3 (FREE_CR2O3). There is no further FeO available to form other normative minerals.

19. Normative ilmenite ($FeO{\cdot}TiO_2$): If $n_{FeO} \geq n_{TiO2}$, set $il = n_{TiO2}$; subtract an amount equal to *il* from n_{FeO}. There is no further TiO_2 available to form other normative minerals. If $n_{FeO} < n_{TiO2}$, set $il = n_{FeO}$; subtract an amount equal to *il* from TiO_2. There is no further FeO available to form other normative minerals.

20. Normative orthoclase ($K_2O{\cdot}Al_2O_3{\cdot}6SiO_2$) **/ potassium metasilicate** ($K_2O{\cdot}SiO_2$): If $n_{Al2O3} \geq n_{K2O}$, set $or' = n_{K2O}$; subtract an amount equal to *or´* from n_{Al2O3}. There is no further K_2O available to form other normative minerals. Add an amount equal to 6*or´* to *Y*. If $n_{Al2O3} < n_{K2O}$, set $or' = n_{Al2O3}$; subtract an amount equal to *or´* from n_{K2O}. There is no further Al_2O_3 available to form other normative minerals. Set $ks = n_{K2O}$; add an amount equal to (6*or´* + *ks*) to *Y*.

21. Normative albite ($Na_2O{\cdot}Al_2O_3{\cdot}6SiO_2$): If $n_{Al2O3} \geq n_{Na2O}$, set $ab' = n_{Na2O}$; subtract an amount equal to *ab´* from n_{Al2O3}. There is no further Na_2O available to form other normative minerals. Add an amount equal to 6*ab´* to *Y*. If $n_{Al2O3} < n_{Na2O}$, set $ab' = n_{Al2O3}$; subtract an amount equal to *ab´* from n_{Na2O}. There is no further Al_2O_3 available to form other normative minerals. Add an amount equal to 6*ab´* to *Y*.

22. Normative acmite ($Na_2O{\cdot}Fe_2O_3{\cdot}4SiO_2$) **/ sodium metasilicate** ($Na_2O{\cdot}SiO_2$): If $n_{Na2O} \geq n_{Fe2O3}$, set $ac = n_{Fe2O3}$; subtract an amount equal to *ac* from n_{Na2O}. There is no further Fe_2O_3 available to form other normative minerals. Set $ns = n_{Na2O}$; add an amount equal to (4*ac* + *ns*) to *Y*. If $n_{Na2O} < n_{Fe2O3}$, set $ac = n_{Na2O}$; subtract an amount equal to *ac* from n_{Fe2O3}. There is no further Na_2O available to form other normative minerals. Add an amount equal to 4*ac* to *Y*.

23. Normative anorthite ($CaO{\cdot}Al_2O_3{\cdot}2SiO_2$) **/ corundum** ($Al_2O_3$): If $n_{Al2O3} \geq n_{CaO}$, set $an = n_{CaO}$; subtract an amount equal to *an* from n_{Al2O3}. There is no further CaO available to form other normative minerals. Add an amount equal to 2*an* to *Y*; set $c = n_{Al2O3}$. If $n_{Al2O3} < n_{CaO}$, set $an = n_{Al2O3}$; subtract an amount equal to *an* from n_{CaO}. There is no further Al_2O_3 available to form other normative minerals. Add an amount equal to 2*an* to *Y*.

24. Normative sphene ($CaO{\cdot}TiO_2{\cdot}SiO_2$) **/ rutile** ($TiO_2$): If $n_{CaO} \geq n_{TiO2}$, set $tn' = n_{TiO2}$; subtract an amount equal to *tn´* from n_{CaO}. There is no further TiO_2 available to form other normative minerals. Add an amount equal to *tn´* to *Y*. If $n_{CaO} < n_{TiO2}$, set $tn' = n_{CaO}$; subtract an amount equal to *tn´* from n_{TiO2}. There is no further CaO available to form other normative minerals. Set $ru = n_{TiO2}$; add an amount equal to *tn´* to *Y*.

25. Normative magnetite ($FeO{\cdot}Fe_2O_3$) **/ hematite** (Fe_2O_3): If $n_{Fe2O3} \geq n_{FeO}$, set $mt = n_{FeO}$; subtract an amount equal to *mt* from n_{Fe2O3}. There is no further FeO available to form other normative minerals. Set $hm = n_{Fe2O3}$. If $n_{Fe2O3} < n_{FeO}$, set $mt = n_{Fe2O3}$; subtract an amount equal to *mt* from n_{FeO}. There is no further Fe_2O_3 available to form other normative minerals.

26. Subdivision of some normative minerals: Add n_{MgO} to n_{FeO} to form $n_{(Mg,Fe)O}$. Compute the ratios $n_{MgO}/(n_{MgO}+n_{FeO})$ and $n_{FeO}/(n_{MgO}+n_{FeO})$ and use these relative proportions to subdivide diopside, hypersthene, and olivine into Mg- and Fe-varieties.

27. Provisional normative diopside ($CaO{\cdot}(Mg,Fe)O{\cdot}2SiO_2$), **wollastonite** ($CaO{\cdot}SiO_2$) **/ hypersthene** ($(Mg,Fe)O{\cdot}SiO_2$): If $n_{CaO} \geq n_{(Mg,Fe)O}$, set $di' = n_{(Mg,Fe)O}$; subtract an amount equal to di' from n_{CaO}. There is no further (Mg,Fe)O available to form other normative minerals. Set $wo' = n_{CaO}$; add an amount equal to $(2di' + wo')$ to Y. If $n_{CaO} < n_{(Mg,Fe)O}$, set $di' = n_{CaO}$; subtract an amount equal to di' from $n_{(Mg,Fe)O}$. There is no further CaO available to form other normative minerals. Set $hy' = n_{(Mg,Fe)O}$; add an amount equal to $(2di' + hy')$ to Y.

28. Normative quartz (SiO_2) **/ undersaturated minerals**: Y now gives the amount of silica required for all the normative minerals so far formed.

If $n_{SiO2} \geq Y$, set $q = n_{SiO2} - Y$. Go to step 36-a. The computation of the norm is then completed by conversion of the molecular proportions to weight percentages of normative minerals, as shown in step 37.

If $n_{SiO2} < Y$, set the deficiency $D = Y - n_{SiO2}$. Further calculations have to be performed (see rules 29-35), until the deficiency has been reduced to zero and the provisional normative minerals have been converted to definite ones (step 36). Finally, the computation is completed by conversion of the molecular proportions to weight percentages of normative minerals and one must therefore go to step 37.

29. Normative olivine ($2(Mg,Fe)O{\cdot}SiO_2$) **/ hypersthene** ($(Mg,Fe)O{\cdot}SiO_2$): If $D < hy'/2$, set $ol = D$ and $hy = hy' - 2D$. The silica deficiency is now zero. Go to step 36-b.

If $D \geq hy'/2$, set $ol = hy'/2$ and $hy = 0$; put $D_1 = D - hy'/2$.

30. Normative sphene ($CaO{\cdot}TiO_2{\cdot}SiO_2$) **/ perovskite** ($CaO{\cdot}TiO_2$): If $D_1 < tn'$, set $tn = tn' - D_1$ and $pf = D_1$. The silica deficiency is now zero. Go to step 36-c.

If $D_1 \geq tn'$, set $pf = tn'$ and $tn = 0$; put $D_2 = D_1 - tn'$.

31. Normative nepheline $Na_2O{\cdot}Al_2O_3{\cdot}2SiO_2$) **/ albite** ($Na_2O{\cdot}Al_2O_3{\cdot}6SiO_2$): If $D_2 < 4ab'$, set $ne = D_2/4$ and $ab = ab' - D_2/4$. The silica deficiency is now zero. Go to step 36-d.

If $D_2 \geq 4ab'$, set $ne = ab'$ and $ab = 0$; put $D_3 = D_2 - 4ab'$.

32. Normative leucite ($K_2O{\cdot}Al_2O_3{\cdot}4SiO_2$) **/ orthoclase** ($K_2O{\cdot}Al_2O_3{\cdot}6SiO_2$): If $D_3 < 2or'$, set $lc = D_3/2$ and $or = or' - D_3/2$. The silica deficiency is now zero. Go to step 36-e.

If $D_3 \geq 2or'$, set $lc' = or'$ and $or = 0$; put $D_4 = D_3 - 2or'$.

33. Normative dicalcium silicate ($2CaO{\cdot}SiO_2$) **/ wollastonite** ($CaO{\cdot}SiO_2$): If $D_4 < wo'/2$, set $cs = D_4$ and $wo = wo' - 2D_4$. The silica deficiency is now zero. Go to step 36-f.

If $D_4 \geq wo'/2$, set $cs = wo'/2$ and $wo = 0$; put $D_5 = D_4 - wo'/2$.

34. Normative dicalcium silicate ($2CaO{\cdot}SiO_2$) **/ olivine** ($2(Mg,Fe)O{\cdot}SiO_2$) **adjustment**: If $D_5 < di'$, add an amount equal to $D_5/2$ to the amounts of *cs and ol* already in the norm; set $di = di' - D_5$. The silica deficiency is now zero. Go to step 36-g.

If $D_5 \geq di'$, add an amount equal to $di'/2$ to the amounts of *cs and ol* already in the norm; put $di = 0$ and $D_6 = D_5 - di'$.

35. Normative kaliophilite $K_2O{\cdot}Al_2O_3{\cdot}2SiO_2$) **/ leucite** ($K_2O{\cdot}Al_2O_3{\cdot}4SiO_2$): If $lc' \geq D_6/2$, set $kp = D_6/2$ and $lc = lc' - D_6/2$. The silica deficiency is now zero. Go to step 36-g.

If $lc' < D_6/2$, set $lc = 0$ and $kp = lc'$. This is the special case when the silica deficiency could not be adjusted to zero; instead set final deficiency $(DEFSIO2) = D_6 - 2kp$. Go to step 36-g.

This final silica deficiency value will have to be converted to % m/m units and subtracted from the final sum of normative minerals.

36. Allocate definite mineral proportions: From steps 29-35, the calculations should be directed to this step where provisional normative minerals are assigned to definite ones.

The successive sub-steps (a to g) are as follows: (a) subdivide normative *hy* into *(hy)-Mg* and *(hy)-Fe* types; (b) assign provisional *tn´* to *tn*; (c) assign provisional *ab´* to *ab*; (d) assign provisional *or´* to *or* and *lc´* to *lc*; (e) assign provisional *wo´* to *wo*; (f) subdivide normative *di* into *(di)-Mg* and *(di)-Fe* types; (g) go to next step 37.

37. Conversion of normative minerals in % m/m units and the normative sum: The moles of all normative minerals are converted to % m/m by multiplying molar data by the respective mineral molecular weights (Tables 4 and 5). Note once again that for the user-option (A) to use only the eleven major oxides (SiO_2 to P_2O_5) in the norm, constant molecular weights are used for all normative minerals except for five FeO-bearing minerals. The results are rounded to three digits after the decimal point and reported.

On the other hand, for the other user-option (B) to use major as well as minor oxides and elements in the norm, the conversion is somewhat different. If there is free-O (*FREEO*) or free-CO_2 (*FREECO2*) available after norm computations, their amounts should be also converted to % m/m. The conversion of *FREECO2* is straight forward by multiplying it by its molecular weight (MW_{CO2} = 44.0095; Table 1). However, conversion of *FREEO* is more complicated and is explained in detail below (see Tables 1 and 4 for constant molecular weights used in these equations).

$$FREEO\_12b\ (\%\ m/m) = \{1+[(0.1)\times(((MW)_{(ap)-CaF2}/328.8691887)-1)]\}\times(AW)_O \times FREEO\_12b \quad (31)$$

$$FREEO\_12c\ (\%\ m/m) = \{1+[(0.1)\times(n_{(ap)-CaF2}/ap)\times(((MW)_{(ap)-CaF2}/328.8691887)-1)]\} \times(AW)_O\times FREEO\_12c \quad (32)$$

$$FREEO\_13\ (\%\ m/m) = \{1+[((MW)_{CaO}/56.0774)-1]\}\times(AW)_O\times FREEO\_13 \quad (33)$$

$$FREEO\_14\ (\%\ m/m) = \{1+[0.5\times(((MW)_{Na2O}/61.97894)-1)]\}\times(AW)_O \times FREEO\_14 \quad (34)$$

$$FREEO\_16\ (\%\ m/m) = \{1+[((MW)_{FeO}/71.8444)-1]\}\times(AW)_O\times FREEO\_16 \quad (35)$$

$$FREEO = FREEO\_12b + FREEO\_12c + FREEO\_13 + FREEO\_14 + FREEO\_16 \quad (36)$$

where all variables of equation 36 are in % m/m. $(AW)_O$ is the atomic weight of O (Table 1).

It should be noted that the conversion of *ap* is somewhat more complex. For the first two options described in step 12 [(a) and (b)], ap-CaO and ap-CaF_2 type molecular weights are used respectively (see Table 4). However, for option 12(c) the conversion is as follows:

$$ap(\%\ m/m) = [n_{(ap)-CaF2}\times(MW)_{ap-CaF2}] + [n_{(ap)-CaO}\times(MW)_{ap-CaO}] \quad (37)$$

Finally, for any of the two options (A or B) there might be unused or free oxides or elements, they are first converted to % m/m units and added together to be reported as FREEOX. The corresponding equations are as follows:

$$FREEP2O5(\%\ m/m) = 141.944522\times FREEP2O5 \quad (38)$$
$$FREEF\ (\%\ m/m) = 18.9984032\times FREEF \quad (39)$$
$$FREECL(\%\ m/m) = 35.4527\times FREECL \quad (40)$$
$$FREESO3(\%\ m/m) = 80.0642\times FREESO3 \quad (41)$$
$$FREES(\%\ m/m) = 32.066\times FREES \quad (42)$$

$$FREECR2O3(\%\ m/m) = 151.9904 \times FREE\ CR2O3 \quad (43)$$

$$FREEOX(\%\ m/m) = FREEP2O5 + FREEF + FREECL + FREESO3 + FREES + FREECR2O3 \quad (44)$$

When the silica deficiency could not be set to zero, there is a *DEFSIO2* which can be converted to % m/m units by multiplying it by the molecular weight of SiO_2 (MW_{SiO2} = 60.0843; Table 1).

The results of all normative minerals are rounded to four digits after the decimal point and reported. Similarly, the sum of all these variables, referred to as the sum of normative minerals (SUM_NORM), is rounded to three or four digits after the decimal point depending on the user-option and reported.

38. Test for correctness of normative sum: The sum of adjusted chemical data (SUM_ADJ from step 5 or SUM_MMT from step 6) should be around 100 (generally between 99.997 and 100.003). Similarly, the sum of normative minerals (SUM_NORM) should also be generally between 99.998 and 100.002 for any of the two user-options (A for major elements only, or B for major and minor or trace elements). This step compares these values and evaluates the correctness of SIN computations. The difference (SUM_NORM - SUM_MMT) can be called DIF_SUM. Values of this difference larger than about 0.01 are not likely.

39. Computation of other petrogenetically useful parameters: The parameters related to normative minerals (% m/m) can now be computed as follows:

$$Salic = q + or + ab + an \quad (45)$$

$$Femic = (di\text{-}Mg) + (di\text{-}Fe) + (hy\text{-}Mg) + (hy\text{-}Fe) + fo + fa + mt + il + hm \quad (46)$$

$$C.I. = an + 2.1570577(di\text{-}Mg) + fo + 0.7007616(hy\text{-}Fe) \quad (47)$$

$$D.I. = q + or + ab + ne + lc \quad (48)$$

where Salic = sum of salic normative minerals; Femic = sum of femic normative minerals, C.I. = crystallization index (Poldervaart and Parker, 1964); D.I. = differentiation index (Thornton and Tuttle, 1960). These values are reported after rounding to three digits after the decimal point, and the norm is now complete!

4. Applications to diverse chemical data

We have applied this procedure to compute the CIPW norm using a compilation of 289 samples of very diverse rock types (see Table 6 for a complete listing of literature references). Most compiled rocks are volcanic in origin; however, some intrusive samples were included, specifically ultramafic ones, to reach a complete compositional range. All samples are plotted in Fig. 1, which shows that our present test database is representative of the diversity of volcanic rocks because all TAS fields are included in our compilation.

CIPW norm calculations

Normative mineral contents were first calculated for all samples (n=289) in the database using only major elements. A synthesis is presented in Table 7, which shows that all types of magmas (e.g., 122 quartz-normative, 102 nepheline-normative, 187 hypersthene-normative, 165 olivine-normative samples) are represented in our database. These results were compared to the literature data for all those cases (106 samples) for which the complete CIPW norm was also reported by the original authors (Fig. 2). Samples with complete chemical analyses (major, minor, and trace elements; 188 samples) were also used to calculate normative minerals using all elements listed in Table 1. These results were then compared to the calculations using only the major elements (Fig. 3).

The differences between the sums of all normative mineral contents from the literature and 100 (the latter taken as the "ideal" sum of normative minerals) are extremely large, because they vary up to about ± 8 (Fig. 2a). More importantly, there is a marked skewness towards lower percentages, indicating that many existing CIPW norm programs give sums of normative minerals significantly lower than 100%. Our proposed procedure, on the other hand, gives very small differ-

Table 6 Literature references (in chronological order) and compiled database used for application of proposed standard igneous norm and rock classification system.

Reference	# Samples compiled	More information on these compiled samples
Kelsey (1965)	1	Table 3, p. 281
Irvine and Barragar (1971)	27	Table of typical analyses, p. 546
Middlemost (1975)	9	Table 1, p. 341, Table 2, p. 347, Table 3, p. 351
Till (1977)	5	Table 10, p. 228
Cox et al. (1979)	10	Appendix 2, pp. 402-405
Basaltic Volcanism Study Project (1981)	56	Tables 1.2.1.4, pp. 14-15, 1.2.1.5a, p. 16, 1.2.2.8, p. 50, 1.2.2.13a, p. 57, 1.2.6.2, p. 166-167
Mahood (1981)	29	Table 6, p. 135, Table 7, pp. 136-137
Glazner (1984)	2	Table 1, p. 449
Hatcher et al. (1984)	6	Table 1B, p. 495
Le Maitre (1984)	22	Appendix, pp. 250-255
Wörner and Schmincke (1984)	5	Table 1, p. 812-814
Fears (1985)	1	Table 1, p. 787
Price et al. (1985)	14	Table 6, 7 and 8, p. 401-403
Ferriz and Mahood (1987)	5	Table 5, p. 184, Table 6, pp. 186-187, Table 7, p. 188, Table 8, p. 189
Le Bas (1989)	6	Table 3, p. 1306, Table 4, p. 1307, Table 5, p. 1308
Frey et al. (1990)	4	Table 1b, p. 1278
Camp et al. (1992)	11	Table 3, p. 386.
Chai and Naldrett (1992)	5	Table 1, p. 288-289
Heinrich and Besch (1992)	4	Table 1, p. 128
Haase et al. (1996)	8	Table 3, p. 226
Liou and Zhang (1998)	4	Table 1, p. 120
Ho et al. (2000)	4	Table 7, p. 367
Kamenetsky et al. (2000)	1	Table 1, p. 418
Morris et al. (2000)	30	Table 1, pp. 49, 51, 53
Panter et al. (2000)	5	Table 2, pp.220-221
Sachs and Hansteen (2000)	2	Table 4, p. 350
Verma (2000)	13	Table 1, p. 38, Table 3, p. 42

Table 7 Comparison of normative minerals and their abundances obtained from standard igneous norm (SIN) for those samples for which CIPW norm data were reported in the literature.

Normative	Number of samples *			Statistical information **				
mineral	$(n_{tot})_{tw}$	n_{tw}	n_{Lit}	Δ_{min}	Δ_{max}	n_{stat}	$\bar{x}$	σ
Quartz (q)	122	31	30	–45.8 (–100.0)	93.9 (1253)	28	5.7	31.5
Orthoclase (or)	276	101	102	–67.7 (–67.7)	8.5 (208)	100	–1.6	7.8
Albite (ab)	269	99	99	–13.3 (–13.3)	57.2 (506)	98	2.6	12.7
Anorthite (an)	235	91	91	–38.1 (–100.0)	8.5 (8.5)	90	–1.2	4.4
Leucite (lc)	18	7	7	–17.6 (–58.0)	18.7 (4186)	5	–0.4	13.0
Nepheline (ne)	102	59	61	–81.4 (–100.0)	124.9 (346.8)	56	2.8	30.6
Corundum (c)	21	7	6	–0.9 (–100.0)	15.8 (15.8)	6	3.2	6.3
Acmite (ac)	54	15	19	–68.5 (–100.0)	54.2 (54.2)	14	-8.3	33.4
Diopside (di)	265	98	99	–64.1 (64.1)	27.9 (692)	96	-3.2	10.2
Hypersthene (hy)	187	47	45	–82.8 (–100.0)	78.6 (78.6)	44	–12.7	31.8
Olivine (ol)	165	75	73	–90.7 (–100.0)	87.4 (469)	71	–3.7	32.7
Magnetite (mt)	245	97	95	–89.6 (–100.0)	177.1 (177.1)	93	4.0	57.8
Ilmenite (il)	286	106	106	–11.6 (–11.6)	33.3 (33.3)	106	–0.3	4.0
Apatite (ap)	255	105	105	–11.5 (–11.5)	13.3 (13.3)	105	0.5	3.7

* Number of samples processed is as follows: $(n_{tot})_{tw}$ = number of normative minerals (SIN) obtained in this work ($_{tw}$ = this work) for all samples compiled in this work (total number of samples processed, n_{tot} = 289); n_{tw} = number of normative minerals (SIN) obtained in this work for only those samples for which there are CIPW data available in the literature (total number of such samples processed = 106); n_{Lit} = number of normative minerals (CIPW) reported in the literature (total number of such samples reported = 106).

** $\Delta = 100*[(A_{mineral})_{Lit} - (A_{mineral})_{tw}]/(A_{mineral})_{tw}$ where $(A_{mineral})_{Lit}$ is the abundance of normative mineral reported in the literature and $(A_{mineral})_{tw}$ is that computed in this work. The subscript $_{min}$ and $_{max}$ refer to the minimum and maximum values of Δ. See text for discussion: n_{stat} = number of samples used for statistical calculations of Δ values; $\bar{x}$ = arithmetic mean of Δ values; σ = standard deviation of Δ values.

ences (most values within ± 0.002, close to the rounding errors) between the sum of normative minerals and 100 (Fig. 2b).

Figure 3 shows three histograms of the differences between the sum of normative minerals and the bulk chemical analysis (adjusted to 100% on an anhydrous basis). The first histogram (Fig. 3a) shows the distribution of these differences for all 289 samples compiled for this work, whereas the second histogram (Fig. 3b) is for 188 samples with reported minor components. Once again, there are extremely small differences of about ± 0.002 that can be readily explained by rounding errors (Fig. 3a and 3b). When the samples with minor components are processed using the option B with major, minor, and trace elements (Fig. 3c), the resulting normative sums show small differences, ranging in most cases between –0.002 and +0.002, with the exception of three observations which range from –0.006 to –0.009. All histograms are ±symmetrically distributed, implying that these differences are related to random errors, probably due to rounding procedures used for presenting normative mineral contents with three digits after the decimal point. We conclude, therefore, that the SIN procedure presented here gives reliable and consistent results for normative minerals. This is true even for samples with extreme chemical compositions, such as ultrabasic rocks.

Those samples, for which CIPW norm was reported in the literature (n = 106), were processed by the SIN procedure and compared in Table 7. The number of samples for a given normative mineral is rather similar in both CIPW (literature) and SIN (this work) procedures (see n_{tw} and n_{Lit} columns in Table 7). Small differences, however, do exist, for example, out of 106 samples processed, 31 samples with normative quartz are obtained by SIN as compared to 30 samples reported in the literature. Similarly, 15 samples with normative acmite are obtained by SIN, whereas 19 were reported in the literature.

In order to compare quantitatively the amount of main normative minerals calculated with the procedure proposed here, to that reported in the literature, relative differences (in terms of Δ values) are calculated using the equation given in the footnote of Table 7. Large differences between these amounts of most normative minerals (Literature versus this work) exist (see Δ_{min} and Δ_{max} columns in Table 7). For example, for quartz these differences varied from –100.0 to 1253 (see values

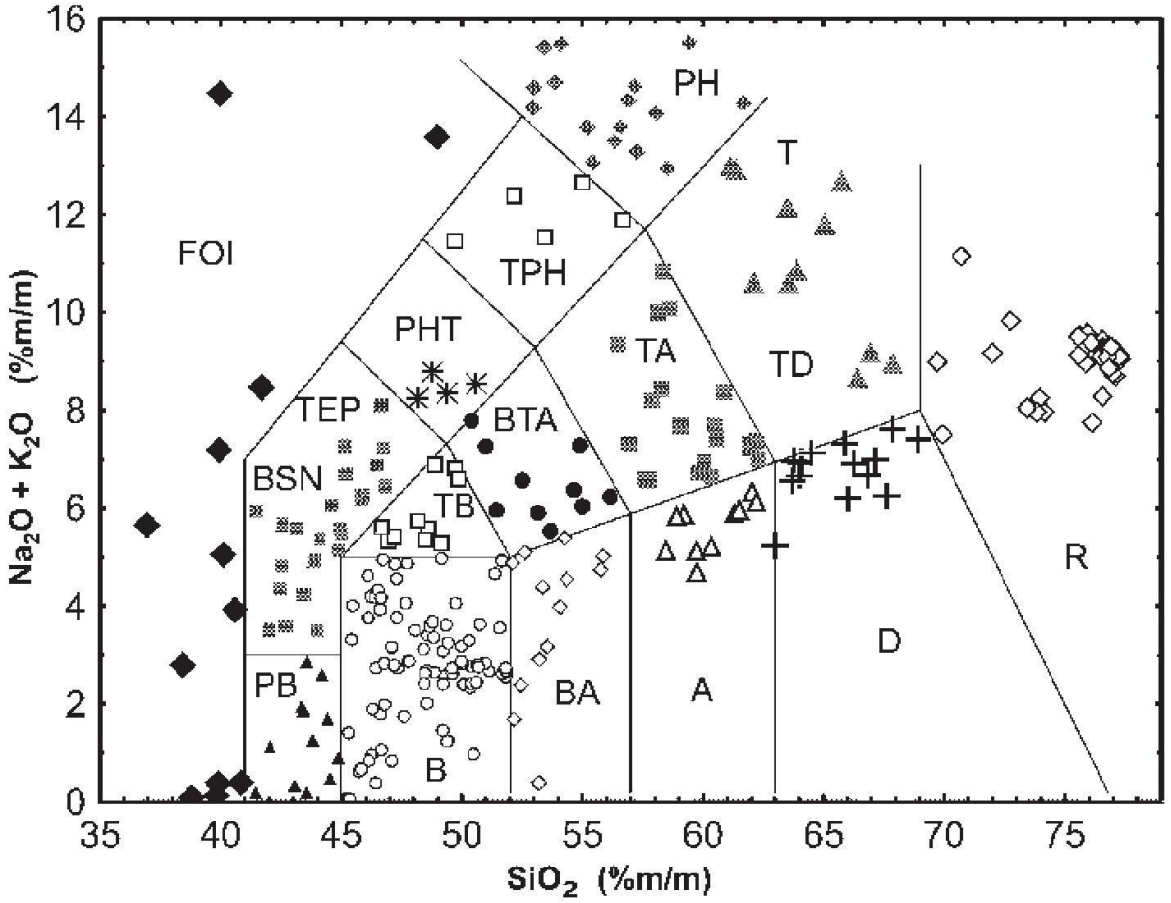

Fig. 1 TAS classification of 289 selected volcanic rocks from the literature data. See Table 6 for the references from which these test data were compiled; also note that different symbols are used for different rock types. Rock abbreviations are as follows: A — Andesite, B — Basalt, BA — Basaltic andesite, BSN — Basanite, BTA — Basaltic trachyandesite, D — Dacite, FOI — Foidite, PB — Picrobasalt, PH — Phonolite, PHT — Phonotephrite, R — Rhyolite, T — Trachyte, TA — Trachyandesite, TB — Trachybasalt, TD — Trachydacite, TEP — Tephrite, TPH — Tephriphonolite.

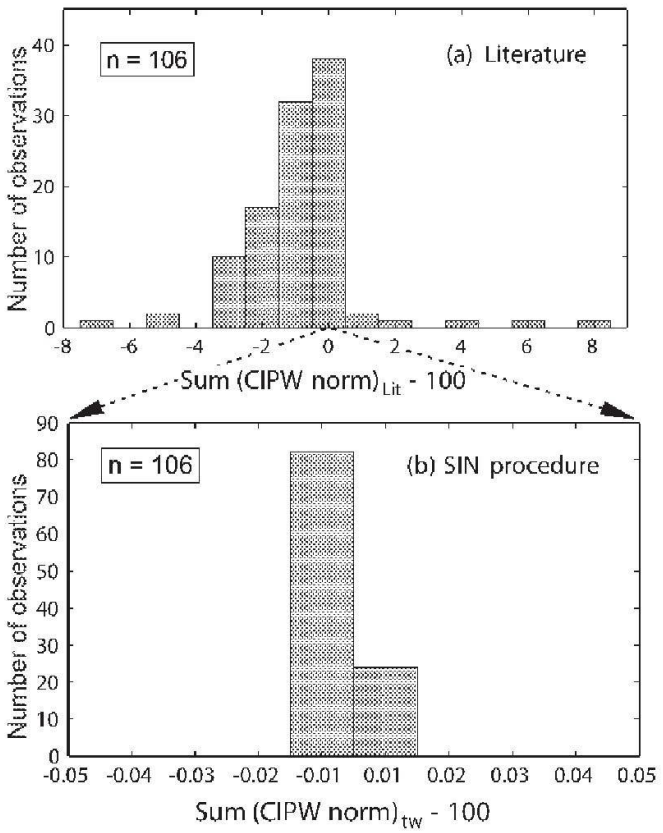

Fig. 2 Histogram of actual differences between total amount of normative minerals compiled from the literature and 100 taken as the "ideal" amount of norm minerals.

in parentheses), and for nepheline Δ values ranged from –100.0 to 346.8. Note that the value –100.0 will be obtained for those samples for which a particular normative mineral was not calculated in the literature (see the definition of Δ notation in Table 7). Such values (–100.0) as well as some extreme values (such as 1253 for quartz) were not included in the statistical calculations presented in Table 7 (n_{stat}, mean and standard deviation of Δ values were based on the Δ_{min} and Δ_{max} values outside parentheses). The outlier nature of such values is graphically visualized in Fig. 4 where the differences for normative minerals between the total amounts reported in the literature and those calculated using our system (Δ parameter) are plotted. Most minerals show significant differences, which range from about +177% to about –90% (see data outside parentheses in Δ_{min} and Δ_{max} columns in Table 7). Besides quartz and nepheline, larger differences are generally observed in the amount of Fe- and Mg-bearing normative minerals (compare or, ab, and an to hy, ol, and mt; Fig. 4). All these discrepancies are probably due to the combination of the following aspects. First, significant differences will arise from the diversity of atomic weights used in the norm programs, as they are used for calculating the molecular proportions of elements and oxides present in rock analysis. We, therefore, recommend (and include in our SIN procedure) the most recent and accurate atomic weights reported in the literature (Vocke, 1999). A wrong mineral formula and corresponding molecular weight for apatite used in most existing programs is also a factor contributing to these differences. Secondly, important changes in the norm arise when the recalculation of the chemical analyses to 100% on an anhydrous basis is omitted. Thirdly, another important aspect to consider is the iron-oxidation ratio used to recalculate the chemical analyses, because it will influence the amount of Fe^{2+} and Fe^{3+} present during the norm calculation. The same observations apply to FeO/MgO ratio, which will affect the calculations of important minerals such as diopside, olivine, and hypersthene, the last two minerals being also critical for rock classification. Since our application makes use of the iron ratios suggested by Middlemost (1989),

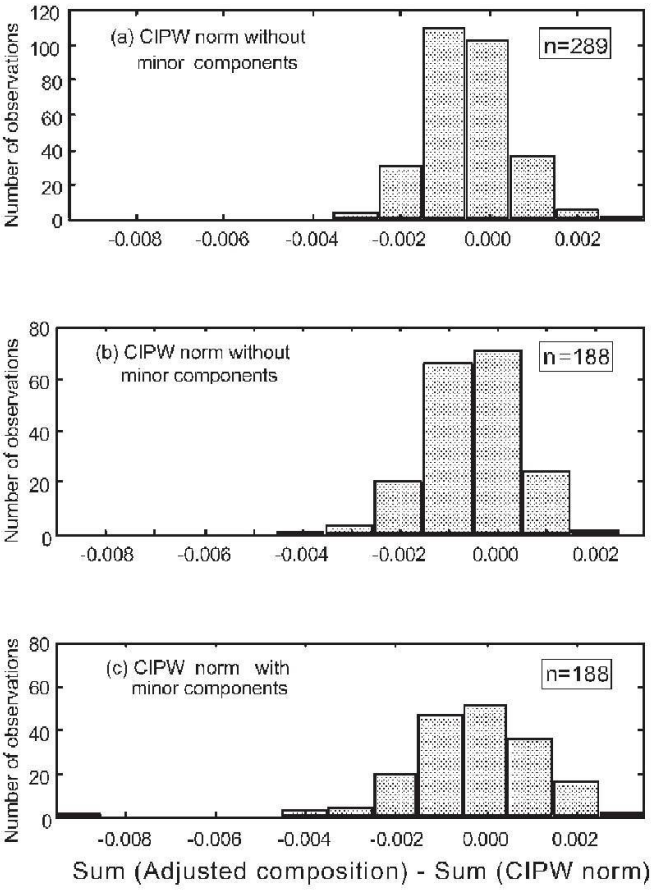

Fig. 3 Histograms of actual differences between the sums of the normative mineral contents and the bulk analysis compositions (adjusted to 100% on an anhydrous basis). (a) Norm calculations using only major elements for all compiled samples (n=289); (b) norm calculations considering only major elements for those samples where trace elements were reported as well (n=188); (c) norm calculations considering major, minor and trace elements for the same samples considered in Figure 3b.

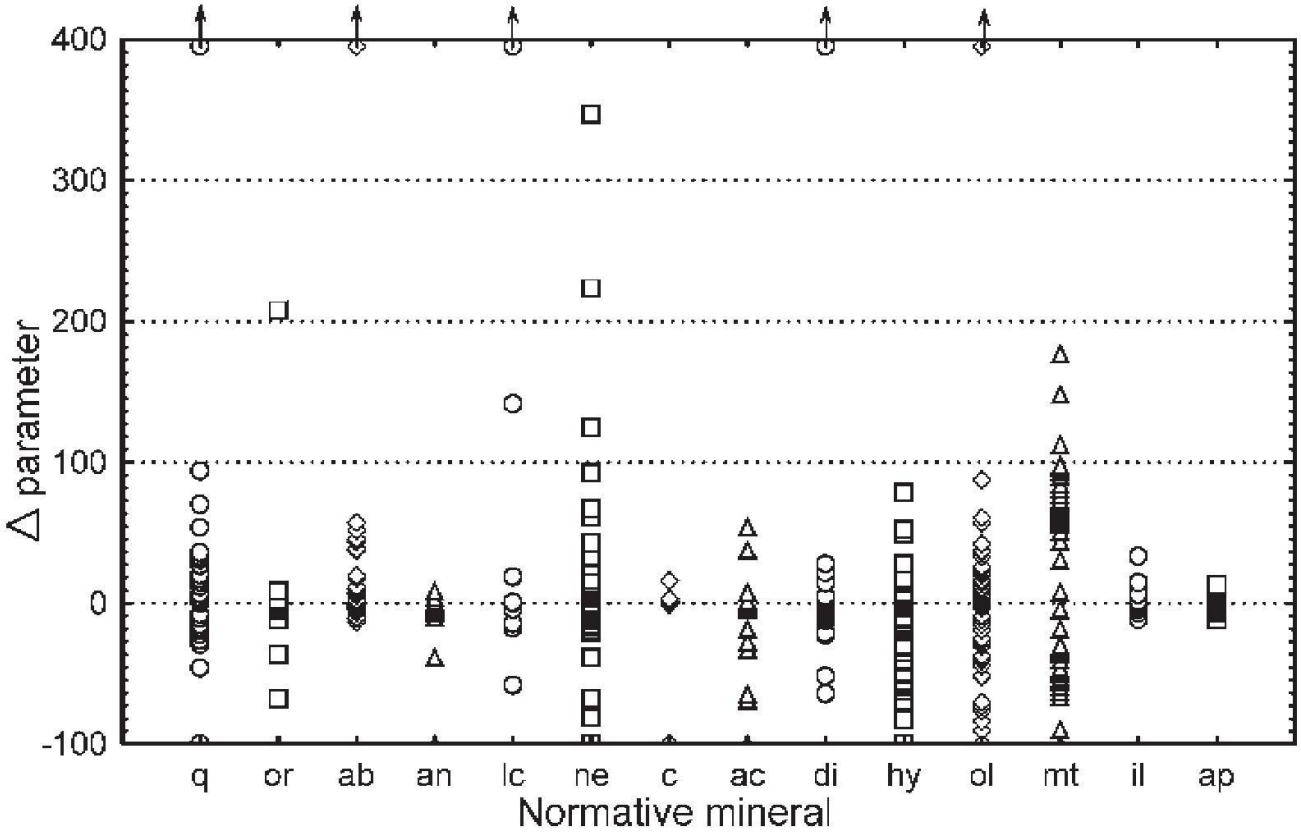

Fig. 4 Relative differences (%) between the amount of calculated normative minerals reported in the literature and that using the SIN procedure proposed here, referred as the "Δ parameter", defined in Table 7 (see footnote). Arrows indicate the existence of some values falling outside the field of this figure. These values are: 1253 for quartz, 506 for albite, 4186 for leucite, 428 and 692 for diopside, and 469 for olivine. See Table 7 for mineral abbreviations.

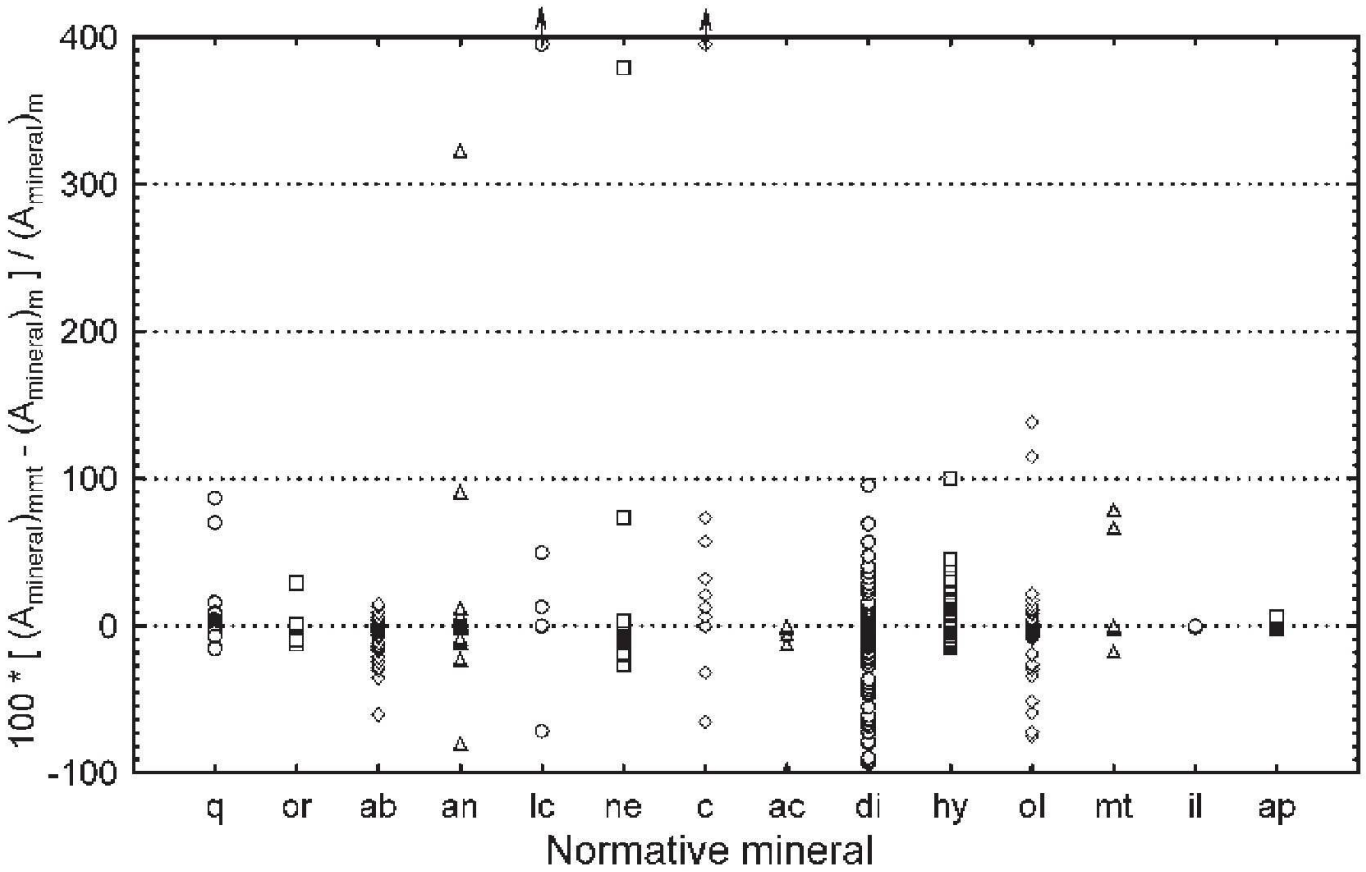

Fig. 5 Relative differences (%) between the amount of calculated normative minerals ($A_{mineral}$) using major, minor, and trace elements (mmt) and that using only major elements (m). See Table 7 for mineral abbreviations. Arrows indicate the existence of some values falling outside the field of this figure. These values are: 586 for leucite, and 415 and 662 for corundum.

which are the lowest values (fresh rock equivalent) for a given rock type, the quotient Fe_2O_3/FeO will be close to that ratio for a fresh rock of similar composition. This might be the reason why no sample was calculated with normative hematite in our database using iron ratios proposed by Middlemost (1989). On the contrary, using the options of Le Maitre (Le Maitre, 1976) and "Measured" Fe_2O_3 and FeO concentrations did show hematite in the norm of some samples. Finally, because quartz and nepheline are calculated towards the end of the norm procedure (steps 28 and 31, respectively), their amounts will be more variable than those for other normative minerals (see Table 7). This late calculation is inevitable because silica saturation and consequent normative quartz formation cannot be known before step 28, until silica requirements for all normative minerals are fulfilled. On the other hand, silica-undersaturation and consequent normative nepheline formation (step 31) can be accomplished only after silica deficiency is diminished by replacing silica-containing minerals to less-silica demanding minerals, viz., hypersthene to olivine (step 29), and sphene to perovskite (step 30).

In Figure 5, the amounts of normative minerals calculated using option B (with all major, minor, and trace elements) are compared with those using option A (with only the eleven major elements). Important differences are observed for all minerals, except ilmenite and apatite. These discrepancies range between +586% and –97%, showing the largest differences for anorthite, leucite, nepheline, corundum, diopside, and olivine. Considering that the differences between the sum of normative minerals calculated by our system and that of the chemical analyses are never larger than ±0.009 (generally less than ±0.002; Fig. 2), these discrepancies (Fig. 5) are not due to errors in the norm calculation. In fact, such small differences (Fig. 2) show the relevance of using variable molecular weights during CIPW norm calculations.

5. Computer programs

Several authors have written programs for CIPW norm computations (see Verma et al., 2002 for an extended discussion); including Hey et al. (1966); Le Maitre (1969 program version, cited in Fitzgerald and Mackinnon, 1977; and 1990 program version, Le Maitre, written communication, 2001); Till (1977); Wheeler (1978); Bickle (1979); Glazner (1984); Fears (1985); and Verma et al. (1986). Although most of the existing CIPW norm programs are based on the norm computation scheme described by Kelsey (1965), none of them, including the public domain packages IGPET and Newpet, and commercial packages such as MINPET, provide consistent results. This may be partially due to the fact that many of these programs were created to calculate the CIPW norm for a limited compositional range of volcanic rocks, resulting in significant inconsistency among programs. An exception is probably the Le Maitre's program (Le Maitre, written communication, 2001).

The SIN procedure presented here has been incorporated in a new computer program called SINCLAS (Verma et al., 2002), available from I. S. Torres-Alvarado or S. P. Verma, or else can be downloaded from http://www.iamg.org/CGEditor/index.htm. We propose that geologists use one of the two extreme options for the CIPW norm computations: (A) Use of only the eleven major elements from SiO_2 to P_2O_5; (B) Use of all major, minor, and trace elements (Table 1), as suggested by Middlemost (1989).

6. Conclusions

The existing CIPW norm computation procedure was significantly modified in order to take into account minor chemical constituents in the normative amounts of rock-forming minerals, variable molecular weights for oxides and minerals, and mass-balance principles. This thoroughly revised standard igneous norm (SIN) scheme for CIPW norm calculations yields in most cases sums of normative minerals within ±0.002, when compared to the bulk chemical analysis used for the norm computation. There are numerous important modifications incorporated in the SIN procedure that can now be considered as a standard CIPW norm.

The procedure presented here has been applied to a large database of mostly volcanic rocks with a wide compositional range. Important discrepancies were observed between the normative mineral concentrations reported in the literature and those calculated with the procedure proposed here. These dissimilarities are due to a combination of several factors, such as differences in the atomic weights used for the computation, different approaches to calculate the Fe_2O_3 to FeO ratio, and adjustment to 100% on an anhydrous basis before norm computation and rock classification. Important differences are introduced when the norm is calculated considering also the minor and trace elements. The significant differences in the concentration of normative minerals between the use of only major elements and that of all ma-

jor, minor, and trace elements require that petrologists use only one of these two options throughout their study, and state clearly which of the two options was used.

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References

Basaltic Volcanism Study Project (1981): Basaltic Volcanism on the Terrestrial Planets. Pergamon, New York. 1286 pp.

Bevington, P.R. (1969): Data Reduction and Error Analysis for the Physical Sciences. McGraw Hill, New York. 336 pp.

Bickle, C.E. (1979): The CIPW normative calculation. *J. Geol. Edu.* **27**, 80–82.

Brooks, C.K. (1976): The Fe_2O_3/FeO ratio of basaltic analyses: an appeal for a standardized procedure. *Bull. Soc. Geol. Denmark* **25**, 117–120.

Camp, V.E., Roobol, M.J. and Hooper, P. R. (1992): The Arabian continental alkali basalt province: Part III. Evolution of Harrat Kishb, Kingdom of Saudi Arabia. *Geol. Soc. Am. Bull.* **104**, 379–396.

Chai, G. and Naldrett, A.J. (1992): The Jinchuan ultramafic intrusion: cumulate of a high-Mg basaltic magma. *J. Petrol.* **33**, 277–303.

Coombs, D.S. (1963): Trends and affinities of basaltic magmas and pyroxenes as illustrated on the diopside – olivine – silica diagram. *Min. Soc. Am. Spec. Paper* **1**, 227-250.

Cox, K.G., Bell, J.D. and Pankhurst, R.J. (1979): The Interpretation of Igneous Rocks. Allan & Unwin, London. 450 pp.

Cross, W., Iddings, J.P., Pirsson, L.V. and Washington, H.S. (1902): A quantitative chemico-mineralogical classification and nomenclature of igneous rocks. *J. Geol.* **10**, 555–690.

Fears, D. (1985): A corrected CIPW norm program for interactive use. *Comput. Geosci.* **11**, 787–797.

Ferriz, H. and Mahood, G.A. (1987): Strong compositional zonation in a silicic magmatic system: Los Humeros, Mexican Neovolcanic Belt. *J. Petrol.* **28**, 171–209.

Fitzgerald, J.D. and Mackinnon, I.D.R. (1977): PETPAK – a computing package for the petrologist. *Comput. Geosci.* **3**, 637–638.

Frey, F.A., Wise, W.S., Garcia, M.O., West, H., Kwon, S.-T. and Kennedy, A. (1990): Evolution of Mauna Kea volcano, Hawaii: petrologic and geochemical constraints on postshield volcanism. *J. Geophys. Res.* **95**, 1271–1300.

Glazner, A.F. (1984): A short CIPW norm. *Comput. Geosci.* **10**, 449–450.

Hatcher, Jr., R.D., Hooper, R.J., Petty, S. M. and Willis, J.D. (1984): Structure and chemical petrology of three southern Appalachian mafic-ultramafic complexes and their bearing upon the tectonics of emplacement and origin of Appalachian ultramafic bodies. *Am. J. Sci.* **284**, 484–506.

Haase, K.M., Devey, C.W., Mertz, D.F., Stoffers, P. and Garbe-Schönberg, D. (1996): Geochemistry of lavas from Mohns Ridge, Norwegian-Greenland Sea: implications for melting conditions and magma sources near Jan Mayen. *Contrib. Mineral. Petrol.* **123**, 223–237.

Heinrich, W. and Besch, T. (1992): Thermal history of the upper mantle beneath a young back-arc extensional zone: ultramafic xenoliths from San Luis Potosí, central Mexico. *Contrib. Mineral. Petrol.* **111**, 126–142.

Hey, M.H., Le Maitre, R.W. and Butler, B.C.M. (1966): A versatile computer program for the recalculation of rock and mineral analyses. *Mineral. Mag.* **35**, 788.

Ho, K.-S., Chen, J.-C., Smith, A.D. and Juang, W.-S. (2000): Petrogenesis of two groups of pyroxenite from Tungchihsu, Penghu Islands, Taiwan Strait: implications for mantle metasomatism beneath SE China. *Chem. Geol.* **167**, 355–372.

Hughes, C.J. and Hussey, E.M. (1976): M and Mg values in igneous rocks; proposed usage and a comment on currently employed Fe_2O_3 corrections. *Geochim. Cosmochim. Acta* **40**, 485–486.

Hughes, C.J. and Hussey, E.M. (1979): Standardized procedure for presenting corrected Fe_2O_3/FeO ratios in analyses of fine grained mafic rocks. *N. Jb. Mineral. (Mh.)* **12**, 570–572.

Hutchison, C.S. (1974): Laboratory Handbook of Petrographic Techniques. John Wiley, New York. 527 pp.

Irvine, T.N. and Baragar, W.R.A. (1971): A guide to the chemical classification of the common volcanic rocks. *Can. J. Earth Sci.* **8**, 523–548.

Johannsen, A. (1931): A Descriptive Petrography of the Igneous Rocks. Vol. 1. Chicago University Press, Chicago. 267 pp.

Kamenetsky, V.M., Everard, J.L., Crawford, A.J., Varne, R., Eggins, S.M. and Lanyon, R. (2000): Enriched end-member of primitive MORB melts: petrology and geochemistry of glasses from Macquarie Island (SW Pacific). *J. Petrol.* **41**, 411–430.

Kelsey, C.H. (1965): Calculation of the C.I.P.W. norm. *Mineral. Mag.* **34**, 276–282.

Kuno, H. (1959): Origin of Cenozoic petrographic provinces of Japan and surrounding areas. *Bull. Volcanol.* **20**, 37–76.

Le Bas, M.J. (1989): Nephelinitic and basanitic rocks. *J. Petrol.* **30**, 1299–1312.

Le Bas, M.J. (2000): IUGS reclassification of the high-Mg and picritic volcanic rocks. *J. Petrol.* **41**, 1467–1470.

Le Bas, M.J., Le Maitre, R.W., Streckeisen, A. and Zanettin, B. (1986): A chemical classification of volcanic rocks on the total alkali-silica diagram. *J. Petrol.* **27**, 745–750.

Le Maitre, R.W. (1976): Some problems of the projection of chemical data into mineralogical classifications. *Contrib. Mineral. Petrol.* **56**, 181–189.

Le Maitre, R.W. (1982): Numerical petrology. Elsevier, Amsterdam. 282 pp.

Le Maitre, R.W. (1984): A proposal by the IUGS Subcommission on the systematics of igneous rocks for a chemical classification of volcanic rocks based on the total alkali silica (TAS) diagram. *Austral. J. Earth Sci.* **31**, 243–255.

Le Maitre, R.W., Bateman, P., Dudek, A., Keller, J., Lameyre, J., Le Bas, M.J., Sabine, P.A., Schmid, R., Sorensen, H., Streckeisen, A., Woolley, A.R. and Zanettin, B. (1989): A Classification of Igneous Rocks and Glossary of Terms. Blackwell, Oxford. 193 pp.

Liou, J.G. and Zhang, R.Y. (1998): Petrogenesis of an ultrahigh-pressure garnet-bearing ultramafic body from Maowu, Dabie mountains, east-central China. *Island Arc* **7**, 115–134.

Mahood, G.A. (1981): Chemical evolution of a Pleistocene rhyolite center: Sierra La Primavera, Jalisco, México. *Contrib. Mineral. Petrol.* **77**, 129–149.

Middlemost, E.A.K. (1972): A guide to the chemical classification of the common igneous rocks. *Bull. Volcanol.* **36**, 382–397.
Middlemost, E.A.K. (1975): The basalt clan. *Earth-Sci. Rev.* **11**, 337–364.
Middlemost, E.A.K. (1980): A contribution to the nomenclature and classification of volcanic rocks. *Geol. Mag.* **117**, 51–57.
Middlemost, E.A.K. (1989): Iron oxidation ratios, norms and the classification of volcanic rocks. *Chem. Geol.* **77**, 19–26.
Morris, G.A., Larson, P.B. and Hooper, P.R. (2000): 'Subduction style' magmatism in a non-subduction setting: the Colville igneous complex, NE Washington State, USA. *J. Petrol.* **41**, 43–67.
Panter, K.S., Hart, S.R., Kyle, P., Blusztanjn, J. and Wilch, T. (2000): Geochemistry of late Cenozoic basalts from the Crary mountains: characterization of mantle sources in Marie Byrd Land, Antarctica. *Chem. Geol.* **165**, 215–241.
Poldervaart, A. and Parker, A.B. (1964): The crystallization index as a parameter of igneous differentiation in binary variation diagrams. *Am. J. Sci.* **262**, 281–289.
Price, R.C., Johnson, R.W., Gray, C.M. and Frey, F.A. (1985): Geochemistry of phonolites and trachytes from the summit region of Mt. Kenya. *Contrib. Mineral. Petrol.* **89**, 394–409.
Ragland, P.C. (1989): Basic Analytical Petrology. Oxford University Press, Oxford. 369 pp.
Rittmann, A. (1973): Stable mineral assemblages of igneous rocks. Springer, Berlin. 262 pp.
Rollinson, H.R. (1993): Using geochemical data: evaluation, presentation, interpretation. Longman, Essex. 352 pp.
Sachs, P.M. and Hansteen, T.H. (2000): Pleistocene underplating and metasomatism of the lower continental crust: a xenolith study. *J. Petrol.* **41**, 331–356.
Thornton, C.P. and Tuttle, O.F. (1960): Chemistry of igneous rocks. I. Differentiation index. *Am. J. Sci.* **258**, 664–684.
Till, R. (1977): The HARDROCK package, a series of Fortran IV computer programs for performing and plotting petrochemical calculations. *Comput. Geosci.* **3**, 185–243.
Verma, M.P., Aguilar-Y-Vargas, V.H. and Verma, S.P. (1986): A program package for major element data handling and CIPW norm calculation. *Comput. Geosci.* **12**, 381–399.
Verma, S.P. (2000): Geochemical evidence for a lithosphere source of magmas from Los Humeros caldera, Puebla, Mexico. *Chem. Geol.* **164**, 35–60.
Verma, S.P., Torres-Alvarado, I.S. and Sotelo-Rodríguez, Z.T. (2002): SINCLAS: Standard Igneous Norm and Volcanic Rock Classification System. *Comput. Geosci.* **28**, 711–715.
Vocke, Jr., R.D. (1999): IUPAC Commission on Atomic Weights and Isotopic Abundances-Atomic weights of the elements 1997. *Pure Appl. Chem.* **71**, 1593–1607.
Washington, H.S. (1930): The chemical analysis of rocks. Wiley, New York. 296 pp.
Wheeler, J.F. (1978): Comments on HARDROCK. *Comput. Geosci.* **4**, 372.
Wörner, G. and Schmincke, H.-U. (1984): Mineralogical and chemical zonation of the Laacher See tephra sequence (East Eifel, W. Germany). *J. Petrol.* **25**, 805–835.
Wright, J.B. (1969): A simple alkalinity ratio and its application to questions of non-orogenic granite genesis. *Geol. Mag.* **106**, 370–384.

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