A simple and robust method for calculating temperatures of granitoid magmas

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Abstract
Calculating the temperatures of magmas from which granitoid rocks solidify is a key task of studying their petrogenesis, but few geothermometers are satisfactory. Zircon saturation thermometry has been the most widely used because it is conceptually simple and practically convenient, and because it is based on experimental calibrations with significant correlation of the calculated zircon saturation temperature \( T_{Zr} \) with zirconium (Zr) content in the granitic melt (i.e., \( T_{Zr} \propto Zr_{MELT} \)). However, application of this thermometry to natural rocks can be misleading, resulting in the calculated \( T_{Zr} \) having no geological significance. This thermometry requires Zr content and a compound bulk compositional parameter \( M \) of the melt as input variables. As the Zr and \( M \) information of the melt is not available, petrologists simply use bulk-rock Zr content (\( Zr_{BULK-ROCK} \)) and \( M \) to calculate \( T_{Zr} \). In the experimental calibration, \( T_{Zr} \) shows no correlation with \( M \), thus the calculated \( T_{Zr} \) is only a function of \( Zr_{MELT} \). Because granitoid rocks represent cumulates or mixtures of melt with crystals before magma solidification and because significant amount Zr in the bulk-rock sample reside in zircon crystals of varying origin (liquidus, captured or inherited crystals) with unknown modal abundance, \( Zr_{BULK-ROCK} \) cannot be equated with \( Zr_{MELT} \) that is unknown. Hence, the calculated magma temperatures \( T_{Zr} \) using \( Zr_{BULK-ROCK} \) have no significance in both theory and practice. As an alternative, we propose to use the empirical equation \( T_{SiO_2} (°C) = -14.16 \times SiO_2 + 1723 \) for granitoid studies, not to rely on exact values for individual samples but focus on the similarities and differences between samples and sample suites for comparison. This simple and robust thermometry is based on experimentally determined phase equilibria with \( T \propto 1/SiO_2 \).

Keywords Zircon saturation thermometry · Magma temperature · Granitoid magmatism · SiO₂ approximation for magma temperature

Introduction
In studying the petrogenesis of magmatic rocks, determination of magma temperature is one of the basic tasks. This is relatively straightforward for basalts and basaltic rocks because of the experimentally well-established phase relationships between the liquidus phases such as olivine, clinopyroxene and plagioclase and the melt as a function of temperature (e.g., Roeder and Emslie 1970; Bender et al. 1978; Walker et al. 1979; Langmuir and Hanson 1981; Nielsen and Dungan 1983; Weaver and Langmuir 1990; Grove et al. 1992). The magma temperature is essentially linearly proportional to the MgO content of the melt, which is the MgO content of quenched basaltic glasses (or approximated with aphyric basalts or groundmass of basalts) (Niu et al. 2002). To calculate the magma temperatures of granites and granitic rocks is not straightforward despite their inverse
correlation with SiO$_2$ content of the melt (Bowen 1928; Tuttle and Bowen 1958). The difficulty is several fold: (1) with the exception of highly evolved granites and rhyolitic glasses, most granites and granitoid rocks do not represent melts but are cumulates (Niu et al. 2013; Chen et al. 2015, 2016; Lee and Morton 2015; Barnes et al. 2019) or melt-solid mixtures because of incomplete melt-solid separation during melt extraction (containing restite minerals/lithic fragments, Clemens and Stevens 2012) and magma (i.e., crystal mush) evolution owing to high melt viscosity; (2) mineral pairs with temperature-sensitive exchange reactions in granitic rocks, if any (e.g., two-feldspar thermometry, Brown and Parsons 1981; Kroll et al. 1993; Benisek et al. 2004, 2010; Anderson et al. 2008), record temperatures of sub-solidus equilibrium, rather than liquidus temperatures (i.e., melt temperatures of mineral crystallization).

This difficulty has been largely overcome by the zircon saturation thermometry thanks to the meticulous experimental calibration by Watson and co-workers (Watson 1979; Watson and Harrison 1983, 1984; Boehnke et al. 2013). This thermometry has been widely used and is considered to “provide a simple and robust means of estimating magma temperatures” (Miller et al. 2003). We agree that the concept of the zircon saturation thermometry is sound, and the experimental calibration is robust by Watson and co-workers (Watson 1979; Watson and Harrison 1983, 1984; Boehnke et al. 2013). Rearranging this equation enables direct calculation of the temperature of the granitic melts (Miller et al. 2003):

\[ T_{Zr} = \frac{12900}{\left[ \ln(D_{Zr}) + 0.85M + 2.95 \right]} \]  

(2)

Because Zr in zircon is stoichiometrically constant (~497,000 ppm), $D_{Zr}$ is solely a function of $Zr_{MELT}$ and $T_{Zr}$ is thus a function of Zr content and $M$ value of the melt. This means that if magmas parental to granitic rocks under study are known to be saturated with zircon and if bulk-rock compositions can be approximated as representing the melt, then the magma temperatures can be calculated using Eq. (2), as widely used over the last decades since 1983.

The assumption of zircon saturation is readily proven because of the widespread occurrence of zircon crystals with crystallization ages (at least at the rims and edges of zircon crystals) in all granite and granitoid samples. However, the assumption that the bulk-rock compositions represent melt compositions cannot be true in almost all cases (see above). If granitoids are proven not to represent melt compositions, then Eq. (2) fails simply because neither $D_{Zr}$ nor $M$ is meaningful. Hence, the zircon saturation thermometry, despite its thermodynamic and experimental footing, cannot be used in practice to calculate the temperatures of magmas parental to granitoid rocks. The problem is serious and is multi-fold.

Although widely used, the bulk-rock Zr content ($Zr_{BULK-ROCK}$) is not $Zr_{MELT}$, but the sum of Zr in zircon crystals and Zr in the rest of the rock. One could assume the latter as representing the melt if the rock is highly evolved, but its Zr content cannot be determined from the bulk-rock without knowing modal proportions of zircons. In this case, because $Zr_{BULK-ROCK} > Zr_{MELT}$ the calculated $T_{Zr}$ overestimates the crystallization temperatures of magmas (Miller et al. 2003). On the other hand, for granitoids with dioritic compositions that accumulate/solidify early from the parental magmas of relatively high temperature and low viscosity, $Zr_{BULK-ROCK} < Zr_{MELT}$ because Zr still resides largely in the residual/evolving melt at this early stage of crystallization. In this case, the calculated $T_{Zr}$ underestimates the crystallization temperatures of magmas.

In granitoids, inherited and xenocrystic zircons are common, and their contribution to $Zr_{BULK-ROCK}$ is difficult to assess. Hanchar and Watson (2003) put forward a method by using back-scattered electrons (BSE) or cathodoluminescence (CL) images to estimate the volume of inherited zircon, which still has large uncertainty. In this case, the calculated $T_{Zr}$ depends on $Zr_{BULK-ROCK}$ that is highly influenced by the volume of inherited and xenocrystic zircons in granitoid samples.

As discussed above, rock samples from granitoid plutons rarely represent pure melt, but cumulates comprising crystals and residual melts. This makes the calculated bulk-rock $M$ parameter irrelevant to the expected $M$ of the melt, which
can further deviate $T_{Zr}$ from the true melt temperatures. However, as the experimentally calibrated $T_{Zr}$ shows no correlation with $M$ and all other compositional parameters (discussed in more detail below), $M$ is not, but $Zr_{\text{BULK-ROCK}}$ is, the primary source of the error for the calculated $T_{Zr}$.

The above analysis states explicitly that the zircon saturation thermometry cannot be used to calculate the temperatures of magmas that solidifies to form granitoid plutons using bulk-rock compositions. That is, the calculated $T_{Zr}$ values have large unknown errors and thus have no significance. Figure 1 illustrates these problems. For a melt parental to granitic rocks with $Zr = 400$ ppm (moderately enriched Zr content in the granitoid rocks from natural samples), $M = 1.3$ and $T_{Zr} \approx 880$ °C, magma cooling causes zircon crystallization and Zr depletion in the residual melt. When the melt cools to ~790 °C, there will be ~0.05 wt% zircon crystallized and ~150 ppm Zr left in the mixture of residual melt and other liquidus phases which are not efficiently segregated from the melt. The ~790 °C would be mistaken as $T_{Zr} = 880$ °C calculated using Eq. (2) because inefficient zircon separation makes the bulk-rock still have the original ~400 ppm Zr. The calculated $T_{Zr}$ would be even higher if there are inherited/captured zircons in the bulk-rock compositions, which is common in granitoid rocks.

On the other hand, for a melt parental to intermediate cumulate dioritic rocks with $Zr = 400$ ppm, a higher $M$ of 1.6 and $T_{Zr} \approx 840$ °C, early cumulation of dioritic rocks effectively separated from the parental melt with low $Zr_{\text{BULK-ROCK}}$ content (~50 ppm estimated with 0.01 wt% zircon in the bulk-rock cumulate) would give $T_{Zr}$ of ~650 °C, in huge contrast with the real $T_{Zr}$ of ~840 °C (Fig. 1). The above simulations may not be perfect but demonstrate significant deviations of the calculated $T_{Zr}$ values using $Zr_{\text{BULK-ROCK}}$ from the true magma temperature values for different types of granitoid rocks (felsic granitic plutons consisting of crystals and residual melts vs. intermediate dioritic rocks of early cumulate origin with less melt trapped or retained).

The examples in Fig. 1 can be further demonstrated by comparing such calculated $T_{Zr}$ values and the $T$ values estimated by using “bulk-rock” SiO$_2$ content of granitoid rocks better reflecting their true crystallization temperatures (see below). Similarly, without knowing major element composition of the melt, but using bulk-rock major element analyses, we can easily have errors on the compound parameter $M$. In addition, uncertainties in the $M$ values between 1.3 and 1.6 due to bulk-rock composition (e.g., containing restite crystals) treated as melt composition would lead to a further ~40 K deviation in the calculated $T_{Zr}$ values although $M$ shows no understood contribution in the zircon saturation thermometry (see below).

**Comparison of data on natural samples with experimental results**

In this section, we use bulk-rock major and trace element data of syn-collisional I-type granitoid samples saturated in zircon from the Qilian, Kunlun and Qinling Orogens in central and western China (Chen et al. 2015, 2016; Zhang et al. 2015; Duan et al. 2016; Li et al. 2016, 2017; Kong et al. 2017, 2019, 2020; Shao et al. 2017).

![Fig 1 Zr versus $T_{Zr}$ plot, visualizing that calculated $T_{Zr}$ values are a function of Zr content and $M$ value. Zr content in the melt phase decreases as the result of cooling and zircon crystallization. Using the bulk-rock Zr content as the substitute of melt Zr content would introduce large errors in the estimated magma temperatures](image1)

![Fig 2 Total alkalis silica (TAS) diagram showing the compositions of plutonic samples from Qilian, Kunlun and Qinling Orogens (Chen et al. 2015, 2016; Zhang et al. 2015; Duan et al. 2016; Li et al. 2016, 2017; Kong et al. 2017, 2019, 2020; Shao et al. 2017)](image2)
et al. 2017, 2019, 2020; Shao et al. 2017). In addition, we have collected granitoid data compiled through the EarthChem portal (http://portal.earthchem.org). This was done to further illustrate that caution is required when using zircon thermometry Eq. (2) to calculate “magma temperatures” for natural granitoid samples.

The syn-collisional granitoids from the Qilian, Kunlun and Qinling Orogens in central and western China show large compositional variations in the TAS diagram (Fig. 2), reflecting their crystallization from variably evolved magmas with varying temperatures (Chen et al. 2016). Figure 3 shows Zr_BULK-ROCK and the calculated $D_{Zr}$ plotted against the calculated $T_{Zr}$ Eq. (2) of granitoid samples, compared with the experimental data (Watson and Harrison 1983). The apparent consistency between the two is not proof of the validity of the calculated $T_{Zr}$ for granitoid samples because they are

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**Fig. 3** Plots of the bulk-rock Zr contents (a) and $D_{Zr}$ zircon/melt (b) against the calculated $T_{Zr}$ values of granitoids (same samples as in Fig. 2) using the zircon saturation thermometry (Watson and Harrison 1983). For comparison, the experiment data used for zircon thermometry calibration (Watson and Harrison 1983) are also plotted. The insets plot all the experimental data. Note that only nine experimental data points are in the compositional range of natural granitoid samples.

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**Fig. 4** Plot of $M \left( [\text{Na} + \text{K} + 2\text{Ca}] \times \text{Al} \times \text{Si} \right)$ and independent major element parameters against the calculated $T_{Zr}$ values of granitoids using zircon thermometry (Watson and Harrison 1983).
intrinsically linked by Eq. (2), but does show the significance of experimental calibration of Eq. (2) with $T_{Zr} \propto Zr_{\text{BULK-ROCK}}$ and $T_{Zr} \propto 1/D_{Zr}$. We point out that while there exist many experimental data for the calibration, only nine of these data sets were found to be appropriate for natural samples in terms of melt compositions and temperature range.

To evaluate the compositional effects on magma temperatures or the calculated $T_{Zr}$ using Eq. (2), we plot compositional parameter $M$ Eqs. (1) and (2) and its constituent parameters against the calculated $T_{Zr}$ (Fig. 4) and $Zr_{\text{BULK-ROCK}}$ (Fig. 5) for both natural rock data and experimental data used for calibrating the equations. One could claim the existence of some sort of correlation between experimental temperatures and experimental charge compositions (although it is not at all obvious), there is certainly no correlation of any sort between the calculated temperatures and compositional parameters for natural bulk-rock compositions. This phenomenon itself is unexpected because $T \propto \text{MgO}$ and $T \propto 1/\text{SiO}_2$ are well understood through experimental petrology (Bowen 1928; Tuttle and Bowen 1958; Gerke and Kilinc 1993; Grove et al. 1997). As seen in Fig. 3 insets and above discussion, most experimental charge temperatures are very high, and the temperature data pertinent to granitoid magmatism are rather sparse (only 9 data points). According to Eq. (1), $M \propto Zr_{\text{MELT}}$ is expected, which seems to be the case for the experimental data with scatter, but is not true for bulk-rock data Zr and bulk-rock compositions (i.e., the compound parameter M and the constituent parameters; Fig. 5). Hence, while the experimental calibration of zircon saturation thermometry is robust, its application to natural granitoid rocks using bulk-rock instead of melt Zr content is erroneous.

![Fig. 5](image-url) Co-variations between $M \{(\text{Na+K+2Ca})/(\text{Al}\times \text{Si})\}$ and independent major element parameters and bulk-rock Zr contents of granitoid samples, compared with experimental data.
Comparison of $T_{Zr}$ and $T_{SiO_2}$ calculated from major element compositions

MgO contents of basaltic melts have been demonstrated experimentally to be proportional to the magma temperature (see above and review: $T = 1026 \times e^{0.01894 \times MgO (wt\%)}$ given by Niu et al. 2002). This simple MgO-$T$ relationship is derived from various experiment data and involves no extra parameters other than MgO content in basaltic melts (quenched glasses or groundmass; Niu et al. 2002). To explore the relationships between major element abundances (e.g., SiO$_2$ and MgO) and temperatures in andesitic and felsic magmas, we compiled the experimental data (including the temperatures and major element compositions of the melts) studying the crystallization evolution of andesitic and felsic magmas (Helz 1976; Carroll and Wyllie 1989; Sisson and Grove 1993; Moore and Carmichael 1998; Alonso-Rerez et al. 2008; Nandedkar et al. 2014, 2016; Ulmer et al. 2018). Only experiments with liquidus minerals of amphibole, plagioclase, quartz and micas which are common mineral phases in granitoid rocks are used; experimental data with liquidus minerals of olivine, clinopyroxene and orthopyroxene are excluded. The data are shown in Figs. 6a, b.

Figure 6 shows that with decreasing temperature, SiO$_2$ increases and MgO decreases in the melt, consistent with cooling induced fractional crystallization of the more mafic minerals from the melts (e.g., amphibole). The large scatter in the temperature at a given SiO$_2$ or MgO results from different experimental conditions (e.g., composition of starting materials, pressure and H$_2$O content). Nevertheless, temperature-dependent trends for both SiO$_2$ and MgO are obvious, especially when these data are averaged with compositional intervals (Figs. 6c, d). In Fig. 6c, SiO$_2$ and temperatures are averaged in 3.0 wt% SiO$_2$ intervals, and in Fig. 6d, MgO and temperatures are averaged in 0.5 wt% MgO intervals, giving significant trends that can be expressed by

$$T_{SiO_2}(^\circ C) = -14.16 \times SiO_2 (wt\%) + 1723$$  \hspace{1cm} (3)  

$$T_{MgO}(^\circ C) = 887.6 \times [MgO(wt\%)]^{0.0989}$$  \hspace{1cm} (4)

![Fig. 6 Plots of silicate melt temperatures measured during experiments against SiO$_2$ and MgO contents of the compiled experimental data (Helz 1976; Carroll and Wyllie 1989; Sisson and Grove 1993; Moore and Carmichael 1998; Alonso-Rerez et al. 2008; Nandedkar et al. 2014, 2016; Ulmer et al. 2018). The temperatures show a negative correlation with SiO$_2$ (a) and a positive correlation with MgO (b) as expected from experimental petrology. The large scatter of the temperature values at a given SiO$_2$ or MgO results from different experimental conditions. These experimental data are further averaged within the intervals of 3 wt% SiO$_2$ and 0.5 wt% MgO and give simple but reasonable SiO$_2$-$T$ (c) and MgO-$T$ (d) relationships](image-url)
These two equations are by no means perfect without considering other compositional effects but can effectively capture the predominance of SiO$_2$ and MgO in describing magma temperatures for felsic and intermediate magmas constrained by experimental phase equilibria.

Figure 7 compares $T_{Zr}$ calculated using Eq. (2) and $T_{SiO_2}$ and $T_{MgO}$ calculated using Eqs. (3) and (4) respectively for the syn-collisional granitoid rocks in central and western China. The good positive trend between $Zr_{BULK-ROCK}$ and the calculated $T_{Zr}$ (with correlation coefficient $R > 0.8$) simply comes from self-correlation seen in Eq. (2) with the scatter coming from the bulk-rock compositional parameter $M$. It is obvious from Fig. 6 that despite the scatter (Figs. 6a, b) and large uncertainties (Figs. 6c, d), SiO$_2$ and MgO in the melts can effectively describe the temperatures of granitoid magmatism. Hence, it is logical to use Eqs. (3) and (4) to estimate “magma temperatures” for natural granitoid samples. Figure 7 shows these estimates, which, as expected, share no resemblance to $T_{Zr}$ nor show any correlation with Zr contents. We should note, as discussed above, that no granitoid samples represent true melts (Niu et al. 2013; Lee and Morton 2015), but cumulates from melts or mixtures of melt with crystals (including inherited restite ones) before magma solidification. Hence, the calculated $T_{SiO_2}$ and especially $T_{MgO}$ derived from experimental melts Eqs. (3) and (4) from Fig. 6 in Fig. 7 are not truly magma temperatures, because cumulate minerals (e.g., amphibole) have lower SiO$_2$ and much higher MgO content than the true melts. This is proven to be the case in Fig. 8, which shows systematically higher $T_{MgO}$ than $T_{SiO_2}$ in the syn-collisional granitoid rocks in central and western China. In contrast to bulk-rock Zr content which varies significantly during magma differentiation and is highly influenced by the crystallized, inherited and captured zircons, the major element composition (especially SiO$_2$) of granitoid rocks is sufficiently similar to the composition of the melt. Therefore, Eq. (3) can be used to approximate the magma temperatures.

Figure 9 compares $T_{SiO_2}$ calculated using Eq. (3) and $T_{Zr}$ calculated using Eq. (2) for the natural granitoid samples. Obviously, there is a large discrepancy between the calculated $T_{SiO_2}$ and $T_{Zr}$, with $T_{SiO_2}$ being generally higher than $T_{Zr}$ for samples with less evolved compositions (e.g., those with SiO$_2 < ~67$ wt%) and and $T_{SiO_2} < T_{Zr}$ for more evolved samples (e.g., those with SiO$_2 > ~67$ wt%) (also see below). In addition, despite the scattering, $T_{SiO_2}$ of granitoid samples have significant correlations with the major element compositions (except for Na$_2$O) as expected in terms of experimental phase equilibria and liquid lines of descent. In contrast, there are no correlations between $T_{Zr}$ and the major element contents. To testify the validity of the above observations, we use downloaded data of worldwide granites from the EarthChem Portal (http://portal.earthchem.org/) on 19 August, 2019, using the following parameters: (1) key words (granites); (2) sample type (plutonic rocks); (3)
chemistry (whole-rock major elements and Zr content). Furthermore, samples with SiO₂ < 53 wt%, MgO > 6 wt% and abnormally high Zr content (> 1000 ppm) were left unconsidered. About 400 granite data sets that meet the conditions are used to plot bulk-rock major element compositions as a function of T_{SiO₂} Eq. (3) and T_{Zr} Eq. (2); Fig. 10. These granite data show similar systematics as the granitoid rocks in central and western China (Fig. 9). The T_{SiO₂} show significant correlations with major element compositions, which are, as expected, consistent with understood liquid lines of decent though these global samples mostly share no genetic relationship. In contrast, the T_{Zr} shows no correlation with major element compositions, indicating its irrelevance to granitoid magma evolution. Hence, it is logical to use bulk-rock based T_{SiO₂}, instead of T_{Zr}, to estimate the temperature of granitic magmas. Nevertheless, we do not encourage to use individual T_{SiO₂} values as being “exact” but emphasize their petrological significance when comparing between samples and between sample suites in studying the granitoid petrogenesis.

In order to further compare the T_{SiO₂} and T_{Zr} values calculated from natural granitoid samples and from data sets collected from the EarthChem portal, we use ΔT (= T_{SiO₂} – T_{Zr}) to show the deviation between the calculated T_{SiO₂} and T_{Zr} and as a function of SiO₂ and bulk-rock Zr content, respectively (Fig. 11). From Fig. 11a, ΔT show tight negative correlation with SiO₂, ranging from ~ + 400 °C for intermediate dioritic rocks with low SiO₂ to ~ 300 °C for felsic granitic rocks with high SiO₂. Figure 11a illustrates significant deviation of the calculated T_{Zr} values from the likely magma temperatures approximated by T_{SiO₂} (see above), with the T_{Zr} values lower than the expected magma temperature (ΔT > 0)

![Graphs showing correlations and deviations](image)

**Fig. 9** Correlations of the major elements and whole-rock Zr contents with calculated T_{SiO₂} vs. T_{Zr} of the granitoid samples. Total Fe expressed as Fe₂O₃* (wt%). Same samples and data as in Fig. 2.
for intermediate dioritic rocks (low SiO$_2$) and higher than the expected magma temperatures ($\Delta T < 0$) for felsic granitic rocks (high SiO$_2$). The above observation is in fact consistent with the simulation in Fig. 1. For intermediate dioritic rocks which usually show cumulate texture and represent early fractionation products from the melts, most Zr resides in the residual melts. In this case, $Zr_{\text{BULK DIORITIC ROCKS}}$ is much lower than the true $Zr_{\text{MELT}}$, and $T_{Zr}$ calculated using this low $Zr_{\text{BULK DIORITIC ROCKS}}$ gives lower values than the actual magma temperatures ($\Delta T > 0$). On the other hand, the more felsic granitic rocks reflecting high viscosity magma are mixtures of melt and crystals with high abundances

Fig. 10 Plots of the major elements and whole-rock Zr contents against the calculated $T_{SiO_2}$ vs. $T_{Zr}$ of granitoid samples compiled from the EarthChem Portal (http://portal.earthchem.org). Total Fe expressed as Fe$_2$O$_3$* (wt%). The $T_{Zr}$ values calculated using zircon saturation thermometry (Watson and Harrison 1983) do not show any correlations with major element compositions

Fig. 11 The differences of calculated temperatures using the two different methods of $\Delta T (= T_{SiO_2} - T_{Zr})$ with SiO$_2$ (a) and bulk rock Zr content (b). $\Delta T$ shows an apparent negative relationship with SiO$_2$; the intermediate rocks with $< 67$ wt% SiO$_2$ having positive $\Delta T$ and more felsic rocks with $> 67$ wt% SiO$_2$ having negative $\Delta T$ (a). Therefore, the deviation between the calculated $T_{Zr}$ and the realistic magma temperature approximated by $T_{SiO_2}$ is mainly caused by the deviation between $Zr_{\text{BULK ROCK}}$ and the true $Zr_{\text{MELT}}$ as illustrated by the negative correlation between $Zr_{\text{BULK ROCK}}$ and $\Delta T$ (b)
of zircons of varying origin (liquidus, captured or inherited crystals). Therefore, the \( Zr_{\text{BULK GRANITIC ROCKS}} \) are much higher than \( Zr_{\text{MELT}} \) and the calculated \( T_{Zr} \) using high \( Zr_{\text{BULK GRANITIC ROCKS}} \) gives higher values than the true magma temperatures (\( \Delta T < 0 \)). This is further illustrated by the negative correlation between the bulk rock Zr content and \( \Delta T \) (Fig. 11b). Samples with low Zr content showing positive \( \Delta T \) and underestimated \( T_{Zr} \), whereas samples with high Zr content showing negative \( \Delta T \) and overestimated \( T_{Zr} \) (Fig. 11b).

In fact, the failure in using bulk-rock Zr content to estimate the magma temperature of granitoids is evident in theory. This is because in contrast with SiO\(_2\) that is essential constituents of silicate minerals and rocks, Zr is petrologically not required for granitoid magmatism. It is important to note that we do not devalue the significance of Zr because it determines the presence and abundance of zircons in granitic rocks and zircons contain valuable information such as the age of granitoid crystallization and also the ages of granitoid magma sources and source histories preserved in captured and inherited zircons. However, we should also note the fact that Zr (as a trace/minor element) and zircon (as an accessory mineral) do not participate in and thus cannot control the granitoid phase equilibria. Hence, it is logical and readily understood that Zr content in a rock cannot provide information on phase equilibria, including the magma temperature. This simple analysis plus the illustrations above explain that there is no thermodynamic and/or petrological reason why the granitoid magma temperatures as approximated by \( T_{SiO_2} \) should correlate with bulk-rock Zr contents (Figs. 9k, l). Hence, the calculated \( T_{Zr} \) values give no information on magma temperatures but are derivatives of \( Zr_{\text{BULK-ROCK}} \). Therefore, we conclude that caution is needed before indiscriminate and continued use of the zircon saturation thermometry.

**Conclusions**

Zircon-saturation thermometry has been a convenient tool widely used to calculate magma temperatures in granitoid studies over the last decades. It uses \( Zr_{\text{MELT}} \) as an input because experimental calibration shows \( T_{Zr} \propto Zr_{\text{MELT}} \). However, what is available in rock samples is \( Zr_{\text{BULK-ROCK}} \), not \( Zr_{\text{MELT}} \). Because for felsic granitic rocks representing mixtures of melts and crystals, \( Zr_{\text{MELT}} \) (unknown) = \( Zr_{\text{BULK-ROCK}} \) – \( Zr_{\text{ZIRCON}} \) (49.7 wt% Zr with unknown abundance) – \( Zr_{\text{OTHER CUMULATE MINERALS}} \), and for early cumulate dioritic rocks, \( Zr_{\text{BULK-ROCK}} \) is lower than \( Zr_{\text{MELT}} \). \( T_{Zr} \) values calculated using \( Zr_{\text{BULK-ROCK}} \) thus have no petrological significance.

Zr as a trace element in rocks and magmas and zircon as an accessory mineral do not participate in and cannot control the granitoid phase equilibria. Therefore, there is no petrological footing that \( Zr_{\text{BULK-ROCK}} \) should correlate with granitoid magma temperatures. We suggest using SiO\(_2\) content as a proxy to estimate granitoid magma temperatures, \( T_{SiO_2} \), because SiO\(_2\) is an essential constituent of granitoid rocks and magmas, and because SiO\(_2\) is more than 1/7 constrained by experimental phase equilibria.

Because granitoids do not represent melt compositions, but the compositions of mixtures of cumulate crystals and inefficiently extracted melt, we do not encourage to accept the calculated \( T_{SiO_2} \) as true magma temperatures for individual samples, but we advocate the petrological and geological significance of varying \( T_{SiO_2} \) values between samples and between sample groups for comparison in the study of granitoid petrogenesis.

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