Geology

Nb-Ta fractionation in peraluminous granites: a marker of the magmatic-hydrothermal transition
--Manuscript Draft--

Abstract:
In their late stages of evolution, peraluminous granitic melts exsolve a large amounts of fluids which can modify the chemical composition of granitic whole rocks samples. The Nb/Ta ratio is expected to decrease during magmatic differentiation of granitic melts, but the behavior of both elements at the magmatic-hydrothermal transition remains unclear. Using a compilation of whole rock geochemical data available in the literature, we demonstrate that fractional crystallization alone is not sufficient to explain the distribution of Nb-Ta in most peraluminous granites. However, we notice that most of the granitic samples displaying evidence of interactions with fluid, regardless of their age or their emplacement conditions, have Nb/Ta < 5. We propose that the decrease of the Nb/Ta ratio in highly evolved melts is the consequence of both fractional crystallization and sub-solidus magmatic-hydrothermal alteration. We suggest that the value Nb/Ta = 5 in peraluminous granite fingerprints the magmatic-hydrothermal transition. Furthermore, a Nb/Ta ratio of 5 appears to be a good marker to discriminate mineralized from barren peraluminous granites.

Suggested Reviewers:
Jarda Dostal, PhD
Emeritus Professor, Saint Mary's University
jdostal@smu.ca
Specialist of igneous petrology and geochemistry

Calvin Miller, PhD
<table>
<thead>
<tr>
<th>Professor, Vanderbilt University</th>
</tr>
</thead>
<tbody>
<tr>
<td><a href="mailto:calvin.f.miller@vanderbilt.edu">calvin.f.miller@vanderbilt.edu</a></td>
</tr>
<tr>
<td>Specialist of igneous petrology and magma chamber processes. Reviewer on a first version of this manuscript</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sasha (Aleksandr) Stepanov, PhD</th>
</tr>
</thead>
<tbody>
<tr>
<td>University of Tasmania, Australia</td>
</tr>
<tr>
<td><a href="mailto:sasha.stepanov@utas.edu.au">sasha.stepanov@utas.edu.au</a></td>
</tr>
<tr>
<td>Specialist of Nb-Ta fractionation during igneous processes</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Philippe Muchez, PhD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Professor, KU Leuven, Belgium</td>
</tr>
<tr>
<td><a href="mailto:philippe.muchez@ees.kuleuven.be">philippe.muchez@ees.kuleuven.be</a></td>
</tr>
<tr>
<td>Specialist of igneous processes and metallogeny</td>
</tr>
</tbody>
</table>
Nb-Ta fractionation in peraluminous granites: a marker of the magmatic-hydrothermal transition

Christophe Ballouard¹, Marc Poujol¹, Philippe Boulvais¹, Yannick Branquet¹,², Romain Tartèse³,⁴, Jean-Louis Vigneresse⁵

¹UMR CNRS 6118, Géosciences Rennes, OSUR, Université Rennes 1, 35042 Rennes Cedex, France
²Institut des Sciences de la Terre d’Orléans (ISTO), UMR 6113 CNRS/Université d’Orléans/BRGM, Campus Géosciences, 1A rue de Férolerie, F45071 Orléans Cedex 2, France
³Institut de Minéralogie, de Physique des Matériaux et de Cosmochimie, Muséum National d’Histoire Naturelle, Sorbonne Universités, CNRS, UMPC & IRD, 75005 Paris, France
⁴Department of Physical Sciences, The Open University, Walton Hall, Milton Keynes, MK7 6AA, United Kingdom
⁵Université de Lorraine, UMR 7539 GéoRessources, BP 23, F-54501 Vandoeuvre Cedex, France

ABSTRACT

In their late stages of evolution, peraluminous granitic melts exsolve a large amounts of fluids which can modify the chemical composition of granitic whole rocks samples. The Nb/Ta ratio is expected to decrease during magmatic differentiation of granitic melts, but the behavior of both elements at the magmatic-hydrothermal transition remains unclear. Using a compilation of whole rock geochemical data available in the literature, we demonstrate that fractional crystallization alone is not sufficient to explain the distribution of Nb-Ta in most peraluminous granites.

However, we notice that most of the granitic samples displaying evidence of interactions with fluid, regardless of their age or their emplacement conditions, have Nb/Ta < 5. We propose that the decrease of the Nb/Ta ratio in highly evolved melts is the consequence of both fractional crystallization and sub-solidus magmatic-hydrothermal alteration. We suggest that the value Nb/Ta = 5 in peraluminous granite fingerprints the magmatic-hydrothermal transition.
Furthermore, a Nb/Ta ratio of 5 appears to be a good marker to discriminate mineralized from barren peraluminous granites.

**INTRODUCTION**

In granitic systems, the magmatic-hydrothermal transition separates a purely magmatic system dominated by crystal-melt interaction from a system dominated by crystal-melt-magmatic fluid phase interaction (Halter and Webster, 2014). Hydrothermal activity in peraluminous granites can be either localized, as evidenced by pegmatites and/or quartz veins, or pervasive, leading to significant element mobility and, in the most extreme cases, to the formation of greisens (Pirajno, 2013). Such alteration events occur during the sub-solidus stage of the granitic melt emplacement and may lead to the deposition of economically significant mineralization such as Sn or W.

Nb and Ta are lithophile elements considered as “geochemical twins” because they have the same charge and similar ionic radius. As a result they have similar geochemical properties and should not be fractionated during most geological processes (Goldschmidt, 1937). However, in granitic rocks, Nb/Ta ratios are highly variable (< 2 - 25; Green, 1995). Some authors have demonstrated that the Nb/Ta ratios decrease in granites during fractional crystallization (Raimbault et al. 1995; Linnen and Keppler, 1997; Stepanov et al., 2014). Other studies have suggested that Nb and Ta could be fractionated in highly evolved peraluminous granites during the interaction with late magmatic fluids (Dostal and Chatterjee, 2000; Tartèse and Boulvais, 2010; Ballouard et al., 2015; Dostal et al., 2015).
In order to decipher the specific role of the magmatic and hydrothermal processes on the evolution of the Nb/Ta ratios, we compiled whole rock geochemical data available in the literature for peraluminous granites emplaced at different times and in various tectonic contexts. Based on these data, we show that fractional crystallization of granitic melts alone is not sufficient to account for the Nb-Ta behavior observed in most peraluminous granites and that hydrothermal processes are necessarily involved.

**PRESENT KNOWLEDGE**

**Magmatic behavior of Nb-Ta**

In highly evolved granites and pegmatites, columbite ((Fe,Mn)Nb$_2$O$_6$) and tantalite ((Fe, Mn)Ta$_2$O$_6$) are the main mineral phases hosting Nb and Ta. Experimental studies have shown that the solubility of these two minerals in granitic melts increases with temperature, but decreases with increasing the Aluminium Saturation Index (ASI), a parameter related to the degree of polymerization of the melt (Linnen and Keppler, 1997; Aseri et al., 2015). The Li content of granitic melts also increases the solubility of columbite and tantalite (Linnen, 1998; Aseri et al., 2015).

Partial melting can produce granitic peraluminous melts with Nb/Ta ratios higher or lower than their source, depending on the temperature. Melts formed during high temperature anatexis tend to have high Nb/Ta ratios, as a result of the complete consumption of biotite and the high abundance of Ti-bearing oxides in the residue, which preferentially incorporate Ta over Nb (Stepanov et al., 2014). Conversely, low temperature partial melting generates melts with low Nb/Ta ratios because residual biotite incorporates preferentially Nb over Ta (Stepanov et al., 2014). Since biotite and Ti-bearing minerals can also be involved during differentiation of
granitic melts, fractional crystallization also changes Nb/Ta ratios: Nb/Ta increases during high
temperature fractional crystallization of Ti-rich melts due to the preferential saturation of Ti-
oxide minerals over biotite, whereas Nb/Ta ratios decrease during low temperature
differentiation of granitic melts due to the fractionation of biotite and/or muscovite (Stepanov et
al., 2014). In the most evolved peraluminous melts, the lower solubility of manganocolumbite
(MnNb_2O_6) compared to manganotantalite (MnTa_2O_6) also enhances the decrease of the Nb/Ta
ratio in the melt (Linnen and Keppler, 1997).
Melt inclusions in Li-F granites (Orlovka massif, Eastern Transbaikalia) indicate a separation of
an immiscible F-rich hydrosaline melt that can induce a decrease of the Nb and Ta contents in
the residual melt (Badanina et al., 2010).

82

**Nb-Ta behavior in hydrothermal systems**

83 Nb and Ta are poorly soluble in aqueous solutions, Ta being even less soluble than Nb (Zaraisky
84 et al., 2010). Experiments with aqueous F-rich fluids and aluminosilicate melt indicate that Nb
85 and Ta preferentially partition in the melt (Chevychelov et al., 2005). However, the solubility
86 and hydrothermal transfer of Ta and Nb are greatly enhanced in F-rich solutions under reducing
87 conditions (Zaraisky et al., 2010). These experimental results are consistent with the fact that
88 several F–rich cupolas of greisenized peraluminous granites are significantly enriched in both Nb
89 and Ta (e.g. Zaraisky et al., 2009).

91

**VARIATIONS OF WHOLE ROCK NB/TA RATIOS IN PERALUMINOUS GRANITES**
We compiled data for peraluminous granites (i.e., with a A/CNK ratio > 1) as well as for some greisens of different ages (Archean to Mesozoic) and emplaced in various geodynamical contexts (see Table DR1 in the GSA Data Repository).

**Nb-Ta fractionation during magmatic processes**

In Figure 1, the Nb/Ta ratios are highly variable between ~15 and ~0 when reported as a function of Nb and Ta, the lowest values being recorded by whole rocks displaying the highest Nb and Ta contents. Mica fractionation in granitic melt induces a decrease of the Nb/Ta ratios (Stepanov et al., 2014). In Figure 1, we modeled the evolution of a melt with an initial Ta and Nb contents of 1.5 ppm and 12 ppm (Nb/Ta = 8), respectively, undergoing fractionation of a cumulate made of 80 wt.% (quartz + feldspar) + 10 wt.% muscovite + 10wt.% biotite, using the Rayleigh distillation law and the silicate-melt partition coefficients compiled by Stepanov et al. (2014). The modeling qualitatively reproduces the behaviors of Nb and Ta, but it requires an unrealistic rate of mineral fractionation (over 90 wt.%) to reach low Nb/Ta ratios around 2 and Nb and Ta contents around 20 and 10 ppm, respectively (Fig. 1). The addition of 0.5 wt.% Fe-Ti oxide (e.g. ilmenite or rutile) in the cumulate, in which Ta and Nb are highly compatibles (Stepanov et al., 2014), makes things even worse. Indeed, the fractionation of this cumulate causes a decrease of the Nb content (Fig. 1A), resulting in a trend opposite to the trend displayed by the peraluminous granites.

If crystal-melt fractionation is likely to occur during the crystallization of granitic melts in magmatic bodies (Dufek and Bachmann, 2010) and during the magma ascent in dykes (Tartèse and Boulvais, 2010; Yamato et al., 2012), numerical modeling shows that the efficiency of crystal-melt segregation is restricted to cases where crystals represent a low percentage of the
total magma volume (Yamato et al., in press). Indeed, 70-75% of crystallization marks the particle locking threshold (PLT in Figure 1B, Vigneresse et al., 1996) where the liquid becomes totally locked, precluding any crystal-melt segregation. The model presented here thus suggests that fractional crystallization alone is not sufficient to explain the behaviors of Nb and Ta in peraluminous granitic rocks.

**Nb-Ta fractionation during magmatic-hydrothermal processes**

**Mineralogical markers**

Secondary muscovitization and greisenization occur under sub-solidus conditions during the interaction between crystallized granites and acidic late magmatic fluids (Pirajno, 2013). The Figure 2 shows that the Nb/Ta ratios of whole rock granites and greisens are anti-correlated with the average MgO/(Na₂O + TiO₂) ratios of the muscovite they host (a chemical marker for secondary muscovitization, Miller et al., 1981). This observed anti-correlation suggests that the fluids involved in the secondary muscovitization processes could also be responsible for the decrease of the Nb/Ta whole-rock values. Whole rock hydrothermal enrichment of Ta during secondary muscovitization is, for example, observed in ongonites (topaz-bearing microleucogranites) from the Ongon Kairkhan (Mongolia) and this process is associated with the crystallization of late Ta-rich overgrowth on Nb-Ta oxides (Dostal et al., 2015).

**Geochemical markers**

The whole rock Nb/Ta ratios of peraluminous granites are anti-correlated with their Sn contents, an element highly mobilized at the magmatic-hydrothermal transition (Fig. 3A): high Sn contents above ~30 ppm are only encountered in granitic samples (or greisens) with low Nb/Ta (< 5).
These samples also display high contents in Cs, F, Li, W and Rb. Because such incompatible elements present a strong affinity for magmatic fluids, their enrichment is commonly used as a marker of a magmatic-hydrothermal alteration in highly evolved crustal granites. Indeed, increasing the abundance of highly incompatible elements, with a bulk partition coefficient $K_d$ between the mineral phases and the melt close to 0, by two orders of magnitude, as observed in Figure 3A (from ~10 to ~1000 ppm), during fractional crystallization requires an unrealistic degree of fractional crystallization up to 99 wt.%, suggesting that hydrothermal processes are also involved. Such enrichments in highly incompatible elements, attributed to interaction with magmatic fluids, have been noticed in the Erzgebirge massif (Förster et al., 1999), in the South Mountain Batholith (e.g. Dostal and Chatterjee, 2000), or in the French Armorican Massif (Tartèse and Boulvais, 2010; Ballouard et al., 2015).

The Nb/Ta ratios also correlate with the K/Rb ratios (Fig. 3B). Most granites with low Nb/Ta display K/Rb values lower than 150, characteristic of the pegmatite-hydrothermal evolution (Shaw, 1968). Such a tendency is observed in the South Mountain Batholith, where it was interpreted as evidence for a magmatic-hydrothermal alteration (Dostal and Chatterjee, 2000).

Finally, the whole rock Nb/Ta ratios can be compared with the magnitude of the tetrad effect, which corresponds to the intra-REE fractionation observed in the REE patterns of highly fractionated magmatic rocks and hydrothermal precipitates (e.g. Irber, 1999). Although Duc-Tin and Kepler (2015) have recently suggested that the tetrad effect could result from monazite and xenotime fractionation, most authors have argued that such REE patterns actually reflect a selective complexation of the REE during the interaction of granitic melts with F- and Cl-rich
aqueous fluids (e.g. Bau, 1996; Irber, 1999; Monecke et al., 2007). Irber (1999) quantified the degree of tetrads effect (TE$_{1-3}$) by determining the deviation of the first and the third tetrads of granites REE-patterns from a hypothetical tetrads effect-free REE pattern. The large majority of the samples with significant tetrads effect (TE$_{1-3}$ > 1.1) are also characterized by low Nb/Ta ratios below ~5 (Fig. 3C).

Metallogenic markers

The Nb/Ta ratio is commonly compared to the Zr/Hf ratio, as the latter has been proposed as either a marker of magmatic-hydrothermal interactions (Bau, 1996) or of fractional crystallization (Linnen and Keppler, 2002; Claiborne et al., 2006). The Zr/Hf ratio is a geochemical indicator of the fertility of granitic rocks as a Zr/Hf ratios below ~25 (corresponding to the lower limit of the CHArge and RAdius Control range; Bau, 1996) are expected in granites where Sn, W, Mo, Be and Ta mineralization are described (Zaraisky et al., 2009). In a Nb/Ta vs. Zr/Hf diagram (Fig. 4), most barren granites plot in the field defined by 26 < Zr/Hf < 46 (CHARAC range of Bau, 1996) and by 5 < Nb/Ta < 16, whereas peraluminous granites associated with Sn, W and/or U deposits have 18 < Zr/Hf < 46 with Nb/Ta ratio lower than 5. Rare metals granites are characterized by even lower Zr/Hf ratios (< 18) with Nb/Ta ratios that are still lower than 5.

From the diagrams presented in Figures 2, 3 and 4, we highlight significant mineralogical (secondary muscovitization), geochemical (Sn contents, K/Rb ratio, tetrads effect) and metallogenic (Sn-W-U and rare metal mineralization) evidence that magmatic-hydrothermal processes account for the decrease of the Nb/Ta ratio in peraluminous granites. The solubility
and hydrothermal transfer of Nb and Ta are greatly enhanced, by up to three orders of magnitude, in reduced F-rich aqueous solutions (Zaraisky et al., 2010). Therefore, in peraluminous granites affected by sub-solidus alteration, the Nb/Ta ratios can be lowered by an increase of the Ta content in Ta-Nb-bearing minerals due to the lower mobility of Ta compared to Nb in aqueous solutions. As a consequence, we suggest here that the decrease of the Nb/Ta ratios to values lower than ~5 in peraluminous granites reflects the concomitant effect of fractional crystallization and sub-solidus magmatic-hydrothermal alteration, likely by F-rich acidic reduced fluids of magmatic origin.

\[ \text{Nb/Ta} = 5: \text{a critical ratio for granite petrogenesis and mineral exploration strategies} \]

The peraluminous granite whole rock samples with Nb/Ta ratios lower than 5 show significant evidence of interaction with fluids. We suggest that Nb/Ta = 5 represents a threshold between a purely magmatic system (Nb/Ta > 5) and a magmatic-hydrothermal system (Nb/Ta < 5). Taking a cut off value of 5 for the Nb/Ta ratio as a marker of the magmatic-hydrothermal transition in peraluminous granites bears some implications for exploration strategies as it can also help to define the economic potential of these granites. Indeed, Figure 4 demonstrates that a Nb/Ta ratio of 5 can be used as a geochemical indicator to differentiate barren granites from granites spatially related to Sn-W-(U) or rare metals mineralization. Since whole rock trace element analyses (including Nb and Ta) are routinely performed in most laboratories around the world, the simple calculation of whole rock sample Nb/Ta ratios can, therefore, help exploration geologists to define potential targets for Sn-W-(U) and rare metals deposits.

CONCLUSION
The mineralogical and geochemical evidence of fluid interaction recorded in granitic whole rock samples, indicate that the value Nb/Ta = 5 is a good marker of the magmatic-hydrothermal transition in peraluminous granites. The decrease of the Nb/Ta ratio in peraluminous granites is associated with an increase of the degree of secondary muscovitization and with geochemical and metallogenic evidence of hydrothermal interactions, suggesting that sub-solidus alteration is involved in the fractionation of Nb-Ta. To further constrain the mechanisms involved in the fractionation of Nb/Ta ratios in peraluminous granites at the magmatic-hydrothermal transition, mineral-scale analyses would now be required. From an exploration point of view, and based on the large compilation of data presented in this study, the Nb/Ta ratio appears to be a good geochemical indicator to differentiate barren from ore-bearing peraluminous granites.

ACKNOWLEDGMENTS

We acknowledge Calvin Miller and two anonymous referees for their fruitful comments on a previous version of this manuscript.

REFERENCES CITED


Dufek, J., Bachmann, O., 2010. Quantum magmatism: Magmatic compositional gaps generated by melt-crystal dynamics: Geology, v. 38, 687–690. doi:10.1130/G30831.1


Green, T.H., 1995, Significance of Nb/Ta as an indicator of geochemical processes in the crust-mantle system: Chemical Geology, v. 120, 347–359, doi: 10.1016/0009-2541(94)00145-X.
Halter, W.E., Webster, J.D., 2004, The magmatic to hydrothermal transition and its bearing on

Pirajno, F., 2013, Effects of Metasomatism on Mineral Systems and Their Host Rocks: Alkali
Metasomatism, Skarns, Greisens, Tourmalinites, Rodingites, Black-Wall Alteration and
Listevenites, in:Harlov, D.E., Austrheim, H., Metasomatism and the Chemical
Transformation of Rock, Lecture Notes in Earth System Sciences, Springer Berlin

Heidelberg, pp. 203–252.

Irber, W., 1999, The lanthanide tetrads effect and its correlation with K/Rb, Eu/Eu*, Sr/Eu, Y/Ho,

Linnen, R.L., 1998, The solubility of Nb-Ta-Zr-Hf-W in granitic melts with Li and Li + F;
constraints for mineralization in rare metal granites and pegmatites: Economic Geology, v.

Linnen, R.L., Keppler, H., 1997, Columbite solubility in granitic melts: consequences for the
enrichment and fractionation of Nb and Ta in the Earth’s crust: Contribution to Mineralogy

Linnen, R.L., Keppler, H., 2002, Melt composition control of Zr/Hf fractionation in magmatic
7037(02)00924-9.


patterns of hydrothermally altered siliceous igneous rocks from the Zinnwald Sn–W deposit,

doi:10.1016/j.gca.2006.09.010

for a multistage magmatic genesis of Ta-Sn-Li mineralization in the granite at Beauvoir,
doi:10.2113/gsecongeo.90.3.548


FIGURE CAPTIONS

Figure 1. Nb/Ta vs. (A) Nb and (B) Ta abundances for peraluminous granites. The colored curves represent a model of evolution of Nb and Ta in a liquid L0 (Nb = 12 ppm, Ta = 1.5 ppm, Nb/Ta = 8) during the fractionation of an assemblage made of 10 wt.% biotite + 10 wt.% muscovite + 80 wt.% (quartz + feldspar). The numbers above the curves indicate the amount of fractional crystallization. The black dashed line represents the same model during the fractionation of an assemblage composed of 10 wt.% biotite + 10 wt.% muscovite + 0.5 wt.% ilmenite + 79.5 wt.% (quartz + feldspar). The Kd used and presented in the table in inset in the diagram are from Stepanov et al. (2014) and reference therein. PLT: Particle Locking Threshold (Vigneresse et al., 1996).

Figure 2. (A) Mg-Na-Ti ternary classification diagram of muscovite (Miller et al., 1981). (B) Diagram reporting the evolution of Nb/Ta ratios for whole rock samples from different peraluminous granites against the average value of the MgO/(Na2O + TiO2) ratios of their dioctaedral micas.

Figure 3: Evolution of Nb/Ta ratios of peraluminous granites as a function of selected markers of magmatic-hydrothermal alteration. The degree of tetrad effect (TE1-3) has been calculated using the equation of Irber (1999). CC: Continental Crust composition (from Rudnick and Gao, 2005).

Figure 4. Nb/Ta vs. Zr/Hf diagram differentiating barren and ore-bearing peraluminous granites.
GSA Data Repository item 2015xxx, [Synthesis of peraluminous crustal granites reported in this study], is available online at www.geosociety.org/pubs/ft2015.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.
Figure 1

(A) Plot of Nb/Ta vs Nb (ppm) showing the rate of fractional crystallization and the position of Ilmenite Fractionation.

(B) Plot of Nb/Ta vs Ta (ppm) with a table showing the distribution coefficients (Kd) for different phases.

<table>
<thead>
<tr>
<th>Phase</th>
<th>X</th>
<th>Nb (Kd)</th>
<th>Ta (Kd)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bt</td>
<td>0.1</td>
<td>3.6</td>
<td>1.2</td>
</tr>
<tr>
<td>Ms</td>
<td>0.1</td>
<td>3.5</td>
<td>0.4</td>
</tr>
<tr>
<td>Ilm</td>
<td>0</td>
<td>73</td>
<td>86</td>
</tr>
<tr>
<td>Qtz-Fds</td>
<td>0.8</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Cumulate</td>
<td></td>
<td>0.7</td>
<td>0.2</td>
</tr>
</tbody>
</table>
Figure 2

A

B

Secondary muscovitization

\[
\frac{\text{MgO}}{(\text{Na}_2\text{O} + \text{TiO}_2) (\text{Ms})}
\]

\[
\frac{\text{Nb}}{\text{Ta}} (\text{WR})
\]
Figure 4

- Average continental crust
- Barren granites
- Lizio granite - Armoric an Massif: Sn
- Questembert and Guérande granites - Armoric an Massif: U - (Sn)
- Beariz, Jalama and Carbalinno granites - Iberian Massif: Sn - W - (Nb - Ta)
- Cornubian batholith: Sn - W - (Cu)
- Li - mica granites and greisens from the Erzgebirge: Sn - W
- Leucogranites and greisens from the Davis Lake pluton - SMB: Sn
- Tanjungpandan pluton - Belitung - Indonesia: Sn-W
- Leucogranites from the Kukul’bei Complex - Transbaikalia: W - Sn
- Dulong granites - Yunnan Province - South China: Sn
- Ogonites from Ongon Kairkhan, Central Mongolia: W
- Li - F granites from the Kukul’bei Complex - Transbaikalia: Ta
- Beauvoir granite - Massif Central: Ta - Be - Sn - Li
- Ponte Segade granite - Iberian Massif: Sn - Ta - Nb - Li - Be - Cs
<table>
<thead>
<tr>
<th>Location</th>
<th>Igneous province</th>
<th>Granite</th>
<th>Age</th>
<th>Related deposit</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Western Europe</td>
<td>French Armorican Massif</td>
<td>Lizio</td>
<td>ca. 316 Ma</td>
<td>Sn</td>
<td>Tartèse and Boulvais, 2010</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Questembert</td>
<td>ca. 316 Ma</td>
<td>(U)</td>
<td>Tartèse and Boulvais, 2010; Tartèse et al., 2013</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Guérande</td>
<td>ca. 310 Ma</td>
<td>U - Sn</td>
<td>Ballouard et al., 2015</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Huelgat</td>
<td>Late Carboniferous</td>
<td>-</td>
<td>Tartèse and Boulvais, 2010; Georget, 1986</td>
</tr>
<tr>
<td></td>
<td>Iberian massif</td>
<td>Brignogan</td>
<td>Late Carboniferous</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ponte Segade</td>
<td>Late Carboniferous</td>
<td>Sn - Ta - Nb - U - Be - Cs</td>
<td>Tartèse et al., 2013</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Jalama</td>
<td>Late Carboniferous</td>
<td>Sn-W (Nb-Ta)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Beariz</td>
<td>Late Carboniferous</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Beariz (Avion)</td>
<td>Late Carboniferous</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Boboraz</td>
<td>Late Carboniferous</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Carballino</td>
<td>Late Carboniferous</td>
<td>Sn-W (Nb-Ta)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Irixo</td>
<td>Late Carboniferous</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pedrobernardo</td>
<td>c.a. 300 Ma</td>
<td>Hercynian</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>S. Mamede de Ribatua</td>
<td>Hercynian</td>
<td>Hercynian</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Panasqueira</td>
<td>Hercynian</td>
<td>Hercynian</td>
<td></td>
</tr>
<tr>
<td></td>
<td>French Massif Central</td>
<td>Colette</td>
<td>ca. 310 Ma</td>
<td>Ta - Be - Sn - Li</td>
<td>Rainbault et al., 1995; Rainbault et al., 1995</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Beauvoir</td>
<td>ca. 310 Ma</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Guéret</td>
<td>ca. 350 Ma</td>
<td>-</td>
<td>Rollin et al., 2006</td>
</tr>
<tr>
<td></td>
<td>Cornubian Batholith</td>
<td>-</td>
<td>295-275 Ma</td>
<td>Sn - W – (Cu)</td>
<td>Chappell and Hine, 2006; Muller et al., 2006</td>
</tr>
<tr>
<td></td>
<td>Erzgebirge</td>
<td>-</td>
<td>Late Carboniferous - Early Permian</td>
<td>Sn - U - W</td>
<td>Förster et al., 1999; Breiter, 2012; Štrempek et al., 2005</td>
</tr>
<tr>
<td></td>
<td>Fichtelgebirge</td>
<td>-</td>
<td>Late Carboniferous - Early Permian</td>
<td>Li - mica granites and greisens</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Central Vosges</td>
<td>-</td>
<td>329 - 322 Ma</td>
<td>-</td>
<td>Tabaud et al., 2015</td>
</tr>
<tr>
<td>Nova Scotia - Canada</td>
<td>South Mountain Batholith</td>
<td>-</td>
<td>Late Devonian</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Kaapvaal Craton</td>
<td>Lekkersmaak granite suite</td>
<td>ca. 2800 Ma</td>
<td>-</td>
<td>Jaguin, 2012</td>
</tr>
<tr>
<td></td>
<td>Cape Granite Suite</td>
<td>Peninsula pluton</td>
<td>556-534 Ma</td>
<td>-</td>
<td>Farina et al., 2012</td>
</tr>
<tr>
<td>South Africa</td>
<td>Hunan Province</td>
<td>Indosinian granites</td>
<td>210 – 243 Ma</td>
<td>-</td>
<td>Wang et al., 2007</td>
</tr>
<tr>
<td></td>
<td>Yunnan Province</td>
<td>Dulong granites</td>
<td>ca. 90 Ma</td>
<td>Sn</td>
<td>Xu et al., 2015</td>
</tr>
<tr>
<td>South China</td>
<td>Indonesia</td>
<td>Bellitung</td>
<td>ca. 215 Ma</td>
<td>Sn - W</td>
<td>Schwartz and Surjono, 1990</td>
</tr>
<tr>
<td></td>
<td>Eastern Transbaikalia</td>
<td>-</td>
<td>Kukul’bei complex</td>
<td>W – Sn</td>
<td>Zaraisky et al., 2009</td>
</tr>
<tr>
<td></td>
<td>Central Mongolia</td>
<td>Ongon Khairkhan</td>
<td>Ca. 120 Ma</td>
<td>W</td>
<td>Dostal et al., 2015</td>
</tr>
</tbody>
</table>

Table DR1: Synthesis of the peraluminous granites reported in this study with their location, their age, their associated metal deposits when available and the corresponding references.
REFERENCES


