

A KALBORSITE-PITIGLIANOITE-KALSILITE-SHCHERBAKOVITE-BARYTOLAMPROPHYLLITE-WADEITE-BEARING LAMPROITIC DIKE FROM THE NORTHERN HIGHWOOD MOUNTAINS, MONTANA, USA.

Scott Kuehner¹, Anthony Irving¹ and Hugh O'Brien²

¹University of Washington, USA,, ²Geological Survey of Finland

INTRODUCTION

The Highwood Mountains represent an eroded Eocene (53-50 Ma) volcanic/intrusive complex located in central Montana, USA. The complex consists of potassic mafic phonolite flows and tuffs intruded by shonkinite, malignite, and a variety of mafic phonolite, latite and minette dikes. One of the youngest dikes (>5 km long) is composed of a potassic peralkaline mafic rock, originally classified as a jumillite by O'Brien (1988). Further sampling of this dike shows it to be mineralogically complex and to contain unusual minerals and mineral associations which make the rock-type difficult to classify and therefore petrologically interesting.

BULK ROCK COMPOSITIONS

Two samples from different locations along the dike have relatively low Al₂O₃, high alkalis and are peralkaline [(K+Na)/Al = 1.13 - 1.18]. HM98-4 is nearly perpotassic

(K/Al = 0.99). These leucite normative rocks are strongly silica undersaturated, and Mg-rich, with very high *mg* (due in part to the moderately high Fe₂O₃/FeO ratios of 0.9-1.1). Except for the somewhat low TiO₂ contents, the major element characteristics indicate affinities with madupitic lamproites or evolved orangeites. The elevated boron, fluorine, chlorine and sulfur concentrations of this dike may signify a subducted seawater component in the mantle source.

MINERAL COMPOSITIONS

Irregular, commonly amoeboid olivine phenocrysts are very magnesian (up to Fo₉₅, Table 2) and contain idiomorphic inclusions of chromite with low TiO₂ (<0.7%) and Cr/(Cr+Al)>0.85. Cores of the olivine grains are of a broadly uniform composition with an abrupt, often cusped or interdigitated, Fe-rich (Fo₈₆), outer margin. The Fe-rich margins do not mimic primary igneous olivine crystallographic forms, but instead are parallel to the irregular olivine shape. These imply resorption and re-equilibration of the olivine crystals suggesting that they are xenocrystic. However, calculation of equilibrium olivine from the bulk rock analysis predicts olivine with Fo₉₅ composition. This implies that the olivine grains may be high-pressure cognate phases, and that the whole rock compositions have not deviated significantly through crystal fractionation since the olivine grains precipitated. One olivine grain contains inclusions of coexisting diopside (1.1% Cr₂O₃, 1.8% Al₂O₃) and chromite (Cr/(Cr+Al) = 0.90, 0.4% TiO₂).

All olivine grains are mantled by rims of tetra-ferriphlogopite (Si + Al < 7.5, ~2.7% TiO₂). Mica phenocrysts are absent. Mica compositions in narrow, <20µm rims immediately adjacent to most olivine grains are extremely deficient in TiO₂ (<0.3%) and Al₂O₃ (<0.3%), and have Mg/(Mg+Fe²⁺) ~ 0.91 (Figure. 1). All micas have 0.8-1.3% F. Mica compositions show a trend of Al-depletion intermediate between those typical of orangeite and lamproite micas (Figure. 2), though the range in Al₂O₃ is small. Unlike orangeite micas, the most extreme Al and Ti-poor compositions are found as early mantles on olivine crystals and not as late rims on mica phenocrysts.

Table 1: Bulk Rock Compositions

Sample	HM562	HM98-4
SiO ₂	46.29	44.50
TiO ₂	0.62	0.68
Al ₂ O ₃	8.05	8.77
Cr ₂ O ₃	0.08	0.09
Fe ₂ O ₃	3.89	4.12
FeO	4.40	3.80
MnO	0.15	0.12
MgO	16.84	15.42
CaO	9.18	9.68
SrO	0.13	0.11
Na ₂ O	2.21	1.03
BaO	0.56	0.45
K ₂ O	5.01	8.03
P ₂ O ₅	0.83	1.23
S	0.07	0.03
Cl	<0.005	0.60
F	0.27	0.25
CO ₂	0.015	0.060
H ₂ O+	1.75	1.40
Total	100.23	100.12
<i>mg</i>	0.872	0.879

Table 2: Mineral Compositions

	Olivine core	Mica	Mica Ol-rim	Cpx pheno	Cpx gdms	Pseudo Lc K-spar	Pseudo Lc Kalsilite	Kalsilite lath
SiO ₂	41.53	38.49	40.04	52.99	51.97	64.04	37.72	37.99
TiO ₂		2.49	0.18	0.39	0.02		0.03	
Al ₂ O ₃		9.79	0.10	1.05	0.53	18.44	30.70	31.88
Cr ₂ O ₃		0.0	0.01	0.54	0.0			
FeO _T	5.13	14.18	18.04	3.25	29.95	0.39	2.71	1.41
MnO	0.09	0.21	0.08	0.05	0.0			
NiO	0.48							
MgO	52.62	18.80	25.05	16.63	0.02			0.27
CaO	0.06			24.73	0.15			0.02
BaO		2.10	0.19			0.04		0.01
Na ₂ O		0.08	0.06	0.21	13.29	0.05	0.07	0.05
K ₂ O		9.63	9.57			16.3	28.31	29.19
Cl		0.0	0.0					
F		1.12	0.92					
Total	99.92	96.43	93.88	99.84	95.91	99.24	99.56	100.82
<i>mg</i>	0.948	0.768	0.902*	0.901	0.001**			

*Fe³⁺ = 8-(Si+Al); **Fe³⁺ by stoichiometry.

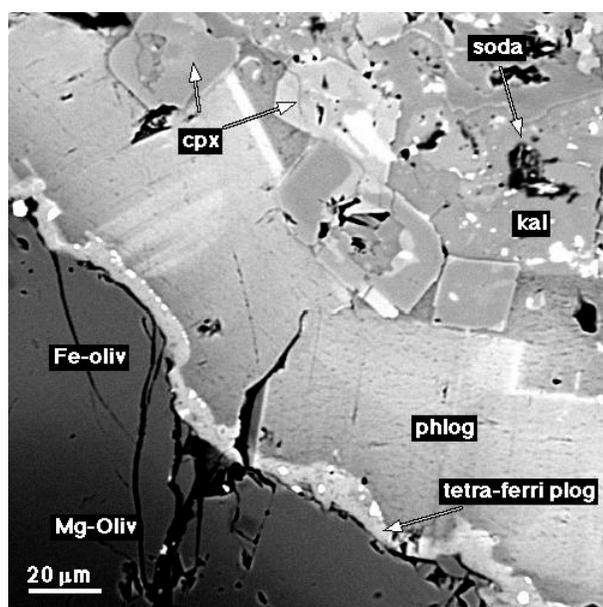


Figure 1: Back-scattered electron image of olivine margin showing narrow tetraferriphlogopite rim intermediate to olivine and Ti-Al-bearing mica mantle (soda=sodalite, kal=kalborsite).

Clinopyroxene is modally the most abundant phase in the samples and varies in size from phenocrysts, to groundmass. Euhedral phenocrysts are oscillatory zoned with compositions from diopside (*mg* 0.90) to salite (*mg* 0.80), are poor in Al₂O₃ (<<3.0%) and TiO₂ (<0.5%) and contain up to 15% of aegirine component (Table 2). Back-scattered electron imaging shows numerous oscillations in growth zoning that are parallel to the crystal edges. Most grains show one prominent episode

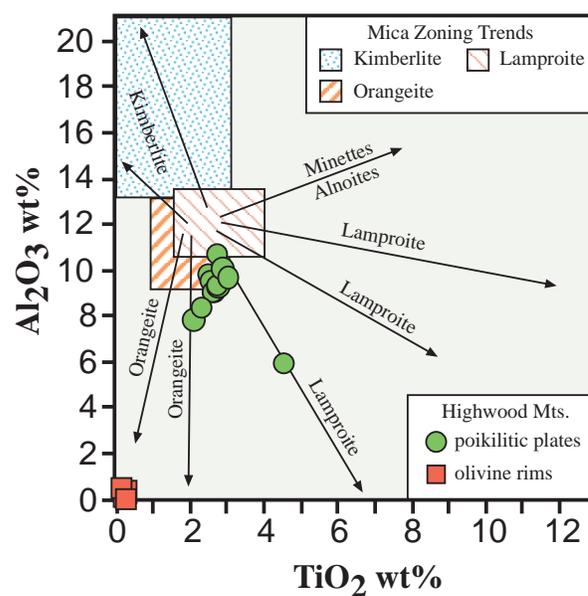


Figure 2: Comparison of mica compositional variations. Fields and differentiation trends are from Mitchell (1995).

of resorption that was subsequently overgrown by additional layers of oscillatory growth (Figure 3). Green clinopyroxene phenocryst rims and groundmass grains are strongly enriched in Na₂O and FeO_T (as low as *mg* 0.001) and depleted in Al₂O₃ (0.5%; Table 2). Pyroxene compositions are indistinguishable from those in lamproites and orangeites on the basis of Al and Ti concentrations (Figure 4).

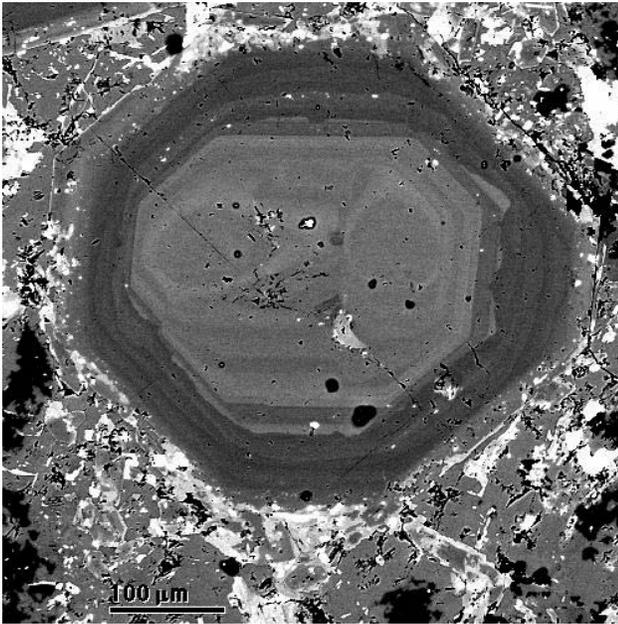


Figure 3: Cross-section of clinopyroxene phenocryst showing oscillatory zoning and prominent resorption boundary. Note the apatite inclusion (large medium gray grain), which are common in the clinopyroxene phenocryst grains.

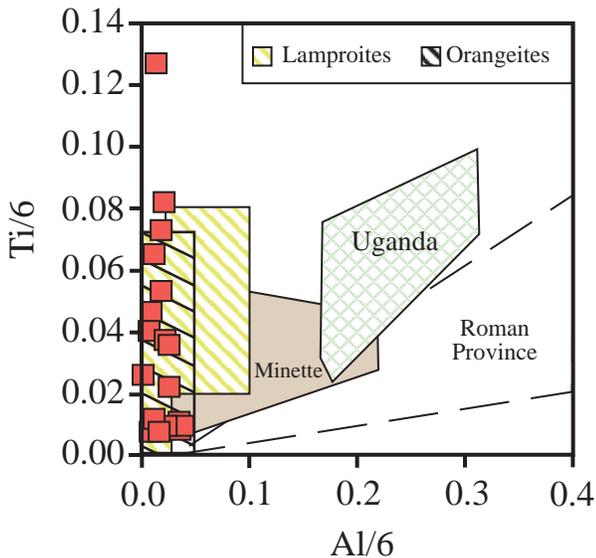


Figure 4: Comparison of Highwood clinopyroxene compositions (red) with those for lamproites, orangeites, and other potassium-rich rock types (after Mitchell, 1995).

Euhedral crystals of chromite are very common as inclusions in the olivine grains. Chromite grains of similar composition also occur throughout the groundmass, and petrographic evidence suggests that at least some of these grains originated as inclusions in olivine that were liberated through dissolution of olivine. The chromite is very Cr-rich with $Cr/(Cr+Al) = 0.88-0.91$

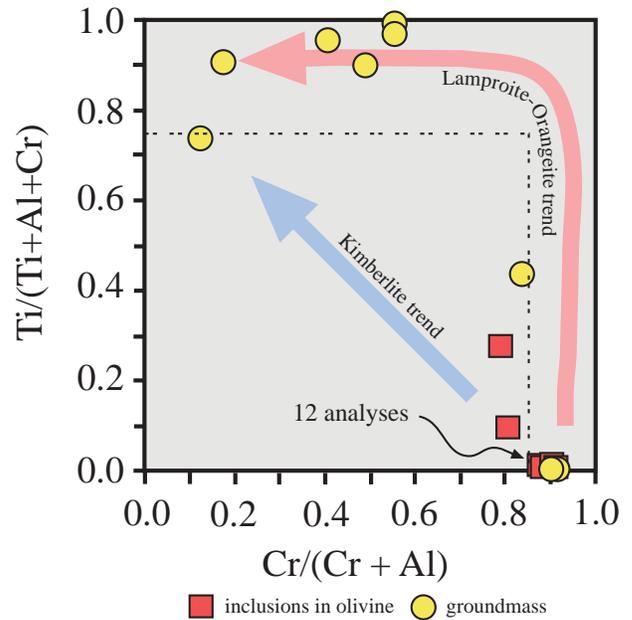


Figure 5: Spinel compositions. Trend lines following Mitchell (1995). Inside of box contains spinel compositions from diverse rock types, including minettes and ultramafic lamprophyres.

and $Ti/(Ti+Al+Cr) < 0.01$. Inclusion and groundmass spinel grains follow the chemical zoning trend of spinel grains from lamproites and orangeites (Figure 5).

Crystals (up to 0.5 mm in size) with the morphology of leucite are scattered throughout the groundmass (Figure 6). These have unmixed into 'graphic' intergrowths of sanidine (avg. 0.30% Fe_2O_3) plus kalsilite (avg. 2.6% Fe_2O_3 ; Table 1). Modal mass-balance calculations of the exsolved components in HM98-4 show that the primary leucite (1.1% Fe_2O_3) had a silica-rich composition (Ks 66, Qtz 33; ideal leucite is Ks 72.5, Qtz 27.5). Leucite is a common component of nearly all lamproite types but is rare or absent in orangeites.

Pseudoleucite grains contain the only occurrence of feldspar in these samples. Pseudoleucite is found in both HM562 and HM98-4, but only HM98-4 has separate crystals of kalsilite. These occur as subhedral, blocky, slightly altered grains through out the groundmass. Their habit, and absence of any intergrown feldspar, indicates that this is a primary magmatic phase and not a component of pseudoleucite. The blocky kalsilite grains have, on average, slightly lower iron (1.1% Fe_2O_3) than that of the exsolved pseudoleucite kalsilite (1.6% Fe_2O_3). The existence of magmatic kalsilite precludes these rocks from being components of any lamproitic or orangeitic lineage based on all recent classification schemes and would require these rocks to be classified instead as kamafugites.

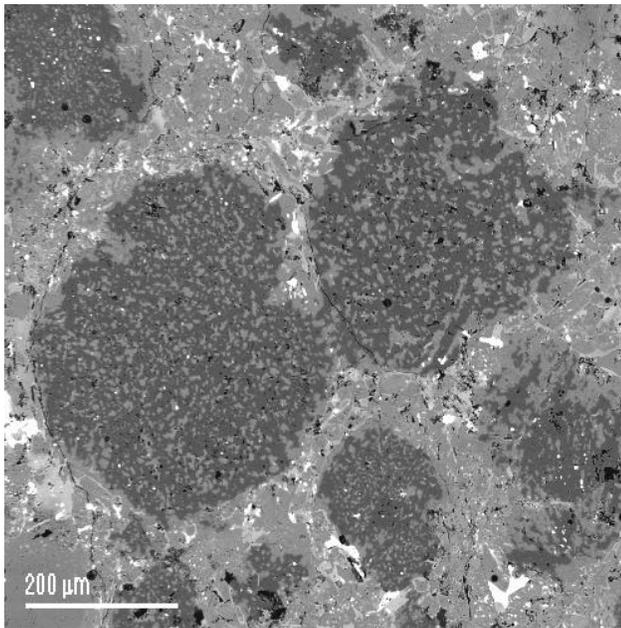


Figure 6: Back-scattered electron image of pseudoleucite. The pseudoleucite grains are composed of Na-free (<0.2% Na₂O) sanidine and kalsilite. Note crystal faces of former leucite grains.

The outer margins of many pseudoleucite grains have been partially replaced by mixtures of sodalite, pitiglianoite [Na₆K₂Si₆Al₆O₂₄(SO₄)₂(H₂O)], and the rare potassium borosilicate mineral, kalborsite [K₆BAl₄Si₆O₂₀Cl(OH)₄]. These minerals are also found separately as late phases throughout the groundmass and particularly in vuggy, angular voids. Pitiglianoite is a feldspathoid that has only recently been described from Tuscany, Italy, where it formed through reaction of trachytic magma and hydrothermally altered vent rocks (Merlino, et al., 1991). The pitiglianoite composition here (Table 3) has a slightly higher Si/Al and lower Na/K than ideal values. Kalborsite has not previously been described outside of the alkaline rocks of the Kola Peninsula. The compositions here have somewhat higher SiO₂ and Al₂O₃ than the reported Kola examples, and lower K₂O. Boron was confirmed in the kalborsite by static TOF-SIMS. However x-ray structure determinations have not been made on either the kalborsite or pitiglianoite. Like kalsilite, the presence of sodalite precludes classification of this rock as a lamproite. Sodalite has not been identified in orangeites.

Clusters of radiating blades and needles of barytolamprophyllite and shcherbakovite, usually associated with apatite, wadeite, barite and titanite, are late-stage minerals that typically fill angular groundmass voids (Figure 7). The shcherbakovite is strongly sector zoned, particularly in the alkali elements (Table 3).

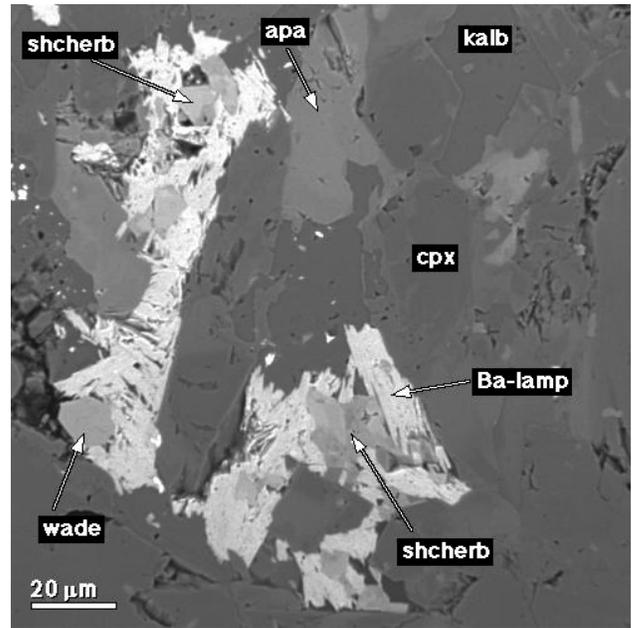


Figure 7: A microcosm of late stage minerals. Groundmass clinopyroxene (cpx) with brighter, aegerine-rich rims, sector zoned shcherbakovite (shcherb), blades of barytolamprophyllite (Ba-lamp), zoned apatite (apa), interstitial kalborsite (kal), and wadeite (wad). The darkest regions are voids. This mineral assemblage is absent from sample HM562.

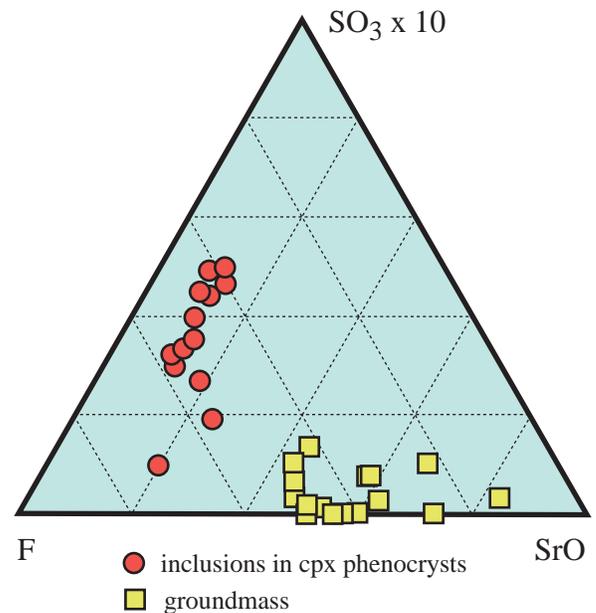


Figure 8: Composition of apatite crystals found as inclusions in clinopyroxene compared to late-stage, vuggy apatite.

Unlike the euhedral/subhedral apatite inclusions commonly found in clinopyroxene phenocrysts, the late-stage apatite is anhedral or massive. The groundmass

apatite is deficient in S and F compared to that included in clinopyroxene phenocrysts, but enriched in Sr (Figure 8).

Some groundmass interstices are filled with potassium richterite in sample HM562, but it is extremely rare in HM98-4. The potassium richterite is magnesian ($mg =$

0.74 – 0.84), contains 1.0-1.3% F, and has insufficient Si+Al to fill the tetrahedral site (similar to potassium richterites from lamproites and orangeites). Unlike the amphiboles in lamproites however, the Ti concentrations in these potassium richterite grains are quite low and are more akin to amphiboles in orangeites (Figure 9).

Table 2: Mineral Compositions

	1	2	3	4	5	6	7	8
SiO ₂	23.34	39.34	41.63	45.66	33.61	37.41	37.59	30.44
ZrO ₂	0.0	0.54	0.02	28.94				0.06
TiO ₂	26.88	20.61	23.56	1.35		25.64		39.03
Al ₂ O ₃	0.12	0.15	0.65	0.01	28.46		31.89	0.05
Cr ₂ O ₃	0.07	0.0	0.0	0.0				
FeO _T	8.16	3.49	2.47	0.24	0.09	0.13	0.04	1.34
MnO	0.71			0.05				
MgO	1.65	0.06	1.17	0.0	0.0			0.0
CaO	1.28	2.02	1.13	0.07	0.04	0.01	0.06	28.27
SrO	1.14	0.14	0.03	0.09	0.0		0.0	0.40
BaO	23.32	19.56	12.92	0.16	0.0		0.18	0.11
Na ₂ O	8.75	5.22	5.19	0.0	13.43	0.11	24.08	0.29
K ₂ O	3.38	8.26	10.95	24.32	12.83	28.89	0.60	0.08
Nb ₂ O ₅	0.17	0.59	0.09					
Cl	0.0					3.97	7.10	0.06
F	1.40							
SO ₃					7.51		0.17	
Total	99.81	99.99	99.82	100.92	95.97	95.26	99.56	100.14

1-Barytolamprophyllite, 2-Shcherbakovite, 3-Shcherbakovite, 4-Wadeite, 5-Pitiglianoite, 6-Kalborosite, 7-Sodalite, 8-Titanite.

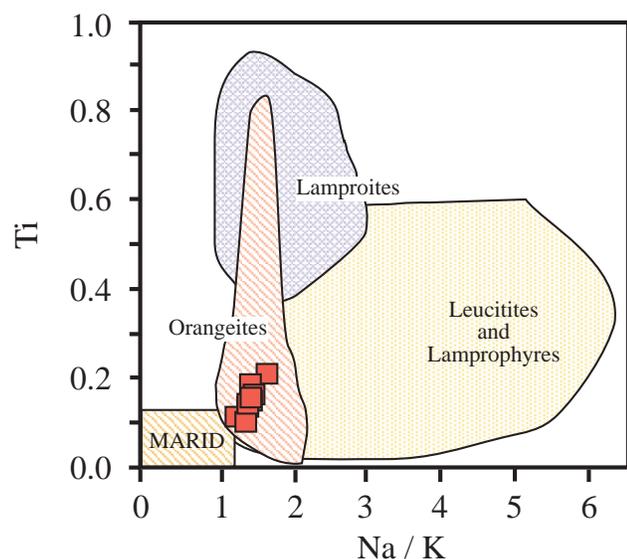


Figure 9: Comparison of amphibole compositions with those from lamproites, orangeites, and other potassic rock types (after Mitchell, 1995).

REFERENCES

- Mitchell, R.H., 1995. *Kimberlites, Orangeites, and Related Rocks*. Plenum, New York.
- O'Brien, H.E., 1988. *Petrogenesis of the Potassic Mafic Rocks of the Highwood Mountains, Montana*. Ph.D. Thesis, University of Washington, Seattle, USA.
- Merlino, S., Mellini, M., Bonaccorsi, E., Pasero, M., Leoni, L., and Orlandi, P. 1991. Pitiglianoite, a New Feldspathoid from Southern Tuscany, Italy: Chemical Composition and Crystal Structure. *Am. Mineral.*, 76, 2003-2008.

Contact: SM Kuehner, Dept. of Earth and Space Sciences, Box 351310, University of Washington, Seattle, WA. 98195, USA, E-mail: kuehner@u.washington.edu