Wenjiite, Ti$_{10}$(Si,P,□)$_7$, and kangjinlaite, Ti$_{11}$(Si,P)$_{10}$, new minerals in the ternary Ti-P-Si system from the Luobusa ophiolite, Tibet, China

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**ABSTRACT**

The new minerals wenjiite, Ti$_{10}$(Si,P,□)$_7$ (IMA2019-107c) and kangjinlaite, Ti$_{11}$(Si,P)$_{10}$ (IMA2019-112b) occur with badengzhuite, zhiqinite, and a K-bearing dmisteinbergite-like mineral in a spheroid 20 μm across enclosed in corundum from the Cr-I1 podiform chromitite orebody near the Kangjinla, Luobusa ophiolite, Tibet, China. In addition, wenjiite occurs with deltalamite, jingsuiite, osbornite-khambaraevite, and the K-bearing dmisteinbergite-like mineral in a lamellar intergrowth 100 μm long, also enclosed in corundum from the same locality. The new minerals were characterized by energy-dispersive spectroscopy and three-dimensional electron diffraction, which enabled us to obtain an ab initio structure solution and dynamical refinement from grains a few micrometers across hosted in a FIB lamella. Four analyses of wenjiite from the spheroid gave in wt% Si 21.67, P 6.24, Ti 66.39, V 1.37, Cr 2.20, Mn 0.97, and Fe 1.17 (normalized to 100), which corresponds to (Ti$_{0.93}$Cr$_{0.03}$Mn$_{0.01}$Fe$_{0.01}$V$_{0.02}$)$_{10}$ (Si$_{6.70}$P$_{0.12}$)$_{5.61}$ on the basis of 10 cations excluding Si and P. The simplified formula is Ti$_{10}$(Si,P)$_{13.5}$, or more generally Ti$_x$(Si,P)$_y$, where $x > y$ and $6 \leq (x + y) \leq 7$, i.e., Ti$_{10}$(Si,P,□)$_7$. Wenjiite has hexagonal symmetry, space group: R6$_3$/mcm (no. 193), with $a = 7.30(10)$ Å, $c = 5.09(10)$ Å, $V = 235(6)$ Å$^3$, $Z = 1$, and is isostructural with xifengite, mavlyanovite, synthetic Ti$_5$Si$_3$, and synthetic Ti$_5$P$_3$. Four analyses of kangjinlaite gave in wt% Si 25.56, P 9.68, Ti 62.35, V 0.21, Cr 0.83, Mn 0.42, and Fe 0.95 (normalized to 100), which corresponds to (Ti$_{0.97}$V$_{0.03}$Cr$_{0.13}$Mn$_{0.06}$Fe$_{0.14}$)$_{10}$ (Si$_{7.43}$P$_{2.55}$)$_{5.09}$, on the basis of 10 cations excluding Si and P. The simplified formula is Ti$_{11}$(Si,P)$_{10}$. Kangjinlaite is tetragonal, with space group: I4/mmm (no. 139), $a = 9.4(2)$ Å, $c = 13.5(3)$ Å, $V = 1210(50)$ Å$^3$, $Z = 4$, and is isostructural with synthetic compounds of the H$_6$O$_3$Ge$_{10}$ type, being the most compact of these phases. Despite there now being over 70 compounds containing 38 elements isostructural with H$_6$O$_3$Ge$_{10}$, synthesis of an analog of kangjinlaite has not been previously reported in either the Ti-P or Ti-Si binary systems or in a multicomponent system. The previously deduced crystallization sequence with decreasing temperature of the four minerals in the spheroid is wenjiite → kangjinlaite → zhiqinite + badengzhuite. This sequence is consistent with relationships reported in 9 binary systems containing intermetallic compounds of Ge and Sn isostructural with Mn$_5$Si$_3$ and H$_6$O$_3$Ge$_{10}$. In eight of these systems the Mn$_5$Si$_3$ analog melts congruently, whereas the H$_6$O$_3$Ge$_{10}$ analog never does. Instead, the H$_6$O$_3$Ge$_{10}$ analog melts peritectically, generally to an Mn$_5$Si$_3$ analog and less commonly to compounds with 5.4 stoichiometry. Final crystallization of the spheroid to zhiqinite + badengzhuite is expected to be well below the temperature of 1500 °C for the congruent melting of zhiqinite in the Ti-Si system, i.e., in the range of ~1100–1300 °C.

**Keywords:** Luobusa chromitite, wenjiite, kangjinlaite, intermetallic melts, crystal structure, transmitting electron microscopy, three-dimensional electron diffraction

**INTRODUCTION**

Intermetallic phases are relatively rare in natural systems, being largely restricted to extra-terrestrial environments. Most of these occurrences are dominated by iron, e.g., in meteorites, whereas occurrences with minerals dominated by Ti are rare. Notable examples include a fulgurite containing TiP (Essene and Fisher 1986), the type locality for native titanium (Fang et al. 2013; Dobrzhinetskaya et al. 2014), and inclusions in corundum from Mount Carmel, Israel (e.g., Griffin et al. 2020, 2022), and the Luobusa ophiolite, Tibet, China (e.g., Xiong et al. 2020, 2021a, 2021b, 2022; this study). Although Ti-bearing intermetallic phases have wide industrial applications and are