Structure of ferrosilite and pentlandite from inclusions in the Muong Nong tektites from Laos

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Tektites (from the Greek *tēktos* = molten) are natural glasses found in geographically defined areas called strewn fields. Currently, five such fields are documented in the literature [1], with ages ranging from 35 million to 780,000 years. It is generally agreed that these glasses result from hyper-velocity impacts of extraterrestrial bodies on Earth's sedimentary or weathered surface sequences [2,3]. Tektite key characteristics include high SiO_2 content (over 70% except for some microtektites), a lack of crystalline phases, low meteorite content, water content up to a few hundred ppm, and the presence of lechatelierite (quartz glass) particles. Tektites can contain crystalline inclusions which can help us to deduce their origin.

Small, up to 20 microns in size, inclusions were studied by SEM and several TEM techniques, such as 4D STEM (ACOM), EDS, 3D ED to identify the phases present, their mutual relationship, and to dynamically refine the structure of two phases [4].

Two types of sulfidic inclusions were observed: (A) with Fe- and (Fe,Ni)-sulfide domains and irregular edges bordered by Mg and Fe silicates, with stoichiometry resembling pyroxene-group minerals, and (B) with small worm-like Fe and Ni sulfides in a matrix of FeS. Type (A) inclusions have complex mineralogy, with pentlandite and pyrrhotite identified as main constituents. These inclusions typically feature a pyroxene-group mineral rim 100-150 nm thick, chemically identified as ferrosilite. A layer of chalcopyrite, up to 100 nm thick, is often present between the rim and the sulfide phase, with rare hercynite domains. Another spinel mineral, magnetite, is found as domains up to 500 nm within pentlandite. Hercynite additionally contains low levels of Ti, Cr, and Zn, while magnetite contains chromium. Type (B) inclusions mainly consist of pyrrhotite, with pentlandite and chalcopyrite also present. Unlike type (A) inclusions, magnetite in type (B) inclusions is pure, without other elements. Native copper is also found in these inclusions.

Structure of two phases was probed for atomic species distribution over two structural positions - Mg/Fe distribution in ferrosilite $MgFeSi_2O_6$ and Fe/Ni distribution in pentlandite $(Fe, Ni)_{9-x}S_8$. The structure of ferrosillite corresponds to low clinoenstatite [5] with slightly larger lattice parameters a = 9.70 Å, b = 8.91 Å, c = 5.25 Å, β = 108.8°. In the structure, the larger, more distorted M1 position contains 73 % Fe, while the smaller, more regular M2 position contains 47 % Fe. The structure of pentlandite contains two metal positions in octahedral and tetrahedral coordination. In addition, a small amount of metals was detected in void positions (the tetrahedral position being occupied by 1-2 %, about twice as much as the octahedral). A preference of iron for the octahedral position (about 60 % occupancy) and nickel for tetrahedral position (about 60 % occupancy) was observed.

The similarity of these sulfidic inclusions to sulfide inclusions found in terrestrial magmatic rocks suggests that their presence is more consistent with the inclusion of (ultra)mafic magmatic rocks or their weathered products into tektite melt, rather than the extraterrestrial origin of the inclusions [6, 7].

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