

## **Nuwaite (Ni<sub>6</sub>GeS<sub>2</sub>) and butianite (Ni<sub>6</sub>SnS<sub>2</sub>), two new minerals from the Allende meteorite: Alteration products in the early solar system**

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### **ABSTRACT**

Nuwaite (Ni<sub>6</sub>GeS<sub>2</sub>, IMA 2013-018) and butianite (Ni<sub>6</sub>SnS<sub>2</sub>, IMA 2016-028) are two new chalcogenide minerals, occurring as micrometer-sized crystals with grossular, Na-bearing melilite, heazlewoodite, and Ge-bearing Ni-Fe alloys in veins and as mono-mineralic crack-filling material in igneous diopside in the Type B1 Ca-Al-rich inclusion (CAI) *ACM-2* from the Allende CV3 carbonaceous chondrite. The chemical composition of type nuwaite is (wt%) Ni 65.3, S 10.3, Ge 8.2, Te 7.9, Sn 5.1, and Fe 1.7, with a sum of 98.5 and an empirical formula of (Ni<sub>5.95</sub>Fe<sub>0.16</sub>)(Ge<sub>0.60</sub>Sn<sub>0.23</sub>)(S<sub>1.72</sub>Te<sub>0.33</sub>). The simplified formula is Ni<sub>6</sub>(Ge,Sn)(S,Te)<sub>2</sub>, leading to an end-member of Ni<sub>6</sub>GeS<sub>2</sub>. The chemical composition of type butianite is (wt%) Ni 62.1, Sn 8.9, Te 10.3, S 8.9, Ge 5.3, Fe 1.3, sum 99.1, giving rise to an empirical formula of (Ni<sub>5.93</sub>Fe<sub>0.13</sub>)(Sn<sub>0.52</sub>Ge<sub>0.41</sub>)(S<sub>1.56</sub>Te<sub>0.45</sub>). Butianite's simplified formula is Ni<sub>6</sub>(Sn,Ge)(S,Te)<sub>2</sub> and the end-member formula is Ni<sub>6</sub>SnS<sub>2</sub>. Both nuwaite and butianite have an *I4/mmm* intergrowth structure with *a* = 3.65 Å, *c* = 18.14 Å, *V* = 241.7 Å<sup>3</sup>, and *Z* = 2. Their calculated densities are 7.24 and 7.62 g/cm<sup>3</sup>, respectively. Nuwaite and butianite are the first known meteoritic minerals with high Ge and Sn concentrations.

Nuwaite and butianite are very late-stage, vapor-deposited, alteration products, filling in pores within preexisting grossular-rich alteration veins and cracks in igneous Al,Ti-diopside. These phases and associated heazlewoodite and Ge-bearing alloys are observed only within the Ca-,Al-rich inclusion (CAI) and not outside it or at the inclusion-matrix interface. As only sections in one half of *ACM-2* contain nuwaite/butianite, they were probably derived through a relatively low *f*<sub>O<sub>2</sub></sub>*f*<sub>S<sub>2</sub></sub> sulfidation process, in which a highly localized, low-temperature Ge-, Sn-bearing fluid interacted with a portion of the host CAI. It is likely that the fluid became relatively more Sn- and Te-enriched with time and that crack fillings post-date vein fillings, possibly due to a late remobilization of vein sulfides.

**Keywords:** Nuwaite, Ni<sub>6</sub>GeS<sub>2</sub>, butianite, Ni<sub>6</sub>SnS<sub>2</sub>, new minerals, Allende meteorite, CV3 carbonaceous chondrite, Ca-Al-rich inclusions