SPINEL FROM THE CRETACEOUS-TERTIARY BOUNDARY: CHARACTERISTICS, ORIGIN AND IMPLICATIONS; E. Robin, J. Gayraud, L. Froget, and R. Rocchia, Centre des Faibles Radioactivités CEA/CNRS, 91190 Gif-sur Yvette, France.

Brief summary. Numerous spinel crystals with various but unique compositions in the spinel group have now been reported worldwide at the Cretaceous-Tertiary (K-T) boundary. We propose that they are derived from ablation droplets produced during the interaction with the atmosphere of large meteoroids decelerated at low altitudes. Our scenario implies multiple meteoroid impacts all over the Earth, resulting either from the fragmentation of the K-T impactor by an oblique impact or from the encounter with a fragmented comet.

Geological setting and characteristics of K-T spinel. Spinel crystals with unusual and unique compositions in the spinel group, have been found throughout the world at the Cretaceous-Tertiary (K-T) boundary: in marine sections in Italy [1-5], in Spain [4,6], in France [5], in Austria [5], in Tunisia [7], in Haiti [8], in Mexico [9], in New Zealand [6], in continental sections in North America in Wyoming [10] and in deep sea cores in the Gulf of Mexico [9], in the Pacific [3,11,12], Atlantic [3] and Indian Oceans [13]. Although large variations in spinel compositions (in particular in the Cr content and Fe3+/Fetotal ratio) are observed from site to site, even for nearby sites [3, 5], the K-T spinel can be distinguished from spinel in terrestrial and extraterrestrial rocks [14-17] on the basis of a distinctly higher Ni content and higher Fe3+/Fetotal ratio [2-6,18]. The spinel crystals are commonly a few micrometers in size, with rare crystals up to 50 µm, display octahedral and skeletal morphologies, with only few dendrites, and are often clustered in more or less spheroidal bodies of 50-500 µm in size [1-4,11,13]. Some of these spheroids have high Cr, Co, Ni and Ir enrichments relative to the surrounding clay matrix, with abundances sometimes approaching those in chondrites, and low REE contents, with a relatively flat pattern [11,19].

Formation conditions and origin of K-T spinel. The high Ni content of the K-T spinel excludes derivation from crustal material, as this material is strongly depleted in Ni, but points to a meteoritic or eventually a mantle source for this mineral [6,18]. The chondritic composition of some spinel-bearing spheroids favor a meteoritic source [11,19]. The high Fe3+/Fetotal ratio of the K-T spinel indicates formation under extremely oxidizing conditions [3,6,18,20]. According to Gayraud et al. [20], the minimum oxygen fugacity required for the formation of this mineral is $\log fO2 \approx -2$ bar (considering a minimum Fe3+/Fetotal ratio of ≈ 80 atom%, [5,18]), and some spinel crystals were formed at $\log fO2 > -0.68$ atm (Fe3+/Fetotal > 90 atom%, [5,18]), or higher than the oxygen partial pressure existing at sea level. Still from Gayraud et al. [20], the abundance of octahedral and skeletal crystals, with only few dendrites, reflects equilibrium crystallization of this mineral below 1500°C. In other terms, the spinel crystals found worlwide at the K-T boundary are derived from melted droplets of meteoritic composition that equilibrated at $\log fO2 \geq -2$ bar and $T \leq 1500$°C (figure). Such formation conditions rule out crystallization of K-T spinel from terrestrial and/or extraterrestrial material melted and/or condensed following a cratering event. Indeed, the oxygen fugacity in such material is several log units below the minimum oxygen fugacity required for the formation of K-T spinel, as both terrestrial and extraterrestrial rocks have equilibrated within a few log units of oxygen fugacity of the fayalite-magnetite-quartz (FMQ) or iron-wustite (IW) buffers [14] (figure). It is the reason why K-T spinel crystals have no counterpart in terrestrial and extraterrestrial rocks [14-17], as all these rocks have crystallized at extremelly low oxygen fugacities. Higher oxygen fugacities can be envisaged in the case of an oceanic impact, due to dissociation of H2O molecules, or if one consider an impact on carbonate and/or evaporite terranes, due to dissociation of CO2 and SO2 molecules (figure). However, high pressures (several Mbars) and high temperatures (≈ 100,000°K) prevail in such events [21] and there is no evidence as yet that it exists a range of P-T conditions that would provide the kind of environment needed for the formation of spinel. High-velocity interaction with the Earth's atmosphere for projectile material remains the one and unique mechanism known to date for producing the K-T spinel [18]. During such interactions, the oxygen fugacity is a function of the ram pressure ($fO2 \propto P_{ram} = \rho_{air}V^2$ at the stagnation point [22]) and a meteoroid decelerated from its cosmic velocity in the Earth's atmosphere experienced maximum $\log fO2$ ranging from -4 to 4 bars depending on its size, density, velocity and incidence angle. As a general rule, a small meteoroid is decelerated at high altitude [22] and experienced a lower oxygen fugacity than a large meteoroid decelerated deeper in the atmosphere. Considering the high Fe3+/Fetotal ratios (> 80 atom%) of the K-T spinel, we propose that this mineral is derived from ablation droplets produced during the interaction with the atmosphere of large meteoroids decelerated at low altitude. We exclude the interaction of small dust particles with the atmophere (for instance melted or condensed droplets generated following a cratering event and ejected worldwide on ballistic trajectory), as such particles would be decelerated in the upper atmosphere, resulting in spinel crystals with low Fe3+/Fetotal ratios (< 80 atom%).

Implications. This conclusion implies multiple meteoroid impacts all over the Earth at the end of the Cretaceous in order to account for the worldwide dispersal of spinel-bearing spheroids [11]. Two mechanisms can be

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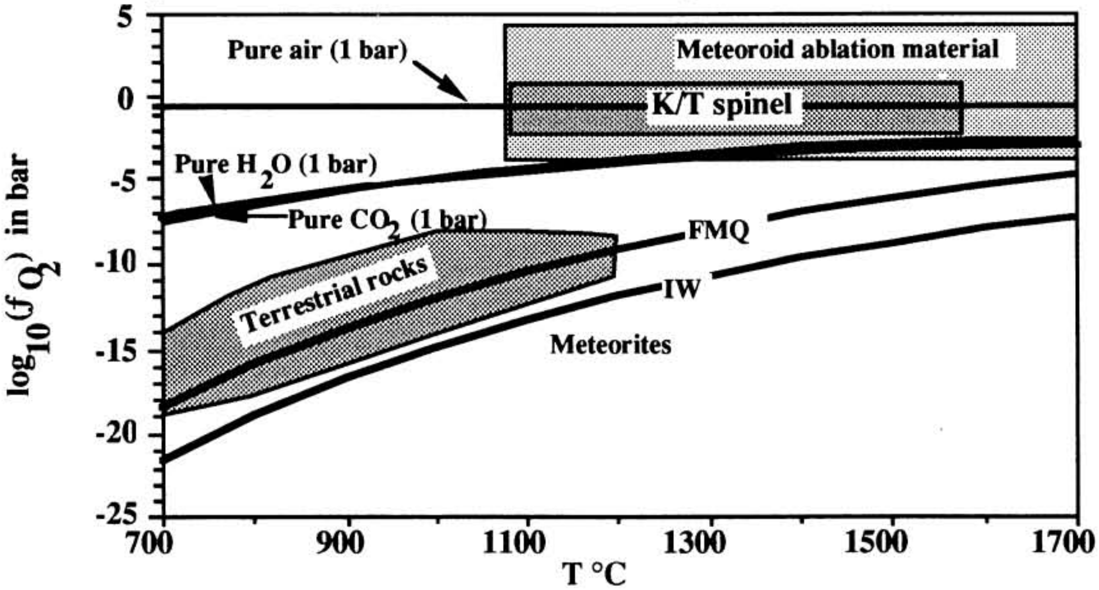
envisaged: oblique impact [23,24] and encounter with a fragmented comet [25-27]. Schultz and Gault [23,24] have extensively discussed the effects of low impact angles on the dispersal of projectile material. They concluded that for sufficiently low impact angles (< 15°) disruption of a single impactor could spawn numerous projectile fragments which could be widely dispersed over the Earth on ballistic trajectories. As these projectile fragments re-enter the atmosphere, they loss a large fraction of their mass in the form of ablation droplets in which numerous spinel crystals precipitate, leading to a worldwide deposition of spinel-bearing debris.The encounter with a fragmented comet may also account for a global deluge of numerous projectile fragments. Such a phenomena was recently observed on Jupiter with the crash of P/Shoemaker-Levy 9 comet [27]. Breakup of a comet occurs through tidal disruption, when it passes within the Roche limit, or by disintegration during volatile loss [25-27]. As the Earth is smaller than Jupiter, the breakup must have occurred far from the Earth, for example near the Sun, in order to separate the fragments over a distance comparable to Earth diameter [26]. In that case, several impacts can occur, within one hemisphere [26], some with low angles, leading here again to a global meteor deluge and to the worldwide deposition of spinel-bearing spheroids. As the composition of spinel varies as a function of oxygen fugacity, temperature, and initial composition of the crystallizing material [20], the regional variations in the compositions of spinel crystals could reflect variations in the physical and chemical environment in which they crystallized, depending on the size, density, velocity, incidence angle and initial composition of projectile fragments that re-entered the Earth's atmosphere.

Figure: $\log_{10} f_{O_2}$ versus temperature illustrating the different conditions of formation of: the K-T spinel, meteoroid ablation material, terrestrial igneous rocks and meteorites.



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