# Causes of color in brown mammoth ivory

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The mammoth species were once the largest terrestrial mammals in the world during the late Pleistocene (approximately 350,000 to 10,000 years ago), inhabiting the northern hemisphere, starting in Europe and extending as far east as North America (Lister & Sher, 2001; Nogués-Bravo et al., 2008). Mammoth ivory has a long history of use in jewelry and artworks because of its beauty and pleasing texture (Saunders et al., 1989; Pitulko et al., 2015). Similar to elephant ivory, mammoth ivory exhibits fascinating colors and patterns and can take on a smoother polish than other organic raw materials. Due to various international bans on the sale of elephant ivory, mammoth ivory has gradually replaced it as an organic gemstone (Martin, 2006; Yin et al., 2013). To date, gemological studies of mammoth ivory have focused mainly on the material's composition, the crystallographic characteristics of inorganic minerals within, and the means of separating it from elephant ivory (Qi et al., 2010; Wu et al., 2013; Ngatia et al., 2019; Sun et al., 2022). The surface of mammoth ivory usually has a brown color (Figure 1) but is occasionally blue to dark blue or even black. Research on the causes of this surface color is scarce, however.

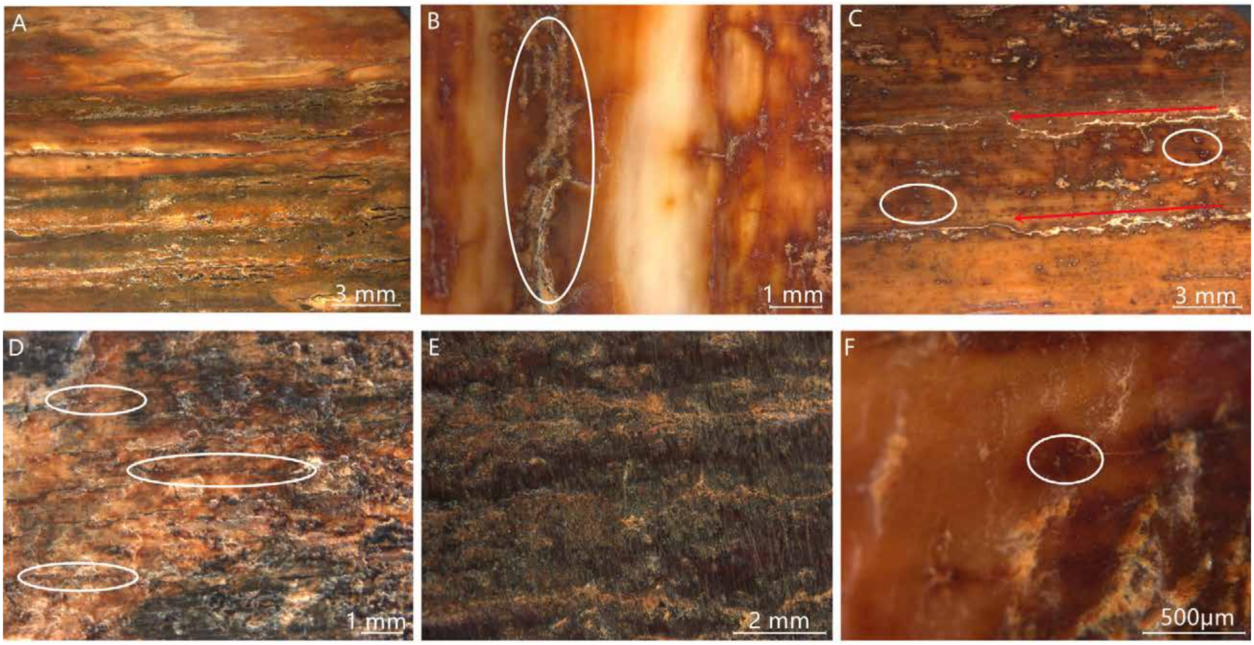


Figure 1. Microscopic images of the surface of mammoth ivory samples. A: Uneven color distribution on the surface. B: Large crack (in the white circle). C: Two parallel cracks consistent with the direction of the blue arrows and tan dots in the white circles. D: Irregular color distribution and darker brown cracks (in the white circle). E: Brown and darker brown interspersed on the surface. F: Tan dots (in the white circle) on the surface.

In order to investigate the causes of this color, Fourier-transform infrared spectroscopy (FTIR), Powder X-ray diffraction (XRD), and scanning electron microscopy with energy-dispersive X-ray spectroscopy (SEM EDX) were used to study the samples' spectroscopic and mineralogical characteristics, surface morphology, and chemical composition. Brown mammoth ivory is composed mainly of hydroxyapatite, carbonate hydroxyapatite, and collagen (Figure 2). With the dissolution and loss of organic matter and phosphate ions ($PO4^{3-}$), fissures and cracks formed. Hematite, pyrite, pyrolusite, and manganite crystallized on the mammoth ivory's surface and concentrated in the cracks of the cementum layer. The phase transformation processes during the burial time promoted the formation of iron oxides, manganese oxides and hydroxides, and iron sulfide, which caused the brown surface color.

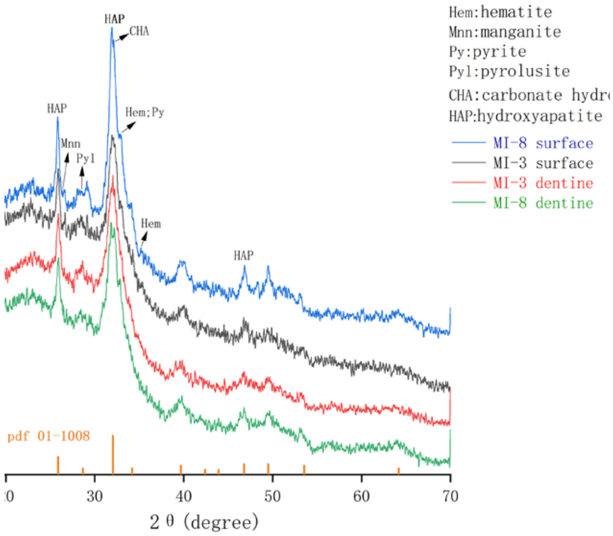


Figure 2. Powder XRD patterns of mammoth ivory samples. Characteristic peaks of hydroxyapatite (ICDD pdf 01-1008), hematite (ICDD pdf 72-0469), manganite (ICDD pdf 74-1631), pyrite (ICDD pdf 71-2219), pyrolusite (ICDD pdf 72-1984), and carbonate hydroxyapatite (ICDD pdf 19-0272) can be distinguished in the XRD pattern.

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