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## The Hydrothermal Mobility of Vanadium: Insights from Modeling with Implications for the Vanadium Enrichment of Iron Oxide-Apatite Deposits

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Vanadium is a critical element, as it is necessary in steel alloys and in V redox batteries, both of which are essential for the development of a low-carbon energy infrastructure. Vanadium is traditionally a by-product of the extraction of Fe and Ti in magmatic deposits and of U in calcrete-hosted U-V deposits. Its current production is limited, and its demand is forecasted to increase significantly, so new sources of this element will be needed in order to achieve the required supply. Iron oxide-apatite (IOA) deposits are dominated by magnetite, an iron oxide mineral. They are major sources of Fe, and recent studies have shown that they can contain substantial V hosted in magnetite as well. This project explores the favorable physicochemical conditions for the formation of V-rich magnetite in these deposits.

Magnetite in IOA deposits is thought to result from magmatic-hydrothermal processes, but the exact conditions of the hydrothermal fluid from which it precipitates are still unclear. We present the thermodynamic modeling of aqueous speciation of a hydrothermal fluid that exsolves from a melt of intermediate composition. Our model evaluates the behavior of V species in the fluid as a function of temperature, pressure, pH, and $fO_2$. Our preliminary results indicate that the solubility of V is higher at higher pH, temperature, and $fO_2$ and that V is most favorably incorporated in magnetite as $V^{3+}$ at high temperature and low pH and $fO_2$ (Fig. 1).

Our results indicate that purely hydrothermal magnetite can host considerable amounts of V in its structure and that the parental melt for the hydrothermal fluid needs to be of intermediate composition. These results have implications within the tectonic setting that is suitable for the formation of IOA deposits, which will allow for improved exploration campaigns to more efficiently find this type of deposit in order to increase the resources of V needed for the energy transition.

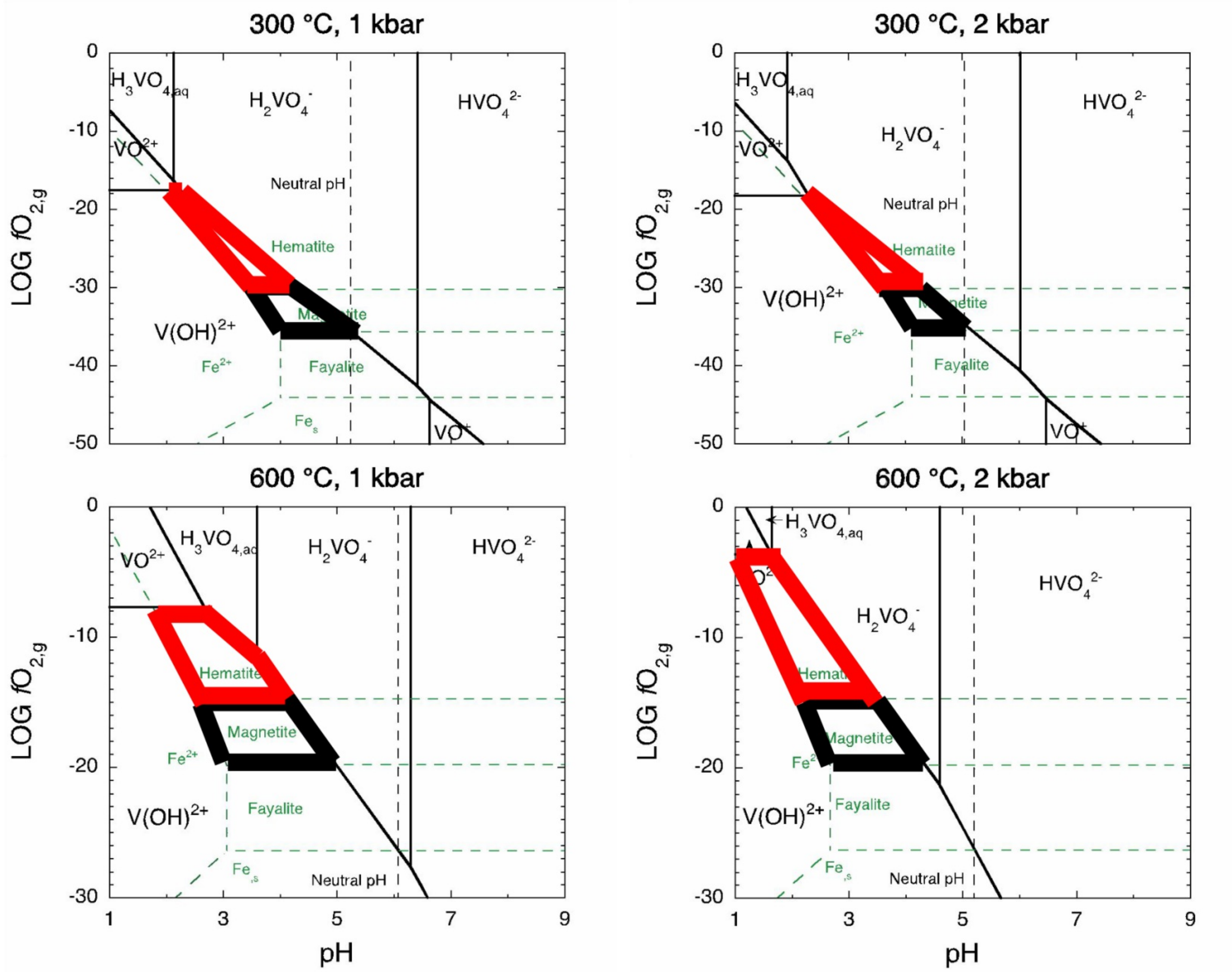


Fig. 1: Phase diagrams showing the stability of iron oxides and V species in pH and fO2 space for different temperatures and pressures. Highlighted are the fields where hematite (red) and magnetite (black) incorporate V3+ in their structure. The favorable conditions for V incorporation in magnetite are high temperature and acid pH.