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The Power of Neutrons in Earth Sciences and Environment Research

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The merits of neutron scattering in Earth Sciences and Environment Research, stem from specific properties of neutrons which make them an ideal probe for the investigation of materials and compounds of interest in these fields. A large variety of favourable and sometimes unique applications can be envisaged when considering some of these properties. 1) - The low attenuation of neutron beams by many metals and materials, can effectively make extreme sample environments (HT, HP, Reaction Cells, differential loading frames, *etc*.) easier to work with for neutron scattering than for other *in situ* experimental techniques, especially where bulk samples are concerned or when gram-scale amounts of sample are available. This allows testing the properties of minerals and Earth materials in their natural environment, be it the surface or the interior of our Planet. 2) - Neutrons, unlike X-rays, are efficiently scattered by hydrogen ^{1}H and deuterium ^{2}H atoms. Many minerals have a structural hydrous component, often in the form of hydroxide ions or water molecules. Water in minerals, rocks and Earth materials is extremely important in regulating a large variety of behaviours and properties of interest to the Earth and Environmental Sciences, spanning from the atomic to the continental scale. The technological efforts aimed at the conversion to the so called H economy, invoked to prevent much of the environmental damage created by the use of fossil fuels, will certainly profit from this property. The same applies for the study of H_2O phases and gas clathrates. 3) - The contrast in neutron-scattering cross-sections between mineralogically common elements having equal or similar numbers of electrons, such as: Ti^{4+}, Ca^{2+}, K^{+}, Cl^{-} or: Na^{+}, Mg^{2+}, Al^{3+}, Si^{4+} or: Fe^{2+} and Mn^{2+}, allows neutron diffraction to be used for the direct determination of their site occupancies and order-disorder distributions in the

crystal structures, independent of the analysis of bond lengths. 4) - The scattering cross-section for neutrons does not change with scattering vector (i.e.: does not fall off as the inverse of the atomic radius) allowing the collection of diffraction data up to large scattering vectors, thus providing a significant increase in the amount of information available in a diffraction pattern. This yields better and decoupled information on thermal motion and site occupancies. 5) - Fundamental structural properties of minerals can be investigated by Inelastic Neutron Scattering (INS) which is not subject to tight selection rules on mode symmetries and wave vectors. INS can be used to determine phonon-dispersion curves and phonon densities of states, providing fundamental information for the prediction of mineral behaviour and phase transformations under pressures and temperatures of the Earth's interior. Applications of INS to *in situ* studies offer a unique opportunity for solving fine structural details (atomic and protonic dynamics, soft modes, *etc*.) and allow modelling and interpretation of fundamental thermodynamic parameters. 6) - In quantitative texture analyses, the high penetration of neutrons and the availability of wide beams allow the investigation of large specimens which produce global volume textures with high grain statistics even on coarse-grained materials. Position-sensitive detectors and time-of-flight techniques, provide reflection-rich diffraction patterns of polymineralic rocks containing low-symmetry mineral constituents. Residual stress analysis of geological material requires high accuracy and sensitivity as natural effects on rocks are orders of magnitude smaller than in technological materials, neutrons offer this sensitivity. 7) - Neutrons are very sensitive to magnetic moment making them the best probe to determine magnetic structures, collective magnetic excitations, and crystal field energy levels of many magnetic elements. 8) – Direct imaging with neutrons, although still somewhat limited in resolution, offers the advantage of large volume sampling for in situ radiographic and tomographic studies of complex materials and apparatus.