Trace-Element Analysis of Geologic Materials

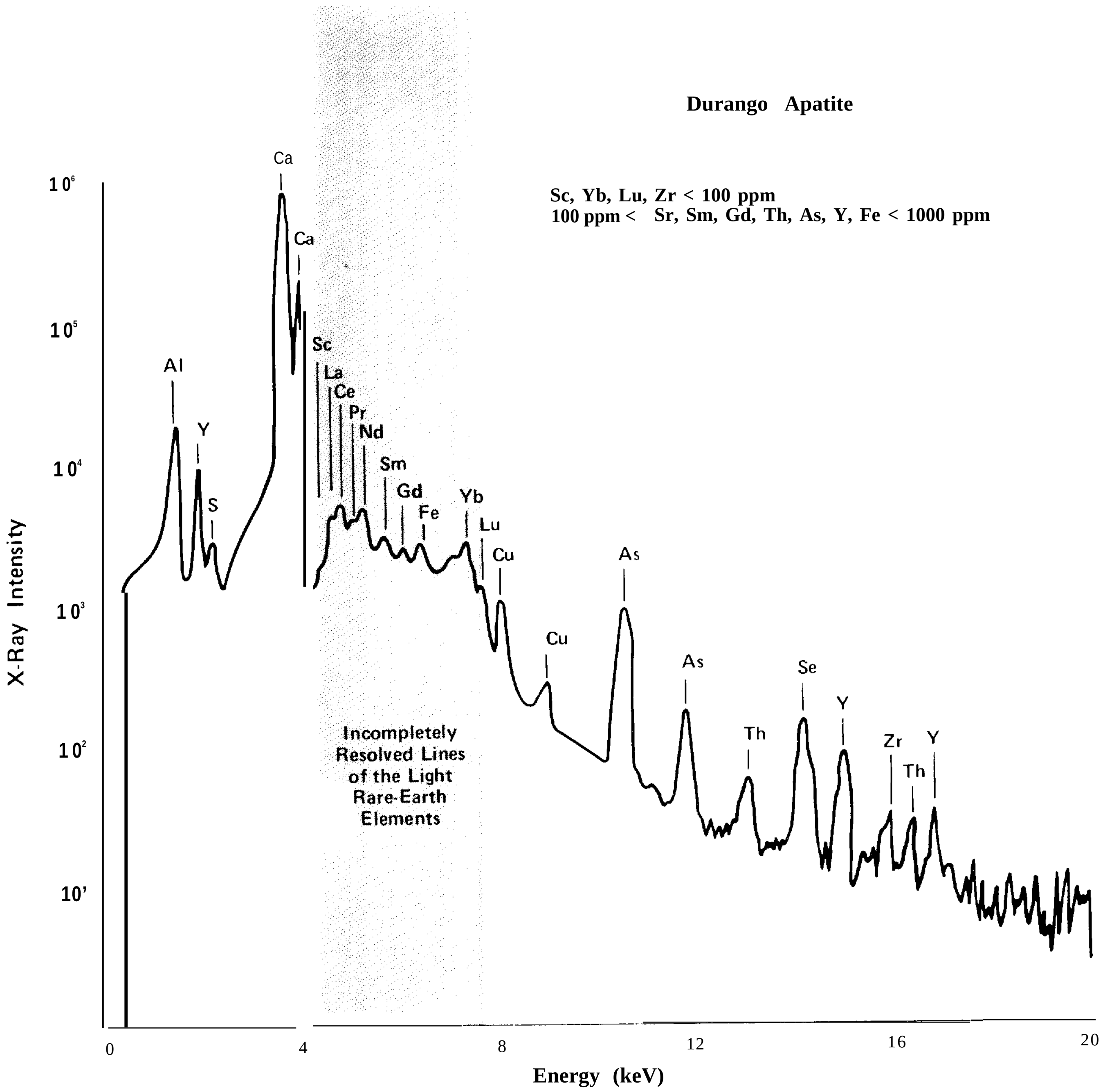
Geologic materials are complex, heterogeneous mixtures of minerals, often small grained and each with a different composition. Study of these materials demands an instrument capable of providing spatially resolved, *in situ* elemental analyses. The electron microprobe is adequate to the task if a sensitivity of 1000 parts per million is sufficient. The nuclear microprobe, which is capable of analysis at the level of 10 parts per million, can measure trace-element distributions in individual mineral grains in addition to major and minor elements. Experiments of this type were not before possible.

For example, consider the problem of determining the relative ages of meteorites, information important to theories of the origin and evolution of the solar system. Relative ages of meteorites can be deduced from the inferred abundances of the isotope plutonium-244. (Plutonium-244 is now extinct; its former abundance in a meteorite can be inferred, for example, from the abundance of its xenon decay product.) Since plutonium has no stable or very long-lived isotopes, this dating technique requires normalizing the plutonium abundance to that of another element in the meteorite. There is evidence suggesting that the geochemical behavior of plutonium is similar to that of uranium and the light rare earths, and therefore one of these elements is usually chosen for the normalization. But the validity of the normalization hinges on whether plutonium and the normalized element undergo similar fractionation during mineral formation. Experiments on synthetic geologic samples have shown that the magnitude of plutonium fractionation is between those of uranium and of the light rare earths. This fact allows application of a proposed "bracketing theorem" leading to the conclusion that if uranium and the light rare earths, when normalized to cosmic abundances, are not fractionated relative to each other in a particular meteoritic mineral, then the plutonium also was not fractionated relative to uranium and the light rare earths. The nuclear microprobe can select those meteorites suitable for plutonium-244 dating by determining that their contents of uranium and light rare earths are unfractionated.

The nuclear microprobe can also be used to study partitioning of trace elements in metal-sulfide-silicate systems. By comparing trace-element concentrations in the rocks of planetary objects with the results of synthetic partitioning experiments, we can obtain information about the differentiation of the planets into metallic cores and silicate mantles. Previously, such studies were hampered by the low concentrations of siderophile (metal-loving) and chalcophile (sulfide-loving) elements in silicate phases, lithophile (silicate-loving) and chalcophile elements in metal phases, and siderophile and lithophile elements in sulfide phases and by the necessity of physically separating the various phases before measuring the trace-element concentrations.

We have undertaken a series of experiments to test the limits of the nuclear microprobe for measuring trace-element concentrations in minerals. The accompanying figure shows the x-ray spectrum from Durango apatite, a calcium fluorophosphate that contains a large number of rare earths and typifies the complexity of geologic materials. Although the nuclear microprobe is able to detect the rare earths at a concentration of 10 parts per million, the solid-state x-ray detector cannot resolve the peaks that overlap. A focusing crystal spectrometer has the necessary energy resolution to resolve these peaks but only about one-thousandth the efficiency of the Si(Li) detector. To overcome this difficulty, the microprobe current could be increased by making use of the high phase-space acceptance of the solenoid. A crystal x-ray spectrometer is being added to the Los Alamos nuclear microprobe to combine high-resolution x-ray spectroscopy with spatially resolved trace-element sensitivity.

This work was performed in conduction with Timothy M. Benjamin and Pamela Z. Rogers of Los Alamos and Dorothy Woolum of the California Institute of Technology.



Results of a nuclear microprobe analysis of Durango apatite, a mineral containing a large number of rare earths. X-ray emission was induced by a beam of 3-MeV protons.