

## BEHAVIOR OF TRACE ELEMENTS DURING MAGMA GENESIS AND EVOLUTION

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**Keywords:** trace elements, igneous petrogenesis, partial melting, fractional crystallization, fractionation equations, tectonic discrimination, laser-ablation ICPMS, basalt, granite, accessory minerals

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### Summary

Trace elements, that is, those with a concentration commonly lower than 0.1%, can provide important information for unraveling the origin and geodynamic environment of igneous rocks. The behavior of trace elements depends on whether they reside as traces in major minerals or are essential structural components in accessory minerals. In the first case, trace elements obey Henry's Law and are almost ideal for modeling the behavior of major minerals during igneous processes. Good examples are Li, Rb, Cs, Be, Sr, and Ba. In the second case, trace elements do not obey Henry's Law and their behavior is controlled by the solubility, solution kinetics, and textural position of the accessories that host them. Zr, Hf, Sn, and the platinum-group elements reside almost entirely in accessories. Nb, Ta, rare earth elements (except Eu), Y, Th, and U dwell partially in major phases and partially in accessories. The concentration ratio of a given element between first, crystals of a given mineral and second, melt in equilibrium with them, is called the "mineral/melt partition coefficient." Fractionation equations are algebraic tools that allow us to model how the concentration of a given trace element changes during either crystallization or partial melting. As input, they use the bulk mineral/melt partition coefficient of an element that obeys Henry's Law. The output is usually the concentration of the trace element, in either the solid or the melt, as a function of the intensity of the process. Fractionation equations are well established for closed systems but not for open systems. Trace-element abundances and element ratios may constitute valuable indexes for discriminating among different tectonic settings.

The process of discrimination is a purely empirical procedure that produces good results in the case of basaltic rocks, but is quite imprecise in the case of granitic rocks.

## 1. Introduction

The term “trace element” is not easy to define. It can be defined as an element present in a system. Trace elements in magmas are those with a concentration usually below 0.1 wt%. They are reported as elements, not as oxides, using parts per million (ppm) or as part per billion (ppb) as concentration units (see introductory article *Igneous and Metamorphic Petrology*). In igneous petrogenesis, the most frequently used trace elements include alkaline and alkaline earths (Li, Rb, Cs, Be, Sr, and Ba), transition elements of the first (Sc, V, Cr, Co, Ni, Cu, and Zn), second (Y, Zr, Nb, and Mo) and third series (Hf, Ta, and W), the platinum-group elements (PGE: Ru, Rh, Pd, Os, Ir, Pt, and Au), 3b (B, Ga, and Ti) and 4b group elements (Sn and Pb), the rare earth elements (REE: La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, and Lu), and the actinides (Th and U).

The distribution of trace elements in igneous rocks can provide important information about the origin and evolution of magmas. Modern igneous petrologists commonly use trace-element studies for two purposes: first, to model the behavior of minerals during a given igneous process, usually by means of trace-element fractionation equations, and second, to identify the tectonic environment in which these magmas formed. The paragraphs below succinctly describe the foundations of both applications.

## 2. Geochemical Modeling Using Trace Elements

The behavior of trace elements in igneous processes depends primarily on their residence in the solid phases. Two extreme cases are possible:

1. Trace elements residing as traces in major minerals; for instance, the alkaline, alkaline earths, Eu and Ga. They obey Henry's Law and are almost ideal for modeling the behavior of major minerals.
2. Trace elements that are essential structural components in accessory minerals. They do not obey Henry's Law. During crystallization, their behavior is controlled by the nature of the crystallizing accessories that contain them, the kinetics of nucleation and crystal growth, and the dynamics of solid–melt segregation. During partial melting, their concentration in melts is controlled by the solubility, solution kinetics, and accessibility of the accessories to the melt. Elements such as Zr, Hf, Sn, and the PGE reside almost totally in accessory minerals. Others such as Nb, Ta, REE (except Eu), Y, Th, and U dwell partially in major phases and partially in accessories. The proportion residing in accessories depends on the rock chemistry and mineral assemblage, but is rarely less than 60 wt%—usually about 90 wt%—of the whole-rock budget. This situation is illustrated in Figure 1, a scanning electron microscope photograph of a common biotite-amphibole granite, one of the most abundant rock types of the continental crust, which shows the abundance and textural position of REE-, Y-, Th-, U-, and Zr-bearing accessory phases.

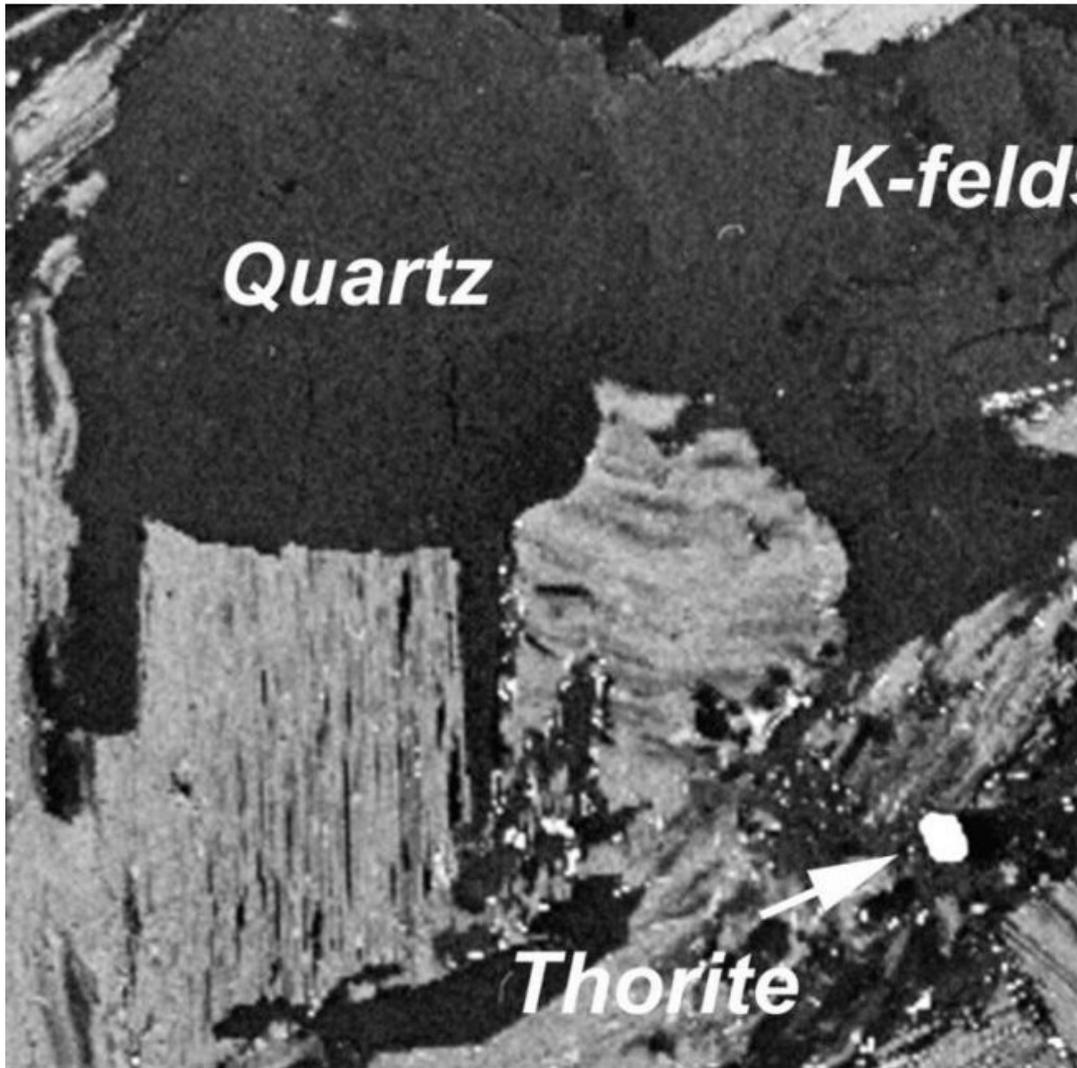


Figure 1. Scanning electron microscope image (back-scattered electrons) of common I-type granite from the Verkhisetsk batholith, middle Urals. The brightness of the minerals depends on the average atomic number of the chemical elements that form them. Thus, accessory minerals such as zircon ( $ZrSiO_4$ ), monazite ( $LREEPO_4$ ) or thorite ( $ThSiO_4$ ) are bright, whereas common silicates are dark gray. In this particular case, mass-balance studies have revealed that, in the whole-rock budget, accessories account for ~75% of LREE and Y, ~90% of Th and U, and ~99% of Zr.

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## Biographical Sketch

**Fernando Bea** was born in Ponferrada, Spain, in 1951. He attended the University of Oviedo, where he graduated in Geological Sciences. In 1972 he moved to the University of Salamanca, where he did his doctoral thesis under the supervision of Professor García de Figuerola, receiving his Ph.D. in geology and geochemistry in 1975. His postdoctoral activity began in the University of Salamanca, from 1975 to 1982 as research assistant, and from 1982 to 1991 as a Senior Lecturer. In 1991 he was promoted to the Chair of Petrology and Geochemistry at the University of Granada, where he has remained since then. His research interest centers on granite geology and geochemistry. He has worked in different geodynamic contexts, especially in the Variscan granitoids and migmatites of Iberia, the Urals, the Ivrea–Verbano zone in northwest Italy, as well as the Proterozoic granitoids and alkaline rocks of Kola. He is also interested in the analytical chemistry of silicate rocks, and has developed methods for rock analysis using atomic absorption, ICP-OES, ICP-MS, and laser-ablation ICP-MS. Since 1992 he has published about 33 research articles in international journals and edited books.