Application of Electron Probe Microanalysis to the Study of Geological and Planetary Materials

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Abstract: The impact of electron probe microanalysis on the study of geological and planetary materials has been tremendous. Electron microprobes evolved into routine analytical instruments in geological research laboratories as instrument capabilities improved and applications to geologic/planetary materials expanded. The contributions of electron probe microanalysis to the characterization of minerals, both terrestrial and extraterrestrial, and to other significant geological research, such as light element analysis, trace element analysis, and element mapping, is described.

Key words: electron microprobe, geology, mineralogy, lunar samples, microanalysis, meteorites, light element analysis, layered synthetic microstructures

INTRODUCTION

Raimond Castaing first presented his idea to use secondary X-rays excited by a focused electron beam from a polished solid sample for microanalysis in 1949 at the First European Regional Conference on Electron Microscopy in Delft, the Netherlands (Castaing and Guinier, 1950). As part of his dissertation, he then not only built the first electron probe microanalyzer, but also established many of the theoretical and analytical principles of the technique (Castaing, 1951). The electron microprobe, and the technique of electron probe microanalysis (EPMA), has had a tremendous impact on research in the geological sciences. The contributions of the technique to geology (including mineralogy and planetary science) are briefly reviewed here. It is beyond the scope of this article to be an all-inclusive review of the applications of EPMA in geological science, however, we attempt to present an overview of some of the more significant aspects and achievements of EPMA in geological research. The impact of the electron microprobe, and the closely related scanning electron microscope (with energy dispersive spectrometer) and ion microprobe (or secondary ion mass spectrometer), is evident both by examination of the geological/geochemical literature and by the prevalence of these instruments in geologic research facilities throughout the world. The geologic community owes a debt of gratitude to Raimond Castaing, the inventor of both the electron microprobe and (with George Slodzian) the ion microprobe. Castaing was honored for these contributions by receiving the distinguished Roebling Medal from the Mineralogical Society of America (Keil, 1978). The present overview of EPMA applications in the geological sciences is presented in this issue in dedication to the late Professor Raimond Castaing.

Microscopy AND

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EARLY USAGE OF EPMA

The potential for application of EPMA to the geological sciences was publicized soon after electron microprobe instrumentation became available. Castaing and Fredriksson (1958) published what we think was the first analytical study of geologic samples using the electron microprobe; they utilized one of the first instruments available in France (at the Institut de Recherches de la Sidérurgie) to analyze 50 μ m diameter cosmic spherules recovered from deep-sea sediments. EPMA offered enormous analytical advantages to earth scientists over other analytical methods available at the time. The advantages were, and still are, quite significant for mineralogists and petrologists. These advantages are as follows:

- EPMA allows qualitative and quantitative analysis of individual mineral grains a few micrometers in diameter.
- Incorporation of a coaxial light optical microscope in the electron optics provides the familiar optical image capability used by mineralogists and geologists for identification of mineral grains and textural features of interest for chemical analysis. More recently, high resolution back-scattered electron images provide atomic number contrast that aids in efficient identification of areas of different composition. These in situ imaging capabilities ensure accurate correlation between composition and grain morphology.
- Fine-scale mineralogical features, such as zoning in minerals, minute inclusions, and exsolution lamellae can be measured because of the small analytical excitation volume.
- With suitable standards and X-ray correction procedures, a large number of quantitative analyses can be obtained in a relatively short time. A single analysis of a mineral can be obtained in a matter of tens of seconds or a few minutes at most. In contrast, the traditional wet-chemical analysis of a mineral would probably consume days (including the time to extract an ample, clean quantity of the mineral from the bulk sample).
- EPMA is non-destructive, so that in situ analysis of minerals in polished thin sections is obtained while retaining textural relationships among coexisting minerals. This also preserves the same sample for analysis by other measurement techniques, such as ion microprobe (see below).
- Electron microprobe designs allowed several wavelength

dispersive spectrometers (WDS) to be attached to the electron column. This provided multiple-element data acquisition in short time intervals.

Prior to the availability of the electron microprobe, mineral analysis was obtained by time-consuming wetchemical analysis of mineral separates. When the first commercially available electron microprobes came on the market in the early 1960s, application of the instrument to mineralogical and geological problems became more common. With the onset of the Space Age, and the need to analyze and preserve valuable and irreplaceable samples such as the returned lunar samples, the National Aeronatics and Space Administration (NASA) and other government agencies helped launch the use of EPMA in geological research by funding laboratories seeking to acquire electron microprobes for their research. This enabled more scientists in the geological scientific community to develop the theoretical and technical background to operate and maintain these complex instruments, and to develop the analytical and calibration procedures necessary for quantitative analysis. By 1971, about 600 articles had been published applying EPMA to problems in geological science, of which about 300 dealt with applications to the analysis of extraterrestrial materials.

The impact EPMA had on the study of extraterrestrial materials can be assessed by the fact that in 1962 there were only 38 known minerals identified in meteorites (Mason, 1962), whereas by 1997 this number had increased to 295 (Fig. 1; Rubin 1997a, 1997b). The dramatic change was due to both the large increase in number of meteorites collected as well as to the ease of EPMA characterization of meteorite constituents. Furthermore, EPMA was vital in the identification and characterization of many new and unusual meteoritic minerals, and a few lunar minerals, most of which are not known to occur on earth (Table 1).

CRITICAL DEMANDS FOR ANALYSIS OF ROCKS AND MINERALS AND EFFECTS ON EPMA DEVELOPMENT

As development of the electron microprobe and expertise in its use continued for geological applications, EPMA gradually became a common technique for the study of the complex properties of rocks and minerals. In turn, application of EPMA to demanding geological problems spurred the



Figure 1. Minerals certified to occur in meteorites (based on data from Rubin, 1997a, 1997b).

design of new, advanced electron microprobes and the development and refinement of theoretical and analytical procedures that continue into the present day. Analytical studies of rocks and minerals placed several demands on EPMA, summarized in the following seven paragraphs.

- 1. Rocks are complex assemblages made of many minerals of highly variable grain sizes and textures. Traditional polished thin sections, used for petrographic study of the rocks, were then used in the microprobe for simultaneous viewing in reflected and/or transmitted light during microprobe analysis. This prompted the development and incorporation of polarizing optical microscopes, higher quality reflected light optics and, eventually, of secondary electron/backscattered electron imaging [comparable to a scanning electron microscope (SEM) in quality] into electron microprobes.
- 2. Rocks and minerals of the crusts of the terrestrial planets primarily consist of relatively low-Z (< Z = 26) elements (Tables 2 and 3). Measurement of the long-wavelength X-rays of these low-Z elements in these minerals required development of suitable diffracting crystals and detectors. Such developments are still going on today with the continued refinement of layered synthetic microstructures as analyzing crystals (see below). Matrix effects (absorption, fluorescence, and atomic number) encountered in the analysis of rock-forming minerals, combined with high uncertainties in mass absorption coefficients, led to development of electron microprobes

with high X-ray take-off angles (to minimize absorption). These matrix effects and uncertainties, along with the need to produce relatively rapid data reduction, also prompted the early development of empirical correction procedures such as that published by Bence and Albee (1968), possibly the most often cited article in the geological literature.

- 3. Minerals often consist of 10 or more major, minor, and trace elements. This inspired the incorporation into electron microprobes of energy dispersive spectrometers (EDS) for fast qualitative and semi-quantitative analysis of many elements simultaneously (Fitzgerald et al., 1968; Heinrich et al., 1999).
- 4. The interest in understanding minor and trace-element behavior in minerals led to development of procedures for trace-element analysis at the ppm level via long counting times and high measurement currents. Such measurements required electron microprobes with improved, highly stable electron gun and electron optics designs to provide a stable high-current beam over relatively long time periods.
- 5. Most rocks and minerals are poor thermal conductors. Sample heating from the incident electron beam can therefore cause adverse effects during analysis of minerals containing volatile elements (e.g., phosphates, micas, amphiboles, Na-rich feldspars, salt minerals, glass). Thus, procedures for analysis at the lowest possible beam currents and accelerating voltages, the shortest possible exposure of the sample to the beam, and with the broadest possible beam had to be developed. Electron column/ lens refinements aided in achieving this, as did the development of cold-stages to minimize element mobility and anti-contamination devices to minimize X-ray attenuation.
- 6. Studies of zoning, exsolution, inclusions, or other compositional variations within minerals require electron microprobes with high spatial resolution, a highly stable beam (both spatially and with respect to current output), and automated spectrometers for multi-element analysis in precisely controlled spots. These requirements led to improvements in spectrometer and stage precision, beam control, and more thorough software automation systems for instrument control and data collection.
- 7. Geologists recognized that EPMA provided a powerful interactive research tool for characterizing the compositional behavior of the minerals as a function of texture and mode of occurrence of the mineral within the rock

Mineral	Formula	Reference
Armalcolite	(Mg,Fe)Ti ₂ O ₅	Anderson et al., 1970
Arupite	Ni ₃ (PO ₄) ₂ ·8H ₂ O	Buchwald, 1990
Barringerite	(Fe,Ni) ₂ P	Buchwald, 1977
Brezinaite	Cr_3S_4	Bunch and Fuchs, 1969
Brianite	$Na_2CaMg(PO_4)_2$	Fuchs et al., 1967
Buchwaldite	NaCaPO ₄	Olsen et al., 1977
Carlsbergite	CrN	Buchwald and Scott, 1971
Caswellsilverite	NaCrS ₂	Okada and Keil, 1982
Chaoite	С	Vdovykin, 1969
Chladniite	$Na_2CaMg_7(PO_4)_6$	McCoy et al., 1994
Djerfisherite	$K_6Na_9(Fe,Cu)_{24}S_{26}Cl$	Fuchs, 1966a
Erlichmanite	OsS_2	Snetsinger, 1971
Galileiite	$NaFe_4(PO_4)_3$	Olsen and Steele, 1997
Haxonite	(Fe,Ni) ₂₃ C ₆	Scott, 1971
Heideite	FeTi ₂ S ₄	Keil and Brett, 1974
Krinovite	NaMg ₂ CrSi ₃ O ₁₀	Olsen and Fuchs, 1968
Lonsdaleite	С	Frondel and Marvin, 1967
Merrihueite	(K,Na) ₂ Fe ₅ Si ₁₂ O ₃₀	Dodd et al., 1965
Nierite	α -Si ₃ N ₄	Lee et al., 1995
Niningerite	(Mg,Fe,Mn)S	Keil and Snetsinger, 1967; Keil, 1968
Panethite	$(Ca,Na)_2(Mg,Fe)_2(PO_4)_2$	Fuchs et al., 1967
Perryite	(Ni,Fe) ₂ Si	Fredriksson and Henderson, 1967
Roaldite	(Fe,Ni) ₄ N	Nielsen and Buchwald, 1981
Roedderite	$(K,Na)_2Mg_5Si_{12}O_{30}$	Fuchs, 1966b
Schöllhornite	$Na_{0.3}(H_2O)[CrS_2]$	Okada et al., 1985
Sinoite	Si ₂ N ₂ O	Andersen et al., 1964
Suessite	Fe ₃ Si	Keil et al., 1982
Tetrataenite	FeNi	Clarke and Scott, 1980
Tranquillityite	$Fe_8(Zr,Y)_2Ti_3Si_3O_{24}$	Lovering et al., 1971
Yoshiokaite	Ca(Al,Si) ₂ O ₄	Vaniman and Bish, 1990

Table 1. Selected Examples of Meteoritic and Lunar Minerals Discovered and Certified with Electron Probe Microanalysis, Most of Which Are Not Known from Earth

matrix. Thus rapid quantitative results were critical in efficiently and completely identifying the systematics of the mineral chemistry within a rock sample. This provided an impetus for faster, more thorough online quantitative corrections of the microprobe measurement data. Improvements in computer memory and processing speed enabled real-time data corrections and recalculation of analytical results into mineral formulas to assess the quality of the analytical results. Correction procedures were continually refined to produce more accurate analytical results (e.g., Armstrong, 1991, 1995; Pouchou and Pichoir, 1991).

INSTRUMENTAL AND ANALYTICAL DEVELOPMENTS THAT AFFECTED ANALYSIS OF GEOLOGICAL AND PLANETARY MATERIALS

Energy Dispersive Spectrometry

Modern electron microprobes are commonly equipped with energy dispersive spectrometers, and these EDS systems can be integrated with the rest of the data collection system on the microprobe in order to provide combined EDS/WDS capability. This capability provides the advan-

 Table 2.
 Elemental Abundances in the Crust of the Earth^a

Element	Weight %	Volume %	Z
0	46.6	93.8	8
Si	27.7	0.9	14
Al	8.1	0.5	13
Fe	5.0	0.4	26
Ca	3.6	1.0	20
Na	2.8	1.3	11
K	2.6	1.8	19
Mg	2.1	0.3	12
All others	1.5		

^aCompilation and recalculation of data from Mason and Moore, 1982.

Table 3. Mineral Abundances in the Crust of the Earth^a

Mineral	Approximate formula	Volume %
Plagioclase	NaAlSi ₃ O ₈ -CaAl ₂ Si ₂ O ₈	42
K-feldspar	KAlSi ₃ O ₈	22
Quartz	SiO ₂	18
Amphibole	Hydrous Fe-Mg-Ca-Na silicate	5
Pyroxene	(Mg,Fe)SiO ₃	4
Biotite	$K(Mg,Fe)_3(AlSi_3O_{10})(OH)_2$	4
Magnetite- ilmenite	Fe ₃ O ₄ -FeTiO ₃	2
Olivine	(Mg,Fe) ₂ SiO ₄	1.5
Apatite	$Ca_5(PO_4)_3(OH)$	0.5

^aCompilation and recalculation of data from Mason and Moore, 1982.

tage of acquiring data more rapidly for a large number of elements, by collecting data for some elements with the wavelength spectrometers and others (usually major elements free of adjacent interfering X-ray lines) with the energy dispersive spectrometer. EDS systems are equipped with a variety of detector window types, providing detection of elements as low in atomic number as Be. Oxygen and fluorine, and to a lesser extent, carbon, are readily observed in geologic samples using EDS with ultra-thin window (UTW) detectors, but quantification is difficult. Quantification of low-Z elements measured by EDS is difficult, due to the low fluorescence yield of X-rays, spectral overlaps, and EDS detector-noise thresholds. The properties and performance of thin-window EDS detectors are discussed by Goldstein et al. (1992), Barkan (1990), L'Esperance et al. (1990), and Hemens et al. (1990). The history and development of the EDS system was the topic of a symposium in 1998; readers are referred to the special issue of Microscopy and Microanalysis presenting papers from that symposium (McCarthy, 1998).

Matrix Correction Procedures

The matrix correction procedures used to correct for the interaction of the electron beam and generated X-rays with the sample interaction volume have been the topic of numerous studies since the electron microprobe was introduced. Programs to correct raw intensity data for the effects of atomic number, absorption, and fluorescence of X-rays have been developed and refined over the years. These correction programs are now integrated with real-time data collection so as to produce corrected, quantitative analyses as soon as the intensity data are measured and read by the automation system. The correction procedures generally fall into one of three general models: the ZAF corrections (e.g., Goldstein et al., 1992; Armstrong, 1995), the $\phi(\rho z)$ correction procedure (e.g., Pouchou and Pichoir, 1991; Brown, 1991; Packwood 1991; Armstrong, 1995), and the alphafactor correction procedures (e.g., Bence and Albee, 1968; Armstrong, 1988b). The alpha-factor procedures were more popular early on when online-data reduction using complicated algorithms was fairly slow due to limited computer processing speeds and memory. The Bence and Albee (1968) procedure was a particularly common method used in geologic applications because its authors focused on developing alpha factors for elements of geologic interest. This procedure provided rapid data reduction and a common correction procedure that enabled inter-laboratory comparison of mineral chemical data. Modern, faster computing capabilities, however, have enabled more common use of the other two data reduction methods. Armstrong (1991, 1995) developed programs that allow correction of electron microprobe intensity measurements by selecting from a list of available algorithms for the effects of atomic number, absorption, and fluorescence.

Layered Synthetic Microstructure Crystals

Since the late 1980s, layered synthetic microstructure (LSM) analyzing "crystals" have been used increasingly in electron microprobe analysis and X-ray spectrometry for improved detection of elements of low atomic number (Z) (Wood et al., 1985; Nicolosi et al., 1986; Huang et al., 1989). Low-Z

elements are difficult to analyze quantitatively for several reasons, including low fluorescence yields and absorption of X-rays, inaccurate absorption correction procedures, interference caused by overlaps of higher order X-ray lines, peak shifts and shape alterations, and contamination (Bastin and Heijligers, 1990). LSM crystals have been developed to provide improved reflectivity and stability, and suppression of high-order reflections, compared with traditional single crystals and organic crystals such as lead stearate (PBSD). LSM crystals also are less sensitive than PBSD to pronounced peak-shape alterations (Bastin and Heijligers, 1990).

LSM crystals are manufactured by depositing alternating low- and high-Z elements on a silicon substrate, forming artificial crystal lattices with specific d-values (Nicolosi et al., 1986). The alternating elements and d-values are chosen to optimize reflectivity for the selected low-Z elements of interest. LSM crystals commonly used for mineralogical applications are WSi (2d ~ 60 Å) for analysis of F, O, N, and C, and MoB₄C (2d ~ 140 to 200 Å) for analysis of B and Be. Analytical characteristics of the LSM crystals have been studied in order to determine appropriate use and to account for potential interference on low atomic number Xray lines by other elements (Potts and Tindle, 1989; McGee et al., 1991; Raudsepp, 1995).

Standards

Homogeneous, well-characterized standards are the foundation of quantitative EPMA. The importance of such materials, preferably including minerals with compositions similar to the materials to be analyzed, cannot be emphasized enough. Essene and Henderson (1999) discussed the use of standards in quantitative EPMA. The geologic and planetary science community has benefited greatly from the characterization and availability of a variety of mineralogical standards. Those distributed by Jarosewich et al. (1980), Jarosewich and Boatner (1991), and McGuire et al. (1992), for example, have proved to be invaluable in mineralogical applications.

Selected Applications to the Analysis of Geological and Planetary Materials

The electron microprobe is now used routinely for mineralogical and petrological sample characterization. Studies report compositions obtained by EPMA for minerals, glasses, and synthetic materials as an almost automatic part of the geologic research problem. In fact, EPMA data presentation has become so routine that there is often a lack of proper description of measurement techniques. Such shortcuts need to be avoided, although the pressures of publication size as well as the "routine" nature of the data tend to combine to eliminate, or reduce, the inclusion of technique recording in reports.

The hundreds of routine applications of EPMA will not be discussed any further in this article. Keil (1967) reviewed early applications of EPMA in mineralogy. In recent years, some of the more significant applications of EPMA are in the areas of low-Z or light-element analysis, trace-element analysis, element X-ray mapping, new mineral characterizations, and combined EPMA-ion microprobe studies. These are discussed in brief in the following sections.

Light Element Analysis

The analysis of light elements (Z < 11) by EPMA has improved during the past decade due to improvements in measurement of low-Z element intensities. This has occurred due to development of thin-window detectors for energy-dispersive spectrometry (EDS); layered synthetic microstructure (LSM) crystals for wavelength-dispersive spectrometry (WDS), and development of anticontamination devices to minimize absorption of X-rays by contamination buildup at the analytical surface. Raudsepp (1995) summarized some of the developments in light element analysis by EPMA and discussed the status of efforts to measure Be, B, C, N, O, and F. McGee and Anovitz (1996) evaluated analytical procedures and the status of efforts to measure B in geologic samples. The efforts to quantify low-Z measurements have introduced additional analytical complexities. For example, variations in low-Z element peak positions and shape in different materials due to crystallographic orientation or bonding conditions may require the use of techniques such as peak integration rather than simple measurement of peak-maximum intensity (Bastin and Heijligers, 1992). Several studies have demonstrated the use of LSM crystals in geologic applications. McGee et al. (1991) and McGee (1996) studied the application of LSM crystals to boron measurements in minerals. McGee and Anovitz (1996) also reviewed EPMA studies of minerals in which boron contents were measured using either PBSD or LSM crystals. LSM crystals have also been used to measure geologic materials for oxygen (Armstrong,

1988a; Nash, 1992), fluorine (Potts and Tindle, 1989), carbon (Bustin et al., 1993, 1996), nitrogen (Wilson et al., 1992; McGee and Krohn, 1994), and beryllium (Evensen and Meeker, 1997).

TRACE ELEMENT ANALYSIS

For the same reasons that EPMA became common for major element analysis in minerals, efforts to obtain trace element compositions has been the focus of much effort. The powerful advantage of speed (relative to other chemical techniques), in situ non-destructive analysis, and a nearly "complete" quantitative chemical analysis combine to make EPMA a valuable technique for trace element analysis, down to routinely attainable detection limits of ~10-50 ppm, and in some cases below 10 ppm. There have been several studies of trace elements in geologic materials, both in individual minerals (e.g., Goldstein, 1967; Smith, 1971; Bence et al., 1977; McKay and Seymour, 1982; Solberg, 1988; Merlet and Bodinier, 1990; Dalton and Lane, 1996) and in glasses (e.g., Ramsden and French, 1990; Fialin et al., 1999). Studies of metamorphic minerals, particularly garnets, and the distribution of trace elements in them have received considerable focus utilizing EPMA, as have studies determining trace element partition coefficients in minerals (e.g., Schwandt et al., 1996; Spear and Kohn, 1996; Kuehner et al., 1989; Sweeney et al., 1994).

A recent application of trace element EPMA has been for geochronologic investigations by measuring U, Th, and Pb in monazites (Montel et al., 1996; Cocherie et al., 1998; Williams et al., 1999). EPMA offers a more rapid, although less precise, means of obtaining age measurements than the more traditional and more costly mass spectrometric techniques of radiogenic age determinations. In the case of monazites from relatively old rocks (> 300 million years), the concentrations of elements needed to make the age estimate are at levels measurable by EPMA.

Element Mapping

The improvements in sample-stage, beam control, automation, and computing capacity in the 1980s and early 1990s led to an increase in the use of the electron microprobe for the acquisition of area maps showing the distribution of elements in a sample. Digital pulse processing of EDS spectra also enabled high signal throughput for element mapping. These improvements opened a tremendous area of



Figure 2. Mineral discoveries in 40-year time intervals (based on data from J.A. Mandarino, written communication, 1999).

research into the study of zoning of individual minerals and the interpretation of this zoning in terms of a sample's thermal history, including crystallization and metamorphic processes. One of the more common applications in this area has been in the analysis of compositional zoning in metamorphic garnets as a means of interpreting the pressure-temperature history of the host rocks and correlation of that information with tectonic history (e.g., Spear and Markussen, 1997; Lang, 1996; Spear and Kohn, 1996). In the monazite age-dating studies, trace-element analyses are combined with compositional maps to reveal and evaluate the response of individual monazite grains to multiple deformation and metamorphic events and thus aid in deciphering the complex tectonic history of some geologic terranes (Williams et al., 1999).

New Mineral Characterization

The impact of the electron microprobe on geological/ mineralogical research has been profound, as indicated by the applications and history described above. Another indication of this impact is to examine the growth of recognized and characterized minerals that exist today (Fig. 2). As can be seen in Figure 2, there has been tremendous growth in the number of new minerals since 1960, corresponding with availability of electron microprobes for geologic research. Of the total number of mineral species (~3,800), over half of them (~2100) were discovered and characterized since 1960. The burgeoning growth of new mineral characterizations starting in the 1960s is due in part to the availability of the electron microprobe for chemical characterization of small samples. This is borne out in part by the fact that most new minerals identified since the 1960s are probably fairly rare and there are limited quantities of material available for characterization. The impact of the electron microprobe is confirmed by the fact that of the over 400 new mineral species characterized in the 1990s, over 90% of them were analyzed, as part of their required characterization, by electron microprobe (J.A. Mandarino, written communication, 1999). Although not statistically documented, the proportion analyzed by microprobe in the 1980s is probably comparable because the microprobe was a fully mature instrument by then and was being used in as many geological labs as during the 1990s.

Ion Microprobe

Besides the electron microprobe, Raimond Castaing, with his student George Slodzian, also introduced the concept of using a focused primary ion beam to sputter secondary ions from the surface of a polished section for analysis of the secondary ions in a mass spectrometer (Castaing and Slodzian, 1962). Like the electron microprobe, the ion microprobe, or secondary ion mass spectrometer (SIMS), also revolutionized the analysis of planetary and geological samples. SIMS studies have been used for trace-element analyses of samples and, in combination with EPMA measurements, to provide more comprehensive studies of the crystallization and history of magmatic systems (e.g., Prinz et al., 1973; Papike et al., 1997; Shervais and McGee, 1998; Floss et al., 1998). Ion microprobes are now capable of producing ion maps and isotope ratio images and of measuring some isotopic compositions with high precision. These capabilities have been used to identify and study minute pre-solar dust grains from primitive meteorites and measure the decay products of extinct radionuclides in individual mineral grains in meteorites as a means of evaluating early solar system history (e.g., Hutcheon et al., 1998; Zinner, 1998). The applications of the ion microprobe to geology have been reviewed by Shimizu and Hart (1982) and by Reed (1989).

CONCLUSIONS

The continued efforts to meet the challenges of geological sample analysis have resulted in the electron microprobe

becoming one of the most important research tools in geological science. Hundreds of articles are now published every year applying EPMA, and the related ion microprobe, to the analysis of planetary and geological materials. The impact that the electron microprobe has had on the earth and planetary sciences is so monumental that it can only be compared to that of the introduction of the polarizing microscope into the geological sciences over 150 years ago.

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