I. INTRODUCTION

An ion microprobe is basically a mass spectrometer with a specialized source incorporating a finely focused primary ion beam to generate secondary ions from the target. The primary ions have energies of the order of 10 keV and so collisions between the primary ions and the surface physically erode, or “sputter”, the sample ejecting particles from the surface. Of these particles, a small fraction are ionized and can be electrostatically removed to the mass spectrometer where they are separated according to mass and the relative ion intensities can be measured.

Ion microprobes have found a niche in materials research, particularly in the semiconductor industry where localized analysis of ppm to sub ppb concentrations are required. The commercially produced CAMECA ion microscopes have been particularly important in this area and over 200 instruments are in operation worldwide. However, only a small fraction of these instruments are used for research in the earth science field, and then mainly for research in cosmochemistry where isotopic and chemical abundance anomalies are at their largest. Of prime importance in the geological sciences has been the SHRIMP (Sensitive High mass-Resolution Ion MicroProbe) at the Australian National University that was designed for isotopic analysis of chemically complex targets. The main application of this instrument has been in situ U-Pb dating of zircon although a wide variety of applications have benefited from its high sensitivity. Until recently SHRIMP was the only instrument capable of undertaking routine U-Pb dating of zircon but now commercially produced machines are being marketed with these capabilities.

The fundamentals for ion microprobe analysis were developed over thirty years ago with the goal of characterizing any sample for its chemical and isotopic abundances. In this same time frame, the electron microscope and microprobe were also being developed. The electron probe uses a focused electron beam to generate X-rays in the target and since the principles governing photon emission from a surface are well understood, quantitative analyses were readily forthcoming and the electron probe quickly became a necessary piece of apparatus in materials research laboratories worldwide. Development of the ion microprobe was much slower, because the principals that describe secondary ionization are not well understood and, despite a great deal of effort, no generally acceptable formulation has been forthcoming. However, the salient point involved in applying the ion microprobe to problems in geochemistry is that the primary ion beam does produce secondary...
ions that reflect in some way the isotopic and chemical characteristics of the sample. Accurately determining that relationship is the cornerstone of all successful applications.

The purpose of this paper is to highlight the successful application of ion microprobe mass spectrometry to a variety of topics principally in the earth and planetary sciences. It is not a review of the development of the ion microscope and microprobe, previous reviews of ion microprobe mass spectrometry (Shimizu and Hart, 1982a; Reed, 1984; Benninghoven et al., 1987) have documented most of these aspects. Nor is it a review of the status of ion production models. While a complete model would be of great benefit to practitioners, it is not a requirement for successful application of the instruments as will be detailed in later sections. Moreover, the physics is complex and a detailed discussion is beyond the scope of this paper and probably beyond the requirements of the interested but non-expert to whom this work is addressed. Detailed discussions of sputtering models are given by Williams (1979; 1982), Harrison (1983) and Benninghoven et al. (1987).

In the following sections, a brief overview of the sputtering process will be given followed by descriptions of the most recent generations of ion microprobes in use today. General aspects of analysis with the ion microprobe will then be discussed followed by specific examples from cosmochemistry, geochemistry, and geochronology.

II. SPUTTERING

A. Ion Production

A $^{16}$O$^-$ ion traveling at 350 km s$^{-1}$ smashes into a wall; $10^{-10}$ s later it's all over! The damage is rather localized and extends only down through several atomic layers and only for several atomic radii around (Figure 1). For a 1 nA primary beam there are some $6 \times 10^9$ impacts per second. An impact results in some 10 to 100 atoms and molecular fragments being ejected and in this way a sample is continually eroded. Felicitously, a small fraction of the emitted particles are ionized and can be electrostatically removed from the sputtering region to be analyzed in a mass spectrometer.

While the basic scheme involved can be appreciated in macroscopic terms, the physical principles governing the ionization probability of individual particles are not readily quantifiable because of the diverse parameters that are needed to fully describe the characteristics of the ejected particles. The pioneering statistical theories of Thompson (1968) and Sigmund (1969) involved the partitioning of energy in collision cascades and were able to predict bulk properties of the sputtered material such as the sputtering yield, ejected atom energy, and secondary atom angular distributions as a function of primary ion energy. In order for a particle to be ejected it must obtain sufficient kinetic energy to overcome the surface binding energy. All sputtered atoms originate from the outer few atomic layers with the