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## Progress in mineralogy†

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Since the fiftieth anniversary of the Mineralogical Society in 1926, there has been an epoch of great progress, resulting from the impact of applied physics and from the generally widened horizons of Earth science. Description of the morphology of crystals by means of the goniometer, determination of the optics of minerals in transmitted light and of their chemistry by wet methods had already been carried to an advanced stage, but in the eight years up to 1934 the full effect of the application of X-ray diffraction to crystallography by von Laue, W. H. & W. L. Bragg, Jackson, Maugin, Pauling, W. H. Taylor, Warren, West and Wyckoff was felt, leading to a virtually complete classification of minerals on the basis of atomic structure (Bragg 1937). This has stood the test of time for all minerals save chrysotile, and has been fundamental to most other developments in mineralogy. Active fields in structure analysis today include the basis of ordering over octahedral and tetrahedral sites in silicates, and the factors controlling bond-lengths and angles; nuclear magnetic resonance (Bloch 1946; Purcell 1946) and electron spin resonance (Zavoisky 1945) are contributory techniques.

The establishment of atomic structure placed ascertainable constraints upon crystal chemistry; molecules no longer had meaning in mineralogy, and the atoms in the unique unit cell could be counted (Bannister 1931). V. M. Goldschmidt and his associates, working mainly with optical emission spectroscopy, laid the foundations of trace-element geochemistry; Sandell introduced improved colorimetric methods for the metals. Where separation of pure minerals often remains very onerous, the special need for chemical analysis of very small quantities was met by the invention of the Kuhlmann balance and its adaptation to semi-micro methods, giving top-grade results on 10 mg or less (Hey 1973). However, the greatest changes in analytical procedures have come from application of electronic techniques: the X-ray vacuum spectrometer (Friedman & Birks 1948); the electron microprobe, analysing down to 1  $\mu\text{m}$  (Castaing & Guinier 1950, with scanning added by Coslett and Duncumb in 1956); the mass spectrometer, used with the ion probe (Castaing & Slodzian 1962). These electronic instruments unfortunately suffer from the disadvantage that they cannot determine the state of oxidation, for example of iron; nuclear gamma resonance (Mössbauer 1958) can accomplish this in favourable cases, but otherwise resort must be had to wet microchemistry. An important research area remains here. Electronic analysers and multichannel optical emission spectrographs require elaborate matrix correction programmes and hence the use of captive computers. Above all, they require very careful standardization by the best chemical procedures of referee quality. The findings of Fairburn (1951) of poor precision and accuracy in a world-wide survey of analysts stimulated improvement where this was necessary. Flame photometry under Walsh (1955) developed into the atomic absorption spectrometer; other valuable tools of the period have been multi-channel detector-systems for discriminating between radioelements.

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The great interest in isotopic mineralogy has revolutionized geochronology, throwing much light on the origins of magmas, providing geothermometers and the means for tracking mineralizing fluids to their sources.

Apart from the general importance of the X-ray diffractometer as a determinative instrument (Hanawalt & Rinn 1936), two special areas of progress deserve mention. The triumphant progress of clay mineralogy springs from this instrument, but also owes much to differential thermal and infrared analysis, as well as to the observation of the tiny particles under the electron microscope. The opaque minerals, for which only qualitative data were available before 1926, have been placed on a firm quantitative foundation by measurements of spectral reflectance (Bowie, Simpson & Atkin 1975).

Experimental mineralogy at high temperatures had started long before 1926 at the Geophysical Laboratory of the Carnegie Institution, Washington, and was already influencing thought about mineral and rock genesis (for example, Bowen 1928). Progress in new materials during World War II opened the way for systematic work at elevated pressures to begin. It now became possible to investigate systems which, while still simple compared with the least complex natural ones, corresponded much more closely with real conditions of mineral paragenesis. In suitable cases the results can be used to obtain geothermometric and geobarometric information on natural assemblages. Meanwhile very valuable thermodynamic data are being obtained (Kelley 1960) and studies of diffusion and reaction rates can be made. An anvil-type apparatus devised by the U.S. Bureau of Standards, with tuned laser-beam heating, now appears to offer the prospect of experimentation up to 500 kbar (50 GPa) pressure and 2000 °C, simulating conditions deep in the Earth's mantle.

Of the genetic results achieved over the past fifty years, petrology was dominated at the outset by the hypothesis of fractional crystallization in magmas, supported by field evidence (for example, Bailey & Thomas 1924) and experimental data (summarized by Bowen 1928). A special application, full of mineralogical interest, came from Wager & Deer (1939) who studied cryptic variation in relation to a layered basic intrusion. Meanwhile Read (1957), Holmes, Reynolds (1946) and others considered the possibilities of near solid-state transformism as a means of producing granite and Tilley (1958) advocated nephelinization of gneiss. The study of metamorphism has benefited greatly from modern experimental work. Some indication of how closely equilibrium is approached may be gained from the partition of certain elements between coexisting minerals. Dominant influences, however, were those of Harker (1932) in interpreting textures and progressive metamorphism, and Bowen (1940) in showing how decarbonation and dehydration sequences could be analysed. More recently, the mineralogical contribution to the international Upper Mantle Project has come from a study of xenoliths brought up by kimberlitic and basaltic pipes; their evidence makes it possible to zone this thick layer, but it has become increasingly apparent that the layer itself is far from homogeneous. The carbonatite intrusions have proved to be of special mineralogical interest, the origins of the carbon dioxide, rare elements and volatiles fixed in them providing lively topics for debate. The vein mineral deposits of economic importance have been the subjects of a revolution in thinking, resulting from zonal, fluid inclusion and stable isotope investigations, many of which fail to support the orthodoxy of 1926 that most such deposits were generated by juvenile waters associated with sialic igneous activity. Deep saline groundwaters forced upward through the crust, and seawater interacting with hot volcanics are two alternatives now widely recognized. The mineralogy of sediments and their diagenesis have begun

to be taken seriously during the half-century, in the light of the physical chemistry involved (Krumbein & Garrels 1952).

The meteorites have continued to provide fascinating glimpses of extra-terrestrial mineralogy; some craters caused by their impact upon the Earth have been shown to be explosive in origin (Spencer 1933). The lunar samples, generously distributed among investigators in this and other countries after the U.S.A. and U.S.S.R. missions, have yielded about 60 minerals (compared with some 2200 on Earth), characteristic of their oxygen-poor environment of formation.

The techniques of mineralogy are of fundamental value in the search for new mineral deposits, be they nuclear fuels, metallic ores or non-metallics. They are also extensively applied in the refractories, ceramics, cement, iron and coke industries and, recently, in some aspects of medicine. They have, therefore, a certain public interest. The discussion meeting marking the centenary of The Mineralogical Society, an account of which follows, indicated that high-quality fundamental research is the only sure key to further progress. It covered such research in very diverse fields: the mineralogy of ocean-bottom sediments, meteorites and lunar basalts; the metamorphism of stratiform ores and the origin of that most controversial of gold-uranium deposits, the Witwatersrand; the extrapolation of activity-composition relations from experiments to rocks and the high-temperature properties of silicate liquids.

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