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## THEORETICAL PETROLOGY

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The central issues in petrology have remained remarkably unchanged in the last 50 years. In igneous petrology, the focus is on understanding the nature and cause of diversity in igneous rocks: on identifying primary magma types and constraints on the compositional and mineralogical characteristics, the physical conditions, and the evolutions of their source regions and on establishing the processes by which derivative magmas evolve from primary magmas. In metamorphic petrology, the major concern is with understanding the conditions and processes experienced by a rock in reaching its present state. In both igneous and metamorphic petrology, the ultimate goal is the integration of petrological constraints with those from other branches of earth science into regional and global theories of earth history. What has changed over the years, however, is the framework within which these issues are addressed: the backdrop provided by plate tectonics and geophysical constraints, the growing sophistication of chemical and physical models of rock systems, the ever increasing inputs from trace element and isotopic geochemistry, the sophistication and complexity of experimental approaches to petrological problems, and the growing body of detailed petrological studies of specific rock suites and associations from all over the world. What I will attempt in this report is to pinpoint and briefly review those

areas of growing interest and emphasis in American efforts in petrology during the 1975-1978 quadrennium and the ways in which they were shaped by this framework.

Structure of Silicate Melts  
and Thermodynamics in Igneous Petrology

One area of growing interest in igneous petrology has been the characterization of the structural and thermodynamic properties of silicate melts and the application of these results to an understanding of phase equilibria and processes in igneous systems. Several approaches have been taken to understanding silicate melt structure and its response to changes in physical conditions and composition. Structural properties of melts have been inferred from theoretical considerations (Waff, 1975), from spectroscopic study of quenched glasses (Velde and Kushiro, 1978), and from variations observed in viscosities and densities of melts as functions of pressure and composition (Kushiro, 1976; Kushiro et al., 1976). Structural implications have also been drawn from the dependence of liquidus phase relations on melt composition (Eggler and Rosenhauer, 1978; Kushiro, 1975; Mysen, 1976). Studies of element partitioning between crystals and silicate liquids also yield information on the structures of silicate liquids (Leeman, 1978; Watson, 1977). These studies of melt structure can provide valuable insights into phase equilibria

and the physical properties of melts as functions of physical conditions and composition.

Several approaches have also been taken to characterizing the thermodynamic properties of silicate melts and to developing the methodology for the application of these results to both qualitative and quantitative prediction of phase equilibria. Thermodynamic properties of silicate melts, such as enthalpy, heat capacity, and heat of fusion, have been measured or estimated in a number of ways (Bacon, 1977; Carmichael et al., 1977; Hon et al., 1977; Peck et al., 1977; Rosenhauer, 1976; Yoder, 1975). Thermodynamic approaches to the prediction of liquidus diagrams were developed by several investigators: Polymer models of silicate systems provide qualitative insights into the properties of more complex systems (Hess, 1975), but are unlikely to provide a basis for their quantitative treatment. Models based on ideal mixing of appropriately chosen components in silicate melt systems have been applied to the prediction of binary and ternary liquidus diagrams (Burnham, 1975). Bottinga and Richet (1978) have developed a promising new approach to the prediction of liquidus diagrams based on a Flory-Huggins formulation. The concept of silica activity in melts continued to be developed (Nicholls, 1977) and applied to petrogenetic problems (Hausel and Nash, 1977). A number of authors carried out thermodynamic treatments of experimental studies of major and minor element exchange equilibria between crystalline and liquid silicates (Drake, 1976b; Longhi et al., 1978). The results of these studies have potential application to the calculation of fractionation trends in liquids, to geothermometry, and to the reconstruction of primitive liquid compositions (Drake, 1976a; Irvine, 1977a), and as mentioned above, provide insights into the structural properties of silicate liquids. Considerable interest focused on trace element partitioning between crystals and liquids and analysis of the results in terms of chemical models (Fraser, 1975; Hart and Davis, 1978; Mysen, 1978; O'Nions and Powell, 1977).

#### Kinetics and Textures in Igneous Rocks

Interest in the textures and mineral zoning patterns of igneous rocks and their interpretation in terms of the conditions under which the rocks crystallized, the transport properties of silicate crystals and liquids, and the dynamics of the crystallization process grew during the 1975-1978 quadrennium. Numerous experimental studies examined crystallization sequences and textures of natural compositions as functions of cooling rate. These studies showed that crystallization sequences depend on cooling rate as well as bulk composition and that textures depend on the presence or absence of phenocrysts in the cooling magma or the amount of superheat if no phenocrysts are present, as well as cooling rate. Overall textural characteristics and measures of crystal shape, crystal size, and nucleation density permit estimation of cooling rates above the solidus and can help to determine whether or not phenocrysts were present in the magma when it began to cool (Bianco and Taylor, 1977; Lofgren et al., 1975;

Walker et al., 1976, 1978a). Other approaches have been applied to estimate cooling rates of igneous rocks at principally subsolidus temperatures: modelling of pyroxene exsolution (Miyamoto and Takeda, 1977), modelling of Zr distribution between ilmenite and ulvospinel (Taylor et al., 1975), and modelling of the homogenization of the initial zoning profiles of olivines (Taylor et al., 1977; Walker et al., 1977). Detailed analysis of cooling rates of igneous rocks has been applied primarily to extraterrestrial basic rocks. In such cases, where geological controls such as field relations are not available, cooling rate estimates can be used to infer the size of the magma body in which a rock crystallized (Brett, 1975; Walker et al., 1976, 1977). There has, however, been experimental study of textures in terrestrial basic rocks (Donaldson, 1977; Lofgren and Donaldson, 1975) and field study of the relationship between cooling history and magma body dimensions (Peck et al., 1977; Wright et al., 1976). Experimental and theoretical characterizations of mechanisms of nucleation and growth of crystals in synthetic and natural melts were based on the studies mentioned above, and others (Fenn, 1977; Gray, 1978; Kirkpatrick, 1975, 1977; Swanson, 1977).

Study of diffusion of major and trace components in silicate glasses (Magaritz and Hofmann, 1978) and silicate melts (Arzi, 1978; Hofmann and Magaritz, 1977) is a growing field of interest. This information can be used to understand crystal growth (Donaldson, 1975; Kirkpatrick, 1977) and to evaluate time scales for homogenization of isotopic and chemical disequilibrium in mantle systems (Hofmann and Hart, 1978). These studies have cast doubt on models of magma genesis invoking disequilibrium melting processes in the mantle to explain certain isotopic features of basic rocks, unless melts are generated and removed from mantle sources on a rapid time scale.

#### Oceanic Basalts

Major efforts were made in the 1975-1978 quadrennium to understand the genesis of basaltic rocks from the ocean floor. The interest in these rocks stemmed largely from the recognition of their importance in a global framework as the rock type produce at accreting plate margins and as one of the most abundant rock types in the earth's crust. Many of the samples for study were provided by the Deep Sea Drilling Project and the FAMOUS project.

Most ocean ridge basalts are tholeiitic and multiply saturated with olivine, high-Ca pyroxene, and plagioclase at their low pressure liquid. This multiply saturated character suggests that the bulk of these basalts evolved by fractionation at low pressures and do not represent primary melts of the mantle. This rarity of primary magmas among erupted basalts is also observed, though to a less extreme extent, on the moon and may be a general feature of basalts on the large terrestrial planets. Detailed analysis of the petrology and chemistry of mid-ocean ridge basalts has led to the suggestion that processes more complex than simple fractional crystallization may be

important in their petrogenesis. A number of studies have concluded that mixing of magmas in magma chambers beneath the mid-ocean ridge plays an important part in their evolution (Bryan and Moore, 1977; Donaldson and Brown, 1977; Dungan et al., 1978). Magma mixing in such chambers may be a reasonable consequence of the current tectonic picture of the ridge, where new pulses of primitive magma are more or less continuously injected into a differentiating magma chamber beneath the ridge. The structural, geochemical, geophysical, and thermal consequences of such a magma chamber have been examined by a number of authors (Dewey and Kidd, 1977; O'Hara, 1977; Sleep, 1978). Thus, one of the interesting developments of the last quadrennium was the notion that magma mixing, once believed to be a rare phenomenon exerting little influence on the compositions of most magmas, may have a profound influence on one of the most abundant magma types on earth. Magma mixing has also been invoked as a significant control on differentiation trends and on the origin of chromitite layers in large basic intrusions (Irvine, 1977b), on the chemical compositions of some Hawaiian magmas (Wright et al., 1975), and on the origin of certain andesitic and related magmas (Eichelberger, 1975). Its importance in triggering eruptions has been discussed by Sparks et al. (1977b).

As somewhat of an aside in the context of oceanic basalts, it should be noted that in addition to magma mixing, other alternatives to fractional crystallization as the major control on the compositions of non-primary magmas were explored during the 1975-1978 quadrennium. In particular, liquid immiscibility continues to attract a loyal following. The phenomenon has been explored by field petrologists and by a growing number of experimental petrologists, who have begun systematic exploration of its extent as a function of pressure, oxygen fugacity, and chemical composition in simplified systems (Irvine, 1976; Naslund, 1976; Philpotts, 1976; Roedder, 1978; Watson, 1976; Watson and Naslund, 1977). McBirney (1975) suggested that the granophyre in the upper level of the Skaergaard intrusion formed by liquid immiscibility, but alternative explanations of this phenomenon in large intrusions, such as melting of roof rocks (Smith and Silver, 1975), may be more attractive. The general importance of liquid immiscibility in petrogenesis remains to be established, although it is probably responsible for some features of certain rock types (e.g., lamprophyres). Assimilation is another process which can exert some influence of petrogenesis (Joesten, 1977) and which may be of considerable importance in explaining the isotopic systematics of certain continental rocks (Carter et al., 1978b).

While studies of ocean ridge basalts have led to an appreciation among many petrologists of the importance of the magma chambers beneath the ridge, studies of ophiolite complexes have provided a complementary view of the processes involved in the formation of oceanic crust and oceanic basalts at mid-ocean ridges since it is widely (but not universally; see, for example, Miyashiro, 1975) believed that most ophiolites represent cross sections of oceanic crust and upper mantle formed at mid-ocean ridge spreading

centers. A variety of petrological and geochemical studies of ophiolite complexes during the last quadrennium contributed to a characterization of the dynamic igneous and metamorphic processes involved in the formation of oceanic crust (Coleman, 1977; Jackson et al., 1975; Menzies et al., 1977; Stern et al., 1976). These petrological studies also provide a framework for the interpretation of geophysical data bearing on the structure of the oceanic crust (Clague and Straley, 1977; Peselnick and Nicholas, 1978; Salisbury and Christiansen, 1978; Spudich et al., 1978) and for models of the ridge zone (Dewey and Kidd, 1977).

A variety of petrological and geochemical studies were carried out on oceanic island volcanic suites (Batiza, 1977; Bonatti et al., 1977; Sigurdsson et al., 1978). The chemical variations within these suites were generally interpreted in terms of partial melting in the mantle and low pressure fractional crystallization. The longstanding question of the origin of the Daly gap in these suites remains unresolved, although it was attributed to both fractional fusion (Chayes, 1977) and fractional crystallization (Clague, 1978) during the last quadrennium. The concepts of hotspots and mantle plumes continued to dominate perceptions of oceanic island magma genesis, but they are becoming more complex in response to increasing information: Dymond (1975) and Jackson (1976) proposed moving hotspots; Bonatti et al. (1977) inferred "hot lines" in the mantle; and Morgan (1978) discussed the possibility of "pipelines" from hotspots to nearby ridge crests. Some difficulties were discussed with the popular view that mantle plumes result from the rising of hot, fertile mantle peridotite through depleted peridotite due to the lower density of the former. O'Hara (1975) and Boyd and McCallister (1976) showed that fertile peridotite is in fact denser than depleted peridotite and will have no tendency to rise buoyantly in mantle plumes. Boyd and McCallister suggested that this difficulty could be avoided if fertile mantle were to rise as crystal plus liquid (~25%) mushes, which would be lighter than depleted peridotite. However, this may also encounter difficulties since liquids may segregate from the crystal plus liquid mush long before the peridotite is 25% molten (Walker et al., 1978b). If Boyd and McCallister's explanation is correct, it could have important implications: melting may not occur in plumes in response to buoyant rise of fertile mantle; rather, it may initiate the rise. An alternative possibility is that hotspots are initiated by the rise of mantle material which is somewhat depleted relative to its surroundings.

#### The Mantle

Efforts to understand the petrology and evolution of the earth's upper mantle were a major focus of the American petrological community during the 1975-1978 quadrennium. Views of the upper mantle have been strongly influenced by studies of the the ultramafic nodules which occur in basalts and kimberlites. They provide the basis for most estimates of its composition (e.g., Smith, 1977). Many detailed

petrological and geochemical studies of xenoliths from kimberlites can be found in papers presented at the First International Conference on Kimberlites (Ahrens et al., 1977).

Paleogeotherms continued to be constructed from both garnet lherzolite nodule suites (Boyd and Nixon, 1975, 1978) and spinel lherzolite nodule suites (Mercier and Carter, 1975), but the approach has been questioned (Irving, 1976; MacGregor and Basu, 1976; Wilshire and Jackson, 1975). The potential importance of paleogeotherms spawned a wide range of studies designed to calibrate and refine techniques for estimating pressures and temperatures of equilibration in ultramafic nodules. A number of these can be found in a special issue of the *American Mineralogist* (Vol. 61, pp. 549-816) in which many of the papers presented to the International Conference on Geothermometry and Geobarometry are published. Pressures and temperatures of garnet lherzolites are probably valid at least in a relative sense, but the calibrations are not yet good enough to be sure of the reality of the kinked geotherm identified in the previous quadrennium. There is considerable controversy concerning spinel lherzolite geobarometry and the geotherms based on these nodules. Some of the contributors to the controversy surrounding the calibrations of the alumina isopleths of orthopyroxene in spinel lherzolites and their applications to geobarometry have been Danckwerth and Newton (1978), Mercier and Carter (1975), Obata (1976), Presnall (1976), and Wood (1975).

Synthesis of pressures and temperatures of equilibration in nodules with their mineralogical, textural, and compositional characteristics has yielded intriguing clues into the structure and evolution of the upper mantle beneath South Africa (Boyd and Nixon, 1975; MacGregor, 1975). Xenoliths from depths of greater than 150 km are strongly sheared, contain no phlogopite, and based on their major element chemistry, appear to have experienced little extraction of a basaltic component. On the other hand, the nodules from shallower depths are coarse-grained and granular, contain phlogopite, and appear, on the basis of their major element chemistry, to be depleted in a basaltic component relative to the sheared nodules from greater depth. Trace element studies, however, demonstrate that the genesis of the granular peridotites must be more complex than simple removal of a basaltic component from peridotites similar to the sheared peridotites (Shimizu, 1975). Although neither the significance nor the generality of the correlation of composition, mineralogy, and texture with depth are entirely clear, the possibility of direct petrologic mapping of the upper mantle by detailed study of ultramafic xenoliths is one of the more important developments of the last two quadrennia and is likely to continue to be actively developed in the future.

The textures of ultramafic xenoliths in basalts and kimberlites and their implications for constraining mantle processes have been explored by a number of authors (Basu, 1977; Goetze, 1975; Mercier and Nicholas, 1975; Wilshire and Pike, 1975). Other aspects of mantle processes relevant to petrology were

investigated during the last quadrennium: several authors modelled the distribution and subsequent segregation of liquid from partially molten peridotite, but there is not general agreement on the geometry of the melt distribution nor on the time scale required for the segregation and escape of melts from their source regions (Arndt, 1977; Turcotte and Ahern, 1978; Waff and Bulau, 1977; Walker et al., 1978b). The flow of magma from mantle source regions to the surface in conduits was modelled by Vogt (1976) and Marsh and Kantha (1978) and the influence of crack propagation on melt rise was considered by Anderson and Grew (1977). Sparks et al. (1977a) made the interesting suggestion that ascending magmas would behave like Bingham rather than Newtonian fluids. On this basis, they suggested that magmas carry nodules from depth because of their rheology, reflecting slow ascent rates, rather than due to rapid ascent rates as is usually assumed. Their analysis, if applicable, could also undermine the widely held assumption that nodule-bearing magmas did not fractionate between the depth at which they incorporated the nodules and the surface and have thus escaped the effects of low pressure fractionation.

Melting experiments on ultramafic rocks or model mantle compositions under a range of conditions provide a framework for the interpretation of melt compositions observed in nature. If an observed magma type (or some of its critical features) can be reproduced experimentally by melting of a reasonable mantle composition, then such a magma could have been produced by melting of such a source under conditions similar to those of the experiment. During the 1975-1978 quadrennium, many experimentalists focused on studies of subsolidus phase relations and melting of model and simplified mantle compositions at various pressures as functions of volatile content and composition and constructed petrogenetic models for basic and ultrabasic magmas based on these studies (Boettcher et al., 1975; Eggler, 1975, 1978; Eggler and Holloway, 1977; Ifysen and Boettcher, 1975; Newton and Sharp, 1975; Wyllie, 1978; Wyllie and Huang, 1975, 1976ab). Other petrogenetic schemes for basic magmas based largely on synthesis of high pressure experimental data relevant to mantle melting and basalt phase equilibria were presented by Mysen and Kushiro (1977), O'Hara et al. (1975), Presnall et al. (1978), Ringwood (1975), and Yoder (1976). The liquid compositions produced by small degrees of partial melting of peridotite in the presence of H<sub>2</sub>O and/or CO<sub>2</sub> vary widely (depending on the experimental conditions and the investigator) and may include melts similar to andesites, kimberlites, carbonatites, olivine-melilitites, melilitite-nephelinites, and other alkali-rich, silica-poor magmas. The primary magmas of the more abundant tholeiitic and alkali olivine basalts appear to form under dry or nearly dry conditions.

One of the uncertainties in problems of magma genesis which has begun to attract attention is the oxygen fugacity in mantle source regions. The oxidation states of magmatic gases (Gerlach and Nordlie, 1975) and inferred from the oxide equilibria in basalts (Haggerty, 1978) indicate

oxygen fugacities near the quartz-fayalite-magnetite buffer, but this is not necessarily a meaningful guide to mantle values, and may largely reflect hydrogen loss from magmas (Sato, 1978). Graphite-gas or diamond-gas equilibria may be the primary controls on oxygen fugacity during partial melting in the mantle (Eggler et al., 1977; Rosenhauer et al., 1977; Sato, 1978). Vesicles in ocean-ridge basalts (Moore et al., 1977), fluid inclusions in phenocrysts from these basalts (Delaney et al., 1978), and fluid inclusions in ultramafic nodules (Green and Radcliffe, 1975; Murck et al., 1978) are all CO<sub>2</sub>-rich. This may have bearing on both the composition of a fluid phase in the mantle and whether it equilibrated with graphite, diamond, and/or a carbonate.

The implications of komatiites and their associates to mantle evolution are not entirely clear, although efforts to characterize these ultrabasic lavas continued during the last quadrennium (Arndt, 1977; Arndt et al., 1977; Arth et al., 1977; Green and Schultz, 1977). They could be produced by large degrees or by successive smaller degrees of partial melting of the mantle. The existence of Ordovician komatiites (Upadhyay, 1978) indicates that conditions required for their origin were not unique to the Archean, although they were apparently rare in later times.

#### Trace Element and Isotope Geochemistry

One of the more important developments in igneous petrology over the last decade has been the growing influence of trace element and isotopic geochemistry. Trace element and isotopic analyses have become a routine part of most studies of specific rocks suites and few petrogenetic questions can be meaningfully addressed without reference to the constraints provided by these branches of geochemistry. Although these fields are reviewed elsewhere in this volume, I will here briefly mention a few of the results most important to petrogenesis.

The initial ratios of  $^{143}\text{Nd}/^{144}\text{Nd}$  and  $^{87}\text{Sr}/^{86}\text{Sr}$  and the isotopic composition of lead in basalts provide means of identifying heterogeneities in their mantle source regions. Some source regions appear to have experienced previous episodes of melt extraction and are "depleted", others appear to have experienced no previous melting and are thus "undepleted", while still others may have been enriched in a low-melting component. Modelling of the evolution of the mantle from an assumed uniform, primitive composition into this heterogeneous spectrum of mantle materials and characterization of these heterogeneities are active areas of interest with important implications for the origins of basalts and their source regions (DePaolo and Wasserburg, 1976ab; Hart and Brooks, 1977; Hedge, 1978; Hurst, 1978; O'Nions et al., 1977, 1978; Sun and Hanson, 1975; Tatsumoto, 1978). The position on the depleted to enriched spectrum occupied by a particular mantle source region plays an important role in the type of melt produced, although the degree of partial melting and the depth also play significant roles. There have been many attempts (e.g., Brooks et al., 1976ab;

Tatsumoto, 1978) to attach temporal significance to the isotopic differences between basalt source regions; these have suggested on the basis of "mantle isochrons" that in oceanic regions, depleted and undepleted source regions have been isolated from each other for at least 1.5 - 2.0 AE. Carter et al. (1976b) demonstrated, however, that in some continental provinces, so-called mantle isochrons can be artifacts produced by contamination with crustal rocks and urged caution in attaching time significance to these features.

Lloyd and Bailey (1975) discussed the idea that regions of the mantle are metasomatized by upwards migrating fluids. Continued flux of volatiles ultimately results in melting of the altered mantle, producing highly alkalic, volatile-rich magmas such as the ultrapotassic lavas of the East African Rift. This concept has also been applied to the source regions of more common alkali olivine basalts and ocean floor and ocean island basalts in addition to those of bizarre ultrapotassic lavas, so the process could be of general significance (Bence et al., 1975; Boettcher et al., 1977; Carter et al., 1978a; Frey et al., 1978b). The metasomatism and light-REE enrichment of the source regions could have preceded the melting event by perhaps even billions of years (Sun and Hanson, 1975). The metasomatizing fluids could be hydrous fluids, kimberlitic melts, or simply light-REE enriched basaltic liquids generated at greater depths. The concept of mantle metasomatism is sure to be explored further in the next quadrennium. It may also require reassessment of some of the petrological inferences previously drawn from geochemical arguments; for example, strongly light-REE enriched patterns in mafic lavas need not necessarily reflect residual garnet in their source regions as is usually inferred, but may simply reflect the light-REE enrichments of their metasomatized source regions.

#### Calc-Alkaline Magmatism

One of the major points of impact of plate tectonic theory on petrology is in the area of calc-alkaline magmatism, where the concept of subducting oceanic lithosphere provides the framework for petrogenetic theory. A variety of processes have been proposed to explain the features of andesites and related volcanic rocks, and associated batholithic intrusions. One model is that primary calc-alkaline magmas are produced by partial melting of subducted oceanic crust composed of metamorphosed oceanic basalt (and its differentiates) plus continental and/or pelagic sediments. The amounts of sediment and seawater involved in the melting are negotiable. Alternative models involve melting of the mantle above the subducted slab, with or without the involvement of H<sub>2</sub>O-rich fluids or partial melts derived from the subducted slab below. Other possibilities include the involvement of overlying continental crust in the melting process and in interaction with melts or other fluids evolved from below in areas where oceanic crust is subducting beneath a continent. The emphasis during the 1975-1978 quadrennium was on exploring the relative contributions of these processes to magma genesis in specific

calc-alkaline suites from a range of environments and on experimental studies aimed at determining the types of magmas which would be produced by these various processes. The message, provided particularly by trace element and isotopic studies, is that the processes leading to the development of calc-alkaline magmas are exceedingly complex, and often involve elements of several of the processes mentioned above (Arculus, 1976; Best, 1975; Church, 1976; DePaolo and Wasserburg, 1977; James et al., 1976; Kay, 1977; Lipman et al., 1978; Lopez-Escobar et al., 1977; Marsh, 1976; Meijer, 1976). In the discussion of ocean floor basalts in an earlier section, I noted that a recurrent theme in studies of basalts from the earth and other planets is the rarity of primary magmas among erupted lavas. This appears to hold for calc-alkaline lavas as well and a number of authors emphasized and modelled the fractionation which appears to be important in the development of andesites and related rocks; amphibole fractionation is considered by many to be particularly important, though other phases are also involved (Allen and Boettcher, 1978; Cawthorn and O'Hara, 1976; Frey et al., 1978; Stern and Wyllie, 1978a).

Many studies during the last quadrennium were concerned with the origins of batholiths near continental margins and granitic magmas in general. Wyllie (1977) presented a model for the genesis of granitic through granodioritic magmas near continental margins and their emplacement in batholiths which synthesized experimental, field, and tectonic constraints. Miller (1978) discussed the origin of monzonitic plutons produced in the early stages of batholith emplacement and Gastil (1975) presented models of the actual emplacement of batholiths. There were a number of studies bearing generally on the origin and evolution of granitic magmas based on experimental and theoretical data (Holloway, 1976; Huang and Wyllie, 1975; Maaloe and Wyllie, 1975; Steiner et al., 1975; Whitney, 1975). Hanson (1978) discussed the application of trace elements to modelling of the evolution of granitic melts. Thompson and Algor (1977) presented a theoretical treatment of the evolution of granitic melts by anatexis of pelitic rocks.

#### Metamorphic Petrology

Refinement and application of techniques for estimating equilibration conditions of metamorphic mineral assemblages constituted an important part of the American effort in metamorphic petrology in the last quadrennium. Exchange reactions (which tend to be useful in geothermometry since they are largely pressure insensitive), such as Fe-Mg distribution coefficients between coexisting phases and miscibility gaps, were calibrated experimentally or with natural metamorphic assemblages, and a variety of approaches to analytical treatment of these equilibria were applied (Evans and Frost, 1975; Ferry and Spear, 1978; Goldman and Albee, 1977; Grover, 1977; Lindsley and Dixon, 1976; Thompson, 1976). Once temperature has been estimated from an exchange reaction, pressure can often be estimated using reactions among the

end-member components of phases present in the rock. Efforts have been made to develop thermodynamic characterizations of relevant reactions by analysis of the results of phase equilibrium experiments and calorimetric studies on the participating phases (Delaney and Helgeson, 1978; Helgeson et al., 1978; Navrotsky and Coons, 1976; Newton et al., 1977; Robie et al., 1978; Zen, 1977). Understanding of the mixing properties of the complex phases found in natural assemblages is necessary in order to apply the end-member reactions to quantitative estimation of equilibration conditions, and many theoretical and experimental studies were directed toward characterizing the activity-composition relations of the solid solutions involved in the reactions (papers in Fraser, 1977; Kerrick and Darken, 1975; Ulbrich and Waldbaum, 1976). The stability limits of specific phases (e.g., the aluminosilicates) and assemblages also provide constraints on equilibration conditions, and there were efforts to determine such limits (e.g., Anderson et al., 1977; Hewitt, 1975). Other approaches such as study of solid inclusions (Adams et al., 1975) can also provide constraints on P-T conditions. Despite the limitations and uncertainties of these methods of estimating metamorphic temperatures and pressures, their application to specific problems to develop local and regional constraints on metamorphic and structural evolution has become almost routine. A more general approach to the problem is to develop petrogenetic grids for model systems which can (1) be correlated with sequences of assemblages observed in the field; (2) serve as a framework for understanding regional metamorphic trends and parageneses; and (3) serve as a basis for comparison from region to region. Thompson and Thompson (1976) developed such a grid for a simplified model of pelitic rocks and roughly located important reactions in P-T-aH<sub>2</sub>O space.

The role played by fluids in metamorphism and particularly what controls the compositions of metamorphic fluids continued to be actively studied during the last quadrennium. There seems to be no general answer to the longstanding question of whether a free fluid phase exists during metamorphism; there are clearly some cases where such a phase was present (e.g., Rice, 1977; Rumble, 1978; Trommsdorff and Evans, 1977) and others where it is likely, or at least possible, that there was not (e.g., Ferry, 1976b). The composition of the fluid phase (if present) in metamorphism can be estimated in several ways. Primary fluid inclusions can provide direct estimates (e.g., Rich, 1975; Hollister and Burruss, 1976). In some situations, stable isotopes have been used to estimate fluid compositions (Taylor and O'Neil, 1977). The presence in rocks of mineral assemblages which buffer the fCO<sub>2</sub> or fO<sub>2</sub> of the fluid phase provides the basis for the most widely applied approach to determining fluid compositions (Eugster, 1977). A number of studies in the last quadrennium dealt with analytic and experimental treatments of these buffer reactions (Kerrick and Slaughter, 1976; Slaughter et al., 1975; Skippen and Trommsdorff, 1975). Application of this approach to studies of specific metamorphic terrains has demonstrated

variations in  $f\text{CO}_2$ ,  $f\text{H}_2\text{O}$ , and  $f\text{O}_2$  on a bed to bed scale (Ferry, 1976a; Rice, 1977; Rumble, 1978), a conclusion confirmed by fluid inclusion studies (Rich, 1975). These studies support the idea that fluid compositions are often buffered by the mineralogy of the rock, reflecting its initial composition, and that fluid components are not always externally imposed, perfectly mobile components. Greenwood (1975a) discussed the buffer capacity of a mineral assemblage and its effect on the progressive changes in mineral assemblages in metamorphic sequences.

Efforts are growing to develop a dynamic picture of fluids in metamorphism. There is not simply a static fluid of unchanging composition throughout a metamorphic event. Some of the changes in fluid composition may simply be due to buffering by a mineral assemblage, where changes in P and T can produce changes in the fluid composition (Greenwood, 1975a). In other cases, emplacement of granites during regional metamorphism may affect fluid compositions by, for example,  $\text{H}_2\text{O}$  flow from the melt into the surrounding metasediments and  $\text{CO}_2$  flow into the granite stock (Ferry, 1978). The importance of fluid interaction between magma chambers and their surroundings has long been recognized by isotope geochemists (Taylor, 1978), and is viewed as an inevitable consequence of plutonism, with important implications for heat and mass transfer (Norton and Knight, 1977).  $\text{H}_2\text{O}$  entering one region or bed may be derived from dehydration reactions in surrounding pelites (Ferry, 1976a). Olsen (1977) discussed another aspect of the dynamic evolution of metamorphic fluids: anatexis produces a granitic melt which soaks up water from surrounding metasediments, producing a gradient in  $f\text{H}_2\text{O}$  between the melt and the surrounding rocks, which in turn results in biotite breakdown, silica migration, and metamorphic differentiation.

Interest in dynamic processes in metamorphism is not restricted to fluids. The traditional approach is to characterize the "highest" grade of metamorphism as it varies on a regional scale and, where possible, to identify an overprinting of a second event or a relict of an earlier event ("polymetamorphism"). There is increasing recognition of the fact that metamorphism consists of the continuous response of a rock system to changes in externally imposed conditions. A rock is continuously chasing after an equilibrium state as the externally imposed conditions of P, T, and certain aspects of its bulk composition change. Rocks which did not reach equilibrium nevertheless contain a record of their chase, and among the developments of recent years are attempts to decipher this record. These attempts must begin with an understanding of kinetics and transport properties during metamorphism. Fisher (1977, 1978) discussed aspects of non-equilibrium thermodynamics as they apply to problems in metamorphism. He was particularly concerned with the kinetics of metamorphic processes and how they relate to the development of metamorphic structures such as metasomatic zones between incompatible assemblages. An important conclusion was that diffusion is the rate determining step in the growth of these structures rather than reaction rate or the flow

of heat in the reaction zone. Metasomatic zones are an obvious place to begin to constrain kinetic factors and diffusion in metamorphic processes. Several authors presented mathematical models or general discussions relating to intergranular diffusion and the growth of metasomatic zones, primarily under constant P and T conditions (Brady, 1975ab, 1977; Frantz and Mao, 1976; Joesten, 1977; Weare et al., 1976). Studies of metasomatic zones have demonstrated the dominance of diffusion metasomatism in most cases (but Kerrick (1977) documented a case where infiltration metasomatism was dominant) and have attempted to determine the relative mobilities of components selected to describe the diffusion process by analysis of chemical potential and diffusion paths (Thompson, 1975; Brady, 1977) or of mineral zoning patterns in the reaction bands (Sack, 1977). Loomis (1977, 1978) has also applied a kinetic treatment to the analysis of metamorphic rocks.

The study of retrograde zoning and cation diffusion of Lasaga et al. (1977) introduced an approach of wide applicability which yielded a quantitative estimate of the cooling rate of a metamorphic rock ( $100^\circ\text{C}/10^6$  years). Application of this approach to other regions and over a regional scale in a particular metamorphic terrain could yield valuable constraints on the structures, uplift rates, and heat budgets of metamorphic belts. There have been several attempts to model the heat balance and development of regional metamorphism based on constraints from metamorphic petrology. Bickle et al. (1975) and England (1978) presented thermal models of the Alpine metamorphic belt and concluded that abnormal heat flow from the mantle was not required to produce the observed metamorphism. Richardson and Powell (1976) reached a similar conclusion for the Dalradian metamorphism. Graham and England (1976) demonstrated the importance of shear heating in areas of thrust sheets in explaining inverted metamorphic zonation. They also emphasized the self-regulatory nature of this effect since the dehydration resulting from increasing temperature and the increasing temperature itself result in reduction of the shear strength of rocks, limiting the amount of shear heating possible.

#### Summary

While it is difficult from the vantage point of the end of a quadrennium to identify which of the developments of the last four years will be regarded as most significant on a time scale of 10 or 50 years, it is nevertheless possible to identify areas of emphasis and growing interest. In igneous petrology, studies of structures and thermodynamic properties of silicate melts and of kinetics of igneous processes are in a period of rapid growth. Plate tectonic concepts have had and will no doubt continue to have an important influence by focusing interest on specific problems and by providing a framework for the understanding of petrogenesis. The emphasis on studies of oceanic igneous processes and on the origin of calc-alkaline magmas are examples of this influence. An understanding of mantle processes and evolution through the integration of petrological, geophysical, and geochemical

constraints has been developing for the past 20 years, and will undoubtedly provide direction for future petrological studies. In metamorphic petrology, the integration of field, experimental, and theoretical studies into a framework for understanding the dynamic evolution of metamorphic systems and their interpretation in terms of the structural and thermal evolution of the crust have been important developments of the past four years and will probably be an important focus for the next quadrennium.

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## KIMBERLITES AND THE MANTLE

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**Introduction.** During the quadriennial period 1975 to 1978 a considerable number of investigations, often closely related, have been undertaken on kimberlites, mantle xenoliths and diamonds. Much progress was made into our knowledge of specific occurrences of kimberlite and diamond in the United States. However, these works are few when compared with the large number of studies carried out on Southern African kimberlites and xenoliths, many by scientists in U.S. institutions. Since the mecca of kimberlite, xenoliths and diamonds in South Africa, particularly Kimberley, it is difficult and unwarranted to separate out the various investigations by nationality. The investigative effort of kimberlites, and<sup>3</sup> associated rocks and minerals is worldwide and accordingly in this brief review of endeavors during 1974 to 1978 as much literature as possible, pertinent to the subject, has been included. Unfortunately, omissions are probable but hopefully there will be few and may perhaps be found through other references cited in the text. Especially useful and worthy of specific note are the Proceedings Volumes of the First and Second International Kimberlite Conferences (*Phys. Chem. Earth*, **9**, 1975; *Diamonds, Diatremes*

and *Diamonds: Their Geology, Petrology, and Geochemistry*; and the *Mantle Sample: Inclusions in Kimberlites and Other Volcanics*; Vols. I and II, *Am. Geophys. Union*, 1979). Also of help are the Extended Abstract volumes for these two Conferences, as well as the papers from the International Conference on Geothermometry and Geobarometry (*Am. Mineral.* **61**, 549-816, 1976).

## Mantle Fragments

A considerable amount of indirect evidence concerning the structure and possible petrology of the upper mantle has been obtained through interpretations of various geophysical data. These interpretations generally indicate vertical and lateral inhomogeneity in mantle density, seismic velocities and thermal regimes; especially between continental and oceanic areas. Unfortunately, when compared to the extensive, and often geographically continuous area covered by the above indirect studies, the total number of known localities where mantle rocks occur is extremely sparse. Nevertheless, mantle samples from these locations have received considerable attention since they alone provide direct evidence of mantle petro-