PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Crustal Evolution by Arc Magmatism [and Discussion]

W. Hamilton and A. Kroner

Phil. Trans. R. Soc. Lond. A 1981 **301**, 279-291
doi: 10.1098/rsta.1981.0111

Phil. Trans. R. Soc. Lond. A **301**, 279–291 (1981)
Printed in Great Briatin

Crustal evolution by arc magmatism

By W. Hamilton
U.S. Geological Survey, Denver, Colorado 80225, *U.S.A.*

Arc magmas generated at depths near 100 km by dehydration of subducting slabs are olivine-rich melabasalts, but the magmas that reach the surface in mature continental magmatic arcs have an average composition near that of rhyodacite. Depth-varying fractionations and equilibrations profoundly modify the initial magmas. Plate tectonics has operated throughout Proterozoic and Phanerozoic time much as it does now, and so many deeply eroded terrains must expose products of arc magmatism. Most exposed middle and deep continental crust consists of igneous rocks plus older rocks equilibrated at magmatic temperatures, variably deformed and metamorphosed subsequently; each crustal level displays a typical assemblage of magmatic rock types, which are here deduced to be products mostly of arc magmatism.

Pre-arc mantle consists of depleted dunite and harzburgite. Rising arc magmas precipitate much additional olivine, and add the equivalent of 10 or 15% of basalt in clinopyroxene, orthopyroxene, garnet and spinel. The seismic M. discontinuity may be controlled primarily by the shallow limit of the depth zone in which crystallization is mostly of ultramafic components, and the fractionated magmas that reach the crust are mostly of gabbroic to granodioritic compositions.

The lower crust is characterized by differentiated layered complexes, which often contain mafic or ultramafic basal cumulates, medial floated-plagioclase anorthosite, and upper quartz-poor pyroxene–mesoperthite granites, and by other magmatic rocks. Magmatic rocks are more voluminous than pre-existing rocks. Supracrustal rocks are in middle granulite facies, and much granitic material has been melted from them by magmatic heat.

The magmatically modified middle crust consists primarily of migmatites in lower granulite facies in the deeper part, and upper amphibolite facies in the shallower part. Much dissociation of hydrous mineral assemblages is caused by the magmatic heat, producing water-rich, aluminous magmas, assimilation and anatexis. The high water contents restrict rise of the equilibrated magmas; voluminous pegmatites are expelled into the wall rocks, and crystallization is forced. Sheets of two-mica granites characterize the upper part of the middle crust.

The comparatively dry magmas that rise into the upper crust are mostly tonalite to adamellite. These magmas spread out in steep-sided batholiths above the migmatites, erupt as ash flow sheets from calderas, and produce voluminous far-travelling volcanic ash. Inverted metamorphic gradients and outward-verging structures are produced beneath the spreading batholiths. Magmatic arcs are extensional at all crustal levels.

Introduction

The concepts of plate tectonics have revolutionized our understanding of the evolution of the shallow parts of continents. Although lateral growth by tectonic accretion has been emphasized in the literature, continents also grow by the rise of arc magmas generated by processes related to the subduction of oceanic lithosphere. Active magmatic arcs now form, along either oceanic island arcs or active continental margins, primarily above those parts of subducted slabs of oceanic lithosphere whose tops are at depths of about 100 km. Dewatering of subducted oceanic crust and partly serpentinized mantle presumably triggers the initial melting at depth, where the magmas must be of very mafic composition. The volcanic rocks erupted at the surface of a magmatic arc, however, vary in average composition as a function of the character of the crust and mantle through which the magmas have risen. Magmas reaching the surface in a primitive oceanic island arc are mainly basalt, in a mature island arc, andesite, and, in a continental margin arc in old, highly evolved lithosphere, rhyodacite. The final magmas are products of equilibrations in the mantle and crust, but little attention has been given to the empirical evidence in deeply eroded terrains for evolution as a function of depth.

Plate tectonics has operated, more or less as it does now, throughout Proterozoic and Phanerozoic time. The rifting apart of continental masses, development on their margins of Atlantic-type continental shelves and slopes, and subsequent conversion to active margins, with the formation of accretionary wedges, magmatic arcs, and thrust belts, complicated by continental collisions and the formation and collision of island arcs, can be read in the geology of most orogenic belts that are exposed at shallow crustal levels. Orogenic complexes exposed at deep crustal levels must have explanations compatible with similar processes, and a major factor must be magmatism above plates of subducting lithosphere.

There are, in many parts of the world, obliquely eroded terrains that expose continuous sections through large fractions of the continental crust. Studies of xenoliths in basalts and kimberlites permit further definition of the lower crust and upper mantle. There appears to be a mainline evolution: most of the middle and lower crust and upper mantle is formed of igneous rocks and of metamorphic rocks equilibrated with magmas, and the assemblages tend to be similar for a given depth zone regardless of the age of the complex. The mainline complexes can be placed in tectonomagmatic context by ordering the obliquely eroded sections downward from the known, shallow products of arc magmatism.

Batholiths and ash flows of the upper crust

Active magmatic arcs developed on mature continental lithosphere are characterized by fields of silicic volcanic rocks, dominantly ash-flow sheets erupted from large calderas atop granitic batholiths, and by stratovolcanoes of intermediate rocks. Sumatra, the central Andes and the North Island of New Zealand display such activity, related to the subduction of oceanic lithosphere. Where erosion has penetrated but not wholly removed such volcanic superstructures, the ash flows are seen to cap the batholiths and large stocks from which they were erupted (Hamilton & Myers 1974). Most large 'epizonal' and 'mesozonal' plutons may have formed capped mostly by their own volcanic ejecta, although many small masses stop as thickly inflated pods within the crust.

The next level of exposure downward in continental magmatic-arc complexes is the composite calc-alkalic batholith, typified by the Sierra Nevada batholith, mostly of Cretaceous age, in California. This batholith is the intrusive substrate of a volcanic arc, formed above subducted oceanic lithosphere (Hamilton 1978). The batholith is a composite of hundreds of plutons, dominantly tonalite and granodiorite in the west, and granodiorite and adamellite in the east. Flow structures demonstrate that each pluton spread laterally as it rose vertically. Petrologic evidence shows the exposed granitic rocks to have crystallized at depths of only 3–10 km. Plutons are bounded sharply and generally steeply against each other, and against the contact-metamorphosed screens of metasedimentary and metavolcanic rocks that separate the upper parts of many of them. Lead and strontium isotopes demonstrate much incorporation

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

of old lithosphere in the magmas. Comagmatic volcanic rocks are preserved primarily in the inter-pluton screens, although volcanic roof rocks are preserved locally. That voluminous pyroclastic volcanism accompanied each episode of granite formation is demonstrated by the composition of correlative sandstones and conglomerates to the west, and by the extremely voluminous altered, reworked volcanic ash in mixed-layer-clay shales in the continental interior and the Gulf Coast continental shelf to the east.

Crustal spreading in magmatic arcs

The widespread assumption that arc-magmatic belts occur within zones of regional compression is shown to be false by examination of modern arc systems. Precise geodetic evidence is available from North Island, New Zealand, where a large silicic batholith is now forming, beneath a complex of calderas and ash-flow tuffs; the continental crust on opposite sides of the magmatic belt is moving apart with a velocity of about 7 mm/a (Sissons 1980). In Sumatra and Java, where the current episode of arc magmatism accompanying subduction of Indian Ocean lithosphere began in middle Tertiary time, premagmatic Eocene and Oligocene strata along the magmatic axis are almost undeformed where they are preserved in the broader gaps between magmatic centres along the volcanic axis, although they are crowded into structures concentric about the volcanoes and underlying intrusive complexes near the magmatic centres. Ash-flow fields formed above young arc batholiths show little deformation. The extreme deformation commonly displayed by the contact-metamorphic wall rocks of large, discordant plutons records strains produced by the rising and spreading plutons. Crustal shortening does not occur across magmatic arcs at any crustal level.

Migmatites and hydrous magmas of the middle crust

The middle continental crust is characterized by migmatites, within which pegmatities and granites, mostly leucocratic and typically peraluminous, are outbulked several-fold by metamorphic rocks. The migmatites form beneath batholiths, represent a depth range in the arc-magmatic systems from about 12 to about 25 km, and display mineralogy of upper amphibolite facies (sillimanite, or sillimanite + potassic feldspar) in their shallower parts, and of lower granulite facies (orthopyroxene, or brown hornblende, or cordierite + garnet + potassic feldspar) in their deeper parts.

Middle crust beneath Cretaceous batholiths of western North America

A single great magmatic arc of Cretaceous age is exposed along western North America in Baja California, the Sierra Nevada, Idaho, interior British Columbia, and other tracts formed in continuity between these. Some sectors of the arc expose the batholiths of the upper crust. In other sectors, the middle crust beneath these batholiths is exposed and is seen to consist of concordant granitic plutons within migmatities.

The best-known shallow batholith in this arc is that of the Sierra Nevada. The Idaho batholith is exposed at markedly deeper levels, and largely lacks such shallow features as steep, sharply bounded plutons of massive rocks, septa of metamorphic rocks and preserved coeval volcanic rocks. The migmatic, amphibolite-facies floor of the batholith is exposed in a broad arch, trending westward across the centre of the batholith that contains abundant reworked Precambrian gneisses (Armstrong 1975). The part of the Idaho batholith north of this arch is rimmed by deep-seated gneisses and migmatites, and is the synformal remnant of a great batholithic sheet (Hyndman & Williams 1977). The base of the batholith is a sharp contact with gently dipping migmatites in some areas, but generally is a broad zone of intercalated granitic, migmatitic, and gneissic rocks, in which dips are more often steep or moderate than gentle, and in which the proportion of granitic rocks decreases downward through a vertical range of several kilometres (Cater *et al.* 1973; Chase & Johnson 1977; Wiswall 1979; Williams 1977). The granodiorite and adamellite of much of the Idaho batholith are characterized by primary muscovite, indicating a probable depth of erosion of at least 10 km.

The Cretaceous batholithic belt continues northwestward from the Idaho batholith, across Washington and British Columbia, and is represented by the Coryell and other batholiths, and by widespread migmatities of amphibolite facies, and locally lower granulite facies, exposed beneath them in domes of Shuswap type (Hamilton 1978). Erosion depths into the belt in British Columbia reach 22 or 25 km in migmatitic, amphibolitic granulites (Ghent *et al.* 1977).

One southern sector of the Cretaceous batholithic belt has been translated northwestward, as part of the Coast Ranges of California, along the San Andreas and related right-slip faults. Uplift and erosion of the crystalline tracts vary widely with local details of the complex pattern of Cainozoic oblique strike-slip deformation. The exposed rocks represent variously shallow batholiths, like those of the Sierra Nevada; amphibolite-facies migmatites, like those beneath the Idaho batholith; and, beneath these migmatites in one part of the region, migmatites and concordant granitic rocks of lower granulite facies (Compton 1960). The U–Pb middle Cretaceous age of granulite-facies metamorphism is the same as the age of the upper-crust granites of the region (J. H. Chen, personal communication, 1980).

In Jurassic, very late Cretaceous and early and middle Tertiary time, North America and slowly sinking, subducting Pacific lithosphere converged more rapidly than they did during most of Cretaceous time, and arc magmas rose into the crust east of the Sierra Nevada – Idaho magmatic belt. Extremely variable uplift and erosion has affected these eastern magmatic complexes, which can now be seen at all levels of exposure, from shallow batholiths and capping ash-flow tuffs to middle-crust migmatites, with concordant granitic sheets, beneath batholiths. The shallow granites have normal ratios of alumina to alkalis plus calcium, and hence contain biotite and often hornblende, but not muscovite. The granites of the exposed middle crust, including those of Tertiary age, are typically peraluminous, contain muscovite and biotite and frequently also garnet, and have incorporated radiogenic crustal material (cf. Miller & Bradfish 1980).

Upper and middle crust of Devonian magmatic belt in the northern Appalachians

The transition from upper to middle crust within a magmatic-arc terrain is exposed in oblique section in the northern Appalachians. Again, there is a change downward from cross-cutting, steep-sided plutons, to a migmatitic terrain of concordant sheets of aluminous granites in gneisses of upper amphibolite and lower granulite facies. The Appalachians display the products of a long and complex history of Palaeozoic subduction beneath island arcs and continental masses until, by late Palaeozoic time, the various tracts were aggregated in a broad domain between collided continents. Only cursory interpretations of this evolution have yet been presented for New England; most igneous rocks cannot yet be tied to specific subduction systems.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Small batholiths of middle Palaeozoic granitic rocks of arch types occur in a zone about 200 km wide in central and eastern Maine, where erosion has been only shallow. Plutons are thick and steep-sided (Kane *et al.* 1972; Sweeney 1976), are surrounded by contact-metamorphic aureoles, and typically are of calc-alkalic biotite and hornblende–biotite granodiorite, adamellite and granite (Loiselle & Ayuso 1980). The magmatic belt is eroded to progressively greater depths as it trends southwestward, thence south-southwestward, through New England, obliquely into a north-trending axis of great uplift (Carmichael 1978; Morgan 1972; Tracy *et al.* 1976). The migmatitic floor of the batholithic terrain emerges in southwest Maine, where the erosion depth is 10 or 12 km; the transition is marked by the beginning of regionally extensive migmatites, by the regional sillimanite isograd, and by the appearance of two-mica granites as the characteristic plutonic rocks, all approximately coincident. The level of exposure within the migmatite terrain deepens southwestward and passes through the depth contour, approximately 15 km, of the aluminum silicate triple point. The migmatite terrain is injected pervasively by thin sheets (Kane *et al.* 1972; Nielsen *et al.* 1976) of pegmatites and peraluminous granitic rocks (Wones 1980). The central part of the migmatite terrain, both north and south of the triple-point depth contour, is inside the sillimanite + potassic feldspar isograd (the dehydration reaction of muscovite) and partial melting due to this dehydration is probably an important cause of formation of the granitic rocks (Grant 1973; Tracy 1978). Similar relationships hold in the Canadian part of the magmatic belt, where deeply eroded sectors display concordant sheets of peraluminous granitic rocks, particularly two-mica adamellite, in extensive migmatite, whereas less eroded tracts expose cross-cutting plutons of more varied granitic rocks bearing biotite and hornblende (L. R. Fyffe, G. E. Pajari Jr & M. E. Cherry, personal communication 1980). In southern New England, uplift of the migmatite terrain locally reaches 20 or 25 km, and migmatites in lower granulite facies are exposed. Both migmatites and granites become less hydrous with increasing depth in the middle crust.

Inverted metamorphism and spreading batholiths

Work at the boundaries of migmatite terrains has in New England and various other regions demonstrated thermal gradients of metamorphism that are both inverted and abrupt: peak temperatures decrease sharply downward beneath the edges of overlying migmatites. Such inversions are commonly interpreted in terms of nappes, whereby hot infrastructures are pictured as being squeezed outward during synmagmatic crustal shortening. As arc magmatism is not in fact accompanied by crustal shortening, the likely explanation lies in gravitational spreading of batholiths above the migmatites (Hamilton & Myers 1974). Magmas spread in the upper crust, partly displacing older rocks outward, and partly spreading over migmatites that move downward and beneath the batholiths.

Granites of the middle crust

Batholiths of Sierra Nevada type nowhere extend downward into the middle crust. Wherever pressures of metamorphism and crystallization equivalent to a depth range from about 12 to 22 km have been clearly defined by petrologic criteria in mature continental arc-magmatic terrains of any age, from Precambrian to Tertiary, migmatites and concordant granites, the former generally dominant, are present.

The characteristic granites in the mature middle crust, where pre-existing rocks are dominantly either older continental crystalline rocks or metamorphosed terrigenous sedimentary rocks, differ petrologically from most granites of shallow batholiths. The deep granites are typically leucocratic adamellite and subordinate granodiorite; tonalite and potassic granite are minor. The rocks tend to be peraluminous (they have relatively high ratios of alumina to alkalis plus calcium) and hence, to contain most commonly primary muscovite + aluminum-rich biotite, and less commonly aluminous garnet or other aluminous minerals; hornblende is lacking. Equilibration of the melts with the aluminous wall rocks is shown abundantly by field, mineralogic and isotopic studies. Pegmatite sheets and veins are superabundant.

The typical magmas that crystallize in the middle crust are equilibrated with richly hydrous wall-rock mineral assemblages, and herein lies the likely explanation for both the composition and the vertical restriction of the granites. Most magmas of upper crustal batholiths probably contain less than 1.5 % water and reach water saturation only at shallow depth after much crystallization, with resultant expulsion of a vapour-rich phase in pegmatites and volcanic eruptions (Maaloe & Wyllie 1975). Two-mica granite magmas, by contrast, contain 3–5 % water (Green 1976; Wall & Clemens 1979) and reach saturation at much greater depth, expelling the voluminous pegmatites that characterize migmatite terrains and forcing crystallization. Magmas deeper in the crust are in contact with water-poor wall rocks, are relatively dry and are not peralimous. Only in the middle crust are hydrous wall rocks present in a setting where they can be raised to solidus temperatures in great volume, and are pressures adequate to permit the development of richly hydrous magmas. The heat for such direct melting of wall rocks as does occur is introduced by the magmas cooling in or rising through the migmatites. The common presence of primary muscovite in middle-crust granites is in accord with the experimental and thermodynamic demonstration that muscovite is stable, in the presence of quartz and feldspars, on the high-pressure side of a compositionally dependent reaction zone that intersects the hydrous-granite solidus at 0.3 to 0.4 GPa (Tracy 1978).

Granulite, anorthosite and charnockite of the lower crust

The middle crust of magmatic arcs is formed of migmatites and subordinate granites, both of which become less hydrous downward as grade of equilibration increases from upper amphibolite through lower granulite. Mature, lower continental crust is exposed in many regions beneath similar migmatite successions, and consists of distinctive igneous rocks, and subordinate other rocks, equilibrated under middle granulite conditions. (The middle granulite subfacies is characterized by the combined assemblages almandine + clinopyroxene, which disappears at the low-grade boundary, and orthopyroxene + plagioclase, which disappears at the high-grade limit.)

Exposed sections of the mature, magmatic, lower continental crust, representing depths of the order of 25 to 40 km, typically display the high-pressure differentiates of magmas intruded from the mantle, and also the products of granitic magmas melted from the wall rocks by the heat of those intrusions, intercalated with other rocks of middle granulite subfacies. The characteristic differentiates are gabbro, norite, anorthosite and granite, occurring either as great layered complexes (variably disrupted by postmagmatic deformation), or as thinner intercalations in other rock types. The relatively sodic plagioclase of the anorthosites and the low quartz content, pyroxenes and mesoperthitic feldspar of the granites (which typically are normative quartz monzonite and adamellite) attest to the high pressure and temperature of crystallization, and to the low water contents of the magmas. Intercalated with these deep-seated magmatic rocks are commonly supracrustal rocks, including quartzite, marble, and aluminous metapelites depleted in granitic components, and also sheets of quartz-rich metagranites, which probably crystallized high in the crust. The depression to deep crustal levels of such initially shallow rocks may be due primarily to the repeated injection of magma above them.

Crustal section in the Alps

A section eroded obliquely through most of the continental crust is exposed in the northwestern Italian Alps (Berckhemer 1969; Mehnert 1975). All but the shallow levels display regional equilibration between igneous and metamorphic rocks. Zircon and monazite U–Pb determinations date the magmatic rocks and pervasive high-temperature metamorphism as of Palaeozoic age at all levels (Köppel 1974; J. E. Wright & J. W. Shervais, personal communication, 1980). Depth of erosion increases down-section to the northwest, and isograds are subparallel to the northeast-striking layering. The shallow part of the section consists of low-grade metasedimentary rocks, cross-cut and contact-metamorphosed by granitic plutons. Next northwest are migmatitic gneisses and mica schists, of sillimanite–muscovite–amphibolite subfacies in their shallower part and sillimanite–orthoclase–amphibolite in their deeper part, injected by voluminous concordant pegmatites and peraluminous granites (Pagliani & Boriani 1967). Next deeper are migmatites of lower granulite facies. Sillimanite, potassic feldspar and garnet increase downward, at the expense particularly of plagioclase and biotite, through the transition zone (Schmid & Wood 1976). As in the overlying amphibolite-facies migmatites, metasedimentary rocks dominate this terrain. Next deeper are interlensed rocks of mostly mafic igneous compositions; primary mineral assemblages were of middle granulite facies, consisting mostly of aluminous orthorhombic and monoclinic pyroxenes, antiperthitic plagioclase, and ilmenite. Layers of anorthositic, intermediate and silicic (charnockitic) rocks increase in abundance upward in this deep zone, and ultramafic rocks increase downward (Capedri 1971; Mehnert 1975; Schmid 1967; Shervais 1980). These rocks crystallized from magmas of varied compositions, and genetic relationships have been obscured by metamorphism, by transposition, and possibly by tectonic rise of mantle rocks into the lower crust. The ultramafic rocks crystallized primarily as spinel lherzolite, and hence at deeper than about 35 km, and phase petrology indicates that adjacent granulites and metagabbros were metamorphosed at a depth of about 40 km (Shervais 1979).

Grenville crustal sections

A terrain of middle- and lower-crust rocks, dominated by magmatic rocks 1100–1400 Ma old and pervasively sheared and metamorphosed about 1000 Ma ago (Gaudette *et al.* 1979), lies along the southeastern margin of the Canadian Shield, and is exposed as the Grenville Province of southeastern Canada and the Adirondack Mountains of New York State. The best-known crustal section is that of the Adirondacks, where successively deeper levels are exposed from northwest to southeast. Temperatures of postmagmatic metamorphism increased downward, from about 550 °C at a depth of perhaps 17 km in the northwest (upper amphibolite facies), through about 650 °C and 23 km at the broad transition to lower granulite facies, and on to 750–800 °C and about 30 km in the deepest tracts exposed (Bohlen *et al.* 1980; E. J. Essene, personal communication, 1980). This metamorphism was superimposed on the products of magmatic crystallization and equilibration displaying the same depth order. In the far northwest are migmatites of upper amphibolite facies, containing two-mica pegmatites in Ontario

(E. J. Essene, personal communication, 1980). Next come migmatites of lower granulite facies. Beneath these is the middle granulite terrain, consisting of charnockites and allied granitic, typically low-quartz, pyroxene–mesoperthite rocks (Brock 1980) intercalated with metamorphosed supracrustal rocks, and, at the bottom of the exposed section, large 'domes' of anorthosite (McLelland *et al.* 1978). The anorthosites crystallized at about 1100 °C, and the charnockites at about 1000 °C, from relatively dry magmas (Bohlen & Essene 1978). Similar complexes and superpositions characterize the Canadian Grenville.

In northern Labrador, the older part of the same magmatic province is present without the Grenville metamorphic overprint. Very large anorthosite masses and closely associated charnockites and other dry-magma granitic plutons produced contact-metamorphic aureoles: the pre-intrusive temperatures of the host rocks were far below magmatic temperatures (Berg 1977; Emslie 1980). Berg's (1977) published geobarometry suggests depths of crystallization of the contact-metamorphic aureoles of the anorthosites and charnockites of only about 18–22 km. As middle crust of Phanerozoic age is exposed widely about the world and lacks anorthosite massifs, at least some Proterozoic magmatism must have been fundamentally different from that of the Phanerozoic, as indeed commonly is assumed to be so, if Berg's pressure determinations are correct.

Anorthosites away from Proterozoic anorthosite 'belts'

Most deep-seated anorthosites are of Archaean and Proterozoic ages. Most investigators assume that Precambrian tectonic and magmatic processes were fundamentally different from those operating later, and that anorthosites are limited to more or less the terrains in which they are now exposed. My contrary assumptions are that magmatic processes of all ages have been fundamentally similar, that anorthosites are characteristic products of magmatic fractionation in the deep crust, and that their exposure depends primarily on depth of erosion. I view the scarcity of Phanerozoic anorthosite as correlated directly with the scarcity of exposures of deep Phanerozoic crust. Exposures of anorthosite–charnockite assemblages in the United States are almost coextensive with exposures of middle granulite assemblages, and this limits them primarily to the Grenville Province. The rest of the Proterozoic exposures of the United States are mostly of the upper and middle crust. The lower crust, including norite–anorthosite–charnockite complexes, is exposed at a Precambrian plate boundary in the Laramie Range of Wyoming, and in the San Gabriel and Orocopia uplifts along the San Andreas fault of southern California. That the lower crust in the broad region between Wyoming and California consists of rocks of middle granulite facies is shown by xenoliths in young basalts and kimberlites in many areas. Such xenoliths in central New Mexico include anorthosite, charnockite, garnet-sillimanite granulite and two-pyroxene granulite (Padovani & Carter 1977). Similar relationships hold in Proterozoic terrains elsewhere in the world.

The rationale that anorthosite is common in Phanerozoic lower crust is difficult to either support or refute by direct evidence, because exposures of middle granulite assemblages of Phanerozoic age are so uncommon. The Palaeozoic crustal section in the Alps, discussed previously, does contain abundant lower crustal magmatic differentiates, including much anorthosite, which, however, occurs as layers, not as huge masses. A norite massif, apparently of Cretaceous age, is exposed in the Karakorum, deep in a crustal section through an island arc (Coward *et al.* 1980; B. F. Windley, personal communication, 1980). The top of a gabbroic anorthosite–norite–hypersthene diorite–charnockite complex of early Palaeozoic age is exposed in a middle granulite terrain in the central Appalachian Piedmont (Foland & Muessig 1978). Presumably other deeply eroded tracts, including anorthosites, undated but now assumed to be of Precambrian age, within Phanerozoic orogenic belts will prove to be also of Phanerozoic age.

Origin of anorthosite and charnockite

Lower crustal exposures so frequently show layered complexes containing anorthosite beneath charnockite that the contrasted magmatic types must have related origins. At the pressures of the lower crust, plagioclase is in equilibrium with liquids of broad compositional and temperature ranges, and is much more sodic than it would be with lower-pressure liquids (Green 1969), and it floats, rather than sinks, in mafic liquids (Kushiro *et al.* 1979). Petrologic (Emslie 1980) and field and gravity (Kearey & Thomas 1979) data indicate that many lower crustal anorthosite masses are differentiates from gabbroic magmas. The general case is probably that the plagioclase accumulates by floating in magma chambers in which cotectically crystallizing mafic minerals sink. Many other anorthosites lack geophysical and field evidence for association with voluminous mafic differentiates and tend to have more sodic plagioclase; these probably are cumulates from granodioritic, tonalitic and leucogabbroic magmas (Green 1969; Philpotts 1968). A Norwegian layered complex has basal cumulate anorthosite, thin transitional hypersthene monozodiorite, and upper charnockite, that neatly fit differentiation patterns (Duchesne 1978). Other charnockites associated with anorthosites have chemical and isotopic features incompatible with simple fractionation complementary to the anorthosites, and presumably represent in part melts produced by partial fusion of lower crustal rocks by the heat of the mafic and calcic magmas (Ashwal 1978; Emslie 1980; but some anti-differentiation arguments are based on assumptions of initial rare-earth patterns and may be simplistic). Some anorthosites (Ashwal 1978; Simmons & Hanson 1978) may crystallize from magmas themselves near anorthosite in composition, presumably as a result of mantle removal of pyroxenes; but advocates of this origin have generally assumed that a magma is required in which plagioclase is the only major liquidus phase over a broad temperature range, and much of the basis for this assumption is obviated by the float–sink relationships of plagioclase and mafic minerals in lower-crustal gabbroic melts.

Relationship to shallow magmas

The arc magmas that reach the mature upper continental crust in magmatic-arc terrains are mostly tonalite, granodiorite and adamellite. These have incorporated variable proportions of the pre-existing rocks with which they partially equilibrated during ascent. Middle-crust magmatic rocks are typically adamellite. Whatever mafic magmas reach the continental crust from the mantle must leave a large proportion of their ferromagnesian and calcic components in the lower crust. Trace-element patterns in shallow continental arc magmas commonly require differentiation by removal of vast amounts of calcic plagioclase and pyroxene from initially gabbroic or quartz–dioritic magmas (Atherton *et al.* 1979; Thorpe *et al.* 1979). The mafic and calcic differentiates are not present in the associated volcanic rocks, shallow batholiths, or mid-crust granites. They presumably are in the anorthositic complexes of the lower crust, and in the largely ultramafic differentiates of the upper mantle.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Archaean crustal development

Archaean terrains are characterized at shallow crustal levels by endlessly repeatedly elliptical granites separated by greenstone belts, and these have no close modern structural analogue. The rock assemblages, however, are much more like those of younger magmatic arcs than is commonly recognized. The deeper crust is also much like that of younger ages; it was formed mostly in response to rising magmas, within a geologically short period in any one region, and the resulting depth-varying complexes resemble those of younger ages. The middle Archaean crust consists typically of migmatities of amphibolite facies; the lower crust consists of granulites, and contains much charnockite and anorthosite. Thermal gradients established after magmatism were little if any higher than those of younger lithosphere. (The common contrary assumption is based on the transient thermal gradients that accompanied magmatism, and these gradients cannot be distinguished from their younger analogues.) The differences that do exist between Archaean and younger terrains may reflect the more rapid motions of smaller lithosphere masses, rather than fundamentally different processes.

Island arcs

Analogues for the depth-varying features discussed here for compositionally mature crust exist also for island arcs. The volcanic rocks erupted in these arcs, which are built on oceanic lithosphere by arc magmatism and derivative sedimentation, typically evolve with time from tholeiitic-basaltic through high-alumina-basaltic to andesitic bulk compositions. Deep exposures in ancient island arcs, accreted tectonically to the continents, show that the characteristic middle-crust rocks, beneath the shallow complexes of volcanic rocks and consanguinous, discordant plutons, are migmatites of isotopically primitive trondhjemitic, tonalitic, granodioritic, amphibolitic and ultramafic compositions. As in the magmatic arcs of mature crust, these migmatites are of upper amphibolite facies above, and lower granulite facies beneath. Presumably the lower crust is dominated by great differentiated mafic igneous complexes in middle granulite facies, as Coward *et al.* (1980) report to be the case for a Karakorum example.

Arc magmatism and the mantle

Oceanic mantle, as observed in ophiolite exposures, consists primarily of olivine and subordinate magnesian orthopyroxene, in dunite and harzburghite, and is largely lacking in the components of basalt, which were removed as the melts that produced oceanic crust at spreading centres. Continental mantle, though also consisting mainly of magnesian olivine, contains the equivalent of 10 or 15% of basalt within its broad-composition clinopyroxene, orthopyroxene, garnet and spinel. The characteristic rock types of the mantle of continental lithosphere are shown by many xenolith studies to be spinel lherzolite (two-pyroxene peridotite) in the upper part and garnet lherzolite in the lower; eclogite, pyroxenite and various other rock types are widespread. Such continental mantle not only occurs beneath old cratons, but also has been formed from young oceanic lithosphere in arc-magmatic settings. The basalt component removed from the mantle at spreading centres is replaced in magmatic arcs. The primary arc magmas, generated at depths of 100 km or so, are much more mafic than basalt; most of their olivine component, and much of their other mafic material, is crystallized within the mantle through which the magmas rise. The seismic Mohorovicic discontinuity can be

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

no deeper than the shallow limit of crystallization of voluminous olivine from rising magmas, and probably is a zone of intercalated mafic and ultramafic rocks rather than sharp boundary.

The continental seismic discontinuity probably can also mark the downward transition, superimposed on increasingly mafic compositions, from rocks of middle granulite facies, bearing plagioclase, to plagioclase-free, garnet-pyroxene rocks (+potassic feldspar and quartz in silicic rocks) of upper granulite and eclogite facies. The top of this zone could not have been far beneath such middle-granulite terrains as that of the southeast Adirondacks when they were metamorphosed, and so the crust, defined seismically, could not then have extended greatly deeper than levels now exposed. Downward migration of the phase changes, compensating for erosion of the upper crust, may help to maintain thickness of the crust as defined seismically. Broad, intracratonic domes and basins, developing during periods of several hundred million years each, may be products of thermally perturbed phase changes by which the base of the crust migrates down or up, respectively.

Deformation and exposure

Depth of erosion tends to increase with geologic age of terrains of all types but is dependent upon uplift, some processes of which superimpose strong imprints on crustal rocks formed initially by other processes. As deeply eroded terrains require exceptional uplift, many of the deformational and metamorphic effects that we see in them probably are not characteristic of the non-uplifted crust that we do not see. Upramping at convergent plate boundaries, accompanied at deeper levels by pervasive deformation, provides many deep crustal exposures. Crustal extension also may be a major cause of deep erosion and exposure. Field relationships in the Basin Range region indicate to some of us working there that rotating normal-fault blocks are bounded by listric faults that become horizontal at depths of 8 or 10 km, beneath which crustal extension is accommodated by laminar flow around megaboudins. Extension steepens geothermal gradients, which results in regional uplift by phase changes, partial melting in the upper mantle, and thermal expansion. Rapid erosion through the fault blocks exposes underlying middle-crust rocks, even including those as young as Tertiary. The regional metamorphism of the Grenville Province was unrelated to the preceding magmatism, and formed a belt whose southeastern half became the rifted-margin continental shelf of late Precambrian and early Palaeozoic time; a Grenville basin-range province may have formed as rifting began, and the anorthosite 'domes' may be the tops of megaboudins. Regional exposures of the middle and lower crust commonly show pervasive subhorizontal shearing and megaboudins and perhaps similarly often reflect crustal extension.

This essay ranges far beyond the topical and geographical limits of my own direct research. Space limitations have prevented citation of more than a few of the investigators whose work is incorporated here. Discussions with scores of other investigators have shaped my opinions beyond those derived from the voluminous literature. I owe particularly large debts to Clifford Hopson, for discussions regarding the significance of the contrasts between oceanic and continental mantle, to V. J. Dietrich, Ennis Geraghty, Yngvar Isachsen and James McLelland, for introducing me to the lower crust in the field, to James Whitney and Peter Wyllie, for discussions of equilibria in the middle crust, and to W. Bradley Myers, for our early collaboration on related synthesis.

MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES
THE ROYAL SOCIETY A
PHILOSOPHICAL TRANSACTIONS OF

References (Hamilton)

Armstrong, R. L. 1975 *Am. J. Sci.* A **275**, 437–467.
Ashwal, L. D. 1978 Ph.D. thesis, Princeton University.
Atherton, M. P. *et al.* 1979 In *Origin of granite batholiths* (ed. M. P. Atherton & J. Tarney), pp. 45–64. Orpington U.K.: Shiva Publishing.
Berckhemer, H. 1969 *Tectonophysics* **8**, 97–105.
Berg, J. H. 1977 *J. Petr.* **18**, 399–430.
Bohlen, S. R. & Essene, E. J. 1978 *Contr. Miner. Petr.* **65**, 433–442.
Bohlen, S. R., Essene, E. J. & Hoffman, K. S. 1980 *Bull. geol. Soc. Am.* **91**, 110–113.
Brock, B. S. 1980 *Bull. geol. Soc. Am.* **91**, 93–97.
Capedri, S. 1971 *Memorie Soc. geol. ital.* **10**, 277–312.
Carmichael, D. M. 1978 *Am. J. Sci.* **278**, 769–797.
Cater, F. W. *et al.* 1973 *Bull. U.S. geol. Surv.* **1304**, 431.
Chase, R. B. & Johnson, B. R. 1977 *NW. Geol.* **6**, 38–50.
Compton, R. R. 1960 *Am. J. Sci.* **258**, 609–636.
Coward, M., King, G. & Windley, B. F. 1980 *Nature, Lond.* **284**, 218.
Duchesne, J.-C. 1978 *Contr. miner. Petr.* **66**, 175–184.
Emslie, R. F. 1980 *Bull. geol. Surv. Can.* **293**, 136.
Foland, K. A. & Muessig, K. W. 1978 *Geology* **6**, 143–146.
Gaudette, H. E., Michard-Vitrac, A. & Allegre, C. J. 1979 *Abstr. Progr. geol. Soc. Am.* **11**, 431.
Ghent, E. D., Nicholls, J., Stout, M. Z. & Rottenfusser, B. 1977 *Can. Miner.* **15**, 269–282.
Gibb, R. A. & Walcott, R. I. 1971 *Earth planet. Sci. Lett.* **10**, 417–422.
Grant, J. A. 1973 *Am. J. Sci.* **273**, 289–317.
Green, T. H. 1969 *Can. J. Earth Sci.* **6**, 427–440.
Green, T. H. 1976 *Geology*, **4**, 85–88.
Hamilton, W. 1978 *Pacific Coast Paleogeography Symp.*, vol. 2, pp. 33–70.
Hamilton, W. & Myers, W. B. 1974 *Bull. geol. Soc. Am.* **85**, 365–378.
Hyndman, D. W. & Williams, L. D. 1977 *NW. Geol.* **6**, 1–16.
Kane, M. F. *et al.* 1972 *U.S. geol. Surv. Map* GP-839.
Kearey, P. & Thomas, M. D. 1979 *J. geol. Soc. Lond.* **136**, 725–736.
Köppel, V. 1974 *Contr. Miner. Petr.* **43**, 55–70.
Kushiro, I., Fujii, T. & Sakuyama, M. 1979 In *IAVCEI Abstr.*
Loiselle, M. C. & Ayuso, R. A. 1980 *Virginia Polytech. Inst. geol. Sci. Mem.* **2**, 117–121.
Maaloe, S. & Wyllie, P. J. 1975 *Contr. Miner. Petr.* **52**, 175–191.
McLelland, J., Geraghty, E. & Boone, G. 1978 *N.Y. Geol. Ass. Guidebk* **50**, 58–103.
Mehnert, K. R. 1975 *Neues Jb. Miner. Geol. Paläont.* **125**, 156–199.
Miller, C. F. & Bradfish, L. J. 1980 *Geology* **8**, 412–416.
Morgan, B. A. 1972 *U.S. geol. Surv. Map* I-724.
Nielson, D. L. *et al.* 1976 *Mem. geol. Soc. Am.* **146**, 301–318.
Padovani, E. R. & Carter, J. L. 1977 *Am. geophys. Un. Monogr.* **20**, 19–55.
Pagliani, G. P. & Boriani, A. 1967 *Rc. Soc. miner. ital.* **23**, 351–397.
Philpotts, A. R. 1968 *Mem. N.Y. St. Mus.* **18**, 207–212.
Schmid, R. 1967 *Schweiz. miner. petrog. Mitt.* **47**, 935–1117.
Schmid, R. & Wood, B. J. 1976 *Contr. Miner. Petr.* **54**, 255–279.
Shervais, J. W. 1979 *J. Petr.* **20**, 795–820.
Simmons, E. C. & Hanson, G. N. 1980 *Contr. Miner. Petr.* **66**, 119–135.
Sissons, B. 1980 Ph.D. thesis, Victoria University, Wellington, New Zealand.
Sweeney, J. F. 1976 *Bull. geol. Soc. Am. Bull.* **87**, 241–249.
Thomas, M. D. & Kearey, P. 1980 *Nature, Lond.* **283**, 61–63.
Thorpe, R. S., Francis, P. W. & Moorbath, S. 1979 *Earth planet. Sci. Lett.* **42**, 359–367.
Tracy, R. J. 1978 *Am. J. Sci.* **278**, 150–178.
Tracy, R. J., Robinson, P. & Thompson, A. B. 1976 *Am. Miner.* **61**, 762–775.
Wall, V. J. & Clemens, J. D. 1979 *Abstr. Progr. geol. Soc. Am.* **11**, 534.
Wiswall, G. 1979 *NW. Geol.* **8**, 18–28.
Williams, L. D. 1977 Ph.D. thesis, University of Montana.
Wones, D. R. 1980 *Virginia Polytech. Inst. geol. Sci. Mem.* **2**, pp. 123–130.

Discussion

A. Kröner (*Department of Geosciences, University of Mainz*, 6500 *Mainz, F.R.G.*). The speaker cited the Labrador Trough as a prime example of Wilson cycle development in the middle Proterozoic and inferred from this that modern plate interaction dates back to at least this time.

Dimroth (1972, 1978, 1980) has shown from very detailed fieldwork that the basalts in the Labrador belt are *not* ophiolites. They constitute a horizontally stratified sequence conformably overlying horizontally stratified sediments and are therefore undoubtedly autochthonous, at least at some places in the belt. There is also convincing evidence that the Trough formed on older Archaean crust and was underlain by a sialic floor during its entire history.

How is it possible that these well documented field relationships can be interpreted as evidence for ocean opening and closing?

References

Dimroth, E. 1972 *Am. J. Sci.* **272**, 487–506.
Dimroth, E. 1978 *Quebec nat. Resour., G.R.* **193.**
Dimroth, E. 1980 Labrador geosyncline: type example of early Proterozoic cratonic reactivation. In *Precambrian plate tectonics* (ed. A. Kröner). Amsterdam: Elsevier.

W. Hamilton. Although Dimroth categorically rejects plate tectonic explanations for the Labrador Trough, the Proterozoic geology there is so similar to that which in late Phanerozoic terrains obviously indicates continental rifting followed by convergence that I am confident that he is wrong. The structural trends of the Superior subcontinent of late Archaean crust to the west were truncated at right angles by a rifting event, following which a lower Proterozoic continental-shelf stratal wedge was deposited on the trailing edge. In middle Proterozoic time, a quite different Labrador continental mass collided with the Superior continent after intervening oceanic crust was subducted beneath Labrador. The Superior miogeoclinal wedge was imbricated westward onto its own craton; suture geology was produced between the subcontinents; magmatic arc rocks formed on the Labrador side. Gibb & Walcott (1971) and Thomas & Kearey (1980) are among those who have described some of the evidence for this history. Most other investigators now working in Proterozoic upper-crustal terrains in the Canadian shield also are using plate tectonic models. Dimroth's repeated assertion that there is unbroken Archaean continental crust beneath the Labrador suture merely displays his faith that plate tectonics has nothing to do with the terrain.