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Introduction

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Science advances by taking new and unexpected turnings, pioneers opening up pathways which later workers follow and explore. This book takes the reader along several such geological paths that have followed from observations and theories first printed in *The Quarterly Journal of the Geological Society of London* (since 1971, the *Journal of the Geological Society*). Following the paths, one sees the history of geological thought during the nineteenth and twentieth centuries.

To achieve this desired structure for the book, leading geologists were invited to present their personal views on significant topics that had been brought to the fore in earlier contributions to the *Journal*, to evaluate the evidence presented and to give their view of how these seminal papers affected our present understanding of geological processes, and further to hazard where future paths of investigation may lie.

Bringing these together under one cover serves two purposes: first to celebrate 150 years of continuous publication of papers by the Geological Society of London; second, it makes a British review of the current 'battle lines' across many fields of geological research. Not only will the serious research investigator discover the several turning points which have governed the paths of his study, but the general reader also will discover the delights, the fortunes and machinations taken by many leading British geologists. Others will use the chapters to answer the question: 'Does historical contingency govern the paths of geological exploration, as it has been said to govern the evolution of living creatures?'

Most of the papers have already been published as Celebration Papers during 1993 in Volume 150 of the *Journal of the Geological Society*, hence the size and format of this book. To emphasize the historical context, all the chapters are preceded by the abstracts or prefaces of the seminal papers reproduced from the *Journal*. The exception is **Rudwick's**, which sets the scene on why the Geological Society of London rated so highly the publication of geological observation. He recounts the creation of the *Journal*, and how it survived growing pains to become a leading international journal.

One of the several maxims followed by geologists is that of uniformitarianism. It was defined by Hutton over 200 years ago and popularized by Charles Lyell in his *Principles of Geology* and in his many papers read before and published by the Geological Society. Earlier this century, it was considered applicable only to the Phanerozoic. Nowadays with the great advances made in dating techniques, **Windley** is able to argue cogently that the plate tectonic paradigm can be successfully applied not only to the Proterozoic but even to the Archaean. He shows how the growth of the North American plate and the Kapvaal craton can be explained by the plate tectonic model, and how secular changes in heat production changed the course of development of igneous and metamorphic processes at subducting plate boundaries. The application to the Archaean is still not universally accepted, but that working model helps interpret the rocks formed during the first half of the Earth's existence. The magmatism during those early times used to be thought to be no different from present-day ones, on the principle of uniformitarianism. In 1951 came the seminal work of Sutton and Watson on the Lewisian gneiss complexes and the mafic dyke swarms cutting them. This became the cornerstone on which gneiss and greenstone dyke complexes were interpreted, and later contributed to the concept of terranes. Pursuing this, **Hall & Hughes** narrate the magmatic differences that emerged, mainly as the result of the early high heat flow: the unstable komatiitic volcanic-dominated crust mainly in the Archaean; and then the onset of noritic magmatism and the concomitant crustal accretion super-event, as markers of the transition from the Archaean to the Proterozoic. Their contribution provides greater understanding of the evolution of Precambrian mafic magmatism and the formation of the Earth's early crust.

The single great technique that enabled the mysteries of Precambrian metamorphic complexes to be unravelled, was the application in 1961 of Rb–Sr isotope systematics to age determination, by the Oxford school led by Moorbath. K–Ar isotope studies had not been enough; too often they produced only thermally reset ages. Nowadays, any study of high-grade metamorphic rocks automatically includes isotope determinations, and the same now applies to igneous rocks. But the whole process has become very sophisticated, and **Rogers & Pankhurst** present a thorough analysis of the process as applied to Scotland. They show how the techniques were expanded to include the use of the isotopes of lead, uranium, samarium and neodymium, with great success but not without considerable controversy, much of it still running (e.g. Ben Vuirich).

Another break-through in studies of the Earth's crust via the rocks of Scotland was the identification by W.Q. Kennedy in the 1940s of the extent of the Great Glen Fault. Here was a fault of apparent massive strike-slip displacement; hitherto faults had been mainly normal, reversed or thrust phenomena. **Bluck** analyses the extent of this and other major Scottish faults, and the implication is made that massive displacement along lines of fracture are possible through the Earth's crust. That such displacements could occur was an essential ingredient to the theory of sea-floor spreading and to the analysis of many tectonic basins and oil-bearing structures, even to creating space as sphenochasms for the permissive emplacement of granites.

Another process which came to be understood through careful field work in Scotland was the identification by George Barrow 100 years ago of metamorphic zones in the

Dalradian schists. It marked the birth of meaningful metamorphic petrology. Barrow's 1893 paper quickly became a classic and was much quoted, even though he mis-identified the heat source for the metamorphism; demonstrating that observation is more important than interpretation. **Brown** shows how a knowledge of mineral chemistry, textural and field relations which identify stability relations, together with a knowledge of the time relations deduced from age determinations, can produce paths across petrogenetic grids which give information on how pressure and temperature varied with time in different tectonic environments. Even within a single tectonic environment, more than one P–T–t path can be recognized.

The next four papers are on stratigraphical classification and correlation, particularly using fossils, one of the main bases of our science and one whose terminology eventually becomes part of everyday language. **McKerrow** discusses Palaeozoic stratigraphy in general, beginning with the works of Sedgwick and Murchison, and then sets out a logical sequence of steps that might, perhaps should, be followed in developing the stratigraphy of an area, once the structural relations of strata within an area are appreciated. **Fortey** focuses on the contribution of Lapworth's work on graptolites in the Southern Uplands of Scotland, **Riley** compares Vaughan's and later work on Early Carboniferous bio- and chronostratigraphy, and **Callomon**, in reviewing Buckman's pioneering work on the Jurassic of Dorset, goes on to discuss the current limits of resolution attainable in biochronology. It is interesting to reflect on how views on some of the problems addressed and concepts advanced by our predecessors have changed over the years. For instance, Fortey shows how durable Lapworth's biostratigraphy (as we should now call it) has been, while ideas on structure and palaeogeography that he derived concurrently with it have changed almost beyond recognition within the scientific lifetimes of many still active in the field. As Callomon describes, Buckman's practice in collecting and recording fossils in the field, and his ideas on the prevalence of gaps in the rock record, were far in advance of their time, entirely compelling, and relevant to many current concerns in sedimentology and sequence stratigraphy. Yet his contribution has been under-recognized for many years, partly because his views on evolutionary palaeontology were based on theories now superceded, and in his own later practice he departed from his earlier standards.

Savage relates the remarkable story of the discovery by Charles Moore of Mesozoic terrestrial vertebrate remains within fissured Carboniferous Limestone, and how the search widened as more species were discovered. This most fortunate means of preservation provided an abundance of material as well as species, and this occurrence and others subsequent have given vertebrate palaeontology a foundation upon which much of our present-day understanding of evolutionary history is based.

Even more remarkable is the story unfolded by **Cocks** of four different faunal assemblages within one set of strata. When fossiliferous quartzite pebbles were found in the Budleigh Salterton Pebble Bed of Triassic age along the Devonshire coast, Salter realized in 1864 that they were different from anything known in Britain but could correlate some of them with Lower Palaeozoic strata in Europe. Then Davidson in 1870 showed there were Devonian fossils as well, and modern work reveals there are four faunas, two Ordovician and two Devonian, with tectonic reconstruction now explaining all in terms of adjacent palaeocontinents.

Present-day geologists sometimes forget the importance of accurate description, going straight to interpretation often based on generalizations of assumed facts. Sorby was a 'quantifier' and had a particularly keen eye, creating meticulous drawings to accompany his precise writings. His President's Address on the study of sedimentary structures, published in 1908 after his death, is taken by **Allen** as the starting point for marrying description to interpretation. After detailed descriptions, he examines the current understanding of aeolian bedforms, sand-wave bedding, tidal bedding, marine storm bedding, hummocky and swaley cross-stratification, soft sediment deformation and dewatering structures, particularly reviewing the past ten years research into these.

Sorby appears again in the next contribution. His 1879 President's Address on the structure and origin of limestone can still be read with pleasure and profit by any modern student. He was far ahead of his time, and virtually invented geological microscopy. From that starting point, **Sellwood** develops current ideas on limestone classification, their environment of deposition and diagenesis, and their significance in sequence stratigraphy.

In the last quarter of the eighteenth century, controversy arose between Geikie and Judd on the interpretation of the Hebridean volcanic complexes of Scotland. Until then, most igneous rocks were regarded in isolation, but Geikie and Judd both realised that there was an association of rock types waiting to be interpreted. This opened the 'school of Hebridean petrology' which was so strongly developed by Harker, Bailey and others, and has flourished ever since. **Walker** investigates the association of flood basalts with volcanic centres and shows that the former have much more to tell us than most have hitherto supposed: evidence of whether the basalt lavas and dykes were fissure-fed or emanated from point-source vents, and the crustal tension implied; tilting of volcanic fields perhaps related to inflation or deflation of volcanic edifices; and direction of flow of magma. As volcanic hazards become a matter of daily concern, more needs to be learnt about the magmatic plumbing of volcanoes, and the magma flow direction of dykes and sills, now laid bare by erosion within old volcanic structures, could supply the vital data. The study of the anisotropy of magnetic susceptibility would seem to be potentially significant in this respect.

In contrast to the structural and mineralogical approach taken by Walker, **Wilson** takes the geochemical approach, which is equally applicable to volcanic and plutonic rocks. One hundred years ago, Harker began a school of thought on the controls of crystallization applied to the differentiation of basic magma as exemplified by variations seen within individual plutonic masses. Nowadays, fine-grained rocks are considered to be better representatives of variation in magma chemistry, and Wilson reviews the many possible processes from fractional crystallization, assimilation and magma mixing to thermogravitational diffusion and liquid immiscibility that can be responsible for magmatic differentiation. These processes concern mainly basaltic magmas which, by and large, are partial melt products of the upper mantle of the Earth.

By contrast, most granites have their origin in the partial melting of the continental crust of the Earth. They are the layman's best known coarsely crystalline rock. Most granites are superficially similar, but all are individually distinct when studied geochemically. Fifty years ago, the 'granite controversy' raged, with the Read school upholding the metamorphic and migmatitic association, and the Tilley–Bowen school maintaining that granites were the product of crystal fractionation from basic magmas. **Atherton** reviews the pros and cons of granitization, the 'room problem' for plutons, the evidence of melting experiments, the use of rock and mineral geochemical analytical data in determining the production of acid magma by partial melting or by fractional crystallization, and the manner in which isotopes may identify the source rock and the region. He takes the example of Garabal Hill in Scotland, which is one of the few Caledonian complexes including ultrabasic to acid igneous rocks, where crustal contamination might be argued. Also considered are thoughts on the association of basins, granites and thermal highs with high-T/low-P metamorphism.

In the penultimate chapter, Sorby's observations on fluid inclusions published almost 140 years ago are shown by **Rankin** to have led directly to the present state of knowledge about the pressures and temperatures of fluids in rocks, especially igneous-related ones. Fluid inclusions tell us much about mineralization processes, fluids being the carriers of the ore components. Rankin analyses the contribution of current fluid inclusion studies to understanding the many mineralization processes, taking several classical examples from the UK and abroad, some related to igneous bodies and others to tectonically driven crustal circulation of fluids. He also includes some original thermometric data on the main British ore fields.

Only recently has undoubted carbonatite been discovered in Britain (and published in the *Journal of the Geological Society*, 1994, **151**, 945). These exotic igneous rocks confounded geologists early this century, who could not believe in igneous 'limestones'—an apparent contradiction. The *Journal of the Geological Society* has a long history of publishing papers on African geology, a product of the past colonial era. In 1956 Campbell-Smith presented his review of African carbonatites, coinciding with a similar review by Pecora in the USA, and the two changed world opinion. Geologists flocked to the 1960 International Geological Congress in Norway and Sweden and saw the Fen and Alno carbonatite complexes. Calcite carbonatite became an acceptable igneous phenomenon. Campbell-Smith's review showed the igneous nature of carbonatites: their occurrence as cross-cutting dykes with fine-grained margins (i.e. chilled) and as small plugs with thermal contacts marked by alkali metasomatic reaction aureoles (fenitization). Their origin remains controversial with three main current theories: they were produced by fractional crystallization of nephelinitic magmas; they were separated by liquid immiscibility from a nephelinitic (or melilititic) magma; they were produced by direct partial melting of the upper mantle. **Bailey** examines the last of these, on the premise that many carbonatites are found without associated nephelinite/phonolite, and on the experimental evidence that dolomite carbonatite melts can be produced in the mantle under CO_2-saturated conditions. This view is contrary to the powerful consensus that now exists: that carbonatites are essentially infracrustal differentiates of alkali silicate melts, to the extent that most modern discussions of petrogenesis begin with this assumption. Bailey's chapter re-dresses this imbalance in the literature. The relation of dolomite carbonatites to calcite carbonatite remains uncertain; perhaps like 'granites and granites' there are 'carbonatites and carbonatites'. Their importance in understanding Earth history is undoubted because, having minimal partial melt compositions, they are potentially the best natural products to give clues to the chemical and thermal evolution of the Earth's mantle.

Many more seminal papers could have been selected from the pages of the *Journal of the Geological Society* for essaying in this book. One which changed the character of the British geologist, is that by Howell Williams on 'The geology of Snowdon (North Wales)' published in 1927 (**83**, 346). Beginning with clear field descriptions, he explicitly interprets glowing avalanches, mass-flow epiclastic deposits, and proximal and distal water-lain tuffs from rocks considered by many to be among the most difficult to interpret. Until this exposition, pyroclastic rocks had been by-passed by geologists in Britain, but this paper fired imaginations. The area described became a training ground, and has spawned several generations of geologists renowned for their pyroclastic expertise.

On more traditional grounds is the 1938 President's Address by O.T. Jones 'On the evolution of a geosyncline' (**94**, lx). For the next 30 years, students pondered on geosynclines which were understood to be crustal down-warped structures filled with sediment, and in so doing opened the subject of conditions of sedimentation and the sources of the sediments. Distinct sedimentary basins were recognized. When 'plate tectonics' burst on the scene, the data accumulated supplied the vital items allowing reinterpretation of geosynclines as oceanic trenches.

A paper which was to turn geological interpretation upside-down was Bob Shackleton's 1957 paper in the Journal (**113**, 361) on 'Downward-facing structures of the Highland Border'. These Scottish schistose rocks had been observed to be largely flat-lying but synformal near Aberfoyle. Shackleton's revelation that they were all upside-down led to the re-interpretation that the 'flat belt' of Loch Tay was the lower half of a nappe with the synform being the inverted anticlinal nose of the nappe, this structure extending across the whole of Scotland. Whereas many geological advances are made on a broad front of carefully documented data, here the break-through depended on a few astute observations of way-up criteria on a bleak mountain side.

Some regard geophysics as beyond the bounds of normal geology. It is not. In 1906, Oldham presented 'The constitution of the interior of the Earth, as revealed by earthquakes' (**62**, 456), which foretold how geophysics would contribute to the fundamentals of geology, i.e. the constitution of the Earth's core, mantle and crust. He pointed out that the seismograph 'enables us to see into the Earth' and that the three wave motions observed allowed interpretation of a shell-structure of the Earth. Having defined the depth to the core-mantle boundary and shown the seismic 'shadow zone', he goes on to discuss the possibility of other discontinuities (now mostly confirmed). This in turn has led on to an explanation of the Earth's geomagnetic field, and to the constitutions of the Moon and planets. This was a truly seminal paper.

In bringing all these topics together, it is hoped that readers will find that the separate topics are not so unrelated; some topics need the others to sustain them, some merge into new topics, but all combined are essential to advancing the frontiers of science. The chapters also give hints on how this frontier may be further advanced.

I thank most sincerely each of the authors of the chapters, for writing so assiduously to the briefs given them. I am grateful to the editors of the *Journal of the Geological Society* for guidance in the early stages of planning this volume and for editing the versions of the chapters published in volume **150** of the journal, and am particularly indebted to John Hudson who provided unstinting assistance at several critical stages.