by John Cobbing

Granites — an overview

Metamorphism or magmatism?

From the very beginning of geology in the modern sense, which can be arbitrarily judged to date from 1838 with the publication of Lyell's *Principles of Geology*, granites have provided a constant focus for controversy among geologists on account of their inherent diversity and their association with a very wide spectrum of geological phenomena. The current perspectives of granite geology have developed against the background of the great granite controversy of the early half of the present century. The controversy centred upon contrasting interpretations of the origin of granites. The magmatists held that granites crystallised directly from liquid magmas whereas the transformists believed that they formed by the transformation of pre-existing, generally metasedimentary rocks, into granite by processes of metasomatism in situ. The main protagonists in the debate were the Europeans on one side, whose opinions were mainly articulated by H H Read, then Professor at Imperial College, who believed that granites were generated by ultrametamorphism of metamorphic rocks, and the North American school represented chiefly by N L Bowen of the Geophysical Laboratory, Washington who, on the basis of his experimental work, considered granites to have developed from basalts by processes of fractional crystallisation.

The opinions of these two schools of thought were to some extent formed by the respective field experience of the proponents. For the North Americans the association of granitoids (*sensu lato*) with volcanic rocks was abundantly clear in the Cordilleras of the Pacific rim, whereas for the Europeans the association of true granite, generally with more than 68% SiO₂, with metamorphic rocks was equally plain. There were moreover, powerful dissenting voices on both sides of the debate.

A major topic in the debate was the room problem: how did huge bodies of granite come to occupy spaces which had formerly been occupied by older rocks? The magmatists believed that adequate explanations were to be found in structural mechanisms such as magmatic stoping, i.e. the foundering of the denser cover to be replaced by buoyant granite magma, and diapirism, deformation of the host rocks to provide space for the plutons. The transformists believed that the metamorphic source rocks were actually transformed into granite and consequently for them the problem was less severe. However, Read and others of the transformist school considered granites to form a series beginning with movement in a plutonic, metamorphic segment, in which granite parted company with the metamorphite in a state varying from nebulous migma to equally nebulous magma. Finally the migma-magma freed itself of its plutonic parents and formed diapiric plutons in extensional systems involving faulting and doming, as well as pushing and shoving along weak belts. He envisaged the series as being represented by the Hercynian Belt of Europe with the Massif Central of France with its migmatites and anatectites representing the active core and the Cornubian batholith of South-west England as being the high level 'dead' plutons. For both schools therefore the space problem was a major difficulty.

Eventually the experimental data of Bowen and Tuttle prevailed, but since their hypothesis envisaged the production of granite by fractional crystallisation from basalts, the actual local preponderance of granites and the common lack of associated basalts provided a fatal obstacle to the full acceptance of the model. The controversy fizzled out in the early nineteen fifties with the comment by Read (1949) that perhaps there were granites and granites. The general perception of the geological community was that perhaps the mag-

Figure 1 Read's Granite Series encapsulating his idea 'per migma ad magma'. (After Read, 1949).

matists had the better of the argument. This at any rate was the understanding of the next generation of geologists who, for the most part followed the magmatist model, though often with reservations, and granites slipped from the forefront of debate to be replaced by other questions which could be more usefully addressed.

There followed a period of consolidation during which geological mapping of granites continued in the Sierra Nevada by Paul Bateman and others; in Donegal and later in Peru by Wallace Pitcher and his colleagues; and in the Lachlan Fold belt of Australia by the school of Chappell and White. It was also during this period that significant progress was being made in the quantitative application of analytical geochemistry and isotopic dating to crystalline rocks which ensured that a wealth of geochemical and isotopic data was progressively accumulated which was to provide a new dimension to future studies. The development of isotopic geology has been particularly important. Although this aspect of geoscience has many ramifications, it is probably true to say that its development has to some extent been driven by the need to establish reliable ages for granites. The reason for this is that it is often difficult or impossible to establish the age of many granites with any degree of certainty by purely geological means, i.e. by reference to the age of formations which they cut or by which they are overlain. This is especially true for granites from terrains of Precambrian age.

Granites and plate tectonics

A full quarter of a century was to elapse towards the end of which plate tectonics was recognised as a unifying global model before granites came once more to the forefront of the field. This was the result of a decade of research in the Lachlan Fold Belt of Australia where Chappell and White (1974) had recognised two contrasted granite types. On the basis of geological, geochemical and

Figure 2 The granitic rocks in their tectonic settings (Reproduced with permission from The nature and origin of granite by W S Pitcher, Chapman and Hall, 1993, p.294).

isotopic studies they were able to distinguish criteria for the recognition of these types, which they designated as S-types for those resulting from the anatexis of sedimentary rocks, and I-types for those having an igneous source. Although this concept both resolved the earlier controversy, since it was apparent that the S-types conformed to the Readian model and the I-types to that of Bowen, the debate was also enlarged because it was obvious that some I-types, as represented by the great batholiths of the western Americas, were directly related to processes of subduction of oceanic crust beneath the continents, initiating, in turn, a new controversy among geologists. This was chiefly because of the rapidly perceived connection between granite-type, source-region and tectonic-setting. Virtually all kinds of granite rapidly came to be included within a plate tectonic framework. Pitcher (1979) recognised Alpinotype, Andinotype and Hercynotype orogens and later he elaborated the concept to include M-type (oceanic island arcs), I-type (Cordilleran), I-type (Caledonian), S-types and A-types (Pitcher, 1983). This and related concepts have placed granite geology firmly within the context of plate tectonics and the alphabet system, as it is called, has been both slavishly followed and fulsomely derided.

In spite of adverse criticism, the model has been expanded in a number of interesting ways which command attention, if not assent. The division by Pitcher of the I-type category into two different groups was widely perceived to reflect a geological reality. His Caledonian I-type group was redesignated as high K calc-alkaline I-type by Roberts and Clemens (1993), who considered them to form 35–40% of all post-Archaeon metaluminous granites. Many of the I-type granites of south-east Australia are of this type (Roberts and Clemens, 1993) as are those from many other regions. In this context, it is useful to consider the model of Collins and Vernon (1994) who suggested that the granite plutonism in that belt was a consequence of crustal delamination. It was envisaged that in certain tectonic settings slabs of the continental lithospheric mantle break away

from the crust and descend into the mantle. This results in the generation of crustal melts in the newly buoyant continental crust. A similar model has also recently been advocated by Rongfu Pei and Dawei Hong (1996) for the granites of south China which, like those of south-east Australia occupy a belt of several hundred kilometres in width. At present this concept remains in the category of an interesting hypothesis which seems to provide an explanation for the development of a very wide category of granites.

Similarly the alkali or A-type granites had always given rise to problems of classification since they were known to occur both in orogenic and anorogenic settings. Their most typical mode of occurrence is in intracratonic settings in association with lithospheric rifting and major faults. They often have an extended period of activity of as much as 100Ma. However, they also occur as late orogenic granites towards the end of a magmatic cycle in the back arc region of an orogen dominated by calc-alkaline plutonism. These two kinds of A-type granite are very difficult to distinguish from one another, though several attempts have been made (Eby, 1992; Bonin, 1988). The most recent paper to deal with this question is by Hong Dawei et al. (1996) who have used a variety of geological and geochemical criteria to effect a distinction between the two categories.

Critics of the MISA notation believed that modal and chemical classifications, which had always been the mainstay of granite classification, should continue to be used in that way without any genetic implications. These classical methods have in fact continued to be used and have actually been considerably expanded. Some classical indices however, have come to be considered as having a genetic implication and it is now becoming practically impossible to avoid some kind of genetic connotation, as increasingly more sophisticated geochemical and isotopic methods provide information relating directly to the nature of the source region.

Criticism of the tectonic classification arose because of two factors. The first was that Chappell and White had distinguished their

two types on the basis of their source regions and not of the tectonic setting. The second was that in many cases the source region, which it was now possible to identify in general terms on the basis of geochemical and isotopic studies, did not always seem to bear any necessary relationship to the prevailing tectonic setting. This was particularly the case for granites with a crustal signature. Cases were documented of both I- and S-types occurring together in Cordilleran and other settings and the concept of using granite geochemistry as a key for understanding the tectonic setting of older orogenic belts began to look increasingly more untrustworthy. At least part of this unsatisfactory state of affairs results from the complexities of the tectonic processes themselves. In some recent configurations such as those of the American Cordilleras and the Pacific islands the composition of the source region is directly related to the predominant plate tectonic configuration. However, the lengthy duration of plate tectonics has ensured that many continents are actually made of a collage of unrelated terrains which have undergone different histories. If such terrains are individually or collectively mobilised the resulting granite will carry a geochemical and isotopic signature reflecting that of the terrain. Even in such modern island arc systems as the Indonesian Archipelago there are disconnected slices of continental fragments derived from Australia which can give rise to S-type granites within a predominantly I-type domain.

A third complicating factor is the question of the immediate structural setting relating to the generation ascent and emplacement of granitic magmas. The concept of the role of deep faulting has been developed in recent years (Pitcher and Bussell, 1977; Leake, 1990) who have suggested that many large faults cut through the entire crust to source regions, where, by adiabatic decompression they initiate partial melting of granitic magmas in the source region and subsequently play a decisive role in controlling the ascent and emplacement of the magmas. Although most orogenic belts are of a predominantly convergent character a variety of structural situations can develop in any belt, all of which can give rise to the generation and ascent of granitic magmas. Atherton (1990) has proposed that the Peruvian Coastal Batholith was generated by the partial melting of a basaltic protolith in a rifting environment. Although this seems a strange notion for a convergent plate margin, it is supported by the former concept of an aborted rift, developed by Aguirre and Offler (1985) and the geophysical identification of a 'basic arch' beneath the batholith (Couch et al., 1981). However, Atherton (1993) pointed out that rifting was also instrumental in generating the S-type granites of the Trois Seigneurs Massif in the Pyrenees (Wickham and Oxburgh, 1985). It is thus apparent that structural mechanisms such as rifting, normal faulting, strike-slip faulting, transpression etc., although the proximal triggers of magma generation and ascent, are actually neutral since they will generate magmas from whatever material is available. This is particularly well illustrated from the Northern Andes of Ecuador where, in a transpressional environment, plutons of the S-type Tres Lagunas Granite and the I-type Zamora Granite are juxtaposed in parallel belts (Litherland et al., 1994). The association of a particular structural style with a tectonic setting, such as rifting and normal faulting with anorogenic and A-type granites, is another matter which brings in train its own problems of definition and necessary association.

Although these structural controls do not bear directly upon the question of granitic typology, except perhaps in the matter of some of the A-types, they do have direct relevance to studies on the ascent and emplacement of granite plutons in the middle and upper crust—the space problem in fact of the older generation of geologists. For them the problem existed because their Earth model was of a solid continental crust with permanent ocean basins. Favourable structures for emplacement were of course known, but they only provided a fraction of the space apparently needed for granite emplacement, and within that framework only stoping, diapirism and metasomatism seemed to be possible. The dynamic Earth model resulting from the recognition of sea floor spreading, and the separation and convergence of continents, provided a completely new framework for addressing the problem.

Numerous structural studies relating to granite emplacement were undertaken during the seventies and eighties and, as a result of these, considerable light has been shed on the manner in which granite plutons were emplaced. Current models for granite emplacement chiefly envisage the rise of granite magma to the site of emplacement in the middle or upper crust along a fairly narrow conduit, which feeds magma into a favourable structural location where it expands into a pluton, either by stoping, diapirism or ballooning, by filling spaces in the envelope generated by structural processes or by deformation of the envelope, perhaps in combination with any of the other processes.

A generalised model for granite emplacement now appeals to the association of granites with major faults, generally rifts or strike-slip faults, which extend through the entire crust and, in the case of strike-slip faults, may be responsible for the lateral translation of crustal segments. Faults of these dimensions are envisaged as reaching such depths that the melting of crustal rocks begins, triggered by adiabatic decompression. The magmas generated rise to the site of emplacement up narrow feeder zones and fill the space eventually occupied by the pluton either by taking advantage of a potential cavity generated by the structural situation, or by the deformation of the envelope accompanied by expansion of the pluton. In many cases the pluton continues to be deformed as it cools, resulting in the development of a gneissic fabric.

In summary the tectonic and structural information which we now have access to has enabled us to see some of the problems which have puzzled geologists of former generations in a completely new light so that problems which seemed to them to be insurmountable are not problems to us at all. At least in principle. On the ground it is usually a different matter.

The separate aspects of tectonic setting versus source region have also been developed in the field of mineralisation and here the role of tectonic setting does seem to be more significant. A great many occurrences of base metals, copper and gold seem to be closely associated with currently active plate margins of continent ocean convergence. In particular kuroko massive sulphide deposits and porphyry coppers form a strikingly restricted geographic assemblage around the Pacific margin. A contrasting association of tin and rare earths is distinctly related to leucogranites in other parts of the world, e.g. the Hercynian granites of Europe and the tin belt of South-east Asia, which are generally of crustal origin, though they are not necessarily of true S-type as defined by Chappell and White (1974). This association is also developed in some anorogenic A-type granites within continental interiors. The concept of different types of mineralisation being related to different terrains within tectonic settings has been applied to South-east Asia (Hutchison and Taylor, 1978) and to south-east China (Rongfu Pei and Dawei Hong, 1996).

Summary

Where does all this leave us? Is the MISA concept valid? Is it useful or is it best avoided? There are probably geologists who would agree with each of these possibilities.

First of all, it has to be said that we are equipped, as no former generation of geologists has ever been, to tackle these problems. The analytical systems which are currently deployed in granite studies are extremely powerful and routinely provide us with information and insights which, until quite recently, required months, and sometimes years, of dedicated work. The use of these systems provides us with data which relates directly or indirectly to the nature of the source region. It does not necessarily tell us much about the tectonic setting, though it may do.

Secondly, as a result of the progressive evolution of granite studies over the last century a whole armoury of criteria has been developed, which enables us to assess the history of the origin and emplacement of most granites, and often enables us to place the granites within a framework of plate tectonics, even though it may still be inappropriate to attach a MISA tag.

Thirdly, it is an entirely laudable aspiration for geologists to seek a process-related classification which reflects the proximal cause of generation of granite magmas. However, as we have seen in the case of crustal granites, this is not so easy because the history of development of the source regions is both unknown and complex.

The whole history of geology has been one of trial and error. Some concepts which I was taught as a student have not stood the test of time, others have endured. So it will be with MISA, or with its derivatives. As an indicator of source regions it is useful, if perhaps oversimplified. With respect to the identification of tectonic setting the jury is still out and probably will be for some time, but I believe it is useful because it identifies problems which can then be addressed. Some would certainly say it is best avoided but I think it does at least provide a framework which enables the degree and significance of incompatibility to be assessed. There is no easy answer and no substitute for careful field work supported by petrological, geochemical and isotopic work. At least in these fields we now have tools for investigation which neither Read nor Bowen could have dreamt of.

References

- Aguirre, L. and Offler, R. 1985, Burial metamorphism in the western Peruvian trough: its relation to Andean magmatism and tectonics, in Pitcher, W S, Atherton, M P, Cobbing, E J, and Beckinsale, R D, eds., *Magmatism at a plate edge*: Blackie Halsted Press, 327pp.
- Atherton, M P, 1990, The Coastal Batholith of Peru: the product of rapid recycling of new crust formed within a rifted continental margin: *Geological Journal*, v. 25, pp.337–349.
- Atherton, M P, 1993, Granite magmatism: *Journal of the Geological Society*, v. 50, pp.1009–1023.
- Bonin, B, 1988, From orogenic to anorogenic environments: evidence from associated magmatic episodes: *Schweiz. Mineral. Petrog. Mitt* 68, pp.301–311.
- Bowen N L, 1928, *The evolution of the igneous rocks*: Dover, New York.
- Bowen, N L, 1948, The granite problem and the method of multiple prejudices: *Geological Society of America Memoir* 28, pp.79–90.
- Chappell, B W, and White, A J R, 1974, Two contrasting granite types: *Pacific Geology*, v. 8, pp.173–174.
- Collins, W J, and Vernon, R H, 1994, A rift-drift-delamination model of continental evolution: Palaeozoic tectonic development of eastern Australia: *Tectonophysics*, v. 235, pp.249–275.
- Couch, R, Whitsett, R, Huehn, B, and Briceno-Guarupe, L, 1981, Structures of the continental margin in Peru and Chile, in Kulm, L D, Dymond, D, Dasch, E, and Hussong, D M, eds., *Nazca Plate: Crustal formation and Andean convergence*: Geological Society of America Memoir 154, pp.703–726.
- Eby, G N, 1992, Chemical subdivision of the A-type granitoids: petrogenetic and tectonic implications: *Geology*, v. 20, pp.641–644.
- Hong Dawei, Wang Shiguang, Han Bofu, and Jin Manyuan, 1996, Post-orogenic alkaline granites from China and comparisons with anorogenic alkaline granites elsewhere: *Journal of Southeast Asian Earth Sciences*, v. 13, pp.13–27.
- Leake, B E, 1990, Granite magmas, their sources, initiation and consequences of emplacement: *Journal of the Geological Society*, 147, pp.579–589.
- Litherland, M, Aspden, J A and Jemielita, R A, 1994, The metamorphic belts of Ecuador: British Geological Survey, Overseas Memoir 11, 147pp.
- Pitcher, W S, 1979, Comments on the geological environment of granites, in Atherton, M P, and Tarney, J, eds., *Origin of granite batholiths: geochemical evidence*: Shiva Publishing Ltd, Orpington, pp.1–8.
- Pitcher, W S, 1982, Granite type and tectonic environment, in K, Hsu, ed., *Mountain building processes*: Academic Press, pp.19–40.
- Pitcher, W S, 1987, Granites and yet more granites forty years on: *Geologische Rundschau* v. 76, pp.51–79.
- Pitcher, W S, 1993, *The nature and origin of granite*: Chapman and Hall, London, 321pp.
- Pitcher, W S, and Bussell, M A, 1977, Structural control of batholith emplacement: *Journal of the Geological Society*, v. 133, pp.249–246.
- Read, H H, 1948, A commentary on place in plutonism: *Quarterly Journal of the Geological Society of London* v. 104, pp.155–206.
- Read, H H, 1949, A commentary on time in plutonism: *Quarterly Journal of the Geological Society of London*: v. 105, pp.101–156.
- Roberts, M P, and Clemens, J D, 1993, Origin of high-potassium, calc-alkaline, I-type granitoids: *Geology* v. 21, pp.825–828.
- Rongfu Pei, and Dawei Hong, 1996, The granites of south China and their metallogeny: *Episodes*, v. 18, pp.77–82.
- Wickham, S M, and Oxburgh, E R, 1987, Continental rifts as settings for metamorphism: *Nature* v. 318, pp.330–333.

John Cobbing a graduate and post-graduate of Durham University, UK, has worked in the Geological Survey of Northern Ireland and the British Geological Survey, Overseas Division. Mapping of the Coastal Batholith of Peru led to a 15-year period of granite research in collaboration with W S Pitcher. Subsequently, he participated in a BGS regional study of the tin-belt granites of SE Asia. Since retirement from BGS in 1988, he has pursued recreational granite geology in Europe with occasional more serious forays to Norway, Russia and Sumatra.