Granite Genesis: In Situ Melting and Crustal Evolution
Granite Genesis: In Situ Melting and Crustal Evolution

by

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Springer
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PREFACE

“We are never devoid of some hope that we shall eventually know everything. It may often be salutary, nevertheless, to recognize the remoteness of that time and to take stock of our ignorance”.

N.L. Bowen—1947 Presidential address to the Geological Society of America

There is a vast amount of published research on granite and we cannot claim to be familiar with it all. However, we are aware of the recent developments with respect to attempts at reaching a consensus on the problem of granite origin. With the concept of granitisation apparently dormant, if not dead, a paradigm of granite magmatism, i.e. melting, segregation, ascent and emplacement, has strengthened over the last 15 years. The combined research presented in this book describes a viable alternative mechanism of granite formation to this widely accepted intrusion model, namely, in-situ melting–intracrustal convection.

The core idea of the in situ melting origin of granite was formulated by GC, who worked as a member of one of the geological teams engaged in mineral prospecting and regional mapping in SE China between 1971 and 1977. It started from being unable to obtain satisfactory answers to the questions; if ore-minerals of hydrothermal deposits are not derived from granite magma, why are they found in their host rocks? If the ore-minerals are from granite magma, why are large granite masses barren of ore deposits? During seven year’s of study at Sun Yat-sen University since 1977, GC spent most of his spare time in the university library trying to find an acceptable solution, but failed. GC gradually realised that perhaps what was generally believed about the origin of granite needed revision. So began an intensive 20-year study from which GC came to the conclusion that granite is produced and remains within the region of crustal melting. Collaboration on this idea began with RG in 2002 who was then at Freiburg University, Germany, and has been at Sun Yat-sen University since October 2005.

In the following pages, we demonstrate that thermal convection within a mid-upper crustal partial melting zone is essential for the formation of granite magma and that without convection partial melting of crustal rocks generates migmatites, not granite batholiths. Granite is layer-like on a crustal scale and the
shape and size of individual granite bodies merely reflects the geometric relationship between the irregular upper part of a granite layer and the erosion surface, rather than the volume of intruded magma. Chemical and isotopic compositions of granites are considered to reflect processes operating within the magma system rather than unknown deep sources. Formation and crystallisation of a crustal magma layer results in reorganization and redistribution of elements within the crust, to form both granite and their related hydrothermal mineral deposits. The in situ melting–intracrustal convection model of granite origin integrates the two-knowledge systems related to continental geology and plate tectonics and explains related geological, geochemical and geophysical observations. The geochemical fields of elements established on the basis of both the in situ melting–intracrustal convection model and periodic table illustrates the harmony and unity between the microcosm and macrocosm of the natural world.

While the views advanced in this book differ from a number of traditional ideas in geology, the same evidence used to support these ideas is also adopted to strengthen our hypothesis. Our main aim is to offer another way of not only looking at granite but the Earth in the hope that this will stimulate further thought and study. As such, we hope that the book will be of interest to both professional and student Earth scientists.

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December 2006
ACKNOWLEDGEMENTS

GC is greatly appreciative of the many encouragements from academicians and in particular, Professors Zunyi Yang and Guoda Chen, during the course of this work. The understanding and dedication from GC’s wife, Wang Dong, during 20 years of persistent study is warmly felt. Financial support from the sciences fund for the doctoral disciplines of universities from the Chinese Education Ministry, and from the sciences fund of Sun Yat-sen University, over the last 10 years has enabled this study to be completed. GC thanks Professor Robert Diffendal (University of Nebraska) for his helpful comments and assistance during a field excursion in the USA, and also thanks his colleagues, Professors Ke Zhang and Jingjian Cao for their help and cooperation. RG would like to thank his wife, Agnes, for her encouragement and help throughout the period of writing this book.

We also wish to acknowledge the help of Ph.D. students, Wenming Zhang, Yan Qiu, Zhuolun Peng, Xiaoming Lin, Haoming Ma, Rongsong Shao, Yanyong Liu; MSc students, Shansen Qui and Xianhe Zhang (Department of Earth Sciences, Sun Yat-sen University) and Christian Bratzdrum (Institute of Mineralogy and Geochemistry, Freiburg University, Germany). The assistance of the Earth Science librarians, Susanne Schuble (Freiburg University, Germany) and Gill Ruthven (Victoria University of Wellington, New Zealand), in locating references is gratefully acknowledged.
CHAPTER 1
INTRODUCTION

1.1. ROCK GENESIS AND ITS RELATIONSHIP TO GEOSYSTEMS

Rocks that form the outer part of the Earth, the crust, provide a record of constant change in the Earth’s environment with time in relation to the movement and/or reaction of rock material during their formation. Thus, understanding the genesis of rocks is the foundation of the geological knowledge system. The nature, size, shape, properties and arrangement of constituent minerals gives rise to the diversity of rocks and their origin so that the challenge of geology is in determining their material source and mechanism of formation. Among the three kinds of rocks, igneous, sedimentary and metamorphic, the material source of metamorphic rocks need not be considered because its predecessor is also rock. Igneous rocks derived by crystallisation of liquids can be divided into mafic and felsic end members represented by gabbro/basalt and granite/rhyolite, respectively, with different sources.

1.1.1. Sedimentary Rocks and Continental Geology

The genesis of sedimentary rocks that form the outermost part of the solid earth was early clarified by Lyell (between 1830 and 1833; 1868) in his *Principles of Geology* and by the geosynclinal hypothesis of Dana (1873), i.e. sediments in basins are derived from weathering and erosion of rocks in mountains or other uplifted areas, lithification of the sediments during burial, return of the new sedimentary rocks to the Earth’s surface by tectonic processes, their subjection to renewed weathering and erosion, and so on as shown in Fig. 1.1. The relationship of endogenic/exogenic forces of the Earth, and the sedimentary rock cycle, demonstrate environmental variation and related material transportation in terms of two different tectonic settings, areas of uplift and subsidence. Without knowledge of this relationship, most theories of continental geology would not exist, and it is the main reason why the geosynclinal hypothesis remained fundamental in geology for over a century.
1.1.2. Basaltic Rocks and Plate Tectonics

Basaltic rocks constitute the oceanic crust, and probably a significant part of the lower continental crust (Sima). From the work of Holmes who put forward the mantle convection hypothesis in the 1920’s to that of Dietz (1961) and Hess (1962) who advanced the idea of ocean-floor spreading, the genesis of oceanic basalt and the corresponding material cycling of the mantle were successfully explained by geology, i.e. mafic magma from the mantle erupts from mid-ocean ridges to form the basaltic rocks of the ocean crust which moves away from the ridge axes, and is returned to the mantle by subduction (Fig. 1.2). Without this model, the plate tectonics hypothesis would not exist and it was probably the main reason why Wegener’s hypothesis of continental drift was eventually accepted because it provided a mechanism for large-scale crustal movement.

1.1.3. ‘Whence the Granites’

The genetic models of sedimentary and basaltic rocks explain environmental variables and material transport of the continents in relation to endo–exogenic forces, and energy/material flow in the Earth’s interior in relation to tectonic plate
movement. These models form the core theories of the two knowledge systems, i.e. Continental Geology and Plate Tectonics. However, as shown in Fig. 1.3, neither the formation process of sedimentary rock nor that of basalt produces granite that is considered to be distributed between the shallow crustal metasedimentary rocks and the lower continental crust.

Granite that belongs to the continent composes the fundamental part of the upper crust and is closely related to tectonism, metamorphism and mineralisation of the continental crust. The origin of granite, however, has been the subject of much debate since the eighteenth century when the science of geology was in its infancy. Accounts of the ‘granite controversy’ and the origin of granite can be found in Gilluly (1948), Pitcher (1993) and Young (2003) and will not be addressed here except to say that since the advent of plate tectonics in the 1960's, a framework has been provided in which the different interpretations of granite genesis can be re-explored and in many cases reconciled, although debate still continues. A misleading idea related to the basalt magma fractional crystallisation-differentiation scheme of Bowen (1914, 1922, 1948) is to combine the order of mineral crystallisation to the formation of basic to acid series igneous rocks. Only a small amount of residual granite liquid is generated by this process and this experimental evidence is clearly at odds with field evidence for the abundance of granite (Holmes 1926; Read 1957). While the mineral reaction series can be applied to the crystallisation of different magma compositions as recorded by their mineral textures, the first rocks formed are not necessarily mafic, and the last are not always felsic, because the rock crystallised from a melt depends on the composition of the melt and not the order of mineral crystallisation (Kennedy 1933). In this respect, the comment on Bowen’s idea by Walton (1960) is relevant,

“Not that there was anything wrong with Bowen’s chemistry or his application of it to the fractionation of basaltic magma; it was and will still remain a keystone of petrology. But there was a crucial tacit assumption involved in tying igneous
theory so rigidly to a single model in which the evolution of most igneous rocks is dependent on the upward intrusion of basaltic magma into a level of the crust where it cools, crystallizes, and fractionates. The same chemistry can be applied to other models”.

The granite controversy that raged between granitisers such as H.H. Read and magmatists such as N.L. Bowen in the late 1940’s (Gilluly 1948) has effectively ended and most earth scientists would now agree that granites are of magmatic origin. In answering the question, how does granite form? or in Bowen’s words ‘Whence the granites?’ the overwhelming opinion of most earth scientists is that granite is derived by partial melting of crustal rocks of various compositions. This idea essentially brings together the earlier competing explanations of granite genesis; magmatic (granites are igneous rocks resulting from the crystallisation of magma) and metamorphic (granites are the result of a dry or wet granitisation process that transformed sialic sedimentary rocks into granite), because granites are the result of ultra-metamorphism involving melting (anatexis) of crustal rocks. This explanation has important implications for the origin and chemical differentiation of the Earth’s crust in relation to the source and evolution of thermal regimes, protolith composition, how much granite can be produced, over what time and at what temperature, the amount and source of available water needed, tectonic processes and plate tectonic settings—a truly holistic association.

1.2. GRANITES, MIGMATITITES AND GRANITE PROBLEMS

1.2.1. Definitions

1.2.1.1. Granite

The maxim ‘there are granites and granites’ originally coined by H. H. Read remains just as true today as it did in 1933. In fact the number of ‘granite types’ has proliferated from at least 20 schemes that have been proposed to classify them (see Barbarin 1990, 1999 for summary, and Frost et al. 2001 for an appraisal of the more commonly used classification schemes). The most widely used classification schemes are geochemical and/or generic-alphabetical, i.e. S-, I-, M-, A-, and C-type granites (S = sedimentary source; I = igneous source; M = mantle source; A = anorogenic; C = charnockitic); calc-alkaline, alkaline, peralkaline, peraluminous, metaluminous granites; or are related to tectonic setting: ‘orogenic’ (oceanic and continental volcanic arc; continental collision), ‘transitional’ (post-orogenic uplift/collapse), and ‘anorogenic’ (continental rifting, hot spot, mid-ocean ridge, oceanic island) granites.

In this book the broad terms ‘granitoid’, ‘granitic rocks’ or simply ‘granite’ are used to mean quartz-bearing (>60 wt % SiO₂) plutonic igneous rocks in general. We adopt (or return to) where necessary a non-genetic classification of granitic rocks based on field and petrographic observation in that we use well-established rock names, e.g. granite, adamellite, granodiorite, tonalite, monzonite, diorite,
together with qualifiers such as mineral (e.g. biotite-, muscovite-, two mica- etc.;
quartz- in the case of syenite, monzonite and diorite), grain size (e.g. fine, coarse,
medium, aplite, pegmatite), texture (e.g. porphyritic, granophyric, orbicular, etc), and
colour (e.g. leuco-, meso-, melanocratic). Other textural/compositional terms,
such as rapakivi granite, are in common usage and are retained because they are
non-generic.

As quartz and feldspars (alkali feldspar and plagioclase) make up nearly 90
modal % of granitic rocks, the non-genetic IUGC classification scheme of
Streckeisen (1976) can best be adopted to ‘pigeonhole’ them (Fig. 1.4A) . The clas-
sification scheme is, as with any such scheme, not without its faults, e.g. it does not
include the mafic mineral component of granitic rocks, and the rock divisions may
not always clearly distinguish natural populations, but it is straightforward and it
is based on what can be seen. Our only modification is to retain the name ‘adamell-
lite’ because it is entrenched in the literature. In the Streckeisen scheme the
adamellite field forms part of a larger granite field. Minerals other than quartz
and feldspars that may be easily distinguished in outcrop and which are used to
identify variation in granitic rocks such as biotite, muscovite and hornblende
(also fayalite, orthopyroxene, cordierite, garnet, tourmaline, topaz, ilmenite, mag-
netite-bearing varieties), can simply be attached to the Streckeisen classification
name. In this way the granite name remains even if ideas on its origin and paleo-
tectonic setting change and it is informative, e.g. porphyritic biotite granite or
leucogranite. ‘Trondhjemite’ is another term in common usage, especially with
respect to the trondjhemite-tonalite-granodiorite (TTG) association characteristic
of Archean terranes. It is not represented in the Streckeisen scheme, but can be
regarded as the leucocratic variety of tonalite, consisting of essentially plagioclase
(oligoclase–andesine) and quartz with minor biotite and accessory Fe-Ti oxide.
The relationship between modal mineralogy, including the common mafic miner-
als and muscovite, granitic rock type and colour index is shown in Fig. 1.4B.

We adopt a normative quartz, alkali-feldspar, plagioclase classification scheme
because there are many more chemical analyses of granites than there are modal
analyses and the normative scheme also allows characterisation of experimental
melt (glass) compositions. The normative classification is approximated using the
orthogonal plot of Streckeisen and Le Maitre (1979) (Fig. 1.5A) , where modal
quartz is analogous to 100 Qz/(Qz + Or + Ab + An) and modal plagioclase/(alkali-
feldspar + plagioclase) is analogous to 100 An/(Or + An) with normative Ab being
ignored. Normative feldspar (An-Ab-Or) composition is also a convenient classi-
fication scheme for granitic rocks in that it allows distinction of the trondhjemitic
variety (Fig. 1.5B).

1.2.1.2. Migmatite: terminology and classification

Migmatites, or mixed rocks, preserve a multitude of structures, mineral textures
and compositions that reveal the process of rock melting (anatexis) that leads to
the production of granite magma. In his classic work, Mehnert (1968) defines a
Figure 1.4. A. Modal classification of granitic rocks according to Streckeisen (1976). B. Modal and colour classification of granitic rocks that includes muscovite, biotite, hornblende and pyroxenes.
Figure 1.5. A. Normative classification of granitic rocks according to Streckeisen and LeMaitre (1979) with inclusion of an adamellite field. The field boundaries are best fits that separate chemically analysed rocks named according to the modal classification shown in Fig. 1.4A. B. Normative Ab-An-Or classification scheme of granites (after O'Connor 1965; Barker 1979).
migmatite as “a megascopically composite rock consisting of two or more petrographically different parts, one of which is the country rock generally in a more or less metamorphic stage, the other is of a pegmatitic, aplitic, granitic or generally plutonic appearance.” Mehnert’s definition is the basis for the latest nomenclature on migmatites proposed by the sub-commission for the nomenclature of metamorphic rocks (SCMR), (Wimmenauer and Bryhni 2002), who provide a revised definition of migmatite: “A composite silicate rock, pervasively heterogeneous on a meso- to megascopic scale. It typically consists of darker and lighter parts. The darker parts usually exhibit features of metamorphic rocks, while the lighter parts are of plutonic appearance. Whenever minerals other than silicates and quartz are substantially involved, it should be explicitly mentioned”. Both definitions attempt to be non-genetic although use of the words metamorphic and plutonic underscores the common understanding that high grade (i.e. high-\(T\)) metamorphism and anatexis are prerequisites for migmatite formation.

The main distinction of a migmatite is the heterogeneous distribution of the light (leucosome) and dark (melanosome) parts relative to the unchanged portion. These are ‘new’ components of the rock, and are collectively termed the ‘neosome’. The ‘unmigmatised’ parent rock (protolith) is called the ‘paleosome’. Another dark-coloured component of a migmatite is the ‘restite’ from which a substantial amount of the more mobile components appear to have been extracted (Wimmenauer and Bryhni 2001). Additional terms that directly relate to migmatites are metatexis and diatexis.

1. Metatexis refers to the initial stage of anatexis where the paleosome is partly segregated into a more mobile part (metatect), and a non-mobilized (depleted) restite. If the migmatisation process has created a rock with obvious and discrete leucosomes, melanosomes, and intermediate coloured mesosomes, the migmatite can be called a ‘metatexite’.

2. ‘Diatexis’ refers to an advanced stage of anatexis where the darker-coloured minerals are also involved in melting and the melt is not removed from its place of origin. The metamorphic paleosome has been largely disrupted, and the leucosomes and melanosomes are intimately combined in a nebulitic or schlieren texture. In such cases the migmatite can be termed a ‘diatexite’ (Ashworth 1985; Wimmenauer and Bryhni 2002). Clearly, flow has occurred and the diatexite could also be regarded as a ‘dirty’ or proto-granite magma.

In addition to quartz, feldspars, muscovite and biotite, migmatites derived from the partial melting of mica-bearing quartzofeldspathic rocks (the most common type of migmatite) contain cordierite, garnet, ± sillimanite, andalusite and kyanite and may be classified on this basis after evaluation of prograde and retrograde mineral textures. A \(P-T\) pseudosection for an average metapelite composition containing excess quartz and plagioclase in the MnNCKFMASH system is given in Fig. 1.6. The diagram shows stable assemblages coexisting with in situ–derived liquid (granitic melt) over a temperature range of 650–740°C that represent conditions of
cordierite and garnet-bearing migmatite formation in the range 10–25 km depth. The areas of cordierite-only, cordierite + garnet and garnet-only depicted in Fig. 1.6 delineate fields in $P$-$T$ space that reflect the formation of compositionally different migmatite terranes or of compositional variation in a single migmatite terrane. A field of low-temperature muscovite-bearing migmatite characterised by very low-melt fractions of $\sim$1 mol % is also shown as part of the cordierite–garnet migmatite field. Temperature gradients $>40^\circ$C/km will produce cordierite and cordierite–garnet-bearing migmatites while gradients $<40^\circ$C/km will generate garnet-bearing migmatites at deeper crustal levels.

1.2.2. Granite Magma Intrusion and Its Problems

Geological studies of ancient orogens show that they contain large volumes of granite and geophysical studies of active orogenic zones suggest that part of the crust could be partially molten. Although common and often of similar
appearance, granites reflect a complicated history of formation that has led to a diversity of opinions about their formation and continues to be a hotly debated topic in geology. Being at one time liquid, granite has become synonymous with intrusion, a genetic connection repeatedly reinforced by the phrases ‘intrusive granites’ or ‘granite intrusions’ so common in the scientific literature. The current paradigm of granite formation is one of crustal melting and melt segregation in the lower crust followed by ascent (continuous or episodic) via dykes with emplacement in the upper crust along structural/rheological ‘traps’, or rising through the crust as large globular diapirs that eventually freeze at some level to form a pluton, or intruding along fault zones to fill extensional openings. There is growing acceptance that the ascent and emplacement of granite magma, e.g. as dykes, is not as sluggish as previously thought and that provided flow is continuous, it may occur at timescales of less than 100,000 years, (Petford et al. 2000), with large bodies of granite (batholiths) for example of 1000 km$^3$, being formed in 1200 years from a 3 m wide, 1 km long (in plan) dyke, provided there was a continuous supply of magma from below (Clemens 2005). This is indeed a geologically catastrophic event! The age-old ‘room problem’ created by the idea that granite batholiths extended to unknown depths is explained by the notion that such bodies in fact have tabular sheet-like geometries (Chamberlin and Link 1927; McCaffey and Petford 1997; Crunden 1998) with thicknesses of only a few kilometres so that their ‘emplacement’ can more easily be explained by a combination of initially lateral (fault opening) and subsequent vertical (inflation by roof uplift and/or floor subsidence) movement. Diapirism as an alternative end member magma transport process is suggested by the roughly circular sections of many granite bodies from a few kilometers to one hundred kilometers in diameter and from analogy with the shape and finite strain field of salt diapiric intrusions (Bateman 1985). In the diapiric model, granite ascent from a ductile lower crust is much slower ($10^5$–$10^9$ years; Marsh 1982; Weinberg and Podladchikov 1994; Miller and Paterson 1999) than in dykes and there are more thermal and mechanical difficulties to overcome with transporting very large volumes of magma, especially into brittle upper crustal rocks. These ideas form the basis of the intrusion model of granite genesis (segregation, ascent, emplacement) (Fig. 1.7) and a vast array of field, geochemical, geophysical and experimental evidence combined with theoretical modelling has been used to support the model. Although theoretical models neither rule out diapirism nor fully support dyking as mechanisms to move granite magma upwards from its lower crustal source, the fact remains that the intrusion model requires that granite magmas be transported upward through progressively cooler crust to their emplacement site at a sufficiently fast rate to prevent them freezing.

Perhaps the weakest part of the intrusion hypothesis is in identifying a focusing site that enables granite melt to escape from its source area either by way of a conduit or in the form of a diapir. It has to be assumed that beneath every granite body there must be a deeper crustal source region. For example, Brown (2001)
calculates that a horizontal semicircular half cone-shaped granite body with a diameter of ~30 km and a half height of 5 km could be formed by ~20 vol % fractional crystallisation of ~20 vol % melt segregated from an underlying ~15 km thick source! with a horizontal diameter of ~30 km, i.e. a lower crustal source volume for this one pluton of ~11,000 km³. As pointed out by Brown, an implication is that granite bodies of this size might be spaced ~30 km apart. As many exposures of granite typically consist of more than one isolated occurrence, it also implies the existence of an extensive source region that must be related to a regional geotherm that enables crustal anatexis to occur.

Field evidence of dyke-like feeders for granite batholiths is rare, because their floors are seldom exposed. Obviously, if feeder dykes extend vertically for many kilometres as they are supposed to, a continuous link between granite batholiths and their source is unlikely ever to be found. Nevertheless, dykes are a requirement as well as a contention for the granite intrusion hypothesis. There are also problems with a rootless diapiric origin of granite where the surrounding rocks deform by viscous flow to allow the buoyant rise of a magma body. Although there is evidence from internal structures in granite bodies that suggest a diapiric origin (Pons et al. 1995) and modelling supports the possibility (Weinberg and Podladchikov 1994), the paucity of evidence such as rim synclines, near vertical cylindrical shear zones and strong thermal effects (Clemens 1988; Clemens and Mawer 1992) associated with granite bodies has raised doubts on the viability of such an ascent mechanism. There is no known structural/thermal evidence of an ascent trail for postulated diapiric granite bodies, so that diapirism, if it occurs, is probably restricted to deep crustal levels because of the exponential increase in crustal viscosity with decreasing depth that would be expected to halt diapiric
ascent at about mid crustal levels (Clemens and Mawer 1992; although see Weinberg and Podladchikov 1994 for the possibility of granite diapirs reaching depths as shallow as 6 km).

‘Ballooning’ (Ramsey 1989) has been considered one way of solving the room problem for granite emplacement, and it predicts that the volume for pluton accommodation can be supplied by deformation of the thermal aureole during in situ radial inflation of a ‘magma intrusion’. Inflation can occur by continuous feeding via dykes, or by way of the hotter ‘tail’ of a diapir continuing to rise whereas the main upper part has ceased its upward ascent. Structural patterns attributed to a ballooning pluton include a circular or elliptical shape in horizontal sections, planar fabric parallel to the contacts and more intensely developed at the border zones where it appears as a gneissic solid-state foliation, concentric zoning of rock facies, the central facies generally being more acidic in composition and later with respect to the marginal facies; a planar fabric parallel to the contacts in the host rocks due to pure shear increasing towards the igneous contact. However, all of these features can also be produced as a result of upward doming of part of an in situ melt layer as described below.

In a large number of cases where granite bodies show a discordant relationship with their host rocks (Fig. 1.8A), the space problem remains. If the granite is allochthonous, where is the pre-existing rock that formally occupied the area now occupied by the granite? Has it been passively engulfed (melted) or stoped by the granite magma? (Fig. 1.8B, C). Has the granite magma been tectonically emplaced along a fault and simply forced apart the country rocks? The stoping mechanism of magma ascent and emplacement first proposed by Daly (1914) has been invoked to explain the first possibility and implies thermal shattering of the host rocks induced by magma, invasion of fractures by the magma and sinking of the disrupted blocks. Sinking of largely unmelted host rocks in the magma could contribute to a more rapid rate of cooling so that the magma body would suffer an early thermal death and if so, one would expect to find abundant fragments of largely unmelted country rock frozen into the marginal areas of the granite.

Migration of granite magma along fault zones has been suggested for some orogenic settings e.g. Hutton et al. (1990); D’Lemos et al. (1992); Davison et al. (1995). This mechanism necessitates the formation of crustal scale fault/shear systems within which extensional jogs can be passively or forcibly filled with granite magma. Also, these active shear zones need to be situated above or perhaps within the zone of magma generation and extend for significant vertical distances through the crust. In many cases, however, granite bodies aligned along faults systems exhibit marginal shearing and truncation indicating that faulting was post-granite ‘emplacement’ or that the faults have been reactivated subsequent to granite emplacement. In other cases discordant granite contacts show no evidence of being faulted and in such cases it has been assumed that shear/fault zone avenues have been obscured by the effects of stoping and ballooning of the granite magma (D’Lemos et al. 1992). Statistical analysis of spatial relationships between faults and granite in the Armorican Massif, France
and southern Appalachians, USA, indicates a tendency for granite to occur away from faults, indicating that faults in these areas, and presumably in others, do not preferentially channel magma in general (Paterson and Schmidt 1999).

Magma transport is a mass transfer process where upward movement of magma is balanced and accommodated by movement of the country rocks. Thus, the prerequisites of granite intrusion are structural control and a suitable mechanism of episodic or continuous injection of magma. With these requirements and other exposure-related questions, it may be pertinent to ask whether it is necessary to separate granite melt from its source area at all. It is a question that also seems to have occupied the mind of James Hutton when he contemplated the magmatic origin of granite in 1790, asking “...whether it were not rather a body

Figure 1.8. A. Simplified geologic map of the Dadongshan batholith, Guangdong Province, SE China, showing discordant contact relationship between batholith and structural trend of the country rocks. B. Cross section of the Gangdise batholith from the Yaluzhangbu River to Mingzhong, Tibet, showing crosscutting relationship between the granite contact and steeply-dipping metasediments with the suggestion that they have been melted (modified after SEGCA 1981). C. A 40 km long section of the Striegau granite, Silesia, Poland, showing variously orientated blocks of country rock within the granite (redrawn after Fig. 3 of Cloos 1923).
which had been originally stratified ... and afterwards consolidated by the fusion of these materials, or whether it were not rather a body transferred from sub-terraneous regions, and made to break and invade the strata.” If granite magmas are not intruded by whatever means from a lower crustal metamorphic source, what is exposed must be granite together with the rocks of, or in the immediate vicinity of its source region, the relationships between them modified more often than not, by subsequent tectonic activity. This is the essence of ‘in situ melting model’ of granite genesis proposed here—that granite magma essentially remains within or close to its source area. The common association of granite and migmatite, e.g. in gneiss domes, and also granulite, provides unequivocal evidence of this, although granite bodies not associated with migmatite and surrounded by narrow metamorphic aureoles imposed upon relatively low-grade rocks, also require explanation. It is also clear that while low-melt (leucogranite) fractions can be efficiently transferred from migmatite to crystallise and sills, dykes and laccoliths in rocks immediately overlying the melting zone (e.g. Himalayas), this is not the case for the much larger volumes of granite, adamellite, granodiorite, tonalite, i.e. the ‘stuff’ of batholiths. In the following pages, we explore the alternative idea that granites have an in situ melting origin using the field, geochemical, geophysical, experimental and modelling evidence that has been marshalled in support of an intrusion origin.
CHAPTER 2

CRUSTAL MELTING: EXPERIMENTS AND CONDITIONS

2.1. INTRODUCTION

The formation of granite magma by a combination of lower $T$ fluid-present melting and higher $T$ fluid-absent dehydration melting of micas and amphibole in the Earth’s crust largely depends on source rock composition, particularly whether the components necessary to produce a granite ‘minimum-melt’ composition ($K_2O$, $Na_2O$, $Al_2O_3$, $SiO_2$, $H_2O$) are available, the pressure at which melting occurs, temperature, type and amount of hydrous minerals present, and the presence or absence of free water. Water is continuously evolved during metamorphism from dehydration reactions. Whether this $H_2O$ remains in the rock or not depends on its porosity, which in turn, is dependent on depth (lithostatic pressure). If the porosity of the rock is small, nearly all $H_2O$ evolved by dehydration leaves the rock. Dihedral angle measurements for hydrous fluids in contact with silicates suggest that it might be difficult to completely remove a fluid phase from a rock undergoing progressive dehydration on metamorphism (Watson and Brenan 1987; Holness 1993; Laporte et al. 1997). Although deformation will enhance fluid escape, it seems possible that at the end of the dehydration event, some fluid will remain in the source rock along grain boundaries, as isolated pockets at grain corners or along grain edges as well as in fluid inclusions. Initial granite melts will be fluid-saturated but the amount of melt maybe small because the proportion of fluid phase present is also small. Therefore, unless there is an external source of fluid, fluid-absent melting will be the predominate mechanism for significant volumes of granite melt to form.

All granitic magmas contain dissolved water, e.g. up to ~6 wt % at 2 kb and ~10 wt % at 10 kb (Holtz and Johannes 1991). This water is derived from;

1. free water occurring along mineral grain boundaries, pores, fractures, fluid inclusions in minerals
2. structurally bound OH ions in phyllosilicates (as wt % $H_2O^+$) such as chlorite (10–12%), muscovite (~4%), biotite (3–4%), amphibole (~2%), or other less hydrous minerals such as epidote (1.5–2%), staurolite (~1%), cordierite (~1%).
The two sources of water give rise to two kinds of melting reaction:

1. water or fluid/vapour-present melting, H$_2$O-saturated melting ($a$H$_2$O = 1.0), or wet melting, where free water is available, e.g. anhydrous minerals + aqueous fluid/vapour = liquid anhydrous minerals + hydrous mineral + aqueous fluid/vapour = liquid

2. fluid/vapour-absent melting, H$_2$O-undersaturated ($a$H$_2$O = <1.0), or dehydration (incongruent) melting, where no free water is available, e.g. anhydrous minerals + hydrous mineral = liquid + anhydrous minerals.

2.2. MINERAL MELTING

(Mineral notations used below are listed in Table 2.1 together with nomenclature and composition.)

<table>
<thead>
<tr>
<th>Table 2.1. Mineral, composition, notation and oxide system notation</th>
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<tbody>
<tr>
<td>Andalusite</td>
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<td>Anorthite</td>
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<tr>
<td>Albite</td>
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<tr>
<td>Apatite</td>
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<tr>
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<td>Biotite</td>
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<tr>
<td>Calcite</td>
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<td>Chlorite</td>
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<td>Ilmenite</td>
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<td>Pyrite</td>
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<td>Pyrrhotite</td>
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2.2.1. Topology of Melting

Topological relationships between subsolidus dehydration, vapour-saturated melting and dehydration melting of a rock containing a hydrous mineral such as muscovite, biotite and/or hornblende are shown in Fig. 2.1. Curve 1 represents a subsolidus dehydration reaction where a hydrous mineral-bearing assemblage reacts to form an anhydrous mineral assemblage $+ \text{H}_2\text{O}$ vapour. Curves 2 and 4 represent the H$_2$O-saturated solidus of the rock on the higher temperature side of which an H$_2$O-saturated melt (M$_s$) is formed. At pressures greater than the invariant point (I), curve 3 represents the vapour-absent solidus of the rock. This curve corresponds to a dehydration melting curve where a hydrous mineral (H) melts to form an anhydrous mineral assemblage $+ \text{H}_2\text{O}$ undersaturated melt (M$_u$). The line P$_1$ intersects invariant point (I) and represents the minimum pressure at which a hydrous mineral in a rock can coexist stably with melt. In the common case where a rock contains two or more hydrous minerals, these minerals react together with dehydration melting taking place over a multivariant T–P interval.

2.2.2. Muscovite Dehydration Melting

The most important muscovite dehydration melting reaction in sialic rocks is,

$$\text{Ms} + \text{Qz} + \text{Ab} = \text{Ksp} + \text{AS} + \text{L}$$

(Fig. 2.2) with addition of Ca (anorthite component in plagioclase) shifting the reaction to higher temperatures, e.g. from ~625 to 700°C at 5 kb (Thompson and...
Figure 2.1. P–T diagram showing schematic relations between subsolidus dehydration, H$_2$O-saturated and dehydration melting reactions. H = hydrous mineral; A = anhydrous mineral; $\dot{V}$ = vapour (H$_2$O); M = melt with $M_s$ and $M_u$ = H$_2$O-saturated and H$_2$O-undersaturated, respectively; I = invariant point.

Figure 2.2. P–T diagram showing various subsolidus and suprasolidus muscovite breakdown reactions in the systems KASH, KNASH, and CKNASH (after Thompson and Algor 1977; Thompson and Tracy 1979). PWS = wet pelitic solidus after Thompson (1982). Labelled 20–80°C/km linear geothermal gradients are shown for reference. For chemical system and mineral abbreviations see Table 2.1.
Algor 1977). If muscovite contains some Fe, Mg and Ti, which is usually the case, then additional reaction products such as Fe-Mg spinel, cordierite and biotite may form (Brearley 1986; Grapes 1986; Rubie and Brearley 1987; Vielzeuf and Holloway 1988; Brearley and Rubie 1990; Patiño-Douce and Harris 1998). In general, however, muscovite dehydration melting occurs abruptly by a near univariant reaction because of its restricted compositional range.

2.2.3. Biotite Dehydration Melting

In the presence of quartz, plagioclase, ± Al-silicate, biotite will breakdown at higher temperatures than muscovite as shown from experimental studies summarised in Fig. 2.3. Model biotite breakdown reactions involve the formation of

![Figure 2.3](image)

*Figure 2.3. P–T diagram showing various biotite-bearing assemblage dehydration melting reactions. Reaction curves labelled 23 (Patiño-Douce and Beard 1995), 44 (Vielzeuf and Montel 1994), 50 (Singh and Johannes 1996) and 55 (Patiño-Douce and Beard 1995) = Xmg content of biotite. Shaded area = range of biotite-out curves in greenschist–amphibolite grade greywacke compositions after Kifle (1992). Curves 1 after Luth et al. (1964), Piwinskii (1968) Johannes (1984), and 2 after Piwinskii (1968). PWS = wet pelitic solidus after Thompson (1982). Labelled 20–80°C/km linear geothermal gradients are shown for reference. For mineral abbreviations see Table 2.1.*