6 ⇠ WET OR DRY?

The Origin of Granite

As we have just seen, many geologists in the opening decades of the nineteenth century accepted the notion that veins and dikes of coarsely crystalline granitic rocks proceeding from larger masses of granite were formed by the intrusion of subterraneous lava. Some eventually carried the concept of igneous dike intrusion to an extreme. For example, the American geologist Ebenezer Emmons (1799–1863) interpreted intrusive dikes of remobilized marble in the Adirondack Mountains of New York as evidence for their igneous origin (Emmons, 1860). In contrast, numerous geologists throughout much of the century remained skeptical that granite was produced by igneous fusion or that dikes prove igneous injection. Despite the successes of the plutonists, no consensus about the nature of granite emerged for several decades.

The writings of James D. Dana, America's premier nineteenth-century geologist, illustrate the uncertainties about the nature of granite. In his geological report on the Wilkes expedition, Dana (1849) referred to granite and syenite as the products of cooling of melt. In the second edition of *Manual of Geology*, however, Dana (1866) included granite in the category of rocks crystallized by heat without fusion, designated as "metamorphic rocks." He also drew a sharp distinction between "plutonic" rocks and true igneous rocks.

Why did the confused state of affairs about granite and coarsely crystalline rocks persist for so long? Ironically, British geologists did relatively little to advance the discussion about granite after the pioneering efforts of Hutton, Hall, and Playfair. Lyell (1833) did discuss granite and plutonic rocks toward the end of the third volume of his *Principles of Geology*, but, despite his major contributions to the interpretation of geological history, he added little new to the discussion about the origin of granite that had not already been stated by the original plutonists. For the most part, British geologists of the first half of the nineteenth century appear to have regarded the issue of the origin of granite as settled. The neptunist conception of dikes, sheets, or masses of basalt and granite as precipitates from the ocean had largely faded during the 1820s. So, too, had the neptunist conception of granite as exclusively a Primitive formation. Since few Wernerian neptunists remained to challenge the idea of intrusive igneous granite, British geologists saw little need for further debate and turned their attention to other aspects of geology, such as paleontology, stratigraphy, and geomorphology, that proved to be exceptionally fruitful. Between 1830 and 1860, the origin of granite became the concern primarily of continental geologists.

During this period, some advocates of igneous granite, particularly Fournet and Durocher in France, emphasized that granite is the product of "dry igneous fusion." For them, water did not play an essential role in the production of granitic melt. Vigorous opposition to the concept of dry fusion arose, however, on several grounds. The opponents of dry fusion concluded that granite had formed in the "wet way."

Several arguments were leveled against the idea of dry fusion origin of granite. These included the claims that the order of mineral crystallization in granite excludes an origin by fusion; that quartz-bearing volcanic equivalents of granite do not exist; that experimental evidence confirmed the production of quartz only in the "wet way"; that field evidence demonstrates the conversion of metamorphic rocks into granite; and that the presence of "pyrognomic" minerals in granite is inconsistent with their origin by dry fusion.

ARGUMENTS AGAINST THE ORIGIN OF GRANITE BY DRY FUSION

Kirwan, Murray, and other opponents of the views of Hutton and Playfair on the nature of granite had already pointed out that the textures of granite indicate that feldspar crystallized prior to quartz. They reasoned that such an arrangement excludes an igneous origin because feldspar is much more easily melted than quartz. If granite were igneous, the argument went, quartz, the mineral with the very high melting temperature, should have crystallized before the more fusible feldspar. Well-formed crystals of quartz should have imposed their faces on the form of the subsequent feldspar rather than the opposite.

The textural argument was persistently repeated throughout the first half of the nineteenth century. Scipione Breislak, for example, made it in his *Traité sur la Structure du Globe*. Johann Fuchs, a Munich chemist, challenged the "pyrogenic" or igneous origin of granite on textural grounds in 1837 in *Über die Theorien der Erde*. One of the most vigorous advocates of the origin of granite in the wet way was Carl Gustav Christoph Bischof (1792–1870). Of all the participants in the debate, Bischof came the closest to reversion to neptunism. After receiving his doctorate from the University of Erlangen, Bischof began a long tenure as Professor of Chemistry and Technology at the University of Bonn in 1819 (Amstutz, 1970). His early studies of hot springs led him to a vulcanist position, but Bischof soon became much more sympathetic toward transformationist views of granite and similar crystalline

6. Theodor Scheerer (1813–1873). Reproduced by permission of the Bergakademie, Freiberg.

rocks. In the second volume of the English translation of his encyclopedic work on chemical geology, *Elements of Chemical and Physical Geology*, Bischof (1855) rehearsed the long-standing objection that the order of succession of minerals is directly opposed to the idea of the derivation of granite by fusion, and in the third volume he flatly asserted that "crystals of quartz are never found to have interfered with the crystallization of the other minerals" (Bischof, 1859, p. 44).

The textural argument, however, was developed the most thoroughly by Theodor Scheerer (1813–1873) (Figure 6), a chemist and mineralogist at the Bergakademie in Freiberg, in a paper read before the Societé Géologique de France on February 15, 1847. The origin of granite was a very hotly contested topic in France during the course of the 1840s. At successive meetings of the Societé Géologique in late 1846 and throughout 1847, several leading geologists, including Fournet, Durocher, Virlet d'Aoust, Scheerer, Élie de Beaumont, and Delesse, presented papers on the nature of granite. These papers, published in *Bulletin de la Societé Géologique de France* for 1847, provide an excellent cross section of the attitudes toward granite at the time. A more recent granite enthusiast, H. H. Read (1957), referred to 1847 as the "annus mirabilis" and discussed several of the papers in his *The Granite Controversy*.

In his paper entitled "Discussion sur la nature plutonique du granite et des silicates cristallins qui s'y rallient," Scheerer (1847, p. 478) stated that early in his career when he had been unaware of Breislak's objections to igneous granite and before Fuchs had published his, he had been "completely saturated with the most orthodox plutonian theories." In 1833, however, he visited Norway and his earlier beliefs about granite were "completely weakened" as a result of his intense study of Norwegian granites. In 1842, he presented his "altered" views on granite to the Society of Scandinavian Naturalists in Stockholm, confessing that the textural evidence of granite on the island of Hitteröé had made an impression on him. In the Hitteröé granite, he reported, the feldspar had clearly crystallized in an "uninhibited" manner, leaves of mica had been puckered into the contacts with feldspar, and "amorphous" quartz filled in the spaces left over after crystallization of the feldspar and mica. The feldspar in graphic granite, Scheerer said, always won out over the quartz in the "struggle" to crystallize first. On the ordinary plutonic theory, namely, that of pure igneous fusion, he had informed his audience, that textural fact was inexplicable on the grounds that silica, because of its difficulty of fusion, should have solidified well before the silicates of potassium and of magnesium. Heat alone, he judged, had not produced the granite. Scheerer further reported instances of granites in which a host of other minerals such as acmite, garnet, tourmaline, amphibole, orthite, allanite, gadolinite, pyrite, arsenopyrite, cobaltite, and mica, too, had solidified prior to feldspar and, therefore, prior to quartz. Even where the most fusible of these minerals occurs in immediate contact with quartz, Scheerer pointed out, the quartz never prevented them from crystallizing perfectly.

Those who were persuaded by the textural argument were, of course, hampered by a lack of understanding of the internal structure of magma. For the most part, chemists and geologists assumed that individual minerals in a silicate rock like mica, feldspar, and quartz somehow retain their chemical integrity when the rock is melted. Those who used the textural argument probably envisioned that silicate lava consists of domains with chemical compositions identical to those of the minerals that would eventually crystallize upon cooling. The struggle to grasp the internal nature of lava was especially pointed in the writing of Scrope (1825, 1856), who never was convinced that lava is a fused material. Throughout his career he advocated the notion that lava achieved its fluidity because vapor thoroughly penetrated extremely finely comminuted mineral particles. In his view, hornblende, mica, feldspar, and other minerals retained their solid character in lava on an extremely fine-grained scale. Advocates of the textural argument were similarly hampered by the lack of knowledge that magma is a solution in which the phenomenon of freezing-point depression occurs.

The textural argument would have lost some of its force if the presence of crystalline quartz in rocks of known igneous origin, namely lava flows of trachyte, could be confirmed. As a result, many advocates of the textural argument also advanced as an argument the supposed nonexistence of crystalline quartz in volcanic rocks. Scheerer (1847), for example, observed that not even very slowly cooled lava flows erupted from the volcano Jurullo had produced quartz. Noting that although volcanic products like obsidian and pumice have granite-like chemical compositions, he pointed out that they do not contain free quartz. To avoid the implications of the embarrassing absence of quartz in materials of appropriate composition and undoubted igneous origin, the plutonists, in Scheerer's view, were forced to resort to the subterfuge that such silica-rich melts cool much too quickly to form quartz. The plutonists, of course, were right.

In the second volume of his work on chemical geology, Bischof (1855, p. 478) asserted that "quartz crystals have never been found in lava." Any quartz that had been found in lava, he maintained, was essentially a rounded pebble that had been picked up as lava flowed over the surface. He also noted that quartz never crystallized from furnace slags unless they were extremely silica-rich. In volume three, Bischof (1859) eventually conceded that quartz crystals, not just pebbles of quartz, had been found in trachyte, but he took great pains to insist that the quartz crystals were deposited by aqueous solution in cavities or thin seams in the trachyte after its solidification. In Bischof's opinion, if free silica never separated from trachyte, the only rock then considered to contain an excess of silica and of which the igneous origin was certain, there were no grounds for the view that quartz was of igneous origin.

A third argument against the production of granite by dry fusion stemmed from experimental evidence. Opponents of dry fusion insisted that no one had ever produced granite by fusion in a furnace despite the assertion of James Hall that he had recreated substances with stony texture from slowly cooled melts. Nor, opponents alleged, had anyone crystallized quartz from silicate melt. In contrast, several investigators formed quartz from hot water, corroborating the idea that granite was produced in the "wet" way. In 1845, Schafhäutl showed that water vapor heated above 100°C dissolves silica. Upon cooling the vapor, Schafhäutl precipitated hexagonal dipyramidal crystals of quartz. Scheerer (1847) reiterated that no one had yet produced free silica by the slow cooling of a silica-saturated silicate melt, and Virlet d'Aoust (1847) appealed to Schafhäutl's experiments on the solubility of silica to support his contention that high temperature was not necessary to produce granite. Although Bischof (1855) acknowledged the origin of some augite and leucite by fusion, he found from his experiments that all silicate minerals could originate from aqueous solutions without increased temperature and pressure. As far as he was concerned, crystallization from melts was out of the question for several of the minerals commonly found in granite including hornblende, mica, orthoclase, and quartz.

The French experimentalist Daubrée also strongly supported the importance of water in the formation of granite. Gabriel-Auguste Daubrée (1814–1896) studied at the University of Strasbourg and the University of Paris (Chorley, 1971). After several years as a mining geologist, Daubrée was called to the University of Strasbourg in 1848 to serve as Professor of Mineralogy and Geology. There he established an experimental laboratory. After 1861, he became Professor of Mineralogy at the Muséum d'Histoire Naturelle, and from 1872 to 1884 he was also Director of École des Mines in Paris. Although Daubrée's primary contributions focused on metamorphism and meteorites, his studies of silicates in the presence of superheated water demonstrated that many of them crystallized from water at temperatures far below their fusion points. He grew quartz, feldspar, and pyroxene in the wet way.

In experiments on metamorphism, Daubrée (1857) examined the behavior of glass tubes filled with a small quantity of water heated to 400°C for at least a week. The water became charged with alkali silicate. The glass was transformed into an opaque white mass composed of various crystalline substances, one of which was quartz, which lined the tube walls much like a geode. After a month of heating, he produced quartz crystals as much as two millimeters long. He also examined the effect of heated water on obsidian. This rock, he discovered, lost its glassy character and was transformed into a grayish mass that looked like a very fine-grained trachyte and contained abundant microscopic feldspar crystals. Daubrée knew that feldspar had previously been observed in the upper parts of copper smelting furnaces. Rather than conclude that the feldspar crystallized during cooling of melted slag, however, he suggested that the feldspar was deposited on the furnace walls by vapor. After all, he noted, the most skillful chemists had been unable to produce feldspar synthetically by dry fusion, but his experiments on obsidian demonstrated convincingly that feldspar readily formed in the wet way. Even in lavas, Daubrée suggested, copious water vapor was the primary agent in bringing about the crystallization of silicates like feldspar or quartz well below their fusion temperatures. "It is still by this aqueous influence," Daubrée (1857, p. 310) reasoned, "that these same silicates are able to crystallize in a succession that is often opposed to their relative order of fusibility." He maintained that his conclusions were just as applicable to the crystallization of granite as to that of lava.

Heinrich Rose (1795–1864), a Professor of Chemistry at the University of Berlin and older brother of mineralogist Gustav Rose, showed that after fusion, quartz is converted into amorphous silica accompanied by a decrease in specific gravity from 2.6 to 2.2. Rose (1859) argued that the quartz in granitic rocks could not have separated from a dry fused mass and could never have experienced elevated temperature because it always has a specific gravity of 2.6. The American geochemist, T. S. Hunt constantly appealed to the experimental work of Rose and others to support his claim that quartz was never known to be formed in any other way than in the presence of water at temperatures far below those of its fusion temperature.

Igneous granite was also questioned on the basis of field evidence. A number of geologists reported occurrences of gradations of other rock types into granite and thereby concluded that at least some granite was the end result of a metamorphic transformation. This line of argument first appeared in 1825 when Balthazar M. Keilhau (1797–1858), Professor of Mineralogy at the University of Christiania in Norway, suggested that some of the sedimentary rocks of Norway had been transformed into granite.

Another participant in the controversial meetings of the Societé Géologique de France was Théodor Virlet d'Aoust (1800–1894), a mining engineer in Paris. In a paper presented at the Society's meeting of February 15, 1847, Virlet d'Aoust (1847) opposed both the plutonist and Wernerian conceptions of the origin of granite and agreed with much of Scheerer's paper. He noted that red granites at Montabon near Chalon-sur-Saone appear to grade into gneisses. He pointed out that gradations from gneiss to granite had been beautifully preserved in polished slabs of granite from Normandy, such as those that are used as a facing for the sidewalks of Paris. These granites, he said, contain thousands of unmelted, yet modified, fragments of ancient rocks.

Léonce Élie de Beaumont (1798–1874), arguably the preeminent French geologist of his day, also presented a paper on granitic rocks before the Societé Géologique de France in 1847. After studying at École Polytechnique and École des Mines, Élie de Beaumont embarked upon an illustrious career as a mining geologist and leading participant in the effort to produce a geological map of France (Eyles, 1950; Birembaut, 1971). Élie de Beaumont accepted the idea of Virlet d'Aoust that some granites were derived in a cyclic fashion from schists and gneisses that in turn had been derived earlier from metamorphosed granites.

The similarity in composition between many eruptive rocks and slates and graywackes together with the interbedding of granite, gneiss, and sedimentary schists also led Bischof (1855) to agree with Keilhau and Virlet d'Aoust that granite represented altered clay slate.

In the same volume of *Annales des Mines* in which Daubrée had issued his study of experiments on metamorphism, the Professor of Geology at the University of Besançon and Engineer of Mines, Achille Delesse, published a massive three-part series on the metamorphism of rocks. Delesse (1857) distinguished between regional and contact metamorphism and pointed out the differences between the kind of contact metamorphism associated with granites and that associated with lava. He noted that in many cases pelitic sedimentary rocks at the contact with granites had experienced a process of feldspathization to such an extent that they looked very much like granitoid porphyries. From these appearances and other lines of evidence, Delesse concluded that granites were not produced by dry fusion.

James Geikie (1839–1915), younger brother of the renowned Director of the British Geological Survey, Sir Archibald Geikie, was a geologist with the Scottish branch of the Survey and later holder of the Murchison Chair of Geology at the University of Edinburgh. Geikie (1866) contributed a paper on granitic rocks in the southern uplands of Scotland in which he described a series of feldspathic Lower Old Red sandstones that had changed into quartzless syenite with granitoid texture. He also reported graywackes that had apparently been converted into granite along strike. Similarly, A. H. Green described the transformation of other rocks into the Donegal granite in Ireland. On more than one occasion, Geikie referred favorably to the views of Hunt, who also called attention to the gradation of metamorphic rocks into granite

The final argument against a purely igneous origin for granite concerned the presence of what Scheerer (1847) called "pyrognomic" minerals in granite. Pyrognomic minerals were said to give off light spontaneously when heated. Scheerer claimed that pyrognomic minerals such gadolinite, orthite, and allanite become less soluble in acids, their color and transparency are altered, and their density increases during intense heating. How is it, Scheerer asked, that such minerals in their pyrognomic state should be in rocks allegedly formed by igneous fusion? Given that they crystallized prior to quartz and that the quartz allegedly crystallized from melt, Scheerer reasoned that the pyrognomic minerals would have been at a high temperature long after they solidified. How then, he wondered, did they acquire and retain their pyrognomic properties on the igneous theory?

THEORIES OF ORIGIN

Opponents of the origin of granite by dry igneous fusion said that they favored the formation of granite in the wet way. Although their conceptions of what that expression meant commonly lacked rigor and clarity, it was clear enough that they believed that water played a major role in the formation of granite. Perhaps two major ideas about the origin of granite prevailed among the advocates of the wet way. On the one hand were those who perceived granite as the product of metamorphism of preexisting rocks in the presence of pervasive aqueous solutions. On the other hand were those who suggested that granite arose from "aqueo-igneous fusion." For a few like Hunt, the truth, as they saw it, lay somewhere in between.

Those who called attention to the gradations of other rock types into granites typically stressed the metamorphic origin of granite. Virlet d'Aoust (1847), for example, suggested that the transitions to granite represent a more advanced, intense stage of metamorphism than that which produced the gneiss. Such rocks, he said, were derived by transmutation of sedimentary rocks, and he described the processes as "gneissification" and "granitification." He believed that the preservation of stratification or schistosity in the granites of central

France and Brittany indicated that low temperatures had prevailed in some cases of "granitification." C.W.C. Fuchs accepted Bischof's views in a memoir on granite in the Harz Mountains. He regarded the granite as a product of progressive alteration of sedimentary greywacke into hornstone and then into granite by means of water. Geikie (1866) concluded that the crystalline rocks in southern Scotland had formed by the in situ alteration of bedded deposits.

One of the leading proponents of "aqueo-igneous fusion" was Scheerer. Despite his preachments against the plutonists like Durocher, Scheerer (1847) conceded in the end that heat played an important role in the formation of granite. Nevertheless, he pointed out that many of the minerals of granite such as mica, tourmaline, and allanite (he also included gadolinite) contain combined water. Because combined water was presumably present when the granite was still a pasty mass, Scheerer suggested that the granite formed from a paste impregnated by water and heated under strong pressure. Such a melt or paste could form, he argued, at a temperature much lower than an equivalent anhydrous melt. He saw the melting of hydrous salts as an analog. Bemoaning the thought that his conclusion might not be experimentally demonstrable, Scheerer reasoned that water particles helped to separate the atoms in a melt from one another more widely than they would be in an anhydrous melt state at high temperatures. He envisioned that early-forming minerals would be those capable of overcoming the atom-separating effects of water. As they crystallized, water would be concentrated in the residual silica-rich liquid. Thanks to the continuing "augmentation" of water in the increasingly siliceous melt, he thought, quartz would solidify very late. At the time of final granite solidification, water would be released from the melt. In such a way, too, Scheerer maintained, pyrognomic minerals could retain their properties because they would be crystallizing at temperatures much below their points of fusion.

Scheerer also believed that his idea of granite forming from a wet paste or melt could account for the transformation of argillaceous schist into gneiss and granite. He envisioned that a wet, hydrous granitic liquid would be sufficiently fluid that it could easily penetrate between the foliation planes of schist.

In writing on volcanic and metalliferous emanations, Élie de Beaumont (1847) observed that volcanic rocks are dominantly basic and that plutonic rocks are dominantly acidic. Each group is characterized by its own suite of mineralizing emanations, he said. He regarded these emanations as volatile substances, either vapors or solutions, that were capable of transporting silicates and metals. Élie de Beaumont noted that the effect of such emanations was particularly striking in the vicinity of granites such that there is commonly found an "aura" surrounding granite that partakes of some of the characters of granite, including pegmatite, graphic granite, and greisen. While acknowledging the possibility of different origins for granite, he accepted the notion that many granites solidify from melts that are charged with various vapors and mineralizers, particularly water.

The ideas of Hunt fell somewhere between these two extremes. Beginning at least as early as 1858, Hunt, the founder of American geochemistry, wrote a never-ending torrent of papers and delivered an unceasing stream of talks in which he espoused a distinctive view of the chemical history of the Earth that incorporated the idea of the sedimentary origin of granites. Thomas Sterry Hunt (1826–1892) spent a couple of years at Yale, without taking a degree, as an assistant to Benjamin Silliman in performing water analyses (Pumpelly, 1893). In 1847, the Geological Survey of Canada hired Hunt as a chemist and mineralogist, a post he held until 1872. During this time, he simultaneously held professorial posts at Laval University (1856–1862) and McGill University (1862–1868). From 1872 to 1878 he was Professor of Geology at Massachusetts Institute of Technology. It was Hunt who made a motion at the 1876 meeting of the American Association for the Advancement of Science proposing the development of a plan for establishing an International Geological Congress. A brilliant chemist and original thinker whose ideas were insufficiently tempered by careful field work and were typically presented in a controversialist style, Hunt often locked horns with other geologists on many issues. Beginning in 1859, Hunt's radical views appeared on a regular basis in *Geological Magazine*, *Quarterly Journal of the Geological Society of London*, and *American Journal of Science*. In a paper originally read before the American Association for the Advancement of Science meeting in Montreal in August 1857, Hunt (1859) explained his theory of transformation of sedimentary deposits into crystalline rocks. This transformation was not, he argued, simply the result of heating these rocks near the point of igneous fusion. Rather, he claimed that the various silicates in crystalline rocks were formed by the interactions of sedimentary rocks with alkali and earthy carbonates in the presence of silica. Even plutonic rocks, he said, were represented among altered sedimentary strata. Crystalline aggregates of quartz, feldspar, and mica were supposed to display transitions from mica schist through gneiss to stratified granite. Diorite and serpentine, likewise, were said to show such transitions and to have resulted from the alteration of sedimentary rocks rich in magnesia. But metamorphic rocks like granite, diorite, dolerite, serpentine, and limestone, he acknowledged, may appear to be intrusive under certain conditions. As a result, he agreed that the theory of aqueo-igneous fusion applied to granites by Scrope, Scheerer, Élie de Beaumont, and others should be extended to other intrusive rocks. These are in all cases, he insisted, altered and displaced sediments. "The metamorphism of sediments in situ, their displacement in a pasty condition from igneo-aqueous fusion as plutonic rocks, and their ejection as lavas with attendant gases and vapours," Hunt (1859, p. 496) asserted, "are, then, all results of the same cause, and depend on differences in the chemical composition of the sediments, temperature, and the depth to which they are buried." For Hunt, water brought about the transformation of sediments into stratified gneiss containing quartz and ultimately brought about sufficient mobility of the gneiss to result in eruptive behavior. Granite, therefore, was remobilized gneiss that had lost its stratification. Although Hunt eagerly applied Scheerer's name of aqueo-igneous fusion to this water-mobilized mass, it was never clear whether he regarded the mobilized mass as actually molten as Scheerer did.

THE DEFENSE OF DRY FUSION

Subsequent to the labors of the early plutonists like Hutton, Hall, and Playfair, the case for the igneous origin of granite was taken up primarily by French and German geologists, many of whom specifically espoused the idea that granite crystallized from a "dry" melt lacking in water, a melt that they began to designate as "magma." In 1844, the French geologist and chemist, Joseph Fournet (1801–1869) provided the first serious attempt since Playfair to answer the argument from texture against the origin of granite by dry fusion. Fournet graduated from École des Mines in 1822 and became Professor in the Faculté des Sciences at the University of Lyon in 1834, where he specialized in the study of metals and mining geology. Fournet was probably the first geologist to use the term "magma" in its modern sense in reference to igneous melt. In a paper on the circumstances of crystallization in veins, Fournet (1838) noted that "petrosilex" could be chemically distinguished from feldspar by a great excess of silica that is intimately disseminated in a "magma." He also referred to "injected magma." The term "petrosilex" had originally been applied by Alexandre Brongniart to felsites on the mistaken assumption that they were hornstones, that is, very finely crystalline, brittle, flint-like quartz rocks. The rock was considered roughly equivalent to the Scandinavian "hälleflinta." Both rocks eventually proved to contain both quartz and feldspar. Despite the fact that the name felsite was already available, the rock name "petrosilex" persisted for a few decades, at least until the 1860s, and then finally faded from view.

In regard to the texture of granite, Fournet (1844) pointed out that under certain conditions the melting points of some substances appear to occur at higher temperatures than those at which they normally freeze. He suggested that the solidification of quartz in granite might be delayed to a much lower temperature than its fusion point by this phenomenon, which he termed "surfusion." The "surfusion" of quartz, he proposed, accounted for the fact that quartz typically forms later than feldspar. We know now that the equilibrium melting and freezing points of a pure mineral are identical. Before crystallizing, however, many silicate liquids may be greatly undercooled because of their extreme viscosity. Such behavior led Fournet and his contemporaries to believe that the melting and freezing points of a mineral are not necessarily the same. For virtually the entire nineteenth century, therefore, experimentalists made a distinction between the melting point and the solidification point of a mineral.

Fournet's theory of surfusion failed to gain much support from any quarter, even from Durocher, one of the most enthusiastic proponents of dry fusion of granite. Joseph Durocher (1817–1860) was a graduate of École Polytechnique and École des Mines (Joubin, 1900; Troalen, 1943). Durocher participated as an engineer on a scientific voyage to Spitzbergen, the Faeroe Islands, and Finland in 1839 and reported on the mountain structure, glacial erosion, and glacial deposits of those regions. In 1841, he was appointed to the Faculty of Sciences at the University of Rennes and continued service as a mining engineer. His research included investigations of glacial phenomena, structural geology, and metalliferous deposits in Scandinavia as well as igneous and metamorphic rocks throughout the Pyrenees, France, the Alps, and Central America. In a major contribution to the discussion about the origin of granite in which he perpetuated Fournet's use of the term "magma," Durocher (1845) began by noting that the relative arrangement of the minerals (which, at the time, many geologists called "elements") in granite seemed to present an anomaly to the laws of physics in that the arrangement appeared to be incompatible with the easy fusibility of feldspar and mica and the heat-resistant character of quartz. As virtually everyone had recognized, the feldspar commonly imprinted its crystal outlines on the enveloping quartz, indicating that the former had crystallized first. Durocher pointed out examples in which that was indeed the case, but, like Playfair, he also described examples in which quartz crystals are surrounded by feldspar. These reversed situations, he argued, pointed inevitably to the conclusion that the solidification of all the constituent "elements" had to occur at about the same time. How then, he asked, do we explain the nearly simultaneous crystallization of substances whose fusibilities are so different?

Fournet's theory of surfusion was insufficient to account for the observed textures. The problem, said Durocher, is that the temperature difference between the melting or fusion point and the point of solidification of a particular substance is rarely more than 100°C. In his estimation, that was much too small a difference to account for the crystallization of feldspar, tourmaline, or garnet prior to quartz. After all, he pointed out, the difference in fusion points between these minerals and that of quartz is hundreds of degrees. Rather than appealing to Fournet's surfusion theory for support, as was erroneously stated by von Zittel (1899) in his work on the history of geology, Durocher made the far-sighted claim that the component parts of the individual minerals in the molten state of granite were not isolated from one another as they are in the minerals within a rock. In other words, he suggested that melted granite did not consist of molten feldspar domains, molten mica domains, and molten quartz domains, as was commonly envisioned. Rather, he believed that the substances of the various minerals were combined into a homogeneous mass composed of silica, alumina, alkaline and earthy bases, potash, soda, lithia, a little lime and magnesia, oxides of iron and manganese, and even hydrofluoric and boric acids. In effect, Durocher suggested that "le magma granitique" was something like a solution without making the identification explicit as Bunsen (1861) would do later. Durocher proposed to show that the granitic magma would stay fluid and homogeneous while losing its heat until a temperature just above the fusion point of feldspar.

Prior to crystallization of the minerals, Durocher suggested, the silica in the melt was combined with the other silicates in a manner that he regarded as analogous to that of sulfuric acid and alkali sulfate. When silicic acid is united to an alkali silicate or an earthy silicate, he said, heat is produced just as heat is released when sulfuric acid unites with an alkali sulfate. Conversely, he pointed out that separation of these compounds would be accompanied by the absorption of heat. Durocher claimed that when quartz separated from cooling magma, it absorbed heat from the melt, thereby keeping the quartz in a softened condition and also lowering the melt temperature and hastening its solidification. The lengthened state of softness of the quartz would enable it to take the imprint of the crystalline form of the feldspars.

Perhaps not fully confident of his own reasoning, Durocher claimed that even if this temperature-lowering mechanism were insufficient, it still would not invalidate the theory of igneous fusion. With nearly simultaneous crystallization, he argued, some minerals will crystallize sooner than others depending on whether they pass through a viscous state in solidifying or take on the solid state almost immediately. The reason that quartz is generally the last mineral to crystallize, he maintained, is because it normally passes through a viscous condition before it solidifies. Under such conditions quartz may even be pulled into threads. In contrast, he said that feldspar, whose solidification is accelerated by a great tendency to become crystalline, passes much more rapidly from the state of fusion to the solid state. As a result, in the process of consolidating, the quartz remains pasty and soft at the moment when feldspar crystallizes. In Durocher's mind, the fact that quartz leaves an imprint on feldspar in some cases obviously showed that feldspar and quartz both pass more or less simultaneously from the liquid state to the solid state although the amount of time required for the passage would not be the same for both minerals.

Durocher then developed an elaborate argument to demonstrate that mica, feldspar, and quartz, the three "elements" of granite, remained in a combined state until their time of solidification. From the variation in the proportions of quartz, feldspar (orthoclase and albite), and mica in granites and the average chemical compositions of feldspar and mica, Durocher determined average chemical compositions for very feldspathic granites, very micaceous granites, and normal granites. He compared these compositions to those of petrosilex and noted the striking similarity in the composition of petrosilex to the feldspathic and micaceous granites. But, Durocher pointed out, petrosilex would easily melt in the flame of a blowtorch, and its fusibility is only a little less than that of feldspar. From this evidence, he concluded that granites are more fusible than one would suspect initially. The key to solving the problem lay in the fact that when the various silicate minerals were combined, they were much less resistant to melting than when they were isolated. In Durocher's view, feldspar, mica, and quartz associated in the same material possessed a fusibility that is greater than the average fusibility of the minerals considered individually. He saw no reason why granite could not keep all of its "elements" together in the liquid state just prior to solidification if petrosilex could do it.

Durocher drew further evidence from the character of porphyry. Porphyries, he noted, have textures ranging from that of petrosilex to that of granite, and in some cases the textural variants may be seen in the same mass. He was persuaded, too, of the similarities in chemical composition, mineralogy, and density among porphyry, petrosilex, and granite. Moreover, he had found porphyries of the same age as granite, in contradiction to the very common opinion that granites are much older than porphyry. He concluded that:

> All the considerations converge then to justify the combination of granite, of quartz porphyries, and petrosilex in the same class of rocks, unquestionably the most important of all. These three substances, if differing outwardly, constitute the three terms of a series, the granite and the petrosilex being the extreme terms and the quartz porphyries establishing a link between the two. Thus, the granite had to be originally from masses of analogous composition to those of petrosilex; when their cooling had taken place without dividing the elements, they remained in the state of petrosilex; when the separation of elements was incomplete, it formed a quartz porphyry . . . . Finally, when the separation of elements reached its last term, when the igneous mass, which was first of all at the state of a soft paste and homogeneous, was entirely decomposed and resulted in three or four different minerals, it gave birth to granites; the petrosilex rocks then achieved complete development. (Durocher, 1845, p. 1283)

Calling on his experience with metal alloys, Durocher likened this difference in crystallization behavior of granitic liquid to that observed in melted iron when cooled. Under some conditions, he said, some of its carbon is released in crystalline form (black melting), but under other conditions it retains all its carbon in a state of combination (white melting). Cooling circumstances, he suspected, played a crucial role in the formation of the end product, whether petrosilex, porphyry, or granite. A more rapid cooling, he asserted, took place during the formation of petrosilex and porphyry, so that the separation of the constituent minerals was more difficult than in more slowly cooled granites.

Durocher concluded his seminal paper by observing that other presumably igneous rocks had their fine-grained equivalents: aphanite was the equivalent of diorite, melaphyre was the equivalent of basalt, and trachytic porphyry the equivalent of trachyte. "It would be astonishing," Durocher (1845, p. 1284) observed, "that the granites alone . . . never present themselves in the compact state; until the present they seemed to be the exception to the general law, but their combination with the quartz porphyries and the petrosilexes made this exception disappear and came to fill the gap in the natural series of igneous rocks."

Durocher also made a presentation on the origin of granite before the Societé Géologique de France at its meeting of June 7, 1847. Having heard Scheerer's paper at the previous meeting, Durocher (1847) prepared a rebuttal in which he reiterated many of the same lines of argument that he had developed in his 1845 paper. He presented hand specimens and drawings of textures demonstrating that quartz is not always the last mineral to solidify from granite. He reviewed his claim that the minerals in granite crystallized almost simultaneously and that granite, porphyritic trachyte, and petrosilex are closely related. He refuted the argument that quartz does not appear in slowly cooled silica-rich lavas by pointing out that, although presumably not common, there are examples of trachytes from Siebenberge, the Auvergne, and Italy that do contain well-formed quartz crystals. Moreover, he asserted that some of the Italian examples display textural gradations among trachyte, trachyte porphyry, quartz porphyry, and granite. In the eyes of Durocher (1847, p. 1028), these rocks provided "one of the most powerful arguments in favor of the igneous origin of granite." He dismissed Scheerer's argument from the presence of pyrognomic minerals by pointing out analogous situations in which a substance, after having been altered, eventually returned to its original state. Why, he asked, might not a pyrognomic mineral also regain its original characters long after having cooled from a melted state?

Durocher said that he would be the first to accept Scheerer's suggestion that granite might have formed by aqueo-igneous fusion if it were in harmony with facts, but he set out to demonstrate that it was not. On the basis of several chemical analyses he had made, he belabored the point that granites contain only small amounts of combined water, in many cases less than one percent. He knew, too, that where obvious signs of alteration, like kaolinization, are present the water content increases markedly. As a result, Durocher was not fully convinced that the water in seemingly fresh granites might not also in some way be the result of atmospheric contamination. Although he conceded that water in granite might be original, he maintained that the source of that water really had to be regarded as uncertain.

Scheerer had suggested that the melting of hydrated salts at lower temperatures than their anhydrous analogs provided a model for the lowering of the fusion point of granitic liquid containing water. Durocher countered that the analogy was invalid because the melting of a hydrated salt entails little more than increased solubility in its water of crystallization at elevated temperature. What evidence is there, Durocher challenged, of a vastly heightened solubility of quartz and feldspars in water? We know next to nothing about the solubility of quartz in water, he said. Moreover, he believed that there is insufficient water in granite to dissolve the silicate minerals.

Noting the copious volumes of water vapor emitted at volcanic centers, Durocher pointed out that no one had cited any evidence that the water had lowered the fusion temperature of the lava to any significant degree in comparison with an anhydrous silicate melt observed in a furnace. In addition, he said, lavas often contain cavities that are filled with druses as a result of the water present, but granite, as a very compact crystalline rock, presented no such cavities or vesicular structure as lava. Durocher took this lack of vesicularity as one more line of evidence that granitic melts contained very little water. In the end, Durocher said that he would find Scheerer's idea of aqueo-igneous fusion of granite easier to accept if granites contained 12 to 15 percent water and if the minerals of granite were more notably soluble in water. Over the next few years, Scheerer and Durocher offered brief rebuttals of each other's views, but neither moved from his fundamental position.

Many prominent German chemists, geologists, and petrographers also leaned toward a plutonic origin of granite. They did not particularly like the term "igneous" because they felt that it implied the presence of fire in the formation of the rocks. They also believed that metamorphic rocks had been subjected to heat just as much as igneous rocks had. As a result, they much preferred to use the terms "eruptive" or, in some cases, "pyrogenic." For the next several decades, therefore, German geologists characteristically referred to igneous rocks as "Eruptivgesteine" (eruptive rocks), a designation that did not meet with universal approval. England's Joseph Jukes, for example, thought it preferable, at least as regards what we now think of as plutonic igneous rocks, to speak of "intrusive" or "irruptive" rocks inasmuch as such rocks were not erupted onto the surface in a molten condition.

Among the German plutonists were Naumann and von Cotta. Karl Friedrich Naumann (1797–1873) was arguably the leading petrographer of the pre-microscopic era (Burke, 1974b). Naumann was a student of Werner at Freiberg in 1816, and much of his early professional career was spent at the University of Jena and the Bergakademie, first as Professor of Crystallography beginning in 1826, and then as Professor of Geognosy beginning in 1835. At the height of his career, Naumann moved to the University of Leipzig in 1842, where he became Professor of Mineralogy and Geognosy. At Leipzig, he issued a two-volume work, *Lehrbuch der Geognosie* (Naumann, 1850, 1854), probably the most authoritative work on petrography of the mid-nineteenth century. A three-volume second edition appeared between 1858 and 1866.

In the first volume of *Lehrbuch der Geognosie*, Naumann (1850) addressed the issue of the origin of granite. He suggested that Durocher (1845) had satisfactorily answered concerns about the textural character of granite. The appearance of quartz, he concluded, offered no serious objection to the pyrogenic origin of granite. Naumann perpetuated Durocher's references to granitic "magma" by using the term repeatedly in expressions such as "homogeneous molten magma" and "water-free magma." Use of the term "magma" was now beginning to take hold in reference to igneous melts. Naumann was, however, attracted to Scheerer's suggestion that granitic melts contain small amounts of water that contributed to considerable lowering of their solidification temperatures.

Another prominent German petrographer who leaned toward plutonic granite was Carl Bernhard von Cotta (1808–1879). Von Cotta graduated in 1831 from the Bergakademie, where he studied under mineralogist Johann F. A. Breithaupt (1791–1873) and learned neptunian geology from K. A. Kühn (Prescher, 1971). After leaving Freiberg he studied under von Leonhard for a year in Heidelberg. In 1833, he began participation in the Geological Survey of Saxony under the leadership of Karl Naumann and brought the project to completion by 1845. During a part of that time, von Cotta taught at the Tharandt Forestry Academy, but upon the departure of Naumann from Freiberg in 1842 for the University of Leipzig, von Cotta succeeded him as Professor of Geognosy and Paleontology. Von Cotta spent the remaining 32 years of his professional career at the Bergakademie. He first lectured on geognosy, but later added paleontology and perhaps the earliest course in ore deposits. In 1848, he was one of the founders of the German Geological Society (die deutsche geologische Gesellschaft).

In his petrographic work, *Die Gesteinslehre*, von Cotta (1855) accepted Durocher's reasoning regarding the order of crystallization in granite and approved the idea of Bunsen (1861) that granitic melt is a solution. Moreover, von Cotta said that the objection against the igneous origin of granite and some other crystalline rocks from the presence of relatively fusible, but early crystallizing accessory minerals lost its force because some of those same accessory minerals occur in lavas of undoubted igneous origin.

The defense of dry igneous fusion by Fournet and Durocher did not convince everyone. Like Durocher, Scheerer (1847) also disputed Fournet's hypothesis of surfusion, taking him to task for forgetting that the maximum difference in temperature between the fusion point and the solidification point observed for any known substance, namely sulfur, was only about 100°C. Knowing that silica requires a higher temperature to melt than platinum metal, Scheerer estimated the fusion temperature of quartz around 2800°C on the grounds that the melting point of platinum was thought to be a little above 2500°C and that quartz had been melted in a blowtorch flame whose temperature was estimated at 3100°C. He believed that minerals like pyrite probably melt around 1000°C and minerals like amphibole, garnet, and tourmaline have fusion points below 1400°C. As a result, Scheerer maintained, quartz would need to have the property of solidifying anywhere from 1300°C to 1800°C below its point of fusion for the surfusion hypothesis to explain granitic texture. Carl Bischof completely agreed that Fournet's idea of "superfusion" was entirely inadequate to save the case for igneous quartz.

Scheerer also noted that Durocher (1845) had attempted to explain the textural evidence in granite by maintaining that crystallization was essentially simultaneous. If so, Scheerer claimed, one should encounter crystals of feldspar and other more fusible minerals, but not quartz. He believed that, on Durocher's theory, an amorphous silicate something like petrosilex should have solidified in the spaces between feldspar crystals. Durocher's conception, he alleged, should lead to the production of a porphyry that lacks quartz.

FOUNDATIONS FOR A RESOLUTION OF THE DEBATE

For several decades, French and German geologists, the principal participants in the debate about the origin of granite, were unable to reach a consensus. Theories of origin included the injection of anhydrous granitic melts (dry fusion), the injection of granitic melts containing water under pressure (aqueo-igneous or igneo-aqueous fusion), and the conversion of sedimentary rocks into granitic rocks by metamorphic processes aided by water. All these views had several able advocates. Had it not been for the application of the polarizing microscope to the study of rock thin sections beginning in the 1850s and 1860s, theorizing about the origin of granite might have remained in a stalemate for many more years to come. Although not appreciated at the outset, the new technique eventually offered new insights toward a solution of the long-standing knotty problem. The development of the new microscopic methods also lured British geologists back into the fold of thinkers about granite after a long absence.

It was Henry Clifton Sorby (1826–1908) who introduced the polarizing microscope into the discussion about granite. He also led Britain back into the discussion about the nature of granite. Sorby early developed interests in science (Judd, 1908; Higham, 1963). As a man of independent means, he was able to devote himself exclusively to a life of scientific research. After an early interest in the chemical analysis of agricultural materials, Sorby became much intrigued by the processes of sedimentation. As a very young man in the 1840s, Sorby had already begun studying the fossil shells in the Bridlington Crag, which crops out near Scarborough on the North Sea coast of his native Yorkshire, and he was in the habit of using a microscope to study them. It was during this period that he made the acquaintance of William Williamson on a trip from Scarborough to York. Williamson, already skilled in the use of diamond and emery wheels to prepare thin sections of hard materials like teeth, bones, scales, and fossil wood, gave Sorby a lesson in making such slices. Given his interest in rocks, Sorby began to make his own thin slices of rocks and began to publish papers on his discoveries. After a handful of papers on both sedimentary and metamorphic rocks, Sorby (1851, 1853) wanted to see if the new method could shed any light on the debate over granite.

In a paper read before the Geological Society of London on December 2, 1857, and entitled "On the microscopical structure of crystals, indicating the origin of minerals and rocks," Sorby (1858) stated that he would demonstrate that both artificial and natural crystalline substances possess characteristic structures indicating whether they were deposited from aqueous solution or crystallized from a state of igneous fusion. He proposed to approach the question through a study of the fluid inclusions within minerals. Sorby compared the character of fluid inclusions within artificial crystals formed by precipitation from solution, by sublimation, and by fusion with those contained in natural crystals collected from deposits of halite and calcite, quartz veins, metamorphic rocks, volcanic rocks, and granitic rocks.

Sorby found that many of the fluid inclusions in granites display the same characteristics as inclusions in known volcanic rocks. He also found that granitic rocks possess water-filled cavities containing crystals of alkali chlorides and sulfates. He concluded that the range of types of inclusions in granites indicated that they were the product of igneous fusion but specifically fusion in the presence of water under pressure. Sorby, therefore, envisioned the molten silicate rock as dissolving water. Consequently, he found himself in general agreement with Scheerer and Élie de Beaumont concerning the origin of granite. Granites were not, in his view, the product of pure dry igneous fusion. Sorby estimated pressures and temperatures from the inclusions and determined that all the granites that he examined were consolidated under pressures equivalent to those exerted by rock columns 18,000 to 78,000 feet thick. He envisioned a continuum extending from volcanic rocks formed by pure igneous fusion to quartz veins formed by aqueous deposition with granite forming the central link in the series.

According to Dawson (1992), one of Sorby's early studies of thin sections entailed an examination of some sections of metallurgical slags, the products of James Hall's fusion experiments on basalt, and fused samples of Mount Sorrel granodiorite. Sorby (1863) compared thin sections of Hall's fused granodiorite sample with those of the natural rock and concluded that the differences could be attributed to the much slower cooling of the natural granodiorite and to the presence of water under pressure in the granodiorite melt. He maintained that the water acted as a flux and promoted the coarse grain of the granodiorite.

Sorby's fellow Englishman David Forbes (1826–1877) also entered the granite debate in the 1860s (Sorby, 1876; J. M., 1877). A graduate of the University of Edinburgh, Forbes spent much of his career as a mining engineer working with private companies. He developed a wide-ranging knowledge of geology through his extensive experience in such diverse locations as Norway, the South Seas islands, and South America. After returning to London, Forbes became one of the very earliest geologists to be exposed to the possibilities of the new thin-section microscopy. He was aggressively enthusiastic in promoting microscopic investigation and became very impatient with other geologists who failed to incorporate the latest knowledge in chemistry and other sciences into their geological work. His zeal for avant garde science brought Forbes into open conflict with James Geikie and Hunt in regard to the granite question. While agreeing with Geikie that the origin of granite would ultimately be solved by the field observer, Forbes (1867a) insisted that it would be a field observer who had a sound knowledge of chemistry, mineralogy, mathematics, physics, and the new microscopic methods developed by Sorby. Even more than his mentor, Forbes lobbied his fellow countrymen to take full advantage of the insights that could be gleaned through this new technique. While the "mere field observer" might be taken in by Geikie's assertions that stratified beds like graywacke could be converted in situ into granite "by the wondrous agency of hydrothermal action," Forbes (1867a, p. 51) charged, the geologist who possessed even a little knowledge of chemistry would immediately see the incorrectness of the chemistry on points "where even the merest tyro ought not to blunder."

Forbes chided Geikie for failing to provide a chemical demonstration that graywackes had been converted into granite. He also thought it suspicious that graywacke could allegedly be converted into diorite and serpentine, rocks that differed considerably from granite both mineralogically and chemically. He criticized Geikie for failing to determine the kind of feldspar present in the allegedly transformed rock. How then, Forbes asked, can he be sure that the rock is a granite?

Forbes also carried on a running feud with Hunt for several years. A typical response of Forbes (1867b, p. 442) to Hunt charged that it had become fashionable to "'pooh-pooh' the igneous origin of eruptive rocks in general, and of granite in particular." Forbes regarded this attitude as a secession from opinions about granite that, he said, had more or less become universally adopted. He complained that Hunt, like so many geologists and chemists earlier in the century, continued to push the tired claims that quartz, one of the constituent elements of granite, resulted only from secondary processes and that granite, because it contains quartz, must always be a rock of sedimentary origin. Does not Hunt know, Forbes (1867b, p. 442) asked, about the "immense masses of undoubted volcanic rocks scattered all over the surface of the globe which contain abundance of free quartz?" He wondered, too, if Hunt knew about Sorby's microscopic studies showing the identity in structure between volcanic quartz and the quartz of granite and if he knew about Sorby's conclusion that modern volcanic trachytes and old granites have a common igneous origin in which water has played some part.

Within a few years, continued prodding by the microscopists would open the door to much wider acceptance of igneous granite. Another development that ultimately contributed to a recognition of the igneous origin of granite was Bunsen's claim that granitic melt is a solution. Robert W. E. Bunsen (1811–

1899) studied chemistry, physics, and mineralogy at the University of Göttingen (Schacher, 1970). Bunsen (Figure 7) spent much of the 1830s visiting various laboratories and sites of geological interest throughout Europe. In 1832, he studied the mineral and rock collections of the mineralogist C. S. Weiss at the Bergakademie of Freiberg. The following year, Bunsen began his academic career with a series of posts at Göttingen, Kassel, and Marburg. He moved to the University of Heidelberg in 1852, where he remained until retirement. Bunsen's brilliant career as an experimental chemist included the discovery of cesium and rubidium, important work on spectroscopy and galvanic batteries, and the development of instruments such as the famous burner that bears his name.

In 1861, Bunsen published a three-page article entitled "Über die Bildung des Granites." Bunsen (1861) wished to call attention to the long-held erroneous assumption that the igneous origin of granite was negated by the fact that the highly infusible quartz had crystallized last. Bunsen said he was at a loss to understand how that erroneous conclusion had survived for so long and was still being used. Although the earlier efforts of Hall and Durocher to explain granitic texture were moving in the right direction, it was Bunsen who first explicitly pointed out that granitic magma is a solution. "No one," Bunsen (1861, p. 61) lamented, "appears to have thought about the fact that the temperature at which a body solidifies independently is never that temperature at which the body becomes fixed in another body when (the first body) solidifies out of its solutions." One may not object, Bunsen said, that granitic melt cannot be a solution simply because it is hotter than aqueous solutions, and no chemist would arrive at the "widersinninge Idee" (absurd idea) that a solution stopped being a solution just because it is heated a few hundred degrees. Moreover, he pointed out, there is the phenomenon of freezing-point depression that occurs in mixtures such as water and calcium chloride where the temperatures at which ice or calcium chloride crystals form depend on the relative proportions. In any case, Bunsen observed, in these mixtures, the solidification point of water can be lowered 59°C below its freezing point as a pure substance, and the solidification point of calcium chloride can be lowered nearly 100°C below its freezing point as a pure substance. Bunsen also reminded his readers that the sequence of crystallization from solution, whether first water and then salt or first salt and then water, depended on the proportions of water and salt in the solution. For the same reasons, Bunsen insisted, quartz and feldspar will not solidify from their molten granitic solution at their respective melting points. He agreed with the observation of Durocher that in feldspar-rich graphic granite, quartz separates before feldspar, that in other granites quartz crystallizes simultaneously with feldspar, and that in still other granites quartz forms after the feldspars. Bunsen claimed that such phenomena are exactly what one would expect of a solution in which the proportions of dissolved quartz and feldspar varied. Quartz, he concluded, crystallizes from a molten

7. Robert Bunsen (1811–1899). Reproduced by permission of the Archives of the University of Heidelberg.

granitic solution well below its melting point just as it crystallizes from an aqueous solution well below its melting point.

The nineteenth-century debate over the origin of granite largely fizzled out with the dispute between Hunt and Forbes in the 1860s. In the 1870s, the growing acceptance of both the results of microscopic petrography and the solution theory of magma also led to widespread acceptance of igneous, eruptive, magmatic granite. The nineteenth-century furor over the origin of granite had continued for several decades and involved the efforts of some of the greatest geologists of the era. At first, the granite debate primarily involved geologists of France, Germany, and, to a lesser extent, Scandinavia. Only after the late 1850s did geologists from Great Britain and finally America enter the fray. Opinions did not fall out markedly along nationalistic lines. The notion of dry igneous fusion was accepted by French geologists Durocher and Fournet and German geologists Naumann and von Cotta. Aqueo-igneous fusion entailing genuine intrusive granitic melt was accepted by Scheerer and also by Naumann in Germany, Delesse and Élie de Beaumont in France, and Sorby and Forbes in England. Conceptions that entailed the idea of metamorphic transformation in the presence of aqueous fluids were posited by Daubrée in France, Bischof and Rose in Germany, Geikie in England, and Hunt in America. Some geologists, like Durocher, linked their view of granite to a larger conception of primitive magma shells in the interior from which magmas of contrasting composition were derived. Others leaned toward derivation of mobilized granite, whether molten or not, from preexisting rocks within the lower part of the solid crust. Into the 1860s, no consensus had been reached, and the views of geologists about granite played a major role in the manner in which they classified the entire spectrum of rocks.

MIND OVER MAGMA

THE STORY OF IGNEOUS PETROLOGY

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PRINCETON UNIVERSITY PRESS
Princeton and Oxford

Published by Princeton University Press, 41 William Street, Princeton,
New Jersey 08540
In the United Kingdom: Princeton University Press, 3 Market Place,
Woodstock, Oxfordshire OX20 1SY

Library of Congress Cataloging-in-Publication Data

Young, Davis A.
Mind over magma : the story of igneous petrology / Davis A. Young.
p. cm.
Includes bibliographical references and index.
ISBN 0-691-10279-1
1. Rocks, Igneous. I. Title.
QE461 .Y66 2003
552'.1—dc21 2002030790

British Library Cataloging-in-Publication Data is available

This book has been composed in Berkeley and Albertus

Printed on acid-free paper. ∞

www.pupress.princeton.edu

Printed in the United States of America

1 3 5 7 9 10 8 6 4 2