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Catastrophic Granite Formation: Rapid Melting of Source Rocks, and Rapid Magma Intrusion and Cooling

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Abstract

The timescale for the generation of granitic magmas and their subsequent intrusion, crystallization, and cooling as plutons is no longer incompatible with the biblical time frames of the global, year-long Flood cataclysm and of 6,000–7,000 years for earth history. Though partial melting in the lower crust is the main rate-limiting step, it is now conjectured to only take years to decades, so partial melting to produce a large reservoir of granitic magmas could have occurred in the pre-Flood era as a consequence of accelerated nuclear decay early in the Creation Week. Rapid segregation, ascent, and emplacement now understood to only take days via dikes would have been aided by the tectonic "squeezing" and "pumping" during the catastrophic plate tectonics driving the global Genesis Flood cataclysm. Now that it has also been established that granitic plutons are mostly tabular sheets, crystallization and cooling would be even more easily facilitated by hydrothermal convective circulation with meteoric waters in the host rocks. The growth of large crystals from magmas within hours has now been experimentally determined, while the co-formation in the same biotite flakes of adjacent uranium and polonium radiohalos, the latter from short-lived parent polonium isotopes, requires that crystallization and cooling of the granitic plutons only took about 6–10 days. Thus the sum total of time, from partial melting in the lower crust to crystallization and cooling of granitic plutons emplaced in the upper crust, no longer conflicts with the biblical time frame for earth history, nor is it an impediment to accounting for most of the fossil-bearing geologic record during the global year-long Flood catastrophe.

Keywords: granites, magma, partial melting, melt segregation, magma ascent, dikes, magma emplacement, emplacement rates, crystallization and cooling rates, convective cooling, hydrothermal fluids, polonium radiohalos

Introduction

The major, almost exclusive, rock type in some areas on the earth's surface, such as in the Yosemite National Park, is granite. Huge masses of many adjoining granite bodies outcrop on a grand scale throughout that area (fig. 1), as they also do along the length of the Sierra Nevada and the Peninsular Ranges of central and southern California respectively.

The Sierra Nevada batholith is the collective name given to all the granite bodies that outcrop in, and form much of, the magnificent Sierra Nevada range. Each recognizably distinctive granite mass, the boundary of which can be traced on the ground, is marked as a separate geologic unit called a pluton on a geologic map. Hundreds of such granite plutons, ranging in size from 1 km^2 to more than 1,000 km^2, and each with its own name, make up the Sierra Nevada batholith. The batholith stretches in a belt approximately 600 km (373 miles) long northwest-southeast and more than 165 km (102 miles) wide. It

Fig. 1. Panoramic view of the Yosemite valley with the Half Dome rising above the cliffs to the right, as seen from Glacier Point. The entire landscape in this panoramic view is composed of granites.

is uncertain how deep the granite plutons are, that is, how thick they are. Evidence suggests that many may only be several kilometers (or less) thick.

The Sierra Nevada batholith, and the Peninsular Ranges batholith just south of it, are part of a discontinuous belt of batholiths that circle the Pacific Ocean basin. For example, granite batholiths are found all through the coastal ranges along the west coast of South America and extend northward from the Sierra Nevada through Idaho and Montana, western Canada, and into Alaska. The granite plutons making up the Sierra Nevada batholith have intruded into and displaced earlier sedimentary and volcanic strata sequences, some of which had been transformed by heat, pressure, and earth movements into metamorphic rocks. These strata sequences have been variously designated as Upper Proterozoic (uppermost Precambrian) to Paleozoic and Paleozoic to Mesozoic. (In the biblical framework for earth history, that makes them Flood strata.) After the granite plutons intruded underground into these strata sequences, erosion (at the end of the Flood and since) removed all the rocks above the granites to expose them at today's ground surface. Again, it is uncertain as to just what thickness of overlying rocks have been eroded away, but it is likely only 1–3 km.

Because we don't observe granites forming today, debate has raged for centuries as to how granites form. While there is now much consensus, some details of the processes involved are still being elucidated. Nevertheless, the conventional wisdom has been adamant until recently that granites take millions of years to form, which is thus an oft-repeated scientific objection to the recent year-long global Genesis Flood on a 6,000–7,000 year-old earth as clearly taught in the Scriptures (Strahler 1987; Young 1977).

Several steps are required to form granites. The process starts with partial melting of continental sedimentary and metamorphic rocks 20–40 km (12–25 miles) down in the earth's crust (a process called generation) (Brown 1994). This must be followed by the collection of the melt (called segregation), then transportation of the now less dense, buoyant magma upwards (ascent), and finally the intrusion of the magma to form a body in the upper crust (emplacement). There, as little as 2–5 km (1–3 miles) below the earth's surface, the granite mass fully crystallizes and cools. Subsequent erosion exposes it at the earth's surface. When reviewing this list of sequential processes, it is not difficult to understand why it has been hitherto envisaged that granite formation, especially the huge masses of granites outcropping in the Yosemite area, must surely have taken millions of years (Pitcher 1993). Of course, such estimates are claimed to be supported by radioisotope dating.

However, this long-accepted timescale for these processes is now being challenged, even by conventional geologists (Clemens 2005; Petford et al 2000). The essential role of rock deformation is now recognized. Previously accepted granite formation models required unrealistic deformation and flow behaviors of rocks and magmas, or they did not satisfactorily explain available structural or geophysical data. Thus it is now claimed that mechanical considerations suggest granite formation is a "rapid, dynamic process" operating at timescales of less than 100,000 years, or even only thousands of years.

Magma Principles

First, however, it will be helpful to explain what magma is and why it is thought to exist underground. The molten material which flows from volcanoes is known as lava and cools to form volcanic rocks. So lavas must be molten rocks; that is, they were originally rocks that melted deep inside the earth underneath volcanoes. When deep inside the earth, these molten rock materials are called magmas because they are slightly different in composition and physical properties due to the steam and gases they have dissolved in them that erupt separately from the lavas through volcanoes.

Before volcanic eruptions there are warning "rumbles" inside volcanoes. These are earthquakes generated by the magmas moving up into the volcanoes. Such earthquakes have allowed geologists to reconstruct how magmas first "pond" below volcanoes in reservoirs known as magma chambers before their final passage upward through volcanoes to erupt as lavas. If the magma cools when it "ponds" in the magma chamber, rather than rising further to erupt at the earth's surface, then it crystallizes as an intrusion. Subsequent erosion of all the overlying rock layers eventually exposes such intrusions at the earth's surface.

This scenario has been confirmed by copper mining operations that have excavated into granite intrusions that must have formed under volcanoes. The remnants of such volcanoes overlie the granite intrusions, and their volcanic rocks are the same compositions as the granite intrusions (the former magma chambers) (fig. 2). Similarly, seismic surveys across the mountains somewhat central to many ocean basins have detected the magma chambers under the rift zones where lavas have erupted onto the ocean floor. Because the magma is less dense than the surrounding rocks, the passage of the seismic (sound) waves when recorded and compiled actually produces images (or three-dimensional pictures) of the magma chambers.

Laboratory experiments have produced very small quantities of magmas by the melting of appropriate

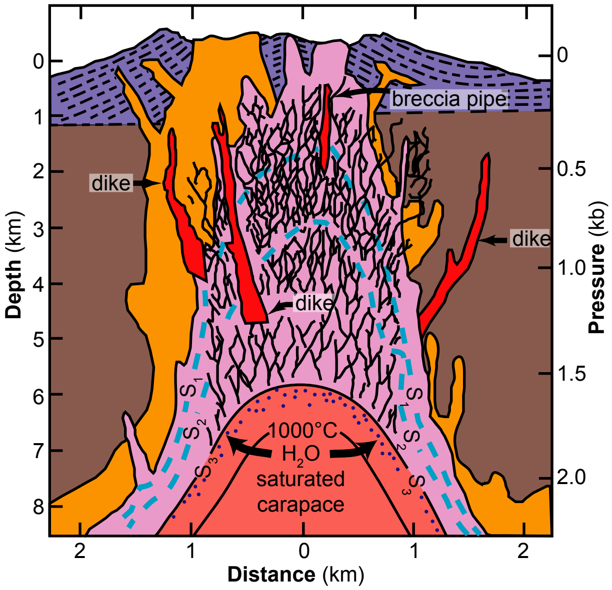

Fig. 2. Schematic cross-section through a small granite pluton at the stage of waning magmatic activity in the development of a porphyry copper ore deposit. The chaotic line pattern represents the extensive fracture system in the apex above the cooling water-saturated granite magma. Note that the granite has intruded into the volcanic rocks that earlier erupted from the volcano its magma supplied.

rocks. Such experiments are not easy to perform because of the difficulties of simulating the high temperatures and pressures inside the earth. The required laboratory apparatus thus only contains a very small vessel in which magmas can be produced. Yet many such experiments have enabled geologists to study and understand the compositions and behavior of magmas.

Magma Processes

Measurements on extruded magma (lava), together with evaluations of the temperatures at which constituent minerals form and coexist, and experimental determinations of rock melting relationships, indicate that magmas near the earth's surface are generally at temperatures from 700°C to 1,200°C (1,300–2,200°F). We know from direct measurements in many deep drillholes that rock temperatures inside the earth's crust increase progressively with depth. This is known as the geothermal gradient. From these measured geothermal gradients it is thus estimated that the temperatures needed to melt rocks and form magmas must occur at depths of greater than 30 km, at and near the bottom of the crust of continents, and in the upper mantle below.

Being molten rock materials, magmas are very dense liquids which have varying abilities to flow. Viscosity describes the ability of the magma to flow. This depends on the degree of immobility of the atoms inside the magma, the resistance of their arrangement or bonding to the stress that would cause flow. Viscosity is the internal friction or "stickiness" of a magma. A more viscous magma is very sticky and flows very slowly. A magma (or lava) that flows easily and thus quickly has a low viscosity.

Rheology is the study of the flow of magmas and of the ways in which magmas (and rocks) respond to applied pressures or stress. If a body of material returns instantaneously to its initial undeformed state once the stress applied to it wanes, it is said to be elastic. Magmas are not elastic, just viscous and plastic, because once deformed by applied stress they do not recover their original shapes, but instead flow.

The viscosity of a magma is dependent on its temperature and composition. It should be fairly obvious that the hotter a magma, the more quickly it will flow, because the heat gives its atoms more energy so their bonding is less resistant to applied stress. A hotter magma is thus less viscous. However, there are two compositional factors that affect magma viscosity the most—silica content and water content.

When igneous rocks are analyzed, their content of silicon atoms is expressed as a compositional percentage of silica, which is silicon dioxide (SiO_2) or the glassy mineral called quartz (similar to window glass). Granites have a silica composition of around 70%, whereas basalts contain around 50% silica. Thus granitic magmas are far more viscous than basaltic magmas. The latter are also hotter. This is why basalt lavas tend to flow freely, compared with rhyolite (granitic) lavas that are very viscous.

The water content of magmas varies, but in general granitic magmas have far more water dissolved in them than basaltic magmas. Indeed, the amount of water dissolved in granitic magmas increases with pressure and therefore depth, from 3.7 wt% water content at 3–4 km depth (Holtz, Behrens, Dingwell, and Johannes 1995) to 24 wt% water at 100 km depth (Huang and Wyllie 1975). The effect of more water in a granitic magma is to reduce its viscosity. It is this greater water content and viscosity of granitic (rhyolitic) magma that make its volcanic eruption so explosive. The viscous granitic magma forms a better/stronger "cork" (as it were) on the volcano, and with so much water as steam, the volcano's top explodes. By comparison a basalt eruption is usually less explosive because the magma contains much less steam and the lava is much less viscous.

Magma Generation by Partial Melting

Typical geothermal gradients of 20°C/km do not generate the greater than 800°C temperatures at 35 km depth in the crust needed to melt common crustal rocks (Thompson 1999). However, there are at least three other factors, besides temperature, that are important in melt generation: (1) water content of magma, (2) pressure, and (3) the influence of mantle-derived basaltic magmas. The temperatures required for melting are significantly lowered by increasing water activity up to saturation, and the amount of temperature lowering increases with increasing pressure (Ebadi and Johannes 1991). Indeed, water solubility in granitic melts increases with pressure, the most important controlling factor (Johannes and Holtz 1996), so that whereas at 1 kbar (generally equivalent to 3–4 km depth) the water solubility is 3.7 wt% (Holtz et al. 1995), at 30 kbar (up to 100 km depth, though very much less in tectonic zones) it is approximately 24 wt% (Huang and Wyllie 1975). This water is supplied by the adjacent rocks, subducted oceanic crust, and hydrous minerals present in the melting rock itself.

Nevertheless, local melting of deep crustal rocks is even more efficient where the lower crust is being heated by basaltic magmas generated just below in the upper (hotter) mantle (Bergantz 1989). Partial melting of crustal rocks preheated in this way is likely to be rapid, with models predicting a melt layer two-thirds the thickness of the basaltic intrusions forming in 200 years at a temperature of 950°C (Huppert and Sparks 1988; Thompson 1999). Experiments on natural rock systems have also shown the added importance of mineral reactions involving the breakdown of micas and amphiboles to rapidly produce granitic melts (Brown and Rushmer 1997; Thompson 1999). One such experiment found that a quartzo-feldspathic source rock undergoing water-saturated melting at 800°C could produce 20–30 vol.% of homogeneous melt in less than 1–10 years (Acosta-Vigil et al. 2006).

A crucial consequence of fluid-absent melting is reaction-induced expansion of the rock that results in local fracturing and a reduction in rock strength due to the increased pore fluid (melt) pressures (Brown and Rushmer 1997; Clemens and Mawer 1992). Stress gradients can also develop in the vicinity of an intruding basaltic heat source and promote local fractures. These processes, in conjunction with regional tectonic strain, are important in providing enhanced fracture permeabilities in the region of partial melting, which aid subsequent melt segregation (Petford et al. 2000).

Melt Segregation

The small-scale movement of magma (melt plus suspended crystals) within the source region is called segregation. The granitic melt's ability to segregate mechanically from its matrix is strongly dependent on its physical properties, of which viscosity and density are the most important. Indeed, the viscosity is the crucial rate-determining variable (Woodmorappe 2001) and is a function of melt composition, water content, and the temperature (Dingwell, Bagdassarov, Bussod, and Webb 1993). It has been demonstrated that the temperature and melt's water content are interdependent (Scalliet, Holtz, and Pichavant 1998), yet the viscosities and densities of granitic melts actually vary over quite limited ranges for melt compositions varying between tonalite (65 wt% SiO_2, 950°C) and leucogranite (75 wt% SiO_2, 750°C) (fig. 3) (Clemens and Petford 1999). An important implication is that the segregation and subsequent ascent processes, which are moderated by the physical properties of the melts, thus occur at broadly similar rates, regardless of the tectonic setting and the pressures and temperatures to which the source rock has been subjected over time. Furthermore, granitic magmas are only 10–1,000 times more viscous than basaltic magmas (Baker 1996; Clements and Petford 1999; Scalliet, Holtz, Pichavant, and Schmidt 1996), which readily flow.

Most field evidence points to deformation (essentially "squeezing") as the dominant mechanism that segregates melt flow in the lower crust (Brown and Rushmer 1997; Vigneresse, Barbey, and Cuney 1996). Rock deformation experiments indicate that when 10–40% of a rock is a granitic melt, the pore pressures in a rock are equivalent to the confining pressure, so the residual grains move relative to one another resulting in macroscopic deformation due to melt-enhanced mechanical flow (Brown and Rushmer 1997; Rutter and Neumann 1995). These experiments also imply that deformation-enhanced segregation can in principle occur at any stage during partial

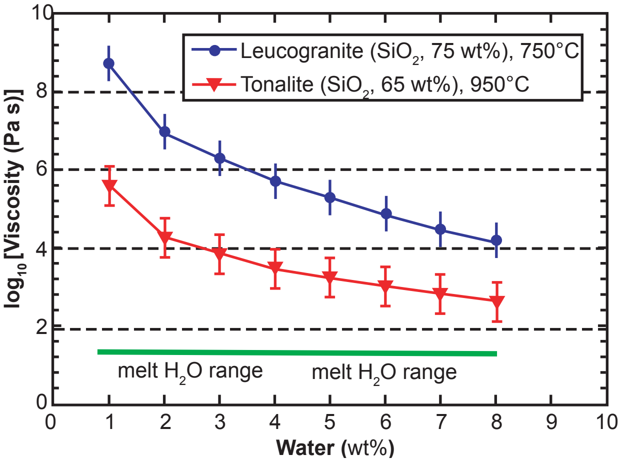

Fig. 3. Melt viscosity as a function of melt water (wt%) content for typical tonalite and leucogranite liquid compositions (after Clemens and Petford 1999) at a fixed pressure of 800 MPa. The horizontal line shows the range of water contents typical for natural melts. The estimated $\log_{10}$ values of the median viscosities (in Pa s) of the liquids at their "ideal" water contents of 4 wt% (tonalite) and 6 wt% (leucogranite) are 3.8 and 4.9 respectively.

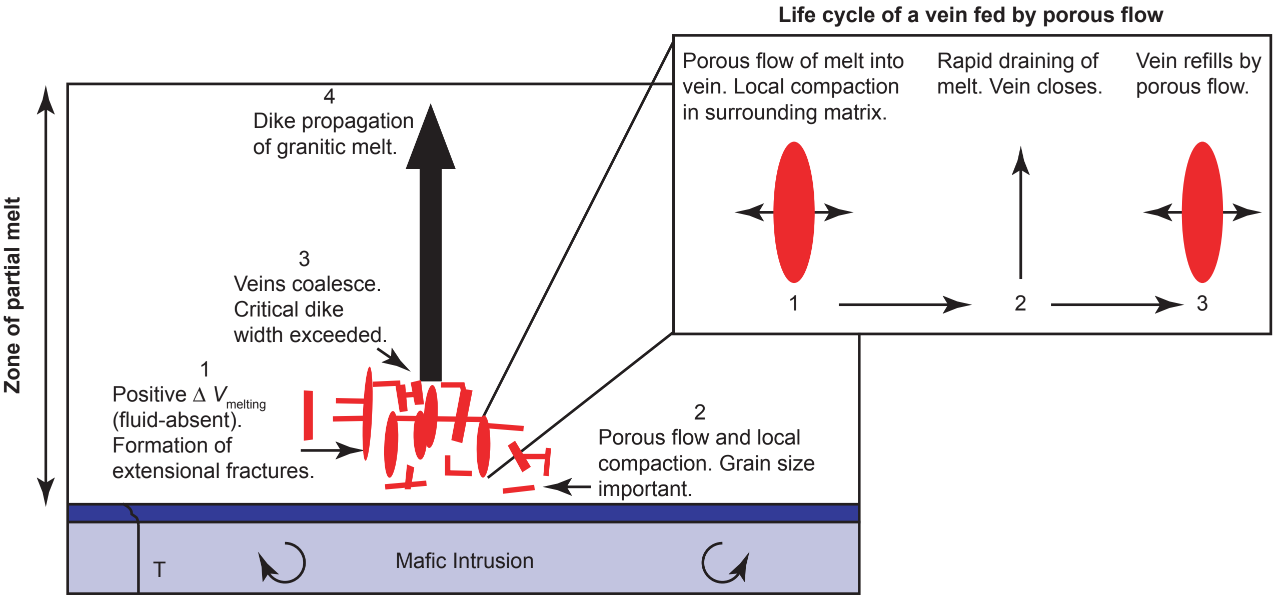

Fig. 4. Schematic representation of a possible sequence of events (1–4) resulting from fluid-absent melting reactions in a protolith above a mafic (intrusive) heat source in the lower crust. Veins fill by porous flow, with some local compaction (inset).

melting. Furthermore, the deformation-assisted melt segregation is so efficient in moving melt from its source to local sites of dilation ("squeezing") over timescales of only a month up to 1,000 years. Thus the melts may not attain chemical or isotopic equilibrium with their surrounding source rocks before final extraction and ascent (Davies and Tommasini 2000; Sawyer 1991).

According to the best theoretical models, melted rock in the lower crust segregates via porous flow into fractures within the source rock (usually metamorphic) above a mafic intrusion (the heat source), the fractures inflating to form veins (Petford 1995). Local compaction of the surrounding matrix then allows the veins to enlarge as they fill further with melt, and the fluid-filled veins coalesce to form a dike (fig. 4). At a certain critical melt-fraction percent of the source rock, a threshold is reached where the critical dike width is achieved. Once that critical dike width is exceeded, "rapid (catastrophic) removal of the melt from the source" occurs. The veins collapse abruptly, only to be then refilled by continuously applied heat to the source rock. Thus the process is repeated, the granitic melt being extracted and then ascending through dikes to the upper crust in rapid and catastrophic pulses.

These rapid timescales for melt extraction are well-supported by geochemical evidence in some granites. For example, some Himalayan leucogranites are strongly undersaturated with respect to the element zirconium (Harris, Vance, and Ayres 2000) because the granitic melt was extracted so rapidly from the residual matrix (in less than 150 years) that there was insufficient time for zirconium to be re-equilibrated between the two phases. Similarly, based on comparable evidence in a Quebec granite, Canada, the inferred time for the extraction of the melt from its residuum was only 23 years (Sawyer 1991).

Magma Ascent

Gravity is the essential driving force for large-scale vertical transport of melts (ascent) in the continental crust (Petford et al. 2000). However, the traditional idea of buoyant granitic magma ascending through the continental crust as slow-rising, hot diapirs or by stoping (that is, large-scale veining) (Weinberg and Podladchikov 1994) has been largely replaced by more viable models. These models involve the very rapid ascent of granitic magmas in narrow conduits, either as self-propagating dikes (Clemens and Mawer 1992; Clemens, Petford, and Mawer 1997), along preexisting faults (Petford, Kerr, and Lister 1993), or as an interconnected network of active shear zones and dilational structures (Collins and Sawyer 1996; D'Lemos, Brown, and Strachan 1993). The advantage of dike/conduit ascent models is that they overcome the severe thermal and mechanical problems associated with transporting very large volumes of granite magmas through the upper brittle continental crust (Marsh 1982), as well as explain the persistence of near-surface granite intrusions and associated silicic volcanism. Yet to be resolved is whether granite plutons are fed predominantly by a few large conduits or by dike swarms (Brown and Solar 1999; Weinberg 1999).

The most striking aspect of the ascent of granitic melts in dikes is the extreme difference in the magma ascent rate compared to diapiric rise, the dike ascent rate being up to a million times faster depending on the magma's viscosity and the conduit width (Clemens, Petford, and Mawer 1997; Petford, Kerr, and Lister 1993). The narrow dike widths (1–50 m) and rapid ascent velocities predicted by fluid dynamical models are supported by field and experimental studies (Brandon, Chacko, and Creaser 1996; Scalliet, Pecher, Rochette, and Champenois 1994). For example, for epidote crystals to have been preserved as found in the granites of the Front Range (Colorado) and of the White Creek batholith (British Columbia) required an ascent rate of between 0.7 and 14 km per year. Therefore the processes of melt segregation at more than 21 km depth in the crust and then magma ascent and emplacement in the upper crust all had to occur within just a few years (Brandon, Chacko, and Creaser 1996). Such a rapid ascent rate is similar to magma transport rates in dikes calculated from numerical modeling (Clemens and Mawer 1992; Petford, Kerr, and Lister 1993; Petford 1995, 1996), and close to measured ascent rates for upper crustal magmas (Chadwick, Archuleta, and Swanson 1988; Rutherford and Hill 1993; Scandone and Malone 1985). Indeed, Petford, Kerr, and Lister (1993) calculated that a granite melt could be transported 30 km up through the crust along a 6 m wide dike in just 41 days at a mean ascent rate of about 1 cm/s. At that rate the Cordillera Blanca batholith in northwest Peru, with an estimated volume of 6,000 km^3, could have been filled from a 10 km long dike in only 350 years.

It is obvious that magma transport needed to have occurred at such fast rates through such narrow dikes or else the granite magmas would "freeze" due to cooling within the conduits as they ascended.Instead, there is little geological, geophysical, or geochemical evidence to mark the passage of such large volumes of granite magma up through the crust (Clemens and Mawer, 1992; Clemens, Petford, and Mawer 1997). Because of the rapid ascent rates, chemical and thermal interaction between the dike magmas and the surrounding country rocks will be minimal. Clemens (2005) calculates typical ascent rates of 3 mm/s to 1 m/s, which, assuming there is continuous, efficient supply of magma to the base of the fracture system, translates to between five hours and three months for 20 km of ascent. Such rapid rates make granite magma ascent effectively an instantaneous process, bringing plutonic granite magmatism more in line with timescales characteristic of silicic volcanism and flood basalt magmatism (Petford et al. 2000).

Magma Emplacement

The final stage of magma movements is horizontal flow to form intrusive plutons in the upper continental crust. This emplacement is controlled by a combination of mechanical interactions, either preexisting or emplacement-generated wall-rock structures, and density effects between the spreading flow and its surroundings (Hogan and Gilbert 1995; Hutton 1988). The mechanisms by which the host rocks make way for this incoming magma have challenged geologists for most of the past century and have been known as the "space problem" (Pitcher 1993). This problem is particularly acute where the volumes of magmas forming batholiths (groups of hundreds of individual granite plutons intruded side-by-side over large areas, such as the Sierra Nevada of California) are 100,000 km^3 or greater and are considered to have been emplaced in a single event.

New ideas that have alleviated this problem are (1) the recognition of the important role played by tectonic activity in making space in the crust for the incoming magma (Hutton 1988), (2) more realistic interpretations of the geometry of granitic intrusions at depth, and (3) the recognition that emplacement is an episodic process involving discrete pulses of magma. Physical models (Benn, Odonne, and de Saint Blanquat 1998; Cruden 1998; Fernández and Castro 1999; Roman-Berdiel, Gapais, and Brun 1997) indicate that space for incoming magmas can be generated through a combination of lateral fault opening, roof lifting. and lowering of the growing magma intrusion floor. For example, space is created by uplift of the strata above the intrusion, even at the earth's surface, and their erosion.

The three-dimensional (3D) shapes of crystallized plutons provide important information on how the granitic magmas were emplaced. The majority of plutons so far investigated using detailed geophysical (gravity, magnetic susceptibility, and seismic) surveys appear to be flat-lying sheets to open funnel-shaped structures with central or marginal feeder zones (Améglio and Vigneresse 1999; Améglio, Vigneresse, and Bouchez 1997; Evans et al. 1994; Petford and Clemens 2000), consistent with an increasing number of field studies (collecting fabric and structural data) that find plutons to be internally sheeted on the 0.1 meter to kilometer scale (Améglio, Vigneresse, and Bouchez 1997; Grocott et al. 1999).

Considerations of field and geophysical data suggest that the growth of a laterally spreading and vertically thickening intrusive flow obeys a simple mathematical scaling or power-law relationship (between thickness and length) typical of systems exhibiting scale-invariant (fractal) behavior and size distributions (McCaffrey and Petford 1997; Petford and Clemens 2000). This inherent preference for scale-invariant tabular sheet geometries in granitic plutons from a variety of tectonic settings (fig. 5) (Petford et al. 2000) is best explained in mechanical terms by the intruding magma flowing horizontally some distance initially before vertical thickening then

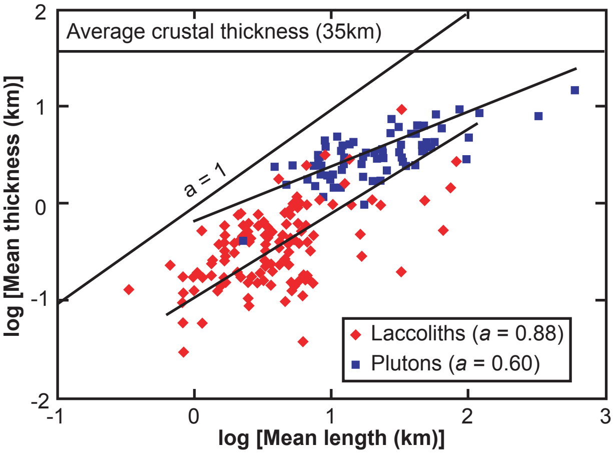

Fig. 5. Mean (vertical) thickness versus mean (horizontal) length for granitic plutons and laccoliths (after Petford et al. 2000). Reduced major-axis regression defines a power-law curve for plutons with an exponent a of 0.6±0.1. Laccoliths (shallow-level intrusions) are described by a power-law exponent of 0.88±0.1 (McCaffrey and Petford 1997). The line $a=1$ defines the critical divide between predominantly vertical inflation ($a>1$) and predominantly horizontal elongation ($a<1$) during intrusion growth. Significantly different power-law exponents rule out a simple genetic relationship between both populations. Differences may be due to mechanical effects, with limits in thickness reflecting floor depression (plutons) and roof lifting (laccoliths).

occurs, either by hydraulic lifting of the overburden (particularly above shallow-level intrusions) or sagging of the floor beneath. Plutons thus go from a birth stage characterized by lateral spreading to an inflation stage marked by vertical thickening.

This intrusive tabular sheet model envisages larger plutons growing from smaller ones according to a power-law inflation growth curve, ultimately to form crustal-scale batholithic intrusions (Cruden 1998; McCaffrey and Petford 1997). Evidence of this growth process has been revealed by combined field, petrological, geochemical, and geophysical (gravity) studies of the 1,200 km long Coast batholith of Peru (Atherton 1999). On a crustal scale this exposed batholith was formed by a thin (3–7 km thick) low-density granite layer that coalesced from numerous smaller plutons with aspect ratios of between 17:1 and 20:1. Thus this batholith would only amount to 5–10% of the crustal volume of this coastal sector of the Andes (Petford and Clemens 2000), which greatly reduces the so-called space problem. Detailed studies of the Sierra Nevada batholith of California (which includes the Yosemite area) reveal a similar picture, in which batholith construction occurred by progressive intrusion of coalescing granitic plutons 2–2,000 km^2 in area, supposedly over a period of 40 million years (as determined by radioisotope dating) (Bateman 1992).

Emplacement Rates

The tabular 3D geometry of granite plutons and their growth by vertical displacements of their roofs and floors enables limits to be placed on their emplacement rates (fig. 6) (Petford et al. 2000). If we assume that a disk-shaped pluton grows according to the empirical power-law relation shown in fig. 5, T=0.6 (±0.15)$L^{0.6\pm0.1}$, then its filling time can be estimated when the volumetric filling rate is known. Taking conservative values for magma viscosities, wall-rock/magma density differences and feeder dike dimensions results in pluton filling times of between less than 40 days and 1 million years for plutons under 100 km across. If the median value for the volumetric filling rate is used, then at the fastest magma delivery rates most plutons would have been emplaced in much less than 1,000 years (Harris, Vance, and Ayres 2000; Petford et al. 2000). Even a whole batholith of 1,000 km^3 could be built in only 1,200 years, at the rate of growth of an intrusion in today's noncatastrophic geological regime (Clemens 2005).

Thus the formation of granite intrusions in the middle to upper crust involves four discrete processes—partial melting, melt segregation, magma ascent, and magma emplacement. According to conventional

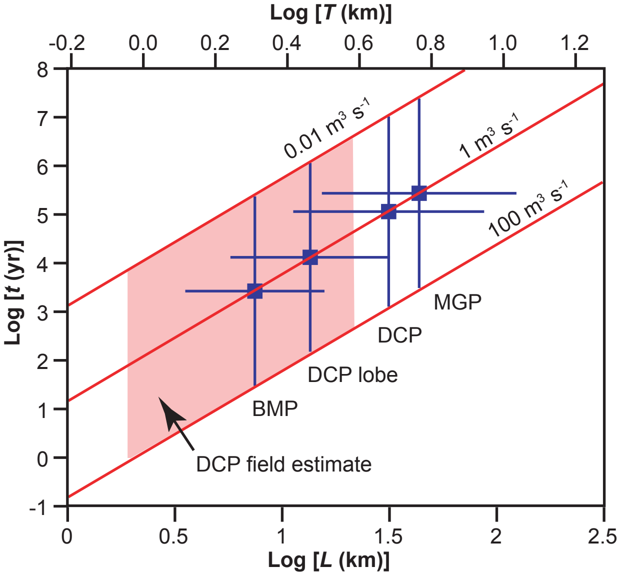

Fig. 6. Estimated filling times for tabular disk-shaped plutons (after Petford et al. 2000). This thickness (T) to width (L) ratio is given by the equation in the text for a range of permissible filling rates (Q). Heavy horizontal lines are the thickness ranges estimated using that equation for the Mount Gwens pluton (MGP), the Dinkey Creek pluton (DCP) and the Bald Mountain pluton (BMP) in the Sierra Nevada batholith, California. Vertical lines are the ranges of their possible filling times, bracketed by their filling rates. The colored prism indicates the range of thicknesses estimated independently for the southwest lobe of the DCP using structural data (Bateman 1992).

geologists (Petford et al. 2000), the rate-limiting step in this series of processes in granite magmatism is the timescale of partial melting (Harris, Vance, and Ayres 2000; Petford, Clemens, and Vigneresse 1997), but "the follow-on stages of segregation, ascent, and emplacement can be geologically extremely rapid—perhaps even catastrophic." However, as suggested by Woodmorappe (2001), the required timescale for partial melting is not incompatible with the 6,000–7,000 year biblical framework for earth history because a very large reservoir of granitic melts could have been generated in the lower crust in the 1,650 years between Creation and the Flood, particularly due to residual heat from an episode of accelerated nuclear decay during the first three days of the Creation Week (Humphreys 2000; Vardiman, Snelling, and Chaffin 2005). This very large reservoir of granitic melts would then have been mobilized and progressively intruded into the upper crust during the global, year-long Flood when the rates of these granite magmatism processes would have been greatly accelerated with so many other geologic processes due to another episode of accelerated nuclear decay (Humphreys, 2000; Vardiman, Snelling, and Chaffin 2005) and catastrophic plate tectonics (Austin et al. 1994), the likely driving mechanism of the Flood event.

Crystallization and Cooling Rates

The so-called space problem may have been solved, but what of the heat problem, that is, the time needed to crystallize and cool the granite plutons after their emplacement? As Clemens (2005) states, given that it has now been established that the world's granitic plutons are mostly tabular in shape and typically only a few kilometers thick, it is a simple matter to model the cooling of granitic plutons by conduction (Carslaw and Jaeger 1980). So using typical values for physical properties of the magma and wall-rock temperatures, thermal conductivities and heat capacities, Clemens (2005) determined that a 3 km thick sheet of granitic magma would take around 30,000 years to completely solidify from the initially liquid magma.

However, this calculation completely ignores, as already pointed out by Snelling and Woodmorappe (1998), the field, experimental, and modeling evidence that the crystallization and cooling of granitic plutons occurred much more rapidly as a result of convection due to the circulation of hydrothermal and meteoric fluids, evidence that has been known about for more than 25 years (for example, Cathles 1977; Cheng and Minkowycz 1977; Hardee 1982; Norton, 1978; Norton and Knight 1977; Paramentier 1981; Spera 1982; Torrance and Sheu 1978). The most recent modeling of plutons cooling by hydrothermal convection (Hayba and Ingebritsen 1997) takes into account the multiphase flow of water and the heat it carries in the relevant ranges of temperatures and pressures, so that a small pluton (1 km × 2 km, at 2 km depth) is estimated to have taken 3,500–5,000 years to cool depending on the system permeability. But this modeling does not take into account the relatively thin, tabular structure of plutons that would significantly reduce their cooling times. Similarly, convective overturn caused by settling crystals in the plutons would be another significant factor in the dissipation of their heat (Snelling and Woodmorappe 1998).

Convective Cooling: The Role of Hydrothermal Fluids

Granitic magmas invariably have huge amounts of water dissolved in them that are released as the magma crystallizes and cools. As the magma is injected into the host strata, it exerts pressure on them that facilitates fracturing of them (Knapp and Norton 1981). Also, the heat from the pluton induces fracturing as the fluid pressure in the pores of the host strata increases from the heat (Knapp and Knight 1977), this process repeating itself as the pluton's heat enters these new cracks.

Following the emplacement of a granitic magma, crystallization occurs due to this irreversible heat loss to the surrounding host strata (Candela 1992). As heat passes out of the intrusion at its margins, the solidus (the boundary between the fully crystallized granite and partially crystallized magma) progressively moves inward towards the interior of the intrusion (Candela 1991). As crystallization proceeds, the water dissolved in the magma that isn't incorporated in the crystallizing minerals stays in the residual melt, so its water concentration increases. When the saturation water concentration is lowered to the actual water concentration in the residual melt, first boiling occurs and water (as superheated steam) is expelled from solution in the melt, which is consequently driven towards higher crystallinities as the temperature continues to fall. Bubbles of water vapor then nucleate and grow, causing second (or resurgent) boiling within the zone of crystallization just underneath the solidus boundary and the already crystallized granite (fig. 7).

As the concentration and size of these vapor bubbles increase, vapor saturation is quickly reached, but initially these vapor bubbles are trapped behind the immobile crystallized granite margin of the pluton (Candela 1991). The vapor pressure thus increases until the aqueous fluid can only be removed from the sites of bubble nucleation through the establishment of a three-dimensional critical percolation network, with advection of aqueous fluids through it or by means of fluid flow through a cracking front in the already crystallized granite and out into the surrounding host strata. Once such fracturing of the

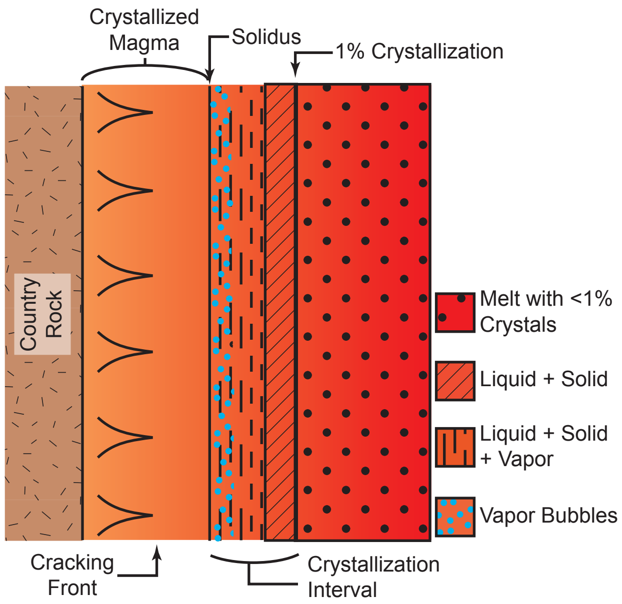

Fig. 7. Cross-section through the margin of a magma chamber traversing (from left to right): country rock, cracked pluton, uncracked pluton, solidus, crystallization interval, and bulk melt (after Candela 1991).

pluton has occurred (because the cracking front will go deeper and deeper into the pluton as the solidus boundary moves progressively inward toward the core of the intrusion), not only is magmatic water released from the pluton carrying heat out into the host strata, but the cooler meteoric water in the host strata is able to penetrate into the pluton and thus establish a convective hydrothermal circulation through the fracture networks in both the granite pluton and the surrounding host strata. The more water is dissolved in the magma, the greater will be the pressure exerted at the magma/granite and granite/host strata interfaces and thus the greater the fracturing in both the granite pluton and the surrounding host strata (Knapp and Norton 1981; Zhao and Brown 1992).

Thus by the time the magma has totally crystallized into the constituent minerals of the granite, the solidus boundary and cracking front have both reached the core of the pluton as well. It also means that a fracture network has been established through the total volume of the pluton and out into the surrounding host strata through which a vigorous flow of hydrothermal fluids has been established. These hydrothermal fluids thus carry heat by convection out through this fracture network away from the cooling pluton, ensuring the temperature of the granitic rock mass continues to rapidly fall. The amount of water involved in this hydrothermal fluid convection system is considerable, given that a granitic magma has enough energy due to inertial heat to drive roughly its mass in meteoric fluid circulation (Cathles 1981; Norton and Cathles 1979).

The emplacement depth and the scale of the hydrothermal circulatory system are first-order parameters in determining the cooling time of a large granitic pluton (Spera 1982). Water also plays a "remarkable role" in determining the cooling time. For a granitic pluton 10 km wide emplaced at 7 km depth, the cooling time of the magma to the solidus decreases almost tenfold as the water content of the magma increases from 0.5 wt% to 4 wt%. As the temperature of the pluton/host rock boundary drops through 200°C during crystallization, depending on the hydrothermal fluid/magma volume ratio, with only a 2 wt% water content, the pluton cooling time decreases eighteen-fold. As concluded by Spera (1982, p. 299):

> Hydrothermal fluid circulation within a permeable or fractured country rock accounts for most heat loss when magma is emplaced into water-bearing country rock . . . . Large hydrothermal systems tend to occur in the upper parts of the crust where meteoric water is more plentiful.

Of course, granitic magmas rapidly emplaced during the Flood would have been intruded into sedimentary strata that were still wet from just having been deposited only weeks or months earlier. Furthermore, complete cooling of such granitic plutons did not have to all occur during the Flood year.

It is also a total misconception that the large crystals found in granites required slow cooling rates (Luth 1976, pp. 405–411; Wampler & Wallace 1998). All the basic minerals found in granites have been experimentally grown over laboratory timescales (Jahns and Burnham 1958; Mustart 1969; Swanson, Whitney, and Luth 1972; Winkler and Von Platen 1958), so macroscopic igneous minerals can crystallize and grow rapidly to requisite size from a granitic melt (Swanson 1977; Swanson and Fenn 1986). So, asks Clemens (2005), how long did it take to form the plagioclase feldspar crystals in a particular granite? Linear crystal growth rates of quartz and feldspar have been experimentally measured and rates of $10^{-6.5}$ m/sec to $10^{-11.5}$ m/sec seem typical. This means that a 5 mm long crystal of plagioclase could have grown in as short a time as one hour, but probably no more than 25 years (Clemens 2005). Actually, it is extraneous geologic factors, not potential rate of mineral growth, which constrain the sizes of crystals attained in igneous bodies (Marsh 1989). Indeed, it has been demonstrated that the rate of nucleation is the most important factor in determining growth rates and eventual sizes of crystals (Lofgren 1980; Tsuchiyama 1983). Thus the huge crystals (meters long) sometimes found in granitic pegmatites have grown rapidly at rates of more than 10^{-6} cm/s from fluids saturated with the components of those minerals within a few years (London 1992).

Crystallization and Cooling Rates: The Evidence of Polonium Radiohalos

There is a feature in granites that severely restricts the timescale for their emplacement, crystallization, and cooling to just days or weeks at most—polonium radiohalos (Snelling 2005; Snelling and Armitage 2003). Radiohalos are minute spherical (circular in cross-section) zones of darkening due to radioisotope decay in tiny central mineral inclusions within the host minerals (Gentry 1973; Snelling 2000). They are generally prolific in granites, particularly where biotite (black mica) flakes contain tiny zircon inclusions that contain uranium. As the uranium in the zircon grains radioactively decays through numerous daughter elements to stable lead, the α-radiations from eight of the decay steps produce characteristic darkened rings to form uranium radiohalos around the zircon radiocenters. Also present adjacent to these uranium radiohalos in many biotite flakes are distinctive radiohalos formed only from the three polonium radioisotopes in the uranium decay chain. Because they have been parented only by polonium, they are known as polonium radiohalos.

The significance of these polonium radiohalos in granites is that they had to form exceedingly rapidly because the half-lives (decay rates) of these three polonium radioisotopes are very short—3.1 minutes (^{218}Po), 164 microseconds (^{214}Po), and 138 days (^{210}Po). Furthermore, each visible radiohalo requires the decay of 500 million to one billion parent radioisotope atoms to form them (Gentry 1973; Snelling 2000). The zircons at the centers of the adjacent uranium radiohalos are the only nearby source of polonium (from decay of the same uranium that produces the uranium radiohalos). The hydrothermal fluids released by the crystallization and cooling of the granites flow between the sheets making up the biotite flakes to transport the polonium from the zircons to adjacent concentrating sites. These then become the radiocenters which produce the polonium radiohalos (Snelling 2005; Snelling and Armitage 2003). Furthermore, the radiohalos can only form after the granites have cooled below 150°C (Laney and Laughlin 1981), which is very late in the granite crystallization and cooling process. Yet uranium decay and hydrothermal transport of daughter polonium isotopes starts much earlier when the granites are still crystallizing. Nevertheless, because of the very short half-lives of these three polonium radioisotopes that necessitate their rapid hydrothermal fluid transport to generate the polonium radiohalos within hours to a few days, it is estimated that the granites also need to have crystallized and cooled within 6–10 days, or else the required large quantities of polonium (from grossly accelerated decay of uranium) would decay before they could form the polonium radiohalos (Snelling 2005; Snelling and Armitage 2003). Such a timescale for crystallization and cooling of granite plutons is certainly compatible with the biblical timescales for the global Flood event and for earth history.

It might be argued that the uranium in the zircon grains could continue to supply polonium and radon isotopes to the polonium deposition sites via hydrothermal fluids for an extremely long time period after the temperature of the granites fell below 150°C, so the polonium radiohalos would not need to form in hours to days. Even though the half-lives of the polonium isotopes are very short, a long steady-state decay of uranium would surely build up slowly the uranium radiohalos, and the hydrothermal fluids would steadily transport the radon and polonium to slowly generate the polonium radiohalos nearby.

However, this presupposes that the hydrothermal fluids continued to flow for long periods of time after the granites cooled below 150°C. To the contrary, once the granites and hydrothermal fluids fall below 150°C most of the energy to drive the hydrothermal fluid flow has already dissipated. The hydrothermal fluids are expelled from the crystallizing granite and start flowing just below 400°C (fig. 8). So unless the granite cooled rapidly from 400°C to below 150°C, most of the radon and polonium transported by the hydrothermal fluids would have been flushed out of the granites by the vigorous hydrothermal convective flows as they diminished. Simultaneously, much of the energy to drive these fluid flows dissipates rapidly as the granite temperature drops. Thus, below 150°C the hydrothermal fluids have slowed down to such an extent that they cannot sustain protracted flow, and with the short half-lives of the radon and polonium isotopes, they would decay before those atoms reached the polonium deposition sites. Furthermore, the capacity of the hydrothermal fluids to carry dissolved radon and polonium decreases dramatically as the temperature continues to drop.

Thus sufficient radon and polonium had to be transported quickly to the polonium deposition sites to form the polonium radiohalos, while there was still enough energy at and just below 150°C to drive the hydrothermal fluid flow rapidly enough to get the polonium isotopes to the deposition sites before the polonium isotopes decayed. This is the time and temperature "window" depicted schematically in Fig. 8. The time "window" is especially brief in the case of the decay of the ^{218}Po and ^{214}Po isotopes (half-lives of 3.1 minutes and 164 microseconds respectively) and the formation of their radiohalos. It would thus be simply impossible for these polonium radiohalos to form slowly over millions of years at today's groundwater temperatures in cold granites. Heat is

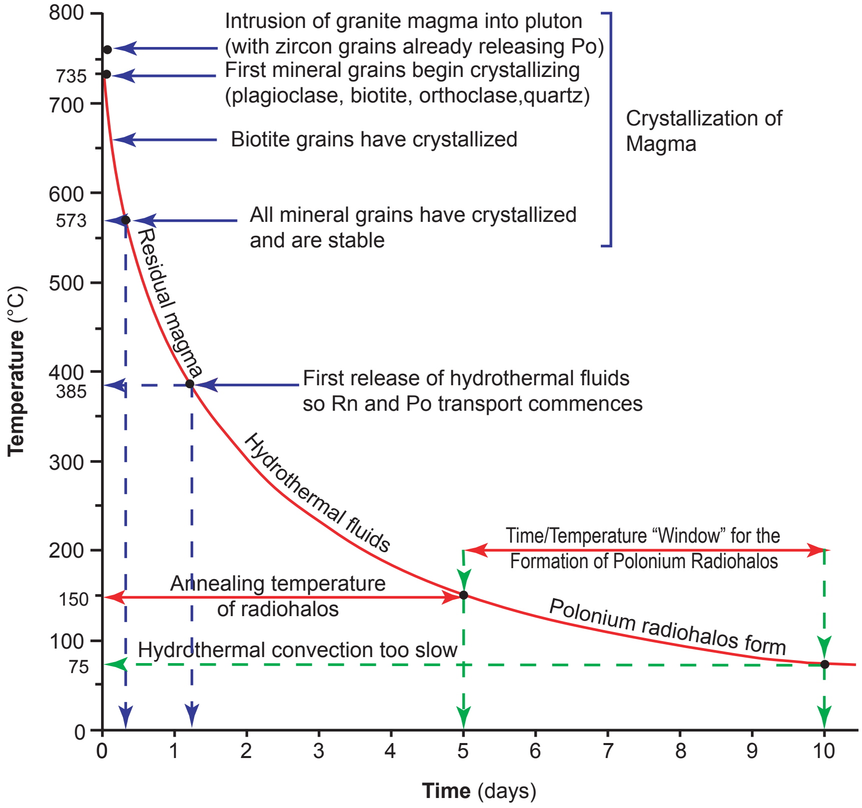

Fig. 8. Schematic, conceptual, temperature versus time cooling curve diagram to show the timescale for granite crystallization and cooling, hydrothermal fluid transport, and the formation of polonium radiohalos.

needed to dissolve the radon and polonium atoms, and to drive the hydrothermal convection that moves the fluids which transport the radon and polonium atoms to supply the radiocenters to generate the polonium radiohalos. Furthermore, the required heat cannot be sustained for the 100 million years or more while sufficient ^{238}U decays at today's rates to produce the required polonium atoms to form the polonium radiohalos. Thus the granites need to have crystallized and cooled rapidly (within 6–10 days) to still drive the hydrothermal fluid flow rapidly enough to generate the polonium radiohalos within hours to a few days.

Formation of the Yosemite Area Granitic Plutons

Finally, the formation of the hundreds of granitic plutons of the Sierra Nevada batholith, some of which outcrop on a grand and massive scale in the Yosemite area, can thus be adequately explained within the biblical framework for earth history. The regional geologic context suggests that late in the Flood year, after deposition of thick sequences of fossiliferous sedimentary strata, a subduction zone developed just to the west at the western edge of the North American plate (Huber 1991). Because plate movements were then catastrophic during the Flood year (Austin et al. 1994), as the cool Pacific plate was catastrophically subducted under the overriding North American plate, the western edge region of the latter was deformed, resulting in buckling of its sedimentary strata and metamorphism at depth (fig. 9). The Pacific plate was also progressively heated as it was subducted, so that its upper side began to partially melt and thus produce large volumes of basalt magma. Rising into the lower continental crust of the deformed western edge of the North American plate, the heat from these basalt magmas in turn caused voluminous partial melting of this lower continental crust, generating buoyant granitic magmas. These rapidly ascended via dikes into the upper crust, where they were emplaced rapidly and progressively as the hundreds of coalescing granitic plutons that now form the Sierra Nevada batholith. The presence of polonium radiohalos in many of the Yosemite area granitic plutons (Gates 2007; Snelling 2005) is confirmation of their rapid crystallization and cooling late in the closing phases of the Flood year. Conventional radioisotope dating, which assigns ages of 80–120 million years to these granites (Bateman 1992), appears to be grossly in error because of not taking into account the acceleration of the nuclear decay (Vardiman, Snelling, and Chaffin 2005). Subsequent rapid erosion at the close of the Flood, as the waters drained rapidly off the continents, followed by further erosion early in the post-Flood era and during the post-Flood Ice Age, have exposed and shaped the outcropping of these granitic plutons in the Yosemite area as seen today.

Conclusions

Even the conventional long-ages geologic community now regards the formation stages of granite plutons, after partial melting of source rocks to form granitic melts, that is, melt segregation, ascent and emplacement, to be "geologically extremely rapid—perhaps even catastrophic." At today's apparently slow rates of partial melting significant granite magmatism is not now occurring. However, a large reservoir of granitic melts could have been generated in the lower crust during the 1,650 years between

Creation and the Flood, particularly due to residual heat from an episode of accelerated nuclear decay during the first three days of the Creation Week. This very large reservoir of granitic melts would then have been mobilized and progressively intruded into the upper crust during the global Flood cataclysm, when another episode of accelerated nuclear decay would have greatly accelerated many geologic processes, including granite magmatism, driven by catastrophic plate tectonics.

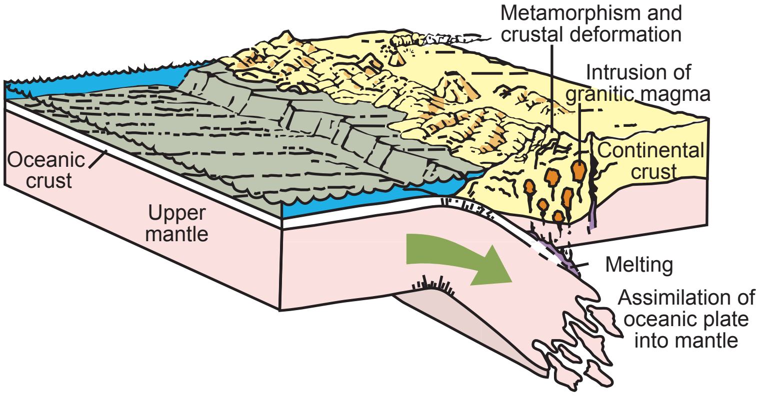

Fig. 9. Subduction of an oceanic plate (Pacific plate) during convergence with a continental plate (North American plate). Magma, formed by partial melting of the overriding continental plate, rises into the continental plate to form volcanoes and granite plutons along a mountain chain (after Huber 1991).

Partial melting occurs, due to heating of the lower crust by basalt magmas intruded from the mantle, to the elevated local water content, and to locally increased pressures as a result of tectonic activity. Once it occurs, continued deformation ("squeezing") segregates the melt so that it flows. Melt-filled veins then coalesce into dikes as "squeezing" continues episodically, effectively "pumping" the granitic melt into the dikes and up the dike-filled fractures into the upper crust. Thus, with a continuous supply of magma at the base of the fracture system in the lower crust, the magma could typically ascend 20 km into the upper crust in five hours to three months. There emplacement occurs rapidly as flat-lying sheets due to lateral fault opening, roof lifting, and floor sagging beneath the intrusion as it thickens in as little as 40 days.

Because granitic plutons are now recognized as being mostly tabular sheets, their crystallization and cooling occurs much more rapidly as a result of convection due to circulation of huge amounts of outgoing hydrothermal fluids released from the magmas and ingressing meteoric fluids from the country rocks. The pressure of these outgoing hydrothermal fluids fractures the inward crystallizing and cooling pluton margins, facilitating the ingress of cold meteoric fluids, which completes the convection cycle and accelerates the cooling of the pluton. Of course, during the Flood these granitic magmas were often intruded into wet sediment layers. Crystal growth rates of 5 mm in an hour have been experimentally determined. These hydrothermal fluids also transported radon and polonium within biotite flakes to generate polonium radiohalos below 150°C, which due to the very short half-lives of the polonium isotopes must have formed within hours to days. Furthermore, due to uranium decay and hydrothermal fluid transport of daughter polonium starting earlier in the crystallization of the granite plutons, and the need to supply the required large quantities of polonium below 150°C to form the polonium radiohalos before the energy to drive the hydrothermal fluids dissipates, the granite plutons need to have crystallized within 6–10 days.

Quite clearly, timescales for the generation of granitic magmas and their intrusion, crystallization, and cooling are no longer incompatible with the biblical time frame for earth history and its global Flood cataclysm.

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