CYLINDRICAL GRANODIORITE PIPES IN THE SOREL POINT IGNEOUS COMPLEX, JERSEY, CHANNEL ISLANDS.

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Salmon, S. 1996. Cylindrical granodiorite pipes in the Sorel Point igneous complex, Jersey, Channel Islands. *Proceedings of the Ussher Society,* **9,** 114-120.

The Sorel Point complex consists of plutonic rocks which can be separated into four groups representing four intrusive episodes. Each group consists of lithologies which were present as coexisting magmas. In the earliest group a sheet of granodiorite separates diorite from an underlying body of aplogranite, although, in a few places, diorite is in contact with aplogranite. Granodiorite intrudes the diorite as veins, sheets and cylindrical pipes. The pipes originate from, and are normal to, granodiorite sheets. Most pipes are circular in cross-section, c. 15 cm in diameter and display varying degrees of sinuosity. The base of pipes flare, imparting a metre-scale lobate form to the granodiorite-diorite interface. The upper termination of some pipes is occupied by pegmatitic quartz and alkali-feldspar. It is proposed that volatile-rich residual fluids from the granitic rocks ponded at the granodiorite-diorite interface until able to pierce the chilled margin of the diorite and rise as bubbles into the diorite magma, followed immediately by a column of granodiorite magma. Bubbles would have to attain an optimum size, which explains why there are no thin pipes, and why many have a similar diameter. Although the granodiorite column may have had the same diameter as the bubble, there is some evidence that the bubbles were wider than the pipes.

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INTRODUCTION

The effects of physical interactions between coexisting acid and basic magmas (the process known as magma-mingling) are well documented (e.g. Blake *et al.,* 1965; Walker and Skelhorn, 1966; Wiebe, 1991). Diagnostic phenomena include sharp, undulose or crenulate contacts; fine-grained (chilled) margins in the basic rocks; extensive sinuous or irregular veins of the acid rock in the basic rock and the presence of rounded or irregularly-shaped basic enclaves in the acid rock. All of these are present in the rocks of Sorel Point (Salmon, 1987, 1992). A less common phenomenon is the intrusion of acid rock into the basic rock in the form of long cylindrical pipes and pipe-like apophyses. These are produced and controlled by density contrasts between the two magmas, but clearly require a specific set of circumstances before they will form. This paper aims to describe the nature of pipes in the multi-magma complex at Sorel Point, Jersey, and to propose a method of formation.

LOCALITY AND GEOLOGICAL SETTING

Sorel Point lies on the north coast of Jersey which, along with the other Channel Islands and Northern Brittany, forms part of the North Armorican Massif. The majority of the rocks within this region are associated with the Cadomian orogeny. Subduction-related magmatism associated with the Cadomian orogeny covered a time span of c. 700-425 Ma. (Brown *et al.,* 1990), with the igneous complexes of Jersey being among the youngest. Sorel Point forms part of the North West Granite Complex (NWGC) of Jersey (Figure 1). This is an annular complex consisting predominantly of granites. Around the eastern edge of the NWGC, and superbly exposed at Sorel Point, is a series of basic and intermediate rocks which have intimate associations with the granites.

Sorel Point consists of plutonic rocks within the compositional spectrum gabbro-diorite-granodiorite-granite (Salmon, 1987; 1992). The rocks can be divided into four groups representing four separate intrusive episodes (Figure 2). The groups are separated by the time required for the preceding group to become solid or substantially crystallized, so that contacts between each group are of an angular, brittle nature. Each group consists of at least two lithologies, with contact relationships which indicate that the component rock-types were originally present as coexisting magmas. This paper will concentrate on Groups A and B, the oldest two groups.

Group A, which occupies most of the north and east of the headland, consists of a body of pink aplogranite underlying a series of mafic rocks. Apart from a few instances, the aplogranite is separated from the mafic rocks by a sheet of granodiorite, which varies in thickness up to c. 1 metre. The mafic rocks pass gradationally

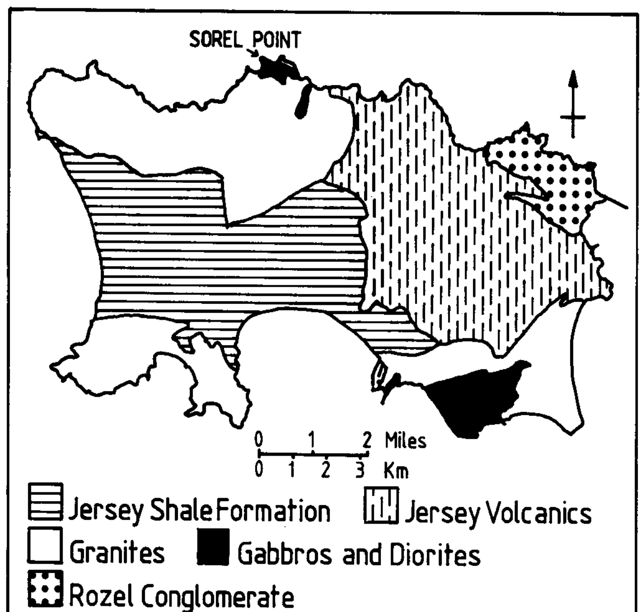

Figure 1. Geological map of Jersey, CI, showing the major units.

upwards, over a distance of c. 14 m, from diorite (immediately adjacent to the granodiorite) through a transitional diorite to hornblende gabbro (Figure 3). Above this is a series of layered gabbros which, although now separated by faulting and later intrusions, are assumed to have been part of the same mafic intrusion. The mafic rocks originated as a single body of gabbro magma into which was intruded, firstly, the aplogranite and, secondly, the granodiorite. The gabbro magma was later modified in parts by infiltration of volatile-rich fluids from the underlying granitic magmas (Salmon, 1992). These compositional modifications produced the marginal diorite (s.s.) and the transitional diorite. The marginal diorite has fine-grained margins (grain-size < 0.5 mm) against both the aplogranite and the granodiorite, which are interpreted as chilled margins. Fine-grained margins adjacent to aplogranite display quench textures in the form of acicular, hollow plagioclase crystals (Salmon, 1992). Granodiorite intrudes the mafic rocks extensively as irregular veins, relatively planar sheets and cylindrical pipes (see below). A few long veins or sheets of granodiorite cut the aplogranite. Contacts between aplogranite and granodiorite vary from sharp to gradational over a few mm. The aplogranite-granodiorite interface varies from relatively planar to highly irregular.

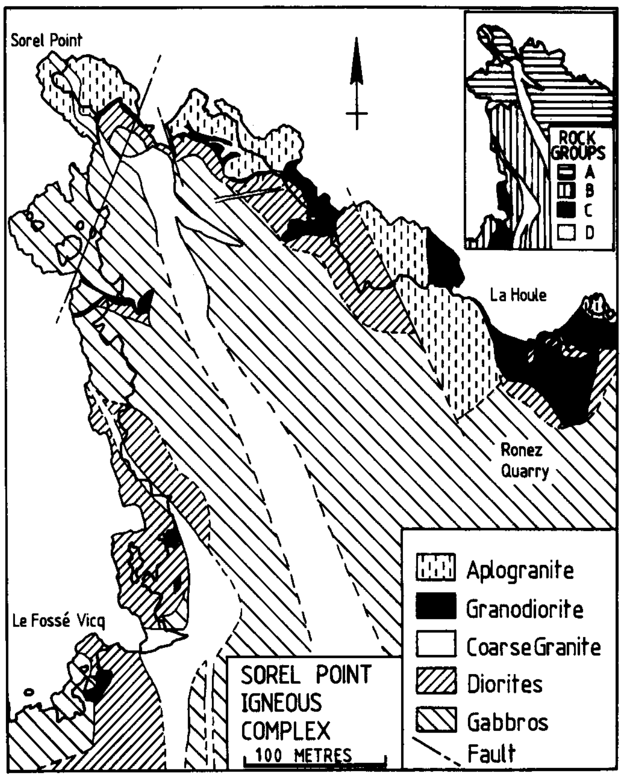

Figure 2. Simplified geological map of Sorel Point.

Group B contains a greater number of different lithologies than any of the other groups and occupies much of the western side of the headland. A body of olivine gabbro has been invaded on its northern margin by granodiorite veins, in places forming a net-vein pattern. Close to the northern margin, the olivine gabbro magma was modified (by fluid infiltration from the granodiorite) to dioritic compositions and the marginal diorites (s.s.) have chilled margins against the granodiorite. To the south the olivine gabbro magma was intruded by a body of quartz-diorite (referred to as the Western quartz-diorite). This surrounds a large body of feldspar-megacrystic diorite and farther to the south is in contact with another body of melanocratic gabbro. Farther south again are more gabbroic and dioritic rocks. All of these mafic lithologies are intruded by granodiorite as sheets, veins and pipes, with some larger granodiorite bodies also being present.

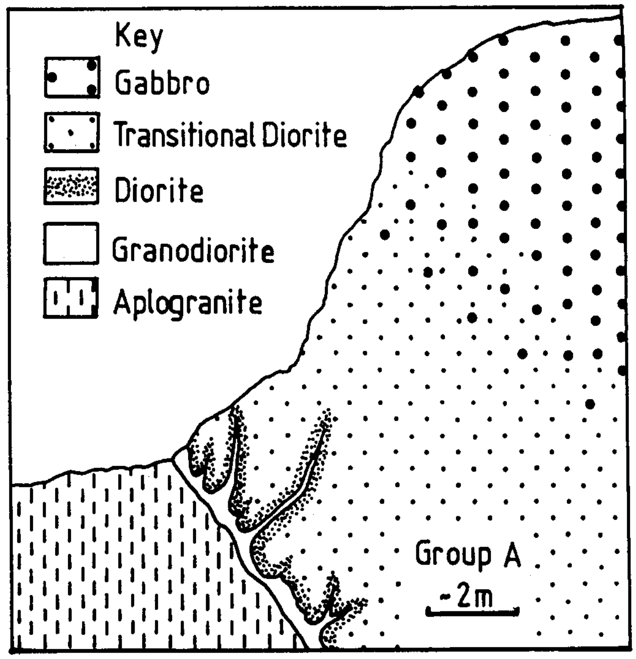

Figure 3. Schematic section through rocks of Group A at the northern end of Sorel Point.

GRANODIORITE PETROGRAPHY

There is evidence in Groups A and B that the granodiorite was intruded as a series of staged pulses (Salmon, 1992). Although the granodiorites of Groups A and B are in no way related, they are similar in appearance, being pale-grey and megacrystic. The megacrysts are subhedral to euhedral tabular feldspars which are 8-10mm long and vary in modal proportion from c. 25% to c. 45%. Most megacrysts have a core of alkali-feldspar (often irregular and/or cellular) with a mantle of plagioclase. Megacrysts often show good alignment sub-parallel to margins of intrusions, this usually being most pronounced between constrictions. This is interpreted as a flow alignment. The fine to medium-grained groundmass is equigranular and consists of quartz, alkali-feldspar, plagioclase, biotite and hornblende.

Pods of granitic pegmatite occur throughout the granodiorites. These consist of red alkali-feldspar, milky quartz, ± plagioclase ± chlorite. In the case of Group A the pegmatites are thought to have originated as residual fluids from the body of aplogranite. Pegmatite pods are frequently situated immediately adjacent to the granodiorite-diorite interface.

GRANODIORITE PIPES

Granodiorite pipes are most numerous around the north and east of the headland but occur throughout most of the area. At the north end of the headland (Group A) a number of pipes originate from the granodiorite which separates the aplogranite and diorite, and from other granodiorite sheets. Pipes also connect sheets and may have been important conduits supplying granodiorite magma to different structural levels. The pipes in this area plunge to the north or north-north-east at 45° to 50° and are approximately normal to the granodiorite screen, which dips c. 45° south, the same as the layered gabbros. Soon after the rocks solidified, a large portion of Group A rotated downwards into a magma chamber which contained the magmas which formed Group B. It was this downward rotation which produced the inclination of the pipes, which were originally vertical (see below), and the dip of the layering in the gabbros, which is assumed to have originally been horizontal. Pipes in Group B are vertical, indicating little or no tilting of the complex since their formation.

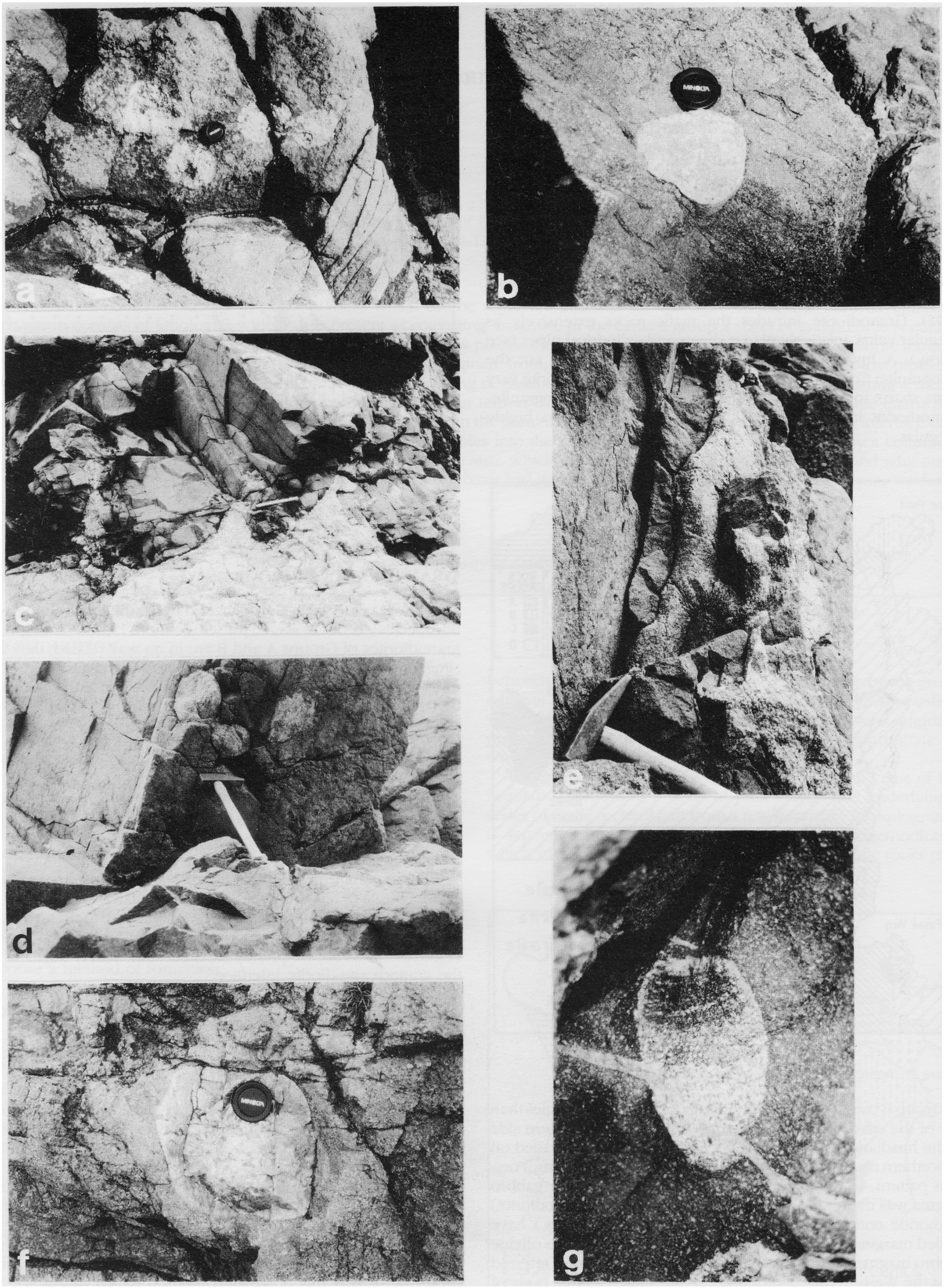

Figure 4. Granodiorite pipes at Sorel Point: (a) pipes with circular cross sections; (b) a pipe with non-circular cross section intruding hornblende gabbro, c. 14 m above the granodiorite screen; (c) flared pipe bases imparting a lobate form to the granodiorite-diorite interface; (d) cross section through pipes which are either bifurcating or intersecting; (e) a pipe within Group B rocks with a pronounced anastomosing structure; (f) a pipe cross section filled with granitic pegmatite. As it is wider than other pipes this is thought to be a bulbous pipe termination; (g) oblique cross section through a pipe (cut by a later granite sheet) with pronounced mafic schlieren.

In cross-section most pipes are circular and range from 10 to 30 cm in diameter, though most are c. 15 cm (Figure 4a). Occasional non-circular cross sections are also found (Figure 4b). Few pipes are exposed longitudinally for any great distance, most of those that are maintain a uniform diameter along their exposed length and display varying degrees of sinuosity. A few pipes maintain a uniform diameter for only part of their length, the remainder being rather thicker. Only the cylindrical part of these pipes is straight. Pipes exposed c. 15 m above the granodiorite screen have the same orientation as pipes adjoining the screen. This infers that pipes can remain relatively straight over considerable distances while maintaining their cylindrical form. In places, pipes intersect thinner, irregular granodiorite veins. The bases of pipes flare where they connect to the granodiorite screen. This imparts a metre-scale lobate form to the granodiorite-diorite interface (Figure 4c). A number of pipes appear to intersect each other (Figure 4d). A pipe exposed within Group B has an anastomosing structure (Figure 4e). Pegmatite is found in pipes and, where these are seen, occupies the pipe terminations (Figure 4f). There is usually a pale aureole in the diorite surrounding these pegmatites. This has been produced by outward migration of felsic material from the pegmatite.

Contacts between the granodiorite in the pipes and the surrounding diorite are sharp and often emphasised by a narrow dark margin. This consists of sub- to euhedral amphibole crystals c. 1 mm in size, concentrated along the interface between the two rock types. Chilled margins in the diorite only extend for a metre or so up the pipes and over most of their length there is little or no grain-size reduction in the diorite.

Although mafic enclaves are common in all of the granodiorites of Sorel Point, enclaves are rare within pipes. In a number of pipes mafic schlieren are present (Figure 4g). The schlieren are rich in biotite and hornblende and have feldspar megacrysts which are distinctly smaller than in the surrounding granodiorite. These schlieren may represent the remains of magmatic enclaves which were carried up into the pipes and disaggregated during pipe elongation.

Similar pipes are present elsewhere in the Channel Islands. Elwell *et al.* (1960) described granitic pipes in meladiorite at Beaucette Battery, Guernsey. These pipes are 5-10 cm in diameter, nearly straight and dip uniformly 30° south-south-east. It is suggested that the pipes rise from ridges on the top surface of the granitic sheet from which they originate. It is possible that the pipe bases at Sorel Point have a similar morphology, accounting for their flared bases. D'Lemos (1992) described pipes of Cobo granite rising into dioritic rocks near Port Soif, Guernsey. The pipes in this area are close to vertical, measure 20 to 40 cm in diameter and vary from circular to elliptical in cross-section. Less-regular pipe-like apophyses are present in the Chouet area of Guernsey where tonalite of the Inhomogeneous Suite intrudes rocks of the diorite group (Brown *et al.,* 1980). Cylindrical pipes up to 3.5 m long and 8 cm diameter occur near Seymour Tower within the South East Granite Complex (SEGC) of Jersey (Bishop and Key, 1983). The author has also observed smaller pipe-like apophyses elsewhere within the SEGC.

PIPE FORMATION

Granodiorite sheets and irregular veins were probably formed during the initial phases of granodiorite intrusion. Pipes are less common phenomena and clearly require a special set of circumstances before they can form. The closest geological analogy, although occurring on a much larger scale, is the diapiric uprise of magma and salt bodies through denser surrounding rocks. Magma bodies rising in diapiric fashion are usually depicted as having a `teardrop' shape, tapering downwards (Ramberg, 1967, 1972). This kind of shape could be envisaged for a small detached `parcel' of granodiorite magma rising through the gabbro magma, although surface tension would probably pull it into a spherical shape. However, such detached bodies rarely occur in the rocks of Sorel Point. As far as can be ascertained from field observations, pipes always remain attached to the underlying sheet of granodiorite. This requires that there be sufficient granodiorite magma available to feed the pipe as it grows, and that the magma in the pipe did not rise too fast and become detached from its magma source. The latter condition will be controlled to some extent by the viscosity of the granodiorite magma and by local density contrasts.

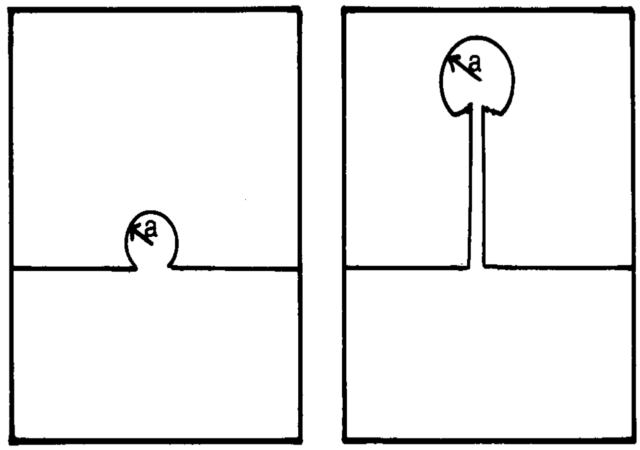

Figure 5. Development of a plume with a bulbous head of radius "a" (redrawn after Maaloe, 1985).

Another characteristic of pipes at Sorel Point is that most appear to maintain a consistent diameter over most of their length. In the physical modelling of magma plumes carried out by Ramberg (1967, 1970) and Berner *et al.* (1972), the rising magma bodies all take on a mushroom-like shape, with a bulbous head fed by a much narrower pipe. Elder (1970) also figures photographs of laboratory experiments in which rising plumes have (at various stages of formation) bulbous or mushroom-shaped heads with long narrow stems. The two factors which control these physical processes are the ascent rate and the growth rate of the plume head (numerical calculations governing plume dynamics are set out concisely in Maaloe, 1985). The growth rate is controlled by the flow of material to the plume, or the rate of production of the material forming the plume. The ascent rate is proportional to the square of the plume radius ('a' in Figure 5) and is also governed by density, viscosity and the acceleration of gravity (buoyancy). A plume fed from below is formed in two stages. First the head is formed and grows in size (Figure 5a). As it grows its ascent rate also increases. As long as the ascent rate is smaller than the growth rate the plume head will continue to increase in size. Eventually, at a critical size, the ascent rate becomes larger than the growth rate and the plume begins to ascend, fed from below by a cylindrical pipe (Figure 5b). At its maximal size a condition is reached where the flow rate up the feeder pipe is equal to the ascent rate. No more material enters the plume head, all new material entering the pipe being used to feed the growth, by elongation, of the pipe.

The key to the formation of the Sorel Point pipes is the presence of pegmatite pods in the granodiorite. Initially the aplogranite magma was intruded into the diorite magma (this was originally gabbroic in composition, but will henceforth be referred to as diorite in order to avoid confusion). The temperature contrast between the two magmas brought about the formation of a chilled margin in the diorite. Granodiorite magma was intruded through the aplogranite magma and ponded below the chilled margin. Irregular veins and planar sheets of granodiorite in the diorite were probably formed during this initial period as they also produced chilled margins in the diorite. Although a large density difference existed between the granitic magmas and the diorite magma (Figure 6a), the presence of the chilled margin, together with the relatively high viscosity of the granitic magmas (Figure 6b), prevented wholesale mixing between them. Volatile-rich residual fluids from the aplogranite and granodiorite also ponded at the granodiorite-diorite interface, eventually to form pegmatites.

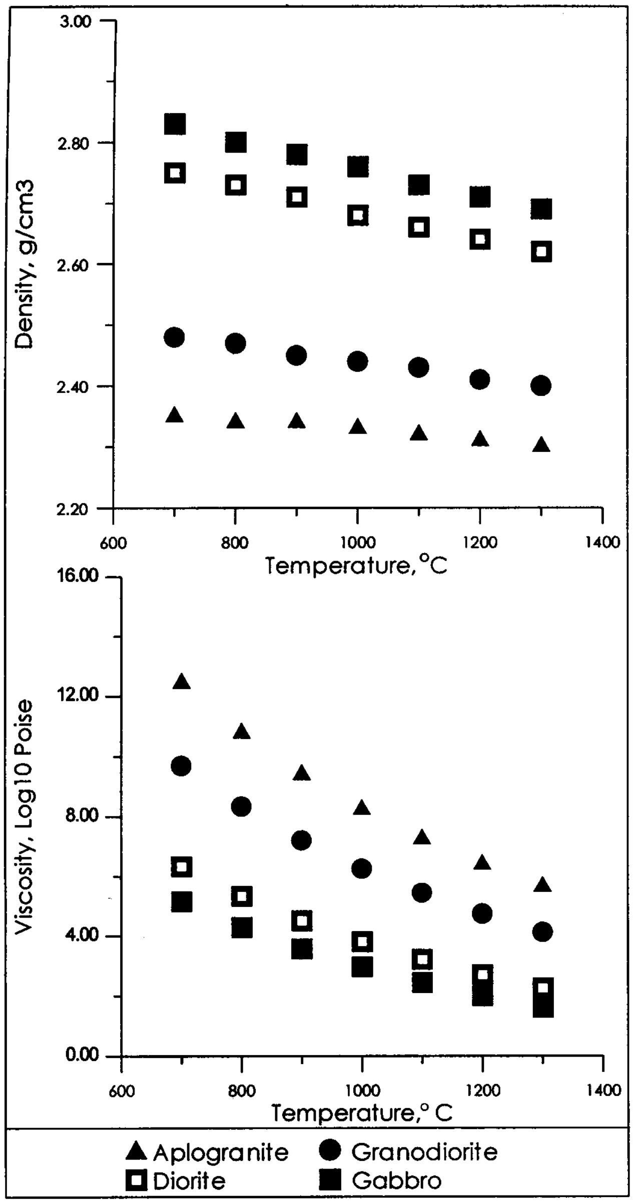

Figure 6. Density and viscosity of rocks from Group A. The physical contrasts between the granitic and basic rocks are clearly seen.

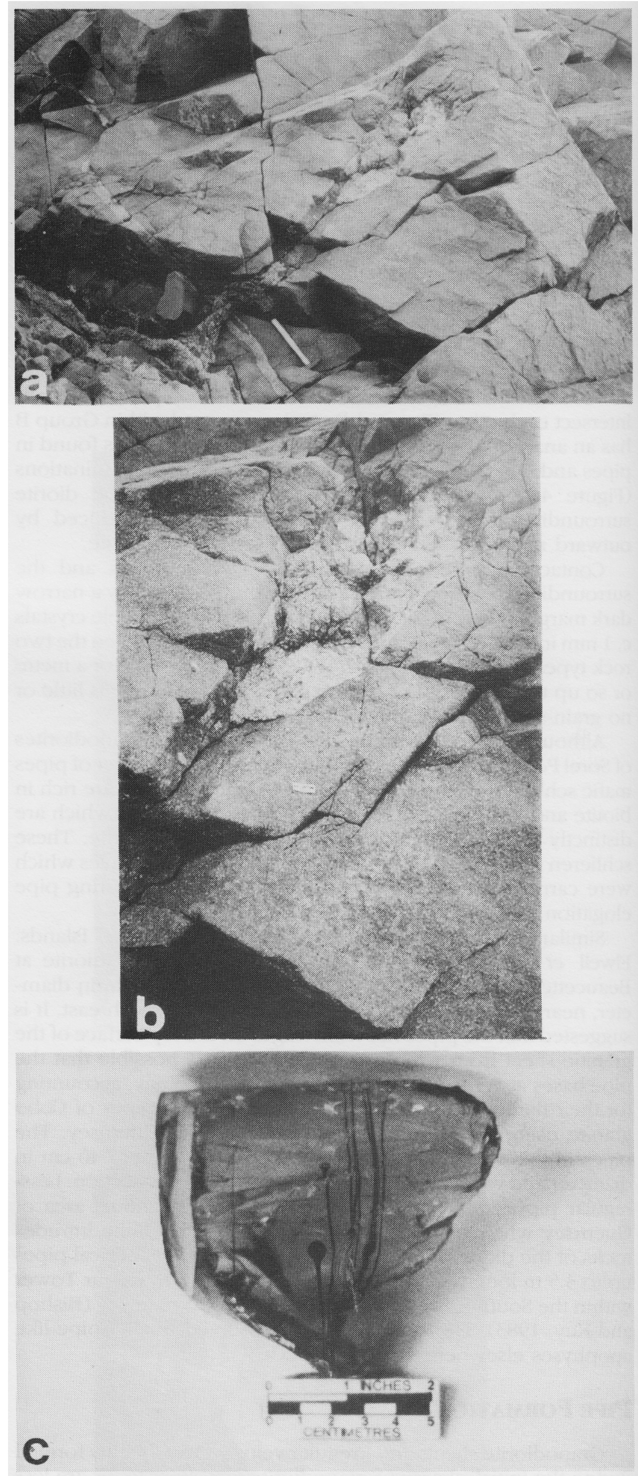

Figure 7. Pipes with bulbous heads: (a) a relatively short pipe with a flared base and a bulbous head which is mostly filled with pegmatite; (b) close up showing the bulbous head. Note that the granodiorite has been removed from the central straight, cylindrical section; (c) a block of glassworks' waste containing pipes of coloured glass with bulbous heads.

The physical behaviour of the granodiorite-diorite interface now becomes important. When a liquid of low density is present below one with a high density, the interface becomes unstable (Maaloe, 1985). The interface is initially planar but has a tendency to become sinusoidal. The wave amplitude increases with time until low density liquid starts to rise from the wave maxima. The wavelength of the simusoidal interface is controlled by a combination of the thickness of the overlying layer and the relative viscosities (Maaloe, 1985). So, for any set of given criteria there will be a characteristic wavelength which, under ideal conditions, will be constant along the interface. The spacing of any pipes rising from wave maxima will thus be regular, as is observed in places along the granodiorite-diorite interface, giving rise to its lobate form (Figure 4c).

The volatile-rich residual fluids would have had a much lower density and viscosity than the other magmas present, especially the diorite, thus increasing their tendency to rise. Eventually the buoyancy of the fluids became such that they were able to overcome the resistance of the chilled margin and break through it in the form of liquid-filled bubbles. The bubbles then rose into the diorite magma from the wave maxima, followed immediately by a column of granodiorite magma. Bubbles would have to achieve an optimum size before they could pierce the chilled margin. This explains why there are no very thin pipes and why most have a similar diameter. Small, isolated pockets of pegmatite within granodiorite veins and pipes represent bubbles of liquid which were not large or buoyant enough to pierce the chilled margin, but rose into the veins and pipes after they had been formed but were still present as magmas. Repeated pulses of incoming granodiorite magma may have prolonged these processes.

The majority of pipes at Sorel Point do not appear to have bulbous heads, suggesting that the critical conditions were achieved by some other means. If the material forming the plume was especially buoyant, i.e. with a very large density difference, the ascent rate may have become greater than the growth rate while the plume head was still small, forming a pipe with no bulbous head. However, at the north end of Sorel Point a well-preserved, though relatively short, pipe does have a bulbous head filled with pegmatite (Figure 7a and b), indicating that the process described above did occur on some, if not all, occasions. A block of glassworks' waste collected in St Helens, Merseyside, U.K. contains straight pipes with bulbous heads, the heads in this case being air bubbles (Figure 7c). The bubbles have a thin skin of the same glass that forms the pipes. The pipes have a large aspect ratio over which they maintain a constant diameter. Although on a much smaller scale, the pipes in this block were clearly formed by the process outlined above.

Once the ascent of the pegmatite bubble and its granodiorite pipe had begun, the large viscosity contrast between the granodiorite and the surrounding diorite magma (Figure 6b) would have inhibited any tendency of the two magmas to mix, thus maintaining the integrity and cylindrical shape of the pipe. During the growth of the pipe any convective (or other) movements within the diorite magma would affect the column of granodiorite. As long as the pipe maintained its integrity these magmatic movements would cause some sinuosity of the pipe. Prolonged elongation of the pipe would require the continued availability of granodiorite magma. The fact that a large amount of granodiorite remains in the screen indicates that there was always enough granodiorite magma to feed further pipe growth. It is likely that the final limiting factor governing ultimate pipe length was the cooling and crystallization of the basic magma, thus increasing its effective viscosity sufficient to inhibit further pipe growth.

Chilled margins in the surrounding diorite do not extend up pipes for further than a metre or so, indicating that the temperature contrast between the two magmas became too small to have an effect. The pegmatite bubble and granodiorite magma were heated as they rose into the hotter basic magma, causing their density to decrease and adding further impetus to their upward progress. Continued heating of the granodiorite and pegmatite (along with some cooling of the basic magma) would start to bring their viscosities closer to that of the basic magma. This would happen to the pegmatite before the granodiorite. Removal of the viscosity contrast between the pegmatite and the surrounding magma would also remove the physical barrier to outward filtration from the bubble, producing pale aureoles. This could occur after pipe growth had ceased, or may even have been the reason for cessation - by removing the driving force of buoyancy.

SUMMARY

The following mechanism (summarised in Figure 8) is proposed for the formation of the Sorel Point pipes:

1. Aplogranite magma was intruded into basic magma (originally gabbro but later modified in parts to diorite).

2. Temperature contrast between the magmas caused the formation of a chilled margin in the basic magma.

3. Granodiorite magma was introduced and ponded below the chilled margin (Figure 8a).

4. Volatile-rich residual fluids from the aplogranite and granodiorite also ponded below the chilled margin.

5. Over time, the granodiorite-diorite interface took on a sinusoidal shape (Figure 8b).

6. Bubbles of volatile-rich residual fluid concentrated in the wave maxima.

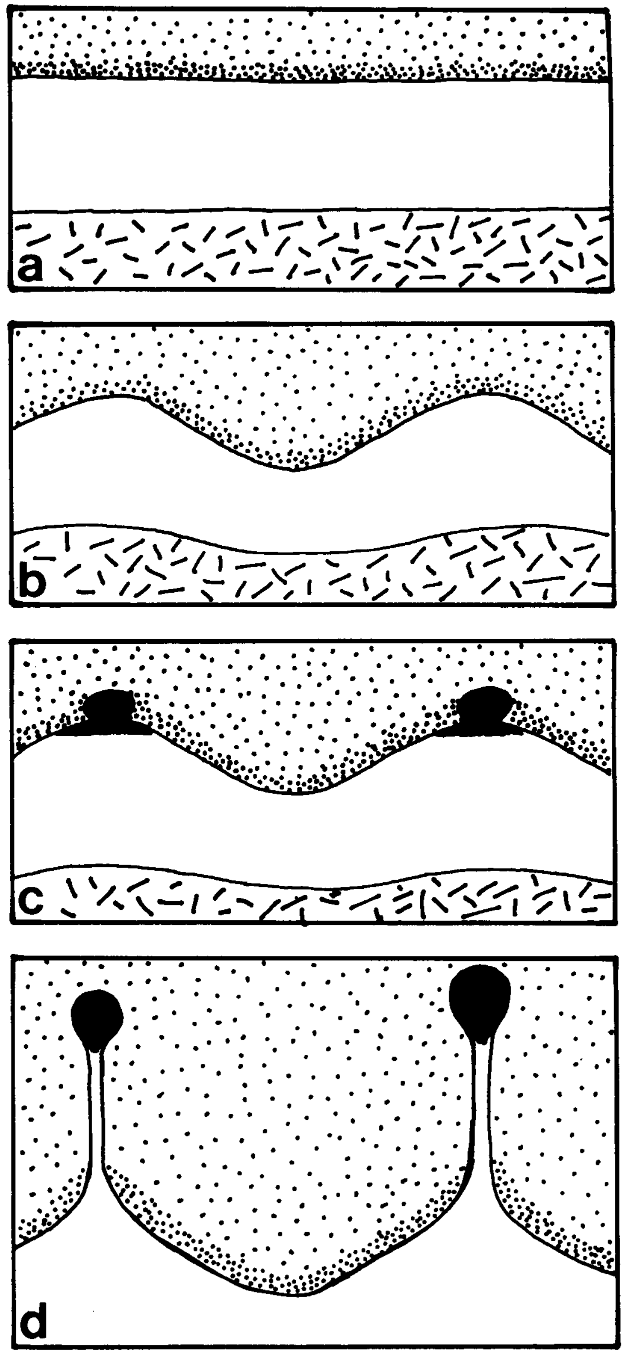

Figure 8. Series of schematic sections illustrating the formation of granodiorite pipes at Sorel Point: (a) aplogranite magma (hatched) intrudes basic magma (stippled) producing a stable interface and a chilled margin (closer stippling) in the basic magma. Granodiorite magma (clear) is intruded and ponds below the stable interface; (b) over time the interface between the dense basic magma and less-dense granodiorite magma becomes sinusoidal; (c) volatile-rich residual fluids (black) pond at the wave maxima and eventually break through the chilled margin; (d) bubbles of fluid rise into the basic magma, each followed by a cylindrical column of granodiorite magma.

7. Bubbles reached a critical size and were thus able to pierce the chilled margin (Figure 8c).

8. Bubbles rose into the basic magma followed by a column of granodiorite magma (Figure 8d).

9. Pipe elongation was finally limited by the cooling and crystallization of the basic magma.

10. When its component rocks were solid, part of group A rotated downwards to the south, producing the northward plunge of the pipes.

ACKNOWLEDGEMENTS

The research for this paper was carried out under the auspices of a Post-Graduate Teaching Assistantship, funded by the Department of Geology and Physical Sciences, Oxford Polytechnic (now Oxford Brookes University), which is gratefully acknowledged. Further support was provided by the Division of Earth Sciences, University of Derby. Thanks to Sally Edwards and Simon Birkett at the University of Derby for their patience and invaluable help with photographs and figures. Thanks also to two anonymous referees for their comments.

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