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Spherulites, quench fractures and relict perlite in a Late Devonian rhyolite dyke, Queensland, Australia

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Abstract

A Late Devonian rhyolite dyke displays perlitic and other fracture sets, as well as textures generated by crystallisation of the glass. The dyke is less than a metre wide and has sharp contacts with ignimbrite. Although originally glassy, no glass is preserved. Aligned magnetite (after pyroxene?) microlites and trains of small (0.5–1 mm) spherical spherulites crystallised early, at temperatures above the glass transition temperature and before formation of the fracture sets. Long, subplanar fractures oriented perpendicular to the dyke walls extend almost the full dyke width and end by merging with adjacent long fractures. Short, subplanar cross fractures are perpendicular to and terminate at the long fractures. Well-defined perlitic fractures are present within the volumes of rock, generally $< 10 \times 5 \times 5$ mm, defined by the long and cross fractures. The geometry of the fracture sets suggests that the long fractures formed first, followed by the cross fractures and finally the perlitic fractures. The long and cross fractures are interpreted to be first- and second-order quench fractures, respectively. The perlitic fractures formed in the closely fractured glass, probably in response to strain inherited from rapid cooling contraction and volume changes associated with low-temperature hydration. Formerly glassy domains now consist of K-feldspar crystals radiating outward from the fractures (similar to axiolitic spherulites) and enclosing areas of polygonal quartz and oligoclase. This assemblage is the result of devitrification of the perlitised glass after initial cooling, most likely promoted by hydration, interaction with groundwater and elevated temperature. Fractures have been accentuated by concentrations of iron oxide deposited during surface weathering.

1. Introduction

Rapid chilling of silicate melt produces volcanic glass. Further slow cooling may allow nucleation and growth of crystals in the hot glass, forming spherulites, lithophysae and micropoikilitic texture (Lofgren, 1970, 1971a, b; Friedman and Long, 1984). Thermal stresses associated with cooling contraction commonly generate subplanar fractures and joints called quench fractures (Pichler, 1965; Yamagishi and Dimroth, 1985; Yamagishi, 1987). Remaining glass may be intricately fractured by abundant delicate overlapping arcuate cracks that surround less-fractured cores of glass, forming the texture known as perlite or marekanite (Ross and Smith, 1955; Friedman and Smith, 1958). Several studies (e.g., Ross and Smith, 1955; Friedman and Smith, 1958; Friedman et al., 1966) have shown that perlitised glass is hydrated, containing elevated H_2O gained by

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adsorption followed by diffusion of external water into the glass. Perlitised glass and pristine glass are metastable and, given enough time, will eventually devitrify or else alter to new mineral assemblages (e.g., quartz, feldspar, clays, zeolites, sericite or chlorite) as a result of metamorphism and/or hydrothermal activity.

Though complex, steps in the cooling history and textural evolution of glassy volcanic rocks can sometimes be deciphered, especially in ancient examples in which textures are commonly accentuated by the effects of weathering and/or alteration. An aphyric rhyolite dyke in central Queensland displays well-developed joint sets interpreted to be quench fractures, relict perlite, spherulites and devitrification textures (Fig. 1). The order of formation is clear and closely constrains the textural evolution in this case. In particular, microlites and small spherical spherulites were present before quench fracturing. Perlitic fractures formed in the closely fractured glass. Devitrification of the perlitised glass generated K-feldspar that radiates from both the perlitic and quench fracture sets, enclosing areas composed of polygonal quartz and oligoclase. The complex pattern of fractures has been accentuated by iron oxides deposited during surface weathering.

2. Geological setting

The perlitic dyke occurs within the Late Devonian Silver Hills Volcanics, the lowermost unit of the Drummond Basin in central Queensland. Outcrop of the Silver Hills Volcanics (Fig. 2) occurs mainly at the southern end of the western margin of the basin (Olgers, 1970; Withnall et al., 1993) where the volcanics form a N–S-striking succession of lavas, pyroclastic rocks and minor intrusions which display a continuous range in composition from basalt through to rhyolite.

Dykes are restricted to the basal parts of Silver Hills Volcanics stratigraphy and adjacent basement schist to the east. They are steeply dipping with N–S strikes. Dyke intrusion may have been controlled by

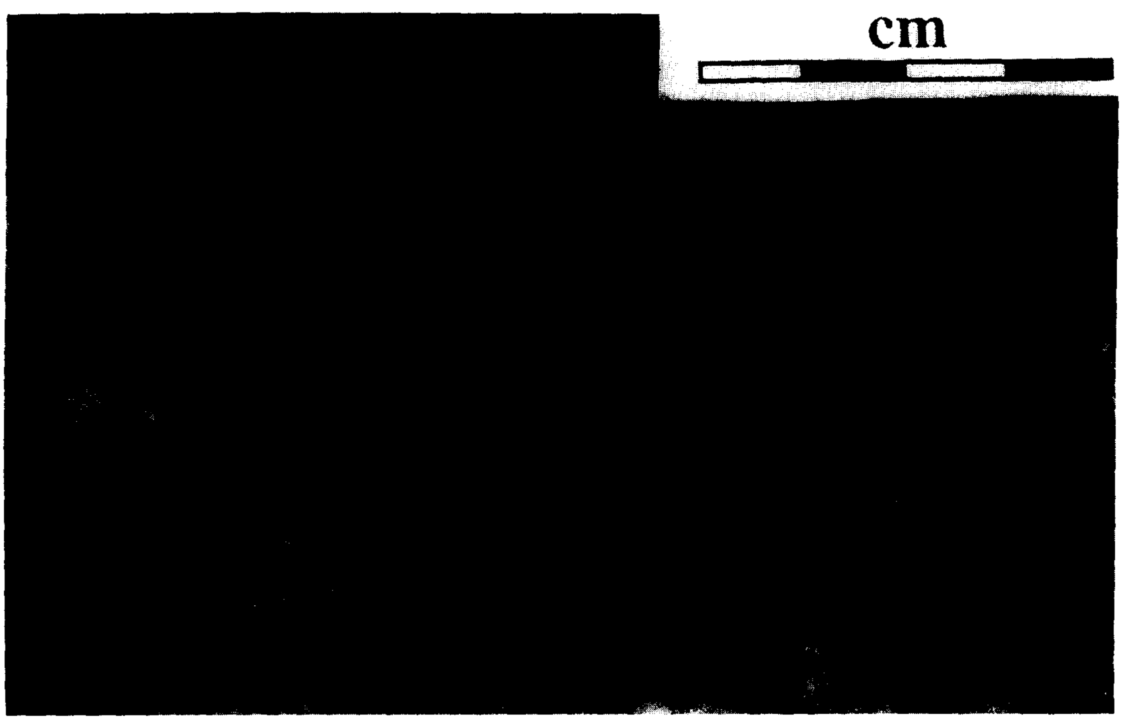


Fig. 1. Weathered surface of the Silver Hills dyke showing well-developed classical perlite. The long fractures appear as straight to curvilinear traces (L) which outline domains of perlite (P).

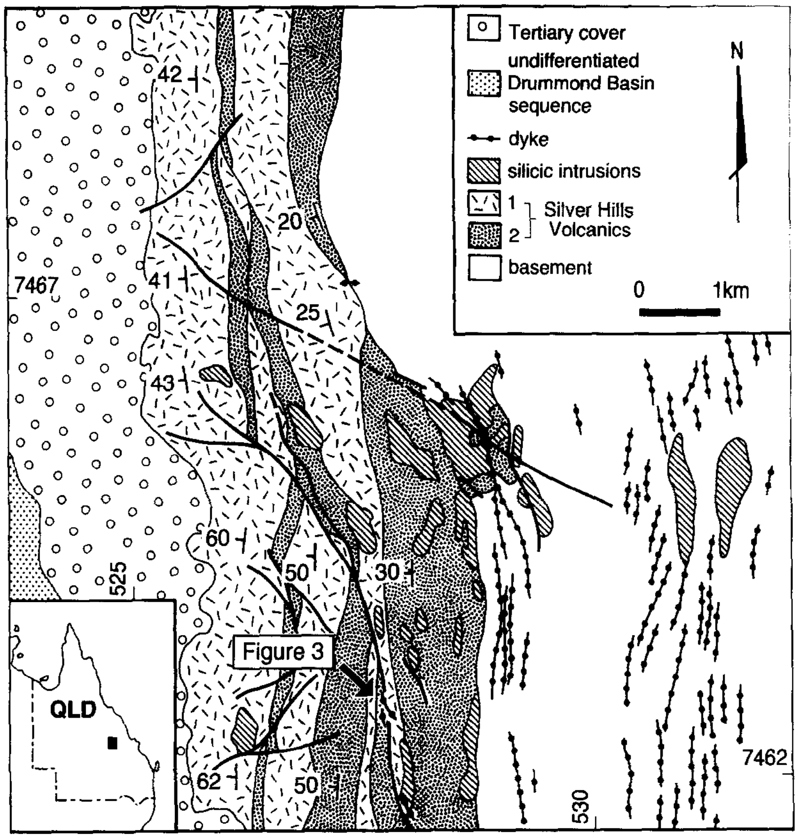


Fig. 2. Simplified geology of the Late Devonian Silver Hills Volcanics in central Queensland, Australia. Unit 1 dominantly comprises pyroclastic rocks and reworked equivalents together with minor lavas. Unit 2 is lava dominated with minor pyroclastic rocks. Arrow indicates the location of the perlitic rhyolite dyke (detail in Fig. 3). The dyke intrudes a feldspar-rich ignimbrite within Unit 1. Grid is Australian Map Grid.

major N–S-trending fractures in the basement, which are parallel to the well-developed N–S-oriented structural grain of the basin and thought to have developed in response to extension during the basin-forming event (Johnson and Henderson, 1991; Davis and Henderson, 1996). For most of the area, the regional metamorphic grade is prehnite-pumpellyite facies although locally higher grade facies occur in areas where the dykes are concentrated.

The perlitic dyke described herein has intruded a feldspar-rich rhyolitic ignimbrite at the base of the Silver Hills Volcanics (Fig. 2). Contacts with the ignimbrite are clearly exposed, sharp and planar. The maximum width of the dyke is 1 m and in most places it is approximately 70–80 cm wide (Fig. 3). It is subvertical with a strike of 170° and can be traced in outcrop for at least 20 m, beyond which it is covered by alluvium. The sample studied comes from a prominent outcrop about 4 m long and 0.5–0.7 m high. The perlitic dyke belongs to a set of dykes which are dacitic to rhyolitic, with silica contents ranging from 64 to 75 wt.%.

3. Macroscopic character of the dyke

The most conspicuous feature of the dyke is the fracture pattern (Fig. 3). Three sets of fractures have been distinguished on the basis of orientation, shape and length:

(a) Long fractures are oriented approximately perpendicular to the dyke walls and are subplanar. Most of the long fractures extend for 50–70 cm, almost the distance between the dyke walls. They terminate

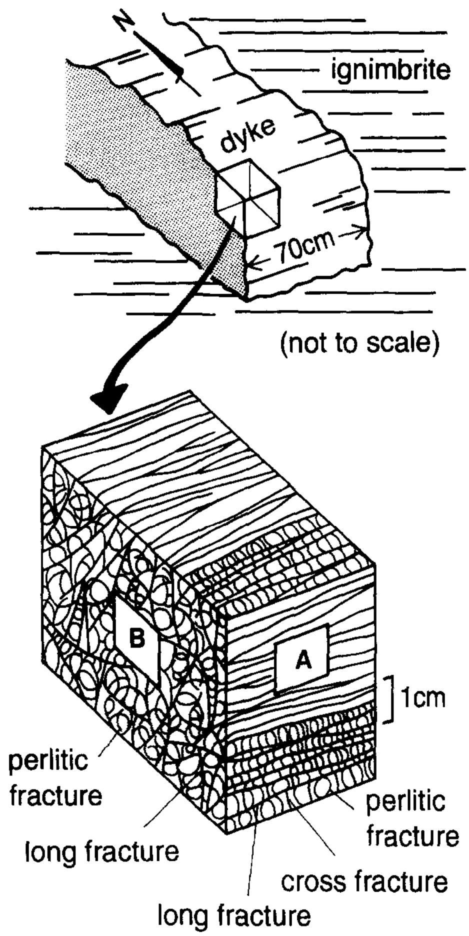


Fig. 3. Outcrop sketch showing the main structures within the Silver Hills dyke that are discussed in the text. Positions of Fig. 4A and B are given. The traces of all three fracture sets can be seen on planes perpendicular to the dyke walls (labelled *A*). The traces of the long fractures and perlitic fractures are present on planes parallel to the dyke walls (labelled *B*).

by merging with adjacent long fractures, defining elongate, 5–10 mm thick, wedge shapes with tapered ends in three dimensions (Figs. 3 and 4A). On surfaces perpendicular to the dyke walls the long fracture set imparts a striated appearance to the outcrop. On sections parallel to the dyke walls the long fracture set appears as a network of curvilinear traces (Figs. 1, 3 and 4B).

(b) Cross fractures are oriented approximately parallel to the dyke walls and perpendicular to the long fractures. The cross fractures are short (up to 10 mm but typically 5 mm), only extending the distance between adjacent long fractures (Fig. 4A). Although some are planar, most are slightly curved. The spacing of adjacent cross fractures is more or less regular and they are about 0.5 to 5 mm apart. Cross fractures are apparent only in sections oriented perpendicular to the dyke walls.

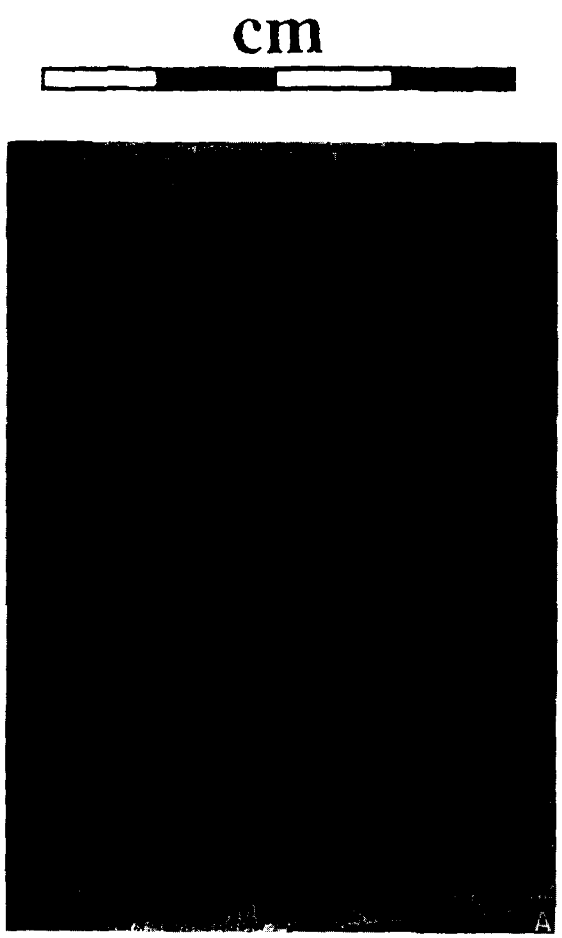
(c) Perlitic fractures are well developed in sections both parallel and perpendicular to the dyke walls (Figs 1, 3 and 4). Sections perpendicular to the dyke walls (Fig. 4A) show that the perlitic fractures are contained within domains defined by cross fractures and long fractures. They comprise overlapping arcuate fractures arranged in a roughly concentric pattern around subspherical less-fractured cores of diameter 1–10 mm (classical perlite). The largest cores (5–10 mm across) are commonly internally divided into two or three segments by subplanar fractures that terminate at the core perimeter. Where the long and cross fractures are closely spaced, the shell-and-core structure characteristic of perlite is absent. Instead, short subplanar fractures oblique to the long and cross fractures define rhomb- and triangular-shaped prisms of rock.

Flow banding could not be positively identified in outcrop or hand specimen and the rhyolite is aphyric.

4. Textures in thin-section

Although perlitic fractures indicate that the dyke was formerly glassy, no glass is preserved and the rhyolite is now totally crystalline. The present mineralogy has been established petrographically and by electron microprobe analyses. Four texturally distinct domains can be discerned (Fig. 5):

Fig. 4. (A) Section perpendicular to the Silver Hills dyke walls showing the long fracture set (*L*), the cross fracture set (*C*) and perlitic fractures (*P*). Perlitic fractures outline circular to elliptical less-fractured cores and are restricted to domains defined by the long and cross fracture sets. The perlite cores get progressively smaller where long fractures merge reflecting control by the spacing of the older fractures. (B) Section parallel to the dyke walls. The long fractures appear as straight to curvilinear traces (*L*) which outline domains of classical perlite (*P*). Note that none of the long fracture traces cut across the perlite cores.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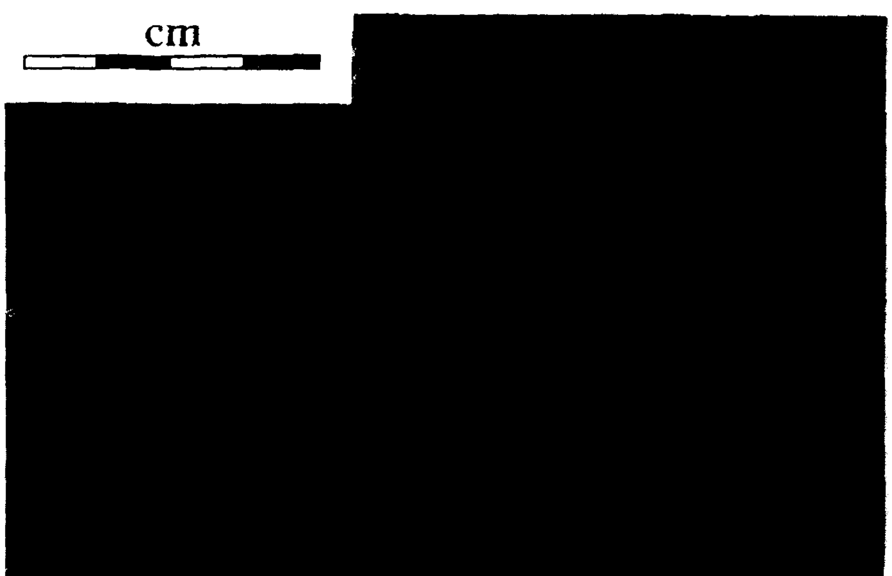
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(a) Narrow (< 1 mm) concentrations of acicular iron oxide (precise composition unresolved) and inclusion-rich K-feldspar delineate the fracture sets (Fig. 5A, B).

(b) "Trains" of translucent pinkish-brown, coalesced or impinging spherical structures define a subtle fabric that is oblique to and cut by the fractures. The spheres are less than 1 mm in diameter and composed of K-feldspar intergrown with quartz (Fig. 5C). They are interpreted to be relict spherical spherulites (cf. Lofgren, 1971b, 1974). Only in a few cases is a radial arrangement of K-feldspar crystals preserved. Many have a core of fine polygonal quartz with sweep extinction and the concentric structure is further accentuated by colour variations in the K-feldspar (shades of pink or brown).

(c) Translucent pinkish-brown fanning aggregates of prismatic K-feldspar crystals (< 0.2 mm long) occur as borders either side of the fractures (Fig. 5B). These aggregates strongly resemble axiolitic spherulites (cf. Lofgren, 1971b, 1974) and are similar to the spherulite trains, differing only in that they lack a concentric structure, in being located along the fractures and in their elongate prismatic crystal habit.

(d) Equant to elongate, colourless domains outlined by the fractures are composed of a fine (grain size 0.05–0.3 mm) polygonal mosaic of quartz and oligoclase (An_{16-18}) throughout which acicular magnetite is dispersed (Fig. 5B). The magnetite crystals range up to 8 μm in length and 0.5 μm in width. They occur as separate crystals aligned in a direction parallel to the dyke walls and less commonly as radiating clusters.

Fig. 5. (A) Photomicrograph of a section oriented perpendicular to the dyke walls. Long fractures (L), cross fractures (C) and perlitic fractures (P) are delineated by concentrations of inclusion-rich K-feldspar and opaque iron oxide. Crossed nicols. (B) Photomicrograph of the same section as in (A) showing the domains originally occupied by perlitised glass but now made of polygonal quartz–oligoclase [domain (d)] and K-feldspar [domain (c)] radiating from the fractures. Magnetite microlites are abundant within the domains of polygonal quartz–oligoclase. Iron oxides [domain (a)] mark the traces of traces of long fractures (L) and perlitic fractures (P). Plane polarised light. (C) Photomicrograph showing the spherical K-feldspar–quartz aggregates [S; domain (b)] interpreted to be recrystallised spherical spherulites (cf. Lofgren, 1971b, 1974). Arrows and dashed lines indicate the alignment direction of the spherulites. Plane polarised light.

5. Textural evolution

The order of formation of the three fracture sets in the dyke can be interpreted from the geometry of

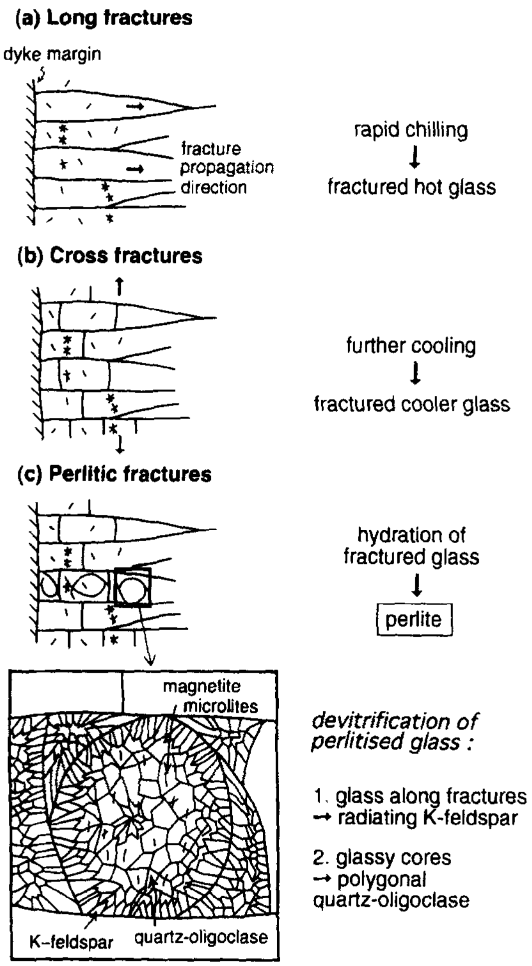

Fig. 6. Summary of the textural evolution envisaged for the Silver Hills rhyolite dyke. (a) The dyke initially comprised rhyolitic melt containing microlites aligned by flowage parallel to the dyke walls. Rapid chilling arrested crystallisation of spherical spherulites and resulted in contraction and the formation of the long fracture set perpendicular to the dyke walls. At this stage the temperature was below the glass temperature. (b) Additional cooling contraction that accompanied and/or followed inward propagation of the long fractures resulted in a second set of quench fractures (cross fractures). (c) Hydration of the rapidly chilled glass generated perlitic fractures within volumes of the rock defined by the two sets of quench fractures. The perlitised glass subsequently devitrified: axiolitic K-feldspar grew along the perlitic fractures, enclosing areas occupied by a relatively coarse, polygonal quartz–oligoclase mosaic. (The final stage, deposition of iron oxides during weathering, has not been illustrated.)

intersections (Fig. 6): the long fractures formed first and controlled the extent of later fracture sets; the cross fractures stop where they meet the long fractures and formed second; the perlitic fractures are contained within the domains defined by the long fractures and the cross fractures, and are therefore inferred to have formed last.

The conversion of the glass to a crystalline aggregate took place in two episodes, one before and one after formation of the fracture sets.

5.1. Microlites and spherical spherulites

The alignment parallel to the dyke walls shown by the acicular magnetite crystals suggests that they are not devitrification or alteration products, but rather that they crystallised directly from the melt and were aligned by flowage during emplacement. In addition, they are similar in size and shape to microlites commonly found in abundance in felsic glass (cf. Ross, 1962; Swanson et al., 1989). The acicular magnetite crystals are thus interpreted to be microlites or pseudomorphs of original microlites (perhaps pyroxene?). Radiating clusters of magnetite (replacing pyroxene?) may have formed at the same stage or later. Ross (1962) found that pyroxene microlites displaying two morphologies, prisms and trichites (radiating clusters of slender, commonly curved crystallites), belonged to early (higher temperature, lower viscosity) and later (lower temperature, higher viscosity) stages of crystallisation, respectively.

Trains of small spherical spherulites [textural domain (b)] are intersected by and evidently pre-date all three fracture sets. Furthermore, the alignment of the trains of spherulites is subparallel to that of the acicular magnetite and to the dyke walls, suggesting that the spherulites nucleated on pre-existing inhomogeneities in the glass developed during laminar flowage of the viscous rhyolite. Aligned acicular microlites are present within the spherulites and thus crystallised first.

5.2. Clear quartz-oligoclase domains and K-feldspar radiating from fractures

These assemblages are the products of devitrification of the perlitised glass between the fractures. Devitrification was controlled by and post-dated all three fracture sets. The presence of aligned magnetite microlites throughout the clear quartz-oligoclase domains provides evidence that devitrification occurred in the solid state and did not involve glass dissolution followed by space-filling crystal growth.

Iron oxide concentrated along all three fractures sets contains widely varying amounts of titanium and manganese, and is interpreted to be the result of surface weathering.

6. Discussion

6.1. Devitrification

The fracture sets in the Silver Hills dyke developed in glass that contained abundant microlites and trains of small (< 1 mm) spherical spherulites, corresponding to the "glassy stage"of Lofgren (1971b). Swanson et al. (1989) concluded that abundant small microlites in Obsidian Dome, California, represent metastable crystallisation in response to a relatively high degree of undercooling. Spherulites crystallise through a wide range of temperature and other conditions in cooling glass although growth is significantly inhibited below the glass transition temperature (Manley, 1992). Lofgren's (1971b) experiments showed that rocks with glassy-stage textures form from rapid cooling of water-undersaturated magma. The small diameter of the spherulites in the Silver Hills dyke suggests that the temperature quickly dropped below the glass transition temperature, consistent with the rapid cooling rate inferred from the closely spaced quench fractures.

The remaining glass devitrified after quench fracturing and perlitic fracturing and presumably also after substantial cooling. Devitrification other than during first cooling (secondary devitrification; Bonney and Parkinson, 1903; Lipman, 1965) commonly produces very fine grained interlocking aggregates that closely reflect the primary composition (e.g., quartzofeldspathic aggregates in rhyolitic glasses), or else reflect addition or removal of components in an accompanying fluid phase during hydrothermal alteration (e.g., phyllosilicate-quartz aggregates). The polygonal quartz-oligoclase mosaic is unusually coarse grained and the fanning aggregates of K-feldspar along the fractures resemble axiolitic spherulites (cf. Lofgren, 1971b, 1974). These textures developed after fracturing and after first-cooling, most likely in response to re-heating and/or hydrothermal alteration.

Terzaghi (1948) described very similar textures in a Permian rhyolitic lava. In one sample, well-developed alkali feldspar crystals, about 0.05 mm across, occur along perlitic fractures and in another, formerly glassy domains between spherulites are composed of coarse polygonal quartz and sericite (after feldspar). Because there was other independent evidence for hydrothermal alteration (veins, druses, sericite alteration of feldspar), Terzaghi (1948) inferred that hot, alkali-rich fluids had accelerated devitrification of the glass.

The perlitised glass in the Silver Hills dyke is replaced by an assemblage of quartz, oligoclase and K-feldspar which is broadly consistent with the rhyolitic composition, implying that no large addition or loss of major components occurred. Neither are there any other signs that the dyke or the enclosing ignimbrite have been affected by hydrothermal alteration. Thus, positive evidence for the involvement of a separate overprinting hydrothermal system is lacking. Rather, devitrification probably reflects an increase in temperature during burial combined with the fact that the glass was perlitised and by inference hydrated. Crystallisation of silicic glass is promoted if the glass is hydrated, if it is in contact with water or alkali-rich solutions and/or if it is heated (Bonney and Parkinson, 1903; Marshall, 1961; Lipman, 1965; Lofgren, 1970, 1971b; Friedman and Long, 1984). In the presence of water, devitrification can occur at temperatures at least 200°C lower than for dry conditions (Marshall, 1961) and the experiments of Lofgren (1971b) involving alkali-rich solutions resulted in devitrification at temperatures as low as 240°C. In experimental runs, devitrification follows hydration though at a slower rate. The intensely fractured and perlitised glass of the Silver Hills dyke would have been permeated by groundwater, possibly enriched in locally leached alkalis. A combination of elevated temperature, fracture-controlled contact with groundwater, and water inherited from the precursor perlite may therefore have been responsible for the remarkable polygonal quartz-oligoclase and axiolitic K-feldspar devitrification textures. These conditions could also have influenced recrystallisation of the earlier-formed spherical spherulites.

6.2. Perlite

Fracture sets in the Silver Hills rhyolite dyke can be arranged in order of formation: the long fractures formed first; the cross fractures formed second; and the perlitic fractures formed last. We interpret the long fracture and cross fracture sets to be first- and second-order quench fractures, respectively (cf. Yamagishi and Dimroth, 1985; Yamagishi, 1987). The dyke walls would have been approximately isothermal surfaces during cooling. First-order joints caused by cooling contraction commonly form perpendicular to isothermal surfaces (Spry, 1962; DeGraff and Aydin, 1987). Hence the long fractures are likely to be first-order quench fractures. The cross fractures are perpendicular to the long fractures and resulted from additional cooling contraction as the first-order set propagated inward from the dyke walls. Neither fracture set shows any sign of deformation by continued flowage and therefore apparently formed after movement had ceased. By this stage the spherulitic glass was clearly sufficiently viscous to respond in a brittle fashion to thermal stress. Rapid cooling also arrested spherulite growth, implying cooling to temperatures below the glass transition temperature (Manley, 1992). We conclude that the last of the three fracture sets, the perlitic fractures, formed after substantial heat loss, perhaps at temperatures as low as 100–200°C (cf. Friedman et al., 1966).

Experimental and geochemical studies of perlite show that the fractured glass is hydrated, containing higher amounts of meteoric water, whereas the cores retain pristine magmatic H_2O contents (Ross and Smith, 1955; Friedman and Smith, 1958; Otvos, 1961; Friedman et al., 1966). These results have been interpreted to indicate that perlite forms in response to hydration of volcanic glass: the fractures release strain imposed by a volume change on the uptake of H_2O (Ross and Smith, 1955; Friedman and Smith, 1958; Nasedkin and Petrov, 1962). In contrast, Marshall (1961) inferred that perlitic fractures form primarily in response to strain derived from rapid cooling, and that external water was later absorbed by the glass. Study of a Late Miocene subaqueously emplaced glassy rhyolite led Yamagishi and Goto (1992) to a similar conclusion. Yamagishi and Goto (1992) described well-developed macroperlite and other fracture sets (columnar and small polygonal joints) in the rhyolite. They stated that the rhyolite is not hydrated, on the basis of the absence of "alteration minerals" although the chemical analysis presented (Table 1; Yamagishi and Goto, 1992) does not include data for H_2O and the petrographic description does not indicate whether the macroperlite fractures are associated with strain birefringence (cf. Ross and Smith, 1955; Marshall, 1961; Nasedkin and Petrov, 1962). Fracture formation, including macroperlite, was thought to be the result of thermal stresses arising from quenching and shear stresses related to flowage. Yamagishi and Goto (1992) also concluded that the macroperlite fractures predated the other fracture sets.

The debate is polarised over the roles of hydration versus cooling contraction as the prime cause of perlitic fracturing. However, studies of the way in which water is held in natural and artificial silicate glasses suggest that formation of classical perlite depends on both rapid cooling *and* exposure to external water. In particular, the textural consequences of glass hydration depend in part on the rate of cooling and the temperature at which hydration begins (Keller and Pickett, 1954; Lacy, 1966; Drysdale, 1979, 1991). Hydration that begins at relatively high temperature in relatively slowly cooling glass, such as in intrusions, results in a structure that can accommodate later low-temperature hydration without contraction, preventing the formation of perlite. In contrast, rapidly chilled glass subject to hydration at low temperature undergoes structural re-arrangement that results in contraction and perlitic fracturing (Lacy, 1966; Drysdale, 1979, 1991). Lacy (1966) inferred that mega-perlite (or macroperlite) represents intermediate circumstances and will develop in cases where low-temperature hydration affects somewhat less rapidly chilled glass. Rapid cooling also results in contraction, imposing strain that may be sufficient to cause brittle fracture of the glass. However, theoretical studies of cooling contraction predict formation of subplanar fractures perpendicular to isothermal surfaces (Spry, 1962; DeGraff and Aydin, 1987). For a narrow dyke such as in this case, cooling contraction would be expected to form successive orders of joints perpendicular and parallel to the dyke walls, rather than the concentrically arranged, arcuate fractures characteristic of perlite. Perlitic fracturing may well release residual stresses in the cold glass inherited from the cooling process (Allen, 1988), but rapid cooling alone does not directly result in classical perlitic fracturing. Important questions remain regarding the controls on the geometry of fractures in glassy volcanic rocks such as the Silver Hills rhyolite dyke; in particular, why are fractures generated by thermal stress typically planar to curviplanar and why are perlitic fractures typically tightly arcuate to sub-spherical in shape?

The intensity of quench fracture development in the Silver Hills dyke indicates very rapid cooling and suggests that the perlitic fractures developed in cool glass. The closely spaced quench fractures were probably important in greatly increasing access of external water to the glass, a factor essential for classical perlite formation. Whether the glass was indeed hydrated cannot be determined for the Silver Hills dyke (as no glass is preserved) but hydration can be indirectly inferred from the axiolitic and coarse polygonal textures of devitrification products.

7. Conclusions

The Silver Hills rhyolite dyke was emplaced at shallow levels into a coeval felsic volcanic succession. At the time of intrusion, the rhyolitic melt contained dispersed microlites, now magnetite (formerly pyroxene?). Small spherical spherulites grew during a brief period of relatively high temperature crystallisation, accentuating a flow foliation defined by microlites aligned subparallel to the dyke walls. Two fracture sets formed in the dyke in response to contraction during quenching. The older of these sets comprises subplanar, relatively long fractures oriented perpendicular to the dyke walls. The younger set consists of short cross fractures connecting, but not cutting, the long fractures and oriented perpendicular to them. These fractures sets allowed access of external water to the interior of the dyke and formation of perlite as a result of low-temperature hydration of the rapidly chilled glass. The perlitised glass subsequently devitrified, producing axiolitic K-feldspar along the fractures and a polygonal quartz-oligoclase mosaic between the fractures. Devitrification to axiolitic and coarse polygonal textures, and recrystallisation of earlier-formed spherical spherulites, may have been promoted by contact with groundwater, elevated temperature and preceding hydration of the glass. All fracture sets have been accentuated by iron oxides deposited during surface weathering.

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