Chapter 4

A shoaling felsic to intermediate volcanic succession in the Highway Member of the Trooper Creek Formation
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4.1 Introduction

This chapter focuses on the physical volcanology of the volcanic and sedimentary sequence exposed in the southern part of Trooper Creek prospect (Figs. 4.1 & 4.2). This area provides some of the best exposures of the upper part of the Highway Member (Trooper Creek Formation) and the transition to the overlying Rollston Range Formation. Strata in this area strike east-west and dip at angles predominantly between 44-60° S. The sequence is cut by several S to SSE striking minor faults and is locally folded on a small scale, but no major structural complexities have been detected. A discontinuous cover of Tertiary alluvium and Recent surficial deposits obscures large parts of the sequence.

The lithofacies exposed at Trooper Creek prospect provide an opportunity to document the complex history of a shoaling submarine andesitic scoria cone. The volcanic and post-volcanic history, changes in the depositional and eruptive setting, and eruption styles are considered. The volcanic centre provides an analogue for other shoaling andesitic scoria cones constructed by strombolian eruptions in a relatively shallow marine environment. The model for this style of volcanism contrasts with that of sertseyan eruptions which are relatively well understood (e.g. Walker and Croasdale, 1972; Kokelaar and Durant, 1983a,b; Cas et al., 1989) and important in the construction of many shoaling volcanic centres.

Basaltic volcanioclastic units on deep marine (1000 m) seamounts have been interpreted as the deposits from submarine lava fountaining (e.g. Batiza et al., 1984; Smith and Batiza, 1989; Batiza et al., 1989). In ancient subaqueous volcanic successions, similar volcanic deposits have been documented (e.g. Carlisle, 1963; Yamagishi, 1982, 1987; Staudigel and Schmincke, 1984; Schmincke and Sunkel, 1987). However, relatively little is known about the eruptive style and products of fire fountain and strombolian eruptions in these environments.
Figure 4.1 Simplified geological map showing the distribution of volcanic and sedimentary units within the three principal lithofacies associations. Strata dip and young to the south.
4.2 Lithofacies associations

In this part of the Seventy Mile Range Group, the Highway Member is characterised by rapid vertical and lateral changes in volcanic and sedimentary facies. Andesites dominate over dacites and both rock types are represented by lavas, intrusions and a variety of volcaniclastic facies. The 14 principal lithofacies can be grouped into three compositionally distinct lithofacies associations. These associations have genetic significance with respect to eruption style, proximity to source, volcano type, provenance and depositional setting.

(1) The sedimentary facies association mostly comprises siltstone and sandstone units that can be volcanic or non-volcanic. Intercalated dacitic to rhyodacitic volcaniclastic breccia and sandstone beds record occasional influxes of volcanic debris into the depositional environment. These beds record explosive silicic eruptions at subaerial or shallow subaqueous volcanic centres, and were emplaced by cold, water-supported, high-concentration turbidity currents.
(2) The andesitic facies association includes both primary volcanic and resedimented volcaniclastic lithofacies. The primary volcanic facies includes lavas and volcaniclastic facies for which eruption, transportation and deposition were directly controlled by volcanic processes. The resedimented lithofacies are composed of clasts that were initially formed and deposited by volcanic processes and subsequently redeposited although not significantly reworked (McPhie et al., 1993). This facies is dominated by graded andesitic scoria breccia facies and globular clast-rich breccia facies.

(3) Lithofacies of the dacitic volcano-sedimentary facies association comprise a complex association of resedimented facies, siltstone and microbialites. Exposures of this facies association are largely limited to one creek section within the central part of the area (around 7741900 mN, 426800 mE; Fig. 4.3, 4.4).

All three associations occur within a 1300 m thick section through the upper part of the Highway Member (Fig. 4.2). The sedimentary facies association dominates the base of the section and includes minor dacitic and rhyodacitic units. The andesitic volcanic facies association overlies the sedimentary facies association. The dacitic volcano-sedimentary facies association largely overlies a disconformity at the top of the andesitic facies association.

4.2.1 Sedimentary facies association

Massive to laminated siltstone facies

Siltstone in the southern part of the area is massive and thickly bedded, or is planar laminated. The siltstone beds are laterally continuous, lack mud cracks, soil horizons and evidence of tractional reworking. They are mostly pale to dark grey but on weathered surfaces are yellow brown. The texture in thin-section consists of a cryptocrystalline mosaic of sericite and quartz. Around 7742800 mN, 426700 mE very thinly bedded (cm's thick) and laminated siltstone contains bedding-parallel gossanous Fe-Mn oxide bands. No primary sulfide minerals remain. Intervals of the siltstone facies range from < 1 m up to 160 m in thickness.

Origin and significance of facies

Recrystallisation hampers textural interpretation of the siltstone. They may record settling of fines from the dilute currents trailing turbidity currents, water-settled fallout, pelagic or hemi-pelagic sediment or deposits from weak bottom currents. Although the composition/provenance is not clear, they record suspension-settled sedimentation in a relatively deep and/or quiet water environment, below storm wave base.
A shoaling volcanic succession

Figure 4.3 Detailed outcrop map showing the distribution of the principal lithofacies within the lower part of the dacitic volcano-sedimentary facies association. The highly irregular contact with the underlying andesitic facies association is interpreted as an unconformity.
Figure 4.4 Measured sections presented as graphic logs for major lithologies in the Trooper Creek Formation in the area of the Trooper Creek Prospect. Locations of sections A-E are given in Figures 4.1 and 4.3.
4.2.2 Andesitic facies association

**Massive andesite**

Coherent andesite at Trooper Creek prospect is plagioclase- and pyroxene-phyric. Phenocrysts (2%, 1 mm long) are euhedral and distributed evenly throughout a groundmass which comprises a network of small (160 µm) aligned feldspar laths, pyroxene crystals and interstitial chlorite (probably after glass). Pyroxene (clinopyroxene) is unaltered or has been variably pseudomorphed by chlorite. The andesites typically contain 3-30% (mostly 3-5 wt%) round to ellipsoidal vesicles or amygdales, 0.5 mm to 5 cm across. Amygdales are filled with quartz, chlorite, carbonate, feldspar or zones of chlorite-feldspar or chlorite-quartz.

Intervals of andesite range between 10 m and 70 m in thickness. Coherent andesite sometimes grades into associated peperite and autoclastic breccia facies along contacts with underlying or overlying volcano-sedimentary rocks.

**Non-stratified andesitic breccia facies**

At Trooper Creek prospect (around 7742100 mN, 426800 mE), coherent and moderately fractured andesite passes outward through a zone of in situ breccia into a framework-supported breccia of the same composition, 1-2 m thick (Fig. 4.5A). The contact between brecciated and coherent andesite is highly irregular. Coherent andesite near the contact has more abundant but smaller vesicles than towards the interior (3-5% vesicles, 1-5 cm across). Trains of aligned ellipsoidal vesicles are tightly contorted. Coherent andesite within 15-30 cm of the breccia facies displays platy joints which mirror the vesicle trains and are spaced 1-2 cm apart. Platy joints and vesicle trains are parallel to contacts with the breccia or are cut by the contact at a high angle. Clasts in the breccia have blocky shapes bound by planar to curvilinear margins along which are joints that penetrate short distances towards clast interiors ("tiny normal joints"; Yamagishi, 1979). Vesicle trains in adjacent clasts have different orientations and can be traced into the coherent facies only within an intervening discontinuous, 10-15 cm wide zone of in situ breccia.

**Origin and significance of facies**

Internal variations within the andesitic breccia facies reflect varying roles for quench fragmentation and autobrecciation in the generation of the breccia (cf. Pichler, 1965). The in situ breccia is regarded as hyaloclastite formed through the propagation of networks of thermal contraction fractures into the cooling andesite (cf. Yamagishi, 1979). Tiny-normal joints and gradations between coherent facies and in situ breccia facies, are characteristic of hyaloclastite (e.g. Allen, 1988). Although jigsaw-fit texture is lost,
fragments in clast-rotated breccia retain shapes characteristic of quench fragmentation. The hyaloclastite has undergone rotation and separation of clasts and probably further granulation due to continued movement of the lava, indicating a role for autobrecciation.

Siltstone pod-bearing andesite facies

Exposures of this facies are limited to one segment of a small unnamed creek in the southern segment of the area at the contact between weakly vesicular andesite and the overlying planar laminated siltstone. Most of the observed contacts are broadly conformable with bedding although locally discordant. The contact zone is marked by intricate interpenetration of andesite and pale yellow-brown siltstone and fine-grained sandstone. Downward from the contact, tongues of sediment penetrate the andesite and sedimentary inclusions up to 40 cm across occur within coherent andesite, up to several metres away from contacts with the sediment. The macroscopic texture of the andesite is unchanged from that of the coherent facies described above. However, the siltstone is cherty and pale green at the contact suggesting that it is indurated.

Origin and significance of facies

The interfingering of the siltstone and magmatic component, and induration of the siltstone at contacts, favour interpretation of this facies as peperite. Peperite provides evidence for the mixing of magma or lava and wet unconsolidated sediment and has been described in many subaqueous volcanic successions (e.g. Fisher, 1960; Schmincke, 1967; Williams and McBirney, 1979; Brooks et al., 1982; Kokelaar, 1982; Busby-Spera and White, 1987; Hanson and Wilson, 1993; Brooks, 1995). Fluidal contacts between the igneous component and sediment are thought to form where a vapour film is established and maintained at the magma-sediment interface. The vapour film insulates the magma from the wet sediment and suppresses both quench fragmentation and steam explosions. Sediment is displaced along the contact zone until cooling below a critical temperature causes the steam to condense and sediment to be deposited (Chapter 5, Appendix A).

Stratified andesitic breccia and sandstone facies association

This association comprises graded andesitic scoria breccia, cross-stratified andesitic breccia and sandstone, and globular clast-rich andesitic breccia facies. The cross-stratified andesitic breccia and sandstone facies overlies the graded andesitic scoria breccia facies, and is overlain by globular clast-rich breccia facies. These facies are essentially monomictic, but chlorite-altered clasts, silicified clasts and hematite-altered clasts can occur in the one bed. Clasts are typically elongate, platy or equant in shape. The degree of
Figure 4.5

Andesitic facies association.

(A) Non-stratified andesitic breccia facies. Coherent and mildly fractured andesite passes outward into a framework supported autoclastic breccia (b) of the same composition. Coherent andesite within 15-30 cm of the breccia displays platy joints (arrow). 7742050 mN, 426800 mE.

(B) Graded andesitic scoria breccia facies. The breccia has a coarse-grained base (bottom of page) and fine, sandstone top. Note pale silicified clasts. 7741900 mN, 426800 mE.

(C) Abundant uncompacted scoria and subordinate trachytic clasts in the graded andesitic breccia facies. Vesicles are filled with calcite, chlorite or zones of hematite-chlorite. Formerly glassy vesicle walls have altered to calcite and quartz. Plane polarised light. Sample 95-318.

(D) Graded andesitic scoria breccia facies. Classical perlite is defined by arcuate chlorite-filled fractures (arrow) surrounding kernels of non-fractured, calcite-altered andesite. Sample 95-132.

(E) Cross-stratified andesitic breccia facies. This breccia includes both planar and cross-stratified intervals. 7741800 mN, 427000 mE.

(F) Globular clast-rich andesitic breccia facies. This massive to diffusely bedded breccia is composed of fragments of bombs (arrow) which are supported in a framework of blocky, weakly vesicular clasts. 7741750 mN, 427000 mE.

(G) Globular clast-rich andesitic breccia facies. One bomb has a partially intact, poorly vesicular rind (arrow) surrounding a more vesicular interior. 7741750 mN, 427000 mE.

(H) Photomicrograph of the globular clast-rich andesitic breccia facies. Within the clasts, flow aligned microlites (arrow) are separated by chlorite, quartz and hematite (probably after glass). Patches of calcite occur between some clasts. Plane polarised light. Sample 95-132; 7741750 mN, 427000 mE.
vesicularity varies and two principal clast populations are present. Poorly vesicular clasts with 0-5% (visual estimate) amygdales are bound by planar to cuspatc margins. Breakage across microlites in the groundmass generated clast margins which are planar but finely jagged. Scoriaceous clasts have 25-50% (visual estimate) round-ellipsoidal amygdales and have vesicle-controlled bounding faces which, although finely cuspatc, are broadly planar. Vesicles are filled with either calcite, chlorite, sericite, hematite or zones of quartz-chlorite or hematite-chlorite.

In thin-section, clasts are aphyric or contain 1-2 % feldspar microphenocrysts less than 1 mm long and rare pyroxene phenocrysts. The trachytic groundmass comprises unaltered feldspar (sanidine and plagioclase) microlites (150-500 µm long) and minor interstitial sericite, chlorite and fine-grained hematite. In many clasts, the original groundmass textures have been overprinted by a quartzfeldspathic mosaic or by calcite, chlorite, epidote and/or sericite alteration. Colloform-like bands of hematite nucleate along some clast margins.

Amygdales in some clasts are round, whereas in others there are varying proportions of round and ellipsoidal amygdales. Small amygdales tend to be round, whereas large amygdales are more ellipsoidal. Some round vesicles must have formed late because groundmass microlites project into them and elsewhere feldspar microlites are displaced by them. In some cases, intense silicification, chloritisation and/or carbonate alteration have obscured or destroyed vesicular textures and clast margins, generating a breccia which is dominated by apparently poorly vesicular fragments (e.g. 95-12, 95-318). Relic chlorite- or quartz-filled vesicles are the only indication of former scoriaceous fragments in these domains. Some clasts, and the vesicles within them, are outlined by fine-grained hematite.

**Graded andesitic scoria breccia facies**

Medium to thick, normally graded breccia beds are dominated by clasts 2-5 cm across although rare clasts up to 20 cm occur at their base (Fig. 4.5B). The breccia and sandstone beds are framework supported, moderately well sorted, and lower contacts are sometimes erosion surfaces. The grains are separated by calcite, chlorite and hematite that may have replaced a fine-grained matrix. Thicker beds are overlain by a series of thinner, normally graded beds, 1-15 cm in thickness. Coarse sandstone at the base of these beds comprises fragments 3 mm across and is sometimes diffusely planar laminated. Tops of beds are mostly finer sandstone (0.2 to 1 mm) although some are siltstone. Planar and cross-lamination characterise the sandstone-siltstone tops of some beds. Intercalated planar laminated siltstone units, a few centimetres to several metres thick, separate some breccia beds.
Poorly vesicular clasts account for 1% of most beds but comprise up to 10% of some units (95-132). The remainder of the fragment population consists of scoriaceous clasts with 30-50% round-ellipsoidal vesicles (Fig. 4.5C). Rare tube vesicle scoria with hematite-lined vesicle walls are present. Some clasts have a trachytic groundmass texture, whereas others may have been more glassy with sparse feldspar microlites. In these samples (e.g. 95-132), the groundmass shows classical perlite (e.g. Ross and Smith, 1955) comprising arcuate, overlapping and intersecting chlorite-filled fractures (Fig. 4.5D). Rare clasts have concentric fractures which define margins, cut microlites in the groundmass, and generate rounded clast shapes. Perlitic fractures suggest that the groundmass of these fragments was in part formerly glassy. In many scoriaceous clasts, recrystallisation or alteration has obscured groundmass textures. Large clasts (10-20 cm) are mostly elongate with irregular shapes but some fluidal spindle-shaped clasts occur. The vesicularity of these clasts varies but is generally low, and some clasts have dense margins with a few ellipsoidal vesicles concentrically arranged around a more vesicular interior.

Intervals of this facies range from 15 m to greater than 120 m in thickness. Thinner intervals comprise a number of graded units (centimetres to metres thick), thicker intervals are made up of a small number of graded units each up to 40 m thick.

**Cross-stratified andesitic breccia and sandstone facies**

This facies consists of high-angle trough cross-bedded sandstone and planar laminated sandstone, interbedded with normally graded breccia to sandstone beds (Fig. 4.5E). Cross-beds occupy broad shallow channels and dip to the south. Stratifications are 0.5 to 3 cm thick and characterised by a coarser, normally graded, lower interval comprising fragments 2 to 7 mm in size, sharply overlain by a thinner sandy top with fragments 0.6 to 1 mm across.

The coarse sandstone to breccia is monomictic, moderately to well sorted and devoid of fine matrix. Five to seven percent of the framework consists of scoriaceous clasts (e.g. 95-317A, 95-272). The remaining fragment population consists of poorly vesicular (1-5% vesicles) fragments. Formerly glassy vesicle walls are now chlorite, sericite and calcite. Chlorite occurs as finely crystalline patches or as radial aggregates nucleating on clast margins and extending out into patches of calcite. A thin (10 μm) rind of recrystallised quartz bounds many fragments. Quartz, chlorite and calcite alteration of clast margins has resulted in smoother, rounder and more bulbous outlines than for weakly altered clasts, creating a more extensive apparent matrix domain.
Globular clast-rich andesitic breccia facies

The globular clast-rich andesitic breccia facies is monomictic, moderately to poorly sorted and characterised by up to 10% globular shaped clasts, 5-50 cm long (Fig. 4.5F-G). Units are massive or else show coarse-tail normal grading. One thin bed (<1 m) is normally graded. Contacts between beds are indistinct and defined chiefly by the abundance of blocks. Single units are mostly between 35 and 40 m in thickness, but because outcrop is poor, the boundaries between some units may not be exposed.

The globular clasts are elongate to ellipsoidal or sub-spherical in shape with smooth, hackly, planar or curviplanar margins (Fig. 4.6). Many clasts have poorly vesicular rinds 5 to 10 mm thick, surrounding a more vesicular interior (20-30% vesicles) in which the size and abundance of vesicles increases inward (Fig. 4.6B-C). Other clasts have surfaces

![Figure 4.6 Field sketches of representative examples of bombs from the globular clast-rich andesitic breccia facies. (A) Intensely hematite-altered poorly vesicular clast; (B-C) these bombs have relic poorly vesicular rinds surrounding a more vesicular interior; (D) irregular block with margins that are in part the former walls of vesicles. This clast type is interpreted to be a fragment of the vesicular interior of bombs that have disintegrated.](image-url)
that lack rinds, and some are entirely coarsely vesicular with margins which are in part the walls of vesicles (Fig. 4.6D). In many clasts, vesicles in the centre are spherical and up to a few centimetres in diameter, and those in the outer portion are ellipsoidal and their long axes are aligned parallel to clast margins. The poorly vesicular interior and non-vesicular rind of a few clasts are separated by a 1-2 cm wide zone with 20% aligned ellipsoidal vesicles up to 5 cm long. In thin-section, vesicles, phenocrysts and feldspar microlites in the pilotaxitic groundmass are truncated at clast margins and no glassy rinds are preserved. Sericite, epidote or quartz occur in the groundmass and have also replaced some microlites.

The globular clasts are supported by a matrix composed of elongate to equant fragments with irregular planar margins (Fig. 4.5H) and ranging from 300 μm to 5 mm across. Up to 90% of these fragments are poorly vesicular with 0-3% round to ellipsoidal vesicles, 50-900 μm across. The remaining fragment population has 10-25% vesicles, some defining cuspsate inflections along planar clast margins. Some smaller clasts are zoned with respect to vesicularity and have groundmass textures and vesicle abundances which suggest that they are fragments of blocks.

Intervals of this facies range from 40 m to greater than 70 m in thickness. Thinner intervals appear to comprise one unit; thicker intervals are made up of a few units each possibly up to 40 m thick.

Interpretation

Fragmentation processes

In volcaniclastic deposits fragment shape may be an indicator of the style of eruption, fragmentation mechanisms and eruption environment (e.g. Kokelaar, 1986; Heiken and Wohletz, 1985). However, particle shapes may be modified during transport and reworking prior to final deposition (e.g. Kokelaar and Romagnoli, 1995). The shapes of fragments in the andesitic breccia facies are dependent largely on their vesicularity. Poorly vesicular fragments have blocky, angular shapes with rare embayments where the clast margins cross the walls of vesicles. Vesiculated fragments that formed by breakage across vesicles have more irregular shapes, although planar surfaces are common.

Scoria — The scoriaceous character of some fragments, particularly within the graded scoria breccia, suggests they are pyroclasts, whereby magma fragmentation was driven primarily by exsolution of magmatic volatiles. However, if vesiculated magma interacts with water, non-explosive quenching or phreaticmagma fragmentation of the magma can also generate clasts with vesicle-controlled surfaces (Kokelaar and Durant, 1983a,b; Houghton and Wilson, 1989). Quenching may initiate magmatic explosions by breaking
vesicle walls allowing rapid decompression and expansion of the magmatic volatiles (Cas et al., 1989).

In the graded andesitic scoria breccia facies, scoriaceous clasts with concentric fractures and perlite imply a role for quench fragmentation in disintegration of the melt. The concentric fractures bound some clasts and are similar to fractures in subaqueous lavas interpreted to record brittle fracturing by thermal contraction (e.g. Yamagishi, 1987, 1991; Goto and McPhie, 1996). Increased rounding of a few clasts appears to record spalling of concentrically fractured margins from non-fractured cores during transport (cf. Cas et al., 1994). Perlitic cracks develop in response to hydration of glass (Ross and Smith, 1955; Friedman and Smith, 1958; Friedman et al., 1966). Although perlitic fractures are not solely the result of quenching, the release of residual stress acquired during rapid cooling is probably important in forming perlite (e.g. Allen, 1988; Yamagishi and Goto, 1992; Cas et al., 1994; Davis and McPhie, 1996).

Globular clasts — Fluidal-shaped clasts in the graded andesitic scoria breccia facies and globular clast-rich andesitic breccia facies have shapes similar to bombs. Bombs are not restricted to subaerial settings. A variety of bomb-like pyroclasts variably termed water-chilled bombs, pyroclastic pillow breccia (Yamagishi, 1982, 1987), scoria pillows (Staudigel and Schmincke, 1984; Schmincke and Sunkel, 1987) clots, spheroids and globules (Carlisle, 1963) have been described from submarine volcanioclastic deposits (Table 4.1). These occur in shallow subaqueous deposits as a result of direct fallout from explosive eruptions (Yamagishi, 1982, 1987) or shallow subaqueous fire fountaining associated with high magma discharge and eruption through a restricted conduit (e.g. Staudigel and Schmincke, 1984). Downslope resedimentation of primary deposits from littoral or shallow subaqueous settings can transport such pyroclasts into deep water (Dolozi and Ayres, 1991). In situ bombs, shards and spatter also occur in modern, deep submarine (> 1000 m) settings on seamounts near the East Pacific Rise, and have been interpreted as proximal “hyaloclastite” deposits from submarine, mildly explosive lava fountaining associated with high effusion rates (Batiza et al., 1984; Smith and Batiza, 1989; Batiza et al., 1989).

Bombs from breccia beds in the Trooper Creek Formation are either ellipsoidal to spindle shaped, with smooth surfaces, and similar to water-chilled bombs, or are elongate with irregular margins and more similar to “clots” described by Carlisle (1963). Fluidal-shaped bombs have been shaped by surface tension during flight, whereas the more irregular clasts are probably the result of the tearing apart of the vesiculating magma. Planar and curvilinear fractures which form the broken margins of some globular-shaped fragments may be quench fractures that formed as the pyroclasts fell into or through water. Bombs from subaerial eruptions are also often fractured and sometimes disintegrate on impact or
**Table 4.1 Characteristics of fluidally-shaped clasts and associated deposits from subaqueous and subaerial volcanic eruptions.**

<table>
<thead>
<tr>
<th>Water-chilled bombs</th>
<th>Water-chilled scoria</th>
<th>Pyroclastic pillow breccia</th>
<th>Clots in broken-pillow breccia</th>
<th>Globules in isolated-pillow breccia</th>
<th>Scoria pillows / lobes</th>
<th>Subaerial bombs</th>
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<td><strong>Environment</strong></td>
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<td>shallow subaqueous</td>
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<td>elongate ellipsoidal; wrinkled margins</td>
<td>elongate ellipsoidal</td>
<td>rounded ellipsoidal to blocky clasts (&quot;pillows&quot;)</td>
<td>irregular nodular-amoebooidal clots</td>
<td>ovate-globular; few segmented, budded or lobate; no tails, spindle forms or beading; astringent &amp; bomb-shaped clasts</td>
<td>branching, irregular, ellipsoidal-amoebooidal agglutinate; stringer &amp; bomb-shaped clasts</td>
<td>spherical, fusiform, ribbon, crown; bomb; subaqueous to subaerial</td>
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<td>5-10 cm</td>
<td>lapilli-sized (2.64 mm)</td>
<td>1-30 cm</td>
<td>0.25 mm-10 cm</td>
<td>spheroidal (5-10 cm); matrix (0.25 mm - 1 cm)</td>
<td>mostly 10-50 cm across; pillows up to 2 m diameter</td>
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<td><strong>Chilled margins</strong></td>
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<td>black chilled glassy rim with palagonite envelope; tiny cracks perpendicular to margin; colour zones</td>
<td>black chilled glassy rim with palagonite envelope; tiny cracks perpendicular to margin</td>
<td>lapilli &amp; ash in matrix have palagonite rims</td>
<td>bleached chloritized former palagonite rims</td>
<td>devitrified chloride altered sideromelane-tephryte rims</td>
<td>partially detached quenched rinds</td>
<td>bombs generally largely glassy; commonly cracked</td>
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<td><strong>Vesicles</strong></td>
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<td>concentric zones; core: spherical to ellipsoidal, few cm across. Outer core &amp; chilled margin: elongate, ram diameter</td>
<td>concentric zones; core more vesicular than interior</td>
<td>vesicular to scoriaceous</td>
<td>elliptoidal vesicles</td>
<td>zones of concentric vesicles</td>
<td>40 to &gt;80 % vesicles; vein-system increases towards interior</td>
<td>variably vesicular; concentric layers; vesicles more abundant &amp; larger in core than rim; rarely hollow</td>
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<td>lapilli-sized scoria and/or ash with associated aceractic lapilli</td>
<td>no interstitial ash</td>
<td>highly vesicular scoriaceous lapilli and ash; more abundant than &quot;pillows&quot;</td>
<td>spheriform matrix of ellipsoidal globules, gravales, shards; meandrop-and spindle-shaped common; little in situ cracking.</td>
<td>spheriform matrix of ellipsoidal globules, gravales, shards; meandrop- &amp; spindle-shaped; in situ cracking</td>
<td>detached vesicular rinds and lapilli-sized, very vesicular stringer-shaped sideromelane fragments; minor ash</td>
<td>irregular vesicular cinder &amp; scoria</td>
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<td>vesicular amoebooidal submarine lava flow (pillows) or submarine lava fountaining (clasts)</td>
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explode in flight (Macdonald, 1972; Self et al., 1974). The size and shape of the bombs in the globular clast-rich andesitic breccia facies strongly suggests that they formed by rupture of the melt due to volatile expansion or, more likely, high eruption rates or eruption through a restricted conduit (cf. Staudigel and Schmincke, 1984; Von der Borch, 1971).

Some submarine volcanioclastic deposits include fluidal-shaped clasts similar to subaerial and water-chilled bombs, but are thought to have formed through budding from vesicular pillow-like lava lobes. This type of breccia is associated with the shoaling stage of La Palma seamount and is composed of lobes ("scoria pillows") and "scoria lapilli/bombs" (Table 4.1; Staudigel and Schmincke, 1984). The scoria pillows were formed by effusion, and the lapilli and bombs which occur in upper part of the unit were thought to result from submarine lava fountains (Staudigel and Schmincke, 1984).

It is unlikely that bomb-shaped fragments from the Trooper Creek prospect formed by budding from lava lobes because: (1) the globular clast-rich breccia facies is not spatially associated with lavas; (2) gradational relationships between intact lava lobes and globular clast-rich andesitic breccia facies have not been observed; (3) the bombs have higher vesicularities than many compositionally similar lavas from the same stratigraphic section; and (4) the bombs differ in size and shape from the scoria pillow clasts.

Poorly vesicular clasts — Magmatic volatile-driven explosivity does not appear to have played a role in the generation of these clasts. Clasts which are segments of former bombs imply that quenching postdated the initial pyroclastic fragmentation mechanism. Other clasts have blocky to elongate shapes and planar margins consistent with brittle fragmentation. An origin involving quench fragmentation of a vesiculating magma or lava is inconsistent with the association with fluidal-shaped bomb fragments, and with the absence of gradational transitions into in situ brecciated and coherent facies. Rather, these components are more likely to be pyroclastic in origin.

Their shapes are similar to phreatomagmatic pyroclasts, which are typically blocky, and also sparsely to moderately vesicular (e.g. Fergusson et al., 1994). However, if vesiculation of the magma is advanced at the time of magma-water interaction, strongly vesicular, irregularly-shaped clasts can be abundant (Houghton and Wilson, 1989). The deposits of subaerial phreatomagmatic explosions are typically fine grained, "at most 8 mm in median diameter" (Wohletz, 1983). Some coarse phreatomagmatic deposits are poor in fine ash and show similar grainsize characteristics tostromboliand scoria deposits (e.g. Self et al., 1980; Kano et al., 1994). Low ash contents in phreatomagmatic deposits are thought to reflect inefficient magma-water interaction, for example, at high confining pressure and/or low magma/water ratios (e.g. Wohletz, 1983). In the Trooper Creek
prospect deposits, the coarse grain size and absence of fine ash suggests that phreatomagmatic explosions were suppressed, or that fines have been lost during transport to the depositional environment. Suppression of phreatomagmatic explosions is consistent with a wholly submerged vent and a low magma-water ratio in the vent, inhibiting the expansion of steam and resulting in incomplete fragmentation (cf. Cas et al., 1989). Both quenching and phreatomagmatic fragmentation were probably important.

Altered clasts — Pale silicified clasts are a subordinate but ubiquitous component in many beds. Clasts have groundmass textures and feldspar phenocryst abundances and sizes which are similar to other clasts in the breccia. Clasts are interpreted to represent either; (1) andesite clasts which were altered prior to redeposition (cf. Kokelaar and Romagnoli, 1995); or (2) accessory or accidental clasts. Patchy and mottled silicic domains which cut across clast boundaries suggests that many clasts are the product of post-depositional hydrothermal alteration.

Transport and depositional processes
The graded andesitic scoria breccia facies and cross-stratified andesitic breccia and sandstone facies are composed of clasts which were initially formed and deposited by pyroclastic processes, but were subsequently redeposited but not substantially reworked. Redeposition was more or less syn-eruptive; hence the deposits are essentially monomictic and primary clast shapes are largely unmodified.

The graded andesitic scoria breccia facies is interpreted to comprise the deposits of high-concentration gravelly turbidity currents. Breccia at the base of beds forms the S3 turbidite division (Lowe, 1982), whereas planar and cross-stratified sandstone and siltstone tops are the Td-e divisions. In the mass flows, clasts were probably supported by more than one mechanism. A combination of dispersive pressure and interstitial fluid turbulence is likely. Siltstone intervals between breccia beds are interpreted as suspension-settled sediment deposited from the dilute sediment clouds trailing mass flows and/or during ambient sedimentation.

The overlying cross-stratified andesitic breccia and sandstone facies is interpreted as a transition zone where traction currents and turbidity currents were both important in sediment transport and deposition. It is possible that the fragments deposited from turbidity currents, but with traction current modification during accumulation to form the cross-stratified intervals. Alternatively, the sandstone units may be genuine traction current deposits emplaced below wave base (Section 4.5) but within a channel setting. Both cross-stratification and planar lamination are identifiable. In relatively well sorted cohesionless sediments, these bedforms imply a transition from a low energy, lower-flow
regime toward high energy, high-flow regime. Channels within the facies may have been cut by turbidity currents or traction currents.

The restricted distribution of the globular clast-rich facies, its massive character and abundance of bombs suggests emplacement proximal to the source vent. The setting of similar bomb-rich deposits from other volcanic successions (e.g. Yamagishi, 1982, 1987; Staudigel and Schmincke, 1984) supports this interpretation. The overall upward fining in some units in the facies suggests a primary eruptive control or else sorting during transport to the depositional environment.

The globular clast-rich facies may be the deposit of water-settled fallout and/or sediment gravity flows. The bedforms, sorting and coarse grain size of the facies favour deposition as near-to-vent fallout. However, the unit probably also includes deposits emplaced by avalanching and rolling of pyroclasts down slope and from sediment gravity flows. Impact sags beneath coarse clasts were not observed, probably because the clasts landed on an accumulating pile of coarse, loosely packed pyroclasts (cf. Cas and Wright, 1987). Settling through water and/or transport from the initial depositional site may also explain the absence of bomb sags. Feeder dykes or spatter, characteristic of vent positions (e.g. Houghton and Landis, 1989), are not exposed in the study area suggesting that the facies flanks source vents. The diffuseness of bed boundaries, absence of any internal discordances and thickness of the globular clast-rich andesitic breccia facies suggest sustained eruptive activity or high eruption rates during deposition of the facies.

4.2.3 Dacitic volcano-sedimentary facies association

The dacitic volcano-sedimentary facies association is best exposed in one small unnamed creek in the central part of the area (Fig. 4.4 - section B).

Planar laminated dacitic pumice breccia facies

This breccia is monomictic and comprises a clast-supported framework of elongate irregular pumice clasts. Pumice fragments are feldspar-phyric suggesting a dacitic composition. Although outcrop is poor, the pumice breccia appears to mantle the underlying stratified andesitic breccia and sandstone facies association and polymictic dacitic lithic-pumice breccia beds. The pumice breccia underlies and is partially replaced by a discontinuous lens of massive quartz-hematite ironstone (Chapter 6). Within a 45 cm wide zone beneath the ironstone lens, the pumice breccia contains abundant hematite nodules, 1-5 mm in diameter.
The pumice breccia consists of upper and lower planar laminated divisions separated by a more massive, diffusely laminated interval (2.9 m thick; Fig. 4.4 - section B; Fig. 4.7A). The lower division is 0.3 m thick but poorly exposed. The upper laminated division is 1 m thick and a thin (0.8-2 cm) pumiceous quartz-hematite horizon occurs 60 cm from the top. Laminae in the upper and lower divisions vary from 5 mm to 1 cm thick, and are defined by thin discontinuous concentrations of unaltered feldspar crystals, and generally also by colour. The breccia is pervasively sericite-hematite-altered but includes pale yellow, bedding-parallel, sericite-rich bands less than a millimetre thick. The breccia appears well sorted. However, most pumice clasts are compacted and strongly altered so that grain size variations are obscured.

Pumice clasts have elongate and ragged shapes. Surfaces normal to the tube vesicles are jagged, whereas the remaining surfaces are smooth and more planar. Formerly glassy pumice have been replaced by sericite and are strongly compacted. The pumice clasts and former vesicles within them are outlined by thin discontinuous trails of fine hematite. Some pumice clasts have been partially or entirely replaced by hematite. In these clasts, vesicle textures have been destroyed but the clast margins are preserved. In more quartz-rich altered domains, relic uncompacted tube- and round-vesicle pumice clasts are preserved. Quartz and sometimes sericite and hematite have infilled vesicles and replaced former glassy walls. Some vesicle fills are zoned with an outer hematite zone passing into quartz and/or sericite zones. The phyllosilicate-altered pumice clasts are commonly deformed around the more competent quartz-hematite-altered pumice and feldspar crystals, and define a bedding-parallel compaction foliation.

Origin and significance of facies
The abundance of highly vesicular pumice within the laminated pumice breccia suggests this facies was sourced from explosive magmatic eruptions from a vent in a shallow subaqueous or subaerial environment. The angularity of clasts and absence of other particle types suggests the pumice clasts were deposited without having experienced significant reworking or abrasion and suggests that the facies is syn-eruptive. Although rich in juvenile pumice, there is no textural or lithofacies evidence for hot emplacement of the facies. Randomly oriented relic tube pumice clasts are preserved and the bedding-parallel foliation is interpreted as a diagenetic compaction foliation (cf. Niem, 1977; Allen and Cas, 1990; Branney and Sparks, 1990; Chapter 3).

The enclosing facies (siltstone, turbidites, microbialite; Section 4.4.1) suggest that deposition occurred in a subaqueous environment. Mantle bedding, good sorting and well developed planar lamination within the pumice breccia bed suggest that the pumice settled through the water column. The pumice may have settled through the water from fallout generated by subaerial eruptions, or from eruption columns above totally or partially
Figure 4.7

Dacitic volcano-sedimentary facies association (7741900 mN, 426800 mE).

(A) Planar laminated dacitic pumice breccia facies. The breccia is non-welded and pervasively hematite-sericite-altered. (B-H) Stromatolitic-oncolitic ironstone facies.

(B) The upper surface of this domed biostrome comprises a series of close linked hemispheroids (arrow). The intercolumn material and substrate(s) is tuffaceous sandstone or breccia.

(C) The structures consist of successive algal cappings or laminae over a nucleus such as an oncolite or irregularity within the substratum (s). At the base, laminae forming compound hemispheroids are not connected and neighbouring columns are separated by small amounts (<1 mm to 5 mm) of tuffaceous sandstone. The columns merge upward forming a continuous mat. Sample 95-216.

(D) Branching columnar stromatolites composed of fingers of gently- to moderately-convex hemispheroids. The intercolumn material comprises crystal fragments and shards. Sample 95-200.

(E) Oncolites comprising alternating quartz- and hematite-rich laminae concentrically arranged around a nucleus. Nuclei are either small ovoid quartz grains, single pumice fragments, crystal, or stromatolite fragments. Plane polarised light. Sample 95-200.

(F) Branching networks of filamentous structures (arrow) preserved within grains. Filament walls are made up of very fine-grained hematite. Cryptocrystalline quartz fills the space between the filaments. Plane polarised light. Sample 95-198.

(G) Fragments of trilobites (arrow) with characteristic cross-sectional morphologies and double thickness walls. The fragments have been infilled with hematite and walls are now composed of finely crystalline quartz and in some cases hematite. Plane polarised light. Sample 95-200.

(H) Brachiopod replaced by hematite (arrow). Plane polarised light. Sample 95-200.
submerged vents. Vitric ash was probably transported elsewhere in the eruption column or remained in suspension to be dispersed by currents. Siltstone beds which overlie the pumice breccia interval may include a component of this vitric ash.

The internal stratification in the pumice breccia may have been caused by changes in eruption column height, fragmentation processes or dispersal directions during the eruption. Shallow water currents may have enhanced stratification in the laminated divisions. The more massive breccia interval is interpreted to record a sustained period of rapid deposition and/or a sustained period of steady eruptive activity.

Distal water-settled fall deposits are composed of glass shards and crystal fragments and can be normally graded with coarse, crystal-rich bases and finer shard-rich tops. They typically occur in thin (centimetres to tens of centimetres) but widespread intervals interbedded with deep marine sedimentary deposits (e.g. Ninkovich et al., 1978; Ledbetter and Sparks, 1979; Sparks and Huang, 1980). Proximal water-settled fall deposits consist of coarse pumice clasts occurring together with finer but denser lithic clasts and crystal fragments. Deposits are typically internally planar stratified, massive or graded, very well sorted, and can be several metres thick (Dimroth and Yamagishi, 1987; Cashman and Fiske, 1991). The grainsize and thickness of the planar laminated pumice breccia facies suggests that it is a relatively proximal deposit.

**Stromatolitic and oncolitic ironstone facies**

“Microbialite” is a general term used for organosedimentary deposits composed of benthic microbial communities and sediments (Burne and Moore, 1987). Microbialites in ironstone at Trooper Creek prospect are composed of oncolites, stromatolites, pyroclastic components and fossil fragments. The microbialites occur in two layers (upper and lower microbialites) separated by a thick interval of polymictic lithic-pumice breccia (Fig. 4.4 - section B).

**Oncolites and stromatolites**

Oncolites are ellipsoidal to spherical, concentrically laminated microbialites. The term stromatolite is used here to describe microbialites with fine, relatively flat, internal laminations (e.g. Burne and Moore, 1987). Laminae in columnar and non-columnar stromatolites are typically very thin (8-20 μm) and are quartz-rich or hematite-rich. In some thick (70-80 μm) quartz-rich laminae, relic tube-vesicle pumice clasts, shards and crystal fragments are preserved. No attempt has been made to apply rigorous taxonomy to the microbialites studied. There is debate over the application of formal nomenclature to structures that are only partly biogenic and were probably constructed by a variety of different micro-organisms (e.g. Monty, 1977; Burne, 1994). Instead the structures have
been described using simple morphological terms following the scheme of Preiss (1976) and Walter et al. (1982) (Fig. 4.8). Both columnar and non-columnar stromatolites are present and these show a range of different internal forms. Non-columnar stromatolites have flat laminated, undulatory, pseudo-columnar, cumulate or columnar layered forms (Figs. 4.7B–C, 4.8). Columnar stromatolites consist of non-linked, vertically stacked thin hemispheroidal laminae. Columns have uniform variability, vary from upright to inclined and have stubby shapes (Fig. 4.8). Laminae are typically smooth but are sometimes wrinkled. Column walls are absent. Single non-branched columns are thin at the base, become wider towards the top, resembling turbinate and bulbous forms. Branching columnar varieties have multifurcate, coalesced or anastomosed forms. Laminae forming turbinate columns vary from steeply to moderately curved. Coalesced and anastomosed columnar varieties have steeply convex laminae or, in laterally linked segments, gently- to moderately-convex laminae. A number of the fingers branch upward, others terminate, and some coalesce upward by development of lateral linkages (Fig. 4.7D). Fingers have increasingly slender shapes as the proportion of pumice, crystals and shards increase.

Oncolites have ellipsoidal to spherical shapes and vary from 0.5 to 1.5 cm in diameter (Fig. 4.7E). The component laminae are concentrically arranged around a nucleus and can be continuous or comprise discontinuous overlapping shells. Nuclei can be: (1) small ovoid quartz grains; (2) quartz-hematite mosaic; (3) stromatolite fragments with interstitial tuffaceous sandstone; (4) single oncolites with ovoid quartz cores; or (5) a single pumice or tuffaceous sandstone fragment. Large oncolites typically have a single pumice or fragment of stromatolitic mat as the nucleus.

Branching networks of filamentous structures are preserved in the cores of oncolites or between grains in sample 95-198 (Fig 4.7F). The filaments form dense networks of randomly oriented fibres with cylindrical cross-sections, 5–8 μm in diameter. Filaments vary from 10 to 200 μm long. Filament walls are made up of very fine-grained hematite. Cryptocrystalline quartz fills the space between the filaments. The filaments are similar to those described and interpreted by Duhig et al. (1992) as microaerophilic chemolithotrophic bacteria or fungi. In most samples, the structure of the laminae forming stromatolites and oncolites has been destroyed during replacement of the components by quartz and hematite. Quartz is very fine grained (5-20 μm) but has locally recrystallised to coarser grains with 120° triple junctions. Cracks which follow or cut across laminae in some stromatolites and oncolites are filled with fine-grained (15 μm) quartz.

Matrix
The matrix between columns, clasts and oncolites consists of crystal fragments, pumice clasts and lithic fragments. Formerly glassy particles have been replaced by finely crystalline (20-50 μm) quartz and subordinate hematite. Some pumice fragments are now
Figure 4.8 Morphological terms for the description of microbialites with stromatolitic and oncolitic forms. Modified from Preiss (1976) and Walter et al. (1982).
entirely hematite. Relic pumice clasts, shards and the vesicles within them are outlined by thin films of hematite. Pumice clasts have uncompacted round- and tube-vesicles and are feldspar-phyric. Feldspar crystal fragments are largely unaltered but some have been pseudomorphed by polycrystalline quartz.

**Fossils and fossil fragments**

Fragments of trilobites display characteristic cross-sectional morphologies and, in the best preserved examples, double thickness walls (Fig. 4.7G). The fragments have been infilled with hematite and walls are now composed of either finely crystalline quartz or hematite. Other biogenic components are possible sponge spicules, gastropods and a brachiopod (Fig. 4.7H). Quartz and hematite alteration has destroyed or significantly modified the structure of these grains so that precise identification is difficult.

**Mode of occurrence**

In situ stromatolites occur as thin laminae 2-3 millimetres thick separated by pumice- and shard-rich sandstone and breccia (lower microbialite); as domed biostromes 1-3 cm thick in which there is an intimate association of stromatolites and associated trapped and bound detrital tuffaceous sediment (lower microbialite); and as subspherical bioherms built upon, and intergrown with, tuffaceous sandstone (upper microbialite). The in situ stromatolites are built on sandstone and pebble conglomerate that contain oncolites and stromatolitic clasts as well as pyroclastic components.

Domed biostromes — The upper surfaces of some mats are wrinkled into a series of small domes or hemispheroids, 0.5-1 cm in diameter and 1-4 mm high. The hemispheroids are linked laterally to neighbouring structures forming the mat. The distance between the hemispheroids is less than 2-3 mm, less than the diameter of the structures, so that they can be classified as close-linked hemispheroids. The structures consist of successive algal cappings or laminae over a nucleus such as a crystal or pumice fragment, an oncolite, or an irregularity within the substratum. In the simplest case, laminae are continuous between neighbouring hemispheroids (simple hemispheroids; Logan et al., 1964; Fig. 4.7B-C). At the base of the structures, compound hemispheroids are not continuous and neighbouring columns are separated by small amounts (<1 mm to 5 mm) of oncolite-bearing tuffaceous sandstone. The turbinate columns widen upward and merge where lateral linkages form a continuous mat covering the substratum. The non-columnar component of the structure can be pseudo-columnar or cumulate in form. Simple laterally linked forms occur within millimetres of compound forms in the same biostrome.

Subspherical bioherms — These are small dome-like structures 6-7 cm high and around 8 cm in diameter (Fig. 4.9A). The microstructural elements of the bioherms are compounded forms composed of concentrically laminated, columnar and non-columnar
elements. The pedestal of the structure comprises a series of oncolites from which extend radially arranged branching and turbinate columnar stromatolites (Fig. 4.9B). At the margins of the pedestal, initially discrete turbinate columns pass into a zone of pseudo-columnar stromatolites and planar laminated stromatolite. The upper part of the bioherm is a complex mixture of stromatolite forms (Fig. 4.9C). Turbinate columns pass into laterally linked hemispheroids forming pseudo-columnar structures. Branching and columnar layered stromatolites have grown upward from these surfaces.

Stromatolite clast-bearing sandstone and breccia — Sandstone beds are dominated by volcanic detritus or consist of grain-supported aggregates of sand- to gravel-sized oncolites, stromatolite fragments and volcanic fragments (principally crystals, pumice and shards). Breccias vary from matrix- to clast-supported. Stromatolite clasts have elongate slabby shapes, vary from 0.3-12 cm long, and are up to 4 cm thick. Clasts are separated by a matrix of volcanic fragments, oncolites and small stromatolite fragments.

Stromatolite clasts within sandstone and breccia beds are fragments of one stromatolite type or are compounded forms comprising several different morphologies. The former include non-columnar, undulatory and flat laminated forms. Others are branching columnar stromatolites. The morphological variability of compounded forms provides insights into the character of the bioherms or biostromes from which they were derived. Many clasts are composed of branching forms which locally develop lateral linkages and pass into pseudo-columnar varieties. Others are zoned with lower and upper zones of pseudo-columnar stromatolite separated by branching divisions. Many stromatolite clasts are encrusted by stromatolite laminae which grew out from the initial clast boundaries. Some encrustations completely surround clasts and comprise thin, smooth, concentric laminae. Other encrustations are restricted to the tops and margins of clasts and are compound forms involving turbinate columnar varieties, non-columnar undulatory forms and concentrically laminated stromatolite.

Origin and significance of facies
Microbialites at Trooper Creek prospect have grown by both trapping and binding of detrital volcanic particles on the organic film (cf. Monty, 1977; Burne and Moore, 1987). Compound structures that exhibit a change vertically from one stromatolite growth form to another are evidence for minor changes in the physical environment during deposition. Although it is not possible to attribute any one factor as responsible for a specific stromatolite form, the influx of volcanic detritus appears to have been a major influence in the Trooper Creek examples. For example, digitate stromatolites have more slender branches in parts of biostromes that are richer in volcanic detritus, and stubby shaped branches where there is less intercolumn sediment. The unlinked branched portions reflect periods of rapid sedimentation when growth was limited to small patches which attempted
Figure 4.9

Dacitic volcano-sedimentary facies association (7741900 mN, 426800 mE). (A-C) Stromatolitic-oncolitic facies.

(A) Simplified sketch showing the distribution of microstructural elements forming a subspherical bioherm. Sample 95-218.

(B) Subspherical bioherm. The pedestal of the structure comprises a series of oncolites (o) from which extend radially arranged turbinate columnar stromatolites (c). Sample 95-218.

(C) The upper part of the bioherm is a complex mixture of turbinate columnar, pseudo-columnar and columnar-layered stromatolite forms. Sample 95-218.

(D) Polymictic lithic-pumice breccia facies. This breccia is a poorly sorted, matrix-supported and weakly normally graded. The clast population includes siltstone (s), ironstone (arrow), dacite (d) and composite clasts of dacite and indurated siltstone (i). (E-F) Laminated siltstone and vitric sandstone facies.

(E) Thinly bedded, normally graded, shard-crystal sandstone beds, some with thin cross-stratified tops. Flame structures (arrow) are locally developed.

(F) Gypsum molds on a parting within siltstone. Isolated euhedra and clusters of intergrown crystals have discoidal or lenticular morphologies similar to those characteristic of displacive gypsum. Sample 95-291.

(G) Trace fossils (*Planolites*) within siltstone (arrow). Sample not oriented. Sample 95-271.
to maintain a surface position. During periods of low sediment influx lateral linkages were able to develop and in some cases non-columnar mat formed. The mechanism of branching and factors controlling differential growth responses are poorly understood (Grey and Thorne, 1985). Retardation of growth and restriction of growth to column margins and sides due to excessive wetting, mechanical erosion, rapid sedimentation and desiccation-induced cracking have been suggested as important (e.g. Haslett, 1976; Logan et al., 1964). At Trooper Creek prospect, pumice clasts, crystal fragments and vitric particles which washed on to the mat interrupted growth until the microbes re-established themselves on the new substrate surface. There is increasing evidence to suggest that the gross morphology and fabric of stromatolites is strongly dependent on the kind of organisms forming the microbial community (e.g. Grey, 1984; Park, 1977).

Preservation of stromatolites and oncolites requires penecontemporaneous lithification. Syn-depositional lithification of Proterozoic stromatolites mostly involves carbonates, but silica (Knoll and Simonson, 1981) and iron oxides (Walter and Hoffman, 1983) have been recorded. In examples of stromatolitic and oncolitic ironstone from Trooper Creek prospect, former microbial laminae were preserved by hematite, while pumice and shards were replaced by quartz and minor hematite. It is not known whether quartz and hematite were the first minerals to precipitate or if they are replaced precursor minerals such as carbonate or oxyhydroxide (e.g. Cloud and Semikhatov, 1969; Kah and Grotzinger, 1992; Hofmann and Jackson, 1987). There is no textural evidence of former carbonate minerals in the stromatolitic samples. Penecontemporaneous lithification by silica has been recorded in modern (e.g. Walter et al., 1976) and ancient (Knoll and Simonson, 1981) microbialites. Knoll and Simonson (1981) noted that filaments comprising digitate stromatolites in the Early Proterozoic Sokoman Iron Formation are preserved as very fine-grained hematite, whereas quartz replaces the remainder of the structure. Conversely, Oehler (1976a) noted that quartz crystallites forming spherules commonly nucleated on the surfaces of organic matter.

Polymictic lithic-pumice breccia facies

This breccia overlies the laminated pumice breccia facies and is poorly sorted, matrix-supported and weakly normally graded. The breccia is 12 m thick and may comprise two units. However, the upper, lower and internal contacts are unexposed. The size of lithic clasts decreases from up to 2 metres at the base to 3 cm towards the top. The matrix is intensely sericite-hematite-altered, but contains an even distribution of euhedral feldspar crystals suggesting the presence of compacted pumice fragments (e.g. McPhie et al., 1993). The clast population is diverse and includes laminated siltstone, quartz-hematite ironstone and vesicular (20 %) aphyric dacite fragments (Fig. 4.9D). Other clasts comprise vesicular dacite with indurated siltstone-filled fractures and rinds. These clasts
are similar to those which characterise the indurated siltstone-matrix breccia facies (Chapter 5.3.2). The sediment immediately surrounding these clasts is different from the matrix of the breccia. Dacite clasts have elongate to blocky shapes with planar and curviplanar to highly irregular margins. Siltstone clasts have elongate blocky shapes, are up to 2 m long and some contain laminae of feldspar crystal-vitric sandstone which are partially replaced by quartz and hematite.

Origin and significance of facies

Weak normal grading and large (1-2 m) matrix-supported clasts are consistent with deposition as a subaqueous mass flow (e.g. Smith, 1986; Lowe, 1982). Clasts in the breccia were either incorporated at source or collected from the substrate during transport. The underlying planar laminated pumice breccia facies suggests that the pumice formed by explosive magmatic eruptions but may not be juvenile. Dacite clasts with indurated siltstone rinds may record the mixing of magma and wet-sediment prior to, or during, their incorporation into the flow. The clasts may have been derived from a partially extrusive cryptodome in the source area of the breccia. One possibility is that the mass flow was initiated by partial extrusion of a cryptodome through a succession of pumice breccia, siltstone and ironstone beds.

Laminated siltstone and vitric sandstone facies

Planar, medium to thick (15-70 cm) beds of fine-grained sandstone interbedded with laminated siltstone characterise this facies. The siltstone and sandstone units are increasingly abundant towards the top of the section and are intercalated with thin intervals of microbialitic ironstone and pumice breccia. The principal components of the siltstone and sandstone beds are devitrified ash and shards, with subordinate crystal fragments (quartz and/or feldspar), suggesting that the beds are rhyolitic to dacitic in composition. Vitric components are now composed of fine-grained (5-10 μm) quartz and the grain boundaries are commonly not preserved. In many beds, devitrification and silicification have combined to destroy most primary textures, hampering their interpretation. Some non-volcanic material is likely to be intermixed with volcanic components and some siltstone intervals may be entirely non-volcanic.

The sandstone beds are massive or normally graded with crystal-rich bases and finer vitric-rich tops (Fig. 4.9E). Some beds display basal scours and flame structures. Cross-stratification is commonly developed within the fine sandstone to siltstone tops of beds. Siltstone units are massive or are planar laminated. Laminae are typically massive but in a few samples (e.g. 95-270) are graded from shard-rich bases to very fine-grained relic ash-rich tops. Although mostly pale to dark grey, some siltstone beds are purple due to intense hematite alteration. One siltstone bed contains sericite pseudomorphs of gypsum.
crystals, best observed on weathered surfaces. The crystals have lenticular shapes and occur separately or in clusters (Fig. 4.9F). Although most crystals occur on bedding-parallel partings in the siltstone, some single crystals occur between the partings. The gypsum crystal-rich bands are 1-2 mm wide and separated by 3-4 cm of massive siltstone.

Evidence for bioturbation within the facies is limited to rare trace fossils within siltstone float from the same area (Fig. 4.9G). The trace fossils are temporary feeding structures (fodinichnia) and comprise mostly Planolites. The trace fossils belong to the Cruziana ichnofacies (Frey and Pemberton, 1984).

**Origin and significance of facies**

The crystal composition suggests that some of the components in this facies may have been sourced from the same eruptions which deposited the underlying facies. Crystal fragments have unmodified angular shapes suggesting that they were not significantly reworked prior to deposition. Sandstone units display bedforms which suggest they are deposits from low-concentration turbidity currents (cf. Lowe, 1982). Crystals and large vitric particles settled from suspension forming a weakly graded division (Bouma Ta). Subsequent deposition of finer particles involved both traction (Bouma Te ± Tb) and suspension (Bouma Te) generating the cross-laminated division and fine siltstone top. Shard-rich siltstone could have originated by settling from suspension in dilute currents trailing volcaniclastic mass flows, and/or water-settled fallout from subaqueous or subaerial explosive eruptions.

Gypsum is traditionally interpreted as evaporitic in origin, being deposited in brine pools at or above the sediment-water interface. However, gypsum can also grow displacively from saline pore fluids within permeable sediment. Displacive growth produces both isolated euhedra and clusters of intergrown crystals which commonly have “discoidal” or “lenticular morphologies” (Demicco and Hardie, 1994) similar to those at Trooper Creek prospect. Intra-sediment growth of gypsum crystals provides evidence for post-depositional crystallisation within an evaporitic environment.

**Graded dacitic pumice breccia facies**

This facies is dominated by feldspar-phyric pumice clasts and feldspar crystal fragments suggesting a dacitic composition. Units are non-welded, up to around 80 m thick, and are normally graded with massive or diffusely bedded tuffaceous sandstone tops, and in some instances, polymictic lithic-rich bases. A few beds have thin reverse-graded sandstone bases overlain by normally graded breccia to sandstone. Sandstone tops consist
mostly of relic pumice and shards. The base of one very thick (> 80 m) unit includes siltstone clasts up to 40 cm long. Lamination in siltstone underlying the breccia is contorted and invaded by tongues of the pumice breccia up to 0.5 m in length. Siltstone clasts are blocky or have wispy contorted shapes and sharp margins. Other clasts have irregular shapes and merge with the matrix, suggesting they were not fully lithified at the time of incorporation into the breccia and are intraclasts.

Thin-sections reveal relic uncompacted round- and tube-vesicle pumice clasts. Vesicles and former glassy vesicle walls are now optically continuous K-feldspar or have altered to albite. A mosaic of fine-grained (5 \(\mu\)m) albite, quartz, sericite and chlorite replaces K-feldspar throughout much of the samples (eg. 95-308), destroying or obscuring pumice textures. In some single pumice clasts, feldspar fills the vesicles and former glassy walls have altered to chlorite. Pumice clasts which have altered to chlorite and/or sericite are compacted and define a bedding-parallel foliation (S1) in outcrop. Most units contain varying proportions of albite-quartz-altered pumice and phyllosilicate-altered pumice. A few units consist entirely of sericite-chlorite-altered compacted pumice. These are characterised by an even distribution of crystals that resembles the porphyritic texture usually found in coherent lavas or intrusions. Margins of pumice clasts and former tube vesicles are defined by thin (2-5 \(\mu\)m) discontinuous trails of chlorite or mica.

Pumice breccia beds vary from a few metres up to more than 80 m in thickness and are interbedded with siltstone and fine-grained vitric sandstone.

Origin and significance of facies

The dominance of juvenile pyroclasts with angular, unmodified shapes and great thickness of some beds suggests that this facies is syn-eruptive and was sourced from explosive magmatic eruptions at a subaerial or shallow marine vent (Chapter 5). Clearly vesiculation was not inhibited by high confining pressures that would be imposed by a deep water column (e.g. Mc Birney, 1963; Fisher and Schmincke, 1984). Although rich in pumice that is most likely pyroclastic in origin, there is no textural evidence for hot emplacement preserved in this facies. Eutaxitic texture, columnar jointing, vapour phase minerals, gas-escape pipes, syn-depositional thermal oxidation, high temperature crystallisation textures (e.g. spherulites) and plastically deformed shards are absent (e.g. Niem, 1977). Some compacted pumice clasts in the breccia beds resemble fiamme in welded pyroclastic deposits. However, tube pumice clasts with randomly oriented uncompacted vesicles are also preserved and the bedding-parallel foliation is interpreted as a diagenetic compaction foliation (cf. Niem, 1977; Allen and Cas, 1990; Branney and Sparks, 1990). Furthermore, the lithofacies characteristics of the pumice breccia beds are consistent with deposition from water-supported subaqueous mass flows, most probably
high-concentration turbidity currents, some of which scour ed the poorly consolidated sediment substrate.

4.3 Lateral and vertical lithofacies variations

The oldest parts of the succession are dominated by the sedimentary facies association. This association displays little internal heterogeneity. In contrast, the overlying andesitic and dacitic facies associations are characterised by rapid lateral and vertical changes in the proportion of resedimented volcaniclastic and sedimentary facies. Because there is no evidence for disruption of the section by post-depositional faults, the facies variations are interpreted as primary and syn-depositional. These facies associations incorporate variations controlled by shifts in relative proximity to source, as well as complexities caused by changes in water depth during emplacement, the rate of sediment supply, and volume of volcanic and non-volcanic material entering the basin.

The initial phase of andesitic volcanism is recorded by intervals of the graded andesitic scoria breccia facies and massive andesite facies. Graded scoria breccia beds dominate the western part of the section, with a clear shift to massive andesite and associated autoclastic breccia in the eastern half of the area (Fig. 4.1). The graded andesitic scoria breccia facies encloses a thin interval of coherent andesite and autoclastic breccia. The overlying cross-stratified breccia facies is thin in the west but thickens to greater than 30 m in the east (Fig. 4.4). Globular clast-rich breccia occurs only in the eastern part of the area and overlies the cross-stratified breccia facies (Fig. 4.4 - section E). At this position, a high angle surface juxtaposes lithofacies of the andesitic facies association (globular clast-rich facies) with those of the overlying dacitic facies association (Fig. 4.1). In the west, the surface is less irregular and marks the top of the graded andesitic scoria breccia facies, or the cross-stratified andesitic breccia and sandstone facies. The contact is draped by overlying dacitic water-settled fall beds. This relationship is inconsistent with post-depositional faulting but does not preclude the presence of syn-depositional growth faults. There are several possible interpretations for the surface: (1) topography generated through growth faulting; (2) erosion; or (3) primary constructional topography reflecting proximity to the vents within the andesitic facies association. The globular clast-rich facies is absent to the west and is interpreted as a near-vent deposit. This is consistent with the eastern sections being closer to source (and so thicker) than the central and western sections. Over 100 m of palaeorelief is suggested (Fig. 4.1). However, the whole surface is highly irregular which suggests that post depositional erosion and/or growth faults were probably also important.

In the central part of the area, the base of the overlying dacitic volcano-sedimentary facies association comprises massive to planar laminated pumice breccia (water-settled fall)
which passes up through a thin interval of microbialitic ironstone (lower microbialite) into polymictic lithic-pumice breccia (mass-flow deposit). The microbialite is around 10 cm thick and consists of thin (1-5 cm) units of tuffaceous sandstone, oncolith-rich sandstone and in situ domed biostromes. Siltstone is increasingly abundant in the upper part of the succession and encloses thin intervals of microbialitic ironstone (upper microbialite), mud-matrix dacitic breccia and pumice breccia (Fig 4.1 — section B). The upper microbialite consists of stromatolite-rich breccia and subspherical bioherms. The relationship between the breccia and bioherms is not clear due to poor exposure. To the east, lithofacies at the base of the volcano-sedimentary facies association are poorly exposed along a steep contact with the globular clast-rich andesitic breccia facies. To the west, the contact between the andesitic facies association and dacitic volcano-sedimentary facies association is marked by a thin (10's of centimetres to a few metres) discontinuous ironstone lens (Chapter 6). The overlying deposits are very poorly exposed and comprise intercalated siltstone, vitric-crystal sandstone and dacitic pumice breccia.

The top of the succession comprises siltstone, rounded lithic-crystal sandstone (Chapter 3) and a thick interval (> 80 m) of dacitic pumice breccia, the top of which is obscured by the Tertiary Campaspe Formation (Fig. 4.4 - section B). To the east, the equivalent dacitic pumice breccia is thinner (around 60 m) and overlain by thick intervals of siltstone intercalated with thin tuffaceous sandstone and breccia beds (Fig. 4.4 - section E). Thickening of the pumice breccia to the west is interpreted to reflect ponding against a palaeotopographic high to the east. The palaeotopographic high is marked by thickening of the underlying andesitic facies association. In the west, the dacitic pumice breccia is absent and a large body of coherent dacite occurs at the same stratigraphic position.

4.4 Evolution of the Trooper Creek centre

At Trooper Creek prospect, the Highway Member provides an excellent example of the impact of changing environment on eruption style and products. The depositional setting of the three principal lithofacies associations is interpreted to have been submarine on the basis of fossil evidence and regional context. The preserved succession records a transition from a relatively deep to shallow water (above fairweather wave base) depositional environment. Three evolutionary stages are identified (Fig. 4.10), each of which corresponds to one phase in the shoaling of an andesitic volcanic centre.
4.4.1 Deep water phase

Conditions in the depositional environment prior to the onset of andesitic volcanism are recorded by the sedimentary facies association. The lithofacies characteristics of this association are consistent with deposition below storm wave base. Furthermore, the thick accumulation of siltstone and fine sandstone (565 m) imply a relatively deep and/or quiet water setting.

The initial phase of andesitic magmatism is recorded by vesicular andesite in the eastern part of the area. Peperitic upper contacts suggest that some intervals of the andesite were syn-sedimentary sills emplaced into poorly consolidated siltstone and sandstone (Fig. 4.10A). In many other cases upper contacts are not exposed, so that interpretation of intrusive versus extrusive emplacement is not possible. The andesites were constructional and are interpreted to have played an important role in initial shoaling of the volcanic edifice. They formed a pedestal in the eastern part of the area upon which subsequent eruptive centres were constructed. Coeval environments in the western part of the area remained in relatively deep water.

4.4.2 Transitional phase

In the west, sedimentation was dominated by scoriaceous turbidity currents together with minor lavas, and ambient deposition of sands and silts (sedimentary facies association) was terminated. The graded andesitic scoria breccia facies also accumulated in water depths below storm wave base as indicated by several lines of evidence: (1) the units are interpreted as turbidites which are, in general, diagnostic of subaqueous below storm-wave-base depositional settings; (2) hyaloclastite which is associated with a single intercalated lava suggests a subaqueous setting; (3) tractional structures which are abundant in subaerial environments and fluvial and shoreline settings are absent. Isolated occurrences of planar and cross-stratification reflect traction and shearing on the depositional boundary layer of the sediment gravity flows.

The high vesicularity of fragments in the graded andesitic scoria breccia facies (30–50%) suggests that eruptions took place in a relatively shallow water or subaerial setting (probably to the east) where confining pressure allowed vesiculation to proceed uninhibited (e.g. McBirney, 1963; Fisher and Schmincke, 1984). Depths shallower than 500 m are implied (McBirney, 1963) and were probably less than 200 m or even subaerial, although no subaerial facies are preserved. The bombs within the graded andesitic scoria breccia facies and globular clast-rich andesitic breccia facies, may indicate a subaerial explosive origin for the pyroclasts. However, bombs can also form by
Figure 4.10 Cartoon of the principal stages in the development of the Trooper Creek prospect andesitic volcano. See following page for discussion.
Figure 4.10 continued. Cartoon of the principal stages in the development of the Trooper Creek prospect andesitic volcano. (A-E) and emplacement of the overlying dacitic volcano-sedimentary facies association (F-J). (A) Subaqueous (below storm wave base) lava effusion and syn-sedimentary intrusion of andesite into wet unconsolidated sediments of the sedimentary facies association; (B) Strombolian-style volcanism in a storm-wave-base (SWB) environment; (C) Post-eruptive erosion and resedimentation of pyroclasts and construction of a platform near fairweather wave base (FWB); (D) Eruption of magma by fire fountaining and hydrovolcanic interactions, above fairweather wave base (FWB). Subsidence concurrent with volcanism (arrow); (E) Slumping and post-eruptive degradation of volcanic edifice; (F) Mass-flows and water-settled fall of pyroclasts sourced from distal dacitic eruptions; (G) Colonisation of platform by microbialites. Ironstone deposition from circulating, low-temperature hydrothermal fluids (arrows); (H) Partial extrusion of a cryptodome generating a polymictic debris flow; (I) Deposition of volcanogenic sediments and recolonisation of platform by microbialites. Minor evaporite minerals. Ironstone emplacement; (J) Subsidence and transition to silstone-dominated sedimentation.
eruption in both deep water (e.g. Batiza et al., 1984) and shallow water (e.g. Yamagishi, 1982, 1987; Staudigel and Schmincke, 1984) and pyroclasts ejected during subaerial eruptions can fall into water after following ballistic trajectories (e.g. Kokelaar and Romagnoli, 1995). During subaqueous eruptions, bombs and agglutinate can form within an insulating vapour plume (Batiza et al., 1984; Kokelaar, 1986; Smith and Batiza, 1989). Hot fluidal clasts are isolated from the surrounding seawater by a steam envelope or cupola, so that hydromagmatic fragmentation is inhibited (Kokelaar and Durant, 1983a, Smith and Batiza, 1989). Magmatic volatiles may also contribute to the vapour plume (Kokelaar and Durant, 1983a; Kokelaar, 1986; Mueller and White, 1992).

Clasts in the graded andesitic scoria breccia facies are interpreted to record strombolian explosive eruptions which built ephemeral scoria coaes subject to collapse and resedimentation into deeper water environments that existed in the western part of the area (Fig. 4.10B). The mean grainsize of scoria in the graded andesitic scoria breccia facies is coarse sand to granule size. This is typical of strombolian scoria deposits. Scoria fall deposits from the 1973 eruption of Eldfell on Heimaey, Iceland (Self et al., 1974) are representative of those of strombolian activity (e.g. Walker, 1973a; Walker and Croasdale, 1972). These deposits contain few pyroclasts finer than 1 mm, and consist of scoria mostly 2-8 mm across and bombs. They contrast with deposits of surtseyan eruptions by being coarser grained, better sorted and containing fragments with more fluidal shapes (Walker and Croasdale, 1972; Kokelaar and Durant, 1983a).

The degree to which the eruption column extended above seawater is uncertain. Vesiculation may have been enhanced by the eruption column reaching shallow water and so lower hydrostatic pressure. Lackschewitz et al. (1994) suggest that convection cells within subaqueous eruption columns are capable of lifting particles several centimetres across to shallower water depths and rapidly decreasing confining pressure. Decreasing confining pressures may promote vesiculation of incandescent fragments generated during initial low-energy fragmentation of the magma by, for example, fountaining driven by high effusion rates. Volatile expansion within vesicles already formed in deep water may cause secondary fragmentation of particles (Lackschewitz et al., 1994).

4.4.3 Shallow subaqueous phase

Following the first phase of magmatic explosivity (stage 1) there was a change in eruption style (stage 2) and depositional setting which is initially recorded by a thick interval of cross-stratified andesitic breccia and sandstone beds in the eastern part of the area. The cross-stratified andesitic breccia and sandstone facies records the transition to an above-storm-wave-base depositional environment. High-angle cross-bedding implies deposition
above fairweather wave base and suggests that the intercalated turbidity current deposits were also deposited above storm wave base (Fig. 4.10C). The depth of fairweather wave base varies but is typically in the 5 to 15 m range (Walker, 1984). The thickness (>70 m) of single mass-flow deposits in the upper part of the graded breccia and sandstone facies suggests very rapid aggradation to an above fairweather wave base depositional environment. The transition to above fairweather wave base probably included removal and redeposition of some deposits from the first phase, especially near vent pyroclastic deposits (Fig. 4.10C).

The globular clast-rich andesitic breccia facies overlies the cross-stratified interval and is also thought to have been deposited partially, if not entirely, above storm wave base for the following reasons: (1) the facies overlies above-storm-wave-base deposits; and (2) the overlying dacitic volcano-sedimentary facies association contains shallow marine fossils. However, an unconformity separates the andesitic facies association and dacitic facies association so the globular clast-rich andesitic breccia facies may have been partially emergent. If deposited subaqueously, the thickness of the globular clast-rich andesitic breccia facies (>70 m) requires that subsidence occurred prior to its emplacement and/or that subsidence kept pace with accumulation. If subsidence did not occur the deposit would have rapidly become emergent during emplacement in the shallow water depositional setting. Base surge deposits which might be expected on the emergent part of a marine cone (cf. Surtsey, Kokelaar, 1986) are absent. The subaerial facies may have been eroded prior to deposition of the dacitic volcano-sedimentary facies association.

There is an overall decrease in the vesicularity of clasts from scoriaceous in the graded andesitic scoria breccia facies to dominantly poorly vesicular in the overlying cross-stratified andesitic breccia facies and globular clast-rich andesitic breccia facies. The clasts within each of the three facies are mineralogically similar suggesting that they were probably sourced from the same eruptive centre although probably not from the same vent. The absence of rounded clasts, intervening silicic volcanic deposits and microbialites (cf. overlying succession) suggests that volcanic activity of stage 1 and 2 was relatively continuous. Vesiculation of a magma is dependent on external confining pressure, primary magmatic volatile content and cooling history (e.g. McBirney, 1963; Kokelaar, 1986). In deeper water, higher confining pressures might suppress volatile exsolution and restrict the increase in magma viscosity that usually accompanies cooling (e.g. McBirney, 1963). Eruption and deposition of the globular clast-rich andesitic breccia facies occurred in water depths shallower than 15 m (above fairweather wave base) where confining pressures would have been insufficient to suppress vesiculation. However, quenching of the magma prior to peak vesiculation may have been important in generating poorly vesicular clasts. Collectively, the evidence suggests a cooling and/or
primary magmatic volatile control on the vesicularity of clasts and an overall upward
decline in vesicularity within the andesitic facies association.

Pyroclasts in the globular clast-rich andesitic breccia facies and cross-stratified breccia
facies appear to have been sourced from eruptions driven mostly by the high magma
pressure, eruption through a restricted conduit and hydrovolcanic interactions (Fig. 4.10D). The expansion of exsolving magmatic volatiles does not appear to have been
important as scoria is a minor component of this facies. The bombs show varying stages
of disintegration and are accompanied by blocky clasts which implies brittle
fragmentation, perhaps involving hydrovolcanic processes, and also suggests that water
gained access to the column and/or that the pyroclasts fell into water. Reddish oxidation
of a few clasts in the andesitic breccia facies suggests these may have suffered subaerial
weathering and oxidation prior to final deposition in a marine setting. However, hematite
alteration of single clasts and domains in the breccias is locally intense and oxidation is
more likely to reflect post depositional hydrothermal alteration.

In the initial phases of eruption the influx of water into the eruption column was high
resulting in effective fragmentation of pyroclasts by quenching and possibly
phreatomagmatic explosivity, so that the proportion of bombs in the resulting deposit was
low. As the eruption proceeded and the magma discharge rate increased, hydrovolcanic
processes were suppressed and fluidly-shaped pyroclasts were favoured. As the eruption
waned and hydrovolcanic processes became more important, the normally graded, bomb-poor top of the globular clast-rich andesitic breccia facies formed.

The absence of epiclasts and the monomictic character of the andesitic breccia suggests
that the edifice was not emergent for more than short periods of time and/or that
aggradation was rapid and there was insufficient time for reworking. However, explosive
eruptions from shallow marine to temporarily emergent volcanoes may deposit poorly
consolidated aggregates which are easily resedimented. In these cases, the resedimented
pyroclasts may not be appreciably rounded and evidence for emergence might not be
recorded in the resedimented equivalent. Lavas are important in preserving the emergent
parts of a volcanic edifice (e.g. Surtsey, Kokelaar and Durant, 1983a,b), being less easily
eroded.

Spatter, agglutinate and feeder dykes are typical of near-vent environments (e.g. Smith
and Batiza, 1989; Houghton and Landis, 1989). The absence of these lithofacies supports
the interpretation that the globular clast-rich andesitic breccia facies was generated by
activity at a vent most probably located a few hundreds of metres to the east.
The stratified andesitic breccia and sandstone facies association at Trooper Creek prospect is interpreted as the submarine apron of a shallow-water volcanic centre. The size of the volcano is not well constrained due to poor exposure. The facies associations are inconsistent with the former existence of a large volcano, the erosion of which would have substantially influenced sedimentation in the Trooper Creek Formation (cf. Romagnoli et al., 1993; Kokelaar and Romagnoli, 1995).

4.4.4 Post-eruptive degradation

The original volcanic cone was probably easily eroded, especially the deposits emplaced subaqueously above storm wave base. Some observed historical shoaling volcanoes are ephemeral and show repeated cycles of construction and degradation. During the 1964-1965 eruption of Surtsey, two satellite vents, Syrilingur and Jolnir, went through cycles of construction above sea level followed by erosion and submergence during storms (Kokelaar and Durant, 1983a,b). They were planed off to the level of storm wave base. Subaerial lavas were important in preserving the island of Surtsey against major erosion from storms (Kokelaar and Durant, 1983a,b). At Trooper Creek prospect, an unconformity at the top of the andesitic facies association records erosion and/or collapse of part of the primary volcanic edifice, possibly by slumping, in the post-eruptive degradational stage (Fig. 4.10E). Collapse may have been initiated by gravitational instability, earthquakes and/or magma intrusion (Siebert, 1984).

Following degradation of the andesitic centre, sedimentation at Trooper Creek prospect was dominated by deposits sourced from a silicic, shallow subaqueous or subaerial volcanic terrain. Thick pumiceous mass-flow and water-settled fall deposits were emplaced onto the relatively stable shallow water platform and maintained an above-storm-wave-base depositional setting (Fig. 4.10F). Pyroclast-rich sediment gravity flow deposits that occur interbedded with marine and lacustrine sedimentary rocks can be sourced intrabasinally or extrabasinally. Such deposits can record: (1) collapse and resedimentation of pumiceous hyaloclastite from the margins of lava domes and flows (e.g. Kurokawa, 1991,1992); (2) explosive tuff cone-forming eruptions accompanying subaqueous dome emplacement (e.g. Horikoshi, 1969; Cas et al., 1990; Allen et al., 1996b); (3) syn-eruptive resedimentation of unstable accumulations of pyroclasts temporarily deposited during subaerial or shallow subaqueous explosive eruptions (e.g. McPhie et al., 1993; White and McPhie, 1996); (4) post-eruptive slumping and sliding of coastal, non-welded, pyroclastic deposits into deep water (e.g. Wright and Mutti, 1981); (5) explosive eruptions from partly or wholly submerged calderas (e.g. Howells et al., 1986; Busby-Spera, 1986) or vents (e.g. Fiske, 1963; Fiske and Matsuda, 1964); (6) passage of subaerially erupted hot, gas-supported, pyroclastic flows into subaqueous
environments and transformation of flows into water-supported volcaniclastic mass flows (e.g. Stanton, 1960; Lock, 1972; Niem, 1977; Carey and Sigurdsson, 1980; Wright and Mutti, 1981; Cas and Wright, 1991; Jagodzinski and Cas, 1993); or (7) sedimentation of pyroclasts from the base of pyroclastic flows moving over water (e.g. Ui et al., 1983; Cas and Wright, 1991; Carey et al., 1996).

Parts of a few lavas and domes in the Trooper Creek Formation are pumiceous (e.g. REW 802, 170-242 m; Chapter 5) and could have supplied pumiceous clasts to volcaniclastic units. However, the small component of non-vesicular juvenile clasts, regional distribution (Chapter 3) and thickness of some intervals of the graded pumice breccia facies suggest that resedimentation from the pumiceous carapace of nearby submarine lavas was not the major source of pumice. The mass flows were not sourced locally but from explosive eruptions at a volcanic centre which is located outside the study area.

A significant feature of the sequence was the colonisation of the platform by microbialites and a variety of other organisms (Fig. 4.10G). Only a few microbialite types are indicative of specific depositional settings (e.g. Grey and Thorne, 1985; Bauld et al., 1992). Conical columnar stromatolites occur only in deep to shallow subtidal environments, and have been identified as the sole or dominant stromatolite type in basin and slope facies, drowned platform sequences, and probable deep ramp facies. Microdigitate columnar stromatolites are almost exclusively restricted to intertidal or supratidal settings (Grey and Thorne, 1985; Bauld et al., 1992). The remaining stromatolite types have a less restricted distribution and occur in deeper subtidal to intertidal reef, open shelf, lagoonal and tidal flat settings (Bauld et al., 1992). The morphologies of stromatolites at Trooper Creek prospect fall within this group and so only provide evidence for deposition in a quiet water environment, above fairweather wave base. Wave activity was of sufficient intensity to generate oncolites (Logan et al., 1964) and disrupt the growing mats. Intercalated siltstone and pumiceous water-settled fall deposits suggest that quiet water conditions prevailed during the deposition of these intervals. The appearance of microbialites was coeval with deposition of a thin horizon of quartz-hematite rock (ironstone). The ironstone partially replaced intervals of the pumice breccia substrate to the microbialites (Fig. 4.10G). The ironstones are interpreted to have been deposited from short lived, low temperature, local hydrothermal systems (Chapter 6).

The polymictic lithic-pumice breccia facies contains clasts which were probably sourced from a dacitic cryptodome extruding through previously deposited pumiceous facies, ironstone and siltstone (Fig. 4.10H). Volcanic siltstone and subordinate fine-grained vitric sandstone become increasingly abundant towards the top of the sequence, reflecting
a return to relatively quiet water conditions following deposition of the upper microbialite horizon (Fig. 4.10J). Gypsum molds within siltstone immediately overlying the uppermost microbialite horizon are interpreted to have grown displacively within the sediment. Displacive gypsum has been reported in many marginal marine and marginal lacustrine sediments in modern evaporites (Demicco and Hardie, 1994). Siltstone units contain trace fossils which can be assigned to the Cruziana ichnofacies (Frey and Pemberton, 1984). The Cruziana ichnofacies is most characteristic of subtidal environments (Frey and Pemberton, 1984). The thickness of siltstone and abundance of pumiceous turbidity current deposits in the overlying section suggests a return to relatively deep water conditions, probably in response to subsidence by compaction and/or tectonism, in the subsequent history of the depositional environment (Fig. 4.10J).

4.5 Summary

The Highway Member (Trooper Creek Formation) in the southern part of the Trooper Creek prospect comprises a complex association of lavas, intrusions, volcaniclastic units and sedimentary facies. The oldest parts of the succession are dominated by the sedimentary facies association which records a relatively deep water depositional setting prior to the onset of andesitic magmatism. The andesitic facies association represents the submerged slopes of a small, submarine, strombolian-style volcano which temporarily emerged above sea level. Internal facies variations suggest that the eastern exposures are more proximal than central and western exposures. The four principal lithofacies record progressive stages in the shoaling of the volcanic centre including: (1) subaqueous (below storm wave base) lava effusion and syn-sedimentary intrusion into wet unconsolidated sediments of the sedimentary facies association; (2) strombolian-style volcanism in a near-storm-wave-base environment; (3) hydrovolcanic interactions, above storm wave base and possibly subaerially. The volcanism played a major role in physically modifying the depositional environment. Lavas, syn-sedimentary intrusions and mass flows of resedimented pyroclasts were important in rapid shoaling of the depositional environment.

The post-eruptive history began with partial erosion/collapse of the edifice creating a stable plateau for deposition of the overlying dacitic volcano-sedimentary facies association. Pumiceous mass-flow and water-settled fall deposits record influxes of pyroclasts into the depositional environment from a distal shallow subaqueous or subaerial environment. These units were important in maintaining a shallow water depositional setting during emplacement of the dacitic volcano-sedimentary facies association. When subsidence outpaced accumulation, the depositional setting returned to below storm wave base.