CHAPTER 7

THE HIANANA TUFF RING AND LAVA FLOW : PRODUCTS OF PHREATOMAGMATIC AND EFFUSIVE ERUPTIONS OF A LATE PERMIAN VOLCANIC CENTRE, NORTHEASTERN NEW SOUTH WALES

INTRODUCTION

Thinly bedded volcaniclastic rocks comprise part of the Hianana Volcanics, a mappable unit within Late Permian silicic subaerial volcanics of northeastern New South Wales (Chapter 6). Superficially similar thinly bedded volcaniclastics are produced by a range of epiclastic and pyroclastic processes operating in modern subaerial volcanic centres. This convenient but artificial genetic distinction is blurred in cases combining initial formation of the grains by volcanic or hydrovolcanic fragmentation processes prior to epiclastic deposition (Cas, 1983). The class of purely pyroclastic processes alone includes numerous mechanisms which produce bedded ash (e.g. fall and surge deposits from primary magmatic or hydrovolcanic vent eruptions, secondary 'rootless' explosions, or associated with pyroclastic flows). Resolution of the origin of any one bedded interval rests on context, geometry and distribution if lithologies and structures are not sufficiently diagnostic. In Quaternary and modern sequences where vent sites still exist or are known with some precision, and original distribution, geometry and internal structures of bedded deposits are undisturbed, genesis is rarely ambiguous and modes of emplacement can be interpreted with considerable sophistication (e.g. Walker, 1973a,1984; Crowe and Fisher, 1973; Schmincke *et al.*, 1973; Sheridan and Updike, 1975; Fisher, 1977; Clough *et al.*, 1981; Rowley *et al.*, 1981; Sheridan *et al.*, 1981). Granulometric analysis (e.g. Fisher, 1964; Sheridan, 1971; Walker, 1971,1984; Sheridan and Wohletz, 1983a) and scanning electron microscopy of clasts (e.g. Heiken, 1972; Kortemeier and Sheridan, 1983; Sheridan and Marshall, 1983; Sheridan and Wohletz, 1983b; Wohletz, 1983) provide additional refinements to models of formation.

Only some of these lines of investigation are open in assessing the origin of the Late Permian bedded unit described below. Knowledge of the present three-dimensional geometry is limited by overlying younger units, incomplete exposure and locally complicated structure. The existing geometry departs from the original geometry as a result of post-emplacement erosion, deformation and truncation at faults. No surface expressions of craters or vent sites are preserved. Granular components have been modified by hydrothermal alteration and/or metamorphism. Such deficiencies are permanent and limit the precision of the analysis presented. Nevertheless the internal facies, stratigraphy and depositional structures, in combination with the local context, constitute the basis for proposing that this Late Permian bedded sequence is the remnant of a tuff ring built around a primary hydrovolcanic vent. Lava erupted at the termination of hydroexplosive activity overlies the bedded sequence, and is responsible for its preservation. Together the lava and bedded sequence record a volcanic cycle in which hydromagmatic exchange diminished with time.

GEOLOGICAL SETTING OF THE HIANANA VOLCANICS

Thinly bedded volcaniclastics and plagioclase porphyry of the Hianana Volcanics are exposed in the southeastern sector of the Coombadjha Volcanic Complex (Figs. 7.1,7.2; Chapter 6). The Coombadjha Volcanic Complex is a small portion (360 km^2) of regionally extensive, Late Permian volcanics comprising predominantly subaerial silicic ignimbrites and lavas. These volcanics unconformably cover complexly deformed, older marine sedimentary and igneous rocks (Leitch, 1974) and range up to 2.5 km in thickness although this is a minimum value controlled by the present day level of erosion.

Volcanic units of the Coombadjha Volcanic Complex, including the Hianana Volcanics, are gently dipping or flat-lying over much of their extent. Steeper attitudes occur adjacent to younger granitoid plutons and faults. The arcuate fault and intrusion at the margin of the Complex formed after the emplacement of the volcanic units. Exposure of the Hianana Volcanics is limited by truncation at the southeastern margin of the Complex and by other overlying volcanic units. Much of this analysis of the unit depends on restricted but excellent outcrop along Coombadjha Creek (for 3 km downstream from GR372425 Coombadjha) and tributaries to the northwest and west, away from the steeply dipping and structurally complicated southeastern border of the Complex.

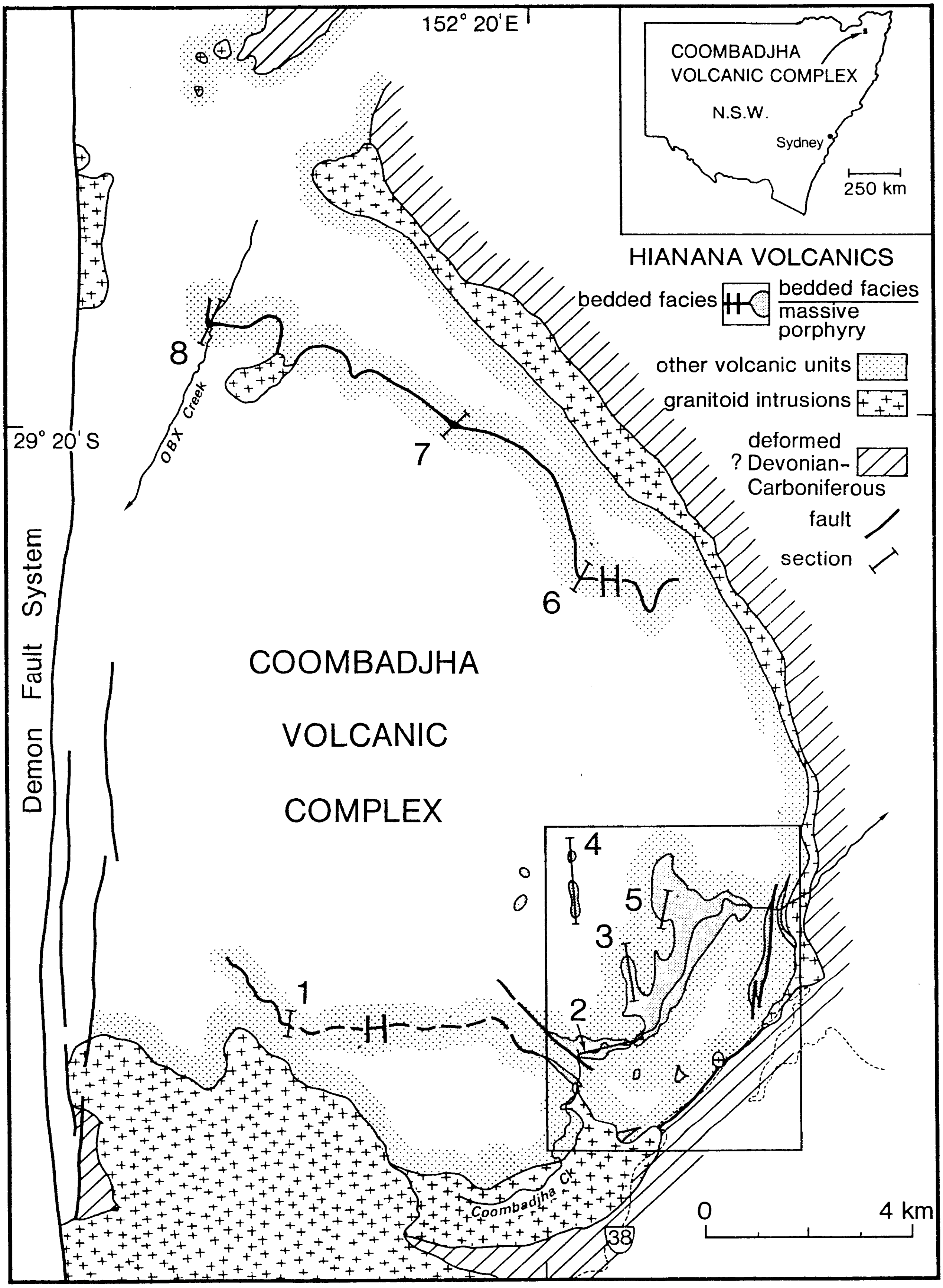

Figure 7.1: Geological setting of the Hianana Volcanics in the Late Permian Coombadjha Volcanic Complex, northeastern New South Wales.

With one volumetrically minor exception (the Babepercy Volcanics, Chapter 6), units above and below the Hianana Volcanics mainly comprise welded silicic ignimbrites, none of which include mappable (at 1:25000) bedded intervals. The Pheasant Creek Volcanics below the Hianana Volcanics contrast in mineralogy as well as facies, containing quartz with K-feldspar and/or plagioclase. Both the Pheasant Creek Volcanics and the Hianana Volcanics include subordinate volcanic breccia and microbreccia. In areas of poor exposure or complicated structure near contacts between these two units, the affinities of a particular occurrence of breccia could not be firmly established. The site of emplacement of the Hianana Volcanics probably had subdued relief controlled by the flat upper surfaces of landscape-smoothing Pheasant Creek ignimbrites, locally interrupted by mounds of silicic lava nearby to the southwest. Older deformed argillites formed hills farther away to the north. Densely welded Pi Pi Ignimbrite above the Hianana Volcanics is the remnant of an outflow sheet, the source of which was beyond the existing margin of the Complex, possibly several kilometres to the southwest. The Pi Pi Ignimbrite is conformable with the Hianana Volcanics but thinner or missing where they are thickest. Thus the Pi Pi Ignimbrite evidently onlaps an original palaeotopographic feature constructed by emplacement of the Hianana Volcanics.

FACIES OF THE HIANANA VOLCANICS

Two facies have been identified: dark and pale, grey-green, bedded volcaniclastics up to 70 m thick; and dark green-black, massive, plagioclase porphyry plus porphyry breccia, 70 to 170 m thick. Massive porphyry is restricted to 14 km^2 in the southeastern part of the Coombadjha Volcanic Complex (Fig. 7.2). Bedded volcaniclastics cover a greater area than the porphyry (approximately 90 km^2), extending around the Complex to OBX Creek (GR290568 Washpool; Fig. 7.1). In the southeastern sector of the Complex where both facies are present (Coombadjha Creek exposures), the bedded volcaniclastics underlie the plagioclase porphyry and breccia. Much thinner intervals of the bedded facies are locally intercalated with breccia in the uppermost parts of the Hianana Volcanics (around GR359424 Coombadjha; Figs. 7.2,7.3, sections 2,4,5). Both facies of the Hianana Volcanics change in thickness over relatively short distances.

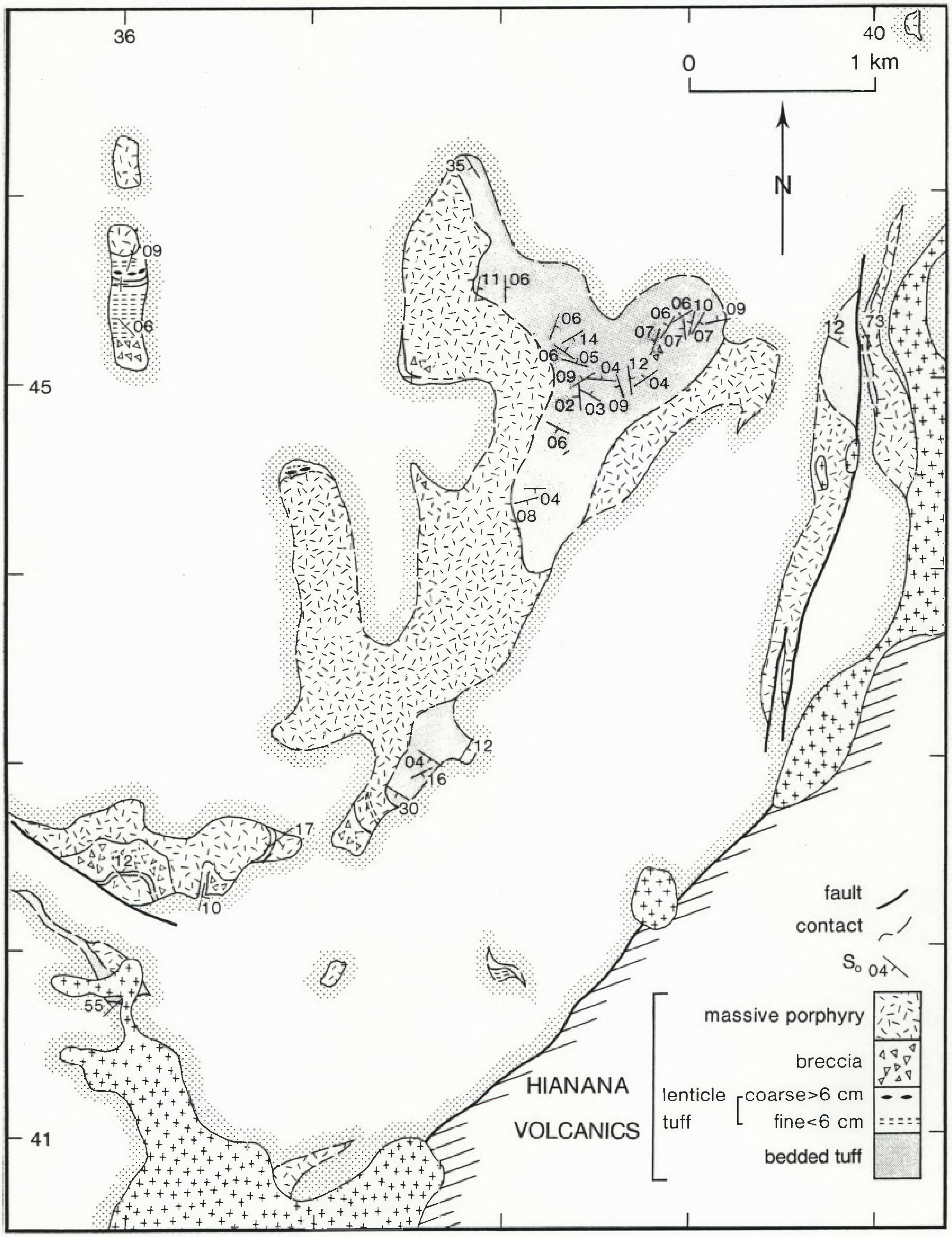

Figure 7.2: Geological map of the Hianana Volcanics in the Coombadjha Creek area of the southeastern part of the Coombadjha Volcanic Complex (indicated on Figure 7.1). The numbered grid is the same as that on the 1:25000 Coombadjha Sheet (9339-II-S), Department of Lands, Sydney. Symbols for rock units other than the Hianana Volcanics are the same as on Figure 7.1. Only bedding readings for the Hianana Volcanics are shown, and inferred contacts are dashed.

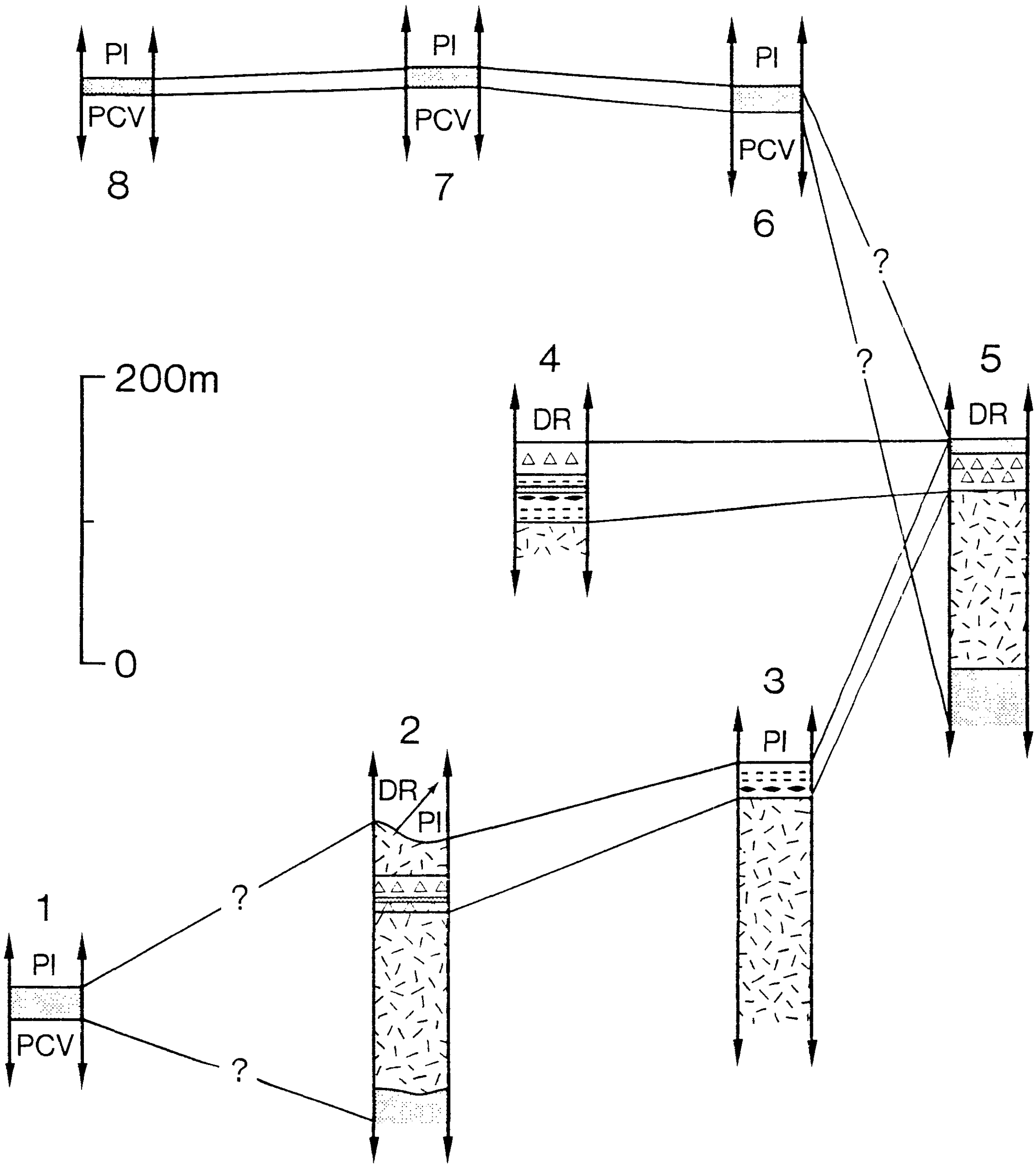

Figure 7.3: Stratigraphic sections for the Hianana Volcanics of the Coombadjha Volcanic Complex. Section locations are indicated on Figure 7.1 Symbols for the Hianana Volcanics match those used on Figure 7.2. Other volcanic units of the Coombadjha Volcanic Complex:

DR, Dundee Rhyodacite;

PI, Pi Pi Ignimbrite;

PCV, Pheasant Creek Volcanics.

BEDDED FACIES

Components and grain size

Principal components of the bedded facies are angular volcanic lithic and crystal fragments approximately 0.5 mm to 3 mm in size and unresolvable finer matrix (less than 0.1 mm; Fig. 7.4a,b). The volcanic lithic fragments are predominantly fine grained plagioclase porphyry and aphyric, non-vesicular, formerly glassy clasts with relic perlitic cracks (Figs. 7.4a,b). Crystal fragments are almost exclusively plagioclase though trace amounts of extensively altered ferromagnesian grains occur in most thin-sections examined. Other constituents found only in small quantities in very few beds are quartz and devitrified shards. Lense-shaped clasts of plagioclase porphyry up to 20 cm long are abundant in volumetrically minor and areally restricted intervals of lenticle tuff in the bedded facies. Some of the lenticles were vesicular and are flattened porphyritic pumice fragments (Fig. 7.4c). Other lenticles appear to have a non-vesicular, fine grained groundmass crowded with plagioclase laths.

Successive beds differ in the grain size of lithic and crystal fragments, in relative proportions of lithic versus crystal fragments, and in the amount of matrix (Fig. 7.4d), all of which contribute to colour variations conspicuous in outcrop. Most thin beds contain crystal and lithic fragments within a narrow grain size range (1 to 3 mm), accompanied by varying amounts of the finer grained matrix, and examples of both poorly sorted and moderately sorted clastic textures occur. Medium thickness beds and the lenticle tuffs are very poorly sorted, and include clasts of centimetre- to submillimetre- size. Very thin beds and laminae in general show better sorting than do the thicker beds.

1. *Coombadjha Creek exposures*

The most striking feature of outcrops of the bedded volcaniclastic facies in the Coombadjha Creek exposures is well defined stratification (Fig. 7.5a). Beds are typically thin (3 cm to 10 cm) and accompanied by less common very thin beds (1 to 3 cm), laminae (less than 1 cm) and medium (10 to 30 cm) to thick (30 to 100 cm) beds. Successive beds are of unequal thickness, a feature accentuated by alternation of recessive and protruding layers. In most cases contacts between beds are diffuse though sharply defined surfaces occur (Fig. 7.5b). Medium thickness beds in some exposures have a faint internal planar stratification (Fig. 7.5c) and there are uncommon instances of normal size grading in thin beds (e.g. GR384450 Coombadjha). Otherwise the thin beds are typically internally massive. The lenticle tuffs are poorly bedded with a crude foliation defined by alignment of porphyritic lenticles.

Bed forms

Separate beds or bedsets in Coombadjha Creek exposures show bed forms of three types, recognised on the basis of their morphology and relationships.

1. Sandwave bed forms: long wavelength (4 to 5 m), low wave height (less than 0.5 m) dunes (Fig. 7.5d); cross beds in sets less than 0.2 m high, some of which are at a very low angle (Fig. 7.6a) and may be truncated, long wavelength dunes; possible chute and pool structures, and wavy bedding (Figs. 7.6b,c). All of these bed forms involve bedsets comprising a few to several, very thin or thin beds.

2. Plane parallel, internally massive beds: In this category the beds vary between two extremes. One end member is of uniform thickness and continuous, and the other is laterally variable and discontinuous, lensing out over distances of several metres, or showing pinch and swell or other irregularities in thickness (Figs. 7.5b,e,7.6d). Thin beds are typical but the thickest individual beds (0.4 m) also belong to this category (Fig. 7.5e).

3. Uniform thickness, continuous mantling beds: These overlie and mimic local irregularities (principally sandwave bed forms), without which they cannot be distinguished from plane parallel beds (Figs. 7.5b,7.6c,e). Mantling beds are thin or very thin, and in most cases finer in grain size than beds of the other types.

Sandwave bed forms are inconspicuous but detectable in most outcrops along Coombadjha Creek. Exposures of complete dunes (e.g. Fig. 7.5d) are uncommon. Instances of gradual lensing of beds are abundant and more continuous lateral exposure could show that many of these are part of

Figure 7.4: a. Volcanic lithic (l) and plagioclase (f) fragments in a comparatively coarse grained example of the bedded volcaniclastic facies. Note the relic perlitic cracks in the lithic fragment at the centre of the field of view. R55405, plane polarised light.

b. Porphyritic lithic (l) and plagioclase (f) grains in a comparatively coarse grained example of the bedded volcaniclastic facies. R55407, plane polarised light.

c. Lenticle tuff with abundant angular volcanic lithic (l) fragments and lenses of porphyritic relic pumice (p). R55406, plane polarised light.

d. Lamination in crystal-rich tuff of the bedded volcaniclastic facies. R55412, plane polarised light.

e. Fine grained, laminated tuff of the bedded volcaniclastic facies from section 7. R55415, plane polarised light.

f. Plagioclase porphyry of the massive porphyry facies. R55429, plane polarised light.

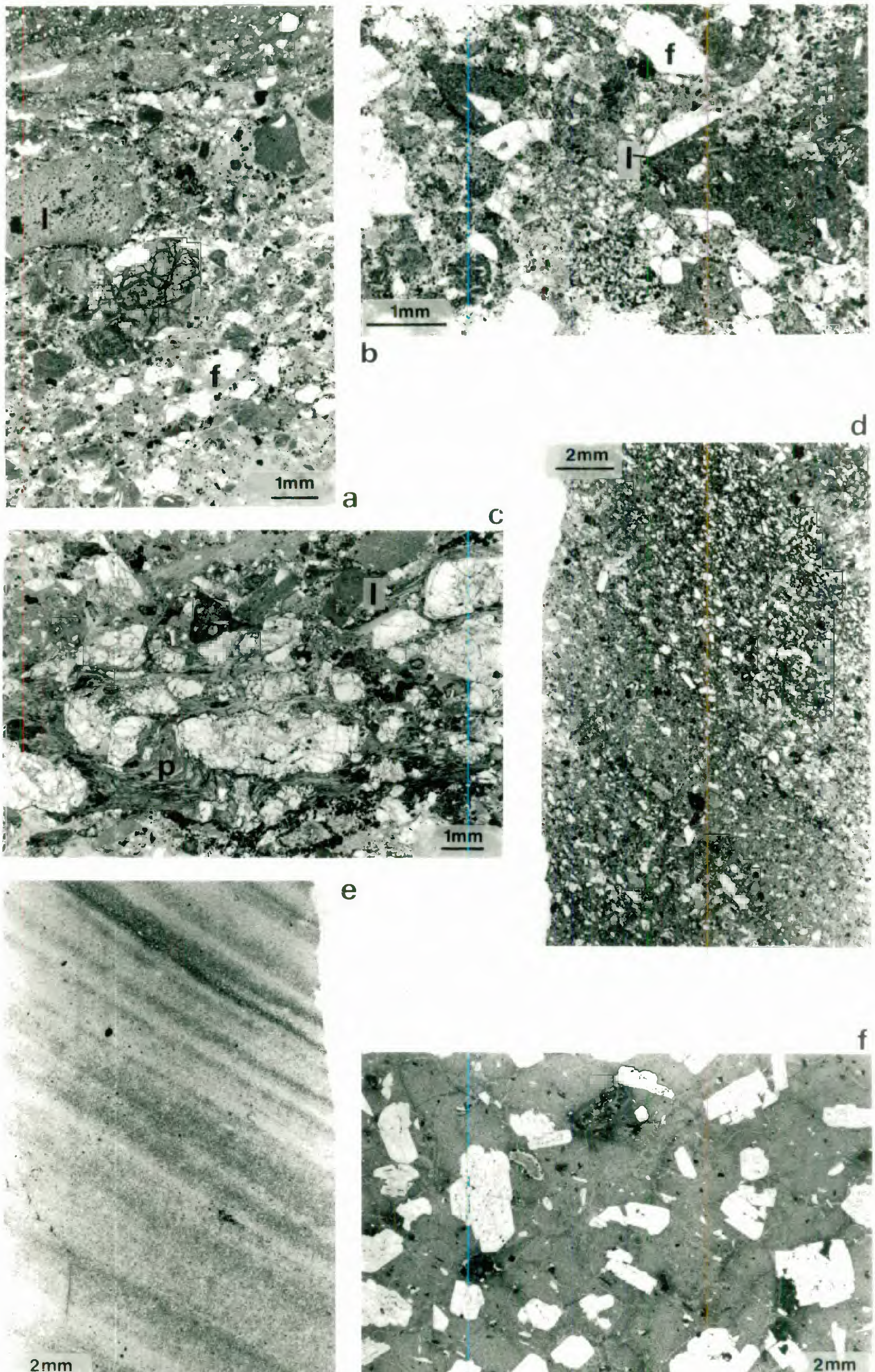
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Figure 7.5: Bedded facies of the Hianana Volcanics in the Coombadjha Creek area. Hammer is 33 cm long; lens cap is 5.5 cm across.

a. Typical well-bedded tuffs; Coombadjha Creek (GR38354485 Coombadjha). Note hammer for scale.

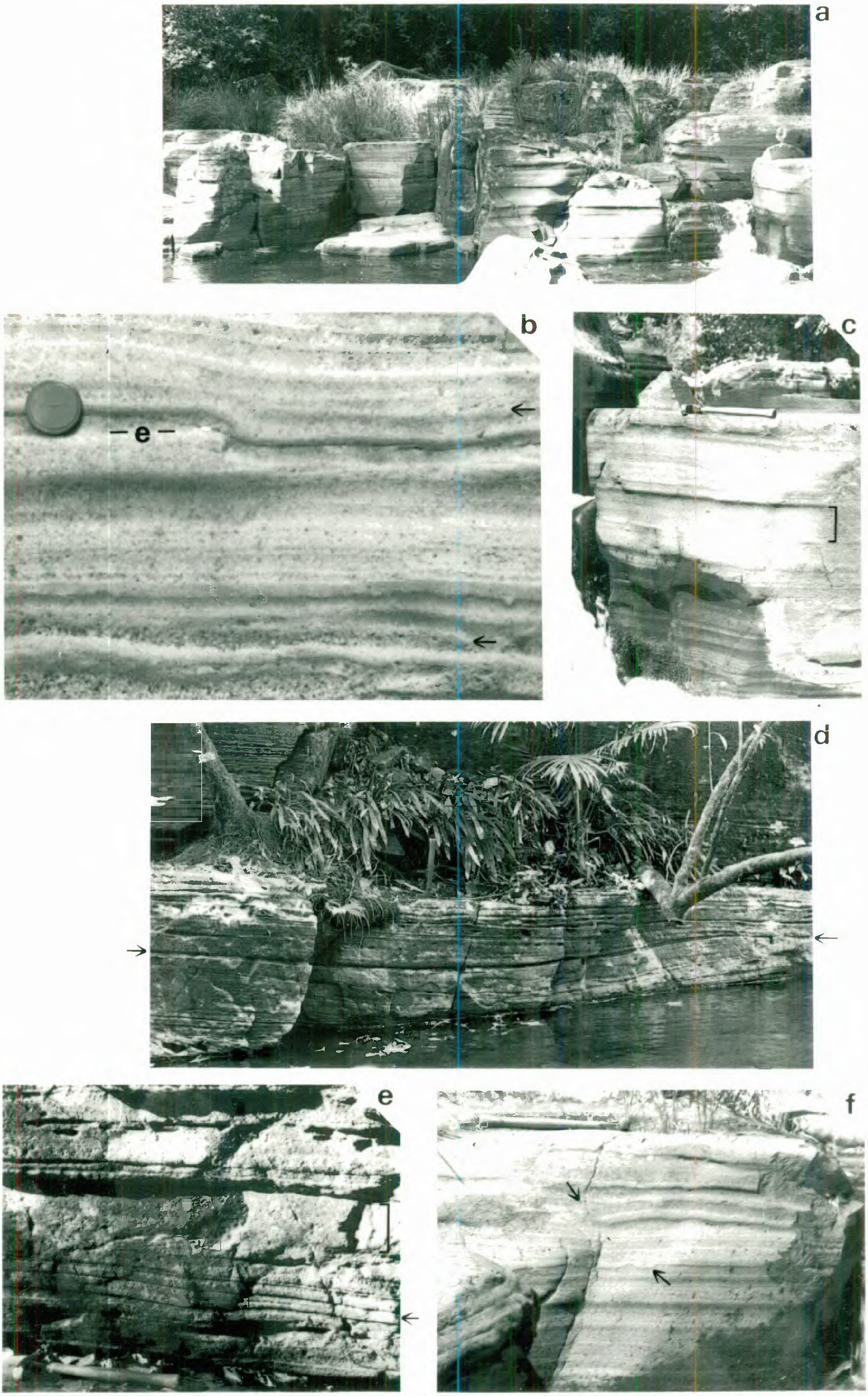
b. Erosion surface (e) in plane parallel beds, overlain by mantling beds; Coombadjha Creek (GR38304473 Coombadjha). Arrows indicate discontinuous very thin beds.

c. Plane parallel beds; medium thickness beds with faint diffuse internal planar lamination below the hammer (bracket); Coombadjha Creek (GR38354485 Coombadjha).

d. Long wavelength, low wave height dune bedding overlain by mantling (arrows) and plane parallel thin beds (GR38304530 Coombadjha).

e. Plane parallel thin beds (arrow) with gradual change in thickness. Medium thickness massive bed (bracket) with faint cross bedding along basal contact (GR38304530 Coombadjha).

f. Small-scale erosion surface and disrupted layer (arrows) in plane parallel thin and very thin beds. A more detailed line drawing is presented in Figure 7.6d. (GR38304530 Coombadjha).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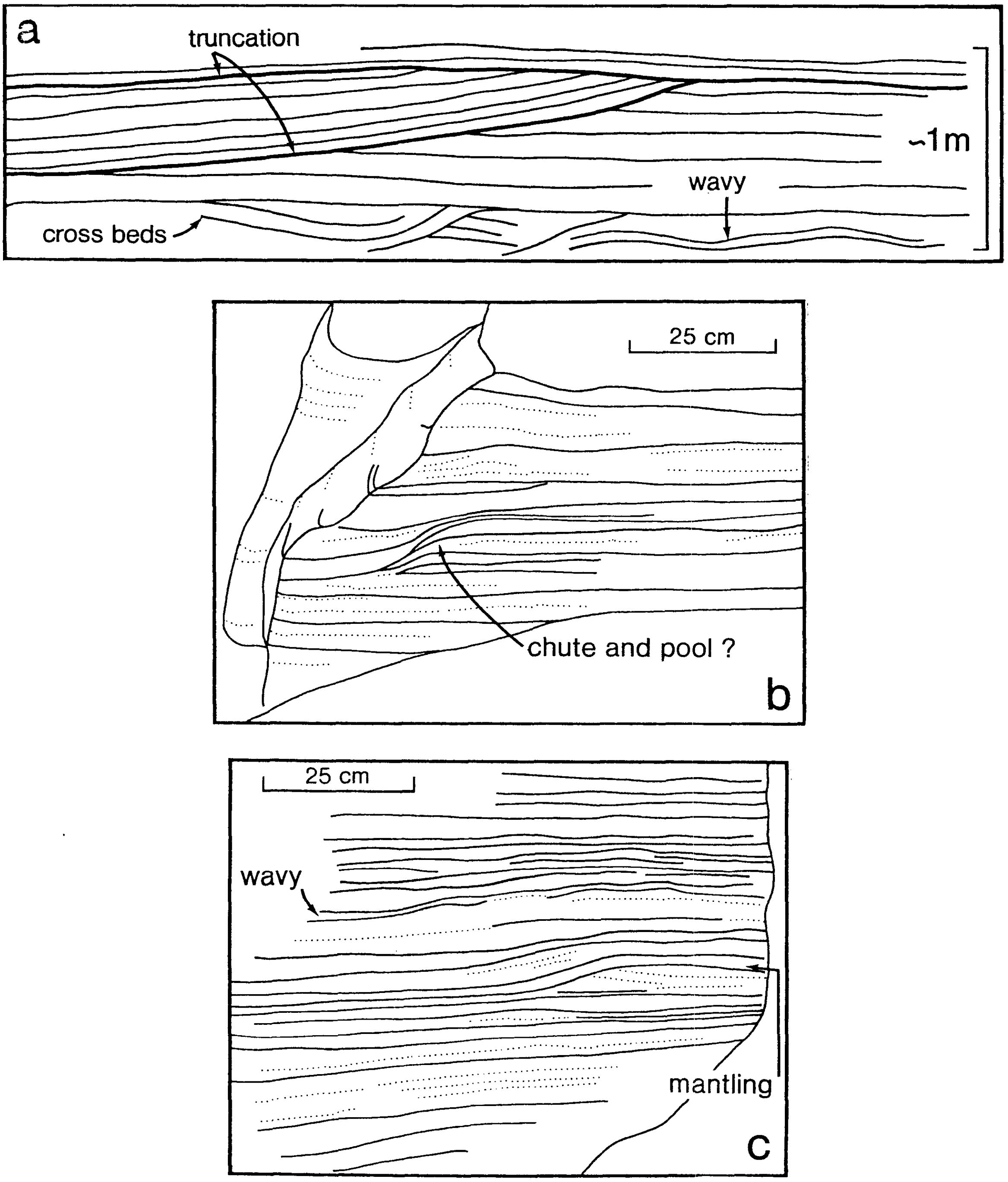


Figure 7.6: Line drawings of outcrops of the bedded facies in the Coombadjha Creek area.

a. Low-angle truncations of thin plane parallel beds, cross beds and wavy bedding. Copied from field sketch (GR38354517 Coombadjha).

b. Possible chute and pool bed form in thin bedded tuff. Copied from photograph (GR38304473 Coombadjha).

c. Wavy bedding, erosion surface mantled by thin beds and beds with laterally variable thickness. Copied from photograph (GR38304530 Coombadjha).

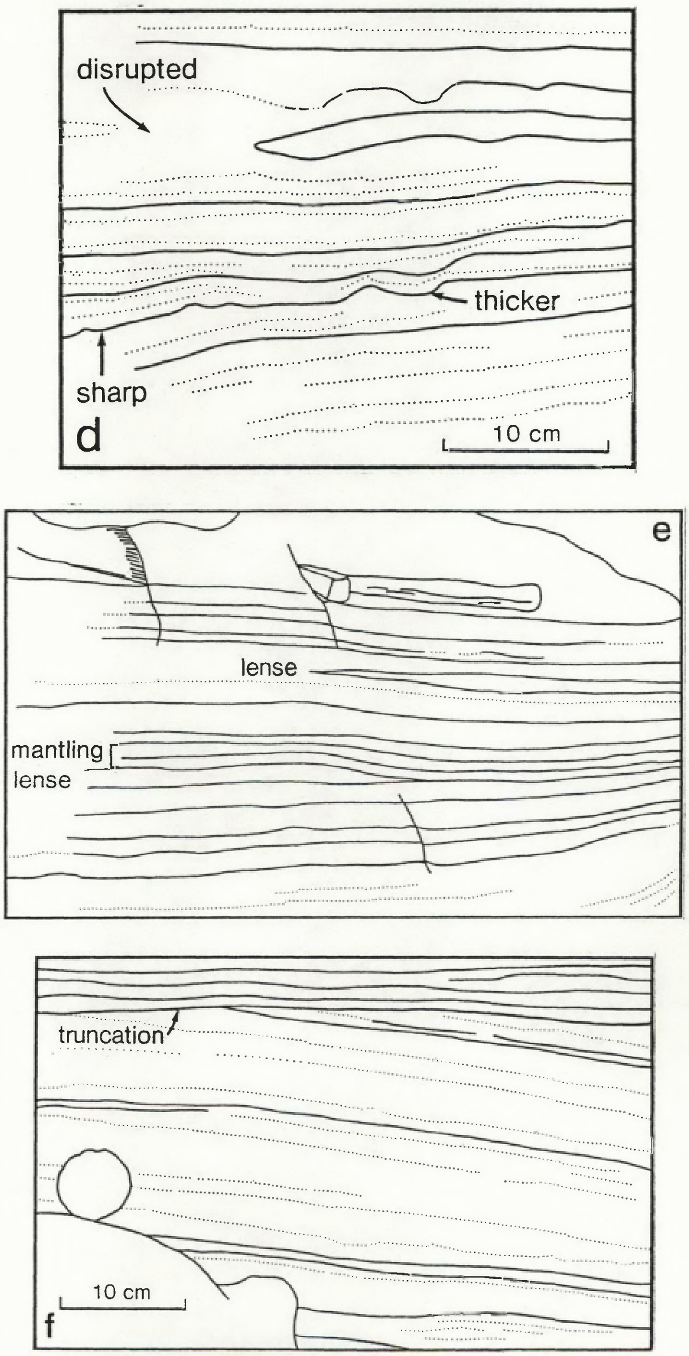


Figure 7.6 continued:

d. Detail of disrupted layer and small-scale erosion surface shown in Figure 7.5f. Thin bed overlying the erosion surface thickens slightly in depressions. Sharp and diffuse bedding contacts. Copied from photograph (GR38354485 Coombadjha).

e. Discontinuous thin beds, mantling beds and continuous beds with lateral variations in thickness. Copied from photograph (GR38354485 Coombadjha).

f. Truncation of plane parallel, thin and medium, internally laminated beds, overlain by very thin, plane parallel beds. Copied from photograph (GR38304473 Coombadjha).

long wavelength, low wave height dunes. In general bedsets with sandwave bed forms are enclosed by plane parallel beds. In detail the vertical transition from beds with irregular thickness to plane parallel uniform beds is complicated and in places includes intervening mantling beds (Figs. 7.5b,7.6c). The upper contact of some planar beds is an erosion surface lined by mantling beds (Fig. 7.5b) or other plane parallel beds (Figs. 7.6d,f). The latter thicken slightly in depressions, returning the bedding to the uniform thickness plane parallel type (Fig. 7.6d). Abrupt truncation of plane parallel beds as illustrated in Figure 7.5f (and Figure 7.6d) is uncommon.

Origin of the bedded volcaniclastic facies

The narrow range of clast type (plagioclase crystals, non-vesicular formerly glassy fragments and plagioclase porphyritic volcanic lithics, minor bubble-wall devitrified shards) and their angularity suggest primary volcanic fragmentation (Cas, 1983). The assemblage of sandwave and plane parallel bed forms in Coombadjha Creek exposures is typical of deposition from either subaerial (aeolian or pyroclastic surge) or subaqueous (fluviolacustrine, shallow marine) traction currents. The association of the Hianana Volcanics with welded ignimbrites above (Pi Pi Ignimbrite) and below (Pheasant Creek Volcanics) eliminates the possibility of a shallow marine setting. Structural relationships with enclosing ignimbrite units imply that the bedded facies together with the massive porphyry constructed a positive landform not attributable to later deformation. Thus deposition was not controlled by a topographic depression as would be required by subaqueous processes in a continental environment. In addition thin bedded lacustrine sequences are typically dominated by sedimentation of clay and silt from suspension and/or from turbidity currents rather than traction current deposition, and are accompanied by marginal fluviatile facies (Selley, 1970, p.71; Collinson, 1978b, p.64).

Confident recognition of aeolian deposits depends on the presence of thick stacks of large scale (sets several to tens of metres high), high angle (15° to 30°), cross stratified beds (Selley, 1970, p.60; Collinson, 1978c, p.92; Walker and Middleton, 1979). Aeolian bedload transportation is specific to a limited range of grain sizes (0.1 mm to 1 mm; Sheridan, 1971; Collinson, 1978c, p.82) and promotes attrition so that deposits are characteristically well sorted and well rounded (Selley, 1970, p.59-60; Collinson, 1978c, p.92). The presence of mantling sand grade beds, massive poorly sorted medium thickness plane parallel beds, substantial amounts of fine matrix, and angular fragments in the bedded volcaniclastic facies of the Hianana Volcanics are inconsistent with the usual features of aeolian transport and deposition. Also the sandwave bed forms of the Hianana Volcanics are confined to a small area in the southeastern-most part of the unit, so the currents involved in their formation were persistently energetic but very local. By contrast present day areas of aeolian sedimentation are extensive, covering hundreds to thousands of square kilometres, or in belts related to coastlines (Collinson, 1978c, p.82; Walker and Middleton, 1979).

There is little evidence in support of epiclastic processes of sedimentation having been involved in the deposition of the bedded facies of the Hianana Volcanics. The setting, components and assemblage of structures are best explained by regarding the bedded facies as tuffs of primary pyroclastic origin.

Sandwave bed forms in pyroclastic sequences are diagnostic of emplacement by pyroclastic surges, that is, expanded, turbulent, dilute gas/particle dispersions which flow laterally (Wright *et al.*, 1980). Similar bed forms have been reported in the deposits of some pumiceous pyroclastic flows (ignimbrite veneer deposits; Walker *et al.*, 1980a,b; Froggatt, 1981; Wilson and Walker, 1982; Walker and Wilson, 1983). The examples described occur in association with more voluminous and widespread pyroclastic flow facies. There is no evidence to suggest that the sandwave bed forms in the tuffs of the Hianana Volcanics were produced in high particle concentration pyroclastic flows and these bed forms in this instance are taken to indicate emplacement by pyroclastic surges.

Pyroclastic surges can be generated by several processes related to primary vent eruptions, or by phreatic explosions at secondary "rootless" vents. Examples of the latter occur above pyroclastic flow deposits which were erupted from Mt St Helens, Washington, in 1980 (Rowley *et al.*, 1981), and are composed of pyroclasts recycled from the freshly-emplaced pumice and ash. Such an origin is inappropriate for the bedded facies of the Hianana

Volcanics in view of their compositional and mineralogical differences from the underlying Pheasant Creek Volcanics. Thus, most of the bedded facies is attributed to deposition from vent-generated pyroclastic surges in a subaerial setting.

Primary vent eruptions produce well-bedded pyroclastic surge deposits in association with the eruption and emplacement of pyroclastic flows (e.g. ground surge and ash-cloud surge deposits; Sparks and Walker, 1973; Sparks, 1976; Fisher, 1979; Wright *et al.*, 1980; Self and Wright, 1983; Walker, 1983) or else by repeated hydrovolcanic explosions (base surge deposits; Moore *et al.*, 1966; Moore, 1967; Lorenz, 1970,1973,1974; Heiken, 1971; Walker and Croasdale, 1972; Fisher, 1977,1979; Wohletz and Sheridan, 1983; Walker, 1984). The latter generate thick (tens of metres), plane parallel and dune bedded sequences of comparatively limited lateral extent (within 5 km from source) which do not include co-eruptive, large volume pyroclastic flow deposits. The thickness, extent, context and bed forms (sandwave and plane parallel types) of the bedded facies of the Hianana Volcanics in the Coombadjha Creek area are consistent with emplacement by base surges. Lithic pyroclasts in tuffs of the bedded facies are exclusively volcanic but texturally and mineralogically different from underlying ignimbrites although closely similar to the overlying massive porphyry, interpreted to be a lava. These relationships suggest that new magma was involved in the hydrovolcanic eruptions responsible for the bedded facies and a purely phreatic origin can be discounted.

Mantling beds and some of the plane parallel beds of the Coombadjha Creek exposures are considered to be airfall deposits from ash clouds associated with base surge explosions (*cf.* Moore *et al.*, 1966; Kienle *et al.*, 1980) and/or generated by surtseyan style vent eruptions (*cf.* Walker and Croasdale, 1972; Walker, 1973a; Kokelaar, 1983). The thinnest and finest of these layers probably comprise fallout that settled from ash clouds trailing the moving surges (*cf.* Walker, 1984).

The mode of emplacement of the massive, medium thickness beds has not been resolved. They resemble the massive beds described by Sheridan and Updike (1975) and Wohletz and Sheridan (1979), attributed to a densely fluidised surge system, but recognised to be superficially similar to deposits from small volume pyroclastic flows. Both origins are compatible with the bedded facies of the Hianana Volcanics (*cf.* Walker and Croasdale, 1972). The origin of the lithic-rich lenticle tuffs of the bedded facies is as yet unclear. They may be pyroclastic flow deposits but are of very limited extent and in places have a better defined bedding-parallel foliation than is typical of most pyroclastic flow deposits, with the implication that other processes have been involved (e.g. proximal, small volume lag breccias? *cf.* Wright and Walker, 1977; Druitt and Sparks, 1982).

Several minor features of the bedded facies in the Coombadjha Creek exposures are also accounted for by the inferred hydroexplosive origin of the sequence. Disrupted bedding (Fig. 7.5f) may be an artefact of a concealed ballistic block. Modern pyroclastic surge and airfall deposits of hydrovolcanic origin display prominent and recessive layers depending in part on the wetness and hence coherence of the tephra when emplaced (Heiken, 1971; Waters and Fisher, 1971; Lorenz, 1974; Fisher, 1977; Beanland, 1982; Wohletz and Sheridan, 1983). The same alternation in the Hianana bedded facies may be inherited from original contrasts in deposit wetness, subsequently accentuated by lithification. Like well-exposed Quaternary surge sequences, the stratification of the Hianana bedded facies is interrupted by both subtle and more marked outcrop-scale disconformities and scours (e.g. Fig. 7.5b). In the modern examples, bedding truncations and gullies have been attributed to the passage of erosive surges and/or to running water (e.g. Fisher and Waters, 1970; Fisher, 1977; Walker, 1984).

Much of the bedded facies of the Hianana Volcanics in the Coombadjha Creek area can thus be related to the processes attendant on the eruption and emplacement of base surges. This conclusion has guided interpretation of the thinner but far more extensive representatives of the bedded facies which occur to the north and west of the Coombadjha Creek area.

2. *Western and northern exposures of the bedded facies*

Away from Coombadjha Creek the bedded facies of the Hianana Volcanics thins to less than 10 m and eventually lenses out (Figs. 7.1,7.3). Continuous, uniform, plane parallel, very thin bedding and lamination predominate in these marginal areas. Neither sandwave bed forms nor massive, poorly sorted, medium thickness beds have been found. Individual beds with grains larger than a millimetre are uncommon and laminae are very fine grained (Fig. 7.4e). A small number of beds contain pumiceous fragments (1 to 3 mm) and some crystal-rich layers have trace amounts of quartz as well as plagioclase. Other components are similar (though generally finer) to those in samples from Coombadjha Creek outcrops.

Lateral variations in the bedded facies

Finer grain size, thinner beds and reduced aggregate thickness in the northern and western exposures indicate that these are more distal to source than those of the Coombadjha Creek area. The apparent lack of surge-related bed forms, particularly sandwaves, may in fact be real as these are usually restricted to proximal localities (less than a few kilometres from source ; Wohletz and Sheridan, 1979,1983; Crisci *et al.*, 1981; Walker and McBroome, 1983; Walker, 1984). The most proximal environments of the bedded facies are thus inferred to be those in the Coombadjha Creek area. Much of the northern and western sections could be ash-fall tuff deposited from vent-generated and surge related ash clouds (*cf.* Taal, Philippines, Moore *et al.*, 1966; Ukinrek, Alaska, Kienle *et al.*, 1980; Self *et al.*, 1980; White Island, New Zealand, Houghton *et al.*, 1983). Without the proximal association of surge and mantling bed forms, firm distinction between epiclastic and primary pyroclastic processes of deposition for the northern and western sequences could not be made. Even given the connection with the proximal surge deposits, the possibility of limited reworking by epiclastic processes cannot be finally eliminated. The more distal character of western and northern sections relative to Coombadjha Creek exposures is nevertheless evident.

MASSIVE PORPHYRY FACIES

Plagioclase porphyry forms a conformable layer covering 14 km^2 overlying the bedded facies in the southeastern part of the Hianana Volcanics outcrop area (Figs. 7.1,7.2). The layer is typically at least 120 m thick and appears to end abruptly rather than lense out. Euhedral plagioclase phenocrysts up to 5 mm across and clusters of two or three such crystals comprise about 25 modal percent (Figs. 7.4f,7.7a, Table B.4).

Hornblende and another, pervasively altered ferromagnesian mineral (?pyroxene) constitute about 2 modal percent. Outcrops are typically devoid of any mesoscopic structures though elongate plagioclase phenocrysts are consistently aligned over small areas (a few square metres). The size of phenocrysts varies through the layer but not in a systematic fashion. The massive porphyry has the chemistry of a calc-alkaline dacite according to the classification of Ewart (1979; Fig. 7.7b, anhydrous SiO_2 68.54%, K_2O 2.39%; Chapter 6, Table 6.1, analysis 5).

On the basis of the shape and conformity of this layer of massive porphyritic dacite and its texture, it is inferred to be a coherent lava flow. This conclusion is further supported by evidence that it formed a topographic feature which strongly influenced the distribution of the ignimbrite unit above (Pi Pi Ignimbrite). Also at some localities there are overlying breccias made almost exclusively of identical massive plagioclase porphyry (e.g. GR363424 Coombadjha).

The massive porphyry presently has an aspect ratio (thickness: lateral spread; Hulme, 1974) of 1:35, in the range typical of subaerial, moderately silicic lava flows (Walker, 1973b). Steep flow fronts, high viscosity and rapid surficial cooling combine to generate fragmental debris below, above and at the margins of such flows (Guest and Sanchez, 1969; Fink, 1980b,1983; Huppert *et al.*, 1982). Explosion breccias (Nairn and Wiradiradjha, 1980; Crisci *et al.*, 1981; Wohletz and Sheridan, 1983) and block and ash flows (Roobol and Smith, 1976; Rose *et al.*, 1977; Sheridan, 1980; Smith *et al.*, 1981; Smith and Roobol, 1982; Newhall and Melson, 1983) related to extrusion of silicic flows and domes also form coarse deposits of fragmented lava, commonly accompanied by minor intercalations of bedded pyroclastics. Breccias which are associated with thin bedded and lenticle tuff intervals in three stratigraphic sections of the Hianana Volcanics (Fig. 7.3) are interpreted to be deposits from explosive events rather than passive crumbling or flow fragmentation. Elsewhere breccias are uncommon and closely confined to the vicinity of the lava, suggestive of a non-violent origin by autobrecciation.

VOLCANOLOGY OF THE HIANANA VOLCANICS

Petrographic similarity of the pyroclastic components in the bedded

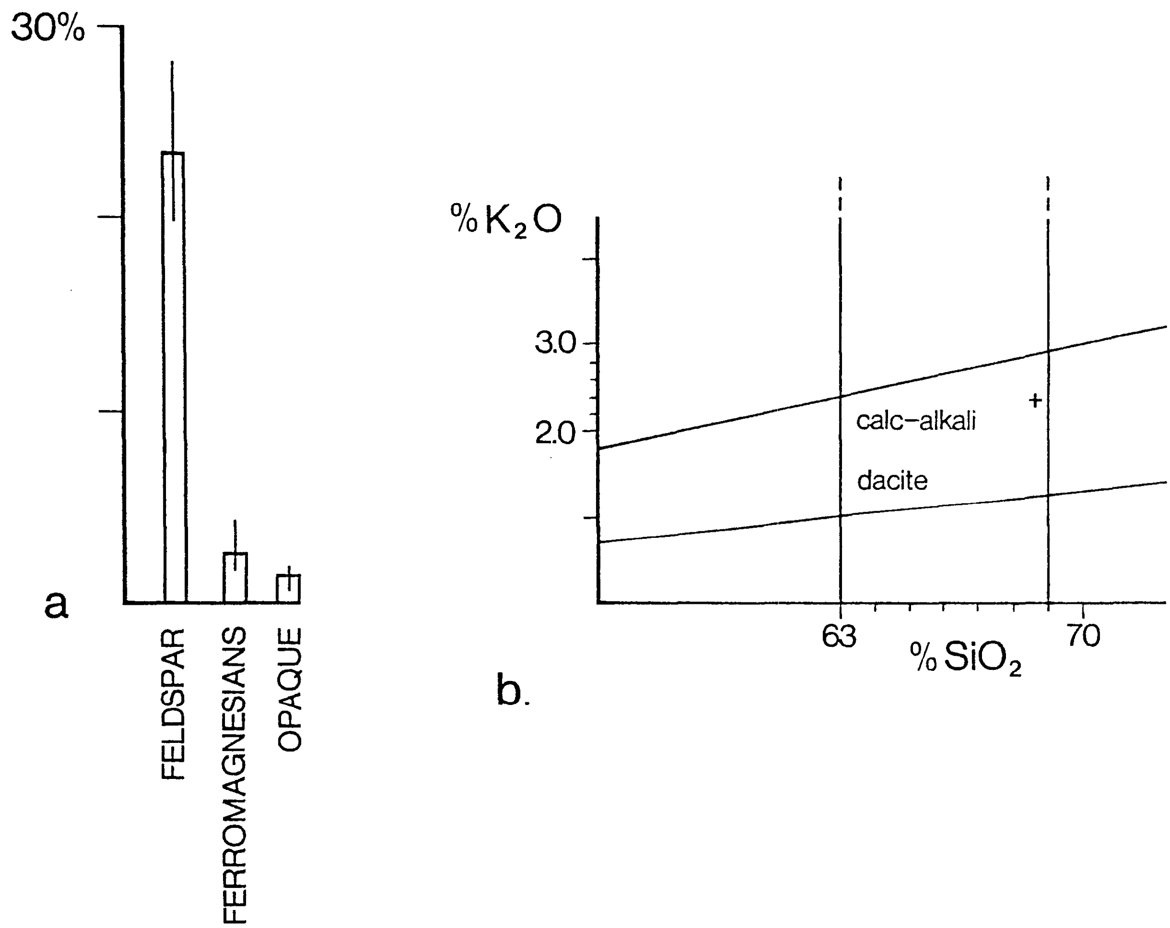


Figure 7.7: a. Histogram of modal data for samples of massive porphyry of the Hianana Volcanics, giving average (columns) and range (bars) of abundance of phenocrysts. The feldspar is predominantly plagioclase. Ferromagnesian phases are extensively altered hornblende and pyroxene. See also Table B.4.

b. Chemical classification of the Hianana massive porphyry using the $\%K_2O$ vs. $\%SiO_2$ diagram of Ewart (1979).

facies with the massive porphyry and their intimate spatial association provide evidence that the two facies are genetically related. There is no sign of any intervening hiatus of significant duration between their emplacement. These two facies are inferred to be the products of one major evolving eruption cycle supplied by a single magma source. Explosive hydrovolcanic eruptions (bedded volcaniclastic facies) were followed by effusion of lava (massive porphyry facies) and minor short-lived more violent outbursts (breccia, lenticle tuff).

The Hianana tuff ring

Thin bedded pyroclastic surge and airfall deposits form rim sequences in modern and Recent tuff rings, tuff cones and maars (e.g. Fisher and Waters, 1970; Lorenz, 1970,1973,1974; Heiken, 1971; Crowe and Fisher, 1973; Wood, 1974; Sheridan and Updike, 1975; Fisher, 1977; Kienle *et al.*, 1980; Yokoyama, 1981; Wohletz and Sheridan, 1983; Walker, 1984). Such volcanic centres are characterised by relatively thick stacks of base surge and airfall deposits confined to tephra aprons within 2 to 3 km radially from source vents (Schmincke *et al.*, 1973; Sheridan and Updike,1975; Wohletz and Sheridan, 1979,1983). In many cases, they are associated with lava flows and lava domes (e.g. Wood, 1974; Sheridan and Updike, 1975; Kienle *et al.*, 1980; Yokoyama, 1981). Breccias generally occur in proximity to vents or to the sites of phreatic explosions (Heiken *et al.*, 1980; Wohletz and Sheridan, 1983) whereas the distal stratigraphy is dominated by thin airfall ash layers (e.g. Waters and Fisher, 1971; Self *et al.*, 1980). Consideration of the assemblage of lithologies in the Hianana Volcanics and their distribution suggests such a model is appropriate for their origin. On the basis of criteria for distinguishing between tuff rings, tuff cones and maars (Lorenz, 1970,1973; Heiken, 1971; Wohletz and Sheridan, 1983), the Hianana bedded facies best match the features of tuff rings: well developed thin bedding is ubiquitous whereas thick, massive beds are either minor or absent; deposits have gentle dips and thin gradually from the inferred source; there are no accretionary lapilli or mudflow deposits which are normally associated with emplacement of excessively wet ash, and eruptions took place in a subaerial setting with the water supply probably limited to groundwater;

the ballistic component of the ejecta is negligible; the bedded facies had a positive topographic expression and no signs of deep excavation into underlying volcanics have been recognised; juvenile pyroclasts are dominant.

Precise location of the source crater is hampered by the cover of younger volcanic units and the complication of incomplete preservation. Facies schemes for lateral variations in structures produced by pyroclastic surges (Sheridan and Updike, 1975; Wohletz and Sheridan, 1979,1983; Crisci *et al.*, 1981), and many published accounts of unmodified tuff rings, identify thick sequences of surge deposits which include sandwave bed forms with near-vent settings (within 2 km from vent, e.g. Moore *et al.*, 1966; Fisher and Waters, 1970; Heiken, 1971; Waters and Fisher, 1971; Crowe and Fisher, 1973; Schmincke *et al.*, 1973; Fisher, 1977; Yokoyama, 1981). The Coombadjha Creek area (Figs. 7.2,7.8) probably coincides with the most proximal part of the original Hianana tuff ring. This conclusion is supported by restriction of the lava to the same vicinity.

The main interval of surge beds which includes sandwaves covers only 2 to 3 km^2 on the eastern and southeastern perimeter of the area occupied by lava (Fig. 7.2). A crater of the order of 1000 m across and a similar or shorter runout length of surge deposits would be consistent with the present distribution of sandwave bed forms (*cf.* Wohletz and Sheridan, 1979,1983). These dimensions yield a height:width ratio of about 1:30, which is lower than several measured ratios of modern tuff rings (*cf.* Heiken, 1971). Base surges did not reach distal sites to the west and north where only a thinner, finer grained but extensive mantle of ash-fall tuff records the existence and evolution of the Hianana tuff ring (Fig. 7.8).

Whether or not a complete ring of surge beds ever existed is unknown. The lava presently occurs mainly to the west of the remnant of the inferred tuff ring. Its flow may have been controlled by an incomplete pyroclastic rampart east of the vent but unhindered to the west where it buries more distal, thinner, bedded facies. Alternatively emplacement of the lava may have partly destroyed the western part of a once-continuous pyroclastic apron.

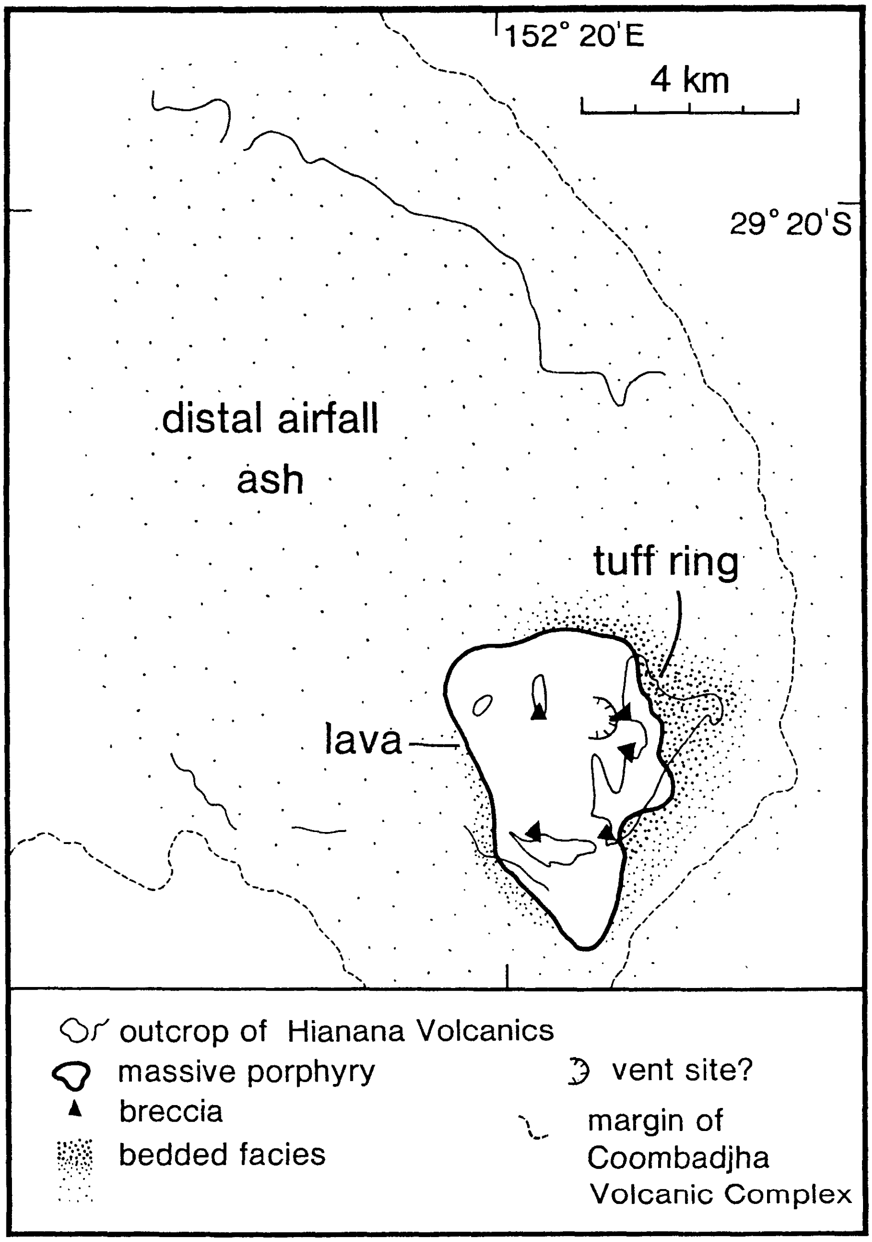


Figure 7.8: Map reconstruction of the Hianana tuff ring and lava flow.

Eruption sequence

The Hianana Volcanics preserve a volcanic stratigraphy which overall reflects an eruption that had a diminishing water:magma mass ratio with time. Surges produced by the initial periodic hydrovolcanic explosions were probably of the dry, highly inflated type from which superheated steam effectively separated and elutriated fine ash (*cf.* Sheridan and Wohletz, 1981). Proximal surge deposits with sandwave bed forms constructed a low-profile rampart or ring of pyroclastic ejecta, partially encircled to the west and north by more distal, thin airfall ash.

Comparatively thin intervals (1 m) of the bedded facies at localities inferred to be proximal (Coombadjha Creek area) include complicated assemblages of sandwave (surge), plane parallel (surge and airfall), and mantling (airfall) layers. A common sequence consists of sandwave bed forms overlain by one or more very thin mantling beds. Similar combinations in modern surge deposits have been interpreted as the record of the passage of an energetic, turbulent surge, followed immediately by settling of airfall ash from the accompanying ash cloud (Walker, 1984). In the Hianana bedded facies there are also proximal sections which change from sandwave bedsets below to plane parallel beds above (e.g. Fig. 7.5d). Modern surge deposits displaying such sequences are thought to reflect a generation of surges in which the explosive energy and degree of inflation systematically declined (Wohletz and Sheridan, 1979; Crisci *et al.*, 1981), perhaps monitoring the progressive exhaustion of water available for conversion to steam in the course of water-magma interaction.

The duration of this hydrovolcanic phase was probably measurable in weeks or months (*cf.* Moore *et al.*, 1966; Kienle *et al.*, 1980; Kokelaar, 1983) and generated about 1 km^3 of tephra (present total compacted volume of the Hianana Volcanics bedded facies). Although subtle fluctuations in the water:magma mass ratio, and hence eruption energy and style, probably occurred, the uniformity of the proximal parts of the Hianana bedded facies suggests that the balance of water and magma was maintained at proportions appropriate to the production of predominantly 'dry' pyroclastic surges. There is no evidence for either prolonged quiescent spells nor for deviations to other eruptive styles having interrupted this series of explosive outbursts.

Hydrovolcanic eruptions were followed by effusion of the Hianana lava in a high-aspect ratio flow amounting to about 1.4 km^3 (DREV). Exhaustion of the water supply and/or increased magma output are implied by cessation of water-magma interaction (Walker and Croasdale, 1972; Sheridan and Wohletz, 1981; Yokoyama, 1981; Kokelaar, 1983). Stratigraphic sections from the Coombadjha Creek exposures indicate minor late complications to the effusive discharge of Hianana lava (Fig. 7.3). Breccias and bedded volcaniclastics overlying the lava in three sections are here tentatively correlated, and interpreted as the record of a brief but violent reversion to explosive activity. Lava may have progressively impounded the vent and if blockage occurred, a violent, vent-clearing explosion would eventually ensue if magma pressure was maintained in the conduit (*cf.* Nairn, 1976). It is also possible that the two facies accumulated at the same time:simultaneous effusive and explosive activity occurred from East Ukinrek Maar, Alaska, during the 1977 eruption (Kienle *et al.*, 1980). Further discharge of Hianana lava followed but the entire eruption was waning and ceased after extrusion of a very small volume flow (Fig. 7.3, section 2).

The effusive stage of the Hianana eruption possibly lasted as little as months or as much as a few to several years in duration (*cf.* Kienle *et al.*, 1980; Huppert *et al.*, 1982; Walker, 1982; Newhall and Melson, 1983), but was rapid enough to cover and preserve older volcaniclastic deposits from erosion. The more distal, thin, gently sloping apron of pyroclastics was eventually smothered by ignimbrite (Pi Pi Ignimbrite), ensuring its survival.

Most aspects of the geology of the Hianana bedded facies have analogues in existing tuff rings. However, there are two features common in tuff rings which the bedded facies lack. The most proximal rim deposits of many existing tuff rings include ballistic blocks and/or structures caused by their impact (e.g. Moore *et al.*, 1966; Moore, 1967; Lorenz, 1970,1973; Heiken, 1971; Waters and Fisher, 1971; Walker and Croasdale, 1972; Fisher, 1977; Self *et al.*, 1980; Beanland, 1982; Houghton *et al.*, 1983). Only one possible example has been found in the most proximal bedded facies of the Hianana Volcanics (Fig. 7.5f). A reasonable explanation is that the available exposures are not sufficiently close to source, as sizeable blocks are most uncommon more than 2 km from vent and in some examples are essentially restricted to rim deposits (closer than 2km, Moore, 1967; Lorenz, 1970,1973; within 1 km, Walker and Croasdale, 1972; Self *et al.*, 1980; less than 250 m at White Island, Houghton *et al.*, 1983). Blocks may also be stratigraphically constrained or scarce in general (*cf.* Big Hole Maar, Oregon; Lorenz, 1970,1973). Otherwise exceptionally efficient and consistent fragmentation processes must be postulated for the Hianana hydrovolcanic eruptions. The lack of accretionary lapilli-bearing layers is also unusual by comparison with descriptions of modern tuff rings (e.g. Moore *et al.*, 1966; Moore, 1967; Fisher and Waters, 1970; Lorenz, 1970,1974; Heiken, 1971; Walker and Croasdale, 1972; Schmincke *et al.*, 1973; Fisher, 1977; Sheridan and Wohletz, 1981,1983a; Beanland, 1982; Walker, 1984) and implies that the steam generated was consistently superheated and separated from pyroclasts before condensation. Again there are modern cases of hydrovolcanic eruptions which produced both surge and airfall deposits without accretionary lapilli (e.g. Self, *et al.*, 1980; Houghton *et al.*, 1983).

CONCLUSIONS

Juvenile volcanic components (crystals, volcanic lithics) of the thinly bedded facies of the Hianana Volcanics were derived from fragmentation of porphyritic magma by primary volcanic processes, probably hydrovolcanic explosions. Sandwave, plane parallel and mantling bed forms in a thick sequence of thin beds deposited in a subaerial environment, and composed of differing proportions of angular grains and very fine matrix, are features consistent with the emplacement of the bedded facies of the Coombadjha Creek area by dry, highly inflated, vent-produced surges, and by fallout from accompanying ash clouds, rather than by epiclastic processes. Much thinner and finer grained intervals of the bedded facies to the north and west constitute the more distal record of the same eruption and are inferred to be mainly ash-fall deposits.

Sandwave bed forms occur in the thickest parts of the bedded facies and are restricted to an area considered to be the site of a Late Permian tuff ring which was surrounded by a more widespread, thin, airfall fan to the northwest. Crater rim height was of the order of 70 m and runout of surges was about a kilometre. The tuff ring was built on an ignimbrite field with no permanent or voluminous surface water supply, so the explosive activity was probably strictly phreatomagmatic (that is, involving groundwater; Walker and Croasdale, 1972; Lorenz, 1973; Kienle *et al.*, 1980; Sheridan and Wohletz, 1983a). Slight fluctuations in the efficiency of explosive interaction occurred from one outburst to the next, but there were no major interruptions to the construction of the thinly bedded pyroclastic rampart.

Hydrovolcanic eruptions were followed by effusive discharge of porphyritic dacitic lava. The lava is texturally and mineralogically similar to the pyroclasts of the bedded hydrovolcanic deposits, suggesting that the explosive and the effusive eruption styles were genetically related in being fed by the same magma supply. The lava spread out over part of the pyroclastic apron of the tuff ring although it had a high aspect ratio. The lava probably impounded its own vent, perhaps when more viscous, volatile-poor magma reached the surface late in the eruption. Small volumes of lava breccia and bedded tuff, possibly from vent-clearing explosions, and minor additional lava were subsequently added to the pile before the Hianana centre became extinct.

Analogy with modern eruptions producing tuff rings and lava implies that the entire episode forming the Hianana Volcanics could have lasted as little as a few months to several years. Subaerial tuff rings generally have poor preservation potential (e.g. those described by Heiken, 1971). Survival of such a structure from the Late Permian is attributed to the late effusion of lava over proximal deposits and subsequent inundation by welded ignimbrite, both of which effectively entombed the tephra.

CHAPTER 8

CRYSTAL-RICH HIGH-ASPECT RATIO IGNIMBRITE FROM A LARGE MAGNITUDE ERUPTION OF LOW VIOLENCE : DUNDEE RHYODACITE, LATE PERMIAN, NORTHEASTERN NEW SOUTH WALES

INTRODUCTION

The Late Permian Coombadjha Volcanic Complex is the remnant of a volcanic cauldron which formed in response to the eruption of voluminous, crystal-rich ignimbrite (Chapter 6). This ignimbrite is preserved within the perimeter of the Complex, reaching thicknesses in excess of 500m, throughout which it is densely welded and texturally homogeneous. The following account of the character and context of this intracaldera ignimbrite aims to elucidate the style of eruption and mode of emplacement of the pyroclastic flows responsible for producing its distinctive features. No modern lithological analogues are known although there are similar ignimbrites in the Tertiary volcanic fields of the western United States which also have intracaldera settings. The conclusions that have emerged from study of the Coombadjha intracaldera ignimbrite may prove relevant to several other occurrences of Late Permian crystal-rich ignimbrite elsewhere in northeastern New South Wales.

REGIONAL GEOLOGICAL SETTING

Subaerial, silicic, calc-alkaline ignimbrites and lavas of Late Permian age form a regionally extensive (about 20,000 km^2), relatively undeformed cover in northeastern New South Wales. The volcanics unconformably overlie complexly deformed, older (middle and late Palaeozoic), mainly marine sedimentary rocks of the New England Orogen (Leitch, 1974; Day *et al.*, 1978), and are intruded by Late Permian and Triassic granitoid plutons of the New England Batholith (Moonbi and Uralla Plutonic Suites, and Leucoadamellites, Shaw and Flood, 1981). The thickness of the volcanics varies considerably but locally exceeds 2 km (e.g. Coombadjha Volcanic Complex, Chapter 6).

Throughout much of the northern part of the New England Tableland, the youngest unit of the Late Permian silicic volcanic pile is crystal-rich ignimbrite that occurs in several discrete areas, or 'masses' separated by other rocks (Fig. 8.1). All occurrences of the ignimbrite are similar in texture, modal mineralogy and chemical composition (Figs. 8.2,8.3; Tables 8.1,8.2), and are characterised by high proportions of crystal fragments (typically 50 modal percent), and tor-like outcrops. The ignimbrite is locally very thick (several hundreds of metres) but is truncated by the present day erosion surface. Recognition of the pyroclastic flow origin of this rock unit has been comparatively recent (Flood *et al.*, 1977). The 'masses' had previously been mistaken for a suite of intrusions and had been known as "the blue granite" (Andrews, 1905; Andrews *et al.*, 1907). Together these areas of crystal-rich ignimbrite constitute the only regional subdivision of the Late Permian volcanic sequence, and are known collectively as the Dundee Rhyodacite (Flood *et al.*, 1977).

The Coombadjha Volcanic Complex

The structure and stratigraphy of the Coombadjha Volcanic Complex are consistent with the interpretation that it is the relic of a Late Permian volcanic cauldron (Chapter 6). The cauldron floor subsided at least 1.5 km in response to eruption of crystal-rich ignimbrite, remnants of which now constitute the Coombadjha 'mass' of the Dundee Rhyodacite. The correlation of cauldron collapse with emplacement of the Dundee Rhyodacite is taken as evidence for the existence of a magma supply underlying the Coombadjha area. The Dundee Rhyodacite that is presently confined within the Coombadjha Volcanic Complex is more than 500 m thick, although the original intracaldera thickness may have been comparable with the amount of subsidence (Fig. 6.15). There are two sites where the Dundee Rhyodacite extends to the margins of the Complex (Fig. 6.2), indicating that it was more widely distributed and perhaps also had equivalent outflow sheets. It overlies a thick (1 to 1.5 km) pile of texturally diverse outflow ignimbrites and subordinate lava which was emplaced prior to the formation of the Coombadjha cauldron. Most of the cauldron margin fault is now occupied by a ring pluton which was intruded after collapse.

Exposure of the Dundee Rhyodacite in the Coombadjha Volcanic Complex is in general very good, allowing clarification of the context of its emplacement and the sequence of associated events.

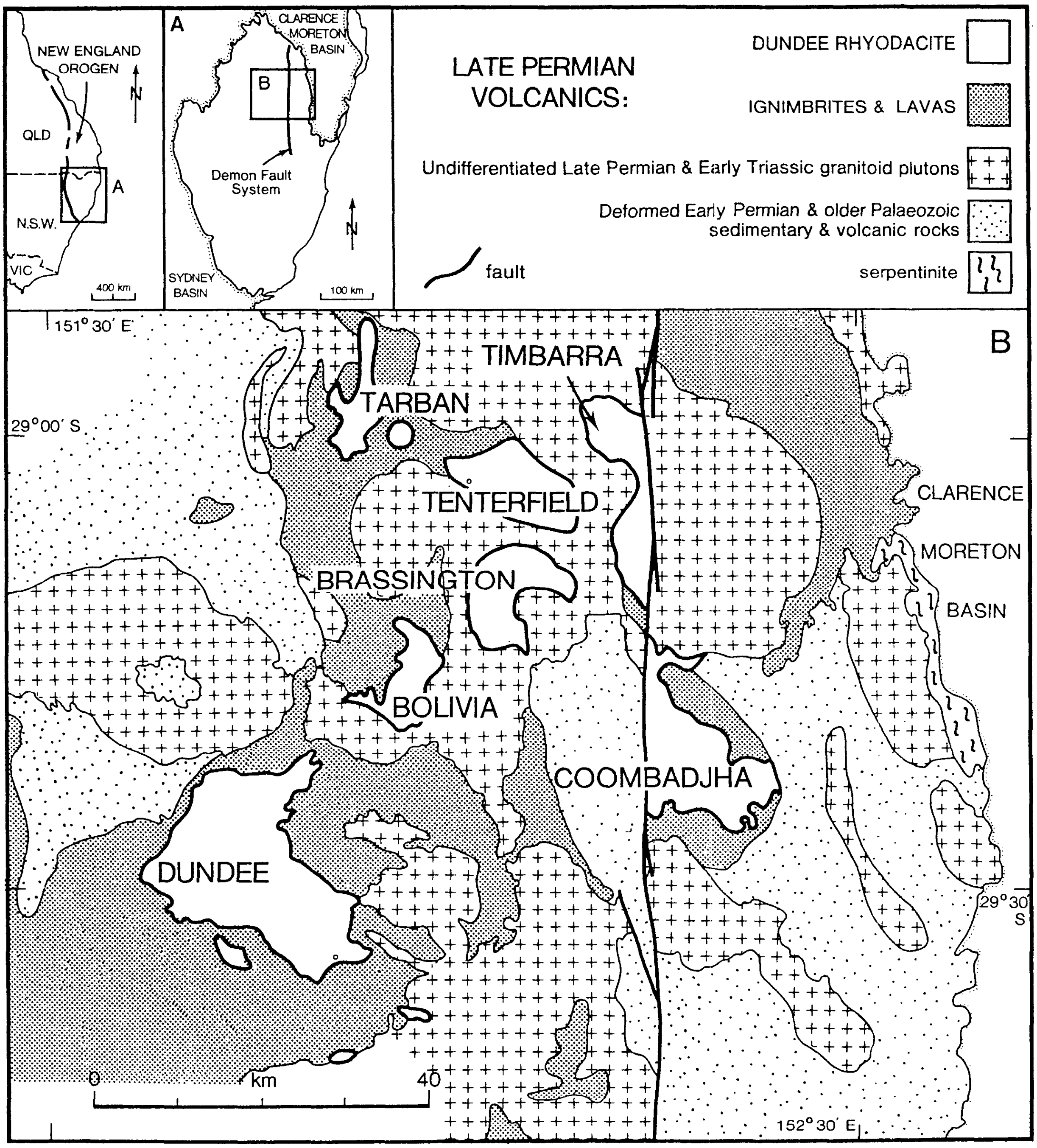


Figure 8.1: Regional setting of occurrences of the Dundee Rhyodacite of northeastern New South Wales. Modified from Pogson and Hitchins (1973).

TABLE 8.1: Major element oxide analyses in weight percent and C.I.P.W. norms of the Basal facies lava of the Dundee Rhyodacite in the Coombadjha Volcanic Complex, undifferentiated Dundee Rhyodacite of other areas, and averages of Dundee Rhyodacite analyses

Sample	Basal facies lava			Brass-ington	Tenterfield		Tarban	Dundee[1]		Average[2] (5 samples)	Average[1] (4 samples)	Average[3] (8 samples)
Oxide	1 R55515	2 R55520	3 R55510	4 R55610	5 R55612	6 R55613	7 R55616	8 D1	9 D16	10	11	12
SiO_2	64.90	66.79	66.98	65.17	65.31	65.03	65.99	64.50	65.31	64.62	64.51	65.82
TiO_2	0.65	0.51	0.51	0.57	0.57	0.61	0.54	0.77	0.59	0.59	0.58	0.60
Al_2O_3	14.60	15.07	15.23	15.63	15.70	15.79	15.49	16.80	15.62	15.88	16.25	15.56
Fe_2O_3	1.46	0.57	1.47	1.58	1.37	1.34	0.93	0.83	1.46	1.45	1.36	1.38
FeO	3.01	3.06	2.26	2.63	2.70	2.97	2.93	3.42	3.51	2.84	3.34	2.91
MnO	0.10	0.10	0.08	0.09	0.08	0.09	0.09	0.07	0.11	0.09	0.12	0.09
MgO	2.52	1.59	1.63	1.82	1.80	1.92	1.75	1.80	1.79	1.93	1.82	1.84
CaO	4.07	3.45	3.39	3.87	3.75	3.88	3.70	4.07	3.99	4.10	4.16	3.97
Na_2O	3.43	3.47	3.18	3.62	3.40	3.50	3.47	3.60	3.36	3.57	3.50	3.46
K_2O	4.26	4.02	4.19	3.92	3.74	3.67	3.75	3.49	3.31	3.60	3.55	3.58
P_2O_5	0.30	0.14	0.13	0.14	0.09	0.09	0.07	0.18	0.24	0.12	0.19	0.15
H_2O^+	0.76	0.83	0.94	0.61	0.85	0.47	0.64	0.75	0.82	0.62	0.64	0.63
H_2O^-	0.15	0.17	0.17	0.12	0.13	0.15	0.10	0.10	0.00	0.16	0.07	0.08
CO_2	n.d.[4]	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	-	-	n.d.	-	0.11
Total	100.21	99.77	100.16	99.77	99.49	99.51	99.45	100.38	100.11	99.57	100.09	100.18
ΣFe as FeO	4.32	3.57	3.58	4.05	3.93	4.18	3.77	4.17	4.82	4.14	4.56	4.15
Fe_2O_3/FeO	0.49	0.19	0.65	0.60	0.51	0.45	0.32	0.24	0.42	0.51	0.41	0.47
K_2O/Na_2O	1.24	1.16	1.32	1.08	1.10	1.05	1.08	0.97	0.99	1.01	1.01	1.03
					C.I.P.W. Norm							
Q	16.95	20.61	22.55	18.18	20.00	18.78	21.10	17.22	20.82	18.1	17.9	20.27
or	25.35	24.05	25.00	23.39	22.44	21.93	22.45	20.57	19.46	21.5	21.1	21.29
ab	29.23	29.73	27.17	30.93	29.20	29.95	29.74	30.39	28.30	30.6	29.3	29.47
an	11.94	13.84	15.05	14.97	16.78	16.72	15.82	19.46	17.79	16.8	18.4	16.46
di	5.20	2.13	0.87	2.84	1.23	1.76	1.91		0.22	2.4	1.4	1.95
hy	7.25	7.50	5.94	5.96	7.03	7.52	7.41	8.86	8.76	7.0	7.8	7.06
mt	2.13	0.84	2.15	2.31	2.02	1.96	1.37	1.16	2.09	2.1	2.1	2.01
il	1.24	0.98	0.98	1.09	1.10	1.17	1.04	1.52	1.22	1.1	1.2	1.15
ap	0.70	0.33	0.30	0.33	0.21	0.21	0.16	0.34	0.67	0.3	0.3	0.35
100 an/ab+an	29.0	31.8	35.7	32.6	36.5	35.8	34.7	39.0	38.6	35.42	38.6	35.8

[1] Data from Wilkinson, Vernon and Shaw (1964, Table 6).

[2] Data from Chapter 6, Table 6.1; Analyses 9 to 13 of the Normal facies ignimbrite, Coombadjha Volcanic Complex.

[3] Data from Flood, Vernon, Shaw and Chappell (1977, Table 1).

[4] n.d. = not detected

TABLE 8.2: Trace element analyses in μg/g of the Basal facies lava of the Dundee Rhyodacite, Coombadjha Volcanic Complex, undifferentiated Dundee Rhyodacite of other areas, and averages of Dundee Rhyodacite analyses

Sample	Basal	facies	lava	Brass-ington	Tenterfield		Tarban	Dundee[1]	Average[2] (5 samples)	Average[3] (8 samples)
	1	2	3	4	5	6	7	8	10	12
Element	R55515	R55520	R55510	R55610	R55612	R55613	R55616	D1		
Ti	4510	3550	3530	3770	3380	3660	3610		3984	
V	105	78	67	75	66	74	77	75	84	
Cr	74	25	26	31	26	28	28	25	31	28
Mn	781	878	763	762	722	747	765		816	
Ni	15	7	7	8	7	8	6	45	8	5
Cu	15	10	11	15	13	14	11		12	
Zn	66	89	63	66	63	65	63		68	
Ga	17	18	18	19	17	19	17	18	20	
Rb	180	178	126	144	144	143	145	250	136	147
Sr	302	292	286	310	314	317	297	250	330	306
Y	31	30	31	32	32	32	29	22	31	25
Zr	174	180	185	195	191	188	183		191	190
Nb	9	8	8	8	8	8	8		8	
Ba	723	724	688	705	714	748	667	600	711	872
Pb	19	37	70	24	23	24	25		32	24
Th	21	20	18	16	20	17	15		16	16
U	5	3	5	9	6	4	6		4	4
K/Rb	198	190	279	228	219	215	218	116	223	204
Ba/Rb	4.0	4.1	5.5	4.9	5.0	5.2	4.6	2.4	5.3	5.9
Th/U	4.2	6.7	3.6	1.8	2.2	4.3	2.5		4.6	4.0

[1] Data from Wilkinson, Vernon and Shaw (1964, Table 9).

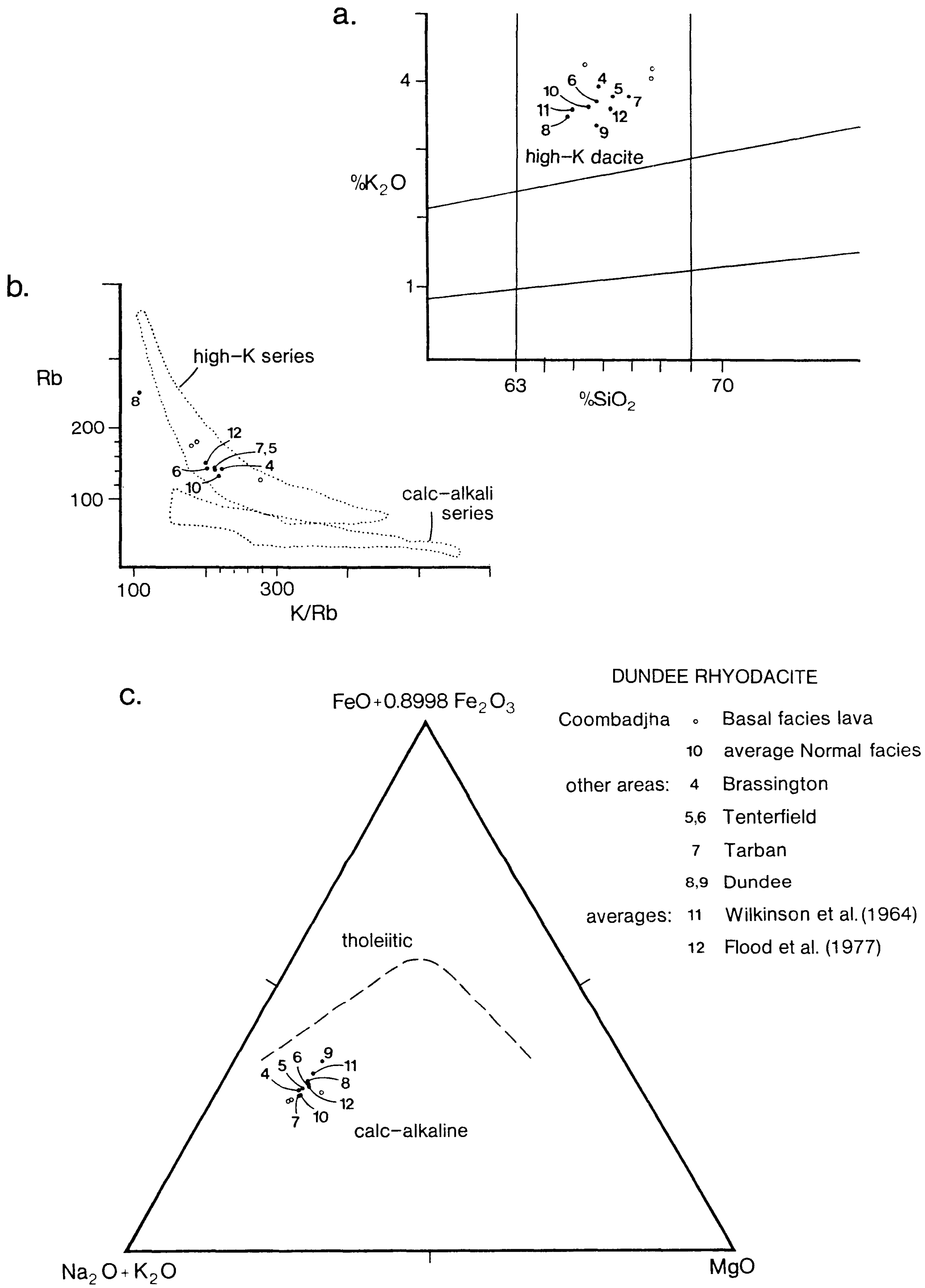
[2] Data from Chapter 6, Table 6.2; Analyses 9 to 13 of the Normal facies ignimbrite, Coombadjha Volcanic Complex.

[3] Data from Flood, Vernon, Shaw and Chappell (1977, Table 1).

Figure 8.2: a. K_2O versus SiO_2 values (recalculated H_2O- and CO_2-free) for the Dundee Rhyodacite of the Coombadjha Volcanic Complex and other localities (Table 8.1) in relation to the subdivisions of Peccerillo and Taylor (1976) and Ewart (1979).

b. µg/g Rb versus K/Rb values for the Dundee Rhyodacite from the same localities as a. (Table 8.2), in relation to the high-K and calc-alkali series of Ewart (1979, Figure 4).

c. AFM diagram showing the Dundee Rhyodacite samples in relation to the tholeiitic and calc-alkali fields of Irvine and Baragar (1971, Figure 2).


a.
4
1
%K2O
63
70
%SiO2
high-K dacite
10
6
4
5
7
11
12
8
9
b.
Rb
200
100
100
300
K/Rb
high-K series
calc-alkali series
8
12
7,5
6
4
10
c.
FeO+0.8998 Fe2O3
Na2O+K2O
MgO
tholeiitic
calc-alkaline
4
5
6
9
11
8
12
7
10
DUNDEE RHYODACITE
Coombadjha ∘ Basal facies lava
10 average Normal facies
other areas: 4 Brassington
5,6 Tenterfield
7 Tarban
8,9 Dundee
averages: 11 Wilkinson et al. (1964)
12 Flood et al. (1977)

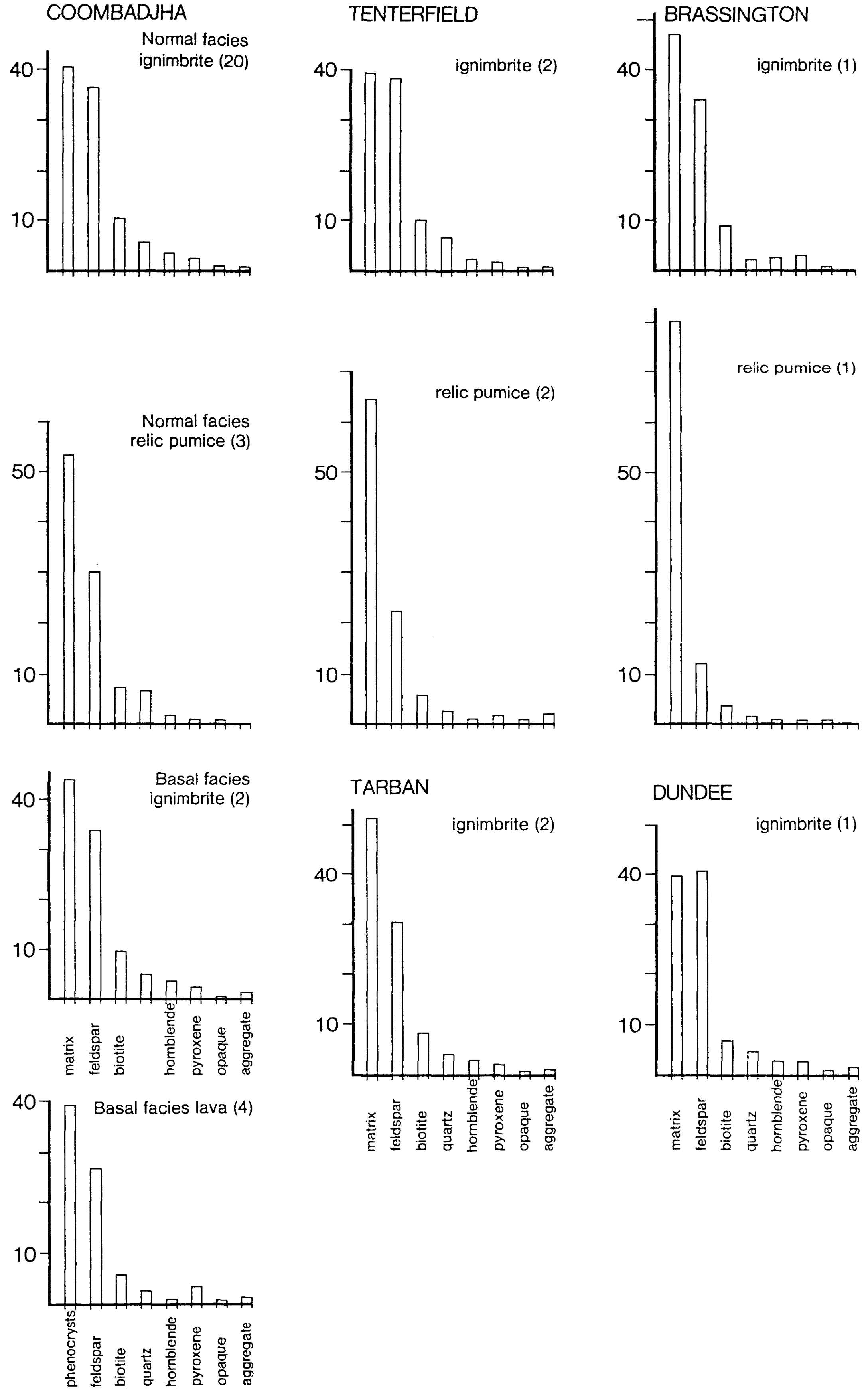


Figure 8.3: Histograms of modal data for the Dundee Rhyodacite of the Coombadjha Volcanic Complex and other localities. The number of samples used for the averages shown on each histogram is given in brackets. Matrix includes all formerly pumiceous components. Feldspar is predominantly plagioclase and clinopyroxene is more abundant than orthopyroxene. The opaque mineral is mainly magnetite.

FACIES OF THE DUNDEE RHYODACITE OF THE COOMBADJHA VOLCANIC COMPLEX

The Dundee Rhyodacite of the Coombadjha Volcanic Complex consists of two parts termed the Normal and Basal facies (Chapter 6).

Normal facies

This facies is the more voluminous part (95 percent) and constitutes a readily mappable ignimbrite marked by textural homogeneity and crystal-rich character. Limited chemical data suggest it is uniform in composition (Fig. 6.4, Tables 6.1,6.2). Tors are typical of weathered outcrops (Fig. 6.8c) whereas cliff exposures are broken into blocks by prismatic joints.

Petrography

The petrography of the Normal facies ignimbrite has been described in some detail (Chapter 6) and only a summary is repeated here. Crystal fragments generally about 2 mm in size are abundant (58 modal percent; Fig. 8.3) comprising quartz, plagioclase, biotite, hornblende, pyroxene, magnetite and minor K-feldspar. Pumice fragments are inconspicuous porphyritic lenses (Fig. 6.8f) with somewhat lower proportions (about 46 modal percent) of slightly coarser grained, euhedral crystals (Fig. 8.4a). Accidental and accessory lithics are only minor components (less than 2 to 3 modal percent). Equigranular fine grained pyroxene + plagioclase ± hornblende ± biotite aggregates ranging in size from microscopic to centimetres across are ubiquitous but also minor (less than 2 modal percent).

Flow and cooling unit subdivision of the Normal facies ignimbrite

Cainozoic ignimbrites are commonly composed of one or more flow units, each of which is interpreted as the depositional record of the passage of a single pyroclastic flow (Smith, 1960a; Ross and Smith, 1961; Ratté and Steven, 1967; Sparks *et al.*, 1973; Sparks, 1976; Wilson, 1980; Wright *et al.*, 1980; Wright, 1981). In many cases, flow units are separated by related pyroclastic or epiclastic deposits or by erosion surfaces (Smith, 1960a). Textural changes within a flow unit, such as laterally continuous concentrations of pumice and/or dense lithics, also indicate proximity to flow unit boundaries (Sparks *et al.*, 1973; Sparks, 1976; Wilson, 1980).

Topographic relief of 500 metres provides continuous sections through the Normal facies of the Dundee Rhyodacite in the central area of deepest subsidence of the Coombadjha cauldron. However, no flow units have been identified. Careful inspection has not been successful in revealing any intercalations of different lithologies in these exposures. The same is true for the thinner remnant of the Normal facies ignimbrite elsewhere in the Coombadjha Volcanic Complex. Nor have any mappable, texturally distinctive zones been detected above the base of the Normal facies, although relic pumice is in general inconspicuous and the proportion of dense lithics is very small.

Smith (1960a,b) and Ross and Smith (1961) have proposed that stacks of flow units with a shared cooling history display systematic vertical changes in outcrop prominence, coherence, jointing, shapes of pumice fragments, deformation of microscopic shards, devitrification and recrystallization, and constitute a mappable 'cooling unit'. Thick (greater than 200 m) simple cooling units have a lower and upper welded, typically devitrified zone, and a central zone of granophyric recrystallization of vitric components (Smith, 1960a,b).

The Normal facies ignimbrite of the Dundee Rhyodacite in the Coombadjha Volcanic Complex shows no conspicuous variations indicative of cooling breaks, although relic pumice fragments are only locally evident and systematic assessment of their shape has not been possible. Welded devitrified shards are preserved in samples from near the base of the Normal facies (Fig. 6.8e); vitroclastic textures are absent throughout the remainder. Instead the ignimbrite has a microcrystalline groundmass mosaic of quartz and feldspar, the coarsest examples of which are in the thickest part of the ignimbrite (near the Demon Fault System). This pattern is consistent with the presence of a single, simple, densely welded but incomplete cooling unit. Such uniformly dense welding is probably responsible for the masking of flow unit boundaries in the Normal facies, as has been reported in some thick cooling units of ignimbrite of Tertiary age in the western United States. Flow unit boundaries in these ignimbrites may be as thin as a few centimetres and involve exceedingly subtle lithological changes (e.g. those in the Mammoth Mountain and Wason Park Rhyolites of the Creede caldera sequence, Colorado; Ratté and Steven, 1967).

The basal shear layer of the Normal facies ignimbrite

In several excellent exposures (e.g. GR27804610, GR29004675 Coombadjha) the base of thick, densely welded sections of the Normal facies ignimbrite is clearly marked by a sharp, planar contact. The ignimbrite above this surface is slightly finer grained and more crystal-rich than is typical of the Normal facies, and also has a pronounced fabric defined by the long dimensions of crystal fragments which are either imbricated or aligned parallel to the contact (Fig. 8.4b). Diffuse base-parallel variations in crystal content occur in the ignimbrite close to the contact in some instances. In thin-section, millimetre sized volcanic lithics are conspicuous but relic pumice is missing. Within 2 to 3 metres above the base,the ignimbrite changes almost imperceptibly to massive Normal facies. Even where contacts are not exposed, or where no planar sharp base exists, the lowermost part of the Normal facies throughout the Coombadjha Volcanic Complex is invariably slightly finer in grain size, more crystal-rich and displays distinct alignment of elongate crystal fragments.

Similar grain size changes and conspicuous fabrics occur consistently near the bases of many young ignimbrites and this part of a pyroclastic flow deposit constitutes the 'basal layer' or Layer 2a of the standard stratigraphy (Walker, 1971,1972; Sparks *et al.*, 1973; Yokoyama, 1974; Sparks, 1976,1978a; Sheridan, 1979; Wright and Walker, 1981). The textures are thought to originate in a basal shear layer that exists during flowage and separates the body of a pyroclastic flow from the substrate (Sparks *et al.*, 1973; Sparks, 1976; Wright and Walker, 1981). The basal shear layer commonly overlies a sharp, planar, erosive surface, although gradational contacts also occur (Sparks *et al.*, 1973). Layer 2a typically has a transitional relationship to the bulk of the overlying ignimbrite (Layer 2b; Sparks, 1976).

Basal facies

The Basal facies comprises four main lithologies: ignimbrite, porphyritic dacite,bedded tuff and breccia. One or more of these components is present below the Normal facies in good exposures and all are interpreted to be early products of the eruption episode which later gave rise to the

Normal facies. The Basal facies is in places very thin (less than a few metres) and does not outcrop as well as the enclosing units. Hence it is not known whether its absence in poorer sections is real or apparent. Descriptions and interpretation of the lithologies and stratigraphy of the Basal facies follow.

Ignimbrite

The Basal facies ignimbrite is blue-black, crystal-rich and welded, and similar in mineralogy and grain size to the Normal facies. In outcrop it is difficult to distinguish from the Normal facies where no other components of the Basal facies intervene. There are however several subtle differences. Relic pumice lapilli are more conspicuous in the Basal facies ignimbrite, being darker than the host, and have provided most of the scant bedding data for the Dundee Rhyodacite layer of the Coombadjha Volcanic Complex. Joints are more closely spaced so that weathered outcrops generally do not form tors. Fresh surfaces of the Basal facies ignimbrite are darker blue than the Normal facies ignimbrite.

Thin sections show that most samples of the Basal facies ignimbrite have welded devitrified shards in the matrix, whereas coarser grained recrystallisation of the matrix is uncommon (Fig. 8.4c). K-feldspar is present as crystal fragments and phenocrysts in relic pumice. Accidental (or accessory?) lithics are more abundant than in the Normal facies ignimbrite, and are predominantly fine grained, trachytic textured lava (?)clasts smaller than 20 mm.

The Basal facies ignimbrite has not been found in the south of the Complex, but is present below the Normal facies from near OBX Creek north to the Malara Trig area (Fig. 8.5). It has not been identified farther east below the Normal facies which occurs in Malara Creek and its tributaries. The thickness is estimated to be 20 to 30 metres and there is no evidence for the presence of more than one flow unit.

Porphyritic dacite

Phenocrysts of quartz, zoned plagioclase, K-feldspar, biotite, hornblende, an opaque mineral, and additional clinopyroxene in some cases, range from

1 to 5 mm in size and constitute about 40 modal percent of this dark blue-grey porphyritic dacite (Figs. 8.2,8.3; Tables 8.1,8.2). Groundmass textures vary, the coarsest being microcrystalline and trachytic textured. Diffuse flow lines are also evident in some samples with cryptocrystalline groundmasses (Fig. 8.4d). Examples with spherulites are common. Zoned subhedral plagioclase grains (up to 3 mm) occur in clusters (5 mm) in most thin sections. Other finer grained crystal aggregates, particularly combinations of plagioclase, clinopyroxene, hornblende, biotite and an opaque mineral, are present though not as abundant as the plagioclase clusters. Outcrops of the dacite appear to be entirely massive and devoid of systematic internal textural variation.

The dacite of the Basal facies is widely distributed though there are many gaps in its mapped extent because outcrop deteriorates away from deeply incised creeks. The best exposures occur around the northern, northeastern and southeastern edges of the layer of Normal facies ignimbrite, and in centrally located windows through it to the underlying volcanics (Fig. 8.5). The dacite does not occur in the southwestern sector of the Complex near Pheasant Creek. Thickness variation is marked, ranging from less than 4 to 5 m at most localities to tens of metres at some central and southeastern sites.

Bedded tuff

Black, fine and coarse ash tuff is a widely distributed component of the Basal facies but few good *in situ* exposures exist. Outcrops display continuous laminae and very thin beds with diffuse contacts and lacking in any signs of grading. Sparse volcanic lithic fragments up to a few centimetres are present in some outcrops but are uncommon. Layering is locally uneven and warped (Fig. 8.6) though no distinctive depositional structures have been observed. These tuffs are composed of non-welded shards, unresolvable finer grained ash (?), and angular crystal (quartz + plagioclase ± biotite) and lithic fragments. Millimetre-sized lenses of porphyritic relic pumice occur in samples from one locality (GR29004675 Coombadjha, R55526). Some examples exhibit clear separation of shard-rich laminae from crystal-rich, shard-free laminae (Fig. 8.4e) although layers with crystal fragments dispersed in shard-rich matrix also occur (Fig. 8.4f).

Figure 8.4: a. Photomicrograph of relic pumice in Normal facies ignimbrite of the Dundee Rhyodacite, Coombadjha Volcanic Complex. Euhedral phenocrysts are set in a microcrystalline groundmass mosaic of quartz and feldspar. R55465, crossed nicols.

b. Photomicrograph of very crystal-rich ignimbrite from close to the base of the Normal facies. Note the distinct alignment of elongate crystal fragments (principally biotite). R55478, plane polarised light.

c. Photomicrograph of the Basal facies ignimbrite with abundant crystal fragments and welded matrix shards. R55502, plane polarised light.

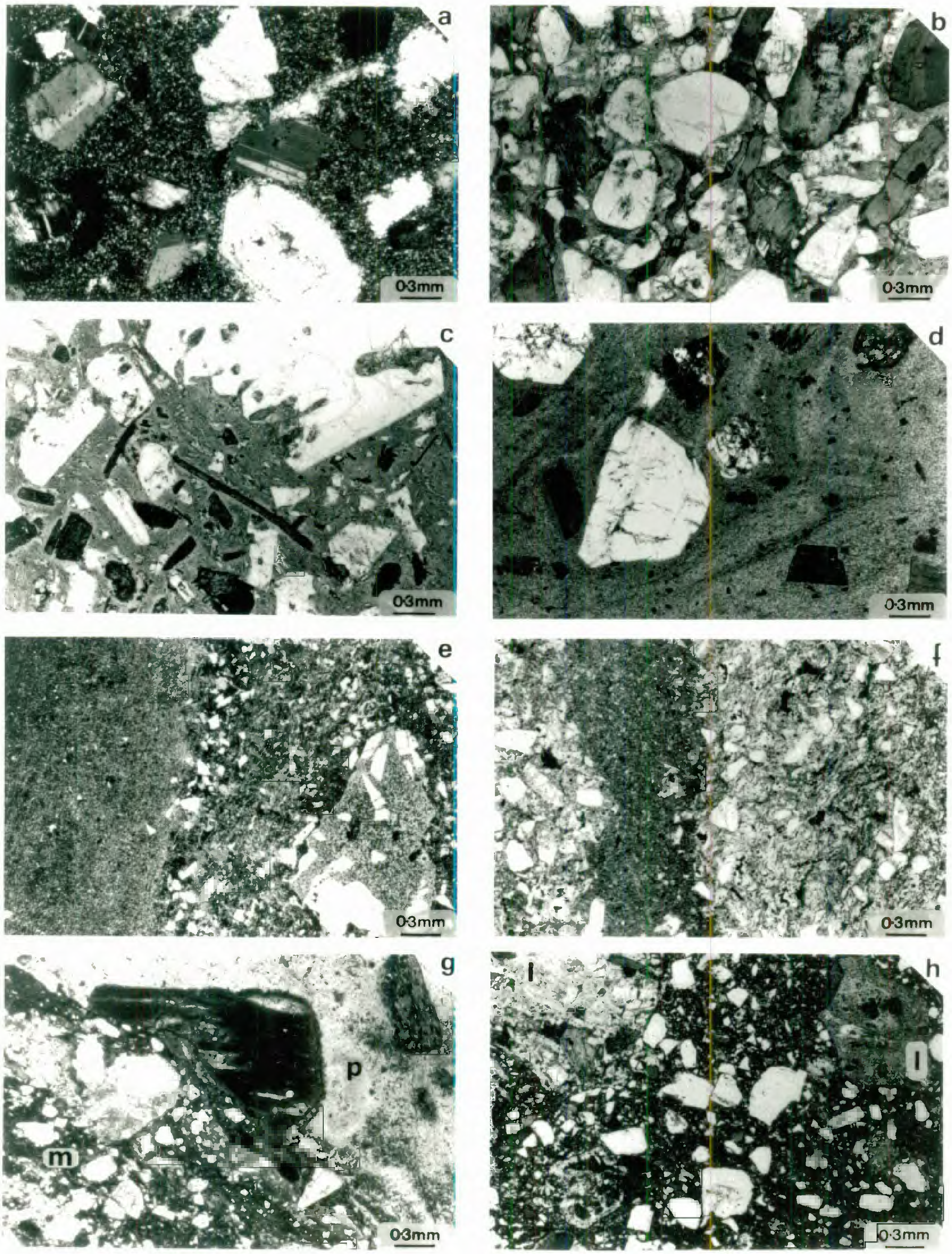
d. Photomicrograph of the porphyritic dacite of the Basal facies of the Dundee Rhyodacite. Euhedral phenocrysts are set in a cryptocrystalline groundmass in which diffuse flow lines are evident. R55514, plane polarised light.

e. Photomicrograph of bedded tuff of the Basal facies of the Dundee Rhyodacite. Shard-rich, very fine grained lamina and more crystal- and lithic-rich poorly sorted lamina. R55529, plane polarised light. Sample from section illustrated in Figure 8.6a.

f. Photomicrograph of bedded tuff of the Basal facies of the Dundee Rhyodacite. Crystal-rich and crystal-poor laminae; isolated crystal fragments also occur in the otherwise crystal-poor lamina. R55530, plane polarised light.

g. Photomicrograph of brecciated porphyritic dacite of the Basal facies. Coherent porphyry (p) has been comminuted to form a fine grained 'matrix' (m) between 'clasts'. R55543, plane polarised light.

h. Photomicrograph of the matrix of lithic- and porphyry-clast breccia of the Basal facies of the Dundee Rhyodacite. Lithic clasts (l). R55542, plane polarised light.


a
0·3mm
b
0·3mm
c
0·3mm
d
0·3mm
e
0·3mm
f
0·3mm
g
p
m
0·3mm
h
l
l
0·3mm

Bedded tuff is a consistent accompaniment to other components of the Basal facies but relationships have not been resolved in sufficient detail at enough localities to state with confidence the number and thickness of intervals present. Of the good exposures, one includes 3 to 4 metres of bedded tuff (GR28205843, Washpool) whereas another has less than 15 cm (GR27804610, Coombadjha). Similar but non-bedded tuff forms the matrix in some breccias (described below), and irregular seams and lenses near the base of the Normal facies ignimbrite and at the contacts of the porphyritic dacite.

Breccia

Breccia of the Basal facies contains fragments of porphyritic dacite, crystal-rich welded ignimbrite and a small proportion of the other volcanic clasts, principally fine grained, trachytic textured porphyries. The amount of black matrix changes erratically at outcrop scale from minor, narrow (millimetres wide) threads and irregular patches to being volumetrically dominant (Fig. 8.6). This matrix is composed of angular crystal fragments, dispersed or crowded in unresolvable dark material (Fig. 8.4g,h). Shards occur in some samples with a high proportion of matrix. The mineralogy of the crystal fragments in the matrix is the same as that in the dominant clast type, and their grain size ranges from less than 0.3 mm to millimetres, though does not exceed phenocryst or crystal fragment dimensions of associated porphyry or ignimbrite clasts. The textural and compositional heterogeneity of this rocktype is difficult to appreciate by means of thin-sections which are probably unrepresentative.

Although there are only a small number of good creek outcrops of the breccia, it is a widespread component of the Basal facies. The lateral continuity of the breccia has not been established. However it is a common accompaniment of the porphyritic dacite and they have similar distributions The intervals of breccia have gradational relationships with other components of the Basal facies. Thicknesses are estimated to be less than a few metres but have not been precisely determined.

INTERNAL STRATIGRAPHY OF THE DUNDEE RHYODACITE OF THE COOMBADJHA VOLCANIC COMPLEX

Figure 8.5 shows seven stratigraphic columns based on the best exposures of the Basal facies which exemplify the variation in arrangement of its components. Correlations have not been verified by mapping between sections because *in situ* outcrop of the Basal facies is mainly restricted to creeks.

Comparatively simple stratigraphy is present throughout much of the southern part of the Complex as illustrated by columns 1,2 and 3 (Fig. 8.5). The Basal facies is represented by black bedded tuff, in places accompanied by breccia and a single layer of porphyritic dacite. Sections in northern areas are complicated by the addition of Basal facies ignimbrite. Although the sections accurately portray the overall succession of components, they necessarily simpify the nature of the actual contacts. Some important cases are described below as the relationships displayed have influenced interpretations of the emplacement style and sequence of the rocktypes of the Basal facies.

Lower contact of the Normal facies

The outcrop depicted in column 1 is particularly instructive and several nearby exposures are similar. About 1 to 1.5 metres of black bedded tuff occur between the Pi Pi Ignimbrite (below) and Normal facies ignimbrite (above). Elsewhere Pi Pi Ignimbrite is characterised by dense welding and two-dimensional relic pumice (Figs. 6.7g,h). In this exposure of its topmost part, welding is noticeably diminished. Poorly welded Pi Pi Ignimbrite grades upward into diffusely laminated, black, fine grained tuff with crystal-rich (quartz + plagioclase + biotite) layers, 1 to 2 centimetres thick. Crystal-rich laminae are increasingly conspicuous within 30 cm of the sharp planar surface at the base of the Normal facies ignimbrite and any signs of affinity with Pi Pi Ignimbrite are completely gone.

In other columns no sharply defined lower contact to the Normal facies has been detected. Where the Basal facies porphyritic dacite occurs (Fig. 8.5, columns 2,3,4 and 6), breccias separate it from the Normal facies. Basal facies ignimbrite underlies Normal facies ignimbrite in column 5. Black bedded tuff and breccia intervene as indicated in column 5 but there are areas where these are missing, and distinction between Normal facies and Basal facies ignimbrite near the transition could not be made with confidence in the field.

Contacts of the Basal facies porphyritic dacite

Nowhere has a sharp contact been observed at the top of the porphyritic dacite. Instead, porphyry-clast bearing 'breccia' separates the dacite from the overlying ignimbrite. The upper transitional zone is approximately conformable but locally irregular as a result of marked small-scale variation in thickness of the porphyry.

The base of the porphyritic dacite is sharp and planar in outcrops used for columns 2,4 and 7 (Fig. 8.5). In column 4 irregularities of small dimensions (centimetres) occur along the contact with the underlying bedded tuff (Fig. 8.6), but in this column and column 2, the dacite contact is entirely conformable with the nearest bedding in enclosing units. In column 7, the dacite overlies ?Devonian-Carboniferous argillite which surrounds the Complex and for which the local bedding attitudes are unknown. Because the upper contact in this column is gradational, the conformity or otherwise of the base relative to attitudes in overlying units cannot be evaluated with precision.

Porphyritic dacite in column 3 is underlain by breccia with irregular masses and clasts of dacite separated by black tuffaceous matrix. Accidental lithics are present where the matrix is dominant. Some areas of the dacite are only partially detached from the main body. The entire breccia is pervasively sheared with cataclastic textures evident both in outcrop (Fig. 8.6) and thin-section. Thin threads of matrix are actually intensely comminuted dacite although true clastic matrix also occurs. The effects of shearing are confined to the breccia. Neither the adjacent porphyritic dacite nor the underlying Pi Pi Ignimbrite are noticeably affected. Columns 5 and 6 also include a transitional zone at the base of the porphyry but there is no indication of shearing. The matrix is ignimbrite similar to the Basal facies ignimbrite below, though in column 6, shards are undeformed.

Contacts of the Basal facies ignimbrite

Three columns for the northern part of the Complex (4,5,6, Fig. 8.5) include Basal facies ignimbrite. Column 4 has a good exposure of the top of the ignimbrite where it grades into black bedded tuff with crystal-rich

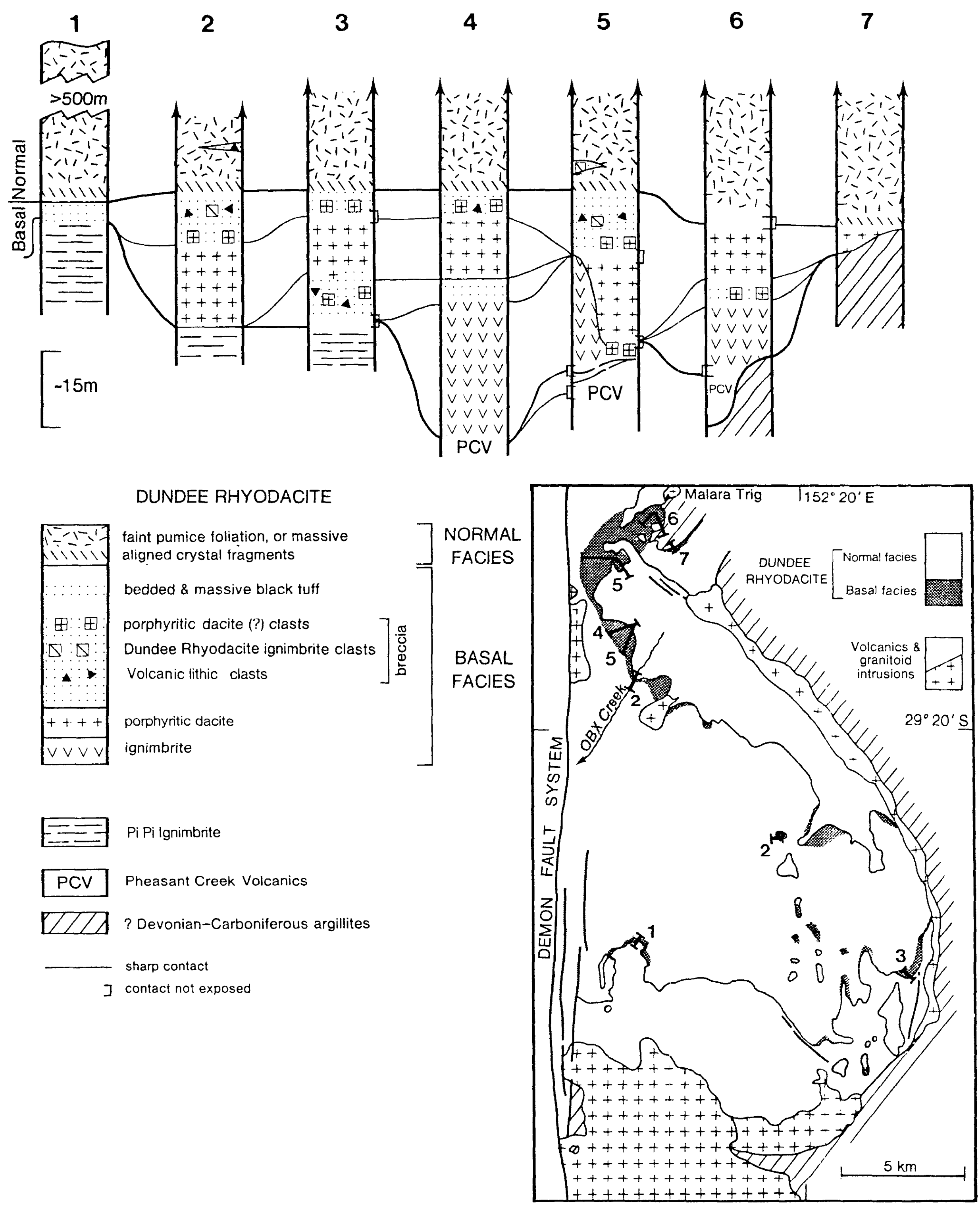
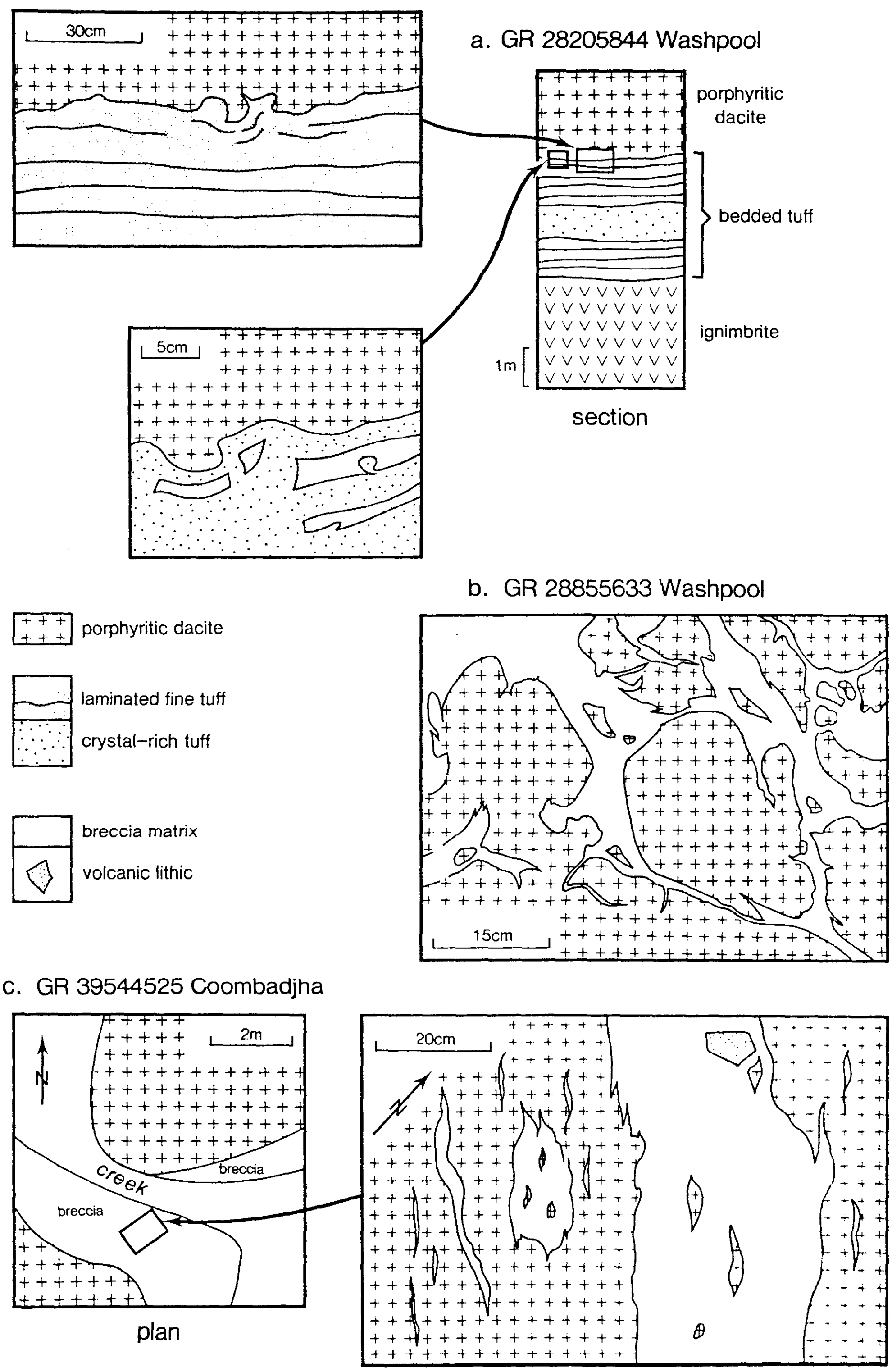


Figure 8.5: Seven stratigraphic columns illustrating relationships within the Basal facies of the Dundee Rhyodacite in the Coombadjha Volcanic Complex. Columns 2 and 5 are each based on two localities (shown on the map) where similar arrangements occur.

Figure 8.6: Field sketches of relationships at the base of the porphyritic dacite of the Basal facies.

a. Section with detail for the locally irregular but generally conformable contact between the porphyritic dacite above and bedded tuff below.

b,c. Plans of irregular contact relationships between porphyritic dacite and fine grained matrix.



a. GR 28205844 Washpool
30cm
5cm
porphyritic dacite
bedded tuff
ignimbrite
1m
section
b. GR 28855633 Washpool
15cm
porphyritic dacite
laminated fine tuff
crystal-rich tuff
breccia matrix
volcanic lithic
c. GR 39544525 Coombadjha
2m
N
creek
breccia
breccia
plan
20cm

laminae. In other columns (5,6, Fig. 8.5) breccia that includes clasts of Basal facies ignimbrite, porphyritic dacite and accidental(?) lithics in black tuffaceous matrix or in ignimbrite matrix, occurs at the same stratigraphic position.

Volcanics of the older units (principally the Pheasant Creek Volcanics) underlie the Basal facies ignimbrite. No distinctive breccias were found though stringers of black fine tuff occur randomly distributed in the ignimbrite and patches of black bedded tuff outcrop close to the contact at localities used for column 5 (e.g. GR28955880 Washpool).

In summary, black bedded tuff and/or breccia commonly separate the ignimbrite and porphyritic dacite components of the Basal facies, and also immediately underlie the Normal facies. The main exceptions are sections where the change from Basal facies ignimbrite below to Normal facies ignimbrite above appears gradational. The base of the porphyritic dacite and of the Normal facies is at least locally a planar, sharp, conformable contact. The composite section in Figure 8.7 incorporates the significant features of the near-base stratigraphy of the Dundee Rhyodacite in the Coombadjha Volcanic Complex, and summarises the inferred origins and emplacement sequence of components of the Basal facies.

INTERPRETATION OF THE BASAL FACIES

Ignimbrite

The Basal facies ignimbrite is indistinguishable from that of the Normal facies in terms of the range of constituents present and differs only slightly in texture. Its stratigraphic discrimination from the overlying Normal facies ignimbrite depends heavily on the presence of intervening dacite, breccia or bedded tuff. Contrasts in mineralogy, crystal content, pumice foliations and welding characteristics between the Basal facies ignimbrite and ignimbrite of older underlying volcanic units (the Pi Pi Ignimbrite or the Pheasant Creek Volcanics, Chapter 6) suggest that no close relationship exists. The Basal facies ignimbrite is thus interpreted as a genetically related precursor of the Normal facies ignimbrite.

Porphyritic dacite and porphyry-clast breccia

Breccias immediately overlying the dacite are derived from it and indicate its extrusive character. That the dacite was originally emplaced as a lava flow is supported by the well-developed flow structures evident in thin-section and is consistent with the general conformity of the dacite layer. Breccia of cataclastic origin locally at the base of the porphyritic dacite is interpreted as sheared flow-base autobreccia. An upper fragmental carapace enclosing coherent porphyritic dacite can also be inferred from the presence of overlying porphyry-clast breccia. There are many examples of Cainozoic silicic lava bodies that have coherent cores encased in an envelope of lava breccia (e.g. Loney, 1968; Smith, 1973,1976; Fink, 1980b,1983).

Three aspects of this interpretation require further explanation. Firstly, the porphyritic dacite underlies a thick, compositionally similar ignimbrite, whereas in many Cainozoic volcanic sequences the order is reversed, with extrusion of lavas post-dating eruptions of major ignimbrites (e.g. Smith and Bailey, 1968; Sparks *et al.*, 1973; Sheridan, 1979; Hildreth, 1981). Secondly, pumice- or ash-fall deposits are commonly found beneath moderate and large volume ignimbrites (Sparks *et al.*, 1973; Sparks, 1976; Wright *et al.*, 1981). For the Normal facies ignimbrite, this stratigraphic position is occupied by the porphyritic dacite. Finally, the porphyritic dacite is widely distributed though comparatively thin in places, whereas Cainozoic silicic lavas are typically high-aspect ratio bodies, with the ratio of thickness to lateral extent being relatively large (Hulme, 1974; Walker, 1973b; Smith, 1976).

The possibility of the porphyritic dacite being a compacted and lithified pumice fall deposit has been considered but rejected principally because there is clear microscopic evidence for groundmass flow. Also, signs of original vesicularity or of co-eruptive fragmental material (shards, crystals, accessory lithics) are absent from the central portion of the dacite layer. Although the mineralogy, grain size and crystal content of relic pumice lenses in Normal facies ignimbrite are very similar to the porphyritic dacite, their groundmass textures differ: devitrification products are coarser grained in the latter, and some samples have micro-crystalline flow-aligned feldspar laths, not known from any relic pumice. Moreover, such lava-ignimbrite sequences are not unique. For example, Byers *et al.* (1976, p.51,52) report that each of two major ignimbrites related to the formation of Timber Mountain caldera, Nevada, is underlain by petrographically similar lava.

The anomalously large spread of the porphyritic dacite remains a problem. Although porphyritic dacite occurs at a consistent stratigraphic level, the existence of a single, laterally continuous layer has not been established. Hence the wide distribution could be explained by extrusion of similar lava from a number of simultaneously active vents which may also account for marked variation in thickness over short distances.

Bedded tuff

Unmodified shards, angular crystal and volcanic lithic fragments, and association with subaerial, undisturbed volcanic units support the conclusion that most occurrences of black bedded tuff are primary pyroclastic deposits. For uncommon cases where sparse subrounded volcanic lithic clasts occur, an epiclastic origin cannot be discounted. Features diagnostic of particular pyroclastic processes are not displayed in the majority of exposures, and the critical evidence provided by data on three-dimensional geometry is not available.

Most studies of young volcanic sequences attribute thinly bedded pyroclastic intervals above and/or below ignimbrite to deposition from pyroclastic surges or fallout from convective ash clouds, generated by vent eruptions and/or associated with moving pyroclastic flows (e.g. Sparks and Walker, 1973,1977; Sparks *et al.*, 1973; Sparks, 1976; Fisher, 1979; Wright *et al.*, 1981; Self and Wright, 1983; Walker, 1983). The stratigraphic position of bedded shard-rich tuff gradationally overlying Basal facies ignimbrite in column 4 (Fig. 8.5) suggests an origin by ash-fall from co-ignimbrite fine grained ash plumes. In column 1 and nearby where Normal facies ignimbrite overlies Pi Pi Ignimbrite, part of the intervening thinly bedded black tuff may be another instance of co-ignimbrite (Pi Pi) ash, gradationally above the poorly-welded top of Pi Pi Ignimbrite and probably reworked to some extent. Closer to but still below the planar base of the Normal facies, there are crystal-rich laminae with mineralogy more akin to the Dundee Rhyodacite. Such stratigraphic intermingling could be attributed to the passage of intermittently erosive, Dundee Rhyodacite-related pyroclastic

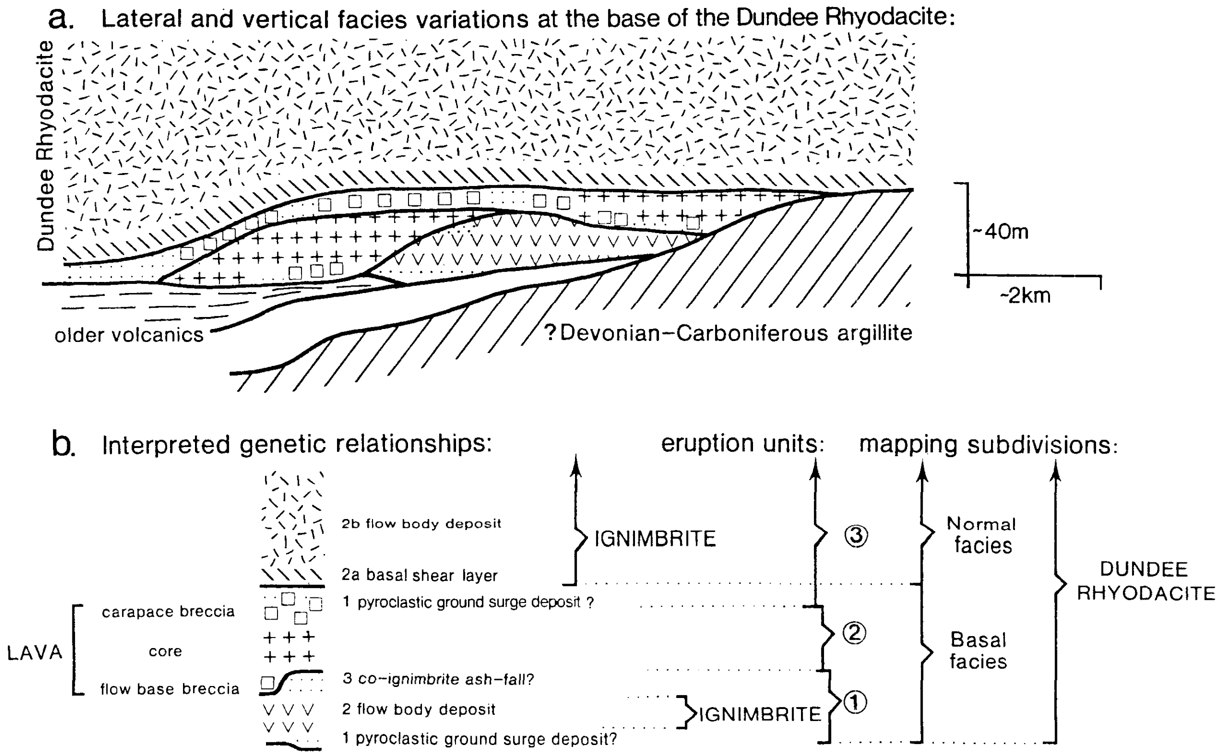


Figure 8.7: Composite stratigraphic section summarising the lateral and vertical variations in lithologies at the base of the Dundee Rhyodacite of the Coombadjha Volcanic Complex, correlated with interpreted origins and genetic relationships.

surges across unconsolidated ash originally of Pi Pi Ignimbrite derivation. Large scale operation of such a process is inferred from the widespread occurrence of bedded tuff immediately below the base of the Normal facies, and of similar material within its lowermost parts, dispersed as irregular seams and stringers. Cainozoic analogues exist at the base of the Fish Canyon Tuff, Colorado (Self and Wright, 1983) and below each member of the Bandelier Tuff, New Mexico (Fisher, 1979). In each case, the pyroclastic surge deposits are underlying genetically related, caldera-forming ignimbrite.

Breccia

The term breccia is applied to intervals of the Basal facies which separate, and are mixtures of, its other components. At least two modes of emplacement have operated, one of which involved the fragmentation of lava (porphyritic dacite) to generate porphyry-clast breccia. Breccias close to the base of the Normal facies ignimbrite combine clasts of porphyritic dacite, basal facies ignimbrite and accidental(?) volcanic lithics in matrix which is ignimbrite. Elsewhere the matrix is similar to black bedded tuff but at best only crudely layered. These breccias are interpreted to be primarily related to emplacement of the Normal facies ignimbrite. Thin lenses of lithic detritus and bedded tuff initially deposited from pyroclastic ground surges were apparently disrupted by the subsequent emplacement of the Normal facies ignimbrite (*cf.* surge deposits at the base of the Fish Canyon Tuff, Colorado; Self and Wright, 1983).

ERUPTION SEQUENCE OF THE DUNDEE RHYODACITE OF THE COOMBADJHA VOLCANIC COMPLEX

The lithological similarity and stratigraphic coincidence of components of the Basal facies with the Normal facies of the Dundee Rhyodacite provide the bases for inferring a co-magmatic relationship between the two parts. The emplacement of the Normal facies ignimbrite in the Complex has been identified as a formative stage in its history (Chapter 6). Recognition and analysis of the Basal facies allows a detailed evaluation of fluctuations in eruptive style that preceded sustained production of the ignimbrite of the Normal facies.

Opening stages of the eruption of the Dundee Rhyodacite at Coombadjha

The earliest sign of volcanic activity related to the Dundee

Rhyodacite is provided by the Basal facies ignimbrite. Minor bedded tuff below the ignimbrite may have been deposited by precursor pyroclastic ground surges (*cf.* Sparks *et al.*, 1973; Sparks, 1976; Fisher, 1979; Wright *et al.*, 1980,1981; Walker, 1983) but there is no stratigraphic record of a preceding plinian style pumice or ash eruption phase. The ignimbrite was possibly originally more widespread because at the time it was emplaced, the Coombadjha landscape had been smoothed by earlier ignimbrites and no caldera was in existence (Chapter 6).

Although the Basal facies ignimbrite is relatively rich in lithic lapilli, nowhere in the available exposures have breccias potentially indicative of proximity to the source been recognised (co-ignimbrite lag breccias or "transitional" ignimbrite, Wright and Walker, 1977; Wright *et al.*, 1981; Druitt and Sparks, 1982; Wilson and Walker, 1982). Positive evidence for the source of the Basal facies ignimbrite is lacking. The proposed co-magmatic relationship with the dacite lava and their coincident distribution invites speculation that their vents were spatially associated and located beyond the present margins of the volcanic units of the northern part of the Complex (Fig. 8.8a).

Extrusion of highly porphyritic dacite lava followed, registering an effusive interlude of unknown duration between the explosive eruptions which produced ignimbrite of the Basal and Normal facies. Bedded tuff which occurs both below and above the lava could however include a contribution from minor explosive activity accompanying its extrusion. Similar associations are common in Recent proximal lava piles (e.g. Mono Craters, California, Loney, 1968; numerous examples are cited by Newhall and Melson, 1983).

Wide areal extent and marked variation in thickness of the lava probably indicate eruption from several simultaneously active vents (Fig. 8.8b). Lava from any one vent would have been closely confined to the immediate vicinity as is known to be characteristic of subaerial silicic lavas (Walker, 1973b). Coalescence of the products of a number of nearby vents may however build far more extensive shields of silicic lava such as those of Mogollon Plateau, New Mexico (Smith, 1976; Rhodes, 1976a,b), bordering Long Valley caldera, California (Bailey *et al.*, 1976), and around Sierra La Primavera, Mexico (Mahood, 1980).

Arcuate arrangements of lava vents near the margins of some Cainozoic calderas have been interpreted as ring-fault controlled (Smith *et al.*, 1961; Loney, 1968; Smith and Bailey, 1968; Eaton *et al.*, 1975; Bailey *et al.*, 1976; Rhodes, 1976b; Elston, 1984). Sources for the Basal facies lava are not known to exist within its present area of occurrence. Its distribution inside the northeastern perimeter of the Complex mirrors the bounding ring intrusion, which delineates the ring fault system of the Coombadjha cauldron (Chapter 6). Any vents originally located along or near the ring fault system would have been destroyed later when the cauldron formed by collapse, and by emplacement of the intrusion. Cauldron subsidence, and by inference, the principal development of the ring fault system post-date the Basal facies lava but are responses to the eruptive episode of which the lava is an early stage. Hence the lava vents were probably situated at the margins of the area which later subsided. The same proposal has been offered with regard to the location of vents which produced the ignimbrites of both facies of the Dundee Rhyodacite (above, and Chapter 6). Lava eruption may then be considered as symptomatic of the inception of a ring fracture-controlled vent system, the development of which culminated in the production of voluminous ignimbrite and cauldron collapse. These links are supported by the petrographic and compositional similarity of the dacite and the Dundee Rhyodacite ignimbrites, and their temporal coincidence in the eruptive history of the Coombadjha Volcanic Complex. Bailey *et al.* (1976) attach the same significance to the lava flow and dome complex of Glass Mountain situated around the Long Valley caldera in California. The caldera formed later (approximately 0.2 Ma) in response to eruption of the Bishop Tuff, two-thirds of which was emplaced within the caldera, burying offset distal portions of the older ring-fracture lavas.

Emplacement of the Normal facies ignimbrite

Pyroclastic surge deposits

No pumice- or ash-fall layer has been identified beneath the Normal facies ignimbrite. Thinly bedded and laminated shard-rich and crystal-rich tuff, locally containing dispersed accidental lithics and clasts derived from the underlying dacite, has been mapped as a component of the Basal facies but is genetically related to the emplacement of the overlying Normal facies ignimbrite.

Features preserved directly below the base of the Normal facies are all attributable to the erosive passage of, and deposition from, turbulent pyroclastic ground surges. This interpretation is supported by the equivalence of this part of the sequence to Layer 1 of the 'standard' stratigraphy proposed for the products of ignimbrite eruptions by Sparks *et al.* (1973), Sparks (1976) and others. More recently Wilson and Walker (1982), and Walker (1983) have demonstrated that some 'Layer 1' deposits can also be generated by exceptional fluidisation in the head of a pyroclastic flow. These Layer 1 deposits are excessively depleted in fine grained components and are unlike the pre-ignimbrite interval described here. Layer 1 surge deposits are known to exhibit sharp or gradational relationships with overlying ignimbrite (Sparks *et al.*, 1973).

The original ground surge deposits to the Normal facies ignimbrite were disturbed in many places when subsequently overriden by dense (that is, high particle concentration) pyroclastic flows. As a result, the near-base stratigraphy is complex in detail and involves partially disrupted bedded tuff, lithic-rich Normal facies ignimbrite and its basal layer. A similar but lithologically simpler sequence of pyroclastic ground surge deposits overlain by ignimbrite in the Fish Canyon Tuff, Colorado, has been described by Self and Wright (1983). Emplacement of laminated surge sets was accompanied by erosion of the mudstone substrate and the surge deposits were in turn partially eroded and incorporated, along with other locally derived accidental debris, into the ignimbrite.

Ignimbrite

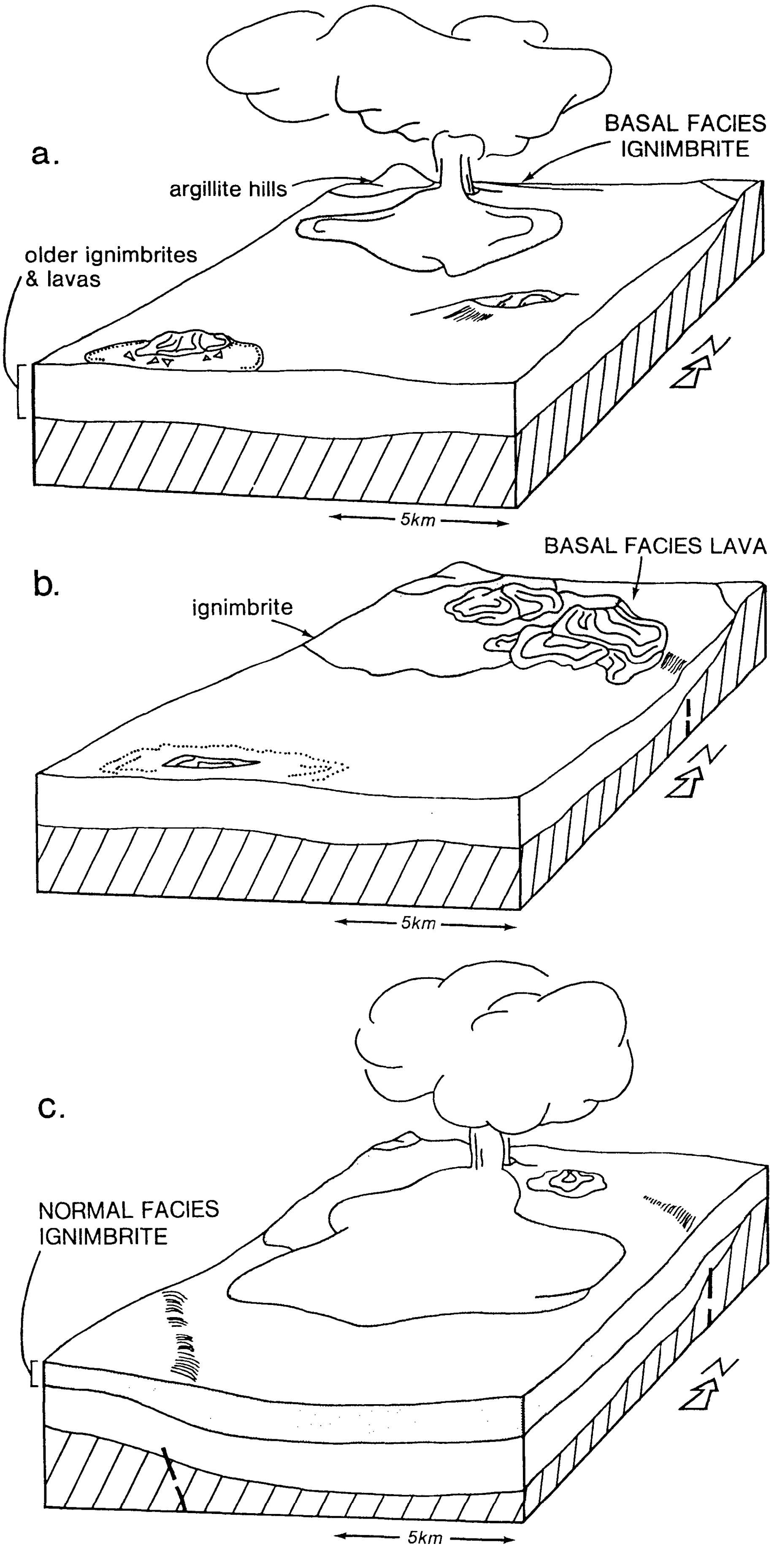
The Normal facies ignimbrite has a poorly defined basal shear layer attributed to deposition from the lower parts of the body of the first-erupted pyroclastic flows. The basal shear layer of the Normal facies ignimbrite (Layer 2a), the lithologies occurring in the directly underlying Basal facies (disrupted Layer 1), and the different relationships that exist between the two facies (sharp and gradational), are consistent with the characteristics of other younger ignimbrites.

Figure 8.8: Schematic reconstructions of the Coombadjha area during initial stages of emplacement of the Dundee Rhyodacite.

a. Eruption of the ignimbrite of the Basal facies, with pyroclastic flows limited to the northern part of the area.

b. Effusion of small lava domes and flows, now represented by the porphyritic dacite lava of the Basal facies.

c. Eruption of the Normal facies ignimbrite at a stage when centripetal sagging of the central cauldron floor may have commenced.


a.
BASAL FACIES
IGNIMBRITE
argillite hills
older ignimbrites
& lavas
5km
b.
BASAL FACIES LAVA
ignimbrite
5km
c.
NORMAL FACIES
IGNIMBRITE
5km

In the remainder of the Normal facies ignimbrite, none of the typical signs of flow unit subdivisions are apparent. The obscurity of flow units indicates that the preserved layer of ignimbrite was emplaced without significant interruptions. Simple cooling units of comparable thickness (more than 600 m) have been reported in detail from the Tertiary ignimbrite sequences of the western United States (e.g. Ratté and Steven, 1967; Lipman, 1975; Byers *et al.*, 1976). Even though these thick cooling units were not known to R.L. Smith in 1960, he correctly predicted that they would be so changed by welding and crystallization to be easily mistaken for "an intrusive mass" (Smith, 1960b, p.156), as has been the case for the Dundee Rhyodacite occurrences elsewhere in New England.

Analysis of the structural history of the Coombadjha Volcanic Complex (Chapter 6) led to the conclusion that eruptions of crystal-rich ignimbrite centred at the Coombadjha cauldron did not cease with emplacement of the existing layer of Dundee Rhyodacite preserved in the Complex. This conclusion is further supported by recognition that the Normal facies ignimbrite is an incomplete simple cooling unit, because the former existence of an additional thickness of ignimbrite within the cauldron is implied by the presently truncated crystallization/welding profile.

VOLCANOLOGY OF THE NORMAL FACIES IGNIMBRITE OF THE DUNDEE RHYODACITE

This section outlines constraints on the character of the pyroclastic flows which deposited the Normal facies ignimbrite of the Dundee Rhyodacite in the Coombadjha Volcanic Complex. The conclusions reached provide a basis for reconstruction of the style and scale of the eruption episode and discussion of the physical controls on the eruptive behaviour with reference to relevant theoretical models.

Pyroclastic flow type

Flow types and criteria for identification

The grain size, internal textural variations and distribution of ignimbrites can be accounted for by deposition from partially fluidised pyroclastic flows (Sparks, 1976,1978a; Sheridan, 1979; Wilson, 1980, 1984; Wright, 1981). Dispersed lapilli and blocks are graded according to their density relative to the matrix of gas-fluidised fine grained pyroclasts (Sparks, 1976,1978a). Wilson (1980,1984) has identified three flow types as members of a spectrum in which the degree of fluidisation of the particulate flow varies. The behaviour of flows of each type and the characteristics of their deposits were predicted. This approach has been applied to modern ignimbrites which have been mapped in detail (e.g. Wilson and Walker, 1981,1982; Wright and Walker, 1981; Wright, 1981; Walker and Wilson, 1983), and has proven to be capable of elucidating complicated combinations of ignimbrite facies (e.g. the Taupo Ignimbrite, New Zealand, Wilson and Walker, 1981,1982; Walker and Wilson, 1983), and also the textural variations in more typical ignimbrites that conform to the standard flow unit stratigraphy of Sparks *et al.* (1973) and Sparks (1976).

Ignimbrites deposited by effectively fluidised pyroclastic flows (type 3, Wilson, 1980) display segregation structures, in which dense and coarse particles are preferentially concentrated (pipes, lenses, layers), well defined vertical grading of coarser components according to density, and conspicuous enrichment in crystal fragments compared with magmatic proportions. Such ignimbrites are likely to have a well developed fines-depleted facies at their base ('jetted' deposits and ground layer described by Wilson and Walker, 1982) and to occur in association with proximal co-ignimbrite lag breccias, and voluminous fine grained, vitric enriched deposits (co-ignimbrite airfall ash and/or segregation layers; Wilson, 1980; Wilson and Walker, 1982). In some extreme cases, these ignimbrites have clast-supported fabrics (e.g. pumice flow deposits, St Lucia, West Indies; Wright *et al.*, 1984).

In contrast, poorly fluidised, weakly expanded pyroclastic flows (type 1, Wilson, 1980) deposit ignimbrites which are far more homogeneous in texture, both vertically and laterally. Elutriation of fine ash during flow is inhibited, resulting in only slight crystal enrichment and a reduced contribution to co-ignimbrite airfall deposits (Wright, 1981). Basal layers may be missing altogether (Wilson, 1980). Any associated pyroclastic ground surge deposits are likely to be vent-generated and restricted to proximal settings. Ignimbrites deposited by flows of the intermediate case (type 2, Wilson, 1980) show well developed grading but lack segregation structures and loss of fine ash is less extreme than in those deposited by type 3 flows. These ignimbrites have definite basal layers (*cf.* type 1 deposits) commonly overlying a ground layer and pyroclastic ground surge deposits (Wilson, 1980; Druitt and Sparks, 1982; Wilson and Walker, 1982). After emplacement, gas is lost preferentially via vertical segregation structures if these are present (as in deposits from type 3 flows). Degassing of ignimbrites without vertical segregation structures (that is, deposits from type 1 and 2 flows) takes place evenly through the entire thickness.

The experimental studies of fluidisation by Wilson (1980, 1984) have shown that segregation structures and grain size-controlled compositional layering formed at peak gas velocities persist as the gas velocity diminishes. Wilson (1984, p.78, 80) concludes that deposits from parts of a pyroclastic flow that have undergone fluidisation should exhibit such features. Attempts to identify the flow types responsible for ancient ignimbrites are critically dependent on the validity of this conclusion.

Application to the Normal facies ignimbrite

Comparison with the criteria of Wilson (1980, 1984) suggests the Normal facies ignimbrite of the Dundee Rhyodacite was deposited by poorly fluidised type 1 pyroclastic flows. This ignimbrite is overwhelmingly characterised by textural homogeneity so extreme that flow unit boundaries and lateral variations are obscure. Only the lowermost flow unit has a recognisable though rudimentary basal layer, and no segregation structures have been detected. Although the Dundee Rhyodacite is a very crystal-rich ignimbrite (approximately 62 weight percent crystals; Table 8.3) so too are the associated relic pumice fragments (approximately 49 weight percent crystals). The ignimbrite contains about 15 weight percent more crystals (and crystal aggregates) than does relic pumice, giving an enrichment factor (Walker, 1972) of approximately 1.7 (Table 8.3) ranging up to a maximum of only 2.3. These are only modest enrichment factors because values close to 1 indicate negligible crystal enrichment. Ignimbrites tested by Walker (1972) had a minimum average enrichment factor of 4 (for the finest grain size class, 0.25 to 0.5 mm) and those tested by Sparks and Walker (1977) had an average of 3.1 (for grain sizes finer than 2 mm).

TABLE 8.3: Estimates of crystal enrichment factors for the Normal facies of the Dundee Rhyodacite, the Fish Canyon Tuff (Lipman, 1975) and the Snowshoe Mountain Quartz Latite (Ratté and Steven, 1967)

			modal %	weight %	enrichment factor[1]
Dundee Rhyodacite					
Normal facies ignimbrite:	average	crystals	59	62	1.7
		matrix[2]	41	38	
	maximum	crystals	66	69	2.3
		matrix	34	31	
relic pumice fragments:	average	crystals	46	49	
		matrix[3]	54	51	
Fish Canyon Tuff, Colorado					
intracaldera ignimbrite:		crystals	50	53	1.2
		matrix	50	47	
pumice fragment:		crystals	45	48	
		matrix	55	52	
Snowshoe Mountain Quartz Latite, Colorado					
intracaldera ignimbrite:		crystals	52	55	1.6
		matrix	48	45	
pumice fragment:		crystals	40	43	
		matrix	60	57	

[1]Enrichment factor calculation follows Walker (1972, p.137):- (weight ratio crystals: pumice in ignimbrite x weight ratio pumice: crystals in artificially crushed pumice).

[2]Devitrified shards, fine ash and pumice <2 mm. Density 2300 kg/m^3.

[3]Devitrified, formerly vesicular glass, now compacted. Density 2300 kg/m^3.