STRUCTURAL INVESTIGATIONS OF THE
EARLY PALEozoic VICTORIA LAND DIKE SWARM IN THE
FERRAR-KOETTLITZ GLACIER REGION,
SOUTHERN VICTORIA LAND, ANTARCTICA

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by
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CHAPTER I
INTRODUCTION

The Ross orogen developed along the margin of the East Antarctic craton, along the entire length of the present Transantarctic Mountains. The Neoproterozoic to Early Paleozoic Ross orogenic event was characterized by deformation and metamorphism of metasedimentary sequences of the “Ross System” and widespread magmatism with emplacement of granitoids and mafic dike swarms referred to as the “Granite Harbour Intrusive Complex“ by Gunn and Warren (1962). Recent tectonic interpretations regarding the evolution of the Ross orogen invoke compressional to transpressional tectonic regimes along a convergent margin (Allibone et al., 1993b; Goodge et al., 1993; Borg and DePaolo, 1991). A means to test these models lies in the extensive, continuous dike swarm of the region, called here the Victoria Land dike swarm. Reconstruction of the paleostress field(s) present at the time of dike emplacement can be compared with those implied by the proposed models for evolution of the Ross orogen.

The occurrence of mafic dike swarms throughout the Dry Valleys and the Koettlitz Glacier area were documented by the first systematic mapping programs in the region (McKelvey and Webb, 1962; Allen and
Gibson, 1962; Blank et al., 1963; Haskell et al., 1965). Documentation of the regional extent and orientation of Ordovician mafic dike swarm occurrences in this area through compilation of the previous mapping and petrological observations was performed by Janosy (1991). Apart from measurements acquired from around Granite Harbor (Wilson, unpub. 1989), no systematic structural investigations of the Victoria Land dike swarm has been previously undertaken.

**Objectives of Study**

This study concentrated on documenting the distribution and orientation of Ordovician mafic dikes in the Ferrar-Koettlitz Glacier region of southern Victoria Land, specifically to:

1. Construct an accurate map showing the regional extent of the dike swarms. The map is a compilation of published schematic mapping, recently acquired field mapping, and interpretations derived from aerial photographs.

2. Determine whether there are multiple dike sets exhibiting different regional orientations that would indicate separate intrusive events. Different generations of dike emplacement can be identified by dike cross-cutting relations observed in the field or through establishing a correlation between dike composition and orientation.

3. Establish whether the dikes propagated their own fractures or intruded pre-existing ones through systematic field investigations of relations between the dikes and structures present in the surrounding
host rock.

4. Reconstruct the paleostress field history of the area through the use of relative age chronology (i.e. cross-cutting relations) and the trends of the dikes.

5. Relate the paleostress history to proposed models of plate interactions along the margin of the East Antarctic craton.
CHAPTER II
DIKES AS STRUCTURAL AND TECTONIC MARKERS

Structural features

A dike swarm is a concentration of dikes thought to have been emplaced during the same igneous episode and typically consisting of a subparallel to fanning array of multitudes of individual dikes. Where dikes occur in parallel arrays, emplacement was controlled by the regional tectonic stress field within the continental crust (Delaney et al., 1986), and the dike swarm records the orientation of extensional strains in deforming continental lithosphere. In cases where dike swarms extend for hundreds or thousands of kilometers, the stress field patterns derived from the dikes are inferred to reflect the interactions of tectonic plates.

Dikes represent tensile hydrofractures propagated by intruding magma at the fracture tip where extensional stresses are the greatest and where tensile fractures originate (Anderson, 1951). Dikes are emplaced in an orientation normal to the least compressive stresses and parallel to the plane containing the maximum and intermediate compressive stresses (Anderson, 1951; Delaney and Pollard, 1981) (Figure 2.1). The regional paleostress regime that existed at the time of dike emplacement can therefore be reconstructed from dike trends. Dikes are useful paleostress
Figure 2.1 a: Dike propagation as a tensile hydraulic fracture (from Anderson, 1951). b: Orientation of dikes perpendicular to the least compressive stress direction; the dike plane contains the maximum and intermediate principal stresses (from Delaney and Pollard, 1981).
indicators only if they generated their own fractures and didn't invade crustal zones of weakness such as pre-existing faults and joints.

Therefore, understanding field relations are important in establishing the mode of dike emplacement. Delaney et al. (1986) described factors such as orientations, spacing, and dimensions of regional joint sets relative to dike margins that could be used as criteria to establish whether dikes utilized the preexisting joints or generated their own fractures. Delaney et al. (1986) described three scales of joint occurrences based on the horizontal distance from a dike margin over which they are developed. Adjacent joints are present within 100 m of the dike margin, or usually less than 1% of the dike's outcrop length. Local joints are present within 3 km, or distances similar to dike lengths, and joint sets extending more than 3 km from a dike margin are referred to as regional joints. The presence or absence of these types of joints in the host rock can indicate the mode of dike emplacement. In cases where both regional and adjacent dike-parallel joints are absent, dike emplacement probably resulted from a self-generated fracture. If dike-parallel regional joints are lacking but adjacent dike-parallel joints are present, closer observations are required to determine relative ages. If the joints cut the dike, the dike is older or synchronous with joint formation. If the joints terminate against the dike margin, the dike intruded after joint formation. Other indications of dike emplacement into older adjacent dike-parallel fractures include dike tips (horns) splaying obliquely where a dike propagated beyond the end of a joint and curved to attain an orientation parallel to a principal stress
plane.

Delaney et al. (1986) note that if dikes have different strikes and are the same age, they were either 1) indifferent to propagating perpendicular to the direction of least compressive stress and were therefore controlled by pre-existing fracture trends or 2) experienced heterogeneous stresses. Dikes exhibiting scattered orientations are thus poor indicators of paleostress direction. Dikes with similar strikes occur either because of a shared common tectonic element such as planes of weakness, or because they formed as magma-induced fractures oriented normal to the least compressive stress direction.

Propagation paths and fracture mechanics of dikes can change during emplacement if there is a shift in the orientation of the least compressive stress. Pollard (1987) identified three modes of fracture associated with stress-controlled dike paths (Figure 2.2). A Pure mode I fracture involves an ideal dike path in which fractures are induced by a homogeneous stress state with the least compressive stress acting normal to the dike plane. Dikes will be simple planar sheets. When the least compressive stress changes orientation through rotation about an axis parallel to the dike periphery, a mixed mode I, II fracture is produced. If propagation and loading of the mixed mode I, II model is continuous and gradual, the dike tip will follow a smooth curved path. The third model, the mixed mode I, III fracture involves fracturing where rotation of the least compressive stress occurs about an axis parallel to the dike's propagation direction. The net effect is a series of segments which
Figure 2.2 Propagation paths for dikes related to the change in orientation of the least compressive stress. **A:** Mode I fracture is induced by a least compressive stress acting perpendicular to the dike plane and produces a planar dike. **B:** Mixed mode I and II fracture is induced by a spatial rotation of the least compressive stress about an axis parallel to the dike periphery. This produces a curved dike. **C:** Mixed mode I and III fracture is induced by a spatial rotation of the least compressive stress about an axis parallel to the propagation direction. This produces a segmented dike. (from Pollard in Halls (ed), 1987, fig.13).
individually propagate out from dike tips and twist to reorient normal to the local least compressive stress. The plan view of these oblique fractures exhibits an en echelon arrangement (providing stress reorganization is smooth and continuous) (Figure 2.3).

Dike segments typically exhibit a variety of features characteristic of this mode of emplacement (Figure 2.4). Segment ends with blunt terminations probably reflect dike emplacement along pre-existing fractures in which an instantaneous decrease in the stress intensity factor occurred at the tip of the dike (Baer et al., 1990). Segment ends exhibiting overlapping, tapering tips are described as horns by Rickwood (1990) and are indicative of magma propagating its own hydraulic fracture and exerting pressure greater than the normal component of the regional stresses acting along the fracture plane (Delaney et al. 1986). The intervening host rock material between two overlapping dike horns is referred to as a bridge. When en echelon segments propagate along curved paths, the overlapping merging horns may link with the plane of the opposing segment, isolating bridge material within the newly connected dike (Figure 2.4a). Dike propagation of en echelon segments along a straight path and subsequent linkage can sometimes result in preservation of bridge material within the dike after dilation and cooling (Figure 2.4a). The linked portion of two, displaced segments by dike rock material over a distance greater than the segment width is termed a connector (Rickwood, 1990). Horns are commonly preserved after linkage occurs and they serve as indicators of two past en echelon segments.
Figure 2.3 Explanation of en-echelon dikes by the filling of oblique fractures. **A**: Plan view of en-echelon dikes: $\vec{d}_s =$ dike strike; $ss =$ segment strike  **B**: How the en-echelon dikes may be related to a single intrusion plane at depth (after Park, 1989, fig. 11.4).
Figure 2.4 Hypothetical sketch of linkage structures formed at en echelon dike terminations (a), and showing the persistence of various features along the flow directions (b) (from Delaney & Pollard, 1981: figure 11B and Plate 1 - segment 12 in Rickwood, 1990). (c) Drag folds, scour marks, fingers, and steps (after Pollard et al., 1975: figure 13B and Baer & Reches, 1987: figure 2 in Rickwood, 1990). Diagrammatic and not to scale.
During dilation of a dike, local thickening at the margins can produce elliptical buds. Delaney (1987) attributed the formation of buds to the stoping of wallrock and then subsequent magma flow in a neck widened by the dike.

As tensile stresses generate fracture openings, intruding magma will continue to enlarge the fracture through dilation. It has been commonly assumed that dilation occurs in a horizontal direction perpendicular to the trend of the dike. In addition, where primary field evidence of oblique dilation is observed, a common assumption is that the offset resulted from a horizontal shear component. Bussell (1989) describes the use of simple geometric techniques to accurately determine the true dilation direction of dikes. Where the dike walls step laterally, the two offset dike walls will form an offset plane with two offset (step) edges (Figures 2.4, 2.5a). If the trend and plunge of the offset edges can be measured in the field along with the azimuth of the line joining the offset edges, then the plane containing the dilation direction can be constructed through stereographic projection. The dilation plane will be represented by a great circle which contains the net dilation direction (Bussell, 1989). When two pairs of matching offsets from the same dike are present in the field, the actual dilation direction is defined by the intersection of both dilation planes (Figure 2.5b). Dilation directions can only be determined if the dike walls have been preserved during emplacement (Bussell, 1989). Misleading dike offsets can originate from pinch and swell structures and boudins in the dike, faulting of the dike, and from angular blocks formed
Figure 2.5  a: Sketch showing the intersection of a dike wall with an offset plane to form an offset edge; b: Diagram showing geometry of a dike wall with two offsets that intersect to form offset corners (from Bussell, 1989, fig 3 and 5 resp.).
by stoping. Dike offsets formed by the linkage of en echelon structures can also create a misleading pair of offsets when bridge material is subject to breakage and removal.

Dike propagation paths can be determined by using other dike characteristics as indicators. Rickwood (1990) described various dike features as possible criteria for obtaining a generalized magma flow direction following the assumption by Baer et al. (1987) that the direction of initial flow represents the direction of dike propagation. Useful external features include dike width, fingers, forks, branching, and the style of drag folds (Figure 2.4). Dike width usually decreases away from the magma source (Smith, 1987). Finger intrusions are features that occur on the dike margin and extend out in the flow direction. The sense in which the fingers terminate records the magma flow direction (Baer et al., 1987). A dike tip terminating into two horns is described as a fork, and only records a component of flow away from a magma source and not the true flow direction. Dike branchings are similar to forks in recording only a general flow direction. Dikes exhibiting rejoining branches are useless as indicators of flow direction. Drag folds present along dike margins form during movement of partially cooled magma near the walls and the fold closures parallel the flow direction.

Internal structural features thought to have been formed as a result of magma movement and multiple phases of injection include bent columns, secondary shear planes, and ramping structures. The orientation of these features with respect to the dike margin are indicators
of flow direction. The orientation of phenocrysts, tapered particles, xenoliths, and vesicles near dike margins can also determine the sense of magma movement.

Trend and plunge measurements can be obtained from linear morphological features such as flow lines, scour marks, segment ends, horn edges, cusp edges and connector edges, but determination of flow directions from these features can be ambiguous since there is no way of telling whether the intruding magma that produced them originated up or down plunge (Rickwood, 1990). Some initial assumptions would have to be made for use of these features as indicators of flow direction.

**Tectonic Settings of Dike Swarms**

Dike formation occurs in regional stress regimes most commonly associated with extensional tectonic settings such as rifts. Fahrig (1987) described three stages comprising a complete tectonic cycle of continental dike swarm development: 1) dike intrusion during continental rifting, 2) onset of ocean-floor spreading, and 3) closure of the ocean basin and continental collision (Figure 2.6). Tensional forces acting on continental lithosphere will cause it to thin, creating a three-armed pattern of rifting, volcanism, and dike intrusion known as a triple junction. At the onset of subsequent ocean-floor spreading, two of three rift arms will evolve into passive margins bordering the ocean basin. If uplift occurs along the passive margin, the dikes may be subjected to removal by erosion. The third failed arm, or aulacogen, becomes inactive and volcanism ceases.
Figure 2.6 Three-stage plate tectonic cycle in the development of mafic continental dike swarms (from Fahrig in Halls (ed), 1987, fig. 1).
The closure of an ocean basin and ensuing collision typically deforms the passive margin dikes. However, remanent aulacogen dikes of the ancient rift system remain intact and extend deep into the continental interior.

The dike swarms of the latest Paleozoic-Mesozoic Karroo rift system in southern Africa represent the end of Fahrig's stage 1 rifting/dike intrusion and spreading of stage 2. The dikes parallel the arms of the Lower Zambezi - Lower Limpopo triple junction in which the north-south trending dikes represent the passive margin dikes and the east-west trending dikes reflect a remanent aulacogen which extends into the continental interior (Figure 2.7).

The Mackenzie dike swarm of the northern Canadian Shield is the largest in the world and encompasses an area of $2.7 \times 10^6$ km$^2$. They are 1.2 Ga old and represent an aulacogen of a rift triple junction system associated with the spreading of the Poseidon Ocean (Jackson & Iannili, 1981). The dikes form a gigantic fan southward, and are truncated to the north along the Arctic coastline (Figure 2.8). Ancient rift-controlled basins containing volcanic rocks and overlying sedimentary sequences flank the Arctic focal point. The Sudbury dikes of the Great Lakes region are similar in age to the Mackenzie Dike Swarm (Fahrig, 1987). They share the same trend as the Mackenzie swarm but are very different in composition; the Sudbury dikes are undersaturated olivine tholeiites, whereas the Mackenzie dikes are generally quartz normative (Gibson et al., 1987). The Sudbury dike swarm, concentrated east of Lake Superior, also marks a remanent aulacogen of an ancient spreading center which
Figure 2.7 Basic dike swarms of Karroo (Jurassic) age emplaced parallel to triple junction boundaries near the downwarped rifted continental margin of southeast Africa (compiled from Vail, 1970; Burke and Dewey, 1973a; Reeves, 1978) (from Windley, 1984 fig. 16.7).
Figure 2.8 The MacKenzie Dike Swarm of the northern Canadian Shield represents an aulacogen of a rift triple junction system associated with the spreading of the Poseidon Ocean (Jackson & Iannili, 1981). The dikes form a gigantic fan southward towards the Sudbury Dike Swarm (from Fahrig in Halls (ed), 1987, fig. 2).
formed the Sudbury Ocean (Figure 2.8).

Evidence of a large-scale rifting event is represented by the Mesozoic dike swarms in eastern North America. McHone et al. (1987) recognized a suite of dikes known as the Eastern North American Dolerite Province (ENA) that records the rifting of the North Atlantic Ocean. The ENA province extends throughout the entire eastern Appalachian region from Alabama to southern New England. Dike trend and distribution changes reflect differential stress states related to the Jurassic breakup of Gondwana and the formation of the North Atlantic Ocean basin (McHone, 1992). From the southern Appalachians to the Carolinas, dikes trend northwest; from the Carolinas to Pennsylvania, trends overlap and change to a north-south orientation; from New Jersey into New England and the Atlantic Province of Canada, dike trends are northeast (Figure 2.9) (McHone et al., 1987). The Early Jurassic ENA dikes are quartz and olivine tholeiitic dolerites and precursors of the developing mid-ocean ridge basalts of the initial Atlantic Ocean crust. The three different dike trends of the ENA province and the trends of Early Jurassic dikes in Africa and South America closely parallel three rifting directions that opened the proto Atlantic Ocean basin (Figure 2.10).

Dike swarms also record paleostress directions in foreland regions of continent-continent collision belts. Analysis of intraplate deformation shows the close relationship between compression and distension in a regionally compressive setting (Feraud et al., 1987). Feraud et al. (1987) described areas in the European and northwest Arabian plate margins
Figure 2.9 General locations and province boundaries of the Mesozoic dike swarm in eastern North America. Heavy lines are province boundaries, dashed where inferred; ENA = Eastern North America dolerite province; NDB = Notre Dame Bay province; CNE = Coastal New England province; NEQ = New England-Quebec province. Rose diagrams constructed from dike trends throughout the region (from McHone et al. in Halls (ed), 1987, fig. 1).
Figure 2.10 General locations and trends of Early Jurassic dolerite dikes around the initial central Atlantic Ocean basin (from McHone et al. in Halls (ed), 1987, fig. 2).
where Cenozoic dike swarms document paleostress fields adjacent to collisional belt systems. In southern France, a compressional stress field resulted from the formation of the occidental Alpine arc and north-northwest motions of the converging European and African plates (Feraud et al., 1987). Dike formation in the western, foreland region of the Alpine arc is approximately normal to the collision zone and trends parallel to the direction of the maximum horizontal paleostress field that existed at the time of emplacement. Similarly, Cenozoic dike swarms in northwest Arabia resulted from volcanic-injected tensional gashes produced during the Arabian/Indo-European plate collision (Feraud et al., 1987). Extension is generated in response to lateral escape of lithosphere away from the northward advancing Arabian plate. If tensional stresses exceed horizontal compressive stresses, grabens may form in foreland regions of collisional systems. Figure 2.11 compares synchronous tectonic events and the development of dikes in response to compressive stresses for northwest Arabia. The Levantine rift zone in northwest Arabia is marked by tension-induced grabens where northeast-southwest tensile stresses opened the pre-existing Levantine Fault. A similar tectonic setting is present in Europe where development of the Rhine Graben initiated from compressional deformation of the Alps during Eocene-Oligocene time. Rifting continued in the foreland region during most of the Tertiary as Alpine compressional deformation continued.
Figure 2.11 Orientation of the paleostress fields in the NW portion of the Arabian plate determined from the orientation of dated dike swarms. Legend: 1, Basaltic formations; 2, dike and volcanic-cone alignment directions; 3, normal faults; 4, strike-slip faults; 5, folds; 6, lines of potential strike-slip motion. A. Miocene period (20 to 5 Ma); B. Plio-Quaternary period (5 to 0 Ma) (from Feraud et al., 1987).
Regional extension can also occur in the overriding plate at convergent plate margins. Back-arc regions of subduction zones experience extensional strain which produces normal faulting (Nakamura and Uyeda, 1980) (Figure 2.12). The northern Basin and Range of the western United States represents a back-arc extensional province characterized by the intrusion of dike swarms associated with magmatism of the Columbia Plateau basalt province (Hooper and Camp, 1981; Church, 1985). In these back-arc settings, extension is oriented close to normal to, and dike swarms trend parallel to, the convergent plate margin.
Figure 2.12 Orientation of the paleostress fields for various regions along a shallow subduction margin. Regional extension can occur in the back-arc regions where tensional stresses will produce normal faulting (after Nakamura and Uyeda, 1980).
CHAPTER III
THE VICTORIA LAND DIKE SWARM

Introduction

The presence of numerous mafic and felsic dikes in southern Victoria Land was noted in all the early geological investigations and mapping of the region (Prior, 1907; Mawson, 1916; Smith, 1924; McKelvey and Webb, 1962; Allen and Gibson, 1962; Blank et al., 1963; Haskell et al., 1965). The dikes extend at least 600 km from Terra Nova Bay southward to the Brown Hills area near Byrd Glacier, but are heavily concentrated and best known within a region about 165 km along strike in the McMurdo Sound area (Figures 3.1a, 3.2). Since the dikes all have similar trends and cut undeformed, post-tectonic granitoids of the Granite Harbor Intrusive Complex, they are considered to be a continuous dike swarm. This extensive dike swarm, called here the Victoria Land dike swarm, constitutes a major petro-tectonic element of the region. The tectonic setting and geology of the dike swarm as known from work prior to this study are described in the following sections.
Figure 3.1  a. Location map for Transantarctic Mountains. CP = Cotton Plateau, CR = Cobham Range, GR = Geologists Range, MG = Marsh Glacier, MR = Miller Range.  b. Principal lithotectonic divisions of the Ross orogen in the Transantarctic Mountains.  c. Shading indicates outcrop areas of plutonic rocks of the Ross orogen with ± 500 Ma cooling ages. Terrane boundaries are indicated for northern Victoria Land. Black indicates Devonian plutonic rocks in northern Victoria Land (after Stump, 1992).
Figure 3.2 Compilation of mafic dike occurrences in the McMurdo Sound region of the Transantarctic Mountains illustrating dominant northeast trends; from McKelvey and Webb (1962), Blank et al. (1963), and Wilson from Granite Harbor (unpublished, 1989). Heavy dashed lines = 'Kukri Peneplain' unconformity at the base of the Beacon Supergroup (shown by stippled pattern). Dikes shown as short heavy lines. Inset box is study area (see Plate I).
Regional Tectonic Setting

The Transantarctic Mountain range extends approximately 5000 km across the Antarctic continent from northern Victoria Land to the Weddell Sea (Figures 3.3, 3.1). It consists of a Precambrian to Ordovician metasedimentary and igneous basement complex overlain unconformably by relatively flat-lying Devonian to Jurassic sedimentary rocks of the Beacon Supergroup. The varied igneous rock types of the basement complex, consisting of granitoids and mafic dike swarms, were named the 'Granite Harbour Intrusive Complex' by Gunn and Warren (1962). Uplift and erosion of the basement complex resulted in formation of the Kukri Peneplain unconformity surface. Subsequent subsidence and deposition of sedimentary strata of the Beacon Supergroup followed. Thick and extensive Jurassic dolerite bodies (Ferrar Dolerite) intrude the basement complex and Beacon Supergroup strata. Uplift of the present mountain range is related to rifting in the Mesozoic and Cenozoic.

The Ross orogen developed along the margin of the East Antarctic craton in the Proterozoic and early Paleozoic and is exposed along the length of the Transantarctic Mountains. The Ross orogeny was characterized by deformation and metamorphism of metasedimentary sequences of the 'Ross System' (Figure 3.1). Coeval magmatism is mainly represented by granitoids of the basement complex, defined by Gunn and Warren (1962) as the 'Granite Harbour Intrusive Complex,' that are continuous along the length of the Transantarctic Mountains (Figure 3.1). The number and timing of Ross deformational events have yet to be fully
Figure 3.3 Map of Antarctica showing the extent of the Transantarctic Mountains from northern Victoria Land to the Weddell Sea and distribution of Lower Paleozoic rocks (from Laird in Holland (ed), 1981, fig. 1).
constrained. Recent work from the Pensacola and Central Transantarctic Mountain regions of the Ross orogen suggest that there may be at least two episodes of Ross deformation; one during the latest Early Cambrian-early Middle Cambrian and the other during the Late Cambrian-Early Ordovician (Goodge et al., 1992; Rowell et al., 1992). In southern Victoria Land, the metasedimentary rocks of the Skelton and Koettlitz Groups are strongly deformed and metamorphosed and correlation with the Ross Supergroup sequences is difficult and ambiguous. Recent work in the Dry Valleys region has constrained the timing of post-tectonic granitoid emplacement at around 500 Ma (Allibone et al., 1993a; Allibone et al., 1993b; Cox, 1993). In the Skelton Glacier area (Figure 3.4), Rowell et al. (1993) constrained the age of deformation of the Skelton Group metasediments and a post-tectonic granitoid as Neoproterozoic. The post-tectonic quartz syenite granitoid yielded a date of 551 ± 4 Ma (Rowell et al., 1993).

Recent tectonic interpretations for the evolution of the Ross orogen along the Early Paleozoic Antarctic margin suggest compressional to transpressional tectonic processes in a convergent setting.

Accretion of allochthonous terranes along an obliquely convergent East Antarctic margin is evident in northern Victoria Land. Evidence supporting the accretion of the Bowers and Robertson Bay terranes to the margin during or after the late stages of the Ross orogeny includes thrust transport on faults thought to mark the terrane boundaries (Stump, 1992; Bradshaw et al., 1985; Gibson and Wright, 1985). However, isotopic and
Figure 3.4 Geological/locality sketch map for southern Victoria Land from Mackay Glacier to Byrd Glacier. Black areas are basement metasedimentary and granitic rocks, and stippled areas are Beacon Supergroup. GH = Granite Harbor, BH = Brown Hills.
geochemical evidence argues that the outboard terranes were first sutured together around Middle Ordovician time before accretion to the East Antarctic margin during Late Devonian time (Figure 3.5) (Borg and DePaolo, 1991).

Recent work in the Central Transantarctic Mountains (CTM) suggests that Ross deformation was characterized by a compressional to transpressional tectonic regime (Rowell and Rees, 1989; Borg et al., 1990; Goodge et al., 1991; Rowell et al., 1992; Stump, 1992; Goodge et al., 1993). Deformation of the Neoproterozoic to Lower Paleozoic supracrustal rocks of the CTM due to orogen-parallel translation along a broadly contracting convergent margin is indicated by Nimrod tectonism (Goodge et al., 1993). Recent evidence from this area of the Central Transantarctic Mountains suggests a temporal overlap of Nimrod tectonism and Ross deformation (Figure 3.6) (Goodge et al., 1993). Deformation associated with the Ross orogeny in the Nimrod Glacier area (Figure 3.1) is traditionally constrained to post-date deposition of the Lower Cambrian Shackleton Limestone and pre-date emplacement of the Lower Ordovician Hope Granite suite (which may be correlated with the Granite Harbor Intrusive Complex of Victoria Land). However, pervasive tectonite fabrics observed in concordant plutonic and schistose rocks of the Nimrod Group is believed to have resulted from top-to-the-southeast ductile shearing between 520 and 540 Ma (Goodge and Dallmeyer, 1992). Also, 40Ar/39Ar cooling ages of mica and amphiboles from these rocks are synchronous with 500 Ma granite emplacement associated with the Ross orogeny.
Figure 3.5  Tectonic development of terranes of SEA (southeastern Australia) and NVL (northern Victoria Land) allochthonous to pre-Devonian Gondwana. An inferred fault boundary between the Robertson Bay and Surgeon Island Terranes is labelled f in the sketch. S- and I-type granites are indicated in (C) and (D) (from Borg and DePaolo, 1991).
Figure 3.6 Time line showing correlation of geochronometrically and biostratigraphically dated tectonic events in Nimrod Glacier area. Ages are in Ma. All U-Pb data are after Goodge et al. (1993), except those from undeformed Hope plutons; Sketches above time line show relation of fabrics in plutonic and schistose rocks (S = foliation; L = elongation lineation). Relative age of pre-540 Ma ductile deformation is inferred from geologic relations (from Goodge et al., 1993).
(Goodge and Dallmeyer, 1992). The temporal overlap of these distinct
deformational events requires a tectonic regime that could accommodate
both deep-crustal level translation associated with shearing of the Nimrod
Group and shallow-level contraction associated with the orogen-normal
shortening of the Neoproterozoic to Middle Cambrian supracrustal rocks.
A suggested tectonic model for this particular area of the Transantarctic
Mountains that may explain these deformation patterns is orogen-parallel
translation along an obliquely convergent margin (Goodge et al., 1993).

In the Beardmore Glacier region of the Central Transantarctic
Mountains (Figure 3.1), evidence of a transpressive tectonic regime is
represented by deformation associated with the Beardmore orogeny. Rb-
Sr ages from the Darwin granite of 568 ± 10 Ma indicates the development
of a compressive margin between 600 - 560 Ma (Borg and DePaolo, 1991).
Accretion of an outboard terrane, called the Beardmore Microcontinent,
by 570 Ma resulted in eastward folding and thrusting of the Argosy,
Cobham, and Cotton-Plateau-type Goldie formations (Borg and DePaolo,
1991; Borg et al., 1990). Deposition of passive margin shelf carbonates
along the Gondwana Austral-Antarctic margin followed from ~ 570 Ma
until calc-alkaline volcanism marked the onset of the Ross and
Delamerian orogenies and subduction in a new convergent tectonic
regime in the Late Cambrian (Borg and DePaolo, 1991). In the Central
Transantarctic Mountains, these carbonate rocks are part of the Byrd
Group, in northern Victoria Land they are correlated with the Wilson
Group, and in southeast Australia, they are represented by the Adelaide
Supergroup, Kanmantoo Group, and the Glenelg River Complex (Stump et al., 1986); (Borg and DePaolo, 1991). These Middle to Late Cambrian rocks were folded during the Ross/Delamerian deformation and later intruded all along the Austral-Antarctic margin by the 500 Ma granitic plutons.

Accretion of allochthonous terranes through strike-slip translation (of several hundred kilometers) has also been postulated for development of the central Transantarctic Mountains portion of the East Antarctic margin (Rowell and Rees, 1989). Evidence of juxtaposition of a Middle and Upper Cambrian volcanic-rich outboard terrane against a Lower Cambrian carbonate inner terrane (with unconformably overlying clastics) support this model (Figure 3.7). The time of emplacement of the outboard terrane is restricted to after deposition of the Lower Paleozoic Shackleton Limestone and prior to deposition of basal Devonian beds of the Beacon Supergroup. Age uncertainty, and problems understanding volcanic emplacement and facies patterns of the Lower Cambrian rocks, however, creates a need for further investigation of this proposed model.

Geochemistry and isotopic dating of post-tectonic granitoids from the Dry Valleys region of southern Victoria Land indicate changes in the nature of granitoid plutonism. The distinction of three granitoid suites, Dry Valleys DV1a, DV1b, and DV2 (Allibone et al., 1993b, Smillie, 1992) and relative timing of emplacement, reflect changes in tectonic processes along the East Antarctic margin from the Late Proterozoic to the Early Ordovician (Figure 3.8). The first episode of plutonism, DV1a, emplaced
Figure 3.7 Principal terranes of the central and western Transantarctic Mountains. Terrane boundaries shown by heavy broken line. Inboard sequence ornamented by horizontal lines; outboard terrane, which is probably composite, ornamented by vertical lines. Principal characteristics of Middle and Upper Cambrian rocks emphasized (from Rowell and Rees, 1989).
Figure 3.8 The inferred relative timing of emplacement of the various plutons, dike swarms, and granitoid suites of the Dry Valleys area of southern Victoria Land. Emplacement of the DV1a and DV1b suites overlaps with the later stages of deformation and migmatite development in the Koetlitz Group. Emplacement of the DV2 suite postdates emplacement of the DV1a and DV1b suites, and the majority of the Vanda Dikes (from Allibone et al., 1993b).
Cordilleran I-type granitoids along a subduction margin before 500 Ma. Within 10 Ma at 490 ± 14 Ma, a short plutonic event, DV1b, involved intrusion of a granitoid suite that may represent magma derived from melted, underplated marginal metasediments (Allibone et al., 1993a; Allibone et al., 1993b). The cessation of subduction after the first episode of plutonism may coincide with strike-slip accretion of the Bowers terrane around 500 Ma in northern Victoria Land as proposed by Bradshaw et al. (1985) (Allibone et al., 1993a). This accretionary event may have also initiated the second pulse of granitoid emplacement around 490 ± 14 Ma, but is highly speculative (Allibone et al., 1993a). Borg and DePaolo (1991) however, put final emplacement of the allochthonous Bowers and Robertson Bay terranes against the Antarctic Gondwana margin during the Late Devonian (~360 Ma). The third episode of plutonism, DV2, marks the change from compressional tectonism to an extensional setting marked by the emplacement of the Victoria Land dike swarm around 490-486 Ma and then younger Caledonian I-type granitoids at 486-455 Ma (Allibone et al., 1993a). The Caledonian I-type granitoids are considered as post-tectonic intrusions that form in extensional tectonic settings because of their discordant nature and alkali-calcic compositions.

Previous work

Dike Distribution

Mafic and felsic dike occurrences in the McMurdo Sound region of southern Victoria Land were mapped during geological investigations of
the area by McKelvey and Webb (1962), Blank et al. (1963), and Wilson from Granite Harbor (unpublished, 1989) and are compiled on Figure 3.2 (Janosy, 1991). Note the apparent gap in dike occurrences from the northern part of the Ferrar-Koettlitz Glacier area where no previous work has been reported. Systematic mapping of dike distribution and orientation in the Ferrar-Koettlitz region (area inscribed on Figure 3.2) was carried out as part of this study and is presented in detail on Plate I (Appendix A). Descriptions of dike distribution within the study area are presented in detail in Chapter V of this report.

A dense concentration of northeast trending lamprophyres and porphyries near Lake Vanda (Figure 3.9) was cited as the type locality for McKelvey and Webb's (1962) "Vanda Lamprophyres and Porphyry," the early general term for the mafic dike suite in the Dry Valleys region. During other investigations in Wright Valley, McKelvey and Webb (1965) introduced the term "Loke Microdiorite" to describe the dense swarm of low-angle southwest-dipping dikes at Mt. Loke. Later, more detailed descriptions of the Wright Valley dikes were also done by Vennum (1990) and Keiller (1991). Lamprophyre dike swarms in the Asgard Range and Kukri Hills of the Taylor Valley were reported by Haskell and others (1965) and Vennum (1990). Occurrences in the St. Johns Range near Victoria Valley were described by Palmer and White (1986), Vennum (1990), and Waters (1993) and various outcrops north of the St. Johns Range by Gunn and Warren (1962). In the Granite Harbor-Mackay Glacier region, dikes were reported by Gunn and Warren (1962) and measured by Wilson (pers.
Figure 3.9 Geological/locality sketch map of the Dry Valleys region and study area (inscribed) of southern Victoria Land. JR = St. Johns Range; LV = Lake Vanda; BP = east of Bettie Peak; BH = Briggs Hill; SH = Stratton Hills; GK = Granite Knolls; MB = mouth of Blue Glacier; LG = ridge north of Lister Glacier; GV = north of Garwood Valley; SL = Shangri-la; MR = Marshall Ridge; HP = Holiday Peak; HV = Hidden Valley area; WG = north of Walcott Glacier; RR = Rucker Ridge; PL = ridge east of Penny Lake (after Findlay et al., 1984).
comm., 1989). The northernmost occurrences of mafic dikes around Terra Nova Bay were reported by Skinner and Ricker (1968). They were described as lamprophyres and mapped trending mostly northeast with a few dikes trending east-west and northwest. To the south of the Dry Valleys in the Ferrar-Koettlitz Glacier area, biotite and hornblende lamprophyres were described by Blank and others (1963) and Wu and Berg (1992). In the Skelton Glacier region (Figure 3.4), dikes are also mentioned by Gunn and Warren (1962) and Skinner (1982) but not described. Our reconnaissance of the Skelton exposures revealed a few dikes in only one locality. The southernmost dike occurrences were reported north of the Byrd Glacier in the Brown Hills area (Figure 3.4) and described as lamprophyres and meladiorite dikes (Haskell et al., 1965).

Dike Petrology

Dikes of pre-Beacon age described as lamprophyres, microlamprophyres, absarokites, shoshonites, banakites, diorites, microdiorites, monzodiorites, granodiorites, porphyries, granites, leucogranites, microgranites, acidic aplites, and pegmatites occur throughout the Transantarctic Mountains in southern Victoria Land. During early investigations, dike classification was mainly based on petrography and nomenclature became inconsistent due to different classification schemes, difficulty in distinguishing gradational dike types petrographically, and widespread alteration of the dikes.
Within their "Granite Harbour Intrusive Complex," Gunn and Warren (1962) reported occurrences of the following dikes between the Blue Glacier and Granite Harbor in order of increasing age: basaltic and doleritic dikes related to the Jurassic-age Ferrar Dolerites, lamprophyre dikes including camptonites, kersantites, and an augite-bearing vogesite, microgranite dikes found near plutons of the Irizar Granite, and medium to fine-grained quartzо-feldspathic dikes.

Early work by McKelvey and Webb (1962) recognized the "Vanda Lamprophyre and Porphyry" dikes at their type locality east of Lake Vanda in the Wright Valley (Figure 3.9). They described two types of lamprophyres and acid porphyries. Also described by McKelvey and Webb were the "Loke Microdiorite" dike swarms (biotite and hornblende dominated) at Mt. Loke. Allen and Gibson (1962) used the "Vanda Lamprophyre and Porphyry" nomenclature proposed by McKelvey and Webb (1962) to describe the extensive dike swarms in the Victoria Valley region. Vanda Lamprophyres are dark aphanitic dikes composed of zoned plagioclase, hornblende, chlorite, quartz, and iron oxide. Vanda Porphyry dikes contain conspicuous orthoclase and some quartz phenocrysts in a fine-grained groundmass. Murphy (1972) describes four dike suites in order of decreasing age which crop out in places on the south wall of Wright Valley: the Theseus Granodiorite, microdiorites, the Vanda Porphyry, and lamprophyres.
Haskell et al. (1965) described augite-biotite lamprophyres and hornblende lamprophyres as the most abundant dikes in areas of the Kukri Hills and Lower Taylor Valley. Augite-biotite lamprophyres were noted as being grey to black, strongly porphyritic, and slightly deformed. Hornblende lamprophyres, the youngest of the mafic dikes, were described as dark-grey to black, aphanitic, and dominated by phenocrysts of brown hornblende. Other basic to intermediate dike rocks noted were relatively rare, strongly porphyritic mesocratic porphyries, tremolite/actinolite diorite dikes. Microgranite dikes, including a porphyritic type, were also observed.

Additional petrographic descriptions of dikes from the Taylor Valley were made by Manzoni and Nanni (1977), who described dike samples as homogeneous with a microporphryritic seriate texture consisting of subequal amounts of zoned euhedral plagioclase and elongate amphibole phenocrysts.

In the Koettlitz - Blue Glacier region Blank et al. (1963) also noted occurrences of biotite lamprophyres (subschiebose to schistose, strongly deformed and containing andesine, augite and hornblende), abundant hornblende lamprophyres, porphyries, acidic aplites (less common) and coarse to fine grained pegmatites.

Geochemical studies were also performed on the dikes. Vennum (1990), collected mafic dike samples from five localities throughout the Dry Valleys. Geochemical studies concluded that the Dry Valleys mafic dike swarm crystallized from a volatile poor, silicon-oxide enriched
calc-alkaline lamprophyre magma and does not contain euhedral mafic phenocrysts, an essential component of lamprophyres. The mafic dikes are best referred to as “microlamprophyres” (Vennen, 1990).

An intensive geochemical study of both the Mount Loke and Lake Vanda dike swarms of Wright Valley by Keiller (1991) identified three distinct suites of high-K calc-alkaline to shoshonitic affinity. The first suite, characteristic of the Mount Loke region, is a high-K calc-alkaline hornblende-biotite diorite variety and represents the earliest non-deformed dike intrusives of Wright Valley. Dikes from the Lake Vanda region comprise the second suite characterized by high-K calc-alkaline monzodiorite, granodiorite, granite, and leucogranite affinities. Only the monzodiorite dikes are unique to the Lake Vanda area while the others are common throughout the Wright Valley. The third suite is represented by absarokite, shoshonite, banakite, granodiorite, granite and leucogranite dikes and contains a higher K₂O content than the other suites (Keiller, 1991). The absarokite, shoshonite, and banakite varieties occur only in the Mount Loke region while the remaining dikes are mostly present in the Lake Vanda area. The shoshonite and banakite dikes are the most numerous and youngest in Wright Valley and represent the dikes described as lamprophyres by McKelvey and Webb (1962) and Haskell and others (1965). These previous authors incorrectly applied the name ‘lamprophyre’ to a dike suite containing feldspar phenocrysts although nomenclature may have been based on a different classification scheme.
Waters (1993), described the dike swarm within the St. Johns Range (Figure 3.9), and concluded that the mafic dikes were of the same high-K calc-alkaline and shoshonite varieties described by Keiller (1991). The felsic dikes of the same area contain more phenocrysts than in the mafic dikes. Hornblende phenocrysts are up to 4 mm, quartz phenocrysts up to 6 mm, and the feldspar is predominately alkali feldspar with rare plagioclase. These dikes represent the youngest in the Dry Valleys region based on ages and cross-cutting relations. Waters (1993) also considers these dikes to be part of the same swarm described by Keiller (1991). Based on geochemical character, Keiller (1991), proposed that dike intrusion in the greater Dry Valleys region occurred in a post-collisional extensional setting associated with incipient back-arc spreading at the end of the Ross orogeny.

A geochemical study of the lamprophyre dikes from the Dry Valleys to the Koettlitz Glacier area of the Royal Society Range was performed by Wu and Berg (1992). Around Koettlitz Glacier area, a variety of ultramafic, alkaline, and calc-alkaline lamprophyres are present whereas in the Dry Valleys and Granite Harbor regions, lamprophyres are all calc-alkaline, mainly spessartites. The regional variation in dike composition might reflect southwestward subduction beneath the region (Wu and Berg, 1992). The widespread calc-alkaline lamprophyres have chemical features which indicate that subduction-slab-derived components contributed to their mantle sources (Wu and Berg, 1992). In the southwestern part of the study area in the Koettlitz Glacier region,
alkaline and ultramafic lamprophyres which have an intraplate magma character are common. This suggests that mantle sources were further away from the subduction zone than the calc-alkaline dikes to the north (Wu and Berg, 1992).

Mafic and ultramafic inclusions, derived from the lower crust and possibly upper mantle, respectively, were reported in two camptonite lamprophyre dikes south of the Radian Glacier area (Berg, 1988). Electron microprobe analysis of a garnet granulite yielded an equilibrium temperature of 900°C and pressures of 13.3 kilobars reflecting a crustal depth of at least 45 km. An "extremely pristine" inclusion might indicate that lower crustal dike magma propagated very rapidly to the surface (Berg, 1988). Since it would seem unlikely that the one inclusion was derived from the bottom of the crust, it would suggest that crustal thicknesses were greater than 45 km (Berg, 1988). A greater crustal thickness could have resulted from deformation associated with the Early Paleozoic Ross orogeny.

Dike Ages

Dike ages obtained by K-Ar and Rb-Sr radiometric dating techniques of the 1960's represent poorly constrained cooling ages for the dikes of the Transantarctic Mountains. Angino, Turner, and Zeller (1962) obtained an K-Ar age of 458 Ma ± 20 from a biotite lamprophyre in the Taylor Valley. Deutsch and Webb (1964) obtained Rb-Sr dates on biotite, feldspar, and whole rock samples of 477 Ma, 942 Ma, and 1000 Ma
respectively from a porphyry dike cutting Olympus granite-gneiss. Jones and Faure (1967) reported that an age of 1000 m.y. was inconsistent with field relations. They sampled a porphyry which intruded the Asgard Fm and obtained a whole rock and feldspar Rb-Sr age of 470 Ma. Subsequent investigations by Faure and Jones (1974) discovered low Rb-Sr ratios in the Vanda Lamprophyres and they dated both the Vida Granites and Vanda Porphyries of the Victoria Granites instead. They obtained an Rb-Sr age of \( 481 \pm 44 \) Ma (the large uncertainty is due to the combined isochron). This combined isochron age however is invalid in light of recent pluton mapping of the area (Allibone et al., 1993a; Cox, 1993; Smillie, 1992).

Recalculations of old dates obtained by Deutsch and Webb (1964) and Jones and Faure (1967) were provided by Skinner (1983) using new decay constants and yielded dates of \( 465 \pm 15 \) Ma for a hornblende-biotite porphyry and \( 460 \pm 7 \) Ma for a whole rock-feldspar porphyry isochron respectively.

Graham and Palmer (1987) investigated two Granite Harbour granitoids (Avalanche Bay Quartz-monzodiorite and Lion Island Granite) located 18 km. apart, which revealed similar Rb-Sr mineral and whole rock dates of \( 473 \pm 8 \) Ma. Based on the Gunn and Warren (1962) division of the "Granite Harbour Intrusive Complex" into pre-, syn-, and post-tectonic suites, the Avalanche Bay Quartz-monzodiorite and Lion Island Granite are considered post-tectonic and equivalent in age to the Vida Granite. Wilson (1989, personal observations) noted the Avalanche Bay and Lion Island granitoids were cut by the mafic dikes, which therefore
establishes a lower age limit of these mafic dikes at 473 ± 8 Ma.

Observed cross-cutting relations with dated granitoids of the Dry Valleys provide some age constraints on dike emplacement in that region (Allibone et al., 1993a; Allibone et al., 1993b; Waters, 1993). Since both the Vanda mafic dikes (Vanda Lamprophyre, McKelvey and Webb 1962) and the Vanda felsic dikes (Vanda Porphyry, McKelvey and Webb 1962) postdate emplacement of the DV1a and DV1b suites (Allibone et al., 1993), they have a lower age limit between 486 and 490 Ma. The younger Swinford, Brownworth, Pearse and Harker Plutons clearly cut across major swarms of Vanda dikes but are themselves cut by rare, later Vanda dikes (Allibone et al., 1993a; Allibone et al., 1993b; Waters, 1993). Only Waters (1993) observed Vanda mafic dikes cutting the young Swinford and Harker Plutons. This crosscutting relation indicates that most Vanda dikes were emplaced earlier than 477 Ma, the age of the youngest, Harker Pluton, but waning dike intrusion still continued afterwards.

Dike Orientations and Relative Ages

A general northeast trend for the mafic dikes of the McMurdo Sound sector is apparent from Granite Harbour to the Koettlitz Glacier region (Figure 3.2) and mapping near Terra Nova Bay and in the Brown Hills just north of Byrd Glacier (Figures 3.1, 3.4) indicates the same predominant trend in those areas. Evidence for different generations of dikes and the relative ages of dike sets with different orientations has been observed in some places.
Angino et al. (1962) differentiated four lamprophyric dike systems in the Taylor Valley near Mt. Nussbaum (Figure 3.10). Based on cross-cutting relationships, they devised a tentative order of emplacement of these dikes with the initial injection of a north-northwest lamprophyric system followed by cutting of a east and east-northeast-striking dike series. A final north-northwest system was subsequently emplaced, cutting previously injected dike systems. Additional investigations by Gunn and Warren (1962) of dike occurrences in the McMurdo Sound region and Haskell et al. (1965) in the Middle and Lower Taylor Valley noted that lamprophyre and porphyry dikes generally trend east or northeast. Augite-biotite lamprophyres only cut the Wright Intrusives of the "Granite Harbour Intrusive Complex" and are considered to be the oldest of the subsequent cross-cutting microgranite, microdiorite, ultrabasic, porphyry, and hornblende lamprophyre dikes. In the Koettlitz-Blue Glacier region, Blank et al. (1963) also noted the occurrence of northeast-striking older biotite and younger hornblende lamprophyres and porphyry dikes based on cross-cutting relationships. In the Victoria Dry Valley area, Webb and McKelvey (1959) reported two uniform lamprophyre dike systems intersecting each other; one set consisted of fifty northeast-striking dikes cropping out over a distance of one mile intersected by six northwest-striking dikes.
Figure 3.10 Map of Lower Taylor Valley from Lake Bonney to Lake Chad showing distribution and cross-cutting relations of four different lamprophyric systems. Location of Mt. Nussbaum indicated by a solid triangle in right center. Elevations in meters. Heavy solid or dashed lines indicate faults. Light lines of alternating dashes and dots are intermittent streams (from Angino et al., 1962).
Murphy (1972) described lamprophyres cutting porphyries in the lower Wright Valley, whereas Keiller (1991) observed porphyries paralleling lamprophyres at adjacent Mount Loke and in one place found the two in a composite dike, indicating both may belong to a single intrusional event. Keiller (1991) reported that the majority of the dikes have strikes of 040° - 070° with near vertical dip (70° - 90° S). However, the oldest, diorite dikes exhibit a consistent orientation of 090°, 30°- 40° S.

Systematic measurements of lamprophyre and porphyry dike trends in the Granite Harbour-Mackay Glacier region (Figure 3.4) were taken by Wilson (unpublished, 1989). Average dike orientations from the Granite Harbour/Mackay Glacier area is 035° and similar to those in the McMurdo Sound sector (Janosy, 1991).

*Relations Between Dikes and Host Rock Structures.*

The dominant trends of lithological units, regional folds, and foliations in the metasedimentary rocks in the area between the Wright Valley and Koettlitz Glacier are to the northwest (Plate I; Allibone et al., 1993a; Findlay et al., 1984; Blank et al., 1963). These trends are cut at high angles by the younger northeast trending dikes. Gunn and Warren (1962) also reported that in the Nussbaum Riegel region (Figure 3.9) post-tectonic, east-striking dike intrusions cut normal to folded bedding and schistosity.
Lamprophyre dikes were observed by several workers to parallel fractures or fault planes at some localities. Many lamprophyres intruding marbles of the Koettlitz Group were observed by Gunn and Warren (1962) to parallel an existing joint set transverse to the regional structural trend, leading them to suggest that dike emplacement was influenced by the pre-existing fractures. At Nussbaum Riegel in the Taylor Valley, Haskell et al. (1965) reported lamprophyre dikes that were offset dextrally up to 33 m along faults, some of which were later intruded by younger lamprophyres.

Murphy (1972) reported that lamprophyres in the Wright Valley area commonly occupy northeast-trending faults and were later sheared from reactivated movement along the faults. Also in Wright Valley, Keiller (1991) reported a few dikes at Mount Loke that were offset by reverse faults trending 045°. In the Lake Vanda swarm, faults cross-cut dikes and were often traced along the center of a dike, especially within granite and granodiorite dikes (Keiller, 1991).
CHAPTER IV
GEOLGY OF THE STUDY AREA

Rock Units

The generalized bedrock geology in the Ferrar-Koetttltitz Glacier region of southern Victoria Land is presented on Plate I. The basement rock units were adapted from Findlay et al. (1984) with modifications based on Blank et al. (1963) and field observations in local areas. Basement lithologies were assigned to undifferentiated metasedimentary and granitic units (the latter including the Chancellor Orthogneiss mapped by Findlay et al., 1984). Basement dike swarms were mapped from aerial photography. Cenozoic McMurdo Volcanic Group rocks and surficial sedimentary deposits were also mapped from aerial photographs. This simplified map was designed mainly to show regional dike trends and their relations to basement rock trends and does not accurately represent the complex relations between the basement units.

The first regional mapping of the rock units exposed within the Ferrar-Koetttltitz Glacier region was performed by Blank et al. (1963). More recent mapping was completed by Mortimer (1981) between Miers Valley and Salmon Glacier and by Findlay et al. (1984) throughout much of the region, but this mapping was only published as a small figure in a
journal article. The pre-Ordovician amphibolite facies rocks of this region are known as the Koettlitz Group (Grindley and Warren, 1964) and are intruded by a series of pre- and post-tectonic granitoids, gabbro, and igneous dikes comprising the Granite Harbour Intrusives (Gunn and Warren, 1962). These basement rocks are unconformably overlain by Devonian - Jurassic fluvial to shallow marine deposits of the Beacon Supergroup. Large sills and minor dikes of Jurassic Ferrar Dolerite intrude both the basement and Beacon units.

Blank et al. (1963), described five formations of the Koettlitz Group (then called the Skelton Group) but only mapped three general units. The five units are the Marshall Formation (c. 1000 m), Miers Marble (600 m), Garwood Lake Formation (800 m), Salmon Marble Formation (2700 m), and Hobbs Formation (2000 m). Mortimer (1981) investigated the basement rocks between the Salmon and Miers Valleys and recognized three formations: the Marshall Formation, Salmon Marble, and Penance Pass Formation. The revised Marshall Formation includes the Garwood Lake Formation of Blank et al. (1963) and since no difference was recognized between the Salmon Marble and the Miers Marble of Blank et al. (1963), the term Miers Marble was discarded (Mortimer, 1981). Mortimer (1981) renamed the Hobbs Formation of Blank et al. (1963) the Penance Pass Formation because the rocks overlying the Salmon Marble did not correspond to Blank et al.’s (1963) description.
The most recent division of the lithostratigraphy of the Koettlitz Group by Findlay et al. (1984) consists of three formations: a revised Marshall Formation modified after Mortimer (1981), the Salmon Marble Formation, and a redefined Hobbs Formation. The Penance Pass Formation (Mortimer, 1981) was determined by Findlay et al. (1984) to consist of units of the Salmon Marble and Hobbs Formation. Two members comprise the Salmon Marble Formation and four members the Hobbs Formation however, Findlay et al. (1984) did not present a map showing these members.

**Metasedimentary Rocks**

The Marshall Formation of Findlay et al. (1984) is retained as originally described by Blank et al. (1963). It is thought to represent the oldest rocks in the region and consists of approximately 490 m of lower biotite schist, thin marble, banded quartzite, and light-colored diopside-tremolite-quartz granulite and upper, older, black amphibolite interbedded with quartz-biotite schist grading into paragneiss.

The Salmon Marble Formation (Salmon Marble and Miers Marble of Blank et al. (1963) consists of two units; the Heald and Dismal Members (Findlay et al., 1984). The Heald Member is a white to cream, coarse marble containing distinctive, 10 cm thick rusty layers of pyrites, white mica, diopside (Findlay et al., 1984) and scapolite which separate the marble into bands from 20 cm to 1 m thick (Blank et al., 1963). It was mapped as Salmon Marble by Blank et al. (1963) south of Blackwelder
Glacier and on either side of Radian Glacier, including Rucker Ridge. East of Hobbs Peak, and near Bettle Peak, the Heald Member contains 20 m thick intercalations of biotite schist, hornblendic amphibolite, and many leucocratic quartzofeldspathic gneiss layers and boudins. The Dismal Member, a transitional facies to the Hobbs Formation, is a "cream-orange, and grey to black, banded marble interbedded with thin, fissile, to rusty-weathering, hornblendic, biotite-rich pelites and grey to black, sometimes hornblendic, marbles" (Findlay et al., 1984).

Of the four units that comprise the Hobbs Formation, three occur within the study area: the Radian Schist, Con-Rod Hills, and Rucker Members (Findlay et al., 1984). The fourth, Meserve Member, occurs north of the Ferrar Glacier with the exception of a 1 km section exposed at Cathedral Rocks (Findlay et al., 1984). The Radian Schist Member consists dominantly of biotite-actinolite schists, biotite-garnet schists (usually coarser than the actinolite variety), and biotite-sillimanite schist (less common than the first two varieties) (Findlay et al., 1984). The Con-Rod Hills Member, named after the locality which is now the A. A. Thomas Hills, consists of a coarse-grained and fine-grained facies and is the pebble-bearing unit of the Hobbs Formation (Findlay et al., 1984). The coarse-grained type is recognized by the presence of 10-15 cm clasts of granite, quartz, biotite pelite, tremolite/actinolite amphibolite, and rare marble (Findlay et al., 1984). The fine-grained version is mostly a quartz-tremolite/actinolite schist containing sparse pebbles and rarely, cobbles (Findlay et al., 1984). It grades into the Rucker Member, described
as a "distinctive, rusty-weathering, medium-grained, dark, tremolite/actinolite amphibolite containing diopside streaks and blebs parallel to schistosity, and rare pebbles of quartz, granite and pelite" (Findlay et al., 1984). This member crops out throughout the entire study area. The Meserve Member, only seen at Cathedral Rocks, consists of 300 m of biotite schists and biotite-diopside schists which grade west into 650 m of the Con-Rod Hills Member.

Granitic Rocks

All the basement igneous rocks of the McMurdo Sound region were originally assigned to the Granite Harbour Intrusive Complex defined by Gunn and Warren, (1962) to include all of the plutonic and hypabyssal igneous rocks that predate the Kukri Peneplain at the base of the Beacon Supergroup. These rocks were thought to be associated with the Cambro-Ordovician Ross orogeny and were described during initial investigations in terms of pre-, syn, and post-tectonic intrusive suites (Gunn and Warren, 1962; McKelvey and Webb, 1962; Allen and Gibson 1962, Blank et al., 1963; and Haskell et al., 1965). The nomenclature of these various granitoid suites became inconsistent during these investigations. In most cases, the granitoids were subdivided based on composition and the degree of deformation, with the most gneissose comprising the pre-tectonic group and the least deformed the post-tectonic group (Smillie, 1992). Many of the compositional types were given formational status such as the Larsen Granodiorite and Irizar Granite (Smillie, 1992) and inconsistency in
usage resulted in workers assigning the same granitoid a different name, or different granitoids the same name. Smillie (1992) pointed out, for instance, the Larsen Granodiorite of Gunn and Warren (1962) was correlated with the Dais Granite of McKelvey and Webb (1962) by Haskell et al. (1965).

Recent workers have avoided using previous classification schemes and have mapped geographically continuous bodies as batholiths or plutons and then assigned them to granitoid suites based on similarities in whole-rock geochemistry, mineralogy, and age (Smillie, 1992). In the Dry Valleys region, two suites have been defined and informally referred to as the Dry Valleys 1 (DV1) suite and Dry Valleys 2 (DV2) suite (Smillie, 1992; Cox, 1993; Allibone et al., 1993a; Allibone et al., 1993b). Granitoids of the DV1 suite are dated at about 500 Ma and resemble Cordilleran I-type calc-alkaline granitoids which evolved above an ancient subduction zone. They are characteristically concordant and elongate in a northwest-southeast direction and appear to have been emplaced under a regional stress field. The granitoids and dike swarms of the younger, ~480 Ma DV2 suite resemble Caledonian I-type alkali-calcic granitoids emplaced during a period of later crustal extension. These plutons are generally discordant and have been suggested to have been passively emplaced into fractures based on field characteristics (Smillie, 1992).

In the Ferrar-Koettlitz Glacier region, Blank et al. (1963) recognized a complex batholith trending roughly north-south through the center of the area in which the trends of the foliation and inclusions within the body
are generally parallel to the bedding and schistosity of the flanking metasedimentary rocks. Earlier workers recognized the variable foliation development within the batholith and described two granitoid lithologies: McKelvey and Webb (1962) mapped 'foliated' Olympus Granite-gneiss which gradationally changed to a nonfoliated Dais Granite; Gunn and Warren (1962) used the terms syn- and post-tectonic granite; and Findlay (1985) used the terms Dais Phase and Briggs Hill Phase of the Larsen Granodiorite to describe these lithologies (Cox, 1993). Recent workers however, found no geochemical differences between these 'foliated' and 'non-foliated' varieties and described the granitoid as a single body naming it the Bonney Pluton (Allibone et al., 1993a; Smillie, 1992; Cox, 1993). The pluton, belonging to the DV1 suite, is believed to crop out over 1000 km² and extend from McKelvey Valley in the Dry Valleys to the Ward-Howchin Glacier region in the south (Figure 4.1). The pluton consists of coarse-grained, variably megacrystic, monzodiorite-granite and is homogeneous macroscopically and not compositionally zoned (Cox, 1993). Internally, the Bonney Pluton exhibits foliation which progressively develops from the center of the pluton out towards the margins.

Smaller granitoid bodies within the study area occur in the Shangri-la - Miers Valley area. Worley (1992) conducted a detailed field and geochemical study of these intrusive basement rocks and recognized at least six granitoids which represent two independent episodes of intrusion: the Bonney Pluton, Buddha Diorite, Lama Pluton, Rivard Diorite, Miers Granite and Biotite Granite (Figure 4.2). Some of these
Figure 4.1 Location diagram and generalized geological map of southern Victoria Land basement rocks. The extent and trace of the Bonney Pluton is from McKelvey Valley in the north to the Ward-Howchin Valleys to the south. Foliation in Koettlitz Group metasedimentary rocks closely parallels margin of Bonney Pluton and wraps around southern end (from Cox, 1993).
Figure 4.2 Sketch map of the geology of the Miers Valley area showing six mapped granitoids representing two independent episodes of intrusion; DV1 and DV2 suites. The Péwé Peak Phase is part of the Porphyritic Buddha Diorite (from Worley, 1992).
names follow units mapped by Mortimer (1981). The Bonney Pluton conforms to the DV1 suite classification scheme based on field relations and geochemistry and is a southern continuation of the Bonney Pluton described by Allibone et al. (1991). The younger Lama Pluton, which crops out in the Shangri-la - Rivard Glacier region, represents a DV2 suite pluton which is discordant, compositionally variable, and equigranular to coarsely porphyritic (Worley, 1992). The Biotite Granite and Miers Granite also exhibit chemical characteristics of the younger DV2 granitoids (Worley, 1992). The Buddha Diorite, and a mafic phase of it termed the Pévé Peak phase, are also DV2 suite granitoids. They are intimately associated with the Lama Pluton, as the contact between the mafic phase and the pluton are characterized by zones of intermingled mafic and felsic rock types and by swarms of mafic enclaves within the porphyritic Lama Pluton, suggesting mixing of the granitic and dioritic magmas (Worley, 1992). The Rivard Diorite did not fit into the classification scheme and probably formed as a result of crustal contamination (Worley, 1992).

Findlay et al. (1984) mapped a unit called the Chancellor Orthogneiss, described as a leucocratic biotite gneiss by Skinner (1983), as discontinuous patches in the metasedimentary rock units throughout the entire study area. For simplicity in this study, the Chancellor Orthogneiss was grouped and mapped with the other granitoids although it remains questionable as an actual unit based on recent mapping (Worley, 1992) and personal observations (in particular the area between
Howchin and Walcott Glaciers).

Besides the DV2 plutons first described by Smillie (1992), the youngest of the Early Paleozoic intrusives exposed in the study area are mafic igneous dike swarms described by early workers as lamprophyres and porphyries (McKelvey and Webb, 1962; Allen and Gibson, 1962; Blank et al., 1963; Haskell et al., 1965). A recent petrological and geochemical study of these lamprophyres described them as ultramafic, alkaline, and calc-alkaline varieties (Wu and Berg, 1992). Similar dikes which occur in the Dry Valleys and are thought to represent a northern continuation of the Ferrar-Koettlitz Glacier dike swarm have been assigned to the DV2 suite. The dikes in the study area are probably of the same alkali-calcic, Caledonian I-type granitoid suite.

The McMurdo Volcanic Group occurs in the area as small scoria cones and flows, mainly within the Howchin-Walcott-Radian Glacier region (Plate I). These volcanics represent part of the extensive Cenozoic alkali volcanism within the western Ross Embayment and the adjacent Transantarctic Mountains (Kyle, 1990).

**Structural Geology**

Previous workers have recognized two generations (F₁ and F₂) of folding of the basement metasedimentary units during investigations within the Ferrar-Koettlitz Glacier region (Williams et al., 1971; Mortimer, 1981; Findlay et al., 1984; Cox, 1993). The initial F₁ phase is characterized as isoclinal, similar, generally recumbent folds that
probably resulted in large-scale inversion of the lithologic sequence (Findlay et al., 1984). Fold axes trend northwest with plunges mostly gently northward, and there is an axial plane schistosity. In the Salmon Marble, mesoscopic $F_1$ isoclinal folds invariably exhibit angular hinges and fold compositional banding. Later $F_2$ folds sub coaxially refold $F_1$ structures producing similar, open folds, chevron folds and box-like folds with thick hinges and thin limbs (William et al., 1971; Mortimer, 1981; Findlay et al., 1984). $F_2$ axial planes predominantly dip steeply south and fold axes generally plunge to the west at low angles.

In the Radian-Walcott Glacier region of the study area, a third generation of folding ($F_3$) was observed by Findlay et al. (1984) and interpreted by Cox (1993) to be a deflection around the southern end of the Bonney Pluton (Blue Glacier pluton of Findlay et al., 1984). The folding is attributed to non-coaxial deformation at the ends of the expanding Bonney Pluton as the diapir-like intrusion pushed aside the metasediments before breaking through (Findlay et al., 1984; Cox, 1993) (Figure 4.3). The $F_3$ folds are 100 to 1000 m in scale, are asymmetric, open, often monoclinal, and have steeply dipping axial planes (Findlay et al., 1984). They are distinctive in that they fold at least one other fold phase and lack a pervasive axial plane cleavage. Fold axes on Rucker Ridge vary from northeast to east.
Figure 4.3 Schematic model for the emplacement of the Bonney Pluton. The $F_3$ folds resulted from non-coaxial deformation at the southern end of the pluton as diapir-like intrusion pushed aside the metasediments before breaking through the surface (from Cox, 1993).
Two types of interference structures resulting from folding superimposed on F₁ folds were recognized in Salmon Marble by Findlay et al. (1984). Type 2 structures involved refolding of isoclinal F₁ folds about an upright, shallowly northeast plunging F₃ axis (Findlay et al., 1984). A Type 3 pattern formed by refolding F₁ sub coaxially about F₂ occurs in various places throughout the study area, whereas Type 2 structures are limited to the southern outcrops around Rucker Ridge.

Within the arcuate band of Salmon Marble on the north side of Lake Miers, Mortimer (1981) described a large scale F₁ isocline refolded about an open gently west plunging F₂ fold. At the eastern end of Miers Valley, Mortimer (1981) described a large-scale gently west-plunging, upright F₂ antiform with the fold hinge located just north of Lake Miers. Further north between the Garwood Valley and the Salmon Glacier, large scale isoclinal F₁ folds are the major structure in the area and are interpreted by Findlay et al. (1984) to be east-trending, horizontally plunging, and warped coaxially as seen on the southern wall of Garwood Valley.

In the region north of the Hobbs Glacier, both F₁ and F₂ structures are present and invariably form Type 3 interference structures within the Salmon Marble. East of Hobbs Peak and in the A. A. Thomas Hills, minor northwest trending F₃ folds were reported by Findlay et al. (1984) to warp F₂ axial planes. It is not known whether these third generation folds correlate with those observed in the Radian-Walcott Glacier region.
Metasedimentary host rock foliation in the study area predominantly trends northwest parallel to the \( F_2 \) structures. In the Miers-Howchin Valleys area, foliation trends change from northwest (approximately 320°) along the sides of the Bonney Pluton to east-west (about 270° - 280°) at the southern end of the pluton, following those of the \( F_3 \) structures (Figure 4.1) (Cox, 1993). Within the Bonney Pluton, foliation development parallels the host rock/pluton margin and becomes more penetrative at the contact (Cox, 1993).

The only reported occurrence of joints was given by Mortimer (1981) who observed two sets in the central portion of the study area between Salmon Glacier and Miers Valley. A dominant sub-vertical joint set striking north-south commonly cut the lamprophyre dikes and a second set striking between 310° and 330° had northeast dips of 70°-80°. Mortimer (1981) also reported the occurrence of faults with north to northwest trends and subvertical dips on the north wall of Marshall Valley within the metasedimentary rock units.

**Localities Examined in Study**

Seventeen localities were visited throughout the Ferrar-Koetllitz region (Figure 4.4, Plate I). Most sites are within the prominent northwest-trending belt of deformed metasedimentary rocks which continues through the Dry Valleys. Three sites in the Walcott-Radian Glacier area are near the southern end of the DV1-suite Bonney Pluton where non-coaxial \( F_3 \) structures occur (Rucker Ridge, ridge east of Penny Lake, and
Figure 4.4 Geological sketch map of the study area (inscribed area) showing visited localities. BP = east of Bettle Peak; BH = Briggs Hill; SH = Stratton Hills; GK = Granite Knolls; MB = mouth of Blue Glacier; LG = ridge north of Lister Glacier; GV = north of Garwood Valley; SL = Shangri-la; MR = Marshall Ridge; HP = Holiday Peak; HV = Hidden Valley area; WG = north of Walcott Glacier; RR = Rucker Ridge; PL = ridge east of Penny Lake (after Findlay et al., 1984).
north of Walcott Glacier). Six areas are within the foliated Bonney Pluton as mapped by Cox (1993), including Briggs Hill, Stratton Hills, Granite Knolls, the ridge north of Lister Glacier, Holiday Peak, and most of the Hidden Valley region. Most of these localities occur within the central portion of the granitoid where foliation is poorly developed, but marginal localities such as Hidden Valley have a well-developed, penetrative foliation. The Shangri-la-Marshall Ridge-Miers Valley localities are also within granitic basement rock. The Miers Granite, the Biotite Granite, the Lama Pluton and possibly the Buddah Diorite of these areas are DV2-type granitoids (Worley, 1992).
CHAPTER V
RESULTS

Introduction

The overall form of dikes and the nature of their margins are key indicators of the mode of dike emplacement in relation to the stress state within the crust. A systematic search for structures along dike margins and at dike terminations was carried out during this field investigation. Within the study area, however, the lack of in situ exposure obscured dike morphology and complicated accurate determinations of orientations, dimensions, and host-rock relations. Many of the localities exhibit moderate to severe frost wedging of both the dikes and the host rock. Since the dikes typically stand in relief relative to the less resistant host rocks, they commonly have fractured or flaggy outcrops. Although the outcrop conditions prevented collecting observations uniformly from all localities, moderately to well preserved dike features were recorded at scattered sites throughout the study area. These results are summarized in the sections that follow. In interpreting the structural significance of the dikes, it is assumed that the observed features are characteristic of the dike swarm as a whole within the study area.
This study consisted of three phases. The first phase involved a field investigation of dike orientations, morphology, and host-rock relations. The second phase consisted of systematic field sampling and petrographic analysis of the dikes to determine their compositions. The third phase involved mapping of dike distribution, orientation, and morphology from aerial photographs. Combined results from each phase are described in the sections that follow.

**Dike Distribution and Dimensions**

Dike distribution was determined from aerial photographs and Plate I. Because of extensive ice cover and surficial sediments, dike dimensions described below represent minimum estimates.

The study area encompasses an area of about 1900 km² between 77°42'S and 78°16'S latitude and 163°E and 164°50'E longitude where abundant dikes of the regional Victoria Land dike swarm occur (Plate I). Within the study area, two major dike concentrations, or subswarms, are present. A northwest subswarm, henceforth referred to as the A. A. Thomas Hills swarm, lies between the Ferrar Glacier and Hobbs Peak and extends southwest across Granite Knolls, probably to the Lister Glacier area, but that area has not been documented (Plate I). It has a minimum strike length of 22.5 km and an approximate cross-strike extent of 18 km. The other subswarm, henceforth referred to as the Foothills swarm, is located in the southeastern portion of the study area in the ice-free region of the Royal Society Range foothills (Plate I). It is best
developed in the Hidden Valley area and extends south to Penny Lake and north to Marshall Valley. The swarm has a strike length of 37.5 km and a cross-strike extent of 16.5 km. Within the central region of the study area between the Hobbs, Blackwelder, and Joyce Glaciers and the cover of the Blue Glacier, dike abundance appears much less, but the small scattered outcrops and extensive ice in this area may obscure them. In the Garwood-Salmon Glacier area, abundant, but folded dikes are present and no northeast trending dikes from either subswarm appear to continue into this region.

Two dike clusters comprise the A. A. Thomas Hills swarm. A dense cluster is centrally located across the A. A. Thomas Hills and a second cluster occurs east of Hobbs Peak. The first cluster consists of an extensive array of dikes between the Ferrar and Blue Glaciers which litter virtually all of the nunataks of the A. A. Thomas Hills and the ridges east of Bettle Peak. The dikes visible on aerial photos have spacings as small as 50 - 75 m. They appear to continue southward at least 21 km along strike to Granite Knolls. The second, smaller cluster occurs in the Hobbs Peak area south of the Blue Glacier and extends only for 8 km along strike and 4.5 km across strike. Most of the extensive dikes comprising this smaller cluster occur at the eastern end and are spaced 100 - 200 m apart whereas dikes just east of Hobbs Peak are spaced 10's to 100 m apart. An isolated group of three dikes at Hobbs Peak are only 10's m apart.
The Hidden-Ward Valley area (Plate I) of the Foothills swarm contains a dense concentration of lamprophyres and quartz microdiorite bodies. At least 30 prominent, mappable dikes are spaced from 50 m up to 550 m apart, but average 225 m over a 54 km² area. A distinct cluster of about 10-12 dikes occupying 800 m across strike extends 8 km along strike from Ward Valley to the southeastern end of Hidden Valley (Plate I). Three groups of dikes of varying orientations are recognized within this cluster. A small group of 4-5 dikes trending approximately 040° and spaced about 60 m apart appear to show cross-cutting relations with a larger, extensive group of 5-7 dikes trending 050°-055° spaced 40 - 150 m apart at the southern end of the Hidden Valley area. The third group of dikes in Ward Valley trend about 045° and dikes are spaced 35 - 50 m apart.

In the northeastern end of Hidden Valley, a group of three dikes spaced about 50 m apart extends for almost 2 km. In the same area, two parallel zonal distributions of dikes occur 500 m apart (Plate I) and are comprised of 2-3 closely-spaced en echelon dikes. The eastern zone consists of two continuous dikes 30 - 50 m apart which extend for 1.1 and 1.9 km. The western zone has three closely parallel dikes, two spaced 13 m and the third 40 m apart which extend 3 km.

The central area of Hidden Valley has six dikes which are at least 5 - 10 km in extent and probably continue further north and south. Three of these extensive dikes, located just east of Lake Keyhole, are vogesite and spessartite lamprophyres which comprise a group of dikes spaced
40 - 75 m apart (Plate I).

The southern extent of the Foothills swarm includes the areas east of Penny Lake, north of Walcott Glacier, and Rucker Ridge, and generally has widely distributed dikes. There is a dense concentration of dikes between the Walcott and Howchin Glaciers, where dikes are generally spaced about 75 - 300 m apart over a distance of 6 km. Dike lengths vary from 500 m to 2 km but very likely continue south of Walcott Glacier indicating dike continuity over 10 km. North of Walcott Glacier, a group of four continuous dikes are spaced 20 - 50 m apart and extend for at least 6 km. Dike distribution at Rucker Ridge is unlike most localities in that dikes have no consistent orientation and appear to vary in overall length. The area east of Penny Lake has parallel dikes of various lengths spaced about 150 - 375 m apart. A few of these dikes are lamprophyres similar in composition and trend to those at Hidden Valley which may indicate dike continuity over 23 km.

Spotty dike occurrences are prevalent south of Hobbs Glacier and throughout the area surrounding the Blackwelder Glacier. The topography in this particular area consists of a series of inter-fingering ridge lines with steep flanking slopes cropping out through ice and this may account for the lack of a visible, dense concentration of dikes. Near Salmon Glacier and throughout the metasedimentary rocks to the north of Garwood Valley, dikes are common with spacings of 150 - 350 m, but here the dikes are folded and hence spacing is not indicative of original dike distribution. Sparse occurrence of dikes are characteristic of the area
between Garwood Valley and Miers Valley which includes the Shangri-la and Marshall Ridge localities. The dikes however do systematically crop out along the entire expanse of the area every 2.5 to 3 km in clusters where they are only 10's of meters apart. This appears to be more apparent along Marshall Ridge and may indicate the northern continuation of very extensive dikes which are present further south in Hidden Valley. Compositionally, the dikes from the two regions are very similar and do share the same trends.

Dike dimensions are consistent throughout the study area. Dike thicknesses were determined in the field, although true thicknesses were locally obscured by frost wedging. Segment lengths could be determined in the field, but overall dike lengths were estimated from aerial photographs. Because of the extensive cover of ice and surficial sediment, most dike lengths are minimum estimates.

Variations in dike thickness are related to differences in composition. The lamprophyres commonly range from 20 - 200 cm thick. Some larger, extensive lamprophyres, such as at Hidden Valley, have thicknesses of 5 to 11 m. Among the other compositional varieties, dike thicknesses were generally greater. Acid porphyries, andesite porphyries, quartz microdiorites, and latitic dikes were commonly 10 - 12 m thick with some up to 20 m.

Dike lengths were more variable. This may in part reflect the difficulty in establishing the true strike extent of individual dikes in the field. Dikes that could be correlated based on composition across covered
valleys, such as the lamprophyres at Hidden Valley, had strike extents ranging from 6.5 - 10.5 km. Dikes with identical compositions and similar trends occur on Marshall Ridge to the north and Ward Valley to the south and are likely continuations of these lamprophyre dikes which would yield a strike length of 18 km. A spessartite lamprophyre can be correlated across Miers Valley to Marshall Ridge with an overall strike extent of 17.3 km. Dikes that can be traced from southeastern Hidden Valley to south of Ward Valley have lengths from 2.2 - 8.6 km and are made up of segments that are commonly 150 - 525 m in length. Dikes at Hidden Valley which do not appear to be continuous across the valley average 1-2 km in length with individual segments from 150 - 600 m long. Dikes in the Marshall Ridge and Shangri-la area have overall lengths of 150 - 750 m and most commonly near 350 m. In the southern portion of the study area, dike lengths near Penny Lake, Walcott Glacier, and Rucker Ridge range from 150 m to 4.8 km. The only extensive, undeformed dike observed on aerial photographs north of Garwood Valley trends 070° and has a strike extent of 5.7 km. The most extensive dikes in the Hobbs Peak area have strike extents between 2.4 - 3.4 km. The northern, glaciated portion of the study area including the Bettie Peak area and especially the A. A. Thomas Hills, has an extensive concentration of northeast trending dikes on many nunataks. These isolated outcrops show dikes traversing their entire lengths and continuing along the same strike (040°) on other nunataks. Since the nunataks are not very large, observed dike lengths are only 375 m to 1.1 km. However, continuity along strike from Granite Knolls to
outcrops bordering the Bowers Piedmont Glacier would yield strike extents of 21 km.

**Dike Compositions**

During the field study, dike mineralogy was described and samples were collected from each dike type that appeared to have distinctive character. From the approximately 200 dikes measured in the field, 106 were sampled. Based on hand sample comparisons, a preliminary grouping of dike types was made and 82 different dikes were selected for petrographic analysis. Overall the dikes are highly heterogeneous and exhibit many gradational varieties and degrees of alteration. As a result, discriminating between the various dike types based on petrography alone was in some cases difficult and subjective. Detailed rock descriptions from thin section analyses for the various compositions are provided in Appendix B.

The classification of igneous rocks, including dike rock types, is partly based on silica percentage (Table 5.1). Dark-colored dike rocks, termed mafic because of the abundance of dark minerals (70-90%), contain 45-52% silica. Definition of the volcanic calc-alkaline rock series which includes basalt, andesite, dacite, and rhyolite is based on comparison of the alkalinity of different igneous rock types as derived by Peacock (1931). Plots of CaO vs. SiO₂ and Na₂O + K₂O vs. SiO₂ for a series of related igneous rocks define the alkali-lime index which can be used to subdivide rock series (Figure 5.1; Table 5.2) (Hyndman, 1985; Ehlers and Blatt, 1982).
Table 5.1 Chemical classification of igneous rocks based on silica percentage (after Hyndman, 1985).

<table>
<thead>
<tr>
<th>%SiO₂</th>
<th>Designation</th>
<th>% Dark minerals</th>
<th>Designation</th>
<th>Example rock</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt; 66</td>
<td>Acid</td>
<td>&lt; 40</td>
<td>Felsic</td>
<td>Granite, rhyolite</td>
</tr>
<tr>
<td>52–66</td>
<td>Intermediate</td>
<td>40–70</td>
<td>Intermediate</td>
<td>Diorite, gabbro</td>
</tr>
<tr>
<td>45–52</td>
<td>Basic</td>
<td>70–90</td>
<td>Mafic</td>
<td>Gabbro, basalt</td>
</tr>
<tr>
<td>&lt; 45</td>
<td>Ultrabasic</td>
<td>&gt; 90</td>
<td>Ultramafic</td>
<td>Dunite, peridotite</td>
</tr>
</tbody>
</table>

Figure 5.1 Chemical classification of calc-alkaline igneous rocks based on alkalinity as devised by Peacock (1931). Intersection of CaO vs. SiO₂ and alkalis vs. SiO₂ to determine alkali-lime index. The two trends for the hypothetical suite of rocks plotted as heavy lines intersect between 56 and 61% SiO₂ and define the calc-alkaline rock suite.

Table 5.2 Igneous rock classification as devised by Peacock (1931).

<table>
<thead>
<tr>
<th>Type of rock</th>
<th>%SiO₂</th>
<th>Illustrative rock series*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calcic</td>
<td>&gt; 61</td>
<td>Tholeiitic basalt</td>
</tr>
<tr>
<td>Calc-alkaline</td>
<td>56–61</td>
<td>Basalt, andesite, rhyolite series</td>
</tr>
<tr>
<td>Alkali-calcic</td>
<td>51–56</td>
<td>Alkaline olivine basalt, phonolite series</td>
</tr>
<tr>
<td>Alkalic</td>
<td>&lt; 51</td>
<td>Alkali syenite complexes</td>
</tr>
</tbody>
</table>
Calc-alkaline rocks originate from volcanoes on thick continental crust of continental margins or island arcs (Hyndman, 1985). Plutonic members of the calc-alkaline rock series includes gabbro-diorite-granodiorite-granite. The mineralogy of calc-alkaline rocks reflects many nonequilibrium relationships (Hyndman, 1985) and is generally indicated by the composition of the phenocrysts. Abundant plagioclase phenocrysts occur in andesite and basalt whereas quartz and plagioclase are most common in dacite and rhyolite. Augite, hypersthene, and hornblende phenocrysts and occasional biotite, olivine, and sanidine are also common phenocrysts in calc-alkaline rocks.

Lamprophyres are porphyritic rocks which have two types of euhedral mafic minerals (usually combinations of biotite, hornblende, and augite) and feldspars which are confined to the groundmass (Williams et al., 1982). Classification of calc-alkaline lamprophyres in this study follows the scheme recommended by the International Union of Geological Sciences (IUGS) (Rock, 1991; Le Maitre, 1989; Streckeisen, 1979) (Table 5.3). Calc-alkaline lamprophyre nomenclature can be summarized as consisting of two types of biotite lamprophyres, minette (with alkali feldspar) and kersantite (with plagioclase), and two types of hornblende lamprophyres, vogesite (with alkali feldspar) and spessartite (with plagioclase).

Ten compositional varieties were identified in this study and were named based solely on estimated modal mineralogy (Table 5.4). Nine of the rock types are calc-alkaline and account for 95% of the sampled dikes.
Table 5.3 Classification and mineralogical characteristics of lamprophyres (from Hyndman, 1985).

<table>
<thead>
<tr>
<th>Group name and rock name</th>
<th>Phenocrysts and common in groundmass</th>
<th>% mafic minerals</th>
<th>Groundmass and minor other minerals*</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Clinopyroxene</td>
<td>Amphibole</td>
<td>Mica or olivine</td>
</tr>
<tr>
<td>Calc-alkaline and shoshonitic lamprophyres—with postorogenie granitic complexes or shoshonitic rocks</td>
<td>Augite</td>
<td>±</td>
<td>Biotite</td>
</tr>
<tr>
<td>Kersantite</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spessartite</td>
<td>Diopsidic augite</td>
<td>Hornblende (green-brown)</td>
<td></td>
</tr>
<tr>
<td>Minette</td>
<td>Diopsidic augite</td>
<td>±</td>
<td>Biotite</td>
</tr>
<tr>
<td>Vogesite</td>
<td>Diopsidic augite</td>
<td>Hornblende (green-brown)</td>
<td></td>
</tr>
<tr>
<td>Alkaline lamprophyres similar to alkali basalts, nephelinites—with alkaline complexes or carbonatites</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Camptonite</td>
<td>Titanaugite</td>
<td>Ferropargasite ± Ti-biotite and/or hornblende; olivine§ kaersutite</td>
<td>±</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Any lamprophyre may contain, in addition, apatite, opaque minerals, and calcite.
† Andesine or oligoclase.
‡ Ferropargasite hornblende was formerly called barkevikite.
§ For 81-85.
‘ Labradorite or andesine.
Source: After Streckeisen, with additions.
Table 5.4 Compositional varieties of dikes sampled in the Ferrar-Koettlitz Glacier region of southern Victoria Land based on gross mineralogy and modal amounts. Quantities are in ( ).

### Calc-alkaline Dikes

<table>
<thead>
<tr>
<th>Rock Name</th>
<th>Mafics as phenes &amp; in matrix</th>
<th>approx. % mafics</th>
<th>Groundmass</th>
<th>Others</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cpx</td>
<td>Amph</td>
<td>Mica</td>
<td>Feldspar</td>
<td>Others</td>
</tr>
<tr>
<td>Quartz microdiorite  (34)</td>
<td>augite</td>
<td>hornblende</td>
<td>biotite</td>
<td>&gt;35%</td>
</tr>
<tr>
<td>Lamprophyres *</td>
<td></td>
<td></td>
<td>Plagioclase</td>
<td>Others</td>
</tr>
<tr>
<td>Spessartite (30)</td>
<td>±</td>
<td>hornblende</td>
<td>±</td>
<td>&gt;35%</td>
</tr>
<tr>
<td>Minette† (8)</td>
<td>augite</td>
<td>±</td>
<td>biotite</td>
<td>&gt;35%</td>
</tr>
<tr>
<td>Augite (23)</td>
<td>augite</td>
<td>±</td>
<td>Alkali feldspar</td>
<td>others</td>
</tr>
<tr>
<td>Vogesite (4)</td>
<td>±</td>
<td>hornblende</td>
<td>&gt;35%</td>
<td></td>
</tr>
<tr>
<td>Shoshonite * (12)</td>
<td>horblende</td>
<td>±</td>
<td>30%</td>
<td></td>
</tr>
<tr>
<td>Andesite Porphyry (18)</td>
<td>augite</td>
<td>hornblende</td>
<td>biotite</td>
<td>&gt;20%</td>
</tr>
<tr>
<td>Latitic dikes (8)</td>
<td>±</td>
<td>±</td>
<td>5%</td>
<td></td>
</tr>
<tr>
<td>Acid Porphyry (5)</td>
<td>±</td>
<td>±</td>
<td>biotite</td>
<td>1%</td>
</tr>
</tbody>
</table>

### Alkaline Dikes

<table>
<thead>
<tr>
<th>Rock Name</th>
<th>Mafics as phenes &amp; in matrix</th>
<th>approx. % mafics</th>
<th>Groundmass</th>
<th>Others</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lamprophyres *</td>
<td></td>
<td></td>
<td>Plagioclase</td>
<td>Others</td>
</tr>
<tr>
<td>Campionite (15)</td>
<td>augite</td>
<td>hornblende</td>
<td>±</td>
<td>&gt;35%</td>
</tr>
</tbody>
</table>

* includes apatite, carbonate, chlorite, epidote and some opaques as other groundmass components.
† includes biotite-hornblende lamprophyres.
Quartz microdiorites and spessartites are the most abundant type and andesite porphyries and augite lamprophyres are also well represented. The quartz microdiorite variety is the most widespread and occurs in nine of the twelve localities. The only alkaline dikes encountered were camptonite lamprophyres. Dike compositions were typically variable at each locality and only a few sites exhibited a particular dike type. Near Garwood Valley, the majority of the dikes are spessartite lamprophyres, although they could equally be referred to as hornblende-biotite lamprophyres or even microdiorites based on their compositional similarities. Smaller dikes were predominantly fine grained hornblende-rich lamprophyres (spessartites) whereas larger dikes had biotite and quartz-rich margins that graded into an interior dominated by hornblende and plagioclase with subordinate biotite and very little interstitial quartz. These larger dikes are medium to coarse grained. Near Hobbs Peak the dikes are internally homogeneous and are predominantly very fine to fine grained spessartites. Eight dikes of other compositions are also present, consisting of a minette (biotite-alkali feldspar lamprophyre), augite lamprophyres, and quartz microdiorites.

The fifteen dikes encountered at Marshall Ridge are all either spessartites or augite lamprophyres. The two rock types occur in separate groups, with spessartites exposed in the granitic rocks and augite lamprophyres in the metasedimentary rocks (Plate I). The augite lamprophyres are located about 4 km east of the spessartites and exhibit extensive chloritization. This is clearly visible in hand sample as the
rocks exhibit a dark green color. At Shangri-la, only four dikes were observed and all are lamprophyres in which alkali feldspar is the dominant feldspar component. Three are minettes and one is a vogesite (hornblende-rich).

Most of the dikes around Hidden Valley are calc-alkaline lamprophyres (Figure 5.2). Augite lamprophyres are most abundant and are very distinctive petrologically due to the abundance of augite phenocrysts (65% of total minerals present). One augite lamprophyre changes composition along its strike extent to become hornblende-rich. On the southern end of the valley, it is a multiple intrusion in which the outer, earlier phase is a vogesite and the inner, later phase is an augite lamprophyre. Across the valley on the northern ridge, the dike is an augite-hornblende lamprophyre. The presence of hornblende is a distinguishing feature of this particular augite lamprophyre and enabled correlation across the valley. Other extensive and continuous dikes include a minette lamprophyre and a vogesite lamprophyre. On southern exposures, the minette is biotite-rich with minor augite, but on the northern exposures contains very coarse biotite (1 cm phenocrysts) with minor hornblende and augite. The presence of biotite as a major component enabled correlation across the valley since they are the only biotite lamprophyres at this locality. The only other dike type, which commonly crops out as large, anastomosing mafic bands, are quartz microdiorites. The quartz microdiorites are most abundant to the south of Hidden Valley where they are bands with irregular form that are
elongated along northeast trends. One prominent band trends north-northeast and is continuous across the valley on the north side of Hidden Valley. The microdiorites trend northeast, northwest, and west-northwest and are discrete, subplanar bodies. They are mostly unaltered and exhibit a panidiomorphic texture.

At Holiday Peak, just northwest of Hidden Valley, microdiorites and quartz microdiorites were the only dike types observed. Quartz content among the nine dikes varied with some containing significant amounts.

Xenoliths were present in few of the lamprophyres at Hidden Valley and one dike contained abundant granitoid and gneissic xenoliths up to 25 cm in diameter (Figure 5.3). Four other lamprophyres at Hidden Valley contained similar, but smaller xenoliths. Lower crustal and possible upper mantle granulite inclusions have been documented from similar lamprophyres from the Radian Glacier area (Berg, 1988). Two feldspar thermometry analyses yielded equilibrium temperatures of 900°C and pressures of 13.3 kilobars (with +1.6-kilobar correction) reflecting a crustal depth of 45 km. The "extremely pristine" condition of one of the samples would indicate that lower crustal magma propagated quite rapidly to the surface. The origination of upper mantle or lower crustal-derived inclusions seems statistically unlikely (Berg, 1988) and this would therefore put crustal thicknesses over 45 km, probably indicative of deformation and crustal thickening associated with the Cambro-Ordovician Ross orogeny.
Figure 5.3 Abundant granitic and gneissic xenoliths present in a minette lamprophyre dike at Hidden Valley. The xenoliths do not appear to resemble the host rock and may have been derived from lower crustal depths.
Spessartites, camptonites, shoshonites, latitic dikes and a few acid porphyries and andesite porphyries occur in the Bettle Peak area (Figure 5.4). Camptonite lamprophyres are exposed near Herbertson Glacier together with a few latitic dikes. Outcrops just north of Bettle Peak contain a mix of spessartites, latitic dikes, and acid porphyries. A few camptonites are also present. The felsic dikes are numerous in this area and contain abundant hornblende and feldspar phenocrysts (typically 2 to 4 mm) and some granitic xenoliths (2 to 4 cm).

The sparse occurrences of dikes at localities on the Blue Glacier also show varied compositions. Two altered dikes encountered at Briggs Hill are andesite porphyries. A total of five quartz microdiorites were observed at the Stratton Hills, Cathedral Rocks, and Granite Knolls localities. At Granite Knolls there are also a few andesite porphyries. Outcrops at the mouth of the Blue Glacier also contain andesite porphyries. On the western side of the glacier on the ridge just north of Lister Glacier, quartz microdiorites, shoshonites and an acid porphyry are all present.

North of Walcott Glacier, there are mostly andesite porphyries and shoshonites with a few occurrences of quartz microdiorites. The five dikes encountered at Rucker Ridge included three camptonites (alkaline lamprophyres), one shoshonite, and a large and extensive porphyritic andesite. On the ridge to the east of Penny Lake there are a couple of minettes, an augite lamprophyre, a quartz microdiorite, latitic dikes and an andesite porphyry. The augite lamprophyre is partially altered, but
shows similarities to those observed at Hidden Valley, and might actually be a continuation of one of those dikes. Likewise, the minettes are compositionally similar to the minette dike seen in Hidden Valley and may reflect its continuation further south.

Most of the dike types described occur throughout the study area. The Bettie Peak area has the greatest variety of dikes (Figure 5.4). Acid porphyries are only present in the A. A. Thomas Hills swarm and are predominant at Bettie Peak. Calc-alkaline lamprophyres are locally abundant in the Hidden Valley area of the Foothills swarm and the Hobbs Peak area of the A. A. Thomas Hills swarm. Minette and vogesite types only occur in the Foothills swarm at Shangri-la and Hidden Valley. Augite lamprophyres predominantly occur in the Foothills swarm. Spessartites occur in both swarms, but are locally abundant near Hobbs Peak and north of Garwood Valley. Alkaline, camptonite lamprophyres are found in both swarms but are particularly abundant east of Bettie Peak in the A. A. Thomas Hills swarm. Quartz microdiorite dikes are present in both swarms but are locally abundant at Holiday Peak and Hidden Valley in the Foothills swarm. North of Walcott Glacier is the only area within the Foothills swarm where andesite porphyries are abundant. Shoshonite dikes are only found east of Bettie Peak, the ridge north of Lister Glacier, and north of Walcott Glacier. Similarly, latitic dikes occur in both swarms but are only found east of Bettie Peak and east of Penny Lake.
Dike Orientations

Dike orientations in the Ferrar-Koettlitz Glacier region are dominantly northeast (Plate I). The attitudes of 184 dikes were measured directly in the field. Field measurements record local dike attitudes and may reflect the orientation of individual dike segments rather than the dike as a whole. The overall trends of long, continuous dikes were measured from aerial photographs and/or the map compiled from aerial photographs (Plate I). Stereoplots of great circle projections of dike planes from the northern and southern portions of the study area are shown on figures 5.5 and 5.6 respectively. Bold lines outside the periphery of most of these plots represent the overall trend of dike planes measured from aerial photographs and Plate I for a particular locality.

Both east-northeast and north-northwest dikes are present at Cathedral Rocks. One dike plane strikes 012° and dips steeply south. The ~060°-striking dikes all have moderate southeast dips whereas the ~333°-striking dikes have near vertical dips. Since dike occurrences were few and only numbered eleven in total, localities from around the upper, northern area of the Blue Glacier were grouped together for the Blue Glacier stereoplot (BG). They include Briggs Hill (BH), Stratton Hills (SH), and Granite Knolls (GK). Dike strikes from these localities ranged between 035° and 065° and dips were ~80° to both the east and west. One dike plane strikes almost east-west and dips 75° to the north.
Figure 5.5 Stereoplots of great-circle projections of dike planes measured from various localities north of Garwood Valley (GV). Bold lines on periphery of some plots indicate overall map trends. CR = Cathedral Rocks; BG = Blue Glacier localities (includes BH = Briggs Hill; SH = Stratton Hills; GK = Granite Knolls); BP = ridges east of Bettel Peak and including MB (mouth of Blue Glacier); HBP = Hobbs Peak area; LG = ridge north of Lister Glacier. Heavy dashed line = Kukri Peneplain unconformity at the base of the Beacon Supergroup (shown by stippled pattern).
Figure 5.6 Stereoplots of great-circle projections of dike planes measured from various localities south of Garwood Valley. Bold lines on periphery of some plots indicate overall map trends. HP = Holiday Peak; SL = Shangri-la; MR = Marshall Ridge; HV = Hidden Valley; PL = ridge east of Penny Lake; WG = ridge north of Walcott Glacier; RR = Rucker Ridge. Heavy dashed line = Kukri Peneplain unconformity at the base of the Beacon Supergroup (shown by stippled pattern).
Three of the forty two dikes measured from outcrops east of Bettle Peak (BP), just south of the Ferrar Glacier, had north-northwest strikes (350°) and easterly dips. The rest of the dike planes at this locality have northeast orientations and appear to sweep from a northerly trend (010°) to a easterly trend (050°-060°) from northwest to southeast across this area (Plate I). Dike orientations measured in exposures south of the Ferrar Glacier mainly strike north-northeast (008°-016°) and either dip steeply to the east at about 78° or moderately to the west at 60°. Four dikes measured from outcrops near the mouth of the Blue Glacier have similar orientations. A distinct dike trend with an average strike of 056° and uniform dips of about 78° southeast was measured in outcrops in the area south of the Ferrar and adjacent to the Bowers Piedmont Glacier. The overall trend of the dikes north of the Blue Glacier, considering both measured orientations and trends measured off Plate I (especially throughout the A. A. Thomas Hills), is about 042°.

Just south of the Blue Glacier in the area east of Hobbs Peak (HBP), all the measured dikes have a consistent strike averaging 027° and an average dip of 61° east. One dike plane dips about 55° west. This site is unique in the area in having such uniform orientations. A few kilometers to the northeast, the trends of longer, more extensive dikes measured from aerial photographs are 035° to 040° and this may reflect the same sweep towards the east as seen north of the Blue Glacier.
Further south, on ridges just to the north of Garwood Valley (GV), none of the measured dike orientations resemble the average 030° 74° E for the study area. The uncharacteristic east-northeast strikes (averaging 071°) and moderate northward dips (averaging 54°) is due to a deformation event in which the basement rocks and intruding dikes were isoclinally folded. The dikes cut banding in the metasedimentary rocks, but are also folded with them.

On the ridge north of Lister Glacier, where only eight dike orientations were obtained, seven have strikes similar to those north of Garwood Valley. Some are east-northeast with moderate (60°) dips to the southeast, two strike west-northwest with moderate dips to the northeast and one has a typical northeast strike (030°). The dikes cut granite, and no field evidence of folding is present.

Dikes in the southern portion of the study area have northeast strikes between 030° and 060°, and moderate to steep dips averaging 75° with the direction of dip almost equally divided between being east and west (Figure 5.6).

At the Shangri-la locality (SL), dikes strike around 035° and most dip steeply west, with one 88° east. Dike trends measured from the map average 040°, close to the measured strike average. Marshall Ridge (MR), located about 10 to 12 km east of Shangri-la (Plate I), has overall dike trends that are a little more easterly at 050°. The average strike of measured dike planes is about 045°. Six dikes at this locality dip steeply to the west, and a conjugate set of six dip steeply to the east, similar to
Shangri-la.

Dike plane orientations measured at Hidden Valley (HV) have an average northeast strike of about 038°, but vary between 012° and about 055°. The overall trend of the dikes measured off Plate I is 050° which differs by more than 10° from the measured average. This difference is likely due to the change in dike trends along strike in long dikes, which extend up to 10 km. For example, an augite lamprophyre with an along-strike extent of at least 10 km was measured in the field striking 035°, but has an overall trend of 040° measured off Plate I. Along its strike extent, trends vary from 047° at its southern end to 032° at the northern end. Dip and dip directions at Hidden Valley are similar to those at Shangri-la and Marshall Ridge, but more dip to the east. Only four of the 26 dikes deviate from northeast trends. Two dike planes strike northwest (300°) and dip west; one moderately, the other steeply. Another northwest dike strikes 350° and dips about 60° east. One dike strikes 080° and dips 44° west.

The Holiday Peak locality has orientations that are uncharacteristic of the study area. Nine dike planes have an average northwest strike of 298°, and mainly low to moderate easterly dips. Two dikes strike northeast (040°) and have very shallow dips of 15° to the west. Since this area is unique in having mostly northwest trends and very shallow dips, it is probable that these particular orientations indicate that dike emplacement was controlled by a preexisting structure, or that the dikes were deformed after their emplacement. No direct field evidence was found for either of these, however.
Dikes from the three southernmost localities, east of Penny Lake, the ridge north of Walcott Glacier, and Rucker Ridge, all have distinct trends. Eleven dike planes measured on a ridge east of Penny Lake have an average strike of 028° and dip of 73° east. One dike plane strikes 080° and dips about 80° north. Dikes that occur west of the ridge were measured from aerial photographs and trend about 040°. The overall map trend from this locality is 035°. North of Walcott Glacier, seven dikes strike 054° and dips range from 61° to 80° east. One dike strikes 040° and dips about 80° west. The measured strikes correlate well with the overall map trend of 055°.

Eleven dikes planes measured from Rucker Ridge vary greatly in strike from northwest to northeast. Three strike ~305° and dip 70° north and six strike between 023° and 069°, four dipping about 75° south and two 78° north. The remaining two dikes strike 335° and 357° and dip 70° and 86° west respectively.

Each of the ten compositional groups of dikes are also plotted together on stereoplots in Figure 5.7. Distinct trends are present among the different compositions. Quartz microdiorites, which are common throughout the study area, vary the most in orientation and have many shallow dips between 10° and 20°. Calc-alkaline lamprophyres, which include spessartites, minettes, vogesites and augite lamprophyres, are the most abundant dike type. Most spessartite lamprophyres have a dominant 022° strike and steep, easterly dips. Some also strike 050°, but have steep dips to the north and south. The folded dikes north of Garwood
Figure 5.7 Stereoplots of great-circle projections for orientations of the various dike compositions which occur in the Ferrar-Koettlitz Glacier region.
Valley are mostly spessartite lamprophyres, but could equally be referred
to as microdiorites based on their compositional similarities. Augite
lamprophyres strike 035° and predominantly dip steeply east, but a few
also dip west. Minette and vogesite lamprophyres similarly strike
between 030° - 035° but have equal number of planes dipping 70° to the
north and south.

Shoshonites, which compositionally resemble spessartite
lamprophyres, show variable orientations. Five dikes strike between
005° and 030° and have either near vertical dips or moderate dips east
and west. Four dike planes strike between 055° and 085° with steep dips
to the south, and one near vertical plane strikes almost east-west.
The remaining two shoshonite dikes strike 300° and dip about 60° north.

Calc-alkaline intermediate to acid dikes which include andesite
porphyries, latitic dikes, and acid porphyries, all have predominantly
north to northeast strikes. The andesite porphyries strike between 035°
and 050° and have steep to moderate dips both east and west. A few
north-northeast-striking dikes also have steep to moderate dips both east
and west. Seven latitic dikes strike between 015° and 030° and on average
dip 70° east. All five acid porphyries strike about 015° and have moderate
dips both east and west.

Alkaline camptonite lamprophyres, mostly from the Bettle Peak
area, have variable strikes between 295° and 065°. Eight have distinct ~060°
strikes and steep dips to the north and south. One dike strikes 295° and
dips steeply south. The remaining six dikes strike between 340° and 040°
with steep to moderate easterly dips.

On a regional scale, dikes throughout the Ferrar-Koettlitz Glacier region have consistent northeast trends. From the 184 dikes measured in this region, an average orientation of 032°, 74° E was determined through great-circle projection of dike planes and Kamb contouring of great circle poles on stereoplots (Figures 5.8a, 5.8b respectively). Except for localities such as the Garwood Valley area where deformation has reorientated the dikes, and also possibly at Holiday Peak and the ridge north of Lister Glacier, overall map trends are commonly between 040° and 050° and dips mostly 70°-75° east, with some to the west. Map trends from the A. A. Thomas Hills swarm are 040°-045° and 045°-055° for the Foothills swarm.

The 10°-20° overall difference between the measured and map trends reflects the difference between segment strike and dike strike as described by Rickwood (1990) and discussed in Chapter II. The measured trends indicate segment strikes whereas the map trends reflect dike strikes. This variance between segment strike and dike strike is seen at most localities (where indicated, Figures 5.5, 5.6) except north of Walcott Glacier and might suggest that segments were rotated with respect to the overall dike strike through a change in the local stress field during emplacement.

The overall homogeneity of segment strikes throughout the study area (Figure 5.8) is evidence that a uniform regional stress field was the fundamental control during dike emplacement and that rotation could have only been a minor component. In addition, the fact that dikes of
Figure 5.8 Stereoplots of (a.) Great-circle projections and (b.) Kamb contoured great circle poles for all measured dike planes in the Ferrar-Koettlitz Glacier region of southern Victoria Land. The great-circle trace on the Kamb contoured stereoplot represents the average 032°, 74° E orientation of the measured dike planes.
variable compositions all have the same northeast orientations is supporting evidence (Figure 5.7). A change in the regional stress field during dike emplacement would cause a deviation from northeast dike trends and produce a scattering of non-northeast orientations. Since only the older microdiorite dikes show a considerable variation in orientations, this scattering may reflect a variation in the regional stress field before it stabilized and the younger dikes were emplaced.

The fact that the dikes are not vertical means that the orientation of the least compressive stress was not horizontal as in ideal cases, but slightly inclined. Therefore dikes propagated upwards but not vertically. The dikes predominantly have consistent steep dips to the east at 70°-75°, but some dip steeply west. Several possibilities may explain the existence of opposing dip directions. The west dipping planes could reflect the extent of dispersion around an average vertical orientation. A rotation in the stress field may account for the west-dipping planes, however in that case there would likely be numerous cross-cutting relations between east and west-dipping dike planes. Another possibility is that the dikes filled preexisting conjugate fault zones. However, dips of conjugate fault planes in the study area are not steep but generally moderate. Since the majority of the dike planes do consistently dip east at a constant angle, the few occurrences of steeply west-dipping dikes is most likely due to dispersion.
Dike Cross-Cutting Relations

Cross-cutting relations between mafic dikes and between mafic and felsic dikes were observed at several localities. At Hidden Valley where dikes are abundant and well exposed, there were several occurrences of cross-cutting dikes. A northwest-trending dike, containing a schistose fabric and biotite clots and felsic stringers, appears to offset two northeast-trending dikes. Epidote coats both the margins of this dike and the granite host rock, suggesting the presence of hydrothermal fluids during dike emplacement. The same northwest dike also cross-cuts a microdioritic dike striking $351^\circ$, offsetting it 5 m to the right. A very fine grained augite lamprophyre, striking $023^\circ$, cuts a coarse-grained quartz microdiorite striking $062^\circ$ (Figure 5.9). Cross-cutting relations are clear as inclusions of the microdiorite are incorporated in the lamprophyre. Another fine-grained augite-hornblende lamprophyre dike, striking $035^\circ$, displaces a sub-schistose quartz microdiorite dike that strikes $355^\circ$.

On Holiday Peak, two instances of cross-cutting dikes were observed. A schistose dike striking $060^\circ$ cuts a quartz microdiorite that strikes $355^\circ$. A granite pegmatite striking $068^\circ$ cuts off a portion of a quartz microdiorite that strikes due north. Two different cross-cutting relations involving the same dike were observed at Rucker Ridge. A fine grained camptonite lamprophyre striking $308^\circ$ cuts a fine grained granitic dike striking $042^\circ$. An intermediate, fine grained, andesite porphyry that strikes $042^\circ$ cuts the northwest-trending camptonite.
Figure 5.9 A 023°-trending augite lamprophyre (hammer) cuts a 062°-trending quartz microdiorite (trending lower left to upper right) at Hidden Valley.
Near the mouth of the Blue Glacier, an anastomosing, segmented andesite porphyry dike with an overall trend of 024° is cut by three sub-parallel andesite porphyries. The cross-cutting porphyries trend approximately 024°, 016°, and 008°.

Other isolated cases of cross-cutting relations were observed. At the Penny Lake locality, a chloritized augite lamprophyre striking 029° cuts a very schistose quartz microdiorite striking 015°. The lamprophyre dike contains inclusions of possible dioritic material. At Granite Knolls, a linear dioritic intrusion trending approximately 315° is cut by a prominent segmented andesite porphyry with an overall trend of approximately 035°. On the ridge north of Lister Glacier, an aplite vein, striking 067°, is cut by a quartz microdiorite dike striking 278°.

From the observed dike cross-cutting relations, microdiorite dikes are generally the older dike type in the study area. They are typically schistose and irregular and are predominantly cut by northeast dikes. Instances of both northeast-trending dikes cutting northwest dikes and vice versa were observed. Since cross-cutting occurrences are sparse throughout the region, there is little evidence for any consistent change in the regional stress field as the dike swarm was emplaced. The overall dike trend is northeast, indicating that multiple intrusive events occurred under a dominant, uniform regional stress field during the interval when the dike swarm intruded.
**Dike Morphology**

Dikes with in situ margins are either continuous and planar or are subdivided into a series of subparallel segments. Some dikes are wavy with curved margins, but these are rare at most localities. An exception occurs at Hidden Valley where several large mafic bands have an irregular, curving form but trend generally northeast (Plate I).

Dikes commonly consist of a series of sub-parallel en echelon segments where propagating magma-driven fractures rotate to remain perpendicular to the least compressive stress direction (Pollard, 1987; Rickwood, 1990). Segmented dikes are present at all localities with the exception of near Garwood Valley, where the dikes are folded and segmentation may have been obscured by the deformation. Dike segments generally overlap and in many cases display converging horns separated by bridge material. Non-overlapping, offset dike segments with blunted ends were also found. In these cases dike offset could reflect original emplacement morphology or could be due to subsequent faulting. It was often difficult to distinguish between these possibilities due to frost-wedging of both the dike material and host rock. Linked, en echelon dike segments were observed at Granite Knolls, where an andesite? dike shows a preserved segment horn (Figure 5.10). Excellent examples of overlapping, converging dike horns were observed at Marshall Ridge, Shangri-la, and Rucker Ridge (Figure 5.11). Other notable examples were found at Hidden Valley, near Bettle Peak and east of Penny Lake. At Hidden Valley, two segments of an augite lamprophyre dike are connected
Figure 5.10  Preserved segment horn (person) after linkage of two preexisting en echelon segments of an andesite? dike, Granite Knolls.
Figure 5.11 Overlapping, converging segment horns of a spessartite lamprophyre dike at Marshall Ridge.
along an offset plane at high angles to both segments (Figure 5.12). Possible buds formed by localized thickening along dike walls are exposed on one side of dike margins near Bettle Peak and Granite Knolls. A "process zone" is a bundle of extension fractures that splay out from a dike tip and which forms during propagation of a magma-driven tensile crack (Pollard, 1987). This type of feature was found at Hidden Valley, Shangri-la, and Granite Knolls, and is remarkably exposed at Rucker Ridge (Figure 5.13).

Sheeted dike intrusions were encountered at Hidden Valley, but were not found elsewhere in the study area. A prominent dike that trends 030°, made up of overlapping en echelon segments, can be traced on both sides of Hidden Valley. The dike is 25 cm wide and contains an inner, later phase 8 cm wide. Amygdules flank the outer margin of the inner dike and are 1-2 mm in diameter (Figure 5.14). Petrographically, the two dike phases differ in mafic components, but both contain alkali feldspar as the dominant feldspar component. The inner dike is an augite lamprophyre which is moderately altered and has an intergranular texture consisting of 35 percent augite phenocrysts and 20 percent biotite lathes. The outer dike phase is a vogesite lamprophyre and is predominantly composed of hornblende (50 percent) and moderately altered augite phenocrysts. On the northern ridge of Hidden Valley, another well-defined example of a sheeted dike intrusion was discovered. The alkaline lamprophyre dike has an outer, fine grained phase containing mafic vesicular enclaves. The interior of the dike, flanked on
Figure 5.12 Offset segments of an augite lamprophyre dike linked by a 'connector' segment, Hidden Valley.
Figure 5.13 Process zone of a camptonite lamprophyre dike in which magma-generated extension fractures splay off a segment horn, Rucker Ridge. Pencil is scale.
Figure 5.14 Sheeted dike intrusion. The marginal phase is a hornblende lamprophyre (vogesite) and the inner, later dike phase is an augite lamprophyre.
both sides by amygdules, consists of a later, coarse grained phase.

Emplacement of hot intruding dike magma into colder country rock results in the formation of a fine grained chilled margin of igneous rock along the dike's border. Chilled margins were only encountered on dikes north of Garwood Valley, Hidden Valley, near Bettle Peak, and near the mouth of the Blue Glacier. Elsewhere, dikes are homogeneous in grain size across their entire extent. Near Garwood Valley, a hornblende rich lamprophyre (spessartite) exhibits a schistose, fine grained margin that grades into coarse lenses in the center. At Hidden Valley, a biotite lamprophyre (minette) grades from very fine grained margins to a very coarse grained interior with biotite grains up to 1 cm in size. Near Bettle Peak, a fine grained hornblende lamprophyre (spessartite) which has felsic schlieren patches up to 30 cm in diameter, has chilled margins and a coarse grained interior with hornblende laths up to 6 mm. A prominent andesite porphyry near the mouth of the Blue Glacier has a chilled margin in which the grain size variation is not as pronounced as observed at the other localities. The interior is medium to coarse grained and the margins are fine grained.

Field Relations of Dikes and Host Rock Structures

The consistent northeast trends of the southern Victoria Land dikes throughout their regional extent suggests they were emplaced under a uniform regional stress field. To document this, it is necessary to determine whether the dikes propagated independently of any pre-existing
structures in the host rocks. Field relations between the dikes and host rock structures are critical to establishing the mode of dike emplacement, and observations were made where exposure permitted throughout the study area.

**Folds, Compositional Banding, and Foliations**

The basement metasedimentary units of the study area have been isoclinally folded, and thus contain parallel compositional banding and foliation. The overall regional trends of the banding and foliation is northwest between 300°-320°. In general, the dikes throughout the area cut these surfaces at high angles (Plate I, Figure 5.15). Near Garwood Valley, however, dikes were folded with the host rocks (Figure 5.16); dike margins predominantly cut host rock banding at low angles but are also folded with the banding. The dikes are mostly spessartite lamprophyres or quartz microdiorites. The smaller folded dikes (about 100 m in length and 1.5 m in thickness) commonly contain a schistose fabric. Since the area was isoclinally folded, the dikes typically occur as straight fold limbs along ridges and dip moderately north. However, locally, isoclinal fold hinges were observed (Figure 5.17). Since undeformed, planar spessartite lamprophyres exist elsewhere in study area, this would suggest that there must have been at least two episodes of magma intrusion of this composition.
Figure 5.15 Northeast-trending dikes (black arrows) extending from Miers Valley (Miers Lake in foreground) southward across Hidden Valley, cut northwest-trending banding and foliation in the host rocks (double-barbed arrow) at a high angle (Janosy and Wilson, 1992).
Figure 5.16 View of south facing-slope north of Garwood Valley, showing early generation spessartite lamprophyres folded together with the surrounding metasedimentary host rocks (Janosy and Wilson, 1992).
Figure 5.17 Isoclinal fold hinge in a spessartite lamprophyre, Garwood Valley. Hammer is in for scale.
Other localities also have regionally anomalous attitudes. Dikes north of Lister Glacier have northwest orientations similar to those near Garwood Valley, but most have moderate dips south and a few north. Quartz microdiorite dikes at Holiday Peak strike northwest but have shallow dips between 15° and 30° to the north. These unusual orientations from both localities could suggest episodes of folding, however, there was no direct supporting field evidence at either site.

Granitoid units within the study area are both foliated and nonfoliated. Foliation trends in these units are northwest as seen in the metasedimentary units. Dikes were always observed cutting foliation in the granitoids. Foliated granitoid units at Shangri-la and Hidden Valley were cut by dikes at high angles.

In the southern part of the study area near the Radian Glacier, foliation trends in both metasedimentary and granitoid units sweep from northwesterly to easterly-northeasterly trends (Plate I). These trends reflect subsequent deformation events after isoclinal folding. Randomly-oriented dikes at Rucker Ridge were observed cutting the foliation and banding in the host rock.

**Faults**

Numerous brittle fault arrays occur throughout the entire study area. Five distinct sets have been recognized in the region by Wilson (1992) including 030°, 060°, 080°, 320°, and 350° sets. A majority of these faults cut the dikes. Relations with northwest and northeast faults are discussed
separately in sections below.

Northwest-trending faults

Almost all northwest-trending faults within the study area cut and displace northeast-trending dikes with right-lateral strike separation. Near Garwood Valley, two northwest-trending faults striking 325° and 310°, displace dikes 14 m right laterally and 5 m vertically, respectively. A 350°-trending fault 1 m wide displaces a dike 9 m right laterally.

Within the Foothills swarm, many occurrences of northwest-trending faults cutting northeast-trending dikes were observed. Northeast-trending mafic and aplite dikes are cut by ~320° and ~350° trending fault sets at Marshall Ridge. The observed northwest fault planes exhibit right-lateral displacement of dikes up to 15 m (Figure 5.18). A particular site showed multiple right-lateral offsets of individual northeast-striking dikes by both fault sets (Figure 5.19). The ~320° set shows reactivated motion in a different direction along the same fault. This was noticed in the field from offset dike segments which showed opposite sense of drag on either side of several ~320° trending fault zones. Just west of Marshall Ridge at Shangri-la, northwest faults mapped off aerial photographs are continuous up to 3 km, trend 320° and appear to offset northeast-trending dikes and faults right laterally (Figure 5.20). Abrupt right-lateral offsets seen in two dikes trending 035° may be related to northwest faulting.
Figure 5.18 A northeast-trending spessartite lamprophyre dike (white arrows) is offset to the right about 10 m along a northwest-trending fault (double-barbed arrow), Marshall Ridge.
Figure 5.19 Spessartite dike group (heavy solid lines) trending approximately 030°-040° is displaced by two northwest-trending fault sets (~320° and ~350°), and an approximately east-west trending set (thin solid lines and dashed where inferred). Inset boxes show reactivation by motion in different directions along same fault. This is evident by the sense of drag seen on the dike terminations. Scale is approximate.
Figure 5.20 Northeast-trending dikes (heavy lines) parallel chloritized fault zones (lightly dashed lines). Both are cut by northwest-trending faults (heavy dashed lines) and displaced right laterally. Solid lines mark either dikes or faults, which could not be differentiated on aerial photographs. Shangri-la.
Many inferred northwest-trending fault zones at Hidden Valley are defined as snow-lined lineaments on aerial photographs which generally offset northeast-trending dikes right laterally. Most of these lineaments that were observed in the field lacked discernable striated surfaces, but were presumed to be fault zones by the numerous and abrupt dike offsets along their extent. About five prominent fault zones mapped from aerial photographs are up to 3.3 km in length and bisect the valley area trending approximately 300° (Figure 5.21). A few of these extensive fault zones were traced in the field and were observed offsetting several northeast-trending dikes up to 84 m right laterally. Many northeast-trending dikes along the valley's northern ridge were observed having multiple right-lateral offsets from numerous fault zones trending approximately 320°. These fault zones average 525 m in length and lack striated surfaces. They offset at least seven dikes up to 20 m right laterally and one dike 10 m left laterally.

Further south near Penny Lake, a prominent andesite porphyry dike trending 030°, is offset 50 m to the left across a 300°-trending fault zone (Figure 5.22).

Only a few occurrences of northwest-trending faults cutting northeast-trending dikes were observed in the northern A. A. Thomas Hills swarm. Evidence of faulted dikes near Bettle Peak was inferred by the presence of displaced segments since very few fault zones provided convincing striated surfaces. Four north-northeast-trending dikes are displaced ~26 m right laterally across a 1 km fault trending 300° (Figure 5.23). At the same locality, a camptonite lamprophyre striking 053° has
Figure 5.21 Prominent northwest-trending fault zones bisect the Hidden Valley area, offsetting northeast-trending dikes right laterally.
Figure 5.22 A northwest-trending fault (arrow) offsets a northeast-trending andesite porphyry dike 50 m left laterally on the ridge east of Penny Lake (Wilson, 1992).
Figure 5.23 A northwest-trending fault (bottom left) offsets dikes B, C, D, and E 26 m right laterally and a northeast-trending fault (bottom center) offsets undescribed dikes left-laterally, east of Bettle Peak.
multiple 1 m right-lateral offsets by several 330°-trending faults. Near
the mouth of the Blue Glacier, faults trending 295° and 287° with well-
developed striated surfaces, offset a prominent north-northeast-trending
dike right-laterally by 10 m and 2 m respectively. Two northeast trending
dikes east of Hobbs Peak, appear displaced right-laterally 18 m by two
northwest striking faults.

A rare case observed at Hidden Valley involved a dike following a
northwest fault. A northwest-trending microdiorite dike containing
aligned biotite clots, appeared to have filled a preexisting fault zone and
was observed offsetting several dikes right laterally. The presence of
abundant epidote and red feldspar deposits on the granite host rock
suggests a period of hydrothermal alteration.

Northeast-trending faults

Northeast-trending faults generally either paralleled dikes or offset
them left laterally. Within the A. A. Thomas Hills swarm, most northeast-
trending faults offset dikes left laterally and some occurrences of dikes
paralleling the northeast faults were also observed. At Bettle Peak, a
prominent fault mapped off aerial photographs trends 035° and offsets
many north-northeast-trending dikes left laterally (Figure 5.23). An east-
trending fault offsets a northeast-striking latitic dike 1.5 m left-laterally.
Several northeast-trending faults offset a northwest-trending dike left
laterally up to 23 m. A chloritized fault zone trending 055° closely
parallels a camptonite lamprophyre dike but offsets an aplite dike 11 m
left laterally.

A few occurrences of faulted dikes were observed at two localities in the Blue Glacier area. Dikes at Granite Knolls both parallel and truncate northeast fault zones. A large quartz microdioritic dike trending 096° is offset left laterally up to 60 m by two northeast faults trending 028° and 047°. An andesite porphyry and a quartz microdiorite dike were observed trending subparallel to northeast-trending chloritized fault surfaces. At the ridge north of Lister Glacier, a dike trending 290° shows possible left separation across a 053°-trending fault.

In the Foothills swarm, northeast-trending faults were observed mostly paralleling dikes or offsetting them left laterally. Many mafic and aplite dikes at Marshall Ridge are cut by a 060° fault set. The northeast-trending fault set commonly displaces dikes left laterally up to 10 m. At Shangri-la, numerous northeast-trending chloritized fault surfaces, with an average trend of 030°, parallel minette and vogesite lamprophyre dikes (Figure 5.20). These fault surfaces stand up slightly in relief in low exposures above valley gravel material, similar to dike exposures, apparently because alteration along the dikes provided greater resistance to erosion. Approximately six parallel chloritized fault surfaces trending 025°-030° crop out for 250 m between two dikes. One dike, striking 032°, follows a northeast-trending chloritized fault zone. A possible segment of this dike strikes 046° and partially follows a chloritized fault zone, but then veers off along a 021° trend and terminates as a 19 m-long fracture.
At Hidden Valley, most northeast-trending dikes were observed paralleling northeast faults. Three dikes parallel 030°-trending striated, brecciated fault zones within 3 m of their margins. A dike connector observed linking two segments (Figure 5.12), trends 060° and may have partially utilized a preexisting fault as indicated by chloritized breccia flanking the margin. However, no striated surfaces were found.

Northeast trending faults offset shallow-dipping, northwest-striking quartz microdiorite dikes at Holiday Peak. Two dikes striking 300° are displaced ~30 m left laterally by a 038° trending fault first described by Mortimer (1981). A 034°-trending fault also offsets one of the 300°-trending dikes 5 m and has slickenfibers indicating normal left-lateral motion.

Rare occurrences of northeast-trending faults offsetting dikes right laterally were also observed within the study area. A 035°-trending fault zone offsets a northwest-trending wavy microdiorite band right laterally at Hidden Valley. The amount of offset could not be determined due to rubbly outcrop. At Rucker Ridge a fault trending 060° displaces a northwest-trending camptonite lamprophyre 7 m right laterally. Near Garwood Valley, two faults trending 028° and 034° offset east-northeast dikes 19 m vertically and 3 m right laterally, respectively. A fault trending 052° offsets a quartz microdiorite dike 30 m right laterally at Granite Knolls. At the same locality, a northeast-trending fault offsets a mafic dike 3 cm right laterally.
Both northeast and northwest brittle fault arrays cut the dikes within the study area. Field relations have determined the northwest fault set as generally being the younger of the two and that the northeast faults formed during and after late stages of dike emplacement. Evidence supporting this latter claim includes the occurrence of northeast faults predominantly cutting older quartz microdiorite dikes and paralleling younger augite lamprophyre dikes. Most of the dikes that are cut by the northeast-trending faults have non-northeast orientations such as the quartz microdiorite dikes at Holiday Peak and Hidden Valley and the folded spessartite lamprophyres north of Garwood Valley. The younger dikes which generally parallel the northeast faults are lamprophyres as seen at Shangri-la, Hidden Valley, and near Bettle Peak.

Locally there is a strong correlation between dike orientations and fault orientations. For instance, dike planes and fault planes from north of Lister Glacier and Cathedral Rocks show very similar orientations, suggesting the faults were preexisting structures utilized during dike emplacement. At Holiday Peak, however, the dikes are generally unrelated to fault trends. Overall, the dikes are more consistent in orientation throughout the study area than the faults (Wilson pers. comm., 1994). Dips among the dikes are dominantly 70°-75° to the east (Figure 5.8a) whereas the northeast fault set is conjugate with more variation in dip directions.
Fractures

Systematic fracture sets could only be unambiguously identified where host rock exposures are relatively intact. Massive granitoid and marble exposures proved to be the only rock types favorable for preserving fracture sets. Generally two joint sets trending 320°-350° and 020°-040° were recognized in the study area.

Well developed joint sets oriented approximately 035° and 320° cut fine to coarse grained granite near the margins of northeast trending dikes at Shangri-la. Most dike segments cut the 030°-040° trending joint set at low angles. In some cases however, dike segments parallel the northeast-trending joint set but converging dike horns at segment tips cross-cut the jointing at low angles (Figure 5.24).

At Hidden Valley, two joint sets trending 035° and 350° cut through granodiorite and are truncated by a northeast trending augite lamprophyre dike (Figure 5.25). These well-developed joints are locally up to 5 m in length and spaced ~25 cm apart. The northeast joint set intersects the dike margin at a very low angle and the northwest set at a high angle. The dike and the joint sets dip in opposite directions. Closely-spaced fractures less than 1 cm apart also occur within 5 cm of the dike margins. Also in Hidden Valley, two augite lamprophyre dikes have irregular-spaced joints localized within 2 to 3 m of their margins. The joints are spaced 30 - 70 cm apart and are 3 - 5 m in length. Two other dikes have curved horns that cut obliquely to a joint set trending 030°-040°. A process zone spreading out 30 cm obliquely to segment strike from a
Figure 5.24 Well-developed joint sets oriented approximately 035° and 315° in a coarse grained granite at Shangri-la are cut by the curving tips of overlapping dike segments. Rock hammer in upper center of picture is scale.
Figure 5.25 Joint sets trending 035° (hammer) and 350° in a granodiorite are truncated by a northeast-trending augite lamprophyre at low and high angles, respectively, at Hidden Valley.
curved dike horn has fractures spaced 1-5 cm apart.

Granite host rock exposed at the ridge north of Lister Glacier has well developed 320°-trending joints that are cut by a west-northwest striking quartz microdiorite dike.

At both Holiday Peak and Granite Knolls, moderately developed joint sets trending 030° and 310° in host granite are cut obliquely by curved dike horns.

Closely-spaced joints trending 030° and spaced 5-30 cm apart are locally developed at Bettle Peak. The joints are several meters in length and are truncated by a northeast-trending spessartite lamprophyre at low angles. Also within the A. A. Thomas Hills swarm, a wavy andesite porphyry at the mouth of the Blue Glacier cuts a joint set trending 020° at low angles and in places a 320° joint set appears to truncate the dike margin. Spessartite lamprophyre dikes with segment strikes between 020°-025° at Hobbs Peak cross-cut a 030° trending joint set at very low angles and locally appear to parallel the joint set.

Only two joint sets were observed near dike margins and it is not known if they are developed along the entire strike extent of a dike. The joint sets have trends between 020°-030° and 320°-350° and are generally truncated by ~035° striking dike segments at low and high angles which suggests that the dikes did not exploit preexisting joints. Joints were only observed to be up to 5 m in length and do not appear to have overall lengths equivalent to those of the dikes. Occurrences of closely-spaced small scale fractures within 10 cm of the dike margins at Hidden Valley
might indicate that the fracture surfaces formed as tensile cracks during dike intrusion and were too small to be invaded by dike magma.
CHAPTER VI
DISCUSSION

Mode of dike emplacement

Dikes of uniform orientation indicate that emplacement was controlled by either a regional stress field or by pre-existing regional structures. In the Ferrar-Koettlitz Glacier region of southern Victoria Land, the characteristics of the dikes indicate that they filled self-generated tensile hydrofractures and the emplacement of the Early Paleozoic Victoria Land dike swarm was controlled by a regional stress field.

The consistent northeast dike trends throughout the study area is the most compelling evidence for regional stress control. Dike trends average 040°-045° in the northern A. A. Thomas Hills swarm and 045°-055° in the Foothills swarm to the south. Dike dips are predominantly easterly at 70°. Dikes of different composition all have the same northeast orientation suggesting that multiple intrusive events occurred under a uniform stress field.

Several factors indicate that the uniform dike orientation is due to regional stress control rather than emplacement along pre-existing fractures. The regional northeast-east trending fault set is not as
consistent in orientation as the dikes. Northeast faults show considerable scatter in both strike and dip. Although the northeast fault set is known to occur regionally at a mesoscopic scale, the total strike extent of individual fault planes has not been determined due to ice cover. However, from aerial photo mapping, it is likely that individual dikes are much more continuous than the individual fault planes. Most of the northeast-trending faults cut the dikes within the study area and thus postdate dike emplacement, indicating that these zones of weakness were not present during dike intrusion. Evidence of dikes exploiting northeast-trending fault zones was observed at several localities, which indicates that dike emplacement may have overlapped in time with northeast faulting. A northeast-trending joint set is cut by dikes and therefore predates dike formation but is only developed locally along dike margins and thus it is unlikely that the dikes exploited pre-existing joints.

Dike morphology within the study area is typical of magmatic hydrofractures. The dikes are characterized by en echelon segmentation, which forms as a result of mixed mode I, III fracturing due to local rotation of the least compressive stress about an axis parallel to the dike’s propagation direction. A few dikes are curved along their length, indicating they are mixed Mode I, II fractures formed as the least compressive stress changes orientation through rotation about an axis parallel to the dike periphery.
Chronology of dike emplacement

Dikes of different generations with distinct orientations represent a change in the regional stress field during dike emplacement. If the relative ages of the different generations are known through cross-cutting relations, the chronology of dike emplacement can be determined. In the study area several generations of dikes were identified. Quartz microdiorite dikes represent an early generation of dikes that were emplaced under a nonuniform stress field. Trends of these dikes from the study area are highly scattered and dips are also variable. The quartz microdiorite dikes are cut by the other dikes in the region. Two different generations of spessartite lamprophyres occur within the study area. An early generation, which only occurs between Salmon Glacier and Garwood Valley, is folded isoclinally and thus predates the end of ductile deformation in the region. Younger, undeformed spessartite lamprophyres are present throughout most of the study area, particularly in the northern portion, and have uniform northeast trends and steep easterly dips.

Cross-cutting dikes are rare in the study area, and the overall dike trends are consistently northeast, indicating that multiple intrusive events of different magma compositions occurred under a single, uniform regional stress field. Only dikes east of Bettle Peak have different compositions with distinct trends. Alkaline camptonite lamprophyres trend east-northeast and calc-alkaline dikes trend north-northeast, suggesting that these types have different emplacement ages.
**Paleostress History**

Dikes are emplaced in an orientation normal to the least compressive stress and parallel to the plane containing the maximum and intermediate compressive stresses (Anderson, 1951; Delaney and Pollard, 1981). The regional paleostress regime that existed at the time of dike emplacement can therefore be reconstructed from dike trends. In the study area, the regional Victoria Land dike swarm has a dominant northeast trend indicating the least compressive stress, and the regional extension direction, was oriented approximately northwest-southeast, oblique to the Early Paleozoic Antarctic margin. The early generation of spessartite lamprophyres was emplaced before compressive deformation had ceased. The scattered quartz microdiorite dikes were intruded after this deformation, but before a regional extensional regime was established. Intrusion of subsequent magma batches appears to have been controlled by a uniform stress field associated with regional northeast-southwest extension along the East Antarctic margin. The limited age data currently available do not constrain the time period over which this stress regime persisted.

Localities such as north of Garwood Valley, Holiday Peak, the ridge north of Lister Glacier, and Rucker Ridge do not have uniform northeast dike orientations. These areas may have experienced local changes in the stress regime, may have undergone a later, local deformational event, or the dikes may have been emplaced into local pre-existing structures such
as joints or faults.

Tectonic Models

Recent tectonic models for the evolution of the Ross orogen propose compressional to transpressional tectonic processes in a convergent setting (Allibone et al., 1993b; Goodge et al., 1993; Borg and DePaolo, 1991). However, these models have not accounted for the paleostress regime required for emplacement of the regional Early Paleozoic Victoria Land dike swarm. These tectonic models are tested below to determine whether they can generate a stress field necessary to produce northeast-trending magmatic hydrofractures. A model for the Antarctic margin in the Ferrar-Koettlitz Glacier region is proposed.

Early Paleozoic plutonic rocks associated with Ross magmatism are developed in a belt along the Transantarctic Mountains that roughly defines the Early Paleozoic Antarctic plate margin (Figure 6.1). This plutonic belt will be used as a basis to reconstruct and test various tectonic models for southern Victoria Land.

Subduction along a convergent margin has recently been proposed along southern Victoria Land during the Ross orogeny. The Early Paleozoic plutons in the Dry Valleys region are Cordilleran I-type granitoids inferred to have developed above a west-dipping subduction zone along the Antarctic margin (Allibone et al., 1993b; Smillie, 1992). The dike swarms, however, have Caledonian I-type alkali-calcic chemistries and are suggested to have been emplaced within 10 Ma or less
Figure 6.1 Early Paleozoic plutonic rock (stippled) associated with Ross magmatism are developed as a belt along the Transantarctic Mountains (after Stump, 1992). This batholith belt is considered to define the position of the Early Paleozoic Antarctic plate margin.
of the Cordilleran I type granitoids during a period of postsubduction crustal extension (Allibone et al., 1993b; Smillie, 1992; Keiller, 1991). Wu and Berg (1992) postulate that the lamprophyre dikes intruded along tension joint fractures generated from oblique southwestward subduction based on their compositional variation and northeast-southwest orientation.

Four different scenarios may possibly have produced the regional extension associated with dike swarm emplacement. Rifting may have occurred perpendicular to the margin after subduction had ceased (Figure 6.2a). Since the Early Paleozoic plutonic belt was oriented approximately north-south subparallel to the present-day Antarctic margin, extension would have been east-west and the dikes therefore would have been emplaced in a north-south direction. This scenario could not have generated the northeast trends of the dikes unless the Antarctic margin was oriented northeast.

Another possible tectonic scenario involves dike emplacement along an active convergent margin. Regional extension can occur in the back-arc region of an overriding plate above a subduction zone (Nakamura and Uyeda, 1980) (Figure 6.2b). Extension would be oriented close to normal to, and dike swarms emplaced parallel to, the convergent plate margin. Since the Victoria Land dike swarm trends northeast, this scenario is unlikely unless this sector of the active margin was oriented northeast.
Figure 6.2 Various tectonic scenarios along the Early Paleozoic Antarctic margin (thin dashed line) which may have produced the regional extension associated with dike swarm emplacement (thin solid lines). Inset box indicates study area. a. Extension perpendicular to the margin (short arrows) would produce hydrofractures oriented parallel to the margin. To generate northeast-trending hydrofractures, the craton margin would have to be oriented NE-SW (heavy dashed line) and the extension direction NW-SE (long arrows). b. Back-arc regions of a subduction margin may have extension normal to the convergent margin, with normal faulting and dike emplacement parallel to the margin (after Nakamura and Uyeda, 1980).
Large-scale strike-slip translation is a third possibility for producing extension along a plate margin. Sinistral shear would produce tensile hydrofractures oriented northwest and normal to the trend of the Victoria Land dike swarm (Figure 6.2c). Dextral shear, however, would generate extension fractures oriented northeast, similar to the dike trends (Figure 6.2d). This scenario could have produced the Victoria Land dike swarm.

Transtension coupled with oblique subduction could produce northwest-southeast oriented extension along a convergent margin and is proposed here for the evolution of the Early Paleozoic Antarctic margin (Figure 6.2e). Dextral shearing associated with regional strike-slip translation and oblique southwestward subduction would produce an extensional strain regime compatible with emplacement of the northeast-trending dike swarm. This tectonic regime could also produce the regional northeast faulting associated with dike emplacement.
Figure 6.2 (continued) c. Sinistral shearing associated with large-scale strike slip translation parallel to the margin would generate northwest-trending tensile hydrofractures. d. Dextral shearing would produce northeast-trending hydrofractures. e. Transtension and oblique southwestward subduction could produce a northwest-southeast tensional stress field and emplace northeast-trending dikes.
CHAPTER VII
CONCLUSIONS

The major conclusions of this study are:

1) The extensive Victoria Land dike swarm constitutes a major petro-tectonic element in the region.

2) On a regional scale, dikes throughout the Ferrar-Koettlitz Glacier region have consistent northeast trends. The overall map trends of the dikes within the study area are commonly between 040° and 050°. The average measured orientation is 032°, 74E.

3) Ten compositional groups of dikes were identified, nine of which are calc-alkaline. Calc-alkaline lamprophyres are the most abundant dike type. A variety of dike types are present at most of the localities. Several episodes of dike emplacement occurred.

4) The dikes were emplaced as tensile hydrofractures and were not controlled by pre-existing structures. The various compositional types, with the exception of the quartz microdiorites, all have uniform northeast trends. The uniform orientations of the dikes are evidence for emplacement under a regional stress regime. Lower crustal/mantle inclusions in lamprophyre dikes are evidence that magma-generated fractures transect the crust.
5) The regional extension direction associated with dike emplacement was northwest-southeast and oriented obliquely to the Early Paleozoic Antarctic margin.

6) Dextral transtension due to southwestward oblique subduction is proposed as the tectonic setting during emplacement of the Victoria Land dike swarm along the Early Paleozoic Antarctic margin.
Plate I. A 1:100,000 scale geological map showing the distribution of igneous dike swarms in the Ferrar-Koettlitz Glacier region of southern Victoria Land, Antarctica.
DISTRIBUTION OF IGNEOUS DIKE SWARMS IN THE FERRAR-KOETTLITZ GLACIER REGION, SOUTHERN VICTORIA LAND, ANTARCTICA

Robert J. Janosy
1994

LEGEND

- Undifferentiated Late Cenozoic surficial deposits
- Cenozoic McMurdo Volcanic Group
- Undifferentiated Late Precambrian-Early Ordovician plutonic rocks
- Late Precambrian metasedimentary rocks
- Igneous dikes (includes lamprophyres, microdiorites, shoshonites, latitic dikes, andesitic and acid porphyries)
Base map north of 78°00'S latitude compiled from unpublished 1:50,000 topographic series (Cape Chocolate and Granite Knolls sheets) in preparation by the U.S. Geological Survey and the New Zealand Department of Survey and Land Information.

Base map south of 78°00'S latitude compiled from 1983 U.S. Navy vertical aerial photograph series.

APPENDIX B

ROCK DESCRIPTIONS
(Quartz) Microdiorite

In hand specimen the majority of these rocks are melanocratic, fine to medium grained, and equigranular with some showing foliation. This representative sample, E-9, has aligned hornblende crystals approximately 2-3 mm in length. Other noticeable minerals include biotite flakes, quartz, feldspar, and green pyroxene phenocrysts.

In thin section, rock sample E-9 is equigranular, phaneritic, panidiomorphic-granular texture with only slight alteration. Since the thin section was cut perpendicular to the foliation, the alignment of the hornblende grains is not shown. Minerals present include:

Plagioclase - subhedral to euhedral equant crystals mostly 0.6-0.75 mm in diameter with some larger grains up to 1 mm in length. Composition is mostly andesine. Some grains show moderate alteration (seritization) and others in contact with alkali feldspar grains exhibit sodic rims.

Alkali feldspar - predominately unaltered subhedral grains 0.5 mm in diameter with some larger grains up to 0.8 mm. A few grains show some minor alteration (seritization). Occurs intermixed with ferromagnesium minerals and in contact with plagioclase grains.

Hornblende - abundant, and predominately euhedral, green, stubby (basal) prisms 0.5 mm in length with few elongate prisms up to 1.5 mm and all having pleochroism from light yellow to green. Individual grains are scattered throughout with few tight clusters 1 mm in diameter.

Biotite - grains are all euhedral and elongate 0.6-0.75 mm in length with pleochroism from straw yellow to reddish brown. They occur mostly as individual grains scattered evenly throughout, but also closely associated with some hornblende clusters.

Augite - large anhedral crystals up to 3 cm in length showing replacement predominately by feldspar and minor biotite and hornblende.

Quartz - anhedral grains also occur sporadically throughout averaging 0.4 mm in diameter.

Accessory minerals include minor apatite and epidote.
(Quartz) Microdiorite (continued)

Approximate Mineral Proportions

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plagioclase</td>
<td>35%</td>
</tr>
<tr>
<td>Alkali feldspar</td>
<td>20%</td>
</tr>
<tr>
<td>Hornblende</td>
<td>20%</td>
</tr>
<tr>
<td>Biotite</td>
<td>12%</td>
</tr>
<tr>
<td>Augite</td>
<td>10%</td>
</tr>
<tr>
<td>Quartz</td>
<td>3%</td>
</tr>
</tbody>
</table>

Figure B.1 Photomicrograph of a quartz microdiorite dike (uncrossed polars; magnification 25x). Field of view is approximately 4 mm across: a = augite; b = biotite; f = feldspar; h = hornblende; q = quartz.
Spessartite Lamprophyre

In handspecimen, these rock types are all melanocratic, commonly light to dark grey on a fresh surface. They occur as both porphyritic and slightly porphyritic (almost equigranular) and are fine to medium grained. A representative sample, C-2R, is mostly equigranular and medium grained and contains abundant hornblende crystals.

In thin section, sample C-2R is equigranular, phaneritic with a hypidiomorphic-granular texture. It is predominately composed of plagioclase and hornblende with minor biotite. Alteration is minimal and mostly affecting only hornblende grains. In other spessartite samples, subordinate augite is also common as phenocrysts and/or a matrix constituent. Minerals present include:

Plagioclase - euhedral, elongate prisms ranging from 0.5 to 0.75 mm in length. Grains are relatively fresh with some showing slight alteration. Composition is oligoclase and andesine.

Hornblende - grains are subhedral to anhedral and mostly occur as elongate prisms with some stubby, basal varieties. Sizes range from 0.2 mm to 2 mm and commonly 0.6 mm. Some elongate prisms show simple twinning. Pleochroism is light green to light brown. Clustering of grains is common. Grains show moderate alteration and markedly green rims.

Biotite - few anhedral and subhedral grains exist mostly as replacement of hornblende. Grains are about 0.5 mm on average with few isolated grains up to 1.5 mm.

Minor minerals present include sphene, quartz, apatite, allanite, chlorite after biotite, and carbonate.
Approximate Minerals Proportions

Plagioclase  60%
Hornblende  32%
Biotite     5%
Minors      3%

Figure B.2 Photomicrograph of a spessartite lamprophyre dike (uncrossed polars; magnification 25x). Field of view is approximately 4 mm across: f = feldspar; h = hornblende; c = carbonate; cl = chlorite.
Minette Lamprophyre

In hand specimen, the minettes are predominantly aphanitic and slightly porphyritic to strongly porphyritic. They are melanocratic and light greenish-grey to light grey in color. Most often, biotite flakes can be observed as speckles on a fresh surface. Samples with hornblende also exhibit this same surface feature. Only one sample was collected in which biotite flakes form cakes up to 1 cm across.

In thin section, sample E-6M is coarse-grained, porphyritic, phaneritic and moderately to heavily altered. The biotite predominately occurs as large, deformed porphyritic grains. Hornblende and augite are also altered and occurs as microphenocrysts. The matrix is too altered to determine composition. Other samples contain approximately 50% granular alkali feldspar in matrix. This particular sample was described because of its deformed biotite grains. Minerals present include:

**Phenocrysts**

**Biotite** - predominately anhedral to subhedral, deformed, large elongate grains that show significant replacement along edges. Deformational features include ripped ends, kink bands, and internal warping. Sizes range between 2.5 - 5 mm in length. Remnant grains are clean and show pleochroism from straw yellow to pale orange, some with green rims.

**Hornblende** - anhedral to subhedral grains that show slight to severe alteration. Commonly occur in clusters, but also individually. Sizes range between 0.5 to 1 mm. Show light brown/orange pleochroism.

**Augite** - subhedral to anhedral grains showing severe alteration, especially in cores. Most grains occur individually with only few clusterings. Sizes range from 0.5 mm up to 1.25 mm in diameter.

**Minor minerals** present include carbonate, apatite, and epidote

**Matrix** too altered to determine composition of components.
**Minette Lamprophyre** *(continued)*

**Approximate Mineral Proportions**

<table>
<thead>
<tr>
<th>Phenocrysts</th>
<th>80%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biotite</td>
<td>55%</td>
</tr>
<tr>
<td>Hornblende</td>
<td>15%</td>
</tr>
<tr>
<td>Augite</td>
<td>10%</td>
</tr>
<tr>
<td>Matrix</td>
<td>18%</td>
</tr>
<tr>
<td>Minors</td>
<td>2%</td>
</tr>
</tbody>
</table>

* Due to few numbers, this particular group of biotite lamprophyres also includes 3 biotite-hornblende lamprophyres that are not labeled as minettes because of almost equal amounts of hornblende and biotite.

Figure B.3 Photomicrograph of a minette lamprophyre dike (uncrossed polars; magnification 25x). Field of view is approximately 4 mm across: **a** = augite; **b** = biotite; **h** = hornblende.
**Augite Lamprophyre**

In handspecimen, these lamprophyres are all melanocratic, dark grey to black on a weathered surface and grey on a fresh surface. They are predominately equigranular and fine- to medium-grained with some samples having biotite flakes less than 1 mm in diameter. Few samples also contain equant granitic/gneissic xenoliths commonly up to 6 cm across.

In thin section, representative sample E-5D is porphyritic with abundant augite phenocrysts. Secondary minerals (replacing augite?) such as carbonate and feldspar form glomeroporphs up to 2 mm in diameter. The groundmass is moderately altered and contains carbonate material and abundant subradiating acicular biotite grains. Minerals present include:

**Phenocrysts**

**Augite** - abundant euahedral hexagonal grains ranging up to 2 mm in diameter but commonly 0.5 to 1 mm. Grains are slightly to moderately altered and have concentric zoning and thin chloritized rims. They mostly occur individually or less commonly in clusters of only 2 grains.

**Matrix**

Moderately altered and containing abundant acicular biotite grains. The felsic fraction is too altered to identify composition. Minor, identifiable minerals include **augite**, **hornblende**, **carbonate**, **epidote**, **chlorite**, and abundant **apatite**.

**Biotite** - subhedral, acicular grains averaging 0.3 mm in length. Grains do not appear to be as altered as rest of groundmass, but does show some chloritization. Color is reddish brown. Grains appear to subradiate and also outline only the polygonal edges of the carbonate/feldspar glomeroporphs.

Minor minerals present include **carbonate** and **feldspar** as glomeroporph components.
**Augite Lamprophyre** (continued)

**Approximate Mineral Proportions**

<table>
<thead>
<tr>
<th>Phenocrysts</th>
<th>63%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Augite</td>
<td>63%</td>
</tr>
<tr>
<td>Matrix</td>
<td>35%</td>
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<tr>
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<tr>
<td>Feldspar</td>
<td>13%</td>
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<tr>
<td>Minors</td>
<td>2%</td>
</tr>
<tr>
<td>Minors</td>
<td>2%</td>
</tr>
</tbody>
</table>

Figure B.4 Photomicrograph of an augite lamprophyre dike (uncrossed polars; magnification 25x). Field of view is approximately 4 mm across: a = augite; b = biotite; f = feldspar; c = carbonate.
Camptonite Lamprophyre

In hand specimen, these rocks, and representative sample D-1D, are melanocratic - dark grey to black, massive, and predominately equigranular - aphanitic. Few are medium-grained. A particular sample has numerous radiating hornblende lathes up to 2 cm long on a flat, weathered surface.

In thin section, sample D-1D is porphyritic with phenocrysts and abundant microphenocrysts of altered augite. Groundmass is pilotaxitic with subradiating plagioclase microlites and small needles of dark brown, alkali-rich hornblende (barkevikite?). Alteration seems to only be confined to augite phenocrysts. Minerals present include:

Phenocrysts

Augite - altered euhedral to subhedral hexagonal grains showing almost complete replacement by carbonate and chlorite. Microphenocrysts range from 0.25 mm to 0.6 mm in diameter and larger phenocrysts up to 1.25 mm.

Quartz - one subrounded grain approximately 1.25 mm in diameter contains a rim of carbonate material surrounding it. Grain may possibly be a xenocryst.

Matrix

Consists of a pilotaxitic texture and components appear to "flow" around phenocrysts.

Plagioclase - consists of subradiating, euhedral laths averaging 0.3 to 0.4 mm in length that comprise most of the groundmass. Most grains are unaltered and have sodic rims. Some show replacement by carbonate material. Composition could not be determined.

Hornblende - predominately present as subradiating euhedral needles but also as euhedral, stubby basal prisms averaging 0.25 to 0.5 mm in length. Grains are fresh and clean and have a characteristic dark red/brown color.

Other minor minerals present include chlorite (as replacement mineral in augite phenocrysts), carbonate material, apatite, and opaques.
Camptonite Lamprophyre (continued)

Approximate Mineral Proportions

<table>
<thead>
<tr>
<th>Component</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phenocrysts</td>
<td>23%</td>
</tr>
<tr>
<td>Augite</td>
<td>23%</td>
</tr>
<tr>
<td>Matrix</td>
<td>75%</td>
</tr>
<tr>
<td>Plagioclase</td>
<td>50%</td>
</tr>
<tr>
<td>Hornblende</td>
<td>25%</td>
</tr>
<tr>
<td>Minor</td>
<td>2%</td>
</tr>
</tbody>
</table>

Figure B.5 Photomicrograph of a camptonite lamprophyre dike (uncrossed polars; magnification 25x). Field of view is approximately 4 mm across: f = plagioclase feldspar; h = hornblende.
**Shosbonite**

In hand specimen, this melanocratic rock varies from aphanitic and slightly porphyritic to medium-grained and porphyritic. They samples also vary in color from greenish grey to dark charcoal grey. A medium-grained porphyritic representative sample, E-11A, contains noticeable phenocrysts of hornblende and feldspar. The finer grained samples exhibit alignment of hornblende laths.

In thin section, sample E-11A is the cleanest and less altered of its type. It has a pandiomorphic-granular texture and is porphyritic, phaneritic. It closely resembles a hornblende lamprophyre apart from the felsic phenocrysts. Glomeroporphy phenocrysts occur throughout composed mostly of fibrous hornblende and chlorite and average 1 mm in diameter. The matrix is composed mostly of plagioclase and alkali feldspar and hornblende. Other fine-grained shoshonite samples exhibit a pilosaxitic texture of feldspar and hornblende laths. Minerals present in sample include:

**Phenocrysts**

**Plagioclase** - Grains are elongate and equant, euhedral prisms. Some have concentric zoning and altered cores. Sizes range from 1.25 to 4 mm. Composition is andesine.

**Hornblende** - Few hornblende phenocrysts occur as euhedral, elongate prisms between 1.75 to 2 mm in length. Few exhibit simple twinning. Pleochroism is light brown/orange to a rusty color.

**Matrix**

**Plagioclase** - Abundant, predominately unaltered, elongate and equant prisms between 0.25 to 1 mm. Some cores show alteration and sodic rims are common around most grains. Composition is andesine.

**Hornblende** - All grains are euhedral and occur as both elongate and stubby, basal prisms. Sizes range from 0.2 mm to 1.5 mm. Some elongate grains exhibit simple twinning and basal grains show concentric zoning. Most grains also show greenish rims. Only hornblende grains contained in glomeroporphyhs are altered and are usually fibrous and replaced by chlorite.
Shoshonite (continued)

Alkali feldspar - euhedral to subhedral elongate and stubby, subequent prisms from 0.2 to 1 mm. Some show altered cores. Composition is orthoclase and sanidine?

Biotite - occurs in minor amounts mostly as replacement mineral of hornblende. Euhedral to subhedral grains only 0.25 to 0.75 mm in length. More common in glomeroporphs where chlorite is also present.

Minor minerals include chlorite, apatite, carbonate, and quartz.
Approximate Mineral Proportions

Phenocrysts 10%
   Plagioclase 8%
   Hornblende 2%

Matrix 88%
   Plagioclase 35%
   Hornblende 23%
   Alkali Feldspar 25%
   Biotite 5%

Minors 2%

Figure B.6 Photomicrograph of a shoshonite dike (crossed polars; magnification 25x). Field of view is approximately 4 mm across: f = plagioclase feldspar; h = hornblende.
Andesite Porphyry

In handspecimen, the majority of these samples are strongly porphyryitic while in others it is less obvious and mostly equigranular. All samples are melanocratic with a fine- to medium-grained groundmass. Phenocrysts are predominately plagioclase and are up to 1 cm with some mafic grains 4 mm in diameter.

In thin section, representative sample E-11C contains large phenocrysts of fresh, unaltered plagioclase, dark red biotite, and moderate to severely altered augite and hornblende. Glomerophorphs of all four phenocrysts are common and up to 4 mm across. The groundmass is aphanitic and comprised mostly of plagioclase microlites, biotite laths and quartz. Minerals present include:

Phenocrysts

Plagioclase - clean, unaltered euhedral prisms up to 5 mm in length with distinct polysynthetic twinning. Some subrounded grains exhibit concentric zoning. Few grains cluster together in a prismatic habit, while others are part of glomerophorphs with biotite, hornblende and augite. Sodic rims are evident on some phenocrysts. Composition is oligoclase to labradorite, but mostly andesine.

Biotite - dark red-brown, unaltered, elongate prisms up to 2 mm in length, but commonly 0.8 mm. They mostly occur individually, but some are contained in glomerophorphs.

Hornblende - subhedral to anhedral elongate prisms - some stubby or basal prisms. Grains range from 0.5 to 1.75 mm in length, but commonly 1 mm. All have deuteritic alteration to biotite. Some grains show simple or polysynthetic twinning. Most grains occur individually and some in glomerophorphs.

Augite - grains are subhedral to euhedral, stubby, subhexagonal crystals up to 2 mm in diameter, but mostly 1 mm. Rims are deuteritically altered with some smaller grains showing complete alteration. Large phenocrysts occur individually while smaller grains are usually clustered together or in glomerophorphs.

Matrix

The groundmass consists of plagioclase microlites, biotite laths, and some alkali feldspar and quartz. Apatite is present, but not abundant.
**Andesite Porphyry (continued)**

**Approximate Mineral Proportions**

<table>
<thead>
<tr>
<th>Phenocrysts</th>
<th>75%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plagioclase</td>
<td>55%</td>
</tr>
<tr>
<td>Hornblende</td>
<td>10%</td>
</tr>
<tr>
<td>Biotite</td>
<td>5%</td>
</tr>
<tr>
<td>Augite</td>
<td>5%</td>
</tr>
<tr>
<td><strong>Matrix</strong></td>
<td>25%</td>
</tr>
</tbody>
</table>

Figure B.7 Photomicrograph of an andesite porphyry dike (crossed polars; magnification 25x). Field of view is approximately 4 mm across: **f** = plagioclase feldspar; **h** = hornblende; **b** = biotite.
Latitic dike

In hand specimen, this rock type varies from being equigranular aphanitic to aphanitic, porphyritic. Colors also vary from being subleucocratic to melanocratic. Phenocrysts in porphyritic varieties are feldspar up to 1.75 cm with minor quartz and mafic minerals. Darker, rounded mafic xenocrysts up to 6 cm in length occur in few samples. Representative sample E-9A is predominately aphanitic equigranular (slightly porphyritic) and has a light olive green-grey color exhibiting a dull luster, and a granular texture on a fresh surface.

In thin section, sample E-9A is subporphyritic, aphanitic with only a few phenocrysts - a subrounded quartz xenocryst and some completely altered feldspar. The matrix is basically quartz free and composed of granular alkali feldspar? and replaced plagioclase? laths with interstitial chlorite, carbonate and opaques. It is possible that both alkali feldspar and plagioclase make up the groundmass in near equal proportions, but definite modal amounts are indeterminable due to alteration. Minerals present include:

**Phenocrysts**
- **Feldspar** - few large euhedral to subhedral grains 0.25 mm exists. Grains are completely replaced by carbonate material, so composition is indeterminable.
- **Quartz** - one large subhedral xenocryst 3 mm in diameter is present and exhibits a rim of carbonate material.

**Matrix**
- **Feldspar** - euhedral elongate laths averaging 0.75 mm in length exhibit a subradiating habit. Grains show replacement by carbonate material. Fine-grained granular feldspar fills in around elongate laths. Possible composition of laths is plagioclase, and granular material might be alkali feldspar.
- **Mafics** - predominately secondary alteration products such as chlorite (some after biotite).
- **Carbonate** - occurs as an alteration product and is responsible for replacing a majority of (plagioclase?) feldspar.

Other minor matrix components include **apatite** and **opaques**.
Approximate Mineral Proportions

<table>
<thead>
<tr>
<th>Phenocrysts</th>
<th>3%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Matrix</td>
<td>97%</td>
</tr>
<tr>
<td>Feldspar</td>
<td>90%</td>
</tr>
<tr>
<td>Mafics</td>
<td>5%</td>
</tr>
<tr>
<td>Minors</td>
<td>2%</td>
</tr>
</tbody>
</table>

* Due to the altered nature of these rocks (5 total), identification of the feldspar composition was difficult and ambiguous. Therefore, rock name is loosely applied and composition may vary between andesitic and latitic.

Figure B.8 Photomicrograph of a latitic dike (crossed polars; magnification 25x). Field of view is approximately 4 mm across: f = feldspar; c = carbonate; cl = chlorite.
Acid Porphyry

In hand specimen, these rocks are leucocratic with a pea to olive green color and are porphyritic with an aphanitic groundmass. They have a dull, resinous luster and have phenocrysts of quartz and biotite.

In thin section, representative sample, K-1P, exhibits a microfelsitic texture of feldspar and quartz grains with phenocrysts of quartz and heavily altered biotite grains. Minerals present include:

Phenocrysts

Quartz - round anhedral grains 0.7 to 1.25 mm in diameter. They occur mostly as loose aggregates of 3-4 grains up to 1.75 mm in length. The grains are all fresh and unaltered.

Plagioclase - moderate to heavily altered euhedral to subhedral grains showing replacement by iron oxides. Grains range from 0.5 to almost 1 mm in length.

Biotite - possible heavily-altered biotite present as elongate prisms up to 1 mm in length and closely associated with altered plagioclase phenocrysts.

Matrix

Interlocking equant quartz and alkali feldspar grains form a felsitic texture and are commonly 0.25 mm in diameter. A few epidote crystals, only 0.15 mm long, are also present.
**Acid Porphyry** (continued)

**Approximate Mineral Proportions**

<table>
<thead>
<tr>
<th>Phenocrysts</th>
<th>5%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quartz</td>
<td>3%</td>
</tr>
<tr>
<td>Plagioclase</td>
<td>1%</td>
</tr>
<tr>
<td>Biotite</td>
<td>1%</td>
</tr>
<tr>
<td><strong>Matrix</strong></td>
<td>95%</td>
</tr>
</tbody>
</table>

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Figure B.9  Photomicrograph of an acid porphyry dike (crossed polars; magnification 25x). Field of view is approximately 4 mm across:

- **f** = feldspar;
- **q** = quartz;
- **b** = biotite.
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