USE OF THESES

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THE GEOLOGY
OF THE
FRIEDA RIVER COPPER PROSPECT,
PAPUA NEW GUINEA

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A thesis submitted for the degree of
DOCTOR OF PHILOSOPHY

in the

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STATEMENT

Much of the geological framework and description in this thesis is based on field work completed while the author was in the employment of Frieda Exploration Pty. Ltd. (FEPL) from 1974 to 1978. However, the geological mapping was greatly refined by work of other project geologists and I benefited from numerous discussions with these geologists as stated in the acknowledgments. The geology of areas based on the author's work is noted in the section headed 'Basis of This Work'. The areas mapped by the author and those mapped by other FEPL geologists are outlined on a reliability diagram in Map 2.

Appendix 4 contains a reprint of a manuscript co-authored with Mr. N. Asami, formerly a senior project geologist of FEPL. The paper was written shortly after the author arrived at the Australian National University and was based primarily on work completed between 1974 and 1978 by the authors and other project geologists (see the reliability diagram in Map 2 for general distribution). In addition to field mapping, the author's contribution to the paper involved: substantial reorganization and rewriting of an original draft by Mr. N. Asami, re-examination of several hundred thin sections and X-ray diffraction of selected samples, clarification and augmentation of parts of the discussion and interpretation through a literature study, and help in compilation and preparation of figures and plates.

Chapter 4, a study of the geochronology and geochemistry of the Frieda River Prospect is a joint project with Drs. J.B. Whalen and I. McDougall. The author's input throughout this study involved: assistance in selection of samples for analysis and dating, the preparation of 7 mineral separations, the provision of the geological foundation for the work, interpretations of the results in terms of their
geological context, especially the geochronological data, and preparation of the manuscript. All other work was done by Drs. Whalen and McDougall.

Unless otherwise stated in the acknowledgments or text of this thesis, all other work is my own.

Signed: RONALD M. BRITTEN
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The scope of this thesis would have been severely limited without the help of many people and the support, co-operation, and consent of several organizations.

The companies in the Frieda consortium are Mount Isa Mines (MIM), Overseas Mineral Resources Development (OMRD of Japan), Frieda Co. Limited, CRA Exploration Pty Limited, and Norddeutsche Affinerie. Mount Isa Mines Limited is the Manager of the Project and operates through Frieda Copper Pty Ltd’ (FCL), which is a Papua New Guinea incorporated wholly owned subsidiary of MIM Holdings Limited. The consortium companies through FCL provided sponsorship, field support, field data, and other facilities during this study for which they are gratefully acknowledged.

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ABSTRACT

The Frieda River Prospect is located in structurally disrupted middle Miocene eugeosynclinal sediments that form part of the New Guinea Mobile Belt in the West Sepik District of Papua New Guinea. The structurally-controlled comagmatic extrusives and intrusives of the Frieda River Complex represent a remnant volcanic edifice of a near-shore stratovolcano that was interstratified with marine sediments at the southern margin of a submerging trough. Epithermal copper-gold and massive sulphides and porphyry copper deposits are associated with early and late phases, respectively, of a geothermal-hydrothermal system that caused extensive district-scale advanced argillic alteration along the central axis of the Frieda Complex.

Igneous activity, as indicated by K-Ar hornblende ages, extended over an interval of at least 4 m.y. On the basis of field relations and K-Ar ages this igneous activity is subdivided into early intrusion (17.3 to 16.8 m.y.), main intrusion (16.8 to 13.1 m.y.), and late alteration (about 13.5 to 11.2 m.y.) events. Geothermal-hydrothermal activity extended from earlier than 14.0 ± 0.4 m.y. until about 11.2 ± 0.2 m.y. ago. The Nena copper-gold mineralization was emplaced prior to 13.0 ± 0.4 m.y. whereas the porphyry copper systems were developed during a cooling history of at least 2 m.y. between 13.6 ± 0.4 m.y. and 11.5 ± 0.2 m.y. ago.

Igneous rocks of the Frieda River Complex are all of andesitic composition and belong to a normal K calc-alkaline suite. Their diversity in lithology and dispersion in chemistry is due to them representing cumulate-melt mixtures that have recrystallized from hot (> 900°C), oxidized magmas. Exposed intrusive rocks were emplaced at less than 2 km and P_total < 0.5 kb.
Approximately 50 km$^2$, that measures about 13 km by 4 km, has been altered over a vertical extent of 2000 m in the central regions of the Complex. District-scale advanced argillic alteration progresses from deep-level sericite-pyrophyllite-diaspore assemblages upward and outward through assemblages dominated by quartz, alunite, kaolinite-dickite, to propylitic assemblages in marginal zones.

The Nena mineralization represents a zone within this system that was anomalously rich in S, Cu, Au and As. Mainly fracture-controlled luzonite-enargite-chalcolite mineralization of the Nena deposit followed pervasive quartz-rich, inner massive pyrite and outer alunite-dominated alteration. It is estimated to have been emplaced within 200 to 400 m of the surface at temperatures between 200 to 300°C.

Biotitic alteration in the porphyry copper systems is viewed as an extension of magmatic processes and was caused by an alkali-chloride-rich volatile phase that evolved from a hydrated and oxidized cumulate-melt mixture while the magma was above the solidus. Sequential breaching of a solidified carapace and influx of cooler meteoric waters caused the inner zones of vein-controlled transitional alteration and progressively outer zones of chloritic, sericitic ± andalusite and, at deep levels, peripheral propylitic alteration. At higher levels the advanced argillic zones which consist of pyrophyllite-diaspore, alunite, and kaolinite developed as pH and temperature decreased with time from a near maximum of 600°C (Eastoe, 1976) in the inner transitional zone to about 300°C in the upper and outer advanced argillic assemblages.

The major controls on the development of the alteration-mineralization zonation were oxidation of H$_2$S to produce fluids of low pH, temperature decrease, dilution effects, host-rock mineral equilibria reactions and the relation between reaction rates and duration of events.
At least 1 billion tonnes of S has been added to the overall geothermal-hydrothermal system. Pb and K, and Rb and Cu have been added to district-scale advanced argillic alteration and the porphyry copper mineralization, respectively. Trace elements that are depleted in the intensely silicified and massive pyrite zones associated with district-scale are normally enriched in the outer alunitic and kaolinite-dickite alteration zones. Most trace elements in the porphyry copper systems have only been locally transferred. Major element chemistry of the various alteration assemblages are compatible with mineralogic changes.
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CHAPTER 1

INTRODUCTION

1.1 LOCATION, CLIMATE AND ACCESS

The Frieda River copper prospect is located at S4°42' and E141°37' (Fig. 1.1) at the mid-upper reaches of the Frieda River, a north-flowing tributary of the Sepik River in the West Sepik Province of Papua New Guinea. The Frieda River drains the foothills of the Schatteburg Range and overall relief, although locally very dissected and steep, is dwarfed to the south by the massive central ranges that have many peaks over 3000 m and form a formidable 70 km wide east-west barrier. The coastal town of Wewak lies 250 km to the northeast; swampland of the Sepik River constitutes 30-40% of that distance. The border of Irian Jaya, a province of Indonesia, is about 80 km due west of the prospect.

In the area of the prospect, elevations range from 300 m to 1650 m and average roughly 800 m. The topography is very dissected, with dense jungle covering steep slopes. Climate is tropical equatorial; annual rainfall averages 8000 mm and temperatures range from 20° to 30° C. Although heaviest precipitation occurs in a poorly defined wet season from August to March, daily, late-afternoon rain is normal throughout the year. Helicopter access to various parts of the prospect is often hampered by cloudy weather or early morning valley-bottom fog.

Vegetation beneath the high, dense, rainforest canopy is relatively sparse and easily traversed. In contrast, the low scrub vegetation characterized by stunted trees, abundant vines, and thick moss that normally grows in leached, acid soils derived from strongly altered volcanics is more difficult to penetrate.
Figure 1.1 Location and principal physiographic features at the Frieda River Prospect. Names such as Ekwai Debon and Ok Ekwai are derived from the local dialect and translate as Ekwai Mountain and Ekwai River, respectively.
The prospect is very isolated. There are no roads and prior to investigation by mining companies, exploration of the area relied solely on river transport. Access was improved in 1969 with the construction of Frieda airstrip by Carpentaria Exploration Company Pty. Ltd. (CEC) near the junction of the Frieda and Nena Rivers which allowed servicing of the prospect by light aircraft from Wewak or Madang. However, even with the airstrip, the transport system is costly and complex. From the airstrip to the main Frieda base camp it is 22 km by helicopter. Bulk supplies are presently shipped by barge 270 km from Madang to the mouth of the Sepik River and, 570 km up the Sepik River to a supply depot at Inoik, a small village at the mouth of the Frieda River. From Inoik, supplies travel 55 km up the Frieda River by double canoe to another depot at Paupe and a further 18 km by jet boat from Paupe to Frieda airstrip.

The indigenous population probably does not exceed 300 and is divided between the Mianmin villages to the west and the Unamo-Wabian villages to the east. A land boundary between these two villages or clans is marked to the south of the Nena River by the central ridge line of the Frieda Complex. Because of the acid soil and steep topography this area is not suitable for gardening and, has been described by some locals as a 'no-mans land'. The area is crossed by walking tracks, most constructed recently, as a direct result of mining exploration. Another consequence of exploration activity is a noticeable encroachment of villages and gardens toward the margins of the Frieda Complex and Base Camp over the last few years.
1.2 PREVIOUS WORK

The Frieda River area was first mapped by the Bureau of Mineral Resources, Geology and Geophysics, Australia, in 1966 to 1967 (Dow et al., 1972). In 1968, regional exploration geochemistry of the area surrounding the Frieda Prospect was initiated by CEC. Aspects of this work have been reported by Lord (1978) and Smith (1978). Follow-up geochemistry continued to 1973 and, included detailed examination and drilling of two porphyry copper mineralized zones, the Koki and Horse deposits; the results were reported by Smith and Hall (1974) and Hall and Simpson (1975). Detailed mapping of the intrusive and extrusive rocks of the Frieda Complex and two additional centres of mineralization, the Ivaal and Nena, was carried out by Frieda Exploration Pty. Ltd. (FEPL), a consortium of Japanese companies represented by Overseas Mineral Resources Development of Japan (OMRD) Frieda Co. Ltd. from 1974 to 1978; the results of this work have been reported by Asami and Britten (1980, Appendix 4).

A preliminary geochemical examination of the Frieda intrusives, in conjunction with other intrusive complexes throughout Papua New Guinea was undertaken by Mason (1975) and reported by Mason and MacDonald (1978) and Mason (1978). Page (1971) completed a geochronology study of intrusive complexes in Papua New Guinea that also included the Frieda River Prospect (Page and McDougall, 1972a). Whalen et al., (see Chapter 4) have recently completed a detailed study of the geochronology and geochemistry of the Frieda River Complex and Eastoe (1976, 1979) has done a reconnaissance fluid inclusion study.
1.3 AIMS AND FORMAT OF THIS THESIS

The primary aims of this thesis are to document the geology, alteration, and mineralization of the Frieda River Prospect copper deposits, to synthesize a genetic model, and to present criteria to help guide explorationists. Results are classified as preliminary nature because surface exposure is poor and, at the present stage of evaluation, drill core provides the only fresh, continuous sampling, especially of alteration zones.

Seven additional chapters comprise the bulk of this thesis and have the following format. Studies of the geology, structure, and alteration and mineralization are integrated on a regional scale (Chapter 2), the Frieda Complex or district scale (Chapter 3), and ore deposit scale (Chapters 5 and 6). The porphyry copper systems are examined in the greatest detail (Chapter 5) whereas the Nena mineralization (Chapter 6) receives less attention due to time constraints. The regional scale study (Chapter 2) is mainly a literature search that illustrates the temporal and spatial relationships of the Frieda Complex to the regional geology. A joint study of the geochronology and fresh rock geochemistry of the Frieda River Complex (Chapter 4) and the geochemistry of the alteration assemblages (Chapter 7) are integrated with the other chapters of this thesis in a concluding section (Chapter 8) in which the geological history and favoured models are discussed.

1.4 BASIS OF THIS WORK

Field work completed between August 1974 and March 1978, while the author was a prospect geologist in the employment of FEPL, is the basis of many of the ideas and interpretations in this thesis. Early work included follow-up on a copper-gold soil geochemical anomaly that is
located west of the Horse deposit and was originally outlined by a CEC survey. Consequently, the Ivaal chalcocite blanket was discovered and was quickly delineated by the efforts of several FEPL and CEC geologists; the area was subsequently investigated with shallow percussion drilling. Regions peripheral to the Ivaal were also explored and the author mapped in detail the areas west of the Ivaal and, at a later date, east of the Horse deposit. Investigation of these areas was aided by petrologic examination of about 100 thin sections (Britten, 1976; Sumiko Consultants Co. Ltd., 1975, 1977). Following detailed drilling of the Ivaal it was realized that the Horse and Ivaal deposits were not separate mineralized centres, but were offset members of the same orebody which, in consequence, is referred to as the Horse/Ivaal deposit.

Supergene malachite, steel grey chalcocite, and spotty chalcocite-covellite associated with the Nena mineralization were discovered as a result of follow-up investigations of another CEC copper silt anomaly. The author mapped the area in detail and later reconnaissance-mapped and sampled peripheral regions. The vast difference in response of copper in silt, soil, and water samples between the Nena mineralization and porphyry copper systems was noted about this time and further investigation resulted in a preliminary report on the exploration potential of hydrogeochemistry (Britten, 1977).

Toward the latter stages of the author's work for FEPL the northwestern end of the Frieda Complex, the northern end of the Mianmin area, and the valleys between these regions were reconnaissance-mapped. Fill-in reconnaissance mapping of the Frieda Complex volcanics south of the Nena River to Keidalit Creek was completed at a later date. Much of this work and the work of other
Nearly all the drill core from the Horse/Ivaal, Koki, and Nena mineralization, in addition to core recovered from peripheral areas (roughly 30,000 m) were examined, documented in summary form, and sampled. Hand specimens collected by the author and other project geologists from all parts of the prospect were examined and about 800 were sampled for purposes of X-ray diffraction and thin section work.

Armed with a considerable personal and company data base, research commenced at the Australian National University (A.N.U.) in June 1978. These data were used to write a paper on the porphyry copper deposits at the Frieda River Prospect (Asami and Britten, 1980). Later research carried out at A.N.U. included: K-Ar isotopic age dating of igneous events (Whalen et al., in prep.); petrography of rock types and alteration, aided by thin section, polished section, microprobe and X-ray diffraction techniques; and alteration geochemistry.
CHAPTER 2

REGIONAL SETTING

2.1 INTRODUCTION

Chapter 2 illustrates the Frieda Prospect in relation to the regional geology and tectonics of the island and relies heavily on published work. Access, logistic and historical problems have hindered geological work in the central region of both Papua New Guinea and the Indonesian province of Irian Jaya. These problems are reflected in the tectonic interpretations of the island which normally omit Irian Jaya and the western extremity of Papua New Guinea where porphyry copper mineralization of the Frieda River and OK Tebi Prospects is located.

The geology of Papua New Guinea was first presented in a comprehensive framework by Thompson and Fisher (1965). Maps were later compiled by Bain et al. (1972) and D'Addario et al. (1976) and reported by Dow (1975, 1977). Concurrently, scores of authors studied various facets of Papua New Guinea geology and formulated models principally in terms of the plate tectonic theory; these syntheses are reviewed by Johnson (1979).

A simplified speculative account of the geology of Irian Jaya (Hermes, 1974) is based on photogeological interpretation over wide areas and reflects the paucity of data collected and work done in the region. Hamilton (1979) presents a comprehensive study that, in addition to his own studies, is based on field work of government surveys, geophysical data from a variety of sources, and oil exploration company data. Hamilton's work is notable because it examines the geology of Irian Jaya and the bulk of Papua New Guinea, all of Indonesia, the southern parts of Southeast Asia and northern Australia.
2.2 REGIONAL GEOLOGY

The Frieda Complex forms part of a fault-bounded block that is wedged between two major structural features, the Frieda and Lagaip Fault Zones (Fig. 2.1). Major faults, which change trend from westerly to north-northwesterly across the prospect area, commonly bound major changes in stratigraphy and cause uncertain relations between stratigraphic units. The brief descriptions of major stratigraphic units below that are taken largely from Dow et al. (1972) and Davies (1979) reflect this uncertainty.

**Om Beds**: South of the Lagaip Fault Zone are black carbonaceous schist, phyllite and slate of the Om beds (Map 2.1). At their southern margin these beds primarily consist of black carbonaceous siltstone and mudstone. Fossils indicate an age ranging from Middle Jurassic to middle Eocene Dow et al. (1972).

**Ambunti Metamorphics**: These metamorphics occur in the northwest portion of the map area and expand to the north where they underlie much of the Sepik Valley. The Ambunti metamorphics consist mainly of quartz feldspar mica schist and quartz plagioclase hornblende gneiss. Their age and stratigraphic relations are uncertain but they are definitely older than the middle Miocene (Dow et al., 1972).

**Salumei Formation**: The western extent of the Salumei Formation roughly coincides with the location of the Frieda Complex and lies between the Frieda and Lagaip Fault Zones. In this area it consists of slate, phyllite, sericite chlorite schist and metamorphosed sandstone, conglomerate, basalt, and limestone. Unmetamorphosed units of the Salumei Formation which are located off the map area (Fig. 2.1) to the east have an age (based on foraminifera) of Upper Cretaceous to Eocene...
Figure 2.1 Simplified geology of the Mianmin sheet (modified after Davies, 1979).
(Dow et al., 1972). The Salumei Formation is presumed to overlie the Om Beds whereas the relation with the Ambunti Metamorphics is not clear; they could be to more severely metamorphosed time equivalents of the Salumei Formation, or be basement to the Om Beds (Davies, 1979).

April Ultramafics: Bodies of peridotite, dunite and serpentinite that range over 30 km long are found intruding pre-Miocene rocks (mainly the Salumei metamorphics) in the map area (Fig. 2.1). These bodies parallel the west-northwest regional structural trend and are typically bounded by fault or shear zones. The ultramafics must have been emplaced after the Eocene because they intrude the Salumei Formation but before the middle Miocene because ultramafic pebbles occur in basal units of the Wogamush Formation. K-Ar ages indicate the April Ultramafics are younger than 25 m.y. (Page, 1976).

Wogamush Formation: The Wogamush Formation consists primarily of thick-bedded, homogeneous grey, micaceous mudstone, recrystallized limestone, conglomerates, interstratified volcanics of the Frieda Complex and calcareous sandstone. It covers much of the Sepik Valley to the north of the Frieda Fault where it extends both west and east. Volcanics of the Frieda Complex are completely surrounded by lower units of the Wogamush Formation (Fig. 2.1). Foraminifera indicate a middle Miocene age (Dow et al., 1972) which is confirmed by K-Ar ages between 15.1 ± 0.6 and 16.8 ± 0.7 m.y. (Page and McDougall, 1972a). These are the recalculated K-Ar ages using the decay constants of Steiger and Jäger (1977).
2.3 TECTONIC HISTORY

The Frieda Complex is located at the southern margin of the New Guinea Mobile Belt, an east-west zone of intense faulting and less intense folding active since mid Miocene times (Fig. 2.2). The New Guinea Mobile Belt separates stable continental platform sedimentation to the south from oceanic crust and island arcs to the north, and was the site of geosynclinal sedimentation for most of its history. Except for a small patch of Upper Jurassic Shale and boulders of Permian granite the Salumei Formation of Cretaceous, to Eocene age is the oldest exposed unit in the Mobile Belt. It is folded and metamorphosed to greenschist and, less commonly, to epidote-amphibolite and glaucophane schist facies in the area of the Frieda River Prospect, but is not metamorphosed farther east. The April Ultramafics intrude the Salumei Formation and are unconformably overlain by the sediments of the mid Miocene Wogamush Formation.

Localized at intervals along the length of the New Guinea Mobile Belt are intrusive and extrusive rocks of Miocene age. The volcanic and plutonic rocks of the Frieda River Prospect are a part of this activity and are interstratified in the Wogamush Formation. Following the cessation of Wogamush sedimentation in the upper Miocene, orogenic activity caused faulting, folding, and uplift in both the Mobile Belt and the Papuan Fold Belt (Fig. 2.2).

A cross-section (SS' on Fig 2.2) that intersects the Frieda River Prospect area and transects the major tectonic features of the island is used to illustrate the chronology of major events (Fig. 2.3 A to E) and aid the discussion that follows.
Figure 2.2 Main geotectonic units of Papua New Guinea and location of cross-section SS'; the Frieda (1), Ok Tedi (2), and Yanderé (3) porphyry copper prospects are also located (modified after Dow, 1977).
2.3.1 Pre-Cretaceous: (Fig. 2.3A)

During much of the Mesozoic, Paleozoic crystalline rocks formed a stable basement for sedimentation on the Australian Continental Platform south of the Frieda area. The area to the north was occupied by oceanic crust which has since been destroyed (Dow et al., 1972) or buried. Transition from continental platform to eugeosynclinal sediments is abrupt and any evidence of continental margin has been removed or destroyed (Hamilton, 1979). Hamilton invokes Jurassic or Triassic rifting of a Malay-Sumatra subcontinent from New Guinea to explain the abrupt change and, postulates that this subcontinent now forms part of Eurasia. However, a patch of Upper Jurassic Sîtipa Shale located east of the Frieda River Prospect that is probably underlain by crystalline basement (Dow, 1977) and, more importantly, granitic boulders of late Permian age (Hutchinson, 1975) collected north of the Sepik River near the Irian Jaya border indicate that Hamilton's interpretation is tenuous. These localities could represent fault wedges of Paleozoic rock (Dow, 1977; Hamilton, 1979) but, if the main suture, the Lagaip Fault Zone, located between the continental crust and geosynclinal sediments was a rift zone in the Jurassic to Triassic, then Permian granites would not be expected this far north.

A northern extension of largely buried crystalline basement and possibly continental margin rocks located west of the Frieda area in Irian Jaya is a possible alternative explanation. The lower incidence of earthquake foci in this area (see Fig. 9, Johnson, 1979), the northwest flexures to fault zones in the Frieda Complex area that trend nearly east-west in the regions to the east, and the timing and patterns of volcanism might reflect underlying Permian granites. These basement rocks would tend to stabilize seismic activity in the area and deflect fault
Figure 2.3 Regional geologic history depicted along section SS' which is located in Figure 2.1 (see text for explanation.)
patterns northward in a manner similar to faults that border Paleozoic basement in the Aure Trough (see Fig. 2.2). Triassic and Quaternary volcanics have western extents which roughly coincide that are located well to the east of the Frieda River Prospect. The areal extent of Cretaceous and mid-Miocene intrusive and extrusive activity in the Papua New Guinea Mobile Belt appears to decrease to the west. Perhaps a northern extension of relatively stable Paleozoic basement would help explain this lack or decrease of igneous activity in western Papua New Guinea and Irian Jaya.

2.3.2 Cretaceous to Eocene (Fig. 2.3B)

The Continental Platform was submerged from about the mid Mesozoic to the Eocene and platform facies sedimentation predominated (Dow, 1977). To the north of the platform Johnson et al. (1978) postulate southwestward subduction beneath the northeastern edge of the Australian continent between 110 and 85 m.y. ago from the geological mapping of Bain et al. (1972, 1975) and work of Larson and Pitman (1972) and Hays and Pitman (1973): Subduction caused arc-trench-type volcanism in the Cretaceous and, east of the Frieda River Prospect area, resulted in the emplacement of basic marine volcanics and tuffaceous sediments. Later, within the Frieda River Prospect area, intermediate to basic marine volcanics were intercalated in geosynclinal sediments of the Salumel Formation (Dow et al., 1972).

Johnson et al. (1978) postulate that southwestward subduction apparently ceased in the late Cretaceous for unknown reasons and was succeeded by or perhaps initiated northeastward subduction in a zone originally several hundred kilometers to the north but now represented by island arc rocks in the north coastal ranges of Papua New Guinea.
2.3.3 Oligocene (Fig. 2.3C)

The Oligocene was a period of major diastrophism and orogenic activity. Many authors have postulated that a north or northeast dipping subduction zone propagated a late Eocene to Oligocene island arc system which later collided with the older volcanics, marginal trough sediments, and the Australian Continental Platform in the late Oligocene to early Miocene (Hamilton, 1970; Dewey and Horsfield, 1970; Dewey and Bird, 1970; Moores, 1970; Johnson and Molnar, 1972; Curtis, 1973; Johnson, 1976; Hamilton, 1979).

The basic, intermediate, and minor acid volcanics and the largely coeval gabbros, diorites and granodiorite located in the coastal Bewami Mountains north of the Frieda River Prospect area (Hutchinson and Norvick, 1978) constitute part of this accreted arc. Preliminary geochemistry of these rocks indicate calc-alkaline and tholeiitic island arc affinities (Jakes and White, 1972).

The effects of diastrophism and orogenesis on pre-Oligocene rocks were profound, and caused uplift of several thousand meters, folding and metamorphism of the Salumei Formation, and intense faulting in the Mobile Belt (Dow, 1977). A 23 to 25 m.y. age for metamorphism of the Salumei Formation is postulated from K-Ar dating of the Gwin and Ambunti metamorphics which are thought to be near time equivalents of the Salumei metamorphics (Page, 1976). This age might mark the end of major diastrophism and orogenesis associated with early Oligocene island arc collision.

Peridotites, pyroxenites and serpentinites of the April Ultramafics are younger than 25 m.y. (Page, 1976) but older than mid Miocene Wogamaush sedimentation (Dow et al., 1972). Hamilton (1979) interprets these as ophiolite slices and, with the Salumei Formation which includes
minor blue-schist facies rocks, suggests they constitute a melange complex. Dow (1977) states that the ultramafics are 'equivocally' intrusive although he concludes that the blue schist units may be products of an ancient subduction system.

The low-temperature high-pressure glaucophane-lawsonite schists of the Salumei metamorphics are located east of Frieda River Prospect and the high-temperature/low-pressure Ambunti Metamorphics are located north of the prospect (Dow et al., 1972). If these blue schist units are a product of subduction then with the Ambunti Metamorphics they may constitute part of a paired metamorphic belt (cf. Miyashiro, 1967; Landis and Coombs 1967). But, these belts are not compatible with a Cretaceous system because they are spatially the reverse of what is required for southwestward subduction. The belts are in rocks that are located too far south to be products of northeastward subduction. Therefore, the metamorphic belts must be of different ages or were wholly or partially generated by a different tectonic process, such as faulting (Dow et al., 1972) caused by collision.

2.3.4 Mid Miocene (Fig. 2.3D)

During the mid Miocene the Continental Platform was again submerged and the marginal trough was bounded to the north and south by two linear east-west-trending topographic highs or ridges. The trough area or Sepik embayment (Dow, 1977) represents a drowned topography on which the Wogamuh Formation was deposited. In the Frieda River Prospect area which was located on the northern shore of the southern emergent ridge a local trough referred to as the Wogamuah Embayment developed (see Fig. 2.1). Thrust and shear fault activity (Davies, 1979) is a possible mechanism for the development of the
Wogamush Embayment although an alternative is that it is part of a more extensive, drowned, horst and graben system in the Sepik Embayment (Farley et al., 1974). The provenance area for the early sediments in the Wogamush Embayment were the emergent ridges which consisted mainly of metamorphics of the Om Beds and the Salumei Formation.

The extrusives and intrusives of the Frieda Complex intruded and overlaid lower sediments of the Wogamush Formation in the Wogamush Embayment. Conglomerates and coralline limestones in the volcanics and upper sediments of the Wogamush Formation attest to a submerging coastline in the Frieda River Prospect area at this time. Other units of the same age and nature which include the Karawari Conglomerate, Burgers Formation, Yaveuta Formation and Langimer Formation are localized at intervals along the length of the New Guinea Mobile Belt and represent the most voluminous igneous activity in New Guinea (Dow, 1969; Dow et al., 1972; Page, 1976).

Various interacting mechanisms have been proposed to explain the widespread mid-Miocene igneous activity; these include collision and reversal of arc polarity, uplift, and fault activity. Reversal of arc polarity is a consequence of continent-island arc collision and is caused by continental material which, because of its less dense, and therefore buoyant nature, chokes the trench zone and prevents further subduction (McKenzie, 1969). The Bawani and Torricelli Mountains on the north coast of Papua New Guinea contain the accreted late Eocene to Oligocene island arc rocks. The reversal of arc polarity from northeastward to southwestward thought to follow collision in the late Oligocene to early Miocene, (Dewey and Horsfield, 1970; Dewey and Bird, 1979; Moores, 1970) presumably propagated a new subduction zone on the northern margin of the accreted arc. Although the Wewak Trench is located at
this site, it is relatively shallow, and is probably so young that subduction is incipient (Johnson, 1979). Incipient or absence of subduction is also suggested by the low seismic activity and lack of recent volcanism in this area. To the east of the Frieda River Prospect, where there is abundant seismic and volcanic activity, Jaques and Robinson (1978) have found that earthquake foci plots define a north-dipping seismic zone beneath late Cenozoic volcanoes and the southern margin of the Bismark Sea; they suggest that there is no evidence of reversal of arc polarity. In addition, Johnson and Jaques (1980) observe that lithosphere beneath marginal basins to the north of Papua New Guinea is not thick or cold enough to initiate southward subduction.

Geochemical and Sr isotopic studies of igneous rocks in the Mobile Belt and Central Highlands of Papua New Guinea do not support southwestward subduction since the mid Miocene. Incompatible element and rare earth element geochemistry of intrusive rocks from the Frieda River Prospect and other mid Miocene intrusives indicate a source for the parent magma that is unrelated to a subduction slab (Mason, 1975; Mason and Heaslip, 1980). Initial $^{87}\text{Sr}/^{86}\text{Sr}$ values of mid Miocene intrusives and extrusives located east of the Frieda River Prospect average 0.704 and suggest an upper mantle source (Page, 1971, 1976). Johnson et al. (1978) postulate that mid Miocene and Pliocene-Quaternary magmas were derived from lithosphere which was enriched in water and large-ion lithophile elements that evolved from a detached slab following Cretaceous subduction; these magmas were tapped by later Neogene tectonic processes.

The alternative fault mechanisms invoked to explain mid Miocene igneous activity involve, at one extreme, a sinistral strike-slip system that is a consequence of an expanding earth (Carey, 1938, 1970;
Marchant, 1969; Smith, 1965). Arguments that favour an expanding earth model are not dealt with here because discussion of these arguments is beyond the scope of this thesis. Sinistral strike-slip motion in this work is discussed in relation to the plate tectonic model.

Fault activity that followed collision of the late Eocene island arc rocks might have controlled mid Miocene igneous activity (Curtis, 1973; Johnson and Molnar, 1972). This hypothesis is favoured not only because it is compatible with most of the geological and geochemical features previously discussed, but also because it reflects the present-day, fault-bounded, juxtaposed nature of commonly very distinct rock types in the New Guinea Mobile Belt. A change in motion between the Pacific and Australian Plates from north-south to east-northeast-west-southwest about 10 to 20 m.y. ago (Chase, 1971) is compatible with sinistral movement in the mid Miocene. Alternatively, Titley and Heidrick (1978) propose that dextral wrench movement controlled mid Miocene intrusion at southward deflections on major strike-slip zones. Using the motion vectors of Denham (1969, 1975) and the attitudes of intrusions they suggest that the maximum principal stress was south-southeast directed between 16 and 13 m.y. ago.

Fault uplift (Mason and Heaslip, 1980) is another mechanism that might have controlled mid Miocene igneous activity. Mason and Heaslip envision that block faulting caused rapid uplift, of the order of 5 to 8 km, which facilitated fast erosion and subsequent pressure release. This effectively raised isotherms within the uplifted block and caused partial melting at the base of the uplifted block or horst. The partial melts were tapped by deep faults which also controlled intrusion. Mason and Heaslip argue that uplift of this magnitude has been reported (Dow et al.; 1972) although they omit to state that the timing is largely
unknown and there is no hard evidence of vertical fault movement prior to intrusion in the mid Miocene. In fact, the sense of even recent movement on many faults in the Mobile Belt is uncertain although the general characteristics of these faults indicate that they are dominantly transcurrent (Carey, 1938, 1970; Krause, 1965; Dow et al., 1972). Mason and Heaslip imply that the Papua New Guinea Mobile Belt, in part or in whole, may represent a mid Miocene horst. However, the mobile belt was a submerging trough in which both sediment and extrusives were deposited in the mid Miocene. It is possible that the emergent ridge that bordered the trough and the Mobile Belt to the south underwent partial melting at its base during uplift and provided source material for igneous activity to the north. Transfer of partial melts from the base of the emergent ridge may have been facilitated by the complex zone of faulting indicated by the structurally controlled intrusions and, perhaps by southerly tilting of the emerging ridge. Before such a model can be seriously considered a better understanding is required of both timing, sense, and magnitude of displacement on faults in the Mobile Belt prior to the mid Miocene.

2.3.5 Pli–Pliostocene (Fig. 2.3E)

Wogamush Formation sedimentation which deposited 4500 m in some areas of the Sepik Embayment (Farley et al., 1974) probably ceased in the upper Miocene and a new phase of orogeny commenced. Tectonics were again compressive in the region and possibly regenerated thrust movement in the South Sepik Region during the late Miocene (Davies, 1979). By the Pli–Pliostocene, the generation of thrust sheets had migrated south to the Star Mountains where calc-alkaline intrusions contemporaneous with deformation were emplaced into a foreland thrust-
fold belt (Jenkins, 1974; Davies and Norvick, 1974; Arnold et al., 1979; Davies, 1979).

In the New Guinea Mobile Belt strike-slip faults dominate structural movements (Dow et al., 1972; Dow, 1977) and, in the Frieda River Prospect area subvertical faults with subhorizontal movement are typical. Thrust faults have not been identified but recent strike-slip motion would tend to overprint evidence of thrust movement notably along the subvertical leading edge of the thrust sheets. The sinuous trace of faults located northwest of the Frieda River Prospect area could mark overprinted thrust sheet geometry. Fault-plane solutions on seismic activity located north of the prospect area indicate combined strike-slip movement and compressional over-thrust with the compressional axis aligned southwest (Johnson and Molnar, 1972; Ripper, 1975).

In addition to thrust and strike-slip fault motions, compression during orogenesis caused uplift of at least 5500 m in the Star Mountains, which are located north of the Ok Tedi deposit (Arnold et al., 1979) and at least 1600 m in the Frieda area. It also tilted the Wogamush Formation in the Frieda area 15 to 20° to the northwest to west-northwest; east of the Frieda River Prospect it plunged the sediments to the east-northeast (cf. Mianmin Sheet SB 54-3 (Davies, 1979)). The Sepik Embayment was largely filled by Wogamush formation sedimentation prior to uplift and is presently covered by swamp and alluvium of the Sepik River.

2.4 SUMMARY OF TECTONIC HISTORY

More thoroughly studied regions in eastern Papua New Guinea indicate that processes associated with plate tectonics can account for many local geological features. However, the overall tectonic picture of the island is very complex and fraught with uncertainty. This is
especially true of Irian Jaya and western Papua New Guinea where access is a problem and much less work has been done. Consequently, processes which have affected the geological history of these regions before the Oligocene are speculative and those in the period following the Oligocene are only poorly understood.

During the Paleozoic and Mesozoic, crystalline rocks formed a stable basement for sedimentation on the Australian Continental Platform south of the Frieda area. The presence of Late Permian granites (Hutchinson, 1975), lack of seismicity, distribution of volcanics and fault patterns in this area suggest that continental crystalline basement may underlie much of this region.

There is no exposed middle Mesozoic oceanic crust in the Mobile Belt. The presence of Mesozoic volcanics and the chemistry of mid Miocene and Quaternary extrusives however, has led Johnson et al. (1978) to postulate a southwestward subduction system in the Cretaceous. Subduction produced arc-trench-type volcanism and, later, following the Cretaceous but before the mid Miocene, the lower portion of the southwestward subducting slab was detached. Subsequently, volatiles, mainly H$_2$O and large-ion lithophile elements, evolved from the detached slab and rose to the upper mantle. Johnson et al. (1978) suggest that this chemically-modified mantle material lay dormant for a substantial period of time until magma generation was triggered by a later tectonic event, presumably in the mid Miocene and Quaternary.

Following and possibly in consequence of the cessation of southwestward subduction, northeastward subduction of oceanic crust was initiated in an area to the north of Papua New Guinea. An island arc was constructed in the late Eocene to Oligocene and the oceanic crust between the old and new subduction systems was eventually consumed by
the late Oligocene. Subduction culminated in the collision of this island arc system with the Cretaceous island arc rocks and marginal trough sediments that bordered the northern edge of the Australian Continental Platform.

The extensive mid Miocene igneous activity which includes that in the Frieda River Prospect area was probably a delayed effect caused by collision of the island arc in the late Oligocene which triggered faulting, in addition to horst and graben movement, and eventually mid Miocene igneous events. Early dextral and later sinistral faulting and attitudes of intrusions are compatible with a change in movement between the Australian and Pacific Plates (Denham, 1965, 1975; Chase, 1971) during the Miocene (Titley and Heidrick, 1978). Faults penetrated to deep within the crust and tapped the contaminated upper mantle or lower crust that may have undergone partial melting due to uplift (Mason and Heaslip, 1980) of the southern emergent ridge (Dow, 1977). These faults are marked by strongly structurally controlled mid Miocene extrusives and intrusives that are interstratified with sediments at the southern margin of a submerging trough. By the upper Miocene most igneous activity in the Mobile Belt had ceased and in the Frieda River Prospect area deposition of the upper sediments of the Wogamush Formation had also ceased.

Renewed orogenic activity in the Plio-Pleistocene caused mainly transcurrent motion in the Mobile Belt and thrust faulting and intrusion in the Papuan Fold Belt to the south, and uplifted these areas at least 1600 m and 5500 m, respectively.
2.5 PORPHYRY COPPER MINERALIZATION IN THE SOUTHWEST PACIFIC

In the Southwest Pacific major porphyry copper deposits and prospects occur in an arcuate band that stretches from the Philippines, northeast Borneo and Sumatra, to the southeast through Irian Jaya, Papua New Guinea and associated islands, and east to the Solomon Islands and Fiji. The Atlas mine in the Philippines was the first porphyry copper deposit in this region to be brought into production in the late 1850's. Since that time extensive exploration throughout this region has resulted in the discovery of over 50 porphyry copper occurrences. Of these, 7 are currently being mined in the Philippines whereas 3 are in production and 1 is in the developmental stage in the rest of the area (Gustafson and Titley, 1978). The porphyry copper province in the Southwest Pacific is therefore, of similar size and potential to those in the Canadian Cordillera and Southwestern United States.

The geological characteristics of porphyry copper mineralization in the Southwest Pacific have been previously assessed (Titley, 1975, 1978b; Gustafson, 1978); they are only summarized here in relation to mineralization in Papua New Guinea. This region of the Circum-Pacific marks a wide zone of poorly understood tectonics (see section 2.4) that are thought to be primarily caused by complex interactions between the Pacific and Indo-Australian Plates. Consequently, porphyry copper mineralization occurs in a variety of environments that are generally interpreted in the framework of plate tectonics. In Papua New Guinea they are found in island arcs (Panguna), continental margins (Frieda River(?), Yandera) and continental crust (OK Tedi) environments.
In the Papua New Guinea deposits, reserves (not necessarily recoverable) range from 165 million tonnes at Aire, Manus Island to 840 million tonnes at Panguna, Bougainville (see Table 1, Titley, 1978b). Excluding related skarn mineralization at the Ok Tedi deposit, New Guinea, and the Ertsberg deposit, Irian Jaya and the luzonite-ehargite mineralization at the Frieda River Prospect, grades in the proven porphyry copper prospects range between .3 and .75 % Cu, 40 and 183 ppm Mo, and <.1 to .6 ppm Au. Although grades for the average deposit in the Philippines falls within these intervals, their average reserve of 133 million tonnes is below the range for Papua New Guinea prospects. This discrepancy is partly caused by the fact that only a few major mineral occurrences have been sufficiently explored in Papua New Guinea. In spite of this bias the figures do suggest that for some tectonic or other geologic reasons individual porphyry copper prospects or deposits in Papua New Guinea have overall tonnages that are larger than those in the Philippines.

The age of porphyry copper mineralization in Papua New Guinea ranges from 1:2 m.y. at Ok Tedi (Page and McDougall, 1972a) to 25.5 m.y. at Plesyumi (Titley, 1978a). Most other deposits of the Southwest Pacific lie in this interval and compared to other porphyry copper provinces this region is very youthful. It provides a unique opportunity to study deposits that are less likely to have been changed by structural disruption or regional metamorphic effects and that are more likely to be well-preserved. The Frieda River Prospect is one example where a relatively short and fortuitous structural and erosional history has preserved lateral (13 km) and vertical (2 km) exposure of alteration with which porphyry copper mineralization is associated.
CHAPTER 3

GEOLOGY OF THE FRIEDA RIVER PROSPECT AREA

3.1 INTRODUCTION

Descriptions of stratigraphy, intrusions, and structure of the Frieda River Prospect area, hypogene and supergene alteration of the Frieda Complex rocks, and a discussion and interpretation of these features are the subject of Chapter 3. Various facets of the Frieda River Prospect area geology are illustrated in simplified form throughout the next. A more detailed coverage is presented at a larger scale in Maps 1 through 4 which are contained in the accompanying map case.

3.1.1 Nomenclature

At least two major nomenclature systems have been devised for rock types at the Frieda River Prospect. Early nomenclature devised by CEC and reported by Hall and Simpson (1975) was later revised by FEPL following district-scale mapping and was reported by Asami and Britten (1980). Review of the FEPL system while referring to the International Stratigraphic Guide (Hedberg, 1976) indicates that further revision was warranted. Particular confusion is caused by Horse andesite porphyry which has the same geographic name as Horse microdiorite and the Nena Diorite which conflicts with the Nena mineralization. In this thesis the name Horse andesite porphyry (Asami and Britten, 1980) is replaced with the old name, Flinthem trachyandesite (Hall and Simpson, 1975). In consultation with FCL it was decided that the Nena diorite and Nena mineralization will remain as they are.

Recent mapping by the author and other FCL geologists indicates that the volcanic pile is probably more complex and difficult to differentiate than outlined by Asami and Britten (1980). As a result the
Nena pyroclastics and Nena andesites which constitute the Nena volcanics in Asami and Britten are referred to in this work as the upper volcanics. Other rock type nomenclature in this thesis will be that of FEPL and currently used by FCL.

Alteration nomenclature used in Asami and Britten was also reviewed during this study. As a result the terms deuteritic alteration, acid alteration and potassic alteration are replaced by oxidized volcanics, district-scale advanced argillic alteration and biotitic alteration, respectively. Justification for these changes is presented in the appropriate sections of this Chapter and Chapter 5.

3.2 GENERAL GEOLOGY

The Frieda River Prospect can be subdivided into three spatially and geologically different areas: Frieda Complex, Mianmin area and Nena Diorite area (Fig. 3.1). The Frieda Complex is a remnant volcanic edifice of an island stratovolcano that is interstratified in the Wogamush Formation. Intrusive and volcanic units in the Complex occupy about 70 km² and are texturally similar and probably comagmatic. A major stage of hypabyssal intrusion generated a geothermal-hydrothermal system which caused extensive alteration along the central northwest-trending axis of the Frieda Complex. Copper mineralization is associated with both early and late phases of this alteration.

The Mianmin area, which is located in the west part of the map area is a separate but smaller (20 km²) volcanic centre that contains igneous rocks similar to those of the Frieda Complex. Locally, the volcanics unconformably overlie basement and indicate emplacement into a littoral zone (see Section 3.3.2.2, Debon andesite). Both the Mianmin area and Frieda Complex are located between the Frieda and Lagaip Fault Zones,
two major sutures of the New Guinea Mobile Belt. Volcanics of both these areas are overlain by upper sequences of the Wogamush Formation at their north or northwest margins.

The Nena Diorite, occupies about 110 km² and is located north of the Frieda Complex, intrudes basement rocks and is bounded on the south by the Frieda Fault and on the northwest by the Wogamush Formation. Relatively little mapping has been done on this intrusion and it is poorly understood.

A simplified geological map of the area, an idealized stratigraphic section, and stratigraphic columns are provided in Figures 3.1 and 3.2 and photographs of some representative volcanic, sedimentary and igneous rocks are shown in Figures 3.3 and 3.4. A brief description of the copper mineralization at the Frieda River Prospect is given below to provide background information for discussions in Chapters 3 and 4. The various copper deposits are described in much greater detail in Chapters 5 and 6.

3.2.1 Copper Mineralization

Epithermal copper-gold and massive sulphide mineralization is located in the central northwest region of the Frieda Complex (Fig. 3.1) and is called the Nena deposit or mineralization; this is not related to or associated with the Nena Diorite, which is located north of the Frieda Fault. The Nena mineralization is associated with intense alteration of the volcanic pile to quartz-kaolinite-alunite-pyrite-native sulphur assemblages that were described as acid assemblages by Asami and Britten (1980) but, in this study, are described as district-scale advanced argillic alteration. These assemblages occupy most of the central region of the Frieda Complex, from the porphyry copper systems in the southeast to the northwest end of the Complex.
The Nena deposit has both epigenetic and syngentic features. Epigenetic features include pyrite and district-scale advanced-argillic alteration assemblages that mainly replace volcanic material, and later-stage copper mineralization that occurs as replacement bodies or fracture fillings of enargite, luzonite, barite, and pyrite. However, pyrite fragments, deformed fine-grained laminations of pyrite, and multi-fragmented pyrite in massive sulphide lenses are common and suggest at least a partial syngentic origin for the fine-grained massive sulphides. As the deposit has not been drilled in detail, it is poorly understood.

In the southeast region of the Frieda Complex, there are two major centers of porphyry copper alteration and mineralization, the Hórs/vaal and the Kokí deposits (Fig. 3.1). Alteration zonation is centered on a weakly altered or biotitized core zone that is overprinted or crosscut at its outer margins by transitional alteration. This zone is characterized by abundant mineral-bearing vein and vein selvages that control alteration development. Fluid inclusion work indicates that temperatures in these veins ranged from less than 300° to above 600°C, although metastability phenomena may have caused an increase in homogenization temperatures (Eastoe, 1976). The Kokí deposit has a transitional alteration zone, that normally gives way to propylitic or chloritic alteration assemblages. However, the transitional zone in the Horse/Ivaal deposit is generally bounded by sericite + chlorite + andalusite assemblages that give way to propylitic alteration or advanced argillic alteration assemblages in outer regions. Much of the copper and gold mineralization is associated with transitional and sericitic alterations that overprint earlier biotite alteration. Major sulphide phases are pyrite and chalcopyrite with minor bornite and molybdenite. Native gold is rare. A chalcocite enriched zone which averages 30 m thick covers the northwest half of the Horse/Ivaal deposit.
3.3 STRATIGRAPHY

3.3.1 Basement Rocks

South of the Frieda Fault, basement rocks are composed mainly of Upper Cretaceous to Eocene pelitic schists and basic schists of the Salumei metamorphics. Outcrop is generally hard and generally consists of foliated assemblages of quartz, chlorite, and epidote. Trends of foliation, isoclinal fold axes, and the distribution of mafic schist beds roughly parallel the dominant northwest fault direction in the area.

Basement rocks north of the Frieda Fault are mainly amphibolites of the Ambunti Metamorphics. Metamorphism occurred between 25 to 27 m.y. (Page, 1976), a period that probably marks metamorphism of the Salumei Formation in the Frieda area. Metamorphism was followed by intrusion of serpentinite, periodotite, and dunite of the April Ultramafics in the early Miocene (Page, 1976; Dow et al., 1972).

3.3.2 Wogamush Formation

The Wogamush Formation consists of the lower Wogamush sediments, volcanics associated with the Frieda Complex and within the Mianmin area, and the upper Wogamush sediments. The lower Wogamush sediments consist mainly of grey to blue calcareous mudstones and greywackes, and minor limestone and basal conglomerate. They unconformably overlie basement rocks and are conformably overlain by volcanics of the Mianmin area and Frieda Complex. Tertiary f1-2 Stage mid Miocene foraminifera occur in limestone near the base of the formation (Dow et al., 1972).

3.3.2.1 Lower Wogamush Sediments

This is the oldest unit in the Wogamush Formation and consists mainly of grey to blue calcareous mudstone (Fig. 3.3a), and minor
Figure 3.2 (a) Idealized relations between rock types in the Frieda Complex. See (b) for key to volcanic stratigraphy and the legend of Figure 3.1 for other rock units. Width of the diagram represents approximately 10 km.

(b) Differentiated stratigraphic columns at the fringe (A) and central northwest and (B) of the Frieda-Complex. See Figure 3.1 for approximate locations of stratigraphic columns and Map 2 and 4 for the distribution of differentiated volcanics.
turbidites, limestone, calcareous shales and a basal conglomerate containing pebbles of quartz, diorite, and metamorphic rocks. Although the total thickness is not clear due to faults, folds, intrusions and lack of a distinct key horizon, probably more than 1,000 m of muddy sediments were deposited in the area of the Frieda River Prospect and thicken to the northwest.

These sediments are easily eroded and result in the low, relatively gentle topography that fringes the margins of the Frieda Complex. The sediments are extensively hornfelsed and altered to skarn at the margins of the porphyry copper systems at the southeast end of the complex but at other intrusive contacts aureoles are absent or are generally in the range of 1 to 2 m wide.

### 3.3.2.2 Frieda Complex and Mianmin Area Volcanics

In the Frieda Complex the volcanic pile is estimated to have a maximum thickness of about 1500 m and has been mapped as several volcanic units: near basal Koki andesite, Debom pyroclastics, Debom andesite, and upper volcanics (Map 2 and Fig. 3.2b).

**Koki andesite (Ka):** Koki andesite is a pyroclastic-lava unit characterized by coarse-grained plagioclase phenocrysts that commonly exceed 6 mm (Fig. 3.3b). It is located on the northern-northeast margin of the Frieda Complex where it overlies lower Wogamush sediments or is intercalated in lower Debom pyroclastic units (Map 2). Koki andesite is probably comagmatic with Koki diorite porphyry an intrusion to which it is texturally similar and spatially related. The unit has a maximum thickness of about 1500 m and thins toward the west and southwest.

**Debom pyroclastics (Dp):** These are exposed at the periphery and central southeast area of the volcanic pile. The pyroclastics near the
Representative features of the Frieda Complex
volcanic and sedimentary stratigraphy

(a) Unaltered thinly bedded calcareous mudstone typical of the lower Wogamush sediments (scale = 2 cm, sample #R2013).

(b) Photomicrograph of a pyroclastic (Kokt andesite) in which characteristic coarse-grained plagioclase phenocrysts, volcanic fragments, and shell fragments (S) are set in a matrix of feldspar, calcite and clay minerals (plane-polarized light, scale = 4 cm, sample #R1817).

(c) Tuff and lapilli tuff layers preserved in a sample of Debon pyroclastics although it is completely altered to a kaolinite-quartz-pyrite-rutile assemblage (scale = 2 cm, sample #R1931).

(d) Chalazoidite or accretionary lapilli in which strong weathering has caused iron-oxide banding that is perpendicular to bedding (scale = 2 cm, sample #R1504).

(e) Outcrop of thickly bedded but internally cross-laminated, upper Wogamush sediments (bed is approximately 2 meters).

(f) Photomicrograph of a sample of upper Wogamush sediment which consists primarily of subangular quartz (Q) and feldspar (F) grains, fossils and interstitial calcite, lesser amounts of biotite (B), muscovite (M) and glauconite (G); pyroxene, epidote and zircon are minor constituents (plane-polarized light, scale = .200 microns, sample #R954).

(g) Outcrop of a type SI scree deposit in which a chaotic mixture of subangular boulders of a highly variable nature are set in a clayey matrix.
lower Wogamush sediment contact are intercalated with thin mudstone beds; locally, volcanic conglomerates were noted. Toward the outer northwest margin the pyroclastics interfinger with volcanolithic sediments which are probably epiclastics. The green to grey-white commonly chloritized or argillized volcanic breccia, tuff breccia, lapilli tuff, and tuff of this pyroclastic sequence contain essential andesitic fragments characterized by generally altered, 1 to 4 mm plagioclase, 1 to 3 mm hornblende phenocrysts, and rare 1 mm biotite books (Fig. 3.3c).

Debom andesite (Da): Earlier mapping by FEPL suggested that the Debom andesite lavas were a relatively uniform unit that overlaid the Debom pyroclastics. Recent mapping by the author and current project geologists indicates that pyroclastics are commonly intercalated in lava units that are more erratic and less common than previously suspected (Map 2). These Debom andesite lavas are normally composed of medium-grained, uncrowded, hornblende-plagioclase andesite to trachyandesite porphyries that contain accessory apatite, magnetite, ilmenite and rare biotite and clinopyroxene. Subhedral to euhedral, 2 to 5 mm zoned (An$_{30}$ to An$_{45}$) plagioclase and 1 to 4 mm, euhedral, acicular hornblende constitute roughly 15 to 35% and 5 to 15 modal% of the lavas, respectively. The turbid groundmass is generally aphanitic, banded or mottled blue-grey to red-purple in colour, and is normally composed of a mosaic of plagioclase or potassic feldspar, and lesser iron oxide, alteration minerals and quartz. Although massive flows have been mapped the majority of Debom andesite lavas consist of brecciated flows or volcanic breccias of uncertain origin in which colour variation between fragments and matrix is commonly distinct and can be highly variable. Although Debom andesites are commonly altered to district-scale advanced argillic assemblages at their margins or along structurally
controlled alteration zones, the areal extent of hydrothermal alteration is much less than that in the Debow pyroclastics and the upper volcanics. This probably reflects the massive, relatively impermeable nature of the andesites.

The Debow pyroclastics and Debow andesites are not a uniform sequence of pyroclastics and lavas but, include several other distinct although less voluminous units which are located in Map 2. An ochreous-red volcanic breccia is located at the central southwest margin of the Frieda Complex immediately south of the Nena River and stretches to the northwest where it intertingers with epiclastic volcanics of similar colour. South of the Nena River the breccia contains essential fragments and is similar in appearance to flow-top or auto-brecciated lavas of Debow andesite, except for the massive nature of the unit and clastic to granular nature of the groundmass; the unit may be a foot-flow breccia (Parsons, 1969) that is related to extrusion of Debow andesite. Toward the northwest, the unit adopts a more pyroclastic appearance, contains accessory fragments, and is commonly moderately altered to a blue-green assemblage of chlorite, carbonates, albite, quartz, pyrite and hematite.

Other, less common, volcanic features include an unusual laharian (?) breccia in the Minmin area and a boulder deposit on the northern southwest margin of the Frieda Complex. The laharian breccia is characterized by a soft clay matrix and subrounded fragments that vary from less than 1 cm to greater than 6 cm. The andesitic fragments are variously altered to chlorite, clay or sericite-dominated assemblages. One sericitized(?) fragment of particular interest assayed near 2000 ppm molybdenum and is cut by a quartz-molybdenite vein that does not cross-cut the matrix. Identification of the unit as a lahar is based on areal extent (the unit was mapped over several hundred meters), the
relatively massive, chaotic nature of the outcrops that are only locally bedded, the clay-altered matrix, and the close mix of variously-altered fragments. The mineralized fragment is enigmatic but, might indicate minor molybdenum mineralization in the Mianmin area that predated mineralization in the Frieda Complex. Fragments of Salumer metamorphics noted in the lahar deposit near the lower contact with the basement rocks indicate a basement high in the area during emplacement.

A large outcrop of hard, rounded boulders which range up to 3 m in diameter and which are set in a coarse sandy volcanolithic sediment that is similar to other sandy Debom pyroclastic sediments in the area, is located near the southwest margin of the Frieda Complex north of the Nena River (Map 2). The boulders are difficult to sample due to their hard rounded nature but appear to be lavas or breccias derived from higher in the volcanic pile. They could be a recent, boulder-choked, creek deposit that was cemented by reworked volcanolithic sediments, an origin that would explain their apparent location at a stratigraphic level that is dominantly marine sedimentary.

Upper volcanics: Pyroclastics form a lower sequence that consists of volcanic breccia, tuff breccia, lapilli tuff, tuff; tuffaceous mudstone, and minor andesite lava of about 300 m maximum thickness. Chalazoidite (Berry, 1928) or accretionary lapilli units (Fig. 3.3d) which may prove to form useful local marker horizons were also noted. The upper volcanics are host to Nena copper-gold mineralization and have been variously altered to assemblages dominated by quartz, clay minerals, or alunite; consequently, textures are generally obscured or destroyed. Because of intense pervasive quartz-rich alteration these volcanics are normally preserved as weather-resistant, cliff bounded ridges in the north-central region of the Frieda Complex. Other andesite lavas which
overlie the pyroclastics are texturally similar to Debom andesite lava. They are located northwest of the Nena mineralization (Map 2) on a ridge top where outcrops are generally soft and altered to chlorite and clay-dominated assemblages.

3.3.2.3 Upper Wogamush Sediments

The upper Wogamush sediments overlie the northwest fringe of the Frieda Complex and Mianmin area volcanics and are composed of coralline limestone, greenish-grey calcareous sandstone, conglomerate, and volcanolithic calcarenates. The limestone is white to buff coloured, forms massive, often coralline beds that are easily demarcated in the field or on airphotographs by dolines and other karst features. Section AA' (Maps 2, and 4) shows a 50 m limestone lense near the base of the upper Wogamush sediments that is overlain by 100 m of calcareous sandstone. Farther west, the limestone significantly thickens to over 200 m and is areally much more extensive. Cross-bedded laminations in the finer-grained sedimentary units are common within 1 to 3 m beds (Fig. 3.3e). The sediments which total 150 m in the southwest but thicken to over 400 m toward the northwest, are resistant to weathering and form broadly folded, cliff-bounded, table mountains. Constituents of the upper Wogamush sediments indicate that volcanics in the Frieda Complex and Mianmin area and the Salumei metamorphics were the source for much of the detritus (Fig. 3.3f). The subangular grains indicate little reworking and reflect the immature nature of the near shore environment.
3.3.3 Scree and Alluvium

Several distinct types of scree and alluvial deposits have been mapped in the Frieda Complex area and cover about 15 km$^2$, most of which is scree. Significant alluvial deposits occur in the Nena River where they are confined to the river bed within the Frieda Complex but, expand downstream to form more extensive gravel bars and sand banks. Other drainages in the prospect have relatively minor amounts of alluvium due to higher gradients, although enough remains to commonly obscure outcrop and hinder mapping. Scree, however, is much more of a mapping problem because it is not confined to creek beds but has blanketed wide areas depending on the local topography at the time of emplacement.

Three types of scree deposits are recognized. The classical deposit (labeled SI on Map 2) consists of variably altered volcanic boulders, of variable hardness and size, that are unsorted, subangular to subrounded, and chaotically distributed in a clay matrix or soil that is commonly pale cream-yellow to white-grey (Fig. 3.3g). Perched water tables indicate permeable, perhaps reworked sandy or pebbly sections. These deposits project from the cliffs along the center of the Frieda Complex and most commonly extend to the northeast where they occur as tongues that measure up to 4 km long, over .5 km wide, and at least 50 m thick in some areas. A rough lateral sorting is noted with boulders that average less than a meter at the toe to others that average 10 m near the head of the tongue. Other deposits of this type that are normally smaller and more equant in plan occur in the central and southern areas of the Complex.

Etched and pitted, intensely altered, hard volcanic boulders that occur in isolation or in groups, overlying or partially enclosed by soils
derived from underlying lithologies, are classified as a second type of scree deposit (labelled SII on Map 2). In some areas they may represent remnant scree deposits from which the clay or sandy matrix has been removed. Alternatively, in steeper areas, they are probably slump or talus blocks. A deposit located near the northwest end of the Complex is composed of hard, resistant boulders that in the eastern half overlie volcanic outcrops of a similar altered nature on which there has been little soil development. The implication is in situ derivation followed by slump or creep of some boulders downslope to the west. Traversing this type of scree is very difficult, not only because of the stacked nature and huge size of the boulders but also because even large streams can disappear beneath this cover.

A third, less common type of scree-related deposit which is not differentiated on Map 2 is characterized by boulder-choked creeks derived by reworking the other types of scree. Following removal of the matrix and soft boulders, the hard boulders that remain are concentrated by slumping and bank collapse into creek beds. There they are rounded and polished and produce a terrain that is commonly difficult to traverse.

Boulder-choked drainages that are not related to scree deposits are located below cliff-bounded table mountains composed of upper Wogamush sediments and are probably talus derived. In contrast, huge, rounded, relatively non-altered, volcanic boulders that choke creeks draining volcanic terrains between the table mountains may have an origin that is the tropical equivalent of the torr.
3.4 INTRUSIVE ROCKS

Intrusive rocks in the Frieda River Prospect are separable into three groups: the Nena diorite, Frieda Complex porphyries and Mianmin area porphyries. The intrusives are all mid Miocene with K-Ar ages of intrusion that span roughly 13 to 17 m.y. (Page and McDougall, 1972a; Whalen et al., in prep.; see Chapter 4).

3.4.1 Nena Diorite

The Nena Diorite is located to the north of the Frieda Fault, a major structural feature in the area (Fig. 3.1). It is a composite intrusion composed of medium to coarse-grained, intermediate to mafic rock types that include hornblende quartz diorites, hornblende pyroxene diorites, basic diorites, quartz-bearing gabbros and gabbros (Hall and Simpson, 1975).

At the southern end of the stocks near the Frieda Fault where it has been studied in most detail, the Nena Diorite is a medium-grained, holocrystalline hornblende quartz diorite. It is characterized by abundant euhedral sphene (up to 5 vol. %), thin acicular hornblende 2 to 3 mm long, plagioclase (An$_{25}$ to An$_{45}$), interstitial quartz and K-feldspar (Fig. 3.4a), and a strong foliation most prominent near and generally parallel to the Frieda Fault. It also contains accessory apatite, magnetite, and ilmenite with hematite exsolutions.

3.4.2 Frieda Complex and Mianmin Area Porphyries

Five intrusive rock types, classified on the basis of textural, alteration, and field relationships, occur in the Frieda Complex and Mianmin area. Of these, Koki diorite porphyry (Kdp), Frieda diorite porphyry (Fdp) and Horse microdiorite (Hmd) have been altered to various degrees and cross-cutting relationships have established with
Representative intrusive rock types of the Frieda River Prospect area

(a) Nena diorite (Nd): a relatively equigranular intrusive rock which notably contains euhedral hornblendes (sample #JW133).

(b) Koki diorite porphyry (Kdp): note large plagioclase phenocrysts which contain fine-grained magnetite inclusions and the finer grained euhedral hornblende (sample #JW105).

(c) Knob diorite (Kd): crowded porphyry which contains plagioclase, biotite and hornblende phenocrysts (sample #R1913).

(d) Knob diorite (Kd): a relatively phenocryst-poor (phenocrysts = 35.8 modal%) Kd variant. A flow structure is indicated by alignment of plagioclases (sample #JW115).

(e) Flineme trachyandesite (Fta): crowded porphyry (phenocrysts = 50.4 modal%) which contains euhedral plagioclase and hornblende phenocrysts separated by very fine-grained matrix material (sample #JW103).

(f) Flineme trachyandesite (see 3.4e): two large amphibole phenocrysts occur in the middle of the photomicrograph, the left one exhibits marked optical zoning in shades of dark to medium olive green (sample #JW103).

The scale bar in (a) to (e) = 1 cm and in (f) = 1 mm.
reasonable certainty their relative ages (see Fig. 3.2a). The two other intrusions, Knob diorite (Kd) and Flintem trachyandesite (Fta), are relatively unaltered. Each intrusive rock type commonly exhibits a range of textures, even within individual bodies over short distances; therefore, overlap in textural features between intrusive rock types presents a major mapping problem. This is compounded by the presence of extrusive equivalents with similar textures and alteration overprinting.

The porphyries consist of varying proportions of plagioclase (An$_{20}$ to An$_{50}$), one or more of the mafic minerals - hornblende, biotite, and clinopyroxene, and accessory minerals (35 to 65 vol.%) in a turbid aphanitic matrix. The latter is composed of indistinct mosaics of plagioclase, K-feldspar or quartz that are commonly altered to varying degrees, even when phenocryst phases are unaffected. Apatite, magnetite, titanohematite and ilmenite are common accessory minerals; pyrite, chalcopyrite and pyrrhotite are rare.

Koki diorite porphyry (Kdp): This diorite porphyry contains zoned, euhedral, commonly glomeroporphyritic, coarse-grained plagioclase phenocrysts, some greater than 10 mm, and hornblende phenocrysts of variable size, which allow recognition of two main textural variants. An uncrowded variety (Kdp I) has a larger than average plagioclase grain size and a lower than average hornblende grain size (1 to 2 mm) (see Fig. 3.4b). A second variety (Kdp II), has more equant plagioclase (6 mm average) and hornblende (4 mm), a subcrowded texture and is mainly confined to the northern-northeast margin of the Frieda Complex, although it also occurs in the porphyry copper systems to the southeast (Map 2). The terms uncrowded and subcrowded, that are used above, and the term crowded, that is used below, describe.
Textures in which phenocryst phases constitute less than about 40 vol.%, 40 to 60 vol.% and more than 60 vol.% of the rock types, respectively.

Intrusions of Koki diorite porphyry are located along the northeast margin of the Frieda Complex where they crosscut lower Wogamush sediments and Debom pyroclastics. The northwest end of this belt is bordered on the southwest by Koki andesite (Map 2) which contains anomalously large-plagioclase phenocrysts and is probably the extrusive equivalent of Koki diorite porphyry (see Fig. 3.3b). Additional evidence of extrusion is a 50 cm square, subangular block which is texturally identical to Koki diorite porphyry. This ejected block has indented sand-size epiclastic Debom pyroclastics near the base of the volcanic pile at the northwest margin of the Complex. In addition to these field relations, the presence of Koki diorite porphyry xenoliths in younger porphyries indicate that extrusion and intrusion of Koki diorite porphyry were an early igneous event.

Frieda diorite porphyry (FdP): Frieda diorite porphyry is nearly always altered to at least propylitic assemblages. There are many textural variants that range from hornblende diorite porphyry (FdP I) to uncrowded almost vitric andesite porphyry (FdP II). Plagioclase averages between 2 to 3 mm in size while hornblende ranges between 1 to 4 mm. The amount of plagioclase and hornblende varies between 25 to 60 vol.% being less abundant in the vitric varieties; they occur in a turbid matrix, composed of quartz, feldspar and alteration minerals. Textural changes over short distances probably indicate successive intrusive pulses, or textural variations of marginal phases. Major axes to Frieda diorite porphyry intrusions are normally oriented northwest, a trend duplicated by foliations due to phenocryst alignment that were sometimes noted in this rock type.
Frieda diorite porphyry is common in the Mianmin area and widespread in the central region of the Frieda Complex where it has intruded lower Wogamuah sediments, the volcanic pile, and Koki diorite porphyry. It is crosscut by Horse microdiorite and Flintem trachyandesite at the southeast end of the Frieda Complex. Clear field relationships with Knob diorite have not been established. However, the common juxtaposition of altered Frieda diorite porphyry stocks and fresh Knob diorite stocks, which have intruded a strongly hydrothermally altered volcanic pile, indicate that Knob diorite is probably younger.

Knob diorite (Kd): Knob diorite is a medium-grained andesite to diorite porphyry (Fig. 3.4c and d) which occurs as steep, 200 to 1000 m diameter, conical-shaped intrusive plugs (Fig. 3.1). It contains various proportions of hornblende, biotite and clinopyroxene mafic minerals which are, like plagioclase, typically euhedral, unaltered, and average 2 to 3 mm in size. Two varieties are relatively easily distinguished on the presence or absence of biotite and are differentiated on Map 2. Biotite-bearing Knob diorite stocks (Kd II) are located in the northern half of the southwest margin of the Frieda Complex and are erratically distributed in the Mianmin area. Biotite-free stocks (Kd I) are located along the southwest fringe of the Frieda Complex and are found sporadically distributed in the Mianmin area. Although Knob diorite stocks in the Frieda Complex and Mianmin area are not differentiated on Figure 3.1, samples from the Mianmin area are referred to as Knob diorite from the Mianmin area (Kd (M)); this acronym is used in the tables of Chapter 4. Knob diorite samples with lower phenocryst content (<35 modal percent) may represent marginal contact variants of the more crowded (45 to 60 modal percent phenocrysts) Knob diorite.
Knob diorite plugs intrude lower Wogamush sediments and the volcanic pile and, as discussed previously, are probably younger than Frieda diorite porphyry. Similarity in style of intrusion, texture and location, suggest that Horse microdiorite and Knob diorite are closely related, although like Flintem trachyandesite and Knob diorite, there is no field evidence to positively establish a temporal relationship. A Knob diorite stock at the northwest end of the Frieda Complex is in contact with district-scale advanced argillic alteration at its northeast and eastern margins. Evidence that this stock is post-alteration, is the juxtaposition of fresh Knob diorite with non-altered volcanics on its southern and western margins, and with non-hornfelsed lower Wogamush sediments on its northern side.

Horse microdiorite (Hmd): This unit has two main textural variants, generally characterized by the presence of primary biotite books of about 1 mm size. The biotite-hornblende-quartz microdiorite porphyry variant contains phenocrysts ranging from 0.5 to 2 mm, whereas the biotite-hornblende diorite porphyry variant has coarser-grained plagioclase (2 to 6 mm) and a turbid groundmass composed of microscopic, mosaics of plagioclase, and lesser quartz. In both variants plagioclase commonly has soda-rich rims and hornblende is normally pseudomorphed by secondary biotite that averages about 0.1 mm. Horse microdiorite occurs as elongate stocks in the southeast corner of the Frieda Complex (Fig. 3.1) where it crosscuts Koki diorite porphyry, Frieda diorite porphyry, lower Wogamush sediments and the lower part of the volcanic pile (Fig. 3.2a). These stocks, which are central to the alteration-mineralization zonation pattern, are thought to be progenitor to porphyry copper mineralization.
Flintem trachyandesite (Fta): Two varieties of Flintem trachyandesite dikes are recognized on the basis of the presence or absence of biotite. Seriate textures are common in both types, with plagioclase averaging 3 mm and euhedral hornblende ranging in size from 1 to 3 mm (Fig. 3.4e and f). The hornblende-quartz andesite porphyry variant is commonly characterized by a potassic feldspar-rich trachytagoid groundmass, is commonly fresh or only weakly altered, and is regarded as post-mineralization (Hall and Simpson, 1975). In contrast, the groundmass K-feldspar of biotite-bearing Flintem trachyandesite dikes is commonly destroyed by alteration.

Flintem trachyandesite occurs as northeast-trending dikes in the southeast corner of the Frieda Complex (Fig. 3.1). It crosscuts Wogamush sediments, the volcanics, Koki diorite porphyry and Frieda diorite porphyry.

Biotite-bearing Flintem trachyandesite dikes are similar to Horse microdiorite in texture and composition and, although the latter is normally altered, it does have weakly altered to fresh rocks in the cores of some of the bodies. Clustering of dikes within the general area of Horse microdiorite intrusion and the porphyry copper alteration-mineralization zones suggests a close genetic relation between the rock types. There is a possibility that many of the Flintem trachyandesite dikes are apophyses related to various Horse microdiorite intrusive bodies.

3.5 ALTERATION

A generalised Frieda Complex or district-scale alteration map based on field mapping and thin section observations is presented by Asami and Britten (1980; see Appendix 4, Fig. 3b). In this study, extensive X-
ray diffraction work, examination of thin sections, and additional field mapping have greatly refined alteration in the Frieda Complex (Fig. 3.5; Map 3) especially the district-scale advanced argillic assemblages. About 300 thin sections that belong to the operating consortium were re-examined, and these observations were augmented by an additional 250 thin sections and about 100 polished sections made during the course of this study. Over 600 samples were examined using X-ray diffraction techniques; the methods of sample selection, techniques, and tabulated results are in Appendix 2 and locations of thin sections and samples X-rayed are noted on Map 1.

In addition to defining assemblages in more detail, particular attention was paid to lateral and vertical alteration zonation and, the relationships between Nena alteration-mineralization, porphyry copper alteration-mineralization, and district scale alteration. Several cross-sections (Map 4) intersect the areas of interest and illustrate the above relationships.

Three major types of alteration are noted in the Frieda Complex in addition to supergene alteration which overprints all rock and alteration types. These were defined by Asami and Britten and are reviewed and redefined in the sections that follow as oxidized volcanics, district-scale advanced argillic alteration and porphyry copper alteration.

3.5.1 Supergene Alteration

It is important to establish the supergene-altered equivalents of fresh and hypogene altered rock types because most outcrops are extensively altered by weathering processes; this is especially true of hydrothermally altered rocks. Unweathered rocks, if protected from erosion, commonly retain their textures even at the saprolitic stage of
weathering, whereas hydrothermally altered rocks that are leached and bleached by supergene processes can be profoundly changed (Fig. 3.6a). The greatest change occurs at ridge tops where soft saprolite, or leached and bleached but hard outcrop can commonly be traced for over 200 m of vertical relief from the top of ridge lines down the headwaters of small creeks. At lower levels, in better developed and larger drainages, surface exposures are less weathered and non-weathered samples can generally be located.

Weathering of fresh rocks through various stages to soil development depends on a number of factors. High rainfall and steep gradients are the major factors although structures that controlled both intrusion and later patterns of erosion are also important. Knob diorite plugs are a good example of structurally controlled intrusion and subsequent control of erosion by the morphology of the plugs (Figure 3.6b). Their steep-sided nature augments erosion as rocks are weakened by weathering processes and the high rainfall and steep gradients of creeks in the area of the plugs quickly erode weathered rocks. Only thin soil horizons, that in some cases are probably not related to these intrusions, occur on the tops of some plugs and only minor saprolite development are seen in semi-unroofed areas where the Knob diorite stocks are protected from fast erosion. Fresh Koki diorite porphyry stocks located along the northern-northeast margin of the Frieda Complex have similar characteristics. The remainder of igneous rocks in the Frieda Complex are normally hydrothermally altered prior to weathering. Supergene effects are best discussed therefore, in terms of the dominant alteration assemblage rather than rock type and are included with descriptions of Frieda Complex alteration assemblages which follow. These effects are further documented in later sections on
(a) Various degrees of weathering are illustrated in this rock photograph. An unweathered inner core (C) of pyroclastics which have been intensely altered to a quartz-native sulphur-alunite-rutile assemblage is overprinted by black, sooty, and banded iron sulphates (?) of supergene origin. These sulphates abruptly change to a lighter leached and bleached outer zone (L) that contains traces of iron oxides and is enclosed by a thin rind of iron oxides (scale = 2 cm, sample #R411).

(b) A view looking southwest at "The Knob" which is a steep-sided pinnacle of Knob diorite. The more rounded hills to the left of the pinnacle are more representative of the morphology of these plugs. The top of the Knob is 1670 m above sea level and the valley at its base is at 1200 m.
alteration of the porphyry copper deposits (Chapter 5) and Nena mineralization (Chapter 6).

### 3.5.2 Oxidized Volcanics

These volcanics are characterized by reddish-brown to purple-blue lavas, pyroclastics and epiclastic volcanics that are stained by hematite or hydrated iron oxides. Alteration, irrespective of degree, is typically pervasive; fracture and vein controlled alteration are not noted. Volcanic breccia and epiclastics located at the northwest end and central southwest margin of the Complex are commonly softer, brighter, more ochreous-red in color relative to other areas of the prospect where reddish-brown to purple-blue colors dominate in the more competent lava. At the northwest end of the prospect highly siliceous advanced argillic alteration overprints oxidized volcanics and has produced an extremely hard, red jasper.

### 3.5.3 District-Scale Advanced Argillic Alteration

The term acid alteration has been widely used to describe alteration in the native sulphur deposits (Mukaiyama, 1959, 1970; Abe, 1962; Takeuchi et al., 1966); clay deposits in Japan (Utada, 1980) and alteration associated with some geothermal systems in various parts of the world (Schoen et al., 1974) as it encompasses assemblages that are products of extreme hydrolytic base-leaching. Asami and Britten (1980) used acid alteration to emphasize the relationship between this type of alteration and Nena copper-gold mineralization and, to emphasize spatial and suspected temporal differences between this alteration and the porphyry copper alteration system. The term advanced argillic alteration is common throughout the porphyry copper literature and, like
acid alteration, defines assemblages that are products of extreme hydrolytic base-leaching of all aluminous phases (Meyer and Hemley, 1967). Although they are somewhat interchangeable (Hemley et al., 1980) the term acid alteration does have genetic implications which allude to a chemical, rather than a physical or mineralogical property of the alteration assemblages. Consequently, in this study, advanced argillic refers to the more local, porphyry copper-related, alteration assemblage, whereas, the more widespread or acid alteration is called district-scale advanced argillic alteration.

In the prospect area district-scale advanced argillic assemblages have altered more than 16 km², within irregular, fault-offset, northwest-trending zones that occupy the central regions of the Frieda Complex (Fig. 3.5). Two fresh Knob diorite plugs crosscut the alteration at the northwest and central southwest margins. Although some high-level Frieda diorite porphyry stocks appear to crosscut the altered volcanics and are probably younger, many of these stocks which occur at lower stratigraphic levels are spatially related to the district-scale advanced argillic alteration (see Maps 2 and 3).

No detailed work was done on alteration in the Mina Min area, although boulders of volcanics altered to advanced argillic assemblages were rarely noted. In addition, widespread sericite-quartz ± kaolinite (?) alteration in this area was macroscopically identified.

District-scale advanced argillic alteration assemblages that are dominated by quartz, kaolinite, dickite, alunite, pyrophyllite or diaspore, and other less common minerals are described in the sections that follow. A point to emphasize is that these are end-member assemblages and boundaries between adjacent zones are gradational, not abrupt, as shown on Map 3 or Figure 3.5. Pyrite and rutile, like
quartz, are ubiquitous in all assemblages and have numerous habits that are described with other, less common, mineral assemblages found in the Nena deposit (Chapter 5).

**Quartz ridges and Silicification**: Northwest-trending topographic highs that are located in the district-scale advanced argillic alteration zone normally consist of 50 to greater than 90% quartz. These hard, competent, quartz-rich rocks are weather-resistant relative to surrounding rocks and commonly remain as cliff-bounded ridge-lines that are easily delineated on airphotographs and topographic maps. The term, quartz ridges, as used in this thesis, does not define a specific alteration assemblage but refers to these quartz-rich, topographic highs that may contain any of the district-scale advanced argillic alteration assemblages.

Silicification, on the other hand, is a unique alteration assemblage composed of greater than 90% quartz; the remainder is mainly pyrite, native sulphur, rutile, and minor amounts of alunite or clay minerals. The very fine-grained (> 1 micron) chalcedonic quartz is white to tan to grey-cream in colour and generally preserves breccia and sedimentary textures well (Fig. 3.7a, b, and c). Colour variation can commonly be traced to rutile or sulphide content. Surface exposure is normally strongly leached and consists of porous quartz-rich rocks and minor rutile; drusy vugs are primary alteration features. Outcrop is normally hard and brittle and, where shattered as in the Nena mineralized area, sharp, angular, easily eroded fragments about 1 to 3 cm in size are produced. Fragmental rocks or breccias that have been strongly silicified or that occur in the quartz ridges are not all pyroclastic. Some are probably vent, intrusion or fault breccias that are characterized by multi-brecciated fragments (Fig. 3.7b). These breccias and the
Figure 3.7
Features of silicification and alunization associated with district-scale advanced argillic alteration

(a) Disturbed layered tuff which has been intensely silicified to a hard, dense and variable-coloured rock. Except for minor rutile (about 1%), the rock is exclusively quartz, although voids (<2%) may represent cavities from which native sulphur or alunite was leached (scale = 2 cm, sample #R1828).

(b) Intensely silicified breccia which consists of multi-cream-coloured, commonly pyroclastic fragments, set in a pale-cream-white siliceous matrix. This rock has undergone at least two periods of brecciation prior to silicification and has been tectonically shattered following silicification, probably in response to fault movements (scale = 2 cm, sample #R1827).

(c) Various textures of quartz in a sample from an intensely silicified zone. Very fine-grained 'chalcedonic' quartz replaces most of the groundmass and is the typical habit in the silicified zones. Quartz also fills cavities as coarser-grained, equant anhedral crystals (Q1) or, less-commonly, as columnar to radiating crystals (Q2) (cross-polarized light, scale = 0.5 mm, sample #R1840).

(d) Photomicrograph of three common habits of alunite. Fine equant grains of alunite are disseminated throughout the quartz-pyrite groundmass whereas, coarser-grained alunite crystals that have bladed or acicular habits generally replace phenocryst phases (cross-polarized light, scale = 1 mm, sample #D103 142.0).

(e) Photomicrograph of rare and unusual quartz and alunite habits. The doubly terminated quartz crystals have a dark band at their centre in plane-polarized light (e) and according to probe data contain abundant alunite inclusions. These are set in a very fine-grained matrix of primarily alunite and minor quartz. Under crossed polars (f) the extinction characteristics of the quartz crystals are unusual because they travel across opposite ends of the crystals in opposite directions (scale = 200 microns, sample #S138 6.0).
northwest orientation of alteration zones are evidence of structural rather than simply lithological control of this alteration assemblage.

**Alunite-dominated assemblages**: Very fine-grained, moderately dark, grey to brown rocks (other colours possible) that are completely altered to quartz-alunite, lesser amounts of pyrite and clay minerals, and minor marcasite characterize this assemblage. Quartz is generally very fine-grained (>1 micron) whereas alunite is coarser-grained and commonly greater than 100 microns. Coarser alunites are bladed (Fig. 3.7d) and, impart a sugary or saccharoidal texture to the rock that is most apparent where fragments or feldspars are selectively pseudomorphed. Supergene alteration results in sugary, porous outcrop that is leached and bleached to light cream colours. The weathered product depends on hypogene compositions and in general, a sugary, porous texture is more-pronounced in rocks with higher alunite (or native sulphur) contents.

An unusual habit of both quartz and alunite was observed in a scree boulder (Figs. 3.7e & f). Small, 5 to 10 micron grains of subrounded, doubly terminated crystals set in a fine-grained altered matrix have a wavy extinction that is opposite at either end of the crystal. Microprobe analysis of both groundmass and crystals indicates that the doubly terminated crystals are mainly quartz that contain alunite and possibly fluid inclusions. These features imply that intense alunite alteration of a fine-grained rock, possibly a tuff, was followed by quartz crystal growth with nucleation at different extinction attitudes on opposite sides of the doubly terminated crystals.

Alunite and natroalunite are, respectively, K-rich and Na-rich solid solution end-members of an isomorphous series (Parker, 1962). A method described by Cunningham and Hall (1976) uses the (101) quartz
peak at d3.34Å as a reference against which can be measured the (113) hexagonal alunite-natroatunite peak that ranges between d2.987Å and d2.955Å, respectively. Following the determination of a corrected d spacing or 2θ on a given chart, the K to Na atomic proportion in a sample can be read directly from Figure 1 of Cunningham and Hall. Their method cannot be used on samples of lower (≤ 2 to 3%) alunite or natroatunite, because the (113) peak is diffuse and skewed to higher 2θ than is normal for either mineral. To test the reliability of this method several samples that represented a range of K/K+Na contents were both X-rayed and analysed by electron microprobe (Table 3.1); the latter technique is described in Appendix 3 which also contains complete microprobe analyses. Standard deviations for averaged microprobe analyses range between 3 and 17% and indicate considerable variation in K/K+Na between grains of the same sample. Although results obtained using X-ray diffraction are estimated to only the nearest 10% they are probably more representative because the sample used is many orders of magnitude larger than that analysed by electron microprobe. The differences between the results obtained by the two methods range between 1 and 15%. Most are at the lower end of this range and suggest that the X-ray diffraction technique is accurate to ±5 to 10%.

Alunite-dominated assemblages mark the northeast margin of the district-scale advanced argillic alteration zone as irregular semi-continuous patches that occur at a stratigraphic level below that of kaolinite-dickite-dominated assemblages. A vertical zonation from alunite-quartz-pyrite to kaolinite or dickite-quartz-pyrite is indicated (Map 4), although varying amounts of the clay minerals are also found in the alunite zone. Atomic percent K in this area vary from 40 to 80% according to the method of Cunningham and Hall (Map 3). The north to
Table 3.1 Comparison of alunite-natroalunite K/K+Na atomic ratios (in %) by X-ray diffraction (XRD)\(^1\) and electron microprobe analyses\(^2\)

<table>
<thead>
<tr>
<th>Sample</th>
<th>XRD</th>
<th>Microprobe Analyses</th>
<th>Difference between XRD and microprobe</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>n</td>
<td>Avg.</td>
</tr>
<tr>
<td>D87 212.0</td>
<td>70</td>
<td>10</td>
<td>81.9</td>
</tr>
<tr>
<td>D89 329.1</td>
<td>80</td>
<td>8</td>
<td>81.9</td>
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<td>8</td>
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<tr>
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<td>70</td>
<td>7</td>
<td>74.5</td>
</tr>
<tr>
<td>R1872</td>
<td>80</td>
<td>10</td>
<td>64.8</td>
</tr>
</tbody>
</table>

\(^1\) Determined by the X-ray diffraction technique of Cunningham and Hall (1976)

\(^2\) Microprobe Analyses; n = number of analyses, Avg. = average K/K+Na atomic ratio in %; \(\sigma\) = one standard deviation.
northwest-trending series of discontinuous patches that are located near the southwestern margins of the Frieda Complex vary from 10 to 80 atomic percent K.

**Kaolinite or Dickite-dominated assemblages:** Very fine-grained, blue-tinted grey rocks are typical of this type of alteration. Clay minerals are normally less than 1 micron in size, although 10 micron grains have been noted. The groundmass is commonly altered to a mosaic of quartz and clay minerals, whereas, fragments and phenocrysts are replaced by clay minerals of larger grain size which, in hand specimen, appear as blue-tinted translucent pseudomorphs (see Fig. 3.8a and b). Pyrite and lesser amounts of rutile are common in this type of alteration. Outcrops near or within quartz ridges are relatively hard and competent but where sheared, clayey gouge zones are common. Due to the dissolution of pyrite, weathered equivalents are bleached and bleached to lighter colours. They are not as brittle as siliceous assemblages or as porous as weathered equivalents of alunite-dominated assemblages although they commonly exhibit a fine sugary texture.

Kaolinite-dickite assemblages occupy many of the quartz-ridge topographic highs that stretch the length of the Frieda Complex. In areas away from quartz ridges, clay-altered assemblages that border or crosscut oxidized volcanics or propylitic alteration occur as relatively soft, clayey outcrop in which textures and pyrite are preserved because of the impervious nature of the rock. In several areas oxidized volcanics are overprinted by clay mineral alteration along fault and fracture systems that generally trend northwest and, roughly parallel the outer margin of pervasively kaolinite-dickite-dominated alteration. This type of occurrence is probably much more widespread than presently mapped because the soft nature of these outcrops would facilitate erosion, and subsequent covering by alluvium and scree.
Figure 3.8

Photomicrographs of clay minerals, diaspore and opaques associated with advanced argillic alteration textures.

(a) The low birefringent kaolinite-dominated groundmass cements irregular quartz and pyrite phenocrysts (cross-polarized light, scale = 1 mm, sample #R1833).

(b) The high birefringent ribbon-texture mineral is dickite which has pseudomorphed a hornblende phenocryst. Much of the low birefringent material is kaolinite that, with quartz and pyrite, constitute the remainder of the rock (cross-polarized light, scale = 250 microns, sample #R1843).

(c) Diaspore has variable optical properties that range from weakly pleochroic aggregates of grey birefringence (D1) to more typical, generally non-pleochroic, higher-order interference-coloured aggregates of similar texture (D2) (cross-polarized light, scale = 125 microns, sample #S201 97.3).

(d) Photomicrograph of high relief pseudocubic crystals of diaspore (D) which are set in a fine-grained groundmass of kaolinite and quartz. Pyrite rims and kaolinite and quartz replace the core of a hornblende pseudomorph (H) (plane-polarized light, scale = 125 microns, sample #R1556).

(e) Altered tuff-breccia in which the groundmass is composed of turbid K-feldspar, quartz, clay minerals and minor pyrite. Most of the phenocryst phases but, notably hornblende (H) are pseudomorphed by sericite-montmorillonite mixed-layer clays (cross-polarized light, scale = 0.5 mm, sample #R797).

(f) An unusual occurrence of chalcopyrite (Cp) in which the core of the grains are occupied by covellite (Cv) and bornite (B). Covellite also fills microfractures in chalcopyrite which might indicate a supergene origin (reflected light, scale = 200 microns, sample #R1887).

(g) At higher magnification bornite exhibits a lamellar exsolution texture in chalcopyrite (reflected light, scale = 25 microns, sample #R1887).
No well-defined zonation has been established between kaolinite and dickite. However, dickite is more common at the southeast end of the district-scale advanced argillic altered zone whereas kaolinite is typically found in the middle and northwest areas (Map 3). This distribution, while erratic, suggests that dickite formed in a deeper and hotter environment relative to kaolinite.

Distribution of clay minerals in fresh samples X-rayed and the degree of ordering are as follows:

- Kaolinite (positive identification) 126
- Dickite (positive identification) 53
- Kaolinite and Dickite 17
- Ordered > Disordered Kaolinite only 29
- Ordered = Disordered Kaolinite only 39
- Ordered < Disordered Kaolinite only 58
- Uncertain Ordering due to small abundance of clay mineral 172

Although sample density and coverage is erratic and the numbers listed above may not individually be very meaningful, trends are indicated. Positively identified kaolinite is about 2.6 times as common as dickite, a factor roughly comparable to the areal distribution of the two minerals. Disordered kaolinites are about twice as abundant as ordered kaolinites, however, no distinct pattern has emerged. Schoen et al. (1974) have found that ordering in kaolinites decreases from inner to outer regions of the Steamboat Springs geothermal system. Perhaps lack of a distinct pattern at Frieda is due to many centers of alteration that were controlled by a complex structural network.

Pyrophyllite and Diaspore: These minerals are not common but are widespread throughout the district-scale advanced argillic alteration zone.
and occur with quartz, clay minerals, pyrite, alunite, and sericite. A close association between intrusion, porphyry copper alteration, and the occurrence of pyrophyllite and diaspore is indicated by detailed studies in the Horse/Ivaal deposit (Chapter 5). Other plutons altered to sericite-quartz ± kaolinite in the central region of the Complex are also associated with pyrophyllite or diaspore especially near contacts with district-scale advanced argillic alteration (Map 3). Otherwise, pyrophyllite and diaspore most commonly occur with kaolinite-dominated assemblages along the central regions of the Complex. They are not found in the southwest margin or at the northwest end of the district-scale advanced argillic alteration zone.

Diaspore typically occurs as <0.01 to 0.2 mm, anhedral, high-relief, turbid grains or clots, distributed evenly through an otherwise strongly altered rock (Fig. 3.8c). Clear, high relief, commonly euhedral, 'pseudocubic' diaspore (Fig. 3.8d) occurs in several widely scattered localities and may be characteristic of incipient diaspore alteration. Pyrophyllite is variable in grain size, subhedral to euhedral, and cannot be optically distinguished from sericite. Intense pyrophyllite-diaspore alteration imparts a rich, but dull, variable-cream-coloured luster to rocks, is relatively soft depending on quartz content, and can be very similar in colour and texture to other types of advanced argillic alteration.

3.5.4. K-Feldspar-Dominated Assemblage: Pyroclastics that range from fine laminated, tuff to volcanic breccias are composed of a K-feldspar-quartz-pyrite assemblage with lesser amounts of montmorillonite, kaolinite, sericite-illite, chlorite, and rutile (Fig. 3.8e).

This is an unusual assemblage because most other rocks in which K-
feldspar is a major constituent are normally only weakly altered and, consequently, contain abundant plagioclase and albite. Lack of plagioclase and albite in these rocks is a good indication that this assemblage is a product of alteration. The soft porous nature of some rocks might suggest that superegene alteration produced the clay minerals; however, the presence of ubiquitous pyrite in all samples examined and the coherent nature of other samples indicate that alteration was probably of hydrothermal origin.

Mineral constituents are typically very fine-grained except for pyrite which can occur as disseminated, striated, .5 mm cubes. But, pyrite has a variety of habits that include subhedral disseminated aggregates of about .1 mm size or very fine-grains that pseudomorph phenocrysts of 1 to 3 mm size with other alteration minerals. Quartz is both disseminated and occurs as aggregates of irregular outline about 1 mm size. K-feldspar is interstitial in the matrix and fragments of the pyroclastics. Other minerals are microscopic in size and impart a fine-grained, saccharoidal texture to the rock.

Although only relatively small patches of this type of alteration have been mapped, the assemblage is notable because it is located north of the Nena River at the fringe of the Frieda Complex (Fig. 3.5) within propylitic alteration assemblages. The southern patches contain minor amounts of sericite-illite and chlorite, whereas, the northern patch contains minor montmorillonite and kaolinite. It is not known if these assemblages are associated with district-scale advanced argillic alteration or whether they represent a separate hydrothermal system with closer affinity to porphyry copper alteration.
3.5.5 Porphyry Copper Alteration

Propylitic and sericitic alteration assemblages are common in the Frieda Complex and are discussed in terms of porphyry copper alteration because of their close association with this kind of deposit. A more detailed discussion of the alteration in the porphyry copper deposits at the Frieda River Prospect is contained in Chapter 5.

Propylitic alteration: Intrusives and extrusive rocks that are altered to assemblages that consist of chlorite, calcite, pyrite, quartz, albite, montmorillonite, kaolinite, mixed-layered clays, rutile, and epidote are grouped under propylitic alteration. These assemblages are widespread throughout the Frieda Complex where they commonly have an uncertain association with district-scale advanced argillic alteration, porphyry copper alteration, or diagenetic or deuteritic processes. In some areas, they might be related to episodes that are intermediates or combinations of these types of alteration.

Frieda diorite porphyry and Koki diorite porphyry stocks which are widespread in the Frieda Complex are normally altered to propylitic assemblages and have characteristics that are similar to outer zones in the porphyry copper systems. Ferromagnesian minerals are typically pseudomorphed by chlorite, calcite, epidote and rutile, and plagioclase is frequently dusted with sericite and calcite. Groundmass feldspars are altered to similar assemblages although rutile is less common and quartz, albite, and potassic feldspar are more abundant. Unlike alteration of the volcanics, montmorillonite and other clays are not present. Results of X-ray diffraction indicate that chlorite is normally Mg-rich in these assemblages. Fe-rich chlorites have (002) and (004) peaks which are roughly twice the intensity of the (001) and (003) peaks, whereas, Mg-chlorites or those with less than 30% Fe, have peaks of equal intensity. (Brown, 1961).
Sericitic alteration: Sericitic alteration consists of fine-grained sericite, quartz, pyrite, and lesser amounts of kaolinite, pyrophyllite, and diaspore, and is macroscopically very similar to sericitic alteration associated with the porphyry copper systems and other assemblages of district-scale advanced argillic alteration. This type of alteration is generally texturally destructive and is nearly always associated with Frieda diorite porphyry stocks. Results to date indicate that sericitic in barren and mineralized stocks are generally, 1M and 2M₁ polymorphs, respectively; these were identified on X-ray diffraction charts using the standards of Grim (1968). An exception is a gold-bearing (4.1 g/t) 1M sericitic zone located south of Ekwai Debo. In addition to areas within and peripheral to the porphyry copper systems, the 2M₁ sericite polymorph is found southwest of the Nena mineralization associated with minor chalcopryite-covellite-bornite-biotite-chlorite assemblages in Frieda diorite porphyry stocks (see Figs. 3.8f and g). Sericites from nearly all other locations are 1M polymorphs.

3.6 STRUCTURE

The Frieda River Prospect is located in the Papua New Guinea Mobile Belt, a zone of intense faulting and folding. Consequently, structure in the area is complex and many interpretations are possible because of the difficulty in tracing and defining complicated structure in areas of poor exposure and rugged terrain. The structural features are divided into basement, syn-, and post-Frieda Complex intrusive structures and, in the latter case, are further divided into structural domains (Fig. 3.9).