Le seul véritable voyage n'est pas d'aller vers de nouveaux paysages, mais d'avoir d'autres yeux.

(The true voyage consists not in seeking new landscapes, but rather in seeing with new eyes.)

Marcel Proust (1871-1922)
Abstract

The Panorama area, Pilbara, Western Australia provides an excellent location for studying VMS deposits because of the great exposure of relatively unweathered and undeformed rocks (Brauhart, 1999). Hyperspectral imagery has been used in this study, together with other remote sensing data, to create a geological interpretation of the Panorama area including the hydrothermal alteration system associated with the VMS deposits in the area. The linear features that were found in the north-eastern segment of the area have been used in a structural analysis.

The lithological interpretation of previous studies can be recognized from the remote sensing data. The Hymap, MASTER, radiometric imagery and aerial photograph were found most useful. The linear features were best visible from the Hymap, MASTER, Landsat TM imagery and the DEM. The main difference between the interpretation of lithology from remote sensing data and previous studies is that the inner phase intrusion can not be recognized as such from remote sensing data and a clear unconformity between the Gorge Creek Group sediments and the underlying Sulphur Springs Group volcanics is visible.

The Hymap imagery and the K channel of the radiometric imagery combined provide a good method for mapping the hydrothermal system. The alteration in the volcanic sequence is characterized by a white mica rich top and a white mica poor lower volcanic sequence. The white mica rich top compares to the feldspar-sericite-quartz alteration as mapped by Brauhart et al. 1998). An additional division can be made within this sequence based on white mica composition, the top containing Al-rich white mica and the bottom containing Al-poor white mica. Within the white mica poor sequence that is present in the lower half of the volcanic sequence a distinction between Al-poor (upper half) and Al-rich (lower half) white mica can be made as well. The Al-poor white mica sequences (both in white mica rich and white mica poor altered zones) show a strong enrichment in K. A both semi-conformable and conformable alteration sequence characterized by the presence of Al-rich white mica and K depletion is recognizable between the granite and the volcanic sequence. This zone compares to the chlorite-quartz alteration zone mapped by Brauhart et al. (1998), but is more widespread and, especially the K depleted zone, extends deeper into the stratigraphic sequence. The semi-conformable alteration zones may stretch out in the sediments overlying the volcanic sequence. This is suggested by the Al-rich white mica rich and K rich composition of the sediments directly overlying the volcanic sequence. The transgressive alteration zones mapped by Brauhart et al. (1998) are recognizable as zones of relatively Al-poor white mica poor and K poor composition that crosscut the semi-conformable alteration zones. Additional alteration zones that have not been found previously are recognized from remote sensing data. Al-poor white mica enriched sediments with an often disturbed sedimentary structure provide evidence for discharge of hydrothermal fluids in the sediments overlying the Sulphur Spring Group.

The structural analysis showed a syn-volcanic/ syn-sedimentary fault set with an early apparent dextral movement and a later apparent sinistral displacement direction. The main SW-NE orientation of the faults and the presence of intrusions along these faults are indicative of the presence of a pull-apart basin during the deposition of the Gorge Creek Group sediments.

The model that can be formulated on the basis of remote sensing data is different from previous models in that sense that it incorporates the sediment deposition, with discharge zones extending into the sedimentary sequence and possibly the continuous recharge during sediment deposition. The larger extent and deeper presence of alteration zones within the stratigraphic sequence suggests the convective cells of the hydrothermal system were deeper than previously thought.
Acknowledgements

I would like to thank Thomas Cudady of CSIRO for the availability of the Hymap data. Carl Brauhart of Sipa Resources Limited is thanked for providing geological maps. Thanks also go out to Sipa Resources Limited for the use of aerial photograph mosaic and the high resolution DEM. Thanks go out to AGSO for the use of the airborne gamma-ray images. Thanks go out to Peter Hausknecht of Fugro Airborne Surveys for the high resolution airborne gamma-ray images.

I would also like to thank Rod Holcombe for the free use of his software GeOrient 9.2 and Ianko Tchoukanski for the free use of his ET GeoWizards 9.4.1 software.

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Terminology

The Panorama VMS district is also known as the Soanesville Belt or the Strelley Belt. In this thesis the area will be named Panorama area or Panorama district, keeping up with recent work (e.g. Brauhart, 1999, Drieberg, 2003). The granite intrusion of the Panorama area is still named the Strelley Granite.

The term doming is used in this thesis for the (local) upwards doming of layers due to an intrusion. The term diapirism is applied for the theory of vertical tectonics (e.g. Collins, 1989).

The term VMS is used as an abbreviation of “volcanogenic massive sulphide”. 

Chapter 1: Introduction

1.1 Preface

The Panorama area is part of the East Pilbara granite-greenstone terrane of the Pilbara, Australia. This greenstone belt is host to volcanogenic massive sulphide (VMS) deposits and provides an excellent location for studying them, as the relatively unweathered and undeformed rocks are almost fully exposed because of eastward dipping strata (Brauhart, 1999). Over the past decades much progress has been made in the understanding of VMS deposit genesis (Scott, 1997), but there still remain questions. One of these questions is whether the discharge of the hydrothermal fluids from which the minerals precipitate is localized in faults (e.g. Brauhart, 1999; Drieberg, 2003). Another question remaining is whether magmatic fluids have a direct input in the hydrothermal system (e.g. Stanton, 1994; Scott, 1997; Yang and Scott, 2002). These questions might be addressed to when viewing the hydrothermal alteration system of the Panorama with airborne hyperspectral imagery.

1.2 Research Area

The research area is the Panorama area in the Pilbara, Western Australia (Fig. 1.1). The district is located about 120km south of Port Hedland. The coverage of the hyperspectral imagery used in this research is restricted to a 5km wide northwest southeast oriented scene that includes mainly the volcanics and sediments of the Panorama area. Most of the other images, used in this study as a support of the Hymap information, cover a slightly larger area and include the entire Panorama district.

![Figure 1.1: The location of the North Pilbara terrain and the Panorama area (modified from Krapez, 1993, Brauhart, 1998 and Van Kranendonk et al., 2002). Wpggt = West Pilbara granite-greenstone terrain, epggt = East Pilbara granite-greenstone terrane, kt = Kuranna terrane, ssz = Sholl shear zone.](image-url)
1.3 Research Aim

The aim of this research is to determine whether airborne imaging spectroscopy and other remote sensing data sets provide new information on the hydrothermal alteration processes related to VMS deposit genesis in the Panorama district in Western Australia.

1.4 Objectives

The focus of this thesis is to use hyperspectral information for the study of alteration patterns. The research area is the Panorama, Pilbara, Western Australia. The objectives of this thesis are:

- To determine which features from existing geological maps can be interpreted from remote sensing data.
- To determine what additional information is present in the remote sensing data.
- To make a detailed geological interpretation of lithology, alteration and linear features of the Panorama area based on the remote sensing data.
- To make a structural analysis of linear features interpreted from the remote sensing data.
- To use the geological interpretation for new constraints on timing and formation of the Panorama area and formulate the geological history based on remote sensing interpretation and previous work.
- To formulate a model of VMS deposit genesis based on the geological history of the Panorama area.

1.5 Previous Work

The first discovered VMS deposit of the Panorama area is the Cu-Zn Sulphur Springs deposit that was discovered in 1984 by H. Wilhelmij (Morant, 1998). Subsequent exploration of the Panorama area has led to the discovery of five other VMS deposits: Kangaroo Caves, Roadmaster, Breakers, Man O’ War and Anomaly 45 (Morant, 1998). The deposits of the Panorama area, with the focus on the Sulphur Springs deposit and the Kangaroo Caves deposit, were studied by Vearncombe (1995).

The Panorama area was first mapped at a 1:250000 scale by Hickman and Lipple (1978). More detailed mapping (in a 1:10000 and 1:5000 scale) was undertaken by Sipa Resources Limited in 1992 and 1993, but these maps remained unpublished. Brauhart (1998) mapped the volcanic pile at a 1:5000 scale and the Strelley Granite at a 1:25000 scale. A 1:100000 scale map of the North Shaw was published by the Geological Society of Western Australia (Van Kranendonk, 1999). The sediments overlying the Sulphur Springs deposit have been mapped by Hill (1997) and Glikson and Vickers (2005).

The alteration system of the Panorama was studied in detail by Brauhart et al. (1999). This study was based on field research. These conventional methods to describe hydrothermal alteration and reconstruct fluid flow in fossil hydrothermal systems require extensive sampling and laboratory analysis (Van Ruitenbeek et al., 2005). Therefore Van Ruitenbeek et al. (2005) have shown that data from near-infrared spectroscopy can be used to detect and reconstruct fluid
pathways in fossil hydrothermal systems. For this the alteration facies found in the Panorama volcanic pile by Brauhart et al. (1998) and Brauhart (1999) were correlated to reflectance spectra (Van Ruitenbeek et al., 2005). It was found that the spectroscopy could distinguish between high and low Al content in white mica and between chlorite or white mica dominance of the alteration (Van Ruitenbeek et al., 2005). Airborne imaging spectrometry data, first processed by (Cudahy et al., 1999) have been processed by Van Ruitenbeek et al. (in press) into maps of white mica probability, wavelength and a fused image. These images are used in this research and will be further discussed in following chapters.

1.6 Thesis Structure

This thesis is divided into six chapters. The first chapter is an introduction to the thesis. Chapter 2 deals with background information on VMS deposits and the geological setting of the Panorama area at a regional and a larger scale. Chapter 3 starts with an overview of information and data used and continues with research methods. The geological interpretation of the remote sensing data and a structural analysis of linear features are given in chapter 4. The geological interpretation is discussed in chapter 5 in terms of geological history and model formulation for VMS deposit formation. Conclusions and recommendations are given in chapter 6.
Chapter 2: Background and Geological Setting

This chapter deals with the geological setting of the Panorama VMS district and background information regarding VMS deposits. The description of the geological setting will start at the regional scale, with a brief description of the Pilbara Craton (2.1) and the East Pilbara granite-greenstone terrane (2.1.1) of which the Panorama area is a part. In chapter 2.2 the structure (2.2.1), alteration (2.2.2) and formation (2.2.3) of VMS deposits are discussed. Chapter 2.3 deals with the geology of the Panorama district (2.3.1) as well as alteration associated with VMS deposits (2.3.2), models of formation of the Panorama VMS deposits (2.3.3) and a short description of the VMS deposits of the Panorama area (2.3.4).

2.1 The Pilbara Craton

The Panorama area is a part of the Pilbara Craton that is located in the north-west of Western Australia (Fig. 1.1). The Pilbara Craton can be divided into the Achaean granite-greenstones of the northern Pilbara terrain (3.72-2.85 Ga; van Kranendonk et al., 2002) and the younger volcano-sedimentary sequence of the Hamersley basin (2.77-2.4 Ga; van Kranendonk et al., 2002) in the south (Griffin, 1990). The area has not undergone major regional deformation since 2.4 Ga (Griffin, 1990) and it contains the oldest and best exposed granite-greenstone terranes in Australia (Griffin, 1990).

Based on 1:250000 scale mapping in the 1970’s, Hickman (1983) regarded the Pilbara greenstones as one Pilbara Supergroup. This supergroup was divided into four groups: the Warrawoona Group, the Gorge Creek Group and the Whim Creek Group (Hickman, 1983). Later workers have described the geology of the Pilbara as five tectonostratigraphic domains, separated from each other by north east trending lineaments (Krapez and Barley, 1987) and as two Megacycle sets, divided into four Megacycles (Krapez and Eisenlohr, 1998). More detailed mapping (on a 1:100,000 scale) and more geochronologic measurements that have been made since 1994 have led to new insights into the northern Pilbara stratigraphy (Van Kranendonk et al., 2002). Van Kranendonk (2002) divides the terrain into three separate granite greenstone terranes separated by sedimentary basins (Fig. 1.1). These three terranes are; the East Pilbara Granite-Greenstone Terrane (3.72-2.85 Ga); the West Pilbara Granite-Greenstone Terrane (3.27-2.92 Ga) and the Kuranna terrane (≤ 3.29 Ga). Each of these three terranes has its own stratigraphy. The Panorama greenstone belt, the study area of this thesis, is part of the East Pilbara granite-greenstone terrane. This terrane consists of five volcano-sedimentary groups and two formations (Van Kranendonk et al., 2002). A short description of the stratigraphy, based on Van Kranendonk et al. (2002), follows in section 2.1.1.

There are two main hypotheses on the formation of greenstone belts; one involving vertical tectonics and one involving horizontal tectonics. The traditional interpretation is that of solid-state diapirism, where uprise of a batholithic dome causes the dome and keel structures of the granite-greenstone terranes (e.g. Hickman, 1981; Collins, 1989; Collins et al., 1998). The other hypothesis is that the structures formed by normal plate tectonic processes (e.g. Bickle et al., 1980; Zegers et al., 1996; Kloppenburg et al., 2001).

2.1.1 East Pilbara Granite-Greenstone Terrane

The Coonterunah Group (3.51-3.5Ga) forms the base of the stratigraphy (van Kranendonk et al., 2002). The ≤ 5.9km thick formation consists mainly of tholeiitic basalt and around the southern flank intermediate to felsic volcanic rocks (Van Kranendonk et al., 2002). The formation is intruded by the Carlindi Granitoid complex (Van Kranendonk et al., 2002).
Chapter 2: Background and Geological Setting

The Warrawoona group (3.49-3.31 Ga) consists of mainly basaltic rocks, interbedded with felsic rocks and with chert (Van Kranendonk et al., 2002). The group can be divided into three subgroups; the Talga Talga subgroup; the Salgash subgroup and the Kelley subgroup. The estimates of the thickness of this group vary from 9 to 18km (Van Kranendonk et al., 2002).

The Budjan Creek Formation (3.3 Ga) consists of sedimentary and felsic volcanic rocks (Van Kranendonk et al., 2002). It varies in thickness between 150 and 1200m (Van Kranendonk et al., 2002).

The Golden Cockatoo Formation (with an age somewhere between 3240 and 3321 Ma) consists of amphibolite facies metamorphic rocks (Van Kranendonk et al., 2002).

The Sulphur Springs Group (ca. ≤ 3.3 Ga; Buick et al., 2002) is dominantly volcanic (Van Kranendonk et al., 2002). The Sulphur Springs Group can be divided into three formations, from top to bottom the Leilira, Kunagunarrina and the Kangaroo Caves formation (Van Kranendonk et al., 2002).

The Gorge Creek Group (~3426-3016Ma; Nelson, 1998) consists of clastic sediment at the bottom and sandstones and shales at the top (Van Kranendonk et al., 2002). The succession reaches a thickness of 3.5 km at the Panorama area (Van Kranendonk et al., 2000).

De Grey Group consists of coarse clastic synform sediments (Van Kranendonk et al., 2002).

2.2 Volcanogenic Massive Sulphide Deposits

VMS deposits are stratabound, partly strataform, deposits of sulphide minerals formed by hydrothermal fluids that are exhaled at the seafloor. VMS deposits can be classed into the following three types according to their metal content: Cu-type, Zn-Cu-type and Zn-Pb-Cu-type (Solomon, 1976). Over the past three decades of seafloor research progress has been made in the understanding of ore formation (Scott, 1997). The structure of VMS deposits is discussed in section 2.2.1. The alteration surrounding the deposits is discussed in section 2.2.2. The two general models for the formation of VMS deposits are reviewed in section 2.2.3.

2.2.1 Structure

Large (1992) distinguishes between three VMS deposit morphologies: the mound type, the lens blanket type and the pipe and stringer deposit. The mound deposits are lenticular shaped bodies that grade from the base into a pipe-like stringer zone (figure 2.1). The lens consists of semi massive to massive sulphide, whereas the stringer zone consists of vein-type sulphide deposits. The lens and blanket deposit is similar to the mound deposit, only it has a poorly developed, or absent, stringer zone. The pipe and stringer deposit has no or little lense shaped deposit, but only a well developed stringer zone.

VMS deposits are generally Cu-rich at the base and Zn-rich at the top (Franklin et al., 1981). The Cu-rich zones are interpreted to be higher temperature mineralization (Franklin et al, 1981).
2.2.2 Alteration

Franklin et al. (1981) distinguished between four types of alteration associated with VMS deposits. There is alteration in the horizon of the ore itself. The second type is the before mentioned alteration pipe associated with the stringer zone. The third is a semi-conformable alteration zone which is present several hundred meters below the VMS deposits. This alteration zone may be the zone where metals and sulphur were leached from the rocks into the hydrothermal fluid (Franklin, 1986), the zones have a isotherm parallel to the subvolcanic intrusion (Galley, 1993). The fourth type is alteration in overlying layers, which in composition is similar to the alteration in the alteration pipes. The alteration here is typically weaker with stronger alteration directly overlying the VMS deposits (e.g. Doyle and Allen, 2003).

2.2.3 Formation

There are two main models for the formation of VMS deposits, the convection cell model (e.g. Spooner and Fyfe, 1973) and the stratal aquifer model (Lydon, 1988).

In the convective hydrothermal model the hydrothermal system that drives the formation of VMS deposits is thought to be a convective cell (e.g. Spooner and Fyfe, 1973). For the driving of such a convective cell, a heat source is needed within a few kilometres of the seafloor (e.g. Spooner and Fyfe, 1973; Scott, 1997). The circulating fluid is thought to be mainly seawater that modifies its composition as it descents in a convective cell (e.g. Franklin et al., 1981). After it has passed through the hottest part of the convective cycle, the hydrothermal fluid rises again. This might be through zones with the highest permeability like fractures (e.g. Scott, 1997). The first deposition takes place just below the surface in the stringer zone (e.g. Franklin et al., 1981). When the fluid reaches the surface, the rapid drop in temperature causes the minerals to precipitate and form a zoned body of deposition (Franklin et al., 1981). The deposits may also form in a sub-seafloor setting (Doyle and Allen, 2003). The body of deposits can build up to be large when there is a cap rock (e.g. Scott, 1985; Franklin, 1986) or when there are enough permeability variations (Cathles,
1993). The presence of a sedimentary or volcanic cover is essential for the preservation of the deposits after mineralization has ended (Scott, 1997). When the bodies become unstable they can be redepósited as a non-zoned distal deposit (Franklin et al., 1981). Although seawater is considered here as the main fluid source, the water might come from three other sources: connate water, meteoric water and magmatic volatiles (Franklin et al., 1981). So magma contributes as a driving force for convective motion, but the question remains whether the magma contributes directly to the hydrothermal fluids or not (Stanton, 1994).

In the stratal aquifer model (Lydon, 1988), the hydrothermal fluids are derived from pore water below a cap rock. At high temperatures metals are leached from the surrounding volcanic rocks (Lydon, 1988). The hydrothermal fluids are released to the ocean when the cap rock breaks (Lydon, 1988).

2.3 The Panorama Area

The Panorama district is one of the Achaean greenstone belts of the North Pilbara terrain. It is a part of the East Pilbara granite-greenstone terrane. Discovered in 1984 the VMS deposits here proved to be of importance as they give a continuous exposure of the deposit (Brauhart et al., 1998). The deposits are Achaean, but have been preserved well, as only low grade metamorphism has affected the rocks (Vearncombe et al., 1995). This section is divided into different sections dealing with: The geology of the Panorama area (2.3.1), alteration associated with the Panorama VMS deposits (2.3.2) and the formation of the Panorama VMS deposits (2.3.3).

2.3.1 Geology of the Panorama Area

From the stratigraphic succession as described in section 2.1.1, only the Sulphur Springs Group and the Gorge Creek Group are present at Panorama. The Sulphur Springs Group consists of the Strelley granite and the volcanic sequence in the north, east and southeast (Brauhart, 1999). The sediments of the Gorge Creek Group overlie the Sulphur Springs volcanics (Brauhart, 1999). Age measurements that have been carried out in the Panorama area are given in table 2.3.1.

The geology of the Panorama area has been mapped by Brauhart et al. (1998) as part of a PhD research (Brauhart, 1999). The geological map, which is given in figure 2.2, does not include the Gorge Creek Group sediments (Brauhart et al., 1998). These sediments have been mapped by Vearncombe (1995) as part of her PhD research. The sediments overlying the Sulphur Springs deposit have been mapped by Hill (1997).
Chapter 2: Background and Geological Setting

Figure 2.3.1: The geology of the Panorama area (Brauhart et al., 1998). Included on the map are the locations of the VMS prospects.
Chapter 2: Background and Geological Setting

**FIGURE 2.3.2:** The geology of the sediments overlying the Sulphur Springs deposit (modified from Glikson and Vickers, 2006, after Hill, 1997). Inset from Brauhart et al., 1998. The location of this map is indicated on the geological map of Brauhart et al. (1998). Included on the map are the locations of the VMS prospects.

**TABLE 2.3.1:** An overview of age measurements of the Panorama area and the Gorge Creek Group outside of the Panorama area.

<table>
<thead>
<tr>
<th>Location</th>
<th>Age (Ma)</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strelley granite - Inner phase</td>
<td>3238±3 (a)</td>
<td>-21.2133</td>
<td>119.1929</td>
<td>U-Pb SHRIMP</td>
</tr>
<tr>
<td>Strelley granite - Outer phase</td>
<td>3239±2 (a)</td>
<td>-21.2784</td>
<td>119.1044</td>
<td>U-Pb SHRIMP</td>
</tr>
<tr>
<td>Strelley granite - Granophyric margin</td>
<td>3239±5 (a)</td>
<td>-21.1706</td>
<td>119.1507</td>
<td>U-Pb SHRIMP</td>
</tr>
<tr>
<td>Kangaroo Caves Formation - Hanging wall Kangaroo Caves deposit</td>
<td>3235±3 (a)</td>
<td>-21.2336</td>
<td>119.2371</td>
<td>U-Pb SHRIMP</td>
</tr>
<tr>
<td>Kangaroo Caves Formation - Footwall Sulphur Springs deposit</td>
<td>3238±3 (a)</td>
<td>-21.1903</td>
<td>119.2292</td>
<td>U-Pb SHRIMP</td>
</tr>
<tr>
<td>VMS deposits (Sulphur Springs and Kangaroo Caves)</td>
<td>3257±8-6 (b)</td>
<td>-</td>
<td>-</td>
<td>Pb-Pb dating</td>
</tr>
<tr>
<td>Gorge Creek Group</td>
<td>~3426-3016(c)</td>
<td>-</td>
<td>-</td>
<td>U-Pb SHRIMP</td>
</tr>
</tbody>
</table>

(a) Buick et al., 2002 (b) Vearncombe (1995) (c) Nelson, 1998
Chapter 2: Background and Geological Setting

The Strelley Granite
The Strelley granite has an inner and outer phase, the inner phase intruded the outer phase (Brauhart, 1999). The outer phase grades upwards from a coarse-grained hornblende-biotite granite through a finer-grained granite to a fine-grained granophyre (Brauhart, 1999). The granophyre is described as a rapidly quenched outer margin (Brauhart, 1999). The inner phase granite is a biotite-hornblende granite, that is different from the outer phase in “its porphyritic texture, the predominance of biotite over hornblende and the whitish colour of K-feldspar” (Brauhart, 1999).

Sills of microgranite intruded the inner and outer phase (Brauhart, 1999). The sills that intruded the outer phase are considered comagmatic, the sills that intruded the inner phase are regarded as a separate event (Brauhart, 1999).

Linear bodies of mafic and ultramafic intrusions are present in the area, these features are younger than the granite and the volcanic sequence (Brauhart, 1999). Mafic intrusions with a straight western contact and irregular western boundaries are present as well (Brauhart, 1999).

The Volcanic Sequence
Age measurements of the Strelley granite and the volcanic sequence have shown that they both fall in the same error range (Buick et al., 2002), but cross-cutting relationships at outcrop scale have shown that the outer phase granite has intruded the Sulphur Springs volcanics in a conformable manner (Brauhart, 1999). The volcanic sequence is mostly of the Kangaroo Caves Formation, but the Kunagunarrine and Leilira Formations outcrop near the Roadmaster prospect (Brauhart, 1999). The true thickness is 1.5 km (Morant, 1995). The volcanics vary in composition from basaltic to rhyolitic (Brauhart, 1999). In the north the sequence is dominated by andesite basalt, with a dacite intrusion at the top and microdiorite intrusions at the bottom (Brauhart, 1999). The south of the volcanic sequence is dominated by rhyolite and dacite (Brauhart, 1999).

The volcanics have been interpreted as sub-seafloor volcanics (McPhie et al., 1993). The absence of sedimentary deposits between the volcanics has led Brauhart (1999) suggest a rapid extrusion of the volcanics.

Marker Chert
The Marker Chert is considered by Brauhart (1999) as the top of the Kangaroo Caves Formation. The Marker Chert is a siliceous laminate with a sharp upper and lower contact (Vearncombe, 1995). The thickness of the layer is typically 2-10m in thickness, except for near the mineralization, where it can be up to 80m thick (Brauhart, 1999).

The Marker Chert has been variously interpreted (see section 2.3.3).

Olistostrome
A megabreccia immediately overlies the Marker Chert above the Sulphur Springs deposit that has been interpreted as an olistostrome (e.g. Vearncombe, 1995; Hill, 1997; Glikson and Vickers, 2006). The olistostome onlaps the Marker Chert, with a suggested direction of flow towards the south-east (Hill, 1997). Van Kranendonk and Morant (1998) consider the olistostrome a part of the Kangaroo Caves formation, Glikson and Vickers (2006) consider it a part of the Gorge Creek Group. Two bodies of rhyodacite have been interpreted by Vearncombe (1995) as olistoliths. Based on peperitic margins and geochemical correlation to the underlying volcanic sequence Hill (1997) suggests they intruded after sediment deposition. The olistostrome is topped by a chert layer, termed the upper chert (Hill, 1997). The upper chert has been interpreted to represent a depositional hiatus (Hill, 1997).

The Sedimentary Sequence
The sediments of the Gorge Creek Group are turbiditic (e.g. Vearncombe, 1995; Hill, 1997; Brauhart, 1999). The contact between the volcanic sequence and the sedimentary deposits has been differently described as "commonly in a conformable manner" (Brauhart, 1999) and as unconform (e.g. Vearncombe, 1995). The unconformity is considered by Brauhart (1999) as an onlap between the sediments and the Marker Chert as a result of flow direction. Thomas (1997) describes the contact as a downlap.

The turbidite sequence above Sulphur Springs and Kangaroo Caves is described by Vearncombe (1995) as a sandstone-siltstone lithofacies that changed abruptly into a coarse-grained sandstone lithofacies that grades into a fine-grained lithofacies. Hill (1997) studied the sediments overlying the Sulphur Springs deposit in detail. He divides the turbidites into three gradational lithofacies: A sandstone dominated lithofacies; a siltstone dominated lithofacies and parallel-laminated mudstones and shales (Hill, 1997). The sandstone dominated lithofacies pinches out towards the west.

The sedimentary environment of deposition has been interpreted as shallow marine (for the sandstone and siltstone dominated lithofacies, changing from a mid-fan to outer mid to lower fan. The fine-grained lithofacies is interpreted to have deposited in deeper water in distal parts of the fan or the basin plain (Hill, 1997).

Comagmatic microgranite sills and dykes have intruded the outer phase granite (Brauhart, 1999). The microgranite sills and dykes that intruded the inner phase are probably of a separate event (Brauhart, 1999). A series of mafic to ultramafic sills intrude the Gorge Creek Group (e.g. Wilhelmij, 1986; Hill, 1997).

Tectonic History
A detailed structural analysis of the Panorama area is lacking. Vearncombe (1995) and Brauhart (1999) have described synvolcanic faults that they suggest have played a role in localizing VMS deposits. The faults in the sedimentary succession above the Sulphur Springs deposits have been mapped by Hill (1997). Two large scale sinistral faults are related to tectonic event at ~2950Ma (van Kranendonk and Collins, 1998). The other faults in the area are synvolcanic, with possible minor reactivation during later tectonic events (Brauhart, 1999). The faults are interpreted to be syn-volcanic on the basis of a progressively smaller displacement in the Gorge Creek Group (Brauhart, 1999).

2.3.2 Alteration Associated with the Panorama VMS Deposits
Brauhart et al. (1998) have mapped the alteration system at Panorama at a regional scale (Figure 2.3.3). They have found four main alteration facies, with several subgroups and transitional alteration facies. The four main alteration facies are feldspar-bearing background alteration; a feldspar-sericite-quartz alteration; a sericite-quartz alteration and a chlorite-quartz alteration. A short description of the alteration facies follows here from Brauhart et al., 1998 and Brauhart, 1999.
Chapter 2: Background and Geological Setting

Figure 2.3.3: The Alteration map of Brauhart et al. (1998). Included on the map are the locations of the VMS prospects.
**Background alteration**: Primary ferromagnesian minerals are altered to chlorite or sericite.

**Feldspar-sericite-quartz alteration**: This alteration does not contain any ferromagnesian phase. Minor chlorite is present in rocks transitional to background alteration.

**Sericite-quartz alteration**: This alteration is feldspar destructive. Primary ferromagnesian minerals are typically replaced by sericite.

**Greisenization**: This alteration is a coarser grained variation on the sericite-quartz alteration. It may contain chlorite.

**Transitional sericite-quartz alteration**: Alteration zone where there is subequal background and sericite quartz alteration.

**Chlorite-quartz alteration**: This alteration is feldspar destructive. Feldspar is replaced by quartz with lesser chlorite and sericite. Chlorite is present in the groundmass and replacing ferromagnesian minerals.

**Chlorite-quartz-ankerite alteration**: The chlorite-quartz alteration contains ankerite in rare cases, but here the carbonate is coarser grained than in the background alteration.

**Transitional to background alteration**: Mineralogy is transitional between chlorite-quartz and background alteration.

The feldspar-sericite-quartz alteration is present at the top of the volcanic pile and overlies the background alteration (Brauhart, 1999). The chlorite-quartz alteration overprints the background alteration towards the base of the volcanic pile (Brauhart, 1999). Zones of feldspar destructive alteration (sericite-quartz alteration below chlorite-quartz alteration) crosscut the semi conformable alteration zones, they extend from the base of the volcanic pile up to the Marker Chert (Brauhart, 1999). These zones include the transgressive alteration zones that underlie the major VMS deposits (Brauhart, 1999).

Franklin et al. (1981) described alteration zones below VMS deposits, these alteration pipes associated with the stringer zone are much smaller however. Brauhart et al. (1998) therefore
conclude that transgressive alteration zones underlie those VMS deposits that do not have a clearly defined stringer zone.

The completely feldspar destructive alteration facies suggest that there was unusual high fluid flux in the Panorama hydrothermal alteration system (Brauhart et al., 1998).

The hydrothermal vein system of the volcanic sequence and the subvolcanic intrusions of the Panorama area has been studied by Drieberg (2003). The study focussed on the north-eastern part of the area. Drieberg recognized twelve separate vein types of which four were minor, the veins were interpreted in different sets that can be related to the alteration of the Panorama area as mapped by Brauhart et al. (1998) and Brauhart (1999) (Drieberg, 2003). On this accord it is noted that there are no veins present in the chlorite quartz alteration zones (Drieberg, 2003; Brauhart et al., 1998).

One of these sets is a spectrum of vein phases that Drieberg relates to the intrusion of the emplacement of the inner phase granite (Drieberg, 2003). This spectrum consists of magmatic greisen in the inner phase granite, vein greisen in the lower part of the outer phase granite and Cu-Zn-Sn veins in the top of the outer phase granite and the bottom of the volcanic sequence (Drieberg, 2003). The Cu-Zn-Sn veins are interpreted to be hydrothermal veins that crosscut the background alteration of Brauhart et al. (1998).

The set of quartz-chalcopyrite veins is present only in the granophyre roughly below the Sulphur Springs deposit (Drieberg, 2003).

A set of quartz-pyrite veins present only where there is sericite quartz alteration at the top of the outer phase granite.

A set of quartz epidote veins is present only in the microdiorite sills at the bottom of the volcanic sequence (Drieberg, 2003). These veins are what Brauhart (1999) termed actinolite-epidote alteration (Drieberg, 2003).

A set of quartz-carbonate-pyrite veins is present background altered volcanic sequence.

A set of quartz-sericite veins is present in feldspar-sericite-ankerite altered volcanic sequence.
Chapter 2: Background and Geological Setting

FIGURE 2.3.4: The 8 major vein types mapped by Drieberg (2003). (Figure from Drieberg, 2003).

Hill (1997) described the alteration of the sediments overlying the Sulphur Springs deposit. He distinguishes a lower zone of sericite-quartz alteration and an upper zone of carbonate alteration with local chlorite-sericite replacements (Hill, 1997).

2.3.3 Formation of the Panorama VMS Deposits

Based on study of the geology and the alteration system of the Panorama Brauhart (1999) and Brauhart et al. (2000) propose a three stage model for the development of VMS deposits. This model for the Panorama is similar to the convective hydrothermal model described in section 2.2.1.

In the first stage (Fig. 2.3.4a), immediately after the intrusion of the outer phase granite, there are randomly located shallow convection cells where low temperature fluids are discharged at the seafloor. The diffuse discharge of Si-rich fluids at this stage has formed the Marker Chert. The Marker Chert is regarded by Brauhart as a seal. Because it obstructs upward flow, the sulphides are deposited below the Marker Chert. The fluids that pass the Marker Chert along faults deposit banded chert-siderite rock above the Marker Chert.
In the next stage (Fig. 2.4b) the convection cells are larger and stable, they discharge the fluids through the same conduit throughout the entire life of the hydrothermal system. The feldspar-bearing alteration is associated with the broad recharge zones and the chlorite-quartz alteration is associated with the narrow discharge zones. There is a close association between synvolcanic faults and the discharge zones. A second lower convection exists below the cracking front of the 350°C isotherm (Lister, 1983), this system is dominated by magmatic fluids. The alteration associated with this system is the sericite-quartz alteration.

The third stage (Fig. 2.4c) starts when the cracking front descends into the cooling intrusion. The seawater dominated hydrothermal system overprints the alteration of the magmatic fluids.

The chemical gradient is the result from reactions with seawater at increasingly higher temperatures at increasing depth. Because the isotherms controlling these reactions are parallel to the intrusion, the boundaries of the reaction zones are semi conformable with the intrusion. The transgressive alteration zones are formed by the returning more evolved seawater.

Figure 2.3.5: The three-stage model for VMS deposit formation at the Panorama area proposed by Brauhart (1999) and Brauhart et al. (2000). (Figure from Brauhart, 1999.)

The hydrothermal vein system is modelled in terms of four endmember fluids: Seawater; evolved seawater or VMS hydrothermal fluid; inner phase granite related magmatic fluid and a magmatic brine. This last endmember did not interact with the other three endmembers.

There is a main-stage hydrothermal convection within the volcanic stratigraphy that is caused by the intrusion of the outer phase granite. This convection caused the alteration pattern as described by Brauhart et al. (1998) and Brauhart (1999).

During the waning stage of the convection, the cooling of the intrusions allowed the VMS convection cells to collapse downwards. The sericite-quartz alteration then forms in the granite.

The intrusion of the inner phase granite shortly reinvigorated the VMS hydrothermal system.

After the collapse of the hydrothermal system, cold seawater infiltrated the system.

Drieberg states that the Marker Chert can not have formed during the first stage of Brauhart’s model (1999), as there is evidence that seawater and hydrothermal fluids mixed at the site of sulphide mineral deposition. Instead Drieberg proposes that it was formed gradually over the lifetime of the VMS hydrothermal system.
2.3.3 The Panorama VMS Deposits

The VMS deposits of the Panorama district are: Sulphur Springs, Roadmaster, Kangaroo Caves, Breakers, Man ‘O War, Anomaly 45, Bernts and Jamesons (e.g. Vearncombe, 1995; Morant, 1998; Ferguson and Ruddock, 2001). The last two of these have been related to the Lalla Rookh structural corridor (Morant, 1998). The deposits are of the Zn-Cu type with characteristics of the Zn-Pb-Cu type (Vearncombe, 1995). The mineralizations have a metal zonation, the base is Cu-rich and the top is Zn-rich (Vearncombe, 1995), as is typical for VMS deposits (Franklin et al., 1981). Sparsely
Most of the deposits are located immediately below, or within, the Marker Chert (Brauhart, 1999). Some gossans at Man ‘O War and Anomaly 45 are not at, but near the top of the volcanic sequence (Brauhart, 1999).

Vearncombe (1995) found the Suphur Springs and Kangaroo Caves deposits were formed in a seafloor setting. Drieberg (2003) interpreted the VMS deposits to have precipitated at the seafloor, as the VMS hydrothermal fluids mixed with both heated unevolved seawater and cold, ambient seawater.

The commodities of the VMS deposits are given in table 2.1 from Ferguson and Ruddock (2001).

**Table 2.3.1: The commodities of the VMS deposits of the Panorama area**

<table>
<thead>
<tr>
<th>Name</th>
<th>Commodities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sulphur Springs</td>
<td>Cu Zn</td>
</tr>
<tr>
<td>Roadmaster</td>
<td>Zn Cu</td>
</tr>
<tr>
<td>Kangaroo Caves</td>
<td>Zn Cu Pb Au Ag</td>
</tr>
<tr>
<td>Breakers</td>
<td>Cu Zn</td>
</tr>
<tr>
<td>Man ‘O War</td>
<td>Cu Zn</td>
</tr>
<tr>
<td>Anomaly 45</td>
<td>Cu Zn</td>
</tr>
</tbody>
</table>

From Ferguson and Ruddock (2001).
Chapter 3: Data and Methodology

In this chapter an overview of the data used in this study is given (3.1), as well as the methods for studying them (3.2).

3.1 Data

The data used for this thesis can be divided into remote sensing data and existing field-based maps. All data are projected in the AGD_1966_AMG_Zone_50 coordinate system. The geographic coordinate system is GCS_Australian_1966.

The following remote sensing datasets were available for research:

- Hyperspectral imagery (Cudahy et al., 1999; Van Ruitenbeek et al., in press)
- Landsat TM imagery
- MASTER imagery
- Radiometric Imagery (Richardson, 2003; fugro airborne surveys)
- Digital aerial photography
- Elevation (Richardson, 2003)

Geological maps at different scales and data on mineral occurrences were also available.

The datasets have a varying coverage. The coverage of the datasets that do not cover the entire study area has been indicated in figure 3.1.1.

These datasets will be discussed separately in the following seven sections (3.1.1-3.1.7).
3.1.1 Hyperspectral Imagery

The Hymap (hyperspectral mapper) sensor is an airborne multispectral sensor that acquires data in tens to hundreds of bands (Cocks et al., 1998). The Hymap scenes used in this study were collected in November 1998 (Cudahy et al., 1999). From these Hymap scenes the white mica probability and the absorption wavelength were predicted (Van Ruitenbeek et al., in press). These predictions were available in this study in the form of three maps: An absorption wavelength image, a mica probability image and a fused image (Cudahy et al., 1999; Van Ruitenbeek et al., in press).

The white mica probability map shows the probability of white mica being present (Van Ruitenbeek et al., in press). The pixel values range from zero to one, where one is a 100% probability of white mica being present. The absorption wavelength is the “the wavelength position of the absorption minimum in spectra of white micas” (Van Ruitenbeek et al., in press). This absorption wavelength varies with the Al content of white micas (e.g. Van Ruitenbeek et al., 2005). The blue hue indicates Al-rich white micas and the red hue indicates Al-poor and Fe and Mg rich white micas. The fused image is an image where the intensity is the white mica probability and the hue is the absorption wavelength. So this map shows the both the probability and composition of white mica. The blue hue again indicates Al rich white mica and the red hue
indicates Al poor and Fe and Mg rich white mica. Apart from these images a natural colour composite was used as well. The spatial resolution of these images is 5m.

The Hymap imagery is available for a 5km wide northwest southeast oriented scene that includes mainly the volcanics and sediments of the Panorama area.

3.1.2 Landsat TM Imagery
Both the Landsat-4 and -5 carry a Thematic Mapper (TM). The Thematic Mapper is an advanced multispectral sensor (compared to the multispectral scanner) that acquires data in seven spectral bands. The data have been resampled and have a spatial resolution of 25m.

The Landsat TM imagery is available for a large part of the Pilbara area including the entire Panorama area.

3.1.3 MASTER Imagery
The MODIS/ASTER airborne simulator is a multispectral scanner that acquires data in 50 channels over the spectral range of 0.4-13µm (Hook et al., 2001).

The MASTER imagery has a spatial resolution of 15m and covers a northwest southeast trending band of around 11.5 km wide that covers roughly the east of the Panorama area.

3.1.4 Radiometric Imagery
Gamma-ray images show the radiometric elements the abundance of radiometric elements in the upper 30 centimetres of the surface. The only radiometric elements that produce gamma-rays are K, Th and U.

Three large scale maps obtained from gamma-ray surveys were used (Fugro Airborne Surveys): One from 1999, one from 2001 and a merged image (Anderson, 2003). This merged image is a 5.5 to 8 km wide north-northeast – south-southwest trending band that covers the northeast part of the Panorama area. Furthermore there is one small scale (1:250000) radiometric image of a larger area of the Pilbara (Richardson, 2003), apart from the three separate radiometric elements, a total count image is available for is available as well. The total count image shows the total amount of gamma rays present at the surface.

3.1.5 Aerial Photographs
The aerial photographs are present for the entire Panorama area. The spatial resolution is 2m.

3.1.6 Elevation
A 10m resolution elevation map was available (Richardson, 2003), that covers almost the entire Panorama area, except for part of the western edge of the granite body (Fig. 3.1.1). A 90m resolution elevation map that covers the entire Panorama area was available as well (Richardson, 2003).

3.1.7 Field-based Maps
There were three geological maps and one alteration map available for use, as well as mineral occurrence maps:
• The 1:250000 geological map contains the entire Pilbara Craton (Hickman and Lipple, 1978).
• The 1:100000 geological map of the Northern Shaw (Van Kranendonk, 1999).
• The 1:5000 and 1:25000 geological map and alteration map of the Panorama area (Brauhart et al., 1998).
• MINEDEX, a database of mines and mineral deposits of Western Australia (Townsend et al., 1996).
• A map of mineral occurrences in the east Pilbara (Ferguson and Ruddock, 2001), this map is not available in digital form.

3.2 Methodology

The remote sensing data were stored in an ArcGIS 9.0 database. All handling of data was done with ArcGIS9.0. The methods can be divided into three steps: Geological mapping (3.2.1), structural analysis (3.2.2) and model formulation (3.2.3). A flow chart of the research is given in figure 3.2.1.

In order to optimally use the remote sensing data, the images were processed where needed in the first two steps of this research. The different image processes are discussed in section 3.2.4.
3.2.1 Geological Mapping

To make a geological interpretation of the Panorama area both the remote sensing data and the existing geological maps were used. It was first determined which features from the existing geological maps (Hickman and Lipple, 1978; Van Kranendonk, 1999; Brauhart et al., 1998) can be interpreted from the remote sensing data. Features that could be recognized from remote sensing data that are not found on the existing geological maps were interpreted as well. From these features it was determined whether they are related to alteration or lithology. A separate interpretation of linear features was made.

Figure 3.2.1: Flow chart of the research.
Chapter 3: Data and Methodology

All features were visually interpreted. The interpretation was started at the regional scale: the Landsat TM data, radiometric and aeromagnetic images and elevation data. Outlines of regional scale features were traced based on these data. These outlines were improved and new, larger scale, features were then interpreted from larger scale images. These larger scale images are Hymap imagery, MASTER imagery, radiometric images, digital photographs and elevation data.

The boundaries of features (except the linear features) that have been interpreted were traced as polylines on an interpretation map. Attributes were assigned to each line stating the data on which the boundary is based and a specification of the boundary (e.g. a boundary between rocks high and low in K). A portion of these polylines were later polygonized to make a simplified geological map.

The linear features were mapped separately as polylines on an interpretation map of lineaments. Lineaments that have not been recognized as faults on existing geological maps are either: unrecognized faults, joints, veins or lineaments unrelated to geologic structures.

3.2.1 Structural Analysis

The linear features that have been interpreted from remote sensing data are divided into different sets based on characteristics (i.e. high or low in white mica, dextral or sinistral offset of alteration or lithology) and on the lithology in which they are present. The orientation and length of the lineaments is calculated by the COGO inverse function in ArcGIS add-on ET GeoWizards 9.4.1 that calculates orientations and lengths for line features in an ArcGIS shapefile. The orientation of a given lineament may vary, therefore one line feature in a shapefile may give several line segments with orientation and length in the ET GeoWizards 9.4.1 output. The orientation and length of the line segments were plotted in length-weighted rose diagrams using GeOrient 9.2 software.

The rose diagrams are based on lineaments and faults without a measured dip. This method is not as accurate method as one using field measured faults with a dip and dip direction and plotting them using a spherical projection. However, the strata from the Panorama area all dip eastward (Brauhart, 1999), and therefore the method is useable (Twiss and Moores, 2001).

3.2.2 Geological History and Model Formulation

A geological interpretation can be made based on the interpreted geology and structural analysis. The relative timing of events was established by crosscutting relationships, unconformities, the rose diagrams of the orientations of linear features and the extent of alteration zones throughout the lithologic sequence. Also, the work of other authors has been incorporated into the discussion of the geological history. Constraints from the geological history on timing and formation of VMS deposits have been used to formulate a model for the genesis of VMS deposits.

3.2.4 Image Processing

In order to optimally use the remote sensing data, the images are processed where needed in the first two steps of this research. Image processing tasks can be divided into those that restore images and those that enhance the visibility of the images for the use of interpretation. Restoration of the images includes correcting for atmospheric scattering. As the images will only be looked at relative to each other, no such correction is needed.

Images are built up of pixels. All these pixels have a digital number (DN). This number can range from 0 to 255. These pixels form a band. These bands can be displayed as an image, or can be combined with other bands into an image. Image processes are used to increase the visibility of the image. Different processes can be applied to try to attain the best visibility of an image for particular features. These will be discussed under separate headings.
Stretching techniques
To optimize the contrast in images, stretching techniques are applied. Contrast stretching, or linear contrast enhancement, is used where the DNs of images are enclosed in a small field of the 0-255 array. By stretching the DN over the full 0-255 range, the contrast of the image increases. Contrast can also be enhanced in a non-linear way, such as a Gaussian stretch (e.g. Jensen, 1986).

All images were constantly stretched when viewing them.

Ratios
Effects in images can be produced by topography, shadows or by seasonal variations, these effects can be reduced by ratioing images (Friedman, 1978). Apart from reducing these effects, ratios can also be useful for enhancing the occurrence of a certain mineral or for enhancing variations in the radiometric signal.

The reflectance spectra of minerals often show minima and maxima. By taking the ratio of two bands, one in a peak and the other in a minimum, the presence of this mineral will be enhanced on the resulting image. Different ratios have been made, reflectance spectra of minerals from which the ratios were found most useful are included in figure 4.3.2 and figure 4.3.3.

**Figure 4.3.2:** The reflectance spectrum of Muscovite (Clark et al., 1993). Included in the graph are the centre wavelengths of two MASTER channels and the wavelength ranges for two Landsat TM bands.
Chapter 3: Data and Methodology

FIGURE 4.3.3: The reflectance spectrum of Quartz (Clark, 1999). Included in the graph are the center wavelengths of two MASTER channels.

Colour Composites
Three single bands can be combined into one image by making a colour composite. A colour (red, green or blue) is assigned to each of the bands. These bands are then combined. A rule of thumb in assigning colours to bands is to assign the most informative band red, the next green and the next blue (e.g. Drury, 2001).

Colour composites were made, or were already available for: Landsat TM, MASTER and Hymap imagery and the radiometric data.

Data Combination
Different types of data can be combined by making them overlying (transparent) layers. The contrast of images can be enhanced by underlying them with hillshade images.
Chapter 4: Geological Interpretation

This chapter deals with the interpretation of the remote sensing data for the Panorama area. It sets out with a presentation of the geological interpretation based on the remote sensing data in the form of geological maps (4.1). The chapter continues with a description of the interpreted geology in terms of events (4.2). The linear features and the analysis of the linear features are discussed separately (4.3).

The data coverage varies over the area. The north-eastern part of the area is covered the best, as it is covered by the Hymap imagery, the MASTER images and the high resolution radiometric data. The interpretation is therefore focussed on this area.

4.1 Geological Maps

The geology of the Panorama area has been mapped using all available remote sensing data. Existing geological maps have been utilised for purposes of reference (Brauhart et al., 1998; Van Kranendonk, 1999; Hickman and Lipple, 1978; Hill 1997; Glikson and Vickers, 2006).

A map of all polylines of the geologic features is included in figure 4.1.1. The lineament map is given in figure 4.1.2. The geological map given in figure 4.1.1 is a simplified geological map showing the lithological subdivision mainly in themes and the alteration sequences, late-stage mafic dykes and intrusions, cherts and veins in colour. Because of the variation in coverage the alteration sequence of especially the volcanic sequence is not mapped in as much detail in the south of the area as it is in the north of the area. The alteration zone that is indicated in red in this area is based on a K-depleted zone. In the north of the area, where covered by Hymap imagery, a distinction within this zone can be made based on white mica content.
Figure 5.1.1: Simplified geological map of the Panorama area.
Figure 4.2.2: The map of linear features of the Panorama area.
4.2 Geological Events

The geology can be divided into different events: The emplacement of the granite (4.2.1), alteration of the granite (4.2.2), the deposition of the volcanic sequence (4.2.3), the alteration of the volcanic sequence (4.2.4), the deposition of the sediments (4.2.5), the alteration of the sediments (4.2.6) and the late-stage intrusion of mafic volcanics (4.2.7).

The geological interpretations as discussed in this subchapter are based on different types of remote sensing data. Each interpretation in the subchapter will include an account of what is observed from which image. A summary of the findings is included in an appendix. An explanation of how the geological interpretation compares to other interpretations in this subchapter and existing geological maps, will also be included in this subchapter. The map of Brauhart et al (1998) is the most detailed of these interpretations and is referred to wherever possible, with the exception of the sediments overlying the Sulphur Springs deposit that have been mapped by Hill (1997) and the vein system in the granite and the volcanic sequence that has been mapped by Drieberg (2003). In all other instances, the interpretation of Van Kranendonk (1999) was found to be adequate.

4.2.1 Granitoid Complex

The granitoid complex will be described in three separate sections: the spatial extent, the zonation and the layering. The different interpretations of the granitoid complex are given in figure 4.2.1. Included in this figure are the mafic dykes that are interpreted to be formed at an early-stage, the other mafic dykes are discussed in a separate section (4.2.7).
FIGURE 4.2.1: Geologic interpretation of the granitoid complex. The area in the boxes represents the locations of other figures of chapter 4.2.1.

Spatial Extent

The granitoid complex is a relatively flat area. The body has a high total count of radiometric elements and a comparatively high Th and K content (Fig. 4.2.2a and b). Except for the eastern margin of the granitoid, the K content is relatively homogeneous throughout the body (section 4.2.2). There is a zonation of Th (this and other possible zonations are discussed in this subchapter). The granitoid has a straight western margin, while the east side is characterized by a dome-like shape.

The eastern margin of the granite is visible on Hymap imagery as an area of high white mica content. These images, however, did not serve as the sole basis of the positioning of the boundaries, but merely to refine them (where they were similarly established by radiometric images). The reason being that the felsic volcanic rocks or altered volcanic rocks in the volcanic sequence could be white mica rich as well. Also, the sometimes irregular boundaries that can be traced around the white mica rich rocks are not typical of a granite intrusion (see for example figure 4.2.4a). The mica composition was no determinant for the boundary of the granite, as possible effects of alteration on the granite can not be observed in this way. For example: If the
boundary of the granite is placed between Al rich and Al poor mica, possible Al enrichment due to alteration in the granite can not be established as the Al enriched area is not considered a part of the granite.

The outline of the granite based on the remote sensing data is very similar to the one drawn by Brauhart et al. (1998; Fig. 2.3.1 and Fig. 4.1.1).

Within the granitoid there are three and arguably four mafic intrusions that are straight on the western margin and have an irregular shape on the eastern margin (Fig. 4.2.1 and 4.2.2). The dykes have a low amount of radiometric elements (Fig. 4.2.2) and show up as darker areas on the aerial photograph (Fig. 4.2.3a). This particular shape shows these dykes intruded at an angle different from the other mafic dykes discussed in section 4.2.8. The compare to the mafic dykes interpreted by Brauhart (1999) as coeval with the granitoid emplacement. The intrusion indicated with a question mark (Fig 4.2.1) is interpreted as part of the volcanic sequence by Van Kranendonk (1999). The radiometric signal for this part is clearly lower than that of the volcanic sequence however (Fig. 4.2.2e).

Brauhart et al. (1998) have also interpreted microgranite sills in the east of the granitoid complex. These sills do not show up in radiometric images, as they have a similar composition and thus radiometric signal as the granitoid.
Figure 4.2.2: Radiometric images of the Panorama area. (a) Total count, the total amount of gamma ray emission; (b) K pct; (c) Th ppm; (d) U ppm. For legend geological interpretation see next page.
FIGURE 4.2.2 (CONTINUED): (e) Colour composite of K, Th and U in the red green blue channels respectively. (f) Th/K ratio. K is a more mobile element than Th; (g) U/K ratio.
Zonation

The remote sensing data reveals zonation of the granite. The most apparent one is that of the Th content (Fig. 4.2.2c and Fig. 4.2.2e and f). The zonation runs from a relatively low content in the western part of the granite to a relatively high one in the eastern part (Fig. 4.2.1). The zonation is gradual. The areas with the highest Th zonation are mapped on the geologic interpretation in figure 4.2.1. The boundary, however, serves merely as indication.

The Th zonation in the granitoid is similar to the U zonation (Fig. 4.2.1d). The U/K image also reflects this (Fig. 4.2.2c). The U image, however, is patchy: the Th zonation is more evident and defines the outline of the zonation as visible on the colour composite (Fig. 4.2.2a), it is this zonation that has been mapped. (This is indicated as high Th zonation on the geological map in figure 4.1.1).

The Th zonation has not been established in existing geological maps. There is a clear difference here between the remote sensing interpretation and the interpretation based on field observations.

Brauhart et al. (1998) have divided the granite into an inner and outer phase. The outer phase being a coarse-grained, equigranular hornblende-biotite granite sill and the inner phase comprising a porphyritic biotite-hornblende granite (Brauhart, 1999). Although some sections of Brauhart’s boundary between the inner and outer phase granite can be observed in the aerial photograph and, to a lesser extent, in Landsat TM and MASTER images, it lacks clarity and completeness (Fig. 4.2.3a). The brighter areas seem to coincide with the inner phase granite of Brauhart et al. (1998), the darker areas with the outer phase.

There is another division that can be detected in the Landsat TM colour composites and aerial photograph. This division is based on the brightness of the image (Fig. 4.2.3b). In the south and the southeast, this division is formed by a dyke and rivers. The western end is the boundary of the granite. But the north and the north-eastern part show a clear division that can not be explained by one of these features. Other divisions within the granite (also visible on figure 4.2.3.b) are clearly bounded by rivers, which implies that the colour difference is not geological. This division has not been mapped in other studies.
FIGURE 4.2.3: (A) Outline on the aerial photograph that shows a brighter area. In part this outline coincides with the boundary between the inner and outer phase of the granite as mapped by Brauhart et al. (1998); (B) Outline of a possible zonation on the Landsat TM 7:5:4 composite. In the mid-eastern part the outline boundary is formed by a dyke. To the north of this dyke is a clear straight division between a brighter, and a darker area.

**Layering**

The granite predominantly appears as an unlayered body, however, in the northern part of the area, distinct layers are visible towards the eastern edge of the granite (Fig. 4.2.4a and b). The elevation is slightly higher in this area and the topography becomes rougher. As the Hymap imagery shows, there are two faulted white mica rich layers separated by a mica poor, or mica absent layer (Fig. 4.2.4a). The top layer contains Al rich white mica, whereas the bottom layer contains Al poor white mica. Further southwards, part of the layers seems to be visible again, but less obvious, on the Gaussian stretched white mica probability image (Van Ruitenbeek et al., in press; Fig. 4.2.4c). These might also be white mica rich linear features (section 4.2.2 and 4.3.1). As the layers are present only on the outer edge of the granitoid complex, they might be interpreted as an effect of cooling.

The position of the layers, the fault and its offset (in the north) are in concordance with the granophyre mapped by Brauhart et al. (1998). Brauhart however, has mapped the granophyre as a zone, where the transition between the bounding outer phase granite and the granophyre is gradual (Brauhart, 1999). Brauhart has not made a subdivision into different lithologic layers, on the alteration map however, the white mica rich layers are indicated as sericite-quartz altered.
FIGURE 4.2.4: On all images the top of the granite is shown in the east side of the Panorama area. (A) The fused white mica image (Van Ruitenbeek et al.) in the north-eastern part of the Panorama area; (B) The aerial photograph in the north-eastern part of the Panorama area; (C) A Gaussian stretched white mica probability image in the mid-eastern part of the Panorama area.

Underneath the distinct layers in figure 4.2.4b, the layered structure of the granite is visible. This type of structure is visible further south (on the Hymap true colour composite) and west as well (Fig. 4.2.5 a and b).
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4.2.2 Alteration of the Granitoid Complex

On the eastern edge, at the top of the granite is a zone with a relatively high white mica content (Fig. 4.2.6a). On the northern edge, the white mica content is elevated as well, but this area is not covered by the Hymap imagery. Within this zone a few areas are indicated that have an even higher white mica content (Fig. 4.2.6a). The Hymap imagery shows that the zone on the eastern edge is made up primarily by a large amount of linear features with a high white mica content (Fig. 4.2.6b). This means that not the entire granite body, but merely the lineaments are white mica rich. By and large, the white mica of the linear features is Al poor, but some zones and patches of Al rich white mica do exist (Fig. 4.2.6a). Below Kangaroo Caves is a zone with Al rich white mica within a zone that has a higher white mica probability (Fig. 4.2.6a), this entire zone is conspicuously poor in linear features. Indicated on the geological interpretation in figure 4.2.6a is the boundary of the area that is relatively high in white mica, this is not an exact boundary, but a smooth boundary that includes the main part of the white mica rich top.

The linear features can represent several types of objects. Judging by the number of interpreted linear features, the granitoid (or at least the top) seems to be highly fractured (Fig. 4.3.1a). This is typical of a granitoid body, as the granite cools, the volumes reduces and fractures as a result. The white mica richness of the linear features might be explained by alteration processes that influenced these fractures. They might also be pegmatites, although the pegmatites present in the Panorama do not exceed 50 cm in length (Drieberg, 2003). The Al-poor white mica rich linear features are comparable to the Cu-Zn-Sn veins as studied by Drieberg (2003), although they do not overlap exactly. Some of these veins compare to the carbonate quartz veins as well. The Al-rich patches compare to the quartz-topaz greisen and vein greisen mapped by Drieberg (2003). A large amount of the veins does not compare to Drieberg. Some of these might be streambeds.
that were not recognized as such by the author. The orientation, extent and absence of a possible source for the white mica in the streambed, makes it more likely the features are veins not previously recognized or white mica rich fractures. The area below Kangaroo Caves, where few veins were found based from the Hymap imagery, has been mapped by Drieberg (2003) as a zone with quartz-pyrite veins.

The mica rich granite top coincides with the background altered granite as mapped by Brauhart et al. (1998). The zones within the white mica rich top and the white mica rich zones outside the granite top compare to the sericite-quartz alteration (Brauhart et al. 1998). The Al-rich white mica zone below Kangaroo Caves coincides with the chlorite quartz alteration as mapped by Brauhart et al. (1998).

Figure 4.2.6: (A) Image where (highest to lowest resolution) are overlain: Fused white mica map, MASTER 14/22 and Landsat TM 5/7. All these images enhance the presence of white mica; (B) A larger scale image of the white mica rich granite top on the white mica probability map.

There is a K depleted zone at the top of the granite (Fig. 4.2.7a). This zone overlaps with the white mica rich zone and partly overlaps with the granophyre as mapped by Brauhart et al. (1998), although the granophyre as mapped by Brauhart is thicker. Unaltered granophyre itself would not be K depleted, as it is felsic. This is not strongly depleted in this part of the granite (Fig. 4.2.7b). This means that the K depletion is likely not lithological, but alteration or weathering related. As weathering in such a pattern would be highly coincidental, the most likely is alteration.
The K depletion boundary is also roughly parallel to the white mica rich granite boundary, which is interpreted to be alteration related as well.

**Figure 4.2.7:** Radiometric images showing the top of the granitoid body. (a) Image showing the K pct; (b) Image showing the Th ppm.

**Table 4.2.1:** Alteration zones of the granitoid complex

<table>
<thead>
<tr>
<th>Remote Sensing Interpretation</th>
<th>White mica content and composition</th>
<th>K content</th>
<th>Distribution</th>
<th>Alteration Facies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brauhart et al. (1998) and Drieberg (2003)</td>
<td>Al-poor white mica rich (veins)</td>
<td>K rich</td>
<td>Semi-conformable</td>
<td>Background alteration and mainly Cu-Zn-Sn veins</td>
</tr>
<tr>
<td></td>
<td>Al-rich white mica rich (veins)</td>
<td>K rich</td>
<td>Patches</td>
<td>Vein greisen and quartz-topaz greisen (Transitional) sericite-quartz alteration</td>
</tr>
<tr>
<td></td>
<td>White mica enriched within white mica rich top</td>
<td>K poor</td>
<td>Transgressive</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Al-rich white mica rich</td>
<td>K poor</td>
<td>Semi-conformable +transgressive</td>
<td>Chlorite-quartz alteration and background alteration</td>
</tr>
<tr>
<td></td>
<td>(veins)</td>
<td></td>
<td></td>
<td>Background alteration and mainly Cu-Zn-Sn veins</td>
</tr>
<tr>
<td></td>
<td>Al-poor white mica rich (veins)</td>
<td>K poor</td>
<td>Semi-conformable +transgressive</td>
<td></td>
</tr>
</tbody>
</table>
4.2.3 Volcanic Sequence

The contact between the volcanic sequence and the granite body is inferred to be mostly concordant, as the layered structure and the layers of the granite are generally concordant with the layers of the volcanic sequence. In the northern-eastern part of the area however, a volcanic layers end on the granitoid. The contact here is not concordant. From this it can be inferred that the granitoid intruded the volcanic sequence at the base. This finding is in concordance with the intrusive contact established by Brauhart (1999).

The volcanic sequence itself has a low concentration of radio-elements compared to the granitoid complex, with the exception of the top of the volcanic sequence in the south of the area (Fig. 4.2.1a). This means the volcanic sequence generally is more mafic than the granitoid. Lithologic layers that have been mapped are relatively felsic or mafic volcanics. The volcanic sequence becomes more felsic to the south. There is less lithologic variation in the south, therefore, distinct layers are not clearly visible here. The lithological interpretation of the volcanic sequence is given in figure 4.2.8. Indicated are the outlines of the locations of the other figures in this subchapter. The lithology of the volcanic sequence will be discussed from north to south.
The most northern part of the volcanic sequence has a complicated folded structure. The outline of the volcanic sequence in this part is based on the radiometric image in the west and the white mica probability image in the east (Fig. 4.2.9). Some lithologic layers are visible from the image. A relatively mafic layer bounding the granite has been mapped. This layer shows a low radiometric signal (Fig. 4.2.9b). Another layer showing a low radiometric signal that also suggests a very low white mica probability, has been mapped as a banded iron formation, as the layer corresponds to the banded iron formation mapped by Van Kranendonk (1999) in this part (Fig. 4.2.9). Below and to the southeast of the banded iron formation is a layer with a very low white mica probability. This layer has been interpreted as a mafic sill. It can be seen from the radiometric composite that this sill is present within a relatively mafic part of the volcanic sequence (Fig. 4.2.9b). Within the folded structure is a section with a higher white mica probability. This part is roughly parallel to
the boundary of the volcanic sequence. A number of other white mica rich layers seem to appear to the east of this section (Fig. 4.2.9a); these layers have not been mapped.

The outline of the folded structures is comparable to the outline of the metamorphosed andesitic to basaltic lavas mapped here by Van Kranendonk (1999). The mafic volcanics mapped in the south are comparable to the relatively mafic volcanics mapped here by Van Kranendonk (1999) but for a diorite that he observed bounding the granite. The mafic sill found to the south of the banded iron formation corresponds to the mafic intrusion mapped here by Brauhart et al., (1998).

**Figure 4.2.9:** The most northern part of the volcanic sequence. (A) An image of (highest to lowest resolution) the white mica probability map overlying the MASTER 14/22 image. Both images enhance the presence of white mica. (B) A colour composite of the radiometric channels, the radiometric merged image is overlain on the 1:250,000 scale radiometric image.
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FIGURE 4.2.10: The Th radiometric channel of the volcanic sequence. Indicated on the image is the interpreted lithology.

More lithologic layers are visible in the northeast of the volcanic sequence. Two layers with a relatively high Th content are present close to the granitoid (Fig. 4.2.10). The northern most of these layers ends on the granitoid body. Below the Marker Chert another layer is present that is relatively rich in Th, but less so than the other two layers in the north. The layers have been interpreted to be (relatively) felsic because of the comparatively high Th content. These felsic layers are in accordance with the layers mapped by Brauhart et al. (1998). The two layers close to the granite have been mapped by Brauhart as felsic andesite and the layer beneath the Marker Chert has been mapped by Brauhart as a dacite intrusion.

The Hymap imagery shows several white mica rich layers (Fig. 4.2.11a) in the southern part of the northern half of the volcanic sequence. There are three layers placed on top of each other (Fig. 4.2.11a). All three being relatively high in white mica, the middle layer has a lower white mica content than the surrounding ones. The white mica of these three layers is Al poor. To the north, only one layer is visible. This layer contains Al rich white mica. The Th content of the most western layer is relatively high (Fig. 4.2.10). Because of the high white mica probability and to some extent also the relatively high Th content, the layers are interpreted to be felsic volcanics.
Brauhart et al. (1998) mapped a rhyolite that coincides roughly with the layers interpreted in this study.

At the top of the volcanic sequence, partially between two layers of Marker Chert, is an area with a very high white mica probability (Fig. 4.2.11b). This layer is therefore interpreted to be felsic. The layer is in accordance with the calc-alkaline rhyodacite as mapped by Brauhart et al. (1998).

In the southern part of the volcanic sequence, a light coloured layer is traceable (Fig. 4.2.12a). Based on its lighter colour in the aerial photograph and the relatively high mica content indicated by the Landsat 5/7 and MASTER 14/22 images, the layer is interpreted to be felsic. Another white mica rich layer that is interpreted to be felsic is present above this layer (Fig. 4.2.12a). On the map of Brauhart et al. (1998), similar layers are visible. They have been mapped by Brauhart et al. (1998) as rhyolites.
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4.2.12 Figure 4.2.12: Two figures showing lithological layers of the volcanic sequence towards the south of the large sinistral fault. (A) The MASTER 14/22 image is overlain by the white mica probability map. (B) A Gaussian stretched white mica probability map.

A number of additional relatively felsic parts in the south have been traced with dotted lines in figure 4.2.10. The volcanic sequence becomes more felsic here than towards the north and no clear layer structure is visible. Brauhart (1999) found the volcanic sequence to be more felsic towards the south as well.

One mafic sill is visible in the south of the area (Fig. 4.2.12b). This sill shows a lower white mica content than its surroundings; although from the fused image it can be seen it has been altered (section 4.2.4 and Fig. 4.2.16a). The sill is similar to the sill that has been interpreted by Brauhart et al. (1998).

4.2.4 Alteration of the Volcanic Sequence

The alteration of the volcanic sequence is both visible from the white mica content and composition and the radiometric signal. Because the zones interpreted from these different remote sensing data sets do not coincide exactly, they are rendered in separate figures for clarity (Fig. 4.2.13 and Fig. 4.2.14). The folded structure on the north-side of the granite (Fig. 4.2.9) has not been included in this interpretation, as it is difficult to separate signals from hydrothermal alteration and alteration that is the result of a folding process.
Figure 4.2.13: Interpretation of the alteration of the volcanic sequence from the K channel of the radiometric imagery.
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The volcanic sequence can be divided into four semi-conformable zones based on radiometric images. The K content grades from bottom to top from relatively lowest K, to relatively low K, to relatively highest K, to relatively high K (Fig. 4.2.13; Fig.4.2.15). The gradation is both visible from the K channel (Fig. 4.2.15a) and the Th/K ratio (Fig 4.2.15b). K is a more mobile element than Th, this means that a more evolved volcanic will have a lower Th/K ratio. The Th/K ratio in the volcanic sequence does not compare to the state of evolution of the volcanic sequence. The top is more felsic and thus more evolved, whereas the lowest Th/K ratios are present at the bottom of the volcanic sequence. The mobility of K also means it is easily removed or added by processes such as weathering or alteration. Here relative K removal or addition is interpreted to be related to alteration, as the zones are conform to the bedding of the volcanic strata and therefore not likely to relate to weathering.

**Figure 4.2.14**: Interpretation of the alteration of the eastern volcanic sequence from the images that enhance the presence of white mica (from low to high resolution: Landsat TM 5/7, MASTER 14/22 and the white mica probability map). Indicated in boxes are the locations of the other figures of chapter 4.2.4. (A) The white mica richness of the entire eastern volcanic sequence; (B) The white mica richness and composition of the north-eastern part of the volcanic sequence, that is covered by Hymap imagery.
A few transgressive zones of relatively low K content are apparent from the K images as well, they are indicated with small characters on figure 4.2.15. Three of the transgressive zones underlie the Sulphur Springs (a), the Kangaroo Caves (c) and the Anomaly 45 deposit (h). The Breakers deposit is located between the transgressive zones e and f.

FIGURE 4.2.15: The alteration mapped based on the radiometric imagery. Transgressive zones are indicated in lower case (a-f). (A) K channel; (B) Th/K ratio.

The imagery that enhances the presence of white mica (i.e. Landsat 5/7, MASTER 14/22 and the Hymap imagery) shows a clear subdivision in the volcanic sequence between comparatively high and relatively low white mica content (Fig. 4.2.14a; Fig. 4.2.16; Fig 4.2.17). For the area covered by the white mica probability map, this subdivision has been made with the aid of a contour around a 0.5 white mica probability. In this area a distinction between Al-poor and Al-rich white mica can be made as well (Fig 4.2.14; Fig. 4.2.15).
Four semi-conformable zones can be recognized in the volcanic sequence based on white mica content and composition (Fig 4.2.14). This subdivision can be made mainly in the northern part of the volcanic sequence (above the sinistral offset, Fig. 4.2.14b) as the more mafic volcanics here makes the distinguishing of alteration based on white mica easier.

The semi-conformable zone nearest to the top is rich in Al-rich white mica. Underlying this zone is a semi-conformable zone that is, less continuously, rich in Al-poor white mica. Below this is a white mica poor or absent zone with scattered patches of white mica rich volcanic sequence. The white mica in this zone, if present, is Al-poor. The lower most semi-conformable zone is white mica poor or absent with scattered patches of white mica rich volcanic sequence. The white mica composition, if white mica is present, is Al rich.

Bounding the granite, and continuing in the granite (Fig. 2.2.16a) is a white mica rich zone that is not continuous, this zone is both semi-conformable and transgressive. This zone is partly present where felsic lithologic layers are interpreted, which might explain the white mica content. The zone does not completely match to the felsic volcanics however and therefore is interpreted as an alteration zone.

Zones that are relatively white mica poor crosscut the semi-conformable zones. These zones mainly have an Al poor white mica composition. The zones are indicated with capital letters on figure 4.2.16. A transgressive zone is present below the Sulphur Springs deposit, a white mica poor or absent zone underlies this deposit (A on Fig. 4.2.16). To the south of the Sulphur Springs deposit another crosscutting zone is present, the Al poor white mica extends through the volcanic sequence to the Marker Chert (B on Fig. 4.2.16). Below Kangaroo Caves is a white mica rich, Al rich zone that extends from the top of the granitoid, to the top of the volcanic sequence, next to a mica absent or poor zone with the same orientation (C on Fig. 4.2.16). To the south of the sinistral offset is a crosscutting white mica rich, Al rich zone (D on Fig. 4.2.16). Three more transgressive zones can be recognized from a Landsat TM 5/7 image (E-G on Fig. 4.2.16). These transgressive zones differ from zones A-E (Fig 4.2.16) in that the white mica content in the transgressive zone is relatively higher in stead of lower.

The four semi-conformable zones distinguishable from the radiometric element content are not exactly the same as those that can be derived from Hymap imagery, they are comparable however (Table 4.2.1). The top Al-rich white mica rich zone and the top K rich zone compare. The zone that is richest in K compares to the Al poor white mica zones, both white mica rich and poor. The Al-rich white mica poor zone at the bottom coincides with the low K and lowest K zones. The transgressive zones that have been observed from the Hymap imagery are visible from the radiometric images as well. The other transgressive zones that have been mapped from radiometric imagery compare to the three transgressive zones that have been mapped from the Landsat TM 5/7 image.

The alteration zones as mapped from the remote sensing data can be related to the alteration zones mapped by Brauhart et al. (1998). The top zone, that is rich in Al-rich white mica and has a relatively high K content, can be compared to the feldspar-sericite-quartz alteration as mapped by Brauhart et al. (1998). The zone that is relatively highest in K and contains Al-poor white mica does not compare to the alteration zones as mapped by Brauhart et al. (1998). The Al-rich white mica poor zone compares to the background alteration as mapped by Brauhart et al. (1998).

The white mica rich zones coincide with the feldspar-sericite-quartz alteration zone as mapped by Brauhart et al. (1998). Other than in the south where the conformable Al rich white mica rich zones roughly compare to the transitional chlorite quartz alteration as mapped by Brauhart et al. (1998), the distinction within this zone between Al rich and Al poor white mica is not comparable to different alteration types as described by Brauhart et al. (1998). The white mica poor or absent zone, where the white mica, if present is Al rich, is roughly comparable to the chlorite-quartz alteration zone as mapped by Brauhart et al. (1998). The white mica poor or absent zone where
the white mica, if present, is Al poor, generally compares to the background alteration as mapped by Brauhart et al. (1998).

The crosscutting zones underlying the Sulphur Springs and Kangaroo Caves deposits compare to the transgressive chlorite-quartz alteration zones of Brauhart et al. (1998). The other two crosscutting zones based on both radiometric and Hymap imagery do not correlate to Brauhart et al. (1998). The transgressive zones that fall out of the coverage of the Hymap imagery and within the alteration map of Brauhart et al. (1998) compare to transgressive chlorite quartz zones as mapped by Brauhart et al. (1998) as well.

<table>
<thead>
<tr>
<th>Remote Sensing Interpretation</th>
<th>Brauhart et al. (1998)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>White mica content and composition</strong></td>
<td><strong>K content</strong></td>
</tr>
<tr>
<td>Al-rich white mica rich</td>
<td>Somewhat K enriched</td>
</tr>
<tr>
<td>Al-poor white mica rich</td>
<td>K rich</td>
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<tr>
<td>Al-poor white mica poor</td>
<td>K rich</td>
</tr>
<tr>
<td>Al-rich white mica poor</td>
<td>K low and K lowest</td>
</tr>
<tr>
<td>Relatively Al-poor white mica poor</td>
<td>K relatively low</td>
</tr>
<tr>
<td>Al-rich white mica rich</td>
<td>K lowest</td>
</tr>
</tbody>
</table>
Figure 4.2.16: The alteration in the volcanic sequence and the sedimentary deposits based on the Hymap imagery. Transgressive zones are indicated in upper case. (A) Fused white mica image.
FIGURE 4.2.16 (CONTINUED): (B) White mica absorption wavelength.
4.2.5 Marker Chert
The Marker Chert is present between the volcanic sequence and the sedimentary deposits. It was mapped based on the fused white mica and the white mica probability image where it can be observed as a distinct layer either low in, or devoid of white mica (Fig. 4.2.16a). On the MASTER 44/46 image that enhances the presence of silica, it is visible as a layer high in silica. The Marker Chert forms a jagged layer that varies in thickness and is either not present or not visible throughout the entire top of the volcanic sequence. The layer is thickest around the Sulphur Springs deposit and to the south of the Kangaroo Caves deposit (Fig. 4.2.14b; Fig. 4.2.16a).

The Marker Chert as mapped in this study is similar to that of Brauhart et al. (1998), although some differences exist. The Marker Chert mapped in this study has a greater thickness and a more jagged shape. On the map of Brauhart et al. (1998) the gossans and mineralizations present below the Marker Chert are included; from the remote sensing data these are not distinguishable from the Marker Chert.

4.2.6 Sedimentary Deposits
The base of the sedimentary sequence is formed by the sedimentary deposit overlying the Sulphur Springs deposit (4.2.17). This sedimentary deposit is present between two chert layers. The lowest chert is the Marker Chert. The top chert has been mapped by Brauhart et al. (1998) as Marker Chert as well. Hill (1997) and Glikson and Vickers (2006) however, consider this top chert as a separate chert and, like Brauhart (1999), consider the deposits between the Marker Chert and the top chert an olistostrome. This division has been used in this study as well. The olistostrome contains both sedimentary deposits and volcanic rocks, but as it is mainly sedimentary (e.g. Hill, 1997), it is discussed here as a part of the sedimentary sequence.
Between the top chert and the Marker Chert, one clear layer is visible. Like the chert layers, it is low in white mica and has a high quartz content. It has been mapped as a siltstone layer, based on the interpretation of Hill (1997) and Glikson and Vickers (2006). Two white mica rich layers that have been interpreted as felsic appear as well. These are in accordance with the rhyodacite as mapped in other studies (Hill, 1997; Brauhart et al., 1998; Glikson and Vickers, 2006). A few smaller white mica rich sections have been traced as well. These do not show a clear structure, but do seem to coincide with smaller blotches of rhyodacite as mapped by Glikson and Vickers (2006). The remainder of the sequence shows no layering and is relatively rich in white mica, but not as rich as the top of the volcanic sequence. The white mica itself is Al poor.

The predominant absence of layering and the blotches of felsic rocks can be interpreted as chaotic deposits with larger rocks in it as sedimentary products. This is in accordance with the olistostrome interpretation given to it in previous studies (e.g. Hill, 1997; Glikson and Vickers, 2006).

The sedimentary layering seems to drape conformly over the olistostrome (Fig. 4.2.17) and show a low-angle unconformity with the Marker Chert to the south of the olistostrome (4.2.18). Even more to the south the sediments seem to lie conform on the Marker Chert (Fig. 4.2.18).

The sedimentary deposits are recognizable as layered deposits on the Landsat TM, MASTER and Hymap imagery and the aerial photographs. (Fig. 4.2.16a). On the radiometric imagery they are recognizable as an area with a low amount of radioactivity compared to the volcanic
sequence and the granite (Fig. 4.2.2a). The sediments can be divided into sediments rich in white mica and K and sediments relatively poor in white mica and K (further discussed in section 4.2.7). The bedding of the white mica sediments is more clearly visible than that of the white mica poor sediments, as the sequence shows an alternation of white mica rich and white mica poor beds. Still, it seems the two sedimentary sequences lie conformly on top of each other. This is best visible from the Hymap absorption wavelength image (Fig. 4.2.16b). Volcanic or metamorphic layers are present within in the sedimentary sequence (mainly the white mica poor sequence) as well. Above the Al-rich white mica boundary, these have not been mapped.

The sediments directly overlie the Marker Chert, except in above the Sulphur Springs deposit, where they overlie the olistostrome. Where no Marker Chert was found, the boundary between the volcanic sequence and the sedimentary deposits has been determined as a difference in high and low total count of radiometric elements and a relatively higher white mica content in the volcanic sequence compared to the sediments.

![Figure 4.2.19](image.png)

**Figure 4.2.19:** Geological interpretation of the sedimentary sequence. (A) White mica probability image; (B) white mica fused image. Indicated on this figure with upper case B is the transgressive zone interpreted in the volcanic sequence (Fig. 4.2.16).

The white mica rich sediment deposits are continuous in all but one location (Fig. 4.2.18), where the white mica rich bedding is disturbed by a fault. The thickness of the white mica rich sedimentary sequence diminishes towards the south, only to become more pronounced again. There where the white mica rich sequence is smaller, an overlaying bedding can be made out that seems to end on both sides on the white mica rich sequence. This bedding itself is relatively
white mica rich as well, albeit less than the sequence below it. On top of this, the sedimentary sequence continues undisturbed.

Another sedimentary structure is visible to the south of the sinistral offset (Fig. 4.2.21). This is an Al-poor zone that is parallel to the bedding of the sediments, unlike the Al-poor zones discussed in section 4.2.7. This zone might or might not be related to alteration, Al-poor white mica composition may have a detrital origin.

The angular unconformity between the sedimentary deposits and the volcanic sequence as established in this study was not observed by Brauhart (1999), but has been established by other contributors (e.g. Van Kranendonk and Morant, 1998; Hill, 1997). Hill (1997) has indicated an unconformity exists between the olistostrome and the overlying turbidites as well.

### 4.2.7 Alteration of the Sedimentary Deposits

Two types of sediments can be discerned: Sediments with a relatively high white mica content and sediments that are relatively low in or even devoid of white mica (Fig. 4.2.16a). The white mica of the sediments is generally Al-rich. The boundary between the white mica rich and white mica poor or absent sequences is abrupt (Fig 4.2.16a). The sediments with a relatively low white mica content are generally Al poor, apart from a section in the northern part of the Panorama area where the white mica, if present, is Al rich (Fig 4.2.16b). The subdivision coincides with a subdivision into relatively K rich and K poor sediments (apart from the sediments directly to the south of the olistostrome, where the K content is relatively low; Fig 4.2.19).

Al-poor white mica zones are located above the transgressive alteration zones A, B and D in the volcanic sequence (Fig 4.2.16a). The Al-poor zone above transgressive zone A is contained within the olistostrome (Fig. 4.2.17). The zone that overlies the transgressive zone B is more diffuse, part of the sedimentary layering is disturbed here (Fig. 4.2.18b). The Al-poor zone above transgressive zone D is the smallest. The sedimentary layering seems to be intact (Fig. 4.2.20). Owing to the continuing white mica richness of the sedimentary sequence in this part, it is not possible to say anything about the preservation of sedimentary layering here. It can be observed that the Marker Chert is breached below all three Al-poor white mica zones (Fig. 4.2.18b; Fig. 4.2.17; Fig. 4.2.20).
FIGURE 4.2.20: The geological interpretation of the sedimentary sequence based on the Hymap imagery overlain on the K channel of the radiometric imagery. Indicated in upper case are the transgressive zones as indicated in figure 4.2.16.
Both the relatively high K content and the Al-rich white mica rich sequence are comparable to the top of the volcanic sequence, which is enriched in K (compared to the bottom of the volcanic sequence, not the directly underlying alteration zones) and Al-rich white mica. This suggests that the sediments are altered. The Al-rich white mica might also be detrital however. Hill (1997) distinguished between a sandstone dominated, siltstone dominated and mudstone lithofacies in the sediments (Fig 2.3.2). Detrital sericite is present in the quartz-dominated part of the siltstone dominated lithofacies (Hill, 1997). The white mica content is high throughout the lower half of the sedimentary sequence, if the white mica content would be caused by detrital mica, this would most likely not be expected. The sandstone dominated lithofacies contains interstitial sericite replacement and the quartz dominated parts of the siltstone dominated lithofacies has a chlorite-sericite altered matrix (Hill, 1997). The Al-rich white mica alteration compares to the least altered zone as mapped by Hill (1997; Fig 2.3.4). This suggests that the Al-rich white mica content in the sedimentary sequence is related to alteration. Further study of the sedimentary deposits (outside of the Sulphur Springs area) is needed to confirm this however.

The Al-poor white mica zones are located above transgressive zones in the volcanic sequence (Fig 4.2.16), which strongly suggests a genetic relationship. The Al poor zone in the hanging wall of the Sulphur Springs deposit can be related to a lower zone of silica-sericite alteration and upper zone of carbonate alteration with local chlorite-sericite replacements (Hill, 1997; Fig 2.3.4).
Table 4.2.3: Alteration zones in the sedimentary deposits

<table>
<thead>
<tr>
<th>White mica content and composition</th>
<th>K content</th>
<th>Distribution</th>
<th>Alteration facies in Sulphur Springs hanging wall</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al-rich white mica rich</td>
<td>K rich</td>
<td>Semi-conformable</td>
<td>Least altered zone (zone 1)</td>
</tr>
<tr>
<td>Al-rich white mica poor</td>
<td>K poor</td>
<td>Semi-conformable</td>
<td>Least altered zone? (zone 1)</td>
</tr>
<tr>
<td>Al-poor white mica rich</td>
<td>K rich?</td>
<td>Transgressive</td>
<td>Silica-sericite and carbonate alteration (zone 2-4)</td>
</tr>
</tbody>
</table>

4.2.8 Mafic Intrusions

There is a series of mafic dykes that traverses the Panorama area (Fig. 4.2.22). These dykes are recognizable as ridges in the topography. On the radiometric images, the larger dykes show up having a low radiometric signal compared to the granite and on the aerial photographs, the dykes show up as dark areas, suggesting that they are mafic (e.g. Fig. 4.2.7; Fig. 4.2.23). Some dykes have a high MASTER 14/22 signal, which would suggest they are felsic. The white mica probability map however, shows the dykes as linear features with a very low or a relatively low white mica content (Fig 4.2.23b). Also, the Hymap true colour composite the dykes are visible as green linear features (Fig. 4.2.23c). The high pixel values on the MASTER 14/22 image might thus be explained by the growth of vegetation with reflectance spectrum similar to that of white mica. Another possible explanation for a higher white mica content around a mafic intrusion is the presence of alteration along the dykes. No mention of alteration has been made in literature.

Three, possibly four dykes have been discussed in section 4.2.1 as syn-intrusive. The dykes discussed in this section are interpreted to be of a later stage.

One prominent dyke in the centre of the granitoid has a N-S direction (Fig. 4.2.22). There are several SW-NE trending dykes that sometimes originate from the large N-S trending dyke (Fig. 4.2.22). Because of their similar orientation and origin, they are interpreted to belong to one set (indicated as “mafic dykes 3” on Fig. 4.2.22). One SW-NE trending dyke crosscuts the earlier dykes of “mafic dykes 1” (Fig. 4.2.22). In the southern part of the area, an N-S trending dyke is offset by an SW-NE trending dyke (Fig. 4.2.24). This SW-NE trending dyke is, in turn, part of a large southern sinistral fault that offsets the entire lithologic sequence. The offset dyke shows dextral movement. The dykes originate in the granitoid complex or the volcanic sequence, they do not extend further than the volcanic sequence, with the exception of one dyke that may extend into the sediments (Fig. 4.2.22). This dyke is present at Kangaroo Caves, and has been interpreted to extend into the sediments based on the low white mica content. The thin line of low white mica content may also be a fault however. On this location a dolerite dyke has been interpreted by Vearncombe (1995).

From crosscutting relationships it follows that the dykes have intruded during or after the deposition of the sedimentary deposits and they are therefore termed “late-stage”. Most of these dykes are interpreted to postdate alteration as on the white mica probability image, they show a very low white mica probability (Fig. 4.2.16). One dyke however, is altered (Fig. 4.2.23b). This means this dyke intruded during or before the alteration process.

The dykes compare to the mafic dykes as mapped by Brauhart et al. (1998). The dykes are interpreted by Brauhart (1999) as late-stage as well.
FIGURE 4.2.22: The mafic dykes of the Panorama area. The late-stage mafic dykes are termed "mafic dykes 3".
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Figure 4.2.23: Late-stage mafic dykes. Indicated with an A is the altered mafic dyke. (a) Aerial photograph; (B) White mica probability map; (C) Natural colour composite Hymap.
Figure 4.2.24: Indicated on the aerial photograph are a felsic volcanic layer and different mafic dykes. The dyke labelled mafic dyke 1 is offset by another dyke. The broader dyke in the north is part of a large southern sinistral fault system that crosscuts the entire lithologic sequence.
4.3 Structural Analysis

A map of interpreted lineaments has been made based on the Landsat TM, MASTER, DEM and Hymap images as well as the aerial photographs (Fig. 4.1.2). Although the lineaments have been interpreted at set scales (1:200,000; 1:30,000; 1:20,000 and 1:10,000), the number of interpreted lineaments depends on the coverage of the various images. As a result, the area covered by the Hymap MASTER imagery and, to a lesser extent, those sections that can be viewed clearly on the aerial photograph, seem more fractured (Fig. 4.2.1). Because of the variation in coverage, the structural analysis will focus on a small area, where the availability of the remote sensing data is the best. This is in the north-eastern part of the area. The analysis includes lineaments in the top of the granite, the volcanic sequence and the sediments.

The interpreted lineaments can represent various features: fractures, faults or intrusions along fractures or faults. They could also be features unrelated to geology like streambeds or tracks. The white mica rich linear features, as discussed in section 4.2.2, are interpreted as veins. Some of the linear features may be streambeds in fractures or just streambeds. In the interpretation of the linear features this has been taken into account. The lineaments were only identified as faults where they showed a clear offset of lithology. The faults that show an offset were mostly found from Hymap imagery and were shown to have offset alteration. This does not mean all faults were post-alteration. Faults were simply better visible from offset alteration patterns on the Hymap imagery. The faults in the granite, the volcanic sequence and both the granite and the volcanic sequence were found to offset alteration. The faults that pass through the Marker Chert and do not extend further than the Marker Chert were not found to offset alteration. Because the faults are based on remote sensing data, no dip-slip component is known. Therefore the sense of movement should be considered as an apparent movement direction. The movement sense of faults has been used for plotting rose diagrams of (apparent) dextral and sinistral orientations.

Distinct sets of lineaments can be distinguished from the remote sensing data, therefore the lineaments have been analyzed in different sets (Fig. 4.3.1). The first sets are the white mica rich linear features in the top of the granite and the volcanic sequence (section 4.3.1). The white mica poor or absent lineaments throughout the lithologic sequence are analysed separately (section 4.3.2). The mafic dykes that have been found as one set (see section 4.2.8) will be regarded as a part of these lineaments. The linear features analyzed are shown in different sets in figure 4.3.1.
FIGURE 4.3.1: Maps showing the different linear features found in the north-eastern part of the Panorama area. (A) The linear features in the granitoid complex; (B) The linear features that extend from the granitoid into the volcanic sequence; (C) The linear features in the volcanic sequence; (D) The linear features in that extend from the volcanic sequence into the Marker Chert; (E) the linear features that extend from the volcanic sequence into the sedimentary deposits; (F) The linear features that are present in the sedimentary deposits; (G) The linear features, including mafic dykes, that are present in the entire lithologic sequence.
4.3.1 White Mica Rich Linear Features

There is a division between lineaments showing a high white mica content and those that are low in, or devoid of white mica. The interpretations are, as said in the introduction, influenced by the availability of data. Lineaments that do not show a high white mica content, interpreted at larger scales (i.e. 1:20,000 and 1:10,000) in areas outside of the MASTER and Hymap coverage, are not necessarily low in white mica. The aerial photograph from which they were interpreted does not contain such information. However, from the Landsat TM 5/7 image that does cover the entire Strelley granite, it can be derived that it is only the top of the granitoid that is white mica rich (see figure 4.2.6a). The white mica linear features are interpreted to be veins (see section 4.2.2). Streambeds may show can show a high white mica content as well. Where these streambeds were interpreted as just streambeds, they have not been used in the analysis. Where white mica rich streambeds were interpreted as fractures, they have been included in the structural analysis of white mica poor or absent linear features, as the white mica content is interpreted to come from sediments in the streambed.

As said before, the white mica rich linear features are mainly present in the top of the granite, some extend to the volcanic sequence as well. Therefore the orientations of the linear features containing white mica have been analyzed in two sets: Lineaments within the granitoid (Fig 4.3.1a) and lineaments that extend from the granitoid into the volcanic sequence (Fig 4.3.1 b).

The white mica rich linear features show a pronounced WSW-ENE orientation and smaller SSW-NNE orientation (table 4.3.1). An even smaller orientation parallel to the granite boundary is visible as well. The WSW-ENE orientation is found as well in the linear features that extend from the granite into the volcanic sequence (table 4.3.1). The main WSW-ENE orientation is perpendicular to the granite boundary in the north-eastern part of the Panorama area. In the south large veins are visible from the Landsat TM 5/7 image that are perpendicular to the boundary of the granitoid complex here (Fig 4.2.6 a). This means the main orientation of the veins perpendicular to the granite boundary throughout the area. The radial nature of the veins suggests a relation with granite intrusion.

The directions of the veins compare to those mapped by Drieberg (2003) except for an orientation parallel to the granitoid boundary that has not been mapped by Drieberg. This parallel orientation might be related to a thermal cracking front (Cudahy et al., 1999).

<table>
<thead>
<tr>
<th>Table 4.3.1: Rose diagrams of the white mica rich linear features in different sets</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Granite</strong></td>
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<td>White mica rich lineaments</td>
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<tr>
<td>n=607</td>
</tr>
</tbody>
</table>

4.3.2 White Mica Poor or Absent Linear Features

The white mica poor or absent linear features are present throughout the entire lithologic sequence. The linear features have been analyzed in different sets. These sets include the two sets discussed in the previous section (Fig 4.3.1). The other sets are the linear features: In the
volcanic sequence (4.3.1c); Extending from the volcanic sequence into the Marker Chert (4.3.1d); Extending from the volcanic sequence into the sedimentary deposits (4.3.1e); In the sedimentary deposits (4.3.1f) and the linear features that are present throughout the entire lithologic sequence (4.3.1g). As mafic dykes can be found in faults that pass through the entire lithologic sequence, these have been included in this set. The linear features that pass through the Marker Chert have not been regarded as a separate set, as they extend from the volcanic sequence into the sediments.

The linear features present in the granite show a prominent WSW-ENE orientation and a smaller N-S orientation (Table 4.3.2). This N-S orientation comes from two large (km scale) dextral faults that offset late-stage dykes. The WSW-ENE orientation of the linear features in the granitoid is similar to the orientation most prominent white mica rich linear feature orientation.

A WSW-ENE orientation similar to the orientation in the granitoid is also visible as the main orientation in the volcanic sequence (Table 4.3.2). This means that the granitoid and the volcanic sequence were formed under a similar (or even the same) tectonic regime. This is in accordance with the age measurements of Buick et al., 2002) that showed that the granitoid and the volcanic sequence fall in the same error range. The linear features in the volcanic sequence also show a strong SW-NE and NW-SE orientation and a minor N-S orientation. The dextral and sinistral faults in the volcanic sequence all show the WSW-ENE, NW-SE and SW-NE directions (Table 4.3.2).

The lineaments that extend from the granitoid into the volcanic sequence show a strong SW-NE orientation (Table 4.3.2) and a small E-W orientation; this differs from the orientation found for the granitoid and the main orientation in the volcanic sequence. The SW-NE orientation is the orientation of the dextral and sinistral faults in this set as well (Table 4.3.2). The dextral faults also show an E-W orientation.

The SW-NE orientation that is found in the linear features that extend from the granitoid into the volcanic sequence is present as well in the linear features that extend from the volcanic sequence into the sedimentary deposits (Table 4.3.2) and the sinistral faults among these (Table 4.3.2). This set also has a smaller WNW-ESE, WSW-ENE an N-S orientation (Table 4.3.2). The N-S orientation and the WSW-ENE orientation are also found in the sinistral faults (Table 4.3.2).

The SW-NE orientation is reflected again in the linear features, and both sinistral and dextral faults among these, that are present throughout the entire lithologic sequence (Table 4.3.2). This set also has an N-S orientation that is found in the sinistral faults as well.

The linear features in the sediments can be regarded as one set or as three sets, as the sediments can be divided into white mica rich and white mica poor or absent sediments. Although based on the conform relationship between these sedimentary deposits, they have been interpreted to be deposited in one sequence (section 4.2.6), evidence for this might come from linear features as well. The three sediment sets that have been plotted in rose diagrams consist of linear features: In white mica rich sediments; In white mica poor or absent sediments; Extending white mica rich into white mica poor or absent sediments (Table 4.3.3). There are but a few lineaments in these sediment groups, but the rose diagrams seem to show similar orientations. There is a roughly E-W orientation in all three sets and an N-S orientation in the set that contains linear features that extend from the white mica rich sediments into the white mica poor or absent sediments (Table 4.3.3). The rose diagrams for all the linear features in the sedimentary deposits have been plotted as well, including dextral and sinistral movements (Table 4.3.2). The lineaments do not show a strong preferred orientation, which might be due to the small number of linear features interpreted here. There is a stronger NNW-SSE orientation, this orientation is not found in the other sets (Table 4.3.2). This orientation is found in the dextral faults as well, together with a SW-NE orientation (Table 4.3.2). The sinistral faults also show a SW-NE and an E-W orientation (Table 4.3.2).
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As this analysis was carried out solely on the north-eastern segment of the area, it is difficult to state whether the lineament sets are radial or unidirectional and therefore whether they are related to the granite intrusion (e.g. Kloppenburg et al, 2001).

The lineament set that passes from the volcanic sequence into the Marker Chert does not seem to offset alteration. This suggests a syn-volcanic nature of these faults. This fault set is not unidirectional, this can be concluded from a set of faults that crosscuts the Marker Chert in the south-eastern segment of the study area. These faults show an orientation of about 80 to 90 degrees on the bedding, which is a similar angle the faults in the north have with the bedding. A difference between the north and the south is that the faults in the south do seem to offset alteration.

Based on the analysis it can be said that the lineaments that are present in the volcanic sequence and the granite, or both can be regarded as one set. The faults in this set offset alteration, they may have been present before the alteration took place and have offset the alteration because of a later reactivation. There is a faulted structure within zone B (Fig. 4.2.16), the alteration zone here is not offset however. This might indicate a later reactivation of faults in other parts of the area.

The faults within the volcanic sequence and the granite compare to the faults that offset the entire lithology in that sense that they have the same main orientation. The smaller E-W and NW-SE orientation might be regarded as conjugates of this orientation. If the faults and dykes that pass through the entire lithologic sequence are regarded as one set with the volcanic sequence and granite faults, this would leave unexplained why there are faults that die out in the volcanic sequence. Therefore it is more likely the formation of the faults and dykes that pass through the entire lithologic sequence caused a reactivation of the pre-existing faults in the granite and the volcanic sequence. The reactivation would be syn-sedimentary. From remote sensing data it can not be established whether the sediments show a growth fault type of deposition. The unaltered dykes present within the fault set that passes all lithologies indicates they intruded after alteration. One altered dyke intruded before alteration. There are two large sinistral faults (km scale) that do offset the sediments completely. The formation of these faults is therefore post- sedimentary.

There are indications for an even later reactivation. Both a dextral and sinistral movement, in the same direction, have been found in the set that passes all lithologies. The fault-system of which of the large southern sinistral fault offset an earlier dyke dextrally. The faults of this fault set have been related to the faults dated at 2950 Ma by Van Kranendonk and Collins (1998). Van Kranendonk and Collins have only recorded a sinistral movement along the SW-NE direction. The dextral movement found in this study can be related to a dextral pull-apart in the Mulliganinnah shear zone (White et al., 2001). The presence of a dextral pull-apart could have created the extension that facilitated the intrusion of the late-stage mafic dykes. Thomas (1997) found the sedimentology and stratigraphy of the sediments consistent with sediment depositions in pull-apart basins. Vearncombe (1995) found a resemblance between the Panorama area and the Lau and Manus pull-apart basins (Scott and Binns, 1995). An extensional regime is also indicated by the pinch and swell structures in the sediments overlying Sulphur Springs, these structures likely formed in not completely solidated sediments (Hill, 1997).
### Table 4.3.2: Rose diagrams of white mica absent or poor linear features in different lithologies

<table>
<thead>
<tr>
<th>All</th>
<th>Dextral Movement</th>
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### TABLE 4.3.3: Rose diagrams of linear features in different sedimentary sets

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<tr>
<th></th>
<th>White mica rich sediments</th>
<th>White mica poor/ absent sediments</th>
<th>White mica rich + white mica poor/ absent sediments</th>
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</thead>
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<td><img src="image3.png" alt="Diagram" /></td>
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<td>n</td>
<td>3</td>
<td>14</td>
<td>6</td>
</tr>
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</table>
Chapter 5 Geological History and Model Formulation

The results of the remote sensing data interpretations that were presented in chapter 4 will be discussed in this chapter. This chapter is divided into two subchapters. The first subchapter (5.1) deals with the geological history and includes a stratigraphical column and a diagram showing the relative timing of events. The second subchapter (5.2) deals with the implications of the geological history for VMS deposit formation in the Panorama area and a hydrothermal model will be proposed.

5.1 Geological History

For establishing the relative timing of events in the geological history of the Panorama area, it has been assumed the strata have not been overturned (e.g. Brauhart, 1999; Thomas, 1997). The relative timing of events was established by crosscutting relationships, unconformities, the rose diagrams of the orientations of linear features and the extent of alteration zones throughout the lithologic sequence. Throughout this discussion a comparison will be made between what can be concluded from remote sensing data and what is found in previous studies. In coming to a relative timing, the data from previous field studies is used as a complement to the remote sensing data.

5.1.1 Volcanic Sequence Formation and Outer Phase Intrusion

The granite intrusion was interpreted to be generally conformably overlain by the volcanic sequence, apart from a few volcanic strata in the north. These strata that end on the granitoid boundary indicate that the granitoid intruded after or during the formation of the volcanic sequence. The analysis of linear features supports this, as it shows that the granitoid complex and the volcanic sequence were formed under a similar or the same tectonic regime and it is thus likely they are from the same time. This relationship in time was also found for the outer phase intrusion (Brauhart, 1999) and the volcanic sequence (Buick et al., 2002). Brauhart et al. (1998) have found the outer phase granite intruded the volcanic sequence.

The shape of the granitoid, a straight western margin and a dome-like eastern margin, resembles the shape of a laccolith intrusion. Brauhart (1999) has described the Strelley granite as a laccolith-like intrusion. The thickness of the volcanic sequence above the granite is 1.5 km (Morant, 1995). The volcanics are interpreted as submarine volcanics (McPhie, 1993), meaning that the thickness of the layers above the granite during intrusion will not have exceeded 1.5km (as the granite is interpreted in section 5.1.3 to be emplaced before the deposition of the sediments). Laccoliths can only intrude at shallow depths, as a laccolith domes the overlying layers to make room for the intrusion (e.g. Pollard and Johnson, 1973). Such a doming is visible from the geological interpretation of this study as well. Brauhart (1999) has noted that the thickness of the outer phase (at least 5km) would break the overlying deposits, even if the sedimentary deposits were already formed. Vearncombe (1995) has noted the thermal gradients for the Strelley granite were lower than other Achaean environments. A relatively low thermal gradient might be the cause for the not breached overlying layers.

The volcanics were suggested to have rapidly extruded because of the absence of sedimentary deposits within the volcanic sequence (Brauhart, 1999). There are some indications that some volcanism continued after the initial deposition of the sediments. At Kangaroo Caves a felsic volcanic is present between two (discontinuous) layers of Marker Chert. Below this deposit, that has a dome-like shape, the Kangaroo Caves prospect is present. From the remote sensing data it can be seen that the Marker Chert bends around this unit. The sediments seem to bend around it as well. If the sediments do indeed bend around the volcanic deposit, this would suggest the volcanic deposit was formed after the deposition of the sediments. The felsic volcanics overlie the Kangaroo Caves VMS mineralization, of which the upper parts show interaction with seawater
This means these volcanics were deposited after the VMS mineralization (e.g. Vearncombe, 1995).

The timing of sill-like intrusions within the volcanic sequence is difficult to place, as the crosscutting relationships as are visible with dykes are not clear. The two sill-like intrusions in the olistostrome overlying Sulphur Springs (Hill, 1997) indicate that (some) intrusive volcanic activity took place after the deposition of the olistostrome.

### 5.1.2 Marker Chert Formation

The Marker Chert directly overlies the volcanic sequence. The sediments lie unconformly on the Marker Chert. This suggests the Marker Chert is older than the sediments and younger than the volcanic sequence. Van Kranendonk (2000) has found neptunian sandstone dykes from the Gorge Creek group sediments in the Marker Chert, suggesting it was lithified before the deposition of the sediments. Van Kranendonk (2006) interpreted the Marker Chert to have lithified during the hydrothermal process. The role of the Marker Chert in the hydrothermal process, (i.e. the time of formation and the role in localising deposits) is uncertain (e.g. Brauhart, 1999, Drieberg, 2003). Therefore it is difficult to place the formation of this layer relative to the hydrothermal alteration. The relationship between the Marker Chert and the alteration process will be further discussed in the hydrothermal alteration section (5.1.6).

### 5.1.3 Sedimentary Deposits

The unconformity between the sedimentary deposits and the Marker Chert shows the sediments are younger than the Marker Chert. Although an ongrow of this layer might have continued during or after deposition of the sediments (see for discussion on the Marker Chert section 5.1.6). The volcanics underlie the Marker Chert and are therefore interpreted to be generally younger than the sediments, although volcanic activity did not necessarily cease before the deposition of the sediments (see section 5.1.1).

The olistostrome that overlies the Marker Chert above the Sulphur Springs deposit was deposited before the rest of the sedimentary sequence, as the turbidite sediments lie unconformly on the olistostrome (Hill, 1997). Because of the presence of an unconformity between the olistostrome and the sediments, these two sedimentary units can be considered as separate events. The presence of a top chert on the olistostrome was interpreted to have formed from hydrothermal silicification during a depositional hiatus or from localized pelagic sedimentation (Hill, 1997). The intrusion of the inner phase granite might explain both the deposition of the olistostrome and the unconformity between the olistostrome and the rest of the sedimentary sequence (see section 5.1.4). This would signify continuous sediment deposition, the chert layer overlying the olistostrome being a part of the sedimentary deposition.

The sediments can be subdivided into sediments rich and poor in white mica, the transition is abrupt, which might indicate two different sedimentary sequences. However, white mica poor sediments seem to lie conform on the mica rich sediments, indicating that the sediments were most likely deposited continuously without tectonic disruption. The linear features found in the different sediment sets seem to support this (see subchapter 4.3), although few linear features were found in the sediments. The Gorge Creek Group is considered as one succession (Van Kranendonk, 2002).

The sediments (including the olistostrome) generally lie unconformly on the volcanic sequence and the Marker Chert. This unconform relationship might be caused by downlapping sediments (Thomas, 1997), it might also be related to doming of the volcanic sequence due to granite intrusion. The sediments in the NE-SW trending part of the greenstone belt show an onlap in the other direction than in the north (pers. comm. F.J.A. van Ruitenbeek, 2006). If the unconformity would be caused by a certain flow type as suggested by Thomas (1997), the downlap direction would be the same in the north and in the south (Fig. 5.1.1a). The onlapping relationship in two directions suggests (relatively) laminar deposition on (gently) domed layers (Fig. 5.1.1b).
doming of these layers is very likely related to the intrusion of the granite, either the inner phase or the outer phase granite. The apparent conform relationship that is found to the south of Kangaroo Caves might have been a topographic high of the dome-like structure.

![Diagram](image)

**Figure 5.1.1:** Two possible end-scenarios of deposition for the sedimentary deposits (for clarity the Marker Chert has been left out of this figure). (A) Downlapping sediments on an unfolded seafloor; (B) Laminar sediments on a (gently) folded seafloor.

Not only the volcanic sequence and the granitoid complex have a dome-like shape, the sedimentary sequence has a dome-like shape as well. A more pronounced dome-like shape may be explained by the intrusion of the inner phase granite or it might be related to a later tectonic process. As the inner phase granite intrusion can be related to the hydrothermal system (see section 5.1.4-5.1.6) and the sediments are interpreted to have (partly) deposited after the hydrothermal system ceased (see section 5.1.6), the shape of the sediments is more likely related to a later tectonic event.

### 5.1.4 Inner Phase Granite Intrusion

The inner phase intrusion was not convincingly found from remote sensing data. Rather, a zonation of Th was found within the granitoid complex. This makes it difficult to place it in a relative time frame. Buick et al. (2002) have dated the inner phase intrusion at 3238±3 Ma, which falls within the error range of the outer phase intrusion. Brauhart (1999) has found the inner phase granite intruded the outer phase granite.

Both the intrusion of the inner phase granite and the outer phase granite may have formed the dome-like shape of the volcanic sequence. The inner phase intrusion is interpreted by Drieberg (2003) to have caused a reinvigoration of the hydrothermal process. The part the inner phase granite, and related veins, takes in the hydrothermal process suggests it intruded before sediment deposition. If it intruded during the sedimentary sequence, an unconformity would be expected. The turbidite sequence is undisturbed however. The intrusion may have been the cause for the formation of the olistostrome and the unconformity between the olistostrome and the overlying turbidite deposits (Hill, 1997). The role of the inner phase intrusion on the hydrothermal alteration process will be further discussed in section 5.1.6.

### 5.1.5 Formation of White Mica-Rich Veins

White mica rich veins are present in the granite top and in the volcanic sequence. This means the veins formed after the intrusion of at least the outer phase granite and after or during the deposition of the volcanic sequence. The pattern of the veins might be related to hydrothermal brecciation (e.g. Jébrak, 1997). Hydrofracturing is the most common brecciation process in hydrothermal systems (Jébrak, 1997). However, the relatively chaotic assemblage characteristic for such brecciation is not comparable to the pattern of veins in the Panorama area. From the analysis of linear features (section 4.3.1) it has been shown that the veins show a radial pattern, therefore they are likely related to doming caused by granite intrusion. These veins that are perpendicular to the granite boundary extend relatively deep into the granite body (into the inner phase intrusion as mapped by Brauhart et al. (1998)). This might indicate the veins are partly sourced from the inner phase intrusion. The veins may also have precipitated in cracks formed by
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the intrusion of the inner phase granite. Drieberg (2003) relates a spectrum of veins to the inner phase intrusion, including the Cu-Zn-Sn veins to which most of the veins mapped in this study can be related. She suggests formation of these veins by mixing of hydrothermal and magmatic fluids in radial fractures formed by the intrusion of the inner phase granite (Drieberg, 2003).

5.1.6 Alteration

The formation of VMS deposits has been related to hydrothermal alteration (e.g. Franklin et al., 1981; Galley, 1993). Other forms of alteration are possibly present at the Panorama area as well, such as alteration related with submarine volcanism, granite intrusion and diagenesis of sediments. The possibility of the presence and recognisability from remote sensing data of non-hydrothermal alteration is discussed here. The discussion is subdivided (in order of relative timing) into volcanic sequence, granite and sedimentary sequence.

Volcanic Sequence

The volcanic sequence has been interpreted as submarine (McPhie, 1993). Submarine volcanics have distinct alteration associated with them (for a review see Gifkins et al., 2005). There is hydration, diagenesis and early burial metamorphism (Gifkins et al., 2005).

Hydration of glass occurs at temperatures below 50°C (Gifkins et al., 2005). This process will very likely have taken place at the Panorama volcanics. The interpreted rapid extrusion, and thus rapid burial, of the volcanics (Brauhart, 1999), may have limited the hydration process. The alteration zones in the volcanic sequence interpreted from Hymap imagery, have been related to alteration temperatures higher than this (~180 – 323 °C; Van Ruitenbeek et al., 2005). The signal from the Hymap imagery can therefore not be related to hydration.

Diagenesis of volcanic rocks may have created part of the alteration facies that are visible from remote sensing data. Diagenesis of volcanic rocks is described by Gifkins et al. (2005) as the "compaction, dissolution and leaching of components, precipitation of new minerals, and recrystalisation in response to changes in pressure, temperature and chemical conditions in the sub-seafloor." Because of the changing fluid temperature and composition with depth, diagenesis is typically present in diagenetic zones (e.g. Gifkins et al., 2005). The Al-rich white mica-poor, K poor zone, interpreted by Brauhart et al. (1998) as background alteration, can have formed by diagenesis. This zone can be interpreted as not intensely altered, from the low white mica content (the feldspar is only partly altered in this zone; Brauhart, 1999) and the generally Al-rich white mica composition (~270 °C alteration temperatures; Van Ruitenbeek et al., 2005). Brauhart et al. (1998) stated the chlorite-quartz alteration facies overprinted the background alteration, suggesting an earlier development of the background alteration.

The transition from diagenesis to burial metamorphism is not clear (e.g. Gifkins et al., 2005). Burial metamorphism is not likely to have occurred at the Panorama area, as the volcanic sequence has a thickness of 1.5 km (Morant, 1995) and the Gorge Creek Group has a maximum thickness of 3.5 km (Van Kranendonk et al., 2000). Burial metamorphism can occur at such conditions, but the non-isochemical alteration (Brauhart, 1999) suggests diagenetic alteration (e.g. Gifkins et al., 2005; Fyfe et al., 1958).

Granite

Granite intrusion can start regional hydrothermal circulation (e.g. Franklin et al., 1981; Galley, 1993; Galley 2003). Other alteration associated with granite intrusion can be alteration within the intrusion or contact alteration (e.g. Gifkins et al., 2005).

Deuteric alteration is the alteration of the crystallized intrusion by trapped magmatic fluids (Honnorez et al., 1979; Destrigneville et al., 1991). This alteration does not greatly change the chemical composition of the intrusion (e.g. Gifkins et al., 2005), therefore, it is not likely that small compositional changes can be picked up from remote sensing data.
The intrusion of the Strelley granite into the volcanic sequence has been related to an alteration zone between the granite and the volcanic sequence (Drieberg, 2003). This contact alteration zone is present in veinlets and spherulites and is characterized by the replacement and infilling of magnetite, chlorite, quartz, albite, pyroxene and epidote (Drieberg, 2003). This alteration zone is localized and therefore not likely to be visible from remote sensing data. The both semi-conformable and transgressive alteration zone between the granite and the volcanic sequence is not likely to be related to granite intrusion, as an intrusion-related alteration zone would not show transgressive alteration. Other alteration in the granite could exist in the outer edge of the granite. The outer edge was interpreted by Brauhart (1999) to have rapidly cooled. The rapidly cooled edge of the granite is interpreted as a gradual transition by Brauhart (1999). There are no compositional differences however, therefore it is not likely that this granophyre is picked up from remote sensing data.

**Sedimentary Sequence**

The sedimentary deposits, like the volcanics may have been affected by diagenesis (e.g. Hill, 1997). Were diagenesis of the sedimentary sequence visible, it would be expected to be present throughout the entire sedimentary sequence. The Al-rich white mica-rich and K-rich sedimentary sequence is not continuous and therefore not likely to have an origin in diagenesis. Spillage of the sedimentary products of volcanic origin may have caused the alteration as well (e.g. Hill, 1997). This is a more likely origin for the alteration, as the spillage would affect only certain sedimentary products. The absence of these sedimentary products higher up in the sequence could then explain the absence of the alteration pattern observed. Spillage may have occurred on site or the sedimentary products may have been altered products already (i.e. detrital sericite). Hill (1997) has indicated a change in environment of deposition from a submarine fan environment in the lower sedimentary sequence to a basin plain environment in the upper sedimentary sequence. Such a transition in environment of deposition might relate to the change in alteration observed from the Hymap imagery.

**5.1.7 Hydrothermal Alteration**

Hydrothermal alteration in the Panorama area is present in the granitoid complex, the volcanic sequence and most likely the sedimentary sequence. The alteration within these sequences might or might not be related to each other, therefore they are discussed here separately. In the discussion and model formulation (subchapter 5.2) the extension of alteration zones throughout the lithologic sequence will be taken into account.

The extent of the semi-conformable alteration zones suggests the hydrothermal alteration started by the intrusion of the outer phase granite. The outer phase granite was interpreted to have intruded before the deposition of the sediments.

**Volcanic Sequence**

There are two main models for the formation of VMS deposits, these models relate to the interpretation of alteration zones (see section 2.2.3).

Hydrothermal circulation below a cap rock, as suggested in the stratal aquifer model (Lydon, 1988) is not likely to have formed the VMS deposits. The Marker Chert could be regarded as a cap rock, the metal leaching does not directly underlie this rock however (Brauhart, 1999). Brauhart (1999) also inferred high water-rock ratios, these are not in concordance with a pore water fluid source as suggested in the stratal aquifer model (Brauhart, 1999; Lydon, 1988). Another indication against this is that the VMS deposits are found below and not above the potential cap rock and they show interaction with seawater, indicating they formed at or near the seafloor (Vearncombe, 1995; Drieberg, 2003) and therefore at least partly before the formation of the Marker Chert.
The semi-conformable transitional nature of the zones and the presence of transgressive zones (partly) below VMS deposits suggest the VMS deposits have been formed by convective hydrothermal circulation (e.g. Brauhart et al., 1998). The extent and the semi-conformable nature of the alteration zones suggest that the (initial) heat source for the start of the hydrothermal circulation was the outer phase granite (also Drieberg 2003; Brauhart et al., 1998). The semi-conformable zones can be interpreted as broad recharge zones and the transgressive zones as discharges zones (Galley, 1993; Brauhart et al.; Drieberg, 2003). Schardt et al. (2005) have argued the recharge zones of the hydrothermal system are located along faults and laterally from outside of the system. The distribution of white mica and K and the composition of white mica as visible from remote sensing data do not support this view. The alteration in the volcanic sequence as described in section 4.2.4 will be further interpreted in terms of the hydrothermal convection model (e.g. Galley, 1993). The three semi-conformable upper most semi-conformable zones discussed there can be interpreted in terms of broad recharge zones with increasingly higher temperatures (e.g. Brauhart et al., 1998; Galley, 1993). The mineralogical variations in the zones as established from remote sensing data support this. The decrease of white mica content and increase in K content with depth can be interpreted in terms of hydrothermal circulation. The changes in Al content may be related to changes in coexisting mineral phases and fluid chemistry (Van Ruitenbeek et al., 2005).

Transgressive zones cut through the altered volcanic sequence and at some places originate in the granite. The transgressive nature of the zones, the presence of such zones below VMS deposits and the associated high temperatures of alteration (~323°C; Van Ruitenbeek et al., 2005) suggests these zones were high temperature discharge zones. They have been interpreted as such (e.g. Brauhart, 1999).

Brauhart et al. (1998) found the recharge related alteration zones overprinted the background, or diagenesis-related, alteration (discussed in section 5.1.8). This least-altered zone may have also been formed by a waning VMS system. The overprinting relationship might be overprinting of an earlier diagenetic alteration or overprinting by a later reinvigorated hydrothermal system.

The alteration zone that has been interpreted between the granite and the volcanic sequence is discussed in the next section.

**Granitoid Complex**

The sericite-quartz alteration zones in the granite have been variously interpreted. Drieberg (2003) interpreted the zones as a part of the hydrothermal convection cells that collapsed downward due to the cooling of the outer phase granite, whereas Brauhart et al. (1998) have interpreted the zones to be related to magmatic circulation that has later been overprinted by seawater infiltration that formed the Al-rich white mica rich alteration zone. Drieberg (2003) has found the Cu-Zn-Sn veins crosscut the sericite-quartz alteration, placing the timing of the inner phase intrusion after the formation of the sericite-quartz alteration. Remote sensing data provide no new evidence for either of these hypotheses.

The both transgressive and semi-conformable alteration zone that is present between the granite and the volcanic sequence matches the chlorite-quartz alteration zone below Kangaroo Caves. The chlorite-quartz alteration was found by Brauhart (1999) to overprint the sericite-quartz alteration. This suggests the Al-rich white mica rich alteration is from a later stage than the sericite-quartz alteration. The transgressive nature of the zone below interpreted discharge zones suggests a relationship to the discharge of hydrothermal fluids. The semi-conformable layers could then represent lateral fluid flow towards the discharge site. From remote sensing data this alteration zone is found to be more extensive than the chlorite-quartz alteration zone mapped by Brauhart et al. (1998). The extent of this zone suggests a more extensive hydrothermal system. Lateral fluid flow at the depth of the granite-volcanic sequence boundary would indicate the recharge zones of the hydrothermal system were deeper than assumed by other authors (e.g. Brauhart, 1999). The least-altered zone that has been considered to predate hydrothermal circulation (section 5.1.6; Brauhart, 1999) might then be considered a part of the recharge
system. Another interpretation of the zone could be formation through seawater alteration. Seawater related alteration can occur before and after the start of the main regional hydrothermal event (e.g., Gifkins et al., 2005). Regional hydrothermal alteration of volcanic layers fills the pore space of the rocks (Gifkins et al., 2005). The transgressive alteration could then be explained by the flowing of seawater through fractures below discharge zones. The semi-conformable alteration would be lateral flow present below the hydrothermally altered rocks.

The white mica rich veins, discussed in section 5.1.5 can be considered part of the granitoid complex alteration. The boundary of the white mica rich granite top was found comparable to the background alteration as mapped by Brauhart et al. (1998). The relationship between the background alteration and the white mica rich veins suggests they formed in the same time frame. The background alteration may have formed by infiltrating hydrothermal fluids of a descending hydrothermal system (Brauhart, 1999), this could explain the parallel linear features that were found in the top of the granite as well (Cudahy et al., 1999).

Sedimentary Sequence
The Al-rich white mica rich sediments at the bottom of the sedimentary sequence may be either related to hydrothermal or non-hydrothermal alteration (see section 4.2.7). In the following discussion the alteration of the sedimentary sequence is discussed with the assumption of either of these options is discussed in separate sections.

Non-hydrothermal alteration related Al-rich white mica
If the Al-rich white mica in the sedimentary sequence is not of hydrothermal origin, the only alteration in the sediments would be the Al-poor white mica rich zones. The relatively high temperature alteration (app 200-300 °C) to which the Al-poor white mica is related (Van Ruitenbeek et al., 2005), the sometimes disturbed sedimentary sequence and the presence above transgressive alteration zones in the volcanic sequence (that have been interpreted as discharge zones (e.g., Brauhart, 1999; Van Ruitenbeek, 2005) suggests the Al poor alteration zones are related to discharge of high temperature hydrothermal fluids. The presence of these discharge zones above the vents interpreted from remote sensing data, indicates that the discharge sites of the hydrothermal system remained the same throughout the formation of the volcanic sequence and the deposition of the sediments. The interpretation of these zones as zones of discharge also holds if the Al-rich white mica rich sequence is related to hydrothermal alteration.

Hydrothermal Alteration related Al-rich white mica
The enrichment in Al-rich white mica and K in both the top of the volcanic sequence and the lower part of the sedimentary sequence, suggests that the alteration started during the deposition of the sedimentary deposits. The top of the Al rich white mica rich sedimentary layers would then be the seafloor through which the seawater infiltrated, the Al rich white mica in the sediments and the volcanics would form one continuous alteration zone. The seawater would have infiltrated through the sediments and the Marker Chert before reaching the Sulphur Springs volcanics. The VMS deposits would be found below the Marker Chert because it poses a boundary to upward flow (e.g., Brauhart, 1999). The greater thickness of the Marker Chert around VMS deposits (e.g. this study; Brauhart, 1999) could be explained by ongrow from below from discharge of hydrothermal fluids.

Several indications against the start of the hydrothermal system during sedimentary deposition exist, however. The infiltrating seawater would have to pass the Marker Chert, which is supposedly an impermeable layer (e.g., Brauhart, 1999). The Marker Chert would serve as an impermeable layer below which the VMS deposits form, however, not all VMS deposits are found bounding the Marker Chert, or within the Marker Chert (Brauhart, 1999). Also evidence that the VMS deposits were formed in contact with seawater (Vearncombe, 1995; Vearncombe et al., 1995; Drieberg, 2003) does not support this. Alteration in the hanging wall of VMS deposits is a
feature for a sub-seafloor setting of VMS formation, it is not diagnostic however (Doyle and Allen, 2003).

This suggests that the both the Marker Chert and the sediments were deposited after the start of the hydrothermal system.

If the start of the hydrothermal system is placed before the deposition of the Marker Chert, the formation of the Marker Chert may be related to the discharge of hydrothermal fluids during the life-time of the hydrothermal system (e.g. Drieberg, 2003). The explanation for possible hydrothermal alteration of the overlying sediments can be sought in the lifetime of the hydrothermal system, or in a reinvigoration thereof.

A reinvigoration of the hydrothermal system could come from melting of existing rocks or intrusion (i.e. the inner phase intrusion or a meteorite related melt). During the life-time of the hydrothermal system, the Marker Chert was formed and sediments were deposited. Turbidite deposits are deposits that can be deposited over a very short time period. The reinvigoration would lead to the alteration of the sediments due to infiltrating seawater. This recharge zone is visible as white mica rich, Al rich sediment, which can be interpreted as low temperature alteration (Van Ruitenbeek et al., 2005). The Al poor white mica rich zones can be interpreted as discharge sites of high temperature hydrothermal fluids.

The alteration of the sediments can be explained by late-stage low-temperature fluids that discharge (e.g. Hill, 1997; Drieberg, 2003). The late-stage low-temperature fluids would have to pass the Marker Chert however. The late-stage discharge of low-temperature fluids would also not explain the Al poor zones within the sediments, that are likely zones of high temperature fluid discharge. These limitations would not exist if the discharge is considered to have formed above the vents, where the Marker Chert is breached. Hill (1997) suggested the alteration in the olistostrome might be related to late-stage discharge through a fault. The Al-poor composition of the white mica is interpreted as high temperature however (Van Ruitenbeek et al., 2005). Low temperature alteration of the sediments could be explained by a continuation of the fluid flow of cooled high temperature fluids from the discharge site. Cooled fluids could explain the low temperature alteration. The low temperature alteration zone neatly confined to the bedding of the sediments however. This alteration is very unlikely caused by discharge from venting points.

5.1.7 Late-Stage Mafic Dyke Intrusion

The mafic dykes generally do not extend further than the volcanic sequence. One dyke does extend into the sedimentary sequence. Other dykes are present in faults that do extend into the sedimentary sequence. This suggests the dykes are syn-sedimentary. The dykes that do not extend beyond the volcanic sequence could be regarded as syn-volcanic, if this were the case, these dykes would likely have been altered. One dyke that is present in a fault that extends into the sedimentary sequence has been affected by alteration. This suggests the hydrothermal alteration continued throughout the deposition of the sedimentary sequence, as a dyke that is interpreted as syn-sedimentary is altered. The space for intrusion of the dykes might be explained a dextral pull-apart (section 4.3.2).

5.1.8 Tectonic History

The structural analysis of linear features shows a set of syn-volcanic faults that originates in the volcanic sequence and ends in the Marker Chert. The role of syn-volcanic faults in localizing VMS deposits in the Panorama area has been advocated by Brauhart (1999) and Drieberg (2003). The syn-volcanic faults found in this study are present below the interpreted discharge zones as well. The radial nature of this fault set suggests it might be related to the intrusion of the inner phase granite. The faults that pass the Marker Chert have been suggested to be part of grabens however (Vearncombe, 1995; Brauhart, 1999). The different directions throughout the Panorama area might therefore be related to graben formation.
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The faults present in the granite and the volcanic sequence, that offset alteration, are likely re-activated synvolcanic faults. This reactivation is interpreted to have taken place during sedimentary deposits. This is indicated by the faults formed in the lithologic sequence and the late-stage mafic dykes. As suggested in section 4.3.2, the formation of these faults might be related to a pull-apart basin (White et al., 2001). A reactivation of these faults and the turning of the sequence might have been the 2900Ma event Van Kranendonk et al. (2002) related to these faults.

5.1.8 Summary of the Geological History

The volcanic sequence was formed in a submarine setting, volcanics both intruded and extruded. The outer phase granite intruded the volcanic sequence at the base, this gently domed the layers of the volcanic sequence and also started the hydrothermal circulation. Seawater percolated through broad recharge zones and discharged through narrower zones that were likely fault controlled. The Sulphur Springs and Kangaroo Caves VMS deposits formed at the seafloor above zones of hydrothermal discharge. The other VMS deposits formed above zones of discharge as well, these deposits may have been deposited in a subseafloor or a seafloor setting throughout the life of the hydrothermal system. The Marker Chert formed as a non-horizontal layer that topped the volcanic sequence. It was formed either as an exhalative product of the hydrothermal system, or hydrothermal exhalation lithified sedimentary product. At some point during the lifetime of the hydrothermal system, before the deposition of the sedimentary sequence, the inner phase granite intruded and further domed the layers and opened radial cracks. The radial cracks were possibly sourced from below with magma and were infilled from above with evolved hydrothermal fluids. The veins can be considered as a mixing product of hydrothermal and magmatic fluids (Drieberg, 2003). The doming caused by the inner phase intrusion may have been related to the deposition of the olistostrome that deposited on the domed seafloor. The turbidite sediment sequences were deposited on top of this in a horizontal manner, causing an onlap on the olistostrome, the Marker Chert and the volcanic sequence. Because the unconformity between the turbidite sediments and the olistostome (Hill, 1997), the olistostrome and the turbidite sediments are considered as separate events within the sediment deposition. The hydrothermal circulation may have continued into the sedimentary deposition, if this is true, than the Marker Chert was either not lithified or permeable for (slow) downwards flow. The discharge sites remained stable, evidence of discharge of evolved hydrothermal fluids is visible in the sedimentary deposits. Waning of the hydrothermal system (either before or after the intrusion of the inner phase granite) is suggested to have created the least altered zone at the bottom of the volcanic sequence and the Al-rich white mica rich, K-depleted alteration zone between the granite and the volcanic sequence.

The sedimentary deposits can be related to the formation of a pull-apart basin that started forming at the end of the main volcanic sequence formation (but before the volcanic activity during the sediment deposition of the Gorge Creek Group). The dextral shear related to this basin also created space for the intrusion of the mafic dykes. The shear movement may also have triggered the olistostrome deposition.

A schematic stratigraphical column has been included in figure 5.1.2. A chart of relative timing has been included in figure 5.1.3.
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**FIGURE 5.1.2:** A stratigraphical column showing lithology and alteration of the Panorama area stratigraphic sequence. (Thickness of the volcanic sequence from Morant (1995); Thickness of the outer phase granite from Brauhart (1999); Thickness of the Gorge Creek group from Van Kranendonk (2002); Thickness of the olistostrome from Hill (1997); Stratigraphy of the sedimentary sequence from Hill (1997).)

**FIGURE 5.1.3:** A relative timing chart of the Panorama area. Indicated are the timing of formation of lithology and alteration. The alteration zones are indicated with different colours. Where more alteration zones are indicated in one box, this means all zones were (possibly) formed within the same process at that time.
5.2 Hydrothermal Model

Based on the geological history discussed in subchapter 5.1 a hydrothermal model is proposed here. The constraints on timing as summarized in figure 5.2.1 leave open two possible model for VMS deposit formation. In the first possible model, the sericite-quartz alteration in the granite is formed by magmatic circulation (Brauhart, 1999). In the other model this alteration zone is suggested to have formed by fluid infiltration of a waning VMS system (Drieberg, 2003). In this study the first option is preferred for two reasons. The sericite quartz alteration seems to crosscut the inner phase intrusion at some points (Fig. 2.3.3), whereas the inner phase intrusion related veins crosscut the sericite quartz alteration. The location deeper within the granite and the location below the discharge zones would be highly coincidental if these alteration zones were formed by recharge during the lifetime of the hydrothermal system.

As illustrated in the timing diagram in figure 5.1.3, the deeper (waning-stage) alteration zones may have formed either before or after the intrusion of the inner phase granite. In the model they are illustrated to have formed before the inner phase granite intrusion (Fig 5.1.3b). Because it is suggested in the model the sediments were part of the hydrothermal system, the waning system after the inner phase intrusion would not likely reach the depths of these alteration zones.

The hydrothermal model is illustrated in figure 5.2.1 in three stages. The stages are briefly discussed here.

Stage A
Before the start of the hydrothermal circulation diagenesis is likely to have altered the volcanic sequence. The intrusion of the outer phase granite signified the onset of the hydrothermal circulation of infiltrating seawater. Magmatic fluids may have been incorporated into the circulation, but not necessarily so (Brauhart, 1999). The white mica richest alteration formed in the granite as a result of magmatic convection. The three semi-conformable alteration zones formed in the volcanic sequence by infiltration through broad recharge zones. The discharging fluids, likely fault-controlled, formed the transgressive alteration zones. The VMS deposits of Kangaroo Caves and Sulphur Springs formed at or just below the seafloor. The other VMS deposits may have either deposited in a seafloor or subseafloor setting. The Marker Chert started forming around the same time, during the life-time of the hydrothermal system.

Stage B
Waning of the hydrothermal system deepened the convection cells and created the lower semi-conformable alteration zones and the semi-conformable and transgressive alteration zone between the granite and the volcanic sequence.

Stage C
The inner phase granite intruded. This produced a doming of layers and a reinvigoration of the hydrothermal system. Cracks that opened as a cause of the intrusion were infilled with a combination of magmatic and hydrothermal fluids. The olistostrome may have been deposited as a result of the inner phase intrusion. The turbidite sediments deposited on the domed seafloor, likely in a pull-apart basin setting, and were possibly part of the alteration system. Discharge continued through the same discharge sites and overlying sediments were altered where the Marker Chert breached.
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Figure 5.2.1: Schematic model for the formation of VMS deposits. (A) Main stage hydrothermal circulation; (B) Collapse of hydrothermal system; (C) reinvigoration after inner phase intrusion.
Chapter 6: Conclusions and Recommendations

6.1 Conclusions

- Remote sensing data can be used to interpret geologic features, the scale of interpretation depending on the scale of the remote sensing images. The different geologic features are often visible form more remote sensing datasets. The datasets that were used to determine the boundaries of the geological interpretation are summarized here.
  - Granite (body, zonation and layering):
    Radiometric imagery, MASTER, Hymap imagery
  - Lithologic layers (Felsic and mafic volcanics and sedimentary layers):
    Radiometric imagery, MASTER, Hymap imagery, aerial photograph
  - Mafic intrusions:
    Radiometric imagery, MASTER, Hymap imagery, aerial photograph
  - Alteration (of granite, volcanic sequence and sedimentary sequence):
    Radiometric imagery (K% and Th/K), Hymap imagery, MASTER imagery

- The lithological interpretation from remote sensing data generally coincides with field-based interpretations by other workers
  - The inner phase intrusion is not clearly recognizable from remote sensing data
  - A zonation of Th is visible within the granite body
  - The VMS gossans are not distinguishable from the Marker Chert

  - The semi-conformable alteration zones as found by Brauhart et al. (1998) can be recognized from Hymap imagery. The semi-conformable alteration zones are white mica rich at the top and white mica poor at the bottom of the volcanic sequence. Within these zones a distinction can be made between Al-poor and Al-rich white mica. The Al-poor white mica zones are enriched in K. These distinctions have not been made previously. The zones established from the remote sensing imagery go deeper into the volcanic sequence than the zones mapped by Brauhart et al. (1998). There is an Al-rich white mica rich and K depleted zone visible between the granite and the volcanic sequence that is more extensive and extends deeper into the granite than the chlorite quartz alteration zone (Brauhart et al., 1998) to which it compares.
  - The transgressive alteration zones as mapped by Brauhart et al. (1998) are recognizable from remote sensing data. The zones are recognizable as crosscutting zones within the semi-conformable alteration sequence with a relatively Al-poor white mica poor and a relatively low K content. Additional transgressive alteration zones are visible from remote sensing data that were not established in previous studies.
  - The sericite-quartz alteration in the granite (Brauhart et al., 1998) is recognizable as very white mica rich within the white mica rich granite top.
  - Mainly the Cu-Zn-Sn veins as mapped by Drieberg (2003) are recognizable as Al poor white mica rich linear features from Hymap imagery. Veins present in a direction parallel to the granite body can be recognized as well from the hymap imagery.
  - Hymap imagery provides evidence for discharge of hydrothermal fluids in the sedimentary sequence above the discharge zones in the volcanic sequence. This discharge is visible as an Al-poor white mica composition of otherwise Al-rich
white mica rich sediments. The often disturbed sedimentary structure also suggests discharge.
  
  Hymap imagery shows the presence of a possible conformable alteration zone in the sediments. This alteration zone is visible as an Al-rich white mica rich and K rich zone in the sediments that is comparable to the top semi-conformable alteration zone in the volcanic sequence.

- The preliminary structural analysis shows a main (syn-volcanic/ syn-sedimentary) fault set with an apparent dextral movement direction that has later been dextrally reactivated.
  
- The SW-NE orientation of the faults, the apparent early dextral movement and the presence intrusions along the faults are indicative of the existence of a pull-apart basin, mainly during the deposition of the Gorge Creek Group sediments.

6.2 Recommendations

- A detailed structural analysis of the entire Panorama area, looking at possible reactivation and the relation of faults to both alteration and lithology can give more insight into the role of faulting of the formation of VMS deposits and the possible formation of the Gorge Creek Group sediments within a pull-apart basin.

- A more detailed study of the Marker Chert, looking into the permeability and the timing of lithification can give insight into the timing of formation of this layer and may give explanation for possible fluid infiltration through this layer.

- Fieldwork to the Gorge Creek Group sediments focusing of alteration and composition of the sediments might establish the presence of a transition in sediment composition that relates to the transition visible from remote sensing data from white mica and K-rich to white mica and K-poor sediments.

- Fieldwork to the mafic intrusions found altered from remote sensing data can validate this remote sensing observation. Confirmation of hydrothermal alteration of these intrusions would imply they were formed earlier than previously thought.

- Examination of the relationship between the sediments at Kangaroo Caves and the Rhyolite dome overlying the Kangaroo Caves deposit can constrain the duration of volcanic activity in the Panorama area.
References


Griffin, T.J. (1990) North Pilbara granite-greenstone terrane: Geological Survey of Western Australia, Memoir 3, 128-158.


References


Appendix

Table showing if and how different geologic features are recognizable from the different remote sensing data.

<table>
<thead>
<tr>
<th>Dataset</th>
<th>Intrusions</th>
<th>Mafic dykes</th>
<th>Volcanics</th>
<th>Marker Chert</th>
<th>Sediments</th>
<th>Linear features (e.g. veins, fractures or faults)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Hyperspectral</strong></td>
<td></td>
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</tr>
<tr>
<td>Colour composite, Natural colour</td>
<td>Layered structure visible in the north of the granite</td>
<td>Visible as darker areas</td>
<td>-</td>
<td>Visible as a small ridge</td>
<td>Sedimentary layers visible</td>
<td>Visible</td>
</tr>
<tr>
<td>White mica probability, Probability of white mica</td>
<td>Top of the granite visible as a high white mica probability</td>
<td>Mafic dykes visible as white mica absent or a low white mica probability</td>
<td>Division visible between volcanics low and high in white mica, some layers visible</td>
<td>Very low white mica probability</td>
<td>Sedimentary layers clearly visible where the white mica content is high and division between sediment high and low in white mica visible.</td>
<td>Visible; “high mica” lineaments visible as well</td>
</tr>
<tr>
<td>White mica absorption wavelength, Composition of white mica</td>
<td>Visible as mainly Al poor white mica</td>
<td>-</td>
<td>Conformable zones and crosscutting zones of different white mica composition visible</td>
<td>Al poor white mica</td>
<td>Division in sediments visible between Al rich and Al poor white mica.</td>
<td>Not clearly visible as Al poor lines or offset lithology</td>
</tr>
<tr>
<td>Fused image, Intensity shows the white mica probability and the hue the white mica composition</td>
<td>Top of the granite visible as a high white mica probability and Al poor white mica</td>
<td>Mafic dykes visible as white mica absent or a low white mica probability</td>
<td>Mica rich layers traceable</td>
<td>White mica absent or a very low white mica probability</td>
<td>Some volcanic or metamorphic layers in the low white mica sediments visible</td>
<td>Visible; “high mica” lineaments visible as well</td>
</tr>
<tr>
<td><strong>MASTER</strong></td>
<td></td>
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<tr>
<td>Colour composites; enhances geological variation and true colour composite</td>
<td>Boundaries</td>
<td>Boundaries and a zonation in some parts</td>
<td>Boundaries between different volcanic layers visible</td>
<td>-</td>
<td>Boundaries of different sedimentary units visible and some layers distinguishable</td>
<td></td>
</tr>
<tr>
<td>Ratio 14/22, Enhances the presence of phyllosilicates</td>
<td>Top of the granite visible as relatively rich in white mica</td>
<td>Some dykes visible as relatively white mica rich</td>
<td>Boundaries between different volcanic layers clearly visible</td>
<td>-</td>
<td>Boundaries of different sedimentary units visible and some layers distinguishable</td>
<td>Visible; “high mica” faults visible as well</td>
</tr>
<tr>
<td>Ratio 44/46, Enhances the presence of quartz</td>
<td>Visible as an area with a relatively high quartz content</td>
<td>Boundaries and a zonation in some parts</td>
<td>Boundaries between different volcanic layers clearly visible</td>
<td>Visible as a layer with a relatively high quartz content</td>
<td>Boundaries between different sedimentary units visible and some layers distinguishable</td>
<td>Visible; quartz veins visible as well</td>
</tr>
<tr>
<td>Ratio 3/11,</td>
<td>Boundaries</td>
<td>Boundaries and a zonation in some parts</td>
<td>Boundaries between different volcanic layers visible</td>
<td>Boundaries between different volcanic layers visible</td>
<td>Boundaries of different sedimentary units visible and some layers distinguishable</td>
<td>Visible</td>
</tr>
<tr>
<td>Landsat TM</td>
<td>Ratio 5/7, Enhances presence of white mica</td>
<td>Ratio 4/3, Enhances presence of vegetation</td>
<td>Composite 7:4:1, Enhances geological variation</td>
<td>Composite 7:5:4, Enhances geological variation</td>
<td>Composite 3:2:1, Natural colour composite</td>
<td>Composite 4:3:2, Enhances geological variation</td>
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</tr>
<tr>
<td>Not clearly visible</td>
<td>Some dykes appear as relatively high white mica content, a zonation in some parts</td>
<td>Boundaries and some layers clearly distinguishable</td>
<td>Boundaries and some layers clearly distinguishable</td>
<td>Boundaries and some layers clearly distinguishable</td>
<td>Boundaries and some layers clearly distinguishable</td>
<td>Boundaries and some layers clearly distinguishable</td>
</tr>
<tr>
<td>Visible; &quot;high mica&quot; lineaments visible as well</td>
<td>Recent river sediments visible as vegetated areas</td>
<td>Boundaries and different sedimentary units visible and some layers distinguishable</td>
<td>Boundaries and different sedimentary units visible and some layers distinguishable</td>
<td>Boundaries and different sedimentary units visible and some layers distinguishable</td>
<td>Boundaries and different sedimentary units visible and some layers distinguishable</td>
<td>Boundaries and different sedimentary units visible and some layers distinguishable</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Radiometric</th>
<th>Total count, Total amount of radiometric elements</th>
<th>Colour composite, K, Th and U in the red, green and blue channels</th>
<th>K channel, K pct</th>
<th>Th channel, Th ppm</th>
<th>Th/K ratio, K is a more mobile element than Th</th>
</tr>
</thead>
<tbody>
<tr>
<td>Visible as an area with a relatively high total count</td>
<td>Visible as a dark area of little radiometric elements</td>
<td>Visible as areas with a relatively high K content</td>
<td>Visible as areas with a relatively low Th content</td>
<td>Visible as a relatively low Th content</td>
<td>Visible as a relatively high Th/K ratio and a zonation is visible</td>
</tr>
<tr>
<td>Larger dykes visible as a low total count</td>
<td>Visible as an area with a relatively low K content</td>
<td>Visible as areas with a relatively low Th content</td>
<td>Visible as areas with a relatively high Th/K ratio</td>
<td>Visible as a relatively low Th content</td>
<td>Visible as a relatively high K content</td>
</tr>
<tr>
<td>Visible as an area with a relatively low total count</td>
<td>Visible as a dark area of little radiometric elements</td>
<td>Visible as areas with a relatively low K content</td>
<td>Visible as areas with a relatively low Th content</td>
<td>Visible as a relatively low Th content</td>
<td>Visible as a relatively high Th/K ratio and a zonation is visible</td>
</tr>
<tr>
<td>Visible as a relatively low K content; the bottom of the sedimentary sequence was generally found to have a higher K content than the top; recent river sediments show up with a relatively high K content</td>
<td>Visible as a relatively low Th content</td>
<td>Visible as areas with a relatively high Th/K ratio and a zonation is visible</td>
<td>Visible as areas with a relatively high Th/K ratio</td>
<td>Visible as a relatively low Th content</td>
<td>Visible as a relatively high Th/K ratio and a zonation is visible</td>
</tr>
<tr>
<td>Elevation</td>
<td>(Vaguely) visible as a relatively flat area</td>
<td>(Not clearly) visible as ridges</td>
<td>(Vaguely) visible as relatively elevated area</td>
<td>-</td>
<td>(Vaguely) visible as &quot;ridgy&quot; elevation</td>
</tr>
<tr>
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<td>--------------------------------------------</td>
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</tr>
<tr>
<td>Aerial photograph</td>
<td>Granite visible as a relatively smooth surface</td>
<td>Visible as dark coloured</td>
<td>Boundaries visible in some parts and some layers clearly distinguishable</td>
<td>-</td>
<td>Boundaries visible in some parts and some layers visible</td>
</tr>
</tbody>
</table>