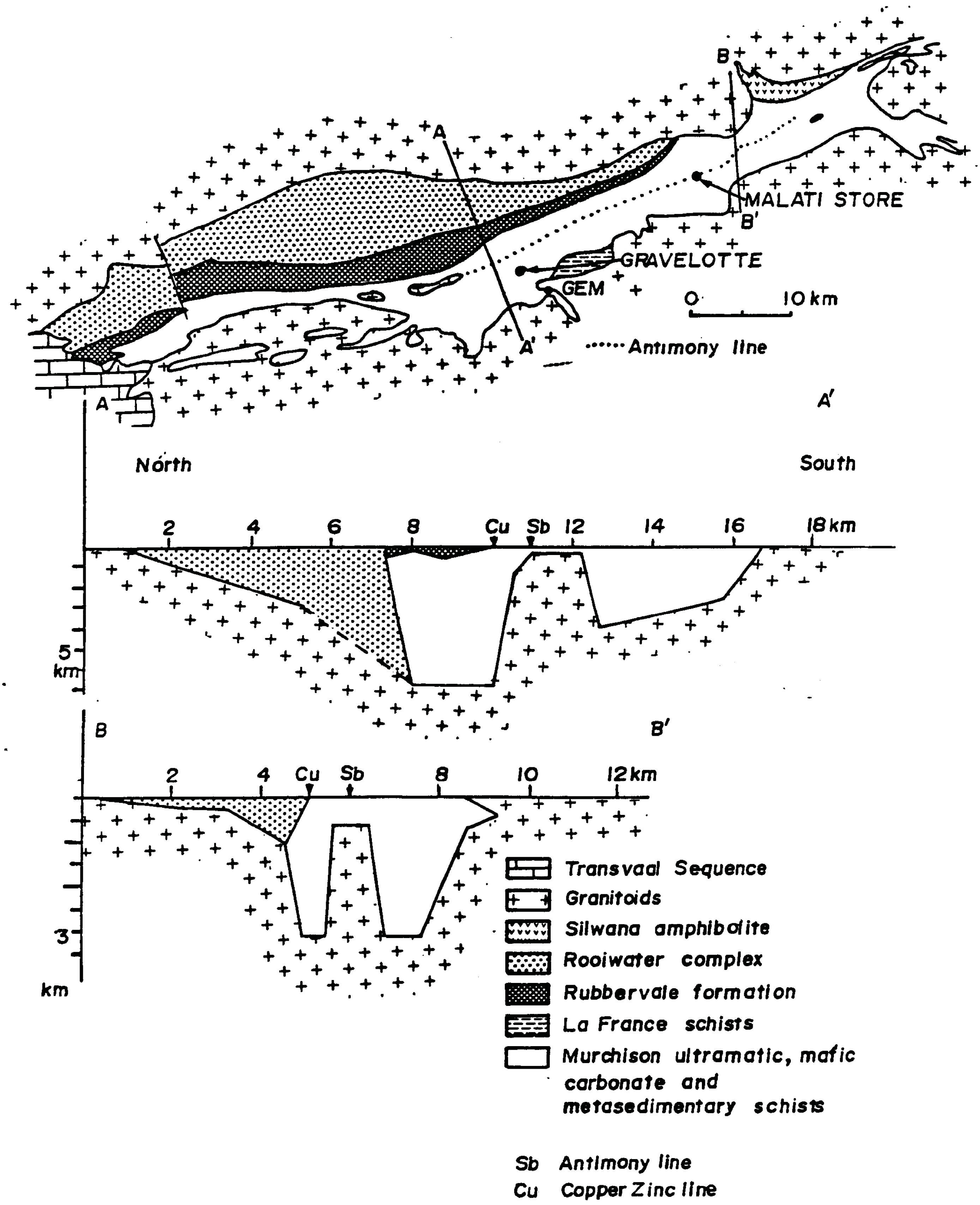

Figure 1.4. A simplified geological map of the Murchison schist belt and select simplified bouger gravity profiles across the schist belt showing the nature of the intrusive granitoids. For further details on the geophysics refer to de Beer *et al.* (1984).

The 1:50 000 geological maps of the Murchison schist belt, suggest that the late stage granite plutons can be divided into two units, based on field characteristics. In addition, a third contact phase is exposed along the southern schist belt margin. The principle unit consists of undifferentiated late stage plutons of granodioritic to granitic composition. The intrusions are generally medium to fine grained, lack phenocrysts and are commonly deformed to varying degrees. The second unit which includes the Willie pluton, is characterised by the presence of coarse potassium feldspar phenocrysts, (See Plate 2.11.) and the lack of internal structure. The Willie pluton is well exposed to the east of the Gravelotte Emerald mine where it is generally undeformed except for a rim fabric which probably relates to forceful intrusion. The Mashishimala granite pluton out-cropping, to the south of the Murchison schist belt, is petrographically similar to the Willie pluton.

The third phase includes the Granville pegmatites and aplites which occur in a narrow zone, not usually more than one kilometre wide, along the southern margin of the schist belt, from the Selati salient to the farm, Pomey, in the east. These pegmatite and aplites are of variable size and occur as dykes and plugs, intrusive into the schist belt. They are commonly related to beryl and molybdenite mineralization. Generally, the pegmatites are massive and undeformed, although in the Cobra North pit they are seen to be deformed, often showing a distinct schistosity and folding. The pegmatites are composed of coarse grained albite feldspar (Robb and Robb, 1986), biotite, carbonate and muscovite with minor beryl, fluorite, tantalite, pyrite, chalcopyrite and columbite. Minor molybdenite and metallic bismuth also occurs within the albite pegmatite at GEM and the BVB emerald deposits (Martini, 1980; Robb and Robb, 1986). The Granville pegmatites are interpreted by Vearncombe *et al.* (in press) to be marginal phases of the late stage plutons and may be older than the undeformed Willie pluton, although a lack of continuous exposure makes confirmation of this hypothesis difficult. Rare earth element data from this study suggest a genetic relationship between the Willie Pluton and the albite pegmatites at GEM.

1.5.3. Dykes

Van Eeden *et al.* (1939), recognized three dyke types in the area, while Pearton (1980) and Pearton and Viljoen, (1986), documented seven dyke varieties. The later studies included dykes which were altered by later fluids, suggesting that the number of intrusions is likely to be less than proposed.

1.6. Structure

The Murchison Range is asymmetrical, with no evidence for repetition of major rock types in the northern and southern flanks. In the absence of clear geological evidence and due to the lack of a specific model for the Murchison Range, the more extensively studied Barberton greenstone is often used as a reference model. Traditionally, the Murchison is interpreted as a synclinal structure along the southern limb of a tightly folded east-north-east tending synform which has been intruded and deformed by diapiric emplacement of gneiss domes and late stage granitic plutons. Although large scale folding does occur within the belt, definite evidence for a tightly folded east-north-east synclinal structure as proposed by Van Eeden *et al.* (1939) and Graham (1974) has not yet been found. Viljoen *et al.* (1978) proposed that the succession is a synclinal keel and Anhaeusser (1983) suggested that it represents a folded synclinorium. Pearton and Viljoen (1986) suggest, however, that the evidence for a broad synclinal structure is tenuous. SACS (1980) interpreted the succession to be younging to the north and that gross layering is apparent from the geophysical work done by de Beer *et al.*, (1984). However field mapping by Vearncombe (1988), indicates that the fold structures of the belt are more complex than can be represented by a simple synclinal model. Vearncombe (1988), indicates that there are tight isoclinal fold structures which are inter-domainal, with major tectonic breaks occurring between each domain, which includes the Antimony Line. Surface geological data indicates that the Murchison schist belt is intruded by fingers of granodiorite, especially along the sub-vertical structure of the Antimony Line (Figure 1.4). A geophysical survey carried out by de Beer *et al.* (1984), provides an insight into the structure of the Murchison Range and offers some fundamental constraints on structural models for the area. It appears as if the Maranda and Baderoukwe granites have intruded along a shear zone which broadly coincides with the Antimony Line. The northern and southern contacts of the belt were found to be fundamentally different as far as physical properties are concerned. The proposed synclinal model through the Gravelotte area suggests that one limb of a synclinal structure has been intruded by the Maranda granite. The interpretation of the other profiles is problematic and cannot be easily reconciled with the synclinal model. De Beer *et al.* (1984), note that the beryl mineralization along the southern contact could be associated with the Maranda granite, the presence of which generally results in a relatively low value in the residual gravity anomalies. The results of the geophysical work indicate that the Murchison is a relatively shallow feature, between 8.8 and 12.3 km mostly less than 4 km, with no evidence of a synclinal keel (de Beer *et al.*, 1984).

The Murchison schist belt has been interpreted as part of a major east-north-east strike slip wrench fault, with either sinistral (Graham, 1974; Pearton, 1978; Viljoen *et al.*, 1978; de Beer *et al.*, 1984; Pearton and Viljoen, 1986) or dextral (Fripp *et al.*, 1980) strike slip motion. Vearncombe (1988), suggests that the Murchison schist belt is characterised by heterogeneous oblique- to dip-slip, north side up shear. He notes, however, that strike-slip deformation occurred in the Letaba shear zone along the north eastern margin of the belt. Button (1973), demonstrated that movements along the Murchison lineament influenced the deposition of the approximately 2450 Ma old Wolkberg Group as well as certain units within the 2200 Ma old Transvaal Group. The Murchison lineament also affected rocks of the Waterberg and Karoo Supergroups further west. Barton (1984) suggested that the Rb-Sr concentrations along the affected lithologies are too small to reflect the emplacement of these units and appear to reflect disturbances in the Rb-Sr system as a result of fluids during movements along the major shear zones over a period of time. Thus it is indicated that movement along the major tectonic breaks including the Antimony Line has occurred sporadically over a extended period of time with much of this movement occurring during the Proterozoic at approximately 2400 Ga to 1000 Ga.

Graham (1974), suggested that deformation related to the Limpopo belt extended into the Craton as far south as the Murchison schist belt and that certain of the structural features evident were due to this event. This is confirmed by Van Reenen *et al.* (1987) and McCourt and Vearncombe (1987a, 1987b), who recognized a series of sub-parallel, steeply north-dipping east-north-east striking, reverse shear zones in the Northern Transvaal. These structures include the Antimony Line in the Murchison schist belt and also the tectonic breaks between the various domains proposed by Vearncombe (1988).

If the deformation features observed in the Murchison Range and intrusion of the surrounding granitoids are due to the Limpopo orogeny, they relate to collision tectonics (Vearncombe, 1988) either between the Zimbabwe and Kaapvaal Cratons (Coward and Fairhead, 1980; Light, 1982) or between the central zone of the Limpopo belt and the combined Zimbabwe and Kaapvaal Cratons (McCourt and Vearncombe, 1987a. 1987b). Vearncombe (1988), has suggested that this feature would serve to distinguish the Murchison Range and other greenstone and schist belts in the northern Kaapvaal Craton, from lesser deformed belts further south, such as the Barberton schist belt.

1.7. Isotope Ages

So far, no definitive primary ages have been obtained for units within the Murchison schist belt. Secondary galena from veins in carbonate metasedimentary schists yielded common lead ages of approximately 3.25 Ga (Saager and Koppel, 1976) based on the two stage lead isotope evolution model (Stacey and Kramers, 1975). Lead isotopic data from galena in the Rubbervale Formation yielded a model age of approximately 3.1 Ga (Vearncombe *et al.*, in press). Data from stibnite mineralization in the antimony-gold mines yielded a Pb-Pb model age of about 2.8 Ga (Vearncombe, 1988). If these ages are reliable it appears that mineralization within the Murchison schist belt occurred sporadically between 3.25 and 2.8 Ga. These ages thus suggest that the precursor to the schists formed prior to 3.25 Ga. Burger and Walraven (1979) obtained a U-Pb zircon age of 2961 ± 150 Ga from analyses of grains separated from the Free State hornblende granite of the Rooiwater Complex. This age may represent the time of emplacement of the granite, however it has been suggested that the zircons may be xenocrysts and the age may not pertain to the Free State hornblende granite at all (Vearncombe, 1988). Vearncombe *et al.* (1987) has suggested that the ages obtained for the rocks of the Murchison schist belt span between 2.8 to 0.9 Ga and that they predominantly between 2.6 and 2.4 Ga, this being due to isotopic resisting thought to relate to alteration and probably synchronous with deformation and regional metamorphism.

1.8. Economic Geology

The Murchison Range is characterised by a variety of unusual mineral deposits, including some which are unique.

1.8.1. Antimony Mineralization

Mineral production in the Murchison schist belt is dominated by the mining of antimony. The area is host to the world's largest antimony producing mines and is currently responsible for 20% of the worlds total antimony production. Mineralisation is associated with the Antimony Line, along which 18 mines and occurrences have been described (Pearton and Viljoen, 1986). The deposit has been mined since the 1940's, when the strategic importance of antimony was first recognised. Peak production occurred in the 1960's, but since 1975 production has been erratic, partly due to declining reserves and to a decrease in industrial demand for the metal. Gold, initially a by-product of the operation, has proved to be of considerable value to the mining operations and is likely to gain more importance in the future since the decline in antimony production has stimulated interest in gold exploration in the area. By 1986, a total of 10 tons of gold had been produced from the Antimony Line, making it the fifth largest Archaean gold producer in South Africa (Pearton and Viljoen, 1986). Mineralization is dominated by stibnite and lesser amounts of pyrite, arsenopyrite and berthierite, with subordinate scheelite, native antimony and other minerals (listed in Davis *et al.*, 1986).

Various views concerning the origin of the mineralization of the Antimony Line have been proposed. Due to its linear nature it was commonly considered to represent a syngenetic, exhalative style deposit. Recent studies Vearncombe (1988), Boocock *et al.* (1988) and Boocock (1984) have stressed the structural controls on antimony mineralization indicating that in its present form it is an epigenetic structurally controlled deposit.

1.8.2. Gold Mineralization

Gold originally attracted the attention of prospectors to the Antimony Line, but since then it has been found to occur in virtually all the rocks of the Murchison Range. Along the Antimony Line gold occurs as coarse, free gold as well as in fine disseminations and as sub-microscopic inclusions in the sulphides and silicates (Davis *et al.*, 1986). Auriferous quartz-lodes are common along the southern margins of the Murchison Range and are associated with short east-west striking shear zones. These are commonly closely related to the granite greenstone contacts (Van Eeden *et al.* 1939; Vearncombe *et al.*, in press), especially along the granite contact south-west of Spitzkop, near Leydsdorp, where several quartz-vein deposits occur in, or in close association with, late granitoid intrusions. Van Eeden *et al.* (1939), noted that most mineral occurrences occur as short east-north east striking bodies, a feature confirmed by this study.

Gold mineralization is also associated with arsenopyrite and pyrite in partially carbonated ferruginous cherts and iron formations, examples include those observed in the Blue Jacket mine (Spitzkop area), in areas south of the Malati Store deposit and at the Ruby gold mine, north of Gravelotte (Viljoen *et al.*, 1978). Gold and minor stibnite, occur in arsenopyrite, pyrite and pyrrhotite ores associated with iron formations along the Antimony Line, such as those found in the Gravelotte mine. Minor gold has also been located in shear zones within the Rooiwater Complex and in the pegmatites of the northern spur of the Murchison Range (Pearton and Viljoen, 1986). Gold-bearing sulphide-rich zones occur in amphibolite and ultra-mafic schists in the southern parts of the belt, although no apparent stratigraphic control is observed. Examples include the Beryl and possibly, the La France, Minerva and the Discovery Shaft gold mines. In these deposits, pyrite is the most common sulphide followed by arsenopyrite, pyrrhotite and chalcopyrite. Ilmenite, rutile, scheelite, tourmaline and biotite may be present in varying amounts. Of particular relevance to the present study is the presence of disseminated, auriferous pyrite occurring within the albitized granodiorite intrusions observed sporadically along the Antimony Line or other major structural discontinuities. Examples include the Malati Store mine, Discovery Shaft mine, Minerva mine, Maranda pluton and the Duchen mine.

1.8.3 Alluvial gold

No major alluvial gravels are present in the area. However, Van Eeden *et al.* (1939), reported that on the farm, Deeside 249, there were slightly auriferous gravels on the southern bank of the Groot Letaba river, as well as along the banks of the Selati river near Lions Kop. Minor auriferous quartz rubble was worked at the Old Stromboli mine and on the claims of the Beryl Gold Mining Company (Steuart, 1899).

1.8.4. Mercury Mineralization

Mercury, in the form of cinnabar and, occasionally, native mercury, occurs at numerous localities in the Murchison range (Wilson-Moore, 1896; Steuart, 1899). The most important deposit is the Monarch Cinnabar mine, situated to the north and east of Monarch Kop which was exploited during World War II. This is the only deposit of this type which has been exploited to any significant degree. The reef consists of narrow sheared zones of cinnabar-bearing cherty carbonate (Wilson, 1945) and coarse-grained crystalline carbonate and silica lenticels (Van Eeden *et al.*, 1939). The reef zone is traversed by numerous quartz veins along which cinnabar and, in some places, native mercury, are concentrated. Other occurrences have been noted and at the Malati Store intrusion for example, a mercury soil anomaly has been detected. Other occurrences include two localities between Selkirk and Antimony Kop (Wilson, 1945). More extensive descriptions of the Monarch Cinnabar workings are to be found in Hausmann (1959) and Pearton and Viljoen (1986). The latter author concludes that this mineralization is epigenetic and possibly derived by leaching of meta-basalt rocks by carbonatizing fluids. This study however, has shown that the presence of minor quantities of cinnabar are associated with the mineralization in the albitized granodiorites.

1.8.5. Emeralds and Associated Minerals.

An extensive area of pegmatite development is present to the south of the Murchison Range. The Granville pegmatites intrude along the southern flank of the belt, giving rise to economically exploitable emerald and beryl deposits, as well as less important aquamarine, tourmaline, molybdenite, garnet, corundum, chrysolberyl, minor cassiterite and tantalite. The most important of these deposits were worked by the Gravelotte Emerald Mine (GEM), (Figure 1.2) south of Gravelotte (Robb and Robb, 1986). Mining here was predominantly open-cast, although underground mining was attempted towards the end of the mine life. Presently, there is no emerald production in the Murchison Range but up to June 1986, 39,635 carats of "A" grade emeralds had been recovered (Cobra Mines Limited, 1986).

All the emerald deposits in the area were situated along the southern flank of the Murchison schist belt between Gravelotte and the Kruger National Park. Spatially, they are restricted to the contact zones between the ultra-mafic rocks and intrusive albite rich pegmatites of the Granville granite series. The most favourable hosts to the emeralds were biotite schists which developed as reaction rims along the contacts of the pegmatites and talc-chlorite schists. In the Cobra pit at GEM the ultramafic schists are, altered to biotite schists, usually comprising in excess of 90% biotite. Although beryl occurs in the pegmatites, the emeralds are restricted to the biotite schists, and rarely, talc-chlorite-carbonate schists along the pegmatite schist contact. They may occur in discrete zones of highly fissile biotitic schist, likely to be due to small scale shear zones which allowed enhanced fluid flow and facilitated mineralising fluids to move into the country rock. The economically bearing zones are generally very irregular in shape and dimension, providing problems for economical extraction (Cobra Emerald Mines Limited, 1986). The beryl-emerald-bearing schists are thought to have resulted from the interaction of beryllium bearing phases from granites and pegmatites with the ultramafic to komatiitic schists of the Mulati Formation (Robb and Robb, 1986). The green colour is due to the presence of chromium within the beryl lattice. Generally the emeralds in the region were of poor quality and are often milky and spotted due to numerous small fluid and biotite inclusions. Accessory minerals associated with beryl mineralization include molybdenite, apatite, pyrite, chalcopyrite and minor tourmaline (Van Eeden *et al.*, 1939). Analysis of the pegmatites reveals that they are predominantly sodium-rich rather than potassium rich pegmatites (Robb and Robb, 1986; Golden Dumps internal reports). The pegmatites spatially related to the emerald mineralization have a high NaO_2:K_2O ratio (Robb and Robb, 1986) and this feature was used as an exploration tool by Cobra Emerald Mines (Limited). Grundmann and Morteani (1989) on their comparative study of the Habachtal (Austria) and GEM emerald deposits concluded that the emeralds were the product of metasomatic alteration associated with ultra-mafic bodies, formed by contact reactions during regional metamorphism. These reactions occurred at the contact of pre-existing beryl- and phenakite-bearing pegmatites and albite pegmatites with biotite-talc and actinolite schists (Grundmann and Morteani, 1989). They note that fluorite associated with the emeralds exhibits HREE enrichment, indicative of hydrothermal fluorite. Fluid inclusion microthermometry undertaken on the emeralds (Nwe and Morteani, in press) indicates a H_2O-CH_4-CO_2-NaCl fluid system, with trapping temperatures of between 450°C and 500°C and pressures of 4 Kb based on model isochores. Nwe and Morteani, (in press) note that the early fluids were of low salinity (<6 wt% eNaCl) and contained variable quantities of CH_4 and CO_2 (detected by laser Ramon spectrometry) they report that the fluids evolved with time to higher salinities (± 38 wt% eNaCl) and where CO_2- and CH_4-free. There are distinct chemical similarities to the proposed pre-phase separation fluids associated with the albitization from this study (See Chapter 6).

Pegmatites to the south of the Murchison Range are exploited for mica, feldspar and quartz contents and were at one time also exploited for corundum (Robb and Robb, 1986). The abundance of the pegmatites to the south of the Range, unlike the north of the schist belt, was attributed by Van Eeden *et al.* (1939) to the mineralized roof zone of a granitic batholith.

Tungsten, occurring as scheelite, also occurs within auriferous veins in sheared granite close to the schist-granite contact along the southern flank of the schist belt. Scheelite is present in several old mine workings, including Minerva, La France, Duchen, Quagga Camp and Mulati (Bowles *et al.*, 1982), as well as in most of the antimony mines. The only recorded example of scheelite being exploited is at the Old Stromboli mine. Minor eluvial wolframite has been reported from near Leydsdorp (Van Eeden *et al.*, 1939).

1.8.6. Copper-Zinc Mineralization

Copper-zinc mineralization is found associated with massive to banded sulphides in the upper portion of the Rubbervale Formation, along the contact with the Weigal Formation, and forms the "Copper-Zinc Line" (Figure 1.2). Two major deposits, Letaba

Copper and Mashawa, as well as several smaller occurrences, are known to occur along this "line". The deposits were originally worked by the ancients and limited mining commenced in 1954 when a small tonnage was removed from the Letaba mine (Hausman, 1959). The deposit occurs along strike for 400-1100m as stratiform or stratabound sulphide horizons which are located within felsic volcanic assemblages, comprising quartz-chlorite schist, quartz porphyry schist and agglomerate. A variation in ore types occurs, which may reflect a spatial proximity to volcanic vents (Minnitt, 1975). The ore is characterised by a high Zn/Cu ratio, which is typical of a volcanogenic base metal, massive, sulphide deposit associated with exhalative vents. Ore minerals are variable and include pyrite, sphalerite, galena, chalcopyrite, digenite and covellite (Hausmann, 1959; Maiden, 1984).

1.8.7 Other Deposits

Numerous, less important deposits are present within the Murchison Range. These include baryte, arsenic (from arsenopyrite associated with the Antimony Line), chrysotile asbestos (Pikes Kop, Leeuw Kop and Serpentine Kop), lead (Old Star mine), magnesite (Antimony Line carbonate rocks) and talc (Antimony Line and basic rocks near granitoid contacts). None of these has been exploited for any major period of time. Fuchsite-quartz- sericite schists of the Mulati formation have been used for paving stones near GEM, south of Mac Kop and south of Malati Store mine.

1.9. Albitites: A Global Review

The term "albitite" has been used to describe a variety of rock types, composed predominantly of albite (Bodart, 1968). Albitites are commonly porphyritic, leucocratic rocks which replace granitic rocks and consist of quartz, albite, microcline, alkali amphibole (generally riebeckite), enclosed in a ground mass of fine grained albite. Many Archaean lode deposits are spatially related to albite-rich veins, dykes or plugs (Smith *et al.*, 1990). Examples include the McIntyre and Hollinger Mines at Timmins (Burrows and Spooner, 1986) and the Golden Mile at Kalgoorlie (Prider, 1940). In general, albitites can be said to have a restricted, but apparently world-wide occurrence and have been found to be associated with almost every major type of plutonic rock (Bodart, 1968). Although they may be derived from low grade metamorphic processes, some are unquestionably the product of deuteric alteration. Bodart (1968), however, proposed that an albite-rich rock may also be produced by liquid immiscibility within ultra-basic melts.

Sodic alteration is commonly associated with tin-tungsten deposits where, under conditions of extreme alteration, the resulting assemblage may consist of as much as 90% albite (Jackson, 1975). The comparatively rare occurrence of albite in high temperature hydrothermal alteration zones is likely to be due to its narrow range of stability. Both Na^+/H^+ and Na^+/K^+ ratios are critical to its formation and, in general, the Na^+/K^+ ratio must be greater than 16 at 200 °C (Jackson, 1975).

Siems (1984), notes that sodium silicate alteration or albitization of host rocks to produce an albitite can be associated with a variety of different kinds of gold deposit and host rocks, ranging in age from Archaean to recent geothermal systems and often accompanied by varying degrees of chloritization and carbonatization. Albitization of intrusions is commonly pervasive and may affect both small and large plutons, resulting in albitite bodies which may be several square kilometres in area and a few hundred meters in depth, but they rarely extend deeper than 700 meters into the intrusion. Albite bodies may be sheet-like, lenticular, pipe-shaped, or irregularly shaped (Siems, 1984). Some are clearly controlled by fractures, but the majority exhibit no such relationship (Smirnov, 1976).

Albitite bodies commonly underlie greisen zones and, as such, both occur within the upper levels of granitic plutons (Smirnov, 1976). Russian geologists believe that deuteric potassium silicate alteration, sodium silicate alteration (albitization) and greisenization are genetically linked and commonly occur together, but are emplaced sequentially in and around the parent intrusion (Smirnov, 1976). Smirnov (1976) suggests that the potassium removed from the zone of albitization is concentrated into the higher greisenized levels of the pluton and into the adjacent country rocks. The zones of potassic and sodic alteration within the Murchison schist belt (i.e. Gravelotte Emerald Mine and the Antimony Line) commonly show a spatial relationship which suggests a similar genetic relationship between the alteration styles.

Cathelineau (1986), describes hydrothermal leaching of quartz associated with sodium metasomatism of granitic rocks in Western European granitic massifs, a process which also produces albitites. The alteration results from a series of reactions between late deuteric fluids and the host rocks. This style of alteration is also very similar to that observed in the Murchison schist belt granodiorites (this study).

Gallagher (1940), reviewed the world-wide association of albite and gold mineralization. He did not however distinguish between tonalities, trondhjemites and smaller dyke-like or plug-like bodies of albite-rich nature, but generalized for all albite-bearing granitic rocks. He proposed that albitites are the differentiated products of a trondhjemitic-tonalite type parent magma, but noted that complex manipulation of the magma would be required to give the required rock type. Prider (1940), proposed that the albitites of Kalgoorlie, Western Australia, were differentiates of a tholeiitic magma.

Ward (1958), recognized that the gold fields of Ontario and Quebec, the Central gold fields of Western Australia and the Kolar gold fields of India, as well several other areas, are associated with albite porphyry dykes which have been called by different names, including keratophyre, albitite and alaskite porphyry. He noted that various types of gold deposit may be associated with albite-rich rocks and suggests that albite-porphyry-hosted gold deposits are characterised by a simple mineralogical association. The commonest associations are with pyrite, pyrrhotite and arsenopyrite.

The albite porphyries of the Barberton Mountain Land (Viljoen and Viljoen, 1961) show highly fractionated REE patterns, which indicates equilibrium with garnet and, therefore, a high pressure origin (Glickson, 1976). Glickson (1976), proposed that a 25% to 35% melting of a quartz eclogite source could account for these albite porphyries. These albite porphyries are not considered to be related to the albitites of the Murchison schist belt.

Pearton (1980), concluded that the albite-rich rocks of the Murchison area were the product of lateral secretion processes produced during carbonation of basaltic rocks from greenstone belts and are therefore unrelated to underlying granitic rocks. He proposed that metamorphism of synclinal keels resulted in fluids being expelled by metamorphic reactions towards the centre of the syncline. These fluids carried CO_2, either liberated from the greenstone pile or derived from the intruding granitoids. The reaction between CO_2-bearing fluids and the ultramafic host rocks at the base of the succession provided the fluid with a elevated content of ultramafic constituents. Reactions between these fluids and the overlying greenstone yielded chlorite-quartz-albite-dolomite rocks from which some Si, Al and Na was expelled. These constituents crystallize at higher levels to form the albitites. The occurrence of mineralization in these rocks is related to the carbonation event in which Sb and Au, released by the carbonate alteration, migrated into the vein system and crystallized together with the albitite. In contrast, the present study has shown that the albite-rich rocks of the Murchison schist belt are related to granodiorite intrusions and are a product of sodium alteration of the cupola zone induced by metasomatically-derived hydrothermal fluids.

Barton *et al.* (1991) and Beattie (1991) described the albitized Roodepoort pluton, in the Pietersburg greenstone belt. The Roodepoort pluton has undergone albitization and carbonate alteration and is mineralized with disseminated auriferous pyrite. The albitized portion is considered to be related to the Turfloop batholith, which has undergone carbonate alteration and mineralization. Sr isotopic data suggest that hydrothermal alteration occurred shortly after the magmatic emplacement of the pluton. Barton *et al.* (1991) proposed that the emplacement of the Roodepoort pluton, the hydrothermal alteration (albitization) and gold mineralization are related to the Limpopo orogeny (± 2660 Ma).

McNeil and Kerrich (1985), have noted that certain trondhjemites, at the Canadian Arrow mine, have elevated Na_2O contents (8.32 ± 1.16 wt.%). Kerrich (1986) proposed that this Na_2O enrichment occurred during pervasive sea water related spilitic alteration at low temperatures. The intrusions have reversed quartz-feldspar fractionation ie. $\delta^{18}O_{quartz} = 9 - 11$, $\delta^{18}O_{feldspar} = 10 - 16$ °/$_{oo}$ (Freyer *et al.*, 1979), indicative of low temperature sea water alteration.

Harris (1980), described a Phanerozoic example of albitization and epigenetic gold mineralization associated with a porphyry stock in Salave, north western Spain. This body has undergone desilicification, albitization and carbonatization. The disseminated sulphide assemblage includes molybdenite, pyrite, arsenopyrite and stibnite. Alteration and mineralization has been attributed to intermittently boiling fluids rich in CO_2, H^+, sulphur, antimony and arsenic. The mineralogical assemblage and alteration characteristics are similar to those observed in the Murchison albitized granitoids.

1.10. Intrusive Rocks Associated With Archaean Gold Deposits

Recent research into Archaean gold-lode deposits has emphasised genetic models whereby fluid access to dilational sites is related to major transcrustal fault zones. In these models, gold deposition is a response to fluid-rock interaction (Colvine *et al.*, 1984; Macdonald 1986), although the source of the hydrothermal fluid and mineralizing components has remained controversial. Several workers have noted the common, although not ubiquitous, association of felsic intrusions with gold mineralization in Archaean greenstone belts, (Gallagher, 1940; Goodwin, 1965; Hodgson, 1983; Boyle, 1979; Cherry, 1983; Colvine *et al.*, 1984, 1988; Burrows and Spooner, 1986; Cameron and Hattori, 1987; Spooner, 1991), resulting in the development of magmatic-hydrothermal models for Archaean gold mineralization (Wood *et al.*, 1984, 1986; Macdonald and Ray, 1984; Spooner *et al.*, 1985; Mason and Melnik, 1986; Burrows *et al.*, 1986). The magmatic model for the source of the fluids is plausible in general terms because of features such as the occurrence of proximal Au skarns (Meinert, 1989), porphyry Cu-Au mineralization (Soloman, 1990) and Au mineralization in intrusion centred systems (Sillitoe and Bonham, 1990). In addition stable isotope and fluid inclusion data are consistent with a magmatic fluid origin and militate against a metamorphic origin.

It has been proposed that the tonalite-trondhjemite-granodiorite (TTG) suite was the source of hydrothermal fluids and mineralization in Archaean gold-lode deposits (Burrows and Spooner, 1986; Cameron and Hattori, 1987). However, many greenstone gold deposits are spatially associated with small felsic intrusions, rather than with granodiorite batholiths (Boyle, 1979; Colvine *et al.*, 1988), although the significance of this association has remained elusive. While displaying a spatial association with gold deposits, the small felsic syn- to late-tectonic intrusions frequently occur within the deformation zones which are host to the gold mineralization. A number of Archaean Au-quartz vein ore systems occur outside the confines of greenstone belts in TTG terrains and batholiths examples include Renabie, N. Ontario (41 tons Au; Callan and Spooner, 1989) suggesting that greenstone lithologies may not always be relevant to the deposition of gold from a ore fluid. This also tends to discount the idea that the greenstones are the source of the gold and associated elements. Igneous stock hosted systems include the Lamaque system, Val d'Or, N.W. Quebec in which 94% of the total production of 138 tons Au was derived from bulk mineable stockwork and quartz-tourmaline veins systems contained within three, late, undeformed plugs of granodiorite composition (Spooner, 1991)

The igneous stocks commonly associated with gold mineralization have a wide range of silica saturated compositions, from trondhjemites, through alkali gabbro, to diorite-granodiorite (TTG) (Boyle, 1979; Daigneault *et al.*, 1983), rather than being affiliated solely to I-type granites, as proposed by Hattori (1987). Porphyritic varieties contain quartz or feldspar phenocrysts. In addition to the quartz-bearing plutons, a suite of silica-undersaturated intrusions also host gold mineralization in the Timmins area of the Abitibi province (Colvine *et al.*, 1988). These include albite-rich dykes which host gold mineralization and cut the quartz porphyries in the McIntyre and Hollinger Mines (Burrows and Spooner, 1986). The geochemistry of the undersaturated intrusions ranges in composition from syenite to monzonite and lamprophyre (Colvine *et al.*, 1988). Cameron and Hattori (1987), noted that several Archaean gold deposits have features indicative of oxidized hydrothermal fluids, including sporadic barite, and that these deposits show a close spatial and temporal relationship with felsic plutonism. Based on the fact that Archaean metamorphic fluids were mostly reducing, they concluded that the most reasonable general source for the mineralizing fluids was felsic magmas. Hattori (1987), showed that the intrusions associated with Archaean gold mineralization in the Abitibi belt were magnetic and had been oxidized in the magmatic stage, similar to Phanerozoic magnetite-series intrusions. Oxidized felsic intrusions are potentially fertile for the following reasons (Hattori, 1987):- (1) Oxidised magma can incorporate Au from source and surrounding rocks into the melt by oxidizing Au to Au^+ and Au^{3+} and dissolving enclosing sulphides; (2) Oxidized magma will not produce sulphide melts due to the high solubility of sulphur (Carroll and Rutherford, 1985), therefore Au would remain in the magmas; (3) oxidised magmas would produce oxidized hydrothermal fluids and hence enhanced gold solubility. This occurs because gold is more soluble in an oxidized fluid occurring as ions or complexes. Similarly gold- thio-complexes has a maximum solubility near the boundary between reduced and oxidized sulphur species (Seward, 1983; 1984). Oxidized magmas can thus effectively extract Au, transport it to upper crustal levels and concentrate it into hydrothermal fluids. However, the applicability of this premise remains to be tested. There appear to be conflicting interpretations as to the link between oxidized felsic intrusions and gold mineralization. It has been shown that the fluid immiscibility of H_2, H_2S, CH_4, or H_2S, will act to oxidize the fluid resulting in increased the SO_4^{2-} activity. This fO_2 shift can result in the precipitation of sulphates, shifting the $\delta^{34}S$ value of the sulphides to more negative values (Romberger, 1986; Spooner *et al.* 1987; Kerrich, 1989). Thus, the presence of sporadic oxidation of the stocks and fluids may be a secondary feature rather than a function of the parental magma, as proposed by Hattori (1987). Gas chromatography techniques have shown distinct similarities exist between the ore fluids of Barberton Archaean ores (de Ronde *et al.*, 1991) and those of the magmatic Mink Lake stock work Au-W enriched MoS_2 deposit.

Fryer *et al.* (1979), propose that the spatial relationship of gold deposits to intrusions is due to the brittle character of the stocks. This results in localized hydraulic fracturing during syn-tectonic mineralization. As such, they may represent more favourable channel ways for later hydrothermal fluids ascending from depth. However, the chemical characteristics, in particular, the relatively low iron content, appears to be less favourable for gold deposition. The intrusions are also continuous over a large vertical range and retain a more brittle response to deformation at a deeper crustal level.

A problem associated with the magmatic model for Archaean gold-lode deposits is related to the timing of mineralization relative to metamorphism and magmatism. High precision geochronological work has indicated that, in many cases the introduction of gold was distinctly later than the crystallization of the suites of intrusions, commonly by 20 to 30 Ma (Corfu and Wood, 1986; Corfu and Andrews, 1987; Colvine *et al.*, 1985; Kerrich, 1989). Jemielita *et al.*, (1989), have dated the Camflo deposit of the Abitibi belt using sphene from an Au-bearing vein, hosted in a felsic intrusion. They showed that the mineralization (± 2625 Ma) is 55 - 60 Ma younger than the zircon dates for the host stock at 2685 - 2680 Ma. This suggests that the gold mineralization is not related to magmatism or peak metamorphism at the time of orogenesis. Spooner (1991), however, interpreted this age difference to reflect dissolution and re-precipitation by later, upper crustal fluids which interacted with the primary Au concentration. Recent ion-probe U-Pb dating from the same deposits by Claoue *et al.* (1990), yielded significantly older ages for the mineralization, which are in fact much closer to the age of the host intrusion. Recent studies on the Fairview deposits in the Barberton greenstone belt have shown the age of gold-quartz vein mineralization is bracketed between a single zircon U-Pb age of 3126 ± 21 Ma for a cross-cutting porphyry dyke and 3084 ± 18 Ma from the country rock (de Ronde *et al.*, 1991). These time constants overlap within statistical uncertainties, but are younger than the adjacent Kaap Valley tonalite (3229 ± 5 Ma), which places doubt on the role of this pluton in gold mineralization.

Another argument against a purely magmatic hydrothermal fluid origin stems from the radiogenic isotope systematics of gold deposits. Most Archaean TTG intrusions are uniformly non-radiogenic ($^{87}Sr/^{86}Sr$ = 0.7005 - 0.7015, Peterman, 1979) whereas the gold deposits are characterised by highly variable Pb (Franklin *et al.*, 1983; Browning *et al.*, 1987) and Sr isotope initial ratios of 0.701 - 0.714 (Kerrich, 1989; Kerrich *et al.*, 1987).

The clustering of major gold deposits in specific areas is largely related to the presence of major structures. Most Archaean terrains have a dense distribution of major structures, although only a few contain significant mineralization, whereas many have the potential to act as structural controls on fluids and or igneous intrusions. This suggests that a certain range of intrusions may be more fertile than others. The mineralisation associated with intrusions of calc-alkaline/shonkonitic compositions (Hollinger-McIntyre "albitites" and the Kerr Addison/ Chesterville "albitites"), rather than the TTG suite or other igneous compositions, may be the basis for providing an explanation for the unusual amount of gold in these areas (Spooner, 1990; 1991).

Anhaeusser (1976), suggests that the gold deposits of Barberton and central Zimbabwe show a close spatial relationship to granitic diaprism. He proposes that this relationship is due to the development of favourable structures and thermal regimes generated by the granitic intrusions. However, a portion of the mines occur within mineralized quartz-diorite stocks. Foster (1980, 1982), investigated the relationship between gold deposits and granitoids of the Sesombi TTG suite in the Midlands greenstone belt. He proposed that the TTG suite was responsible for the generation of a relatively high fO_2 magmatic fluid which became involved in large scale shear zones and which channelled the fluids to higher crustal levels.

The Boddington gold mine (Western Australia) has features consistent with a dioritic gold-rich porphyry ore system (Symons *et al.*, 1990; Roth *et al.* 1991), indicating that the magnetically derived fluids can produce economic ore bodies and are potential sources for mineralizing fluids. The Boddington ore body displays varying degrees of albitization, with the gold mineralization associated with chalcopyrite, pyrrhotite and pyrite in quartz-epidote-actinolite veins which cross cut the intrusion. Fluid inclusions indicate highly saline fluids (up to 40 wt% eNaCl) which are in contrast to typical mesothermal "gold only" deposits (Groves and Phillips, 1987) and which generally have low salinity and are rich in CO_2.

Wyman and Kerrich (1988), Rock and Groves (1988a, 1988b) and Rock *et al.* (1987) have reported on the association between calc-alkaline lamprophyres and mesothermal gold deposits (Archaean to Tertiary) in which lamprophyres are spatially related to mineralization. In some cases, gold is more intimately associated with the lamprophyres than with any other rock type. They suggested that the lamprophyres were transporting agents for Au from Au-rich sources in the deep mantle, which then underwent extensive crustal interaction, generating felsic magmas and releasing their Au into metamorphic hydrothermal systems. The gold-lamprophyre association implies that deep-seated magmatism repeatedly accompanying gold mineralization in specific, well-defined plate tectonic environments. They also proposed a relationship between the observed calc-alkaline magmatism and the lamprophyric intrusions.

Fyon *et al.* (1984), suggest that the alkaline magmatism may be a manifestation of the overall cratonization processes, emphasizing the involvement of mantle diaprism and CO_2 fluxing. Thus magmatism may not have played a direct role in the transport of gold to the depositional site. Spooner (1991), notes that epithermal-mesothermal Au-Ag mineralization in island arc and Cordilleran settings may have been derived from high level fluids unmixing from intrusions of calc-alkaline affinity. Hence by comparison a possibility exists for similar genetic processes within the Archaean.

The data summarized above clearly demonstrate a common association of felsic intrusions and Archaean gold deposits. The strongest evidence indicates that the felsic intrusions are, at the least in some Archaean deposits, a preferred structural and /or chemical site for gold deposition.

1.11. Gold Deposits Associated with Granitoids in the Murchison Schist Belt

The mineralization within the Murchison schist belt has been shown to have a close spatial relationship with granitoid intrusions. The following examples of mines and prospects provides further evidence of this close relationship.

The Neill's Camp deposit consists of carbonate-quartz-stibnite veins which occur within a carbonated granitoid and the surrounding quartz-mica schist (Pearton and Viljoen, 1986; Van Eeden *et al.*, 1939). The Old Stromboli mine has quartz reefs developed along the carbonated and sheared contact of a carbonate- and albite-rich granodiorite intrusion. This is the only mine in the Murchison that has been worked successfully for scheelite (Van Eeden *et al.*, 1939; Pearton and Viljoen 1986). At the Horseshoe mine, cross-cutting antimony-gold veins occur within the Maranda granodiorite and also along the granodiorite-schist contact (Van Eeden *et al.*, 1939; Pearton and Viljoen, 1986 and recent drilling by J.C.I). The Old Treadwell mine contains gold-bearing quartz veins within a carbonated granodiorite near the schist contact. In this case, the intrusion is apparently not related to a shear zone (Van Eeden *et al.*, 1939). The Shotover mine occurs within the sheared contact of a granodiorite body, resulting in quartz-mica schists (Van Eeden *et al.*, 1939). The Sutherland Mine consists of quartz-pyritic stringers developed along the sheared contact of a carbonated albitized granodiorite intrusion (Hall, 1912; Van Eeden *et al.*, 1939). The Shielding prospect is similar to the Discovery Shaft intrusion in that pyritic schist and quartz veins are developed along the contacts of a carbonated granodiorite intrusion. The granodiorite contains disseminated auriferous pyrite (Van Eeden *et al.*, 1939). At Old Gravelotte Gold mine, a granodiorite intrusion appears to cut the ore body (banded ironstone) at depth. Minor antimony mineralization occurs within the granodiorite, especially along its contact (Van Eeden *et al.*, 1939)

1.12 Magmatic Fluid Generation

For the purpose of this study, the term *hydrothermal* is applied to "heated or hot magmatic emanations, rich in water, to the processes in which they are concerned, and to the rocks, ore deposits, alteration products and springs produced by them" (Gary *et al.* 1984). This definition thus implies a link between hydrothermal fluids, the ore deposits produced by them and the magmas from which the fluids are derived (Burnham, 1969). Two differing points of view regarding the nature of this connection are referred to as the colinear and cognate hypotheses (Burnham, 1969). The *colinear* hypothesis proposes that the bulk of the water-rich metal-bearing fluids are derived *from* magmas during their emplacement and crystallization. A modification of this hypothesis is that either meteoric or connate ground waters, heated in close proximity to the igneous bodies, may be incorporated into the convective system, bringing with them dissolved metallic constituents from the country rocks and redistributing them to form ore deposits. The *cognate* hypothesis suggests that ore-forming fluids are cognately related to the associated igneous intrusion and are thus generated in the same source regions as the magma. The intrusions subsequently intruded into higher levels of the earth's crust, along the same lines of weakness utilized by the fluids themselves (Burnham, 1969).

If Archaean mesothermal gold mineralization is to be attributed solely to magmatic processes, there must have been some thing "unique" about the process by which the granitoids were generated, their source, magma type and their magmatic evolution to produce potentially mineralizing fluids. Magmatic fluids are produced when a silicate magma attains vapour saturation and the vapour phase exsolves from the silicate melt-crystal system. The amount of dissolved sulphur in a melt, and its speciation into the associated magmatic aqueous fluids, is dependent on the magmatic fO_2 (Burnham, 1969; Mathez, 1984; Carroll and Rutherford, 1985).

CO_2 is a fundamental constituent of Archaean mesothermal gold deposits. However, Phanerozoic magmatic ore-forming fluids, associated with porphyry copper and gold deposits, generally contain less than 3 mole % CO_2 (Nash, 1976). CO_2-rich, aqueous, magmatic fluids can be generated at various crustal levels by crystallization of a calc-alkaline magma, provided that the magmatic source area contains both H_2O and CO_2 (Mysen, 1976; Eggler, 1974). Because of the low solubility of CO_2 in magma, silicate melts need contain only small amounts of volatiles to become CO_2-saturated. Since CO_2 solubility in magma is greater at high temperatures and pressures, melts generated under mantle conditions and then emplaced into the crust will become saturated with CO_2-rich vapour before H_2O saturation is attained (Holloway, 1976). Thus, vapour-saturated melts will evolve CO_2 (plus minor H_2O) vapour continuously during their ascent from the source region and will crystallize at higher temperatures than magmas which are H_2O-saturated, if the CO_2 remains in equilibrium with melts and crystals. As the magma rises isothermally, the water content of the melt will increase, but the vapour phase, in equilibrium with melt and crystals, will become enriched in CO_2 until the pressure is about 5 Kb, where the CO_2:H_2O ratio of exsolved vapour reaches a maximum (Holloway and Lewis, 1974). Subsequently at lower pressures, the CO_2:H_2O ratio in the evolved vapour is progressively reduced and CO_2 is removed from the system after attaining saturation. Thus, if primary crystallization of the magma occurs at pressures greater than 5 Kb, the majority of the H_2O dissolved in the melt could be taken up by crystallizing hydrous silicate phases, such as biotite and hornblende (Stern *et al.*, 1975) and the composition of the evolved vapour phase could be enriched in CO_2. For a silicate magma to become vapour-saturated at a high temperature early in its ascent, and for it to evolve a CO_2-rich vapour, it is necessary that the anatectic source area contains CO_2. In the absence of CO_2, vapour saturation of the magma will take place only at higher crustal levels and at lower temperatures, and the evolved vapour phase would be dominated by H_2O, with only traces of CO_2. Another important consequence of a CO_2-rich melt is that it provides a means for magmatic, aqueous fluids to form immiscible phases at high temperatures and pressures. The marked immiscibility gap which exists for CO_2-rich fluids results in the unmixing of the fluid into a saline liquid phase and a H_2O-CO_2-rich phase of lower density (Bowers and Helgeson, 1983). This phase separation effect could enhance the CO_2 content of the vapour. The density difference between the saline component and the CO_2-rich phase (Trommsdorff and Skippen, 1986) could result in infiltration of the CO_2 component into the country rocks, away from the silicate melt and saline brines. The coexistence of saline aqueous fluid inclusions with CO_2-rich, low salinity fluid inclusions, has been observed in many gold deposits (Wood *et al.*, 1986; Robert and Kelly, 1987; Colvine *et al.*, 1988).

Thus magmatic fluids, having characteristics similar to those of Archaean gold-related fluids, could be produced by typical magmatic exsolution processes. Upon formation of a magmatic aqueous phase, volatiles and incompatible elements partition into the fluid. Sulphur also partitions into the fluid as SO_2 and/or H_2S, the relative proportions depending on the fO_2 (Carroll and Rutherford, 1985).

The majority of hydrothermal processes giving rise to hydrothermal alteration and ore deposits operate during the late stages of felsic magmatism (Burnham, 1969; Murad, 1974; Burnham and Ohmoto, 1980; Friend, 1985). The major factors influencing these processes include the magma composition (a function of source) and the geological environment of the magma chamber (particularly depth). During its ascent, a magma will "boil" off its volatiles whenever the P_{H2O} in the melt exceeds the total pressure (Pt) (saturation). The level at which phase separation occurs is a function of the initial water content of the magma, and the pressure-temperature regime in the wall rocks. Hence, a rising magma which was initially water-rich, may boil throughout an appreciable part of its descent (Burnham, 1969) especially at pressures of less than 2 Kb. This process has been referred to as "retrograde boiling" (Burnham, 1969). The aqueous phase produced in the process tends to accumulate in the upper portion of the intrusion or, if openings exist, escape into the roof rocks. Retrograde boiling also produces an aqueous phase into which ligand complexes, such as chlorides and sulphide are strongly partitioned. The presence of these complexes greatly enhances the metal-carrying capacity of the hydrothermal fluid, which ultimately depends on factors such as the concentration of ligand complexes and fO_2 (Burnham, 1969). The continued separation of an aqueous phase from the magma during upward movement of the magma or in the final stages of crystallization (Whitney, 1975) will result in a circulatory hydrothermal system being generated within the H_2O saturated carapace of the consolidating granitoid intrusion. The development of this deuteric (i.e. late magmatic), sub-solidus fluid will result in the development of convective hydrothermal cells occurring within and around the intrusion producing distinctive hydrothermal alteration assemblages. However, post-magmatic circulation of meteoric and/or connate waters, induced by the thermal influence of the intrusion, often results in the superimposition of later styles of lower temperature alteration onto the earlier deuteric alteration, as in the case of the systematically zoned porphyry Cu-Mo systems (Lowell and Guilbert, 1970). Felsic-hosted hydrothermal deposits are commonly associated with the cupolas or marginal zones of the igneous intrusions (Burnham, 1969; Murad, 1974; Burnham and Ohmoto, 1980). Generally, the pressure generated by retrograde boiling in the saturated carapace is sufficient to induce brittle failure of the enclosing rock (Burnham, 1969). The resulting hydraulic brecciation may improve the penetration and permeation of hydrothermal fluids into the country rock. This results in extensive vein and vein related hydrothermal alteration in the country rocks which may then combine with external fluid regimes, allowing greater fluid distribution. Such observations may be important with respect to the present study, where the hydraulic brecciation of the altered intrusions indicates possible phase separation and rapid fluid expansion into the country rocks.

1.13. The Solubility of Gold in Hydrothermal Fluids

Sulphur is a ubiquitous component of hydrothermal systems and, because of the generally low prevailing oxidation potential tends to occur predominantly in a -2 oxidation state as H_2S or HS^-. Several early workers (Lindner and Gruner, 1939; Weissberg, 1970) recognized the potential importance of the sulphide complexes of Au (I) and carried out experiments on the solubility of gold, primarily in alkaline sodium sulphide solutions. The stoichiometry and stability of gold sulphide complexes were first determined by Seward (1983, 1984). Seward demonstrated that thio-complexes of gold, in which Au(I) is complexed by a sulphur-donor ligand such as HS^-, are probably the dominant mechanism of gold transport in hydrothermal systems below 300 °C in the near neutral pH regions. His experiments showed that a number of possible stoichiometries of aqueous sulphide complexes are possible but only two species identified occur over a wide temperature range, these being $AuHS^o$ and $Au(HS)^{2-}$. The solubility maximum of gold occurs in the near neutral pH region with the $Au(HS)^{2-}$ complex and many studies of gold transport have assumed that this is the dominant complex over a wide temperature range up to 300°C. Chloride complexes of gold are, however, also likely to be important in fluids of high chloride and low reduced sulphur concentrations, as well as in fluids of elevated oxidation potential and at higher temperatures (>400 °C) (Henley 1973, 1985; Fyfe and Henley, 1973). However, other gold complexes may also be important at higher temperatures. Hayashi and Ohmoto (1991) have shown experimentally that at temperatures between 250°C to 350°C, gold solubility increases with H_2S (aq) activity, indicating that gold could be transported as a bisulphide complex according to the reaction

$$Au(s) + 2H_2S(aq) = HAu(HS)^0 + \tfrac{1}{2}H_2(aq)$$

Recent work by Shenberger and Barnes (1989) and Hayashi and Ohmoto (1991) has determined the solubility of gold in NaCl and H_2S solutions. Results indicate that gold-chloride complexes do not become important unless the fluid is H_2S-poor ($< 10^{-4}$m H_2S(aq) at 250 °C), chloride rich (> 0.5m Cl) and of low pH (< 4.5) (Hayashi and Ohmoto, 1991).

Limited experimental data also indicate that gold may be transported as a carbonate complex (Boyle, 1979). Studies of vein Au-W deposits support the involvement of dilute CO_2 fluids and the possibility of carbonate complexing with gold and tungsten (Kerrich and Fyfe, 1981). Other gold complexes which are feasible in the transport of gold include CO, Br^-,NH_3, COS, as well arsenic species. The role of arsenic in gold solubility is not clear as there are few, if any high temperature experimental data which provides information as to its importance in hydrothermal systems. A few potentially important ligands include those involving tellurium (e.g. Te_2^{2-}, TeS^{2-}) and related species. The abundance of gold telluride minerals with certain deposits implies that these complexes may be important.

If gold is transported as a thio-complex (HS^-), a variety of processes may cause a decrease in the gold solubility of a hydrothermal fluid. These include a decrease in temperature and/or a decrease in the activity of reduced sulphur. This may be accomplished either by phase separation, dilution or oxidation (Seward, 1984). During boiling, the total CO_2 content in a residual liquid falls dramatically, resulting in a significant increase in the pH. In addition, the oxidation potential of the residual liquid phase is diminished significantly by hydrogen loss. These factors combine to bring about a decrease in gold solubility in the hydrothermal fluid. Oxidation is a highly efficient mechanism of reducing gold solubility, due to a "solubility cliff" which occurs when moving to higher fO_2 (See Figure 5.4.2). The destabilization of a thio-complex by fluid oxidation may be caused by wall rock reactions, including sulphidization of iron-bearing oxide, silicate minerals (Phillips and Groves 1984; Roberts, 1987) or organic matter (Hayashi and Ohmoto, 1991). Similarly, fluid reactions with precursor oxidized mineral species, such as sulphates as well as fluid mixing and dilution, may cause oxidation of sulphur species to native sulphur and sulphate, thus diminishing the activity of reduced sulphur and ultimately promoting the precipitation of gold. Other local factors include the piezoelectric properties of sulphides which result in the rapid plating of gold onto sulphide minerals (Bancroft and Jean, 1982). This process may occur even if the fluid is undersaturated with respect to gold (See Chapter 4.) (Springer, 1985). Experimental work by Hayashi and Ohmoto (1991) suggest that simple heating or cooling of the fluids without changing the H_2(aq) and H_2S(aq) contents is not an effective mechanism of gold precipitation when the gold is transported largely as a bisulphide complex.

CHAPTER 2
Geology of the Albitized Intrusions

2.1. The Malati Store Intrusion

The Malati Store intrusion is exposed in a small quarry approximately 1 km south of Castle Koppies (Figure 2.1). From this study the Malati Store intrusion is interpreted to represent the cupola zone of an intrusive granodiorite body which intrudes along the Antimony Line (Figure 2.1). Geophysical profiles indicate that granitoid material occurs close to the surface in the vicinity of the Antimony Line (de Beer *et al.*, 1984). Numerous small granitoid bodies are observed along this linear structure and are interpreted to represent high level projections from a large underlying granodiorite intrusion which has intruded into the shear zone at depth. The Malati Store intrusion is considered to represent one of these high level intrusions. At the exposed surface, the Malati Store intrusion is approximately 50 m in diameter and has intruded discordantly into quartz-chlorite schists (Plate 2.1) which strike approximately east-north-east, and dip steeply to the north (70 - 80°). Vearncombe *et al.* (1988) described the deposit as an "S"-shaped aplitic granodiorite body which has an upright north-south trending cleavage. They proposed that the D2 folding event may have been responsible for the "S" shape. The sigmoidal shape is emphasised by large, north-south trending schist xenoliths which are observed within the quarry (Figure 2.2). This study however has shown that the body does not have a internal cleavage. The granodiorite body has been intruded by a late north-south striking dolerite dyke (Figure 2.3).

Outcrop in the vicinity of the intrusion is poor and the area is generally covered with thick alluvium. Minor quantities of banded iron formation outcrop to the north and south of the intrusion and strike east-north-east. Auriferous banded ironstones occur approximately 1 km south of the Malati Store Mine and these have been exploited on a minor scale. Approximately 1 km to the west of the mine, along strike of the Antimony Line, is an antimony-gold prospect which occurs within a zone of intense silica, carbonate and potassic alteration and contains zones of numerous, sheared, quartz-fuchsite veins. Thus areas of intense potassic alteration occur in close proximity to the sodic alteration present within the Malati Store intrusion.

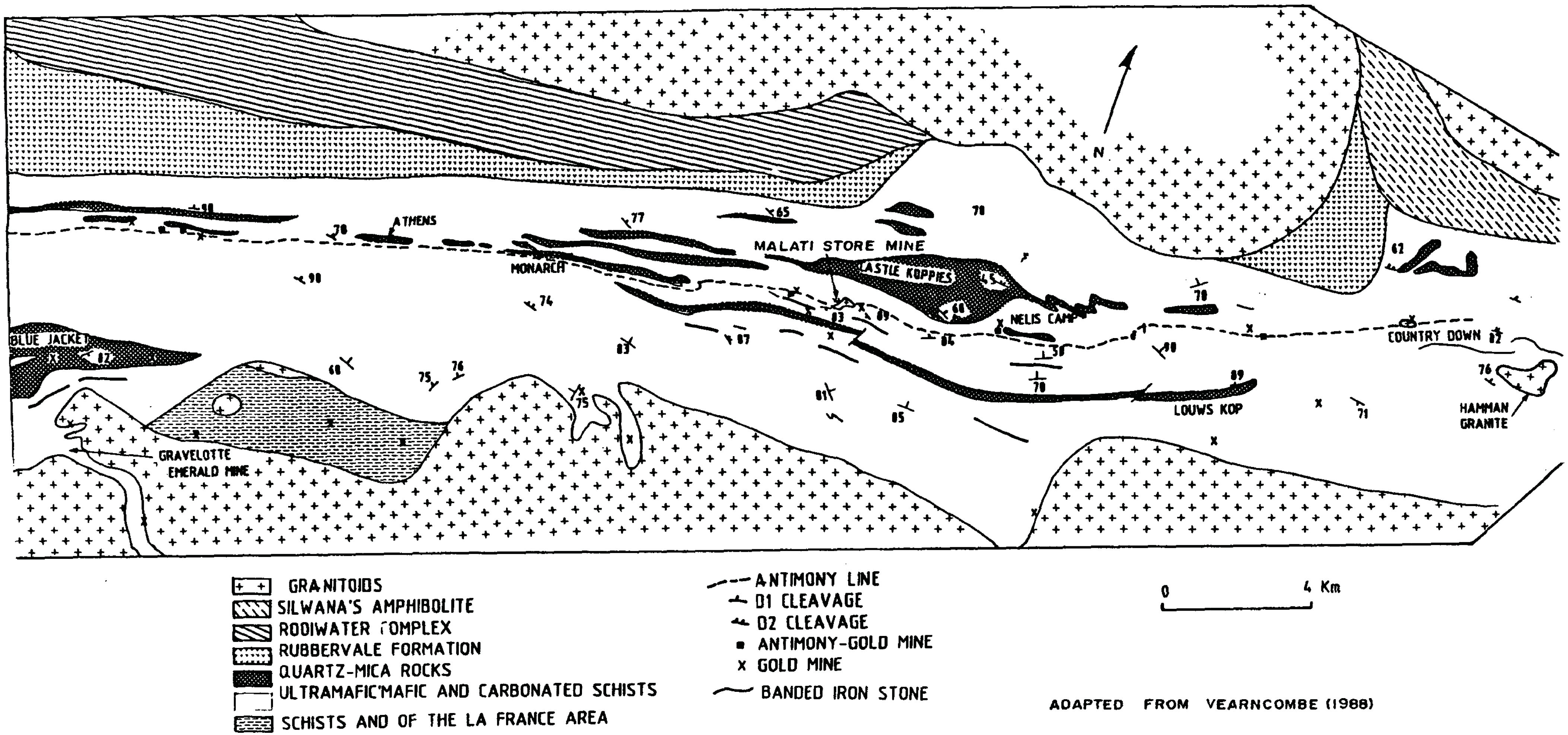

Figure 2.1. GEOLOGICAL MAP OF THE EASTERN PORTION OF THE ANTIMONY LINE

SHOWING THE LOCATION OF THE MALATI STORE MINE AND GEM.

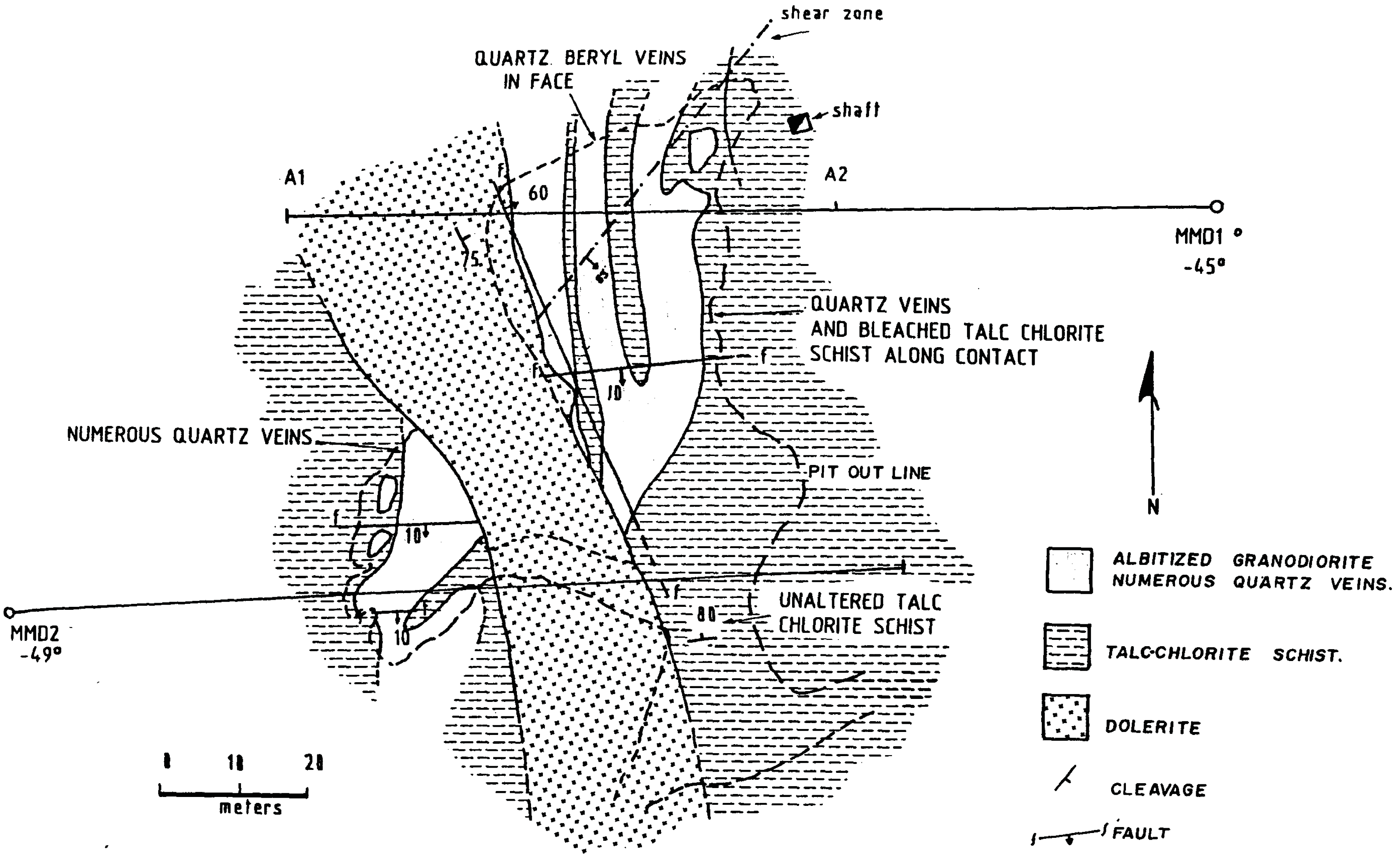

Figure 2.2. Geological plan of the Malati Store intrusion.

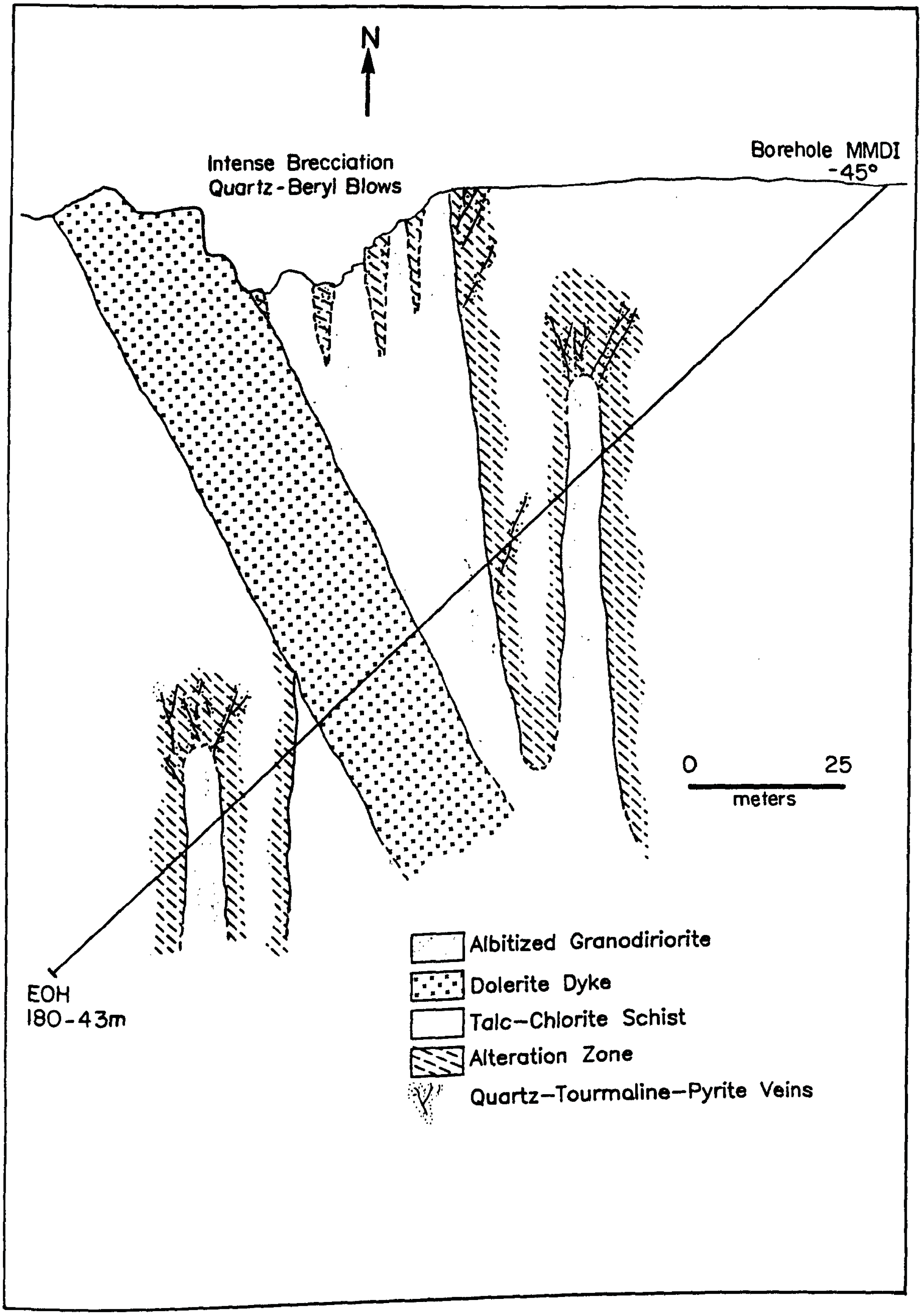

Figure 2.3. Geological section through the Malati Store intrusion looking north.

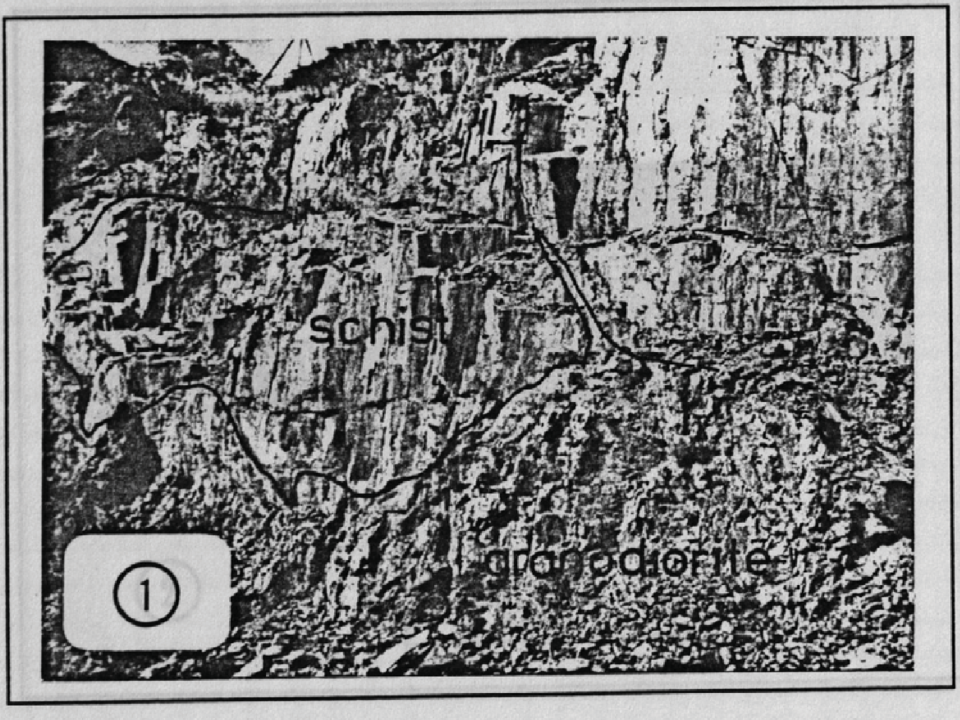

Plate 2.1. Intrusive contact between the granodiorite and talc-chlorite schist at Malati Store mine. Eastern wall of the quarry. The vertical shaft is seen in the top left hand side of the plate.

Numerous, occasionally auriferous, vein-quartz blows and veins of various dimension occur in the area and usually have an east-north-east strike. The quartz veins are commonly associated with zones of potassic alteration, identified by the presence of fuchsite. Approximately 1 km to the east of the intrusion, small (<5 m wide), brecciated, albite-rich rocks outcrop. These rocks are similar to the Malati Store intrusion and assays indicate that they contain gold (1-2 g/t). The Malati Store intrusion has been investigated by Phelps Dodge Pty (Ltd), this investigation included a diamond drilling program to a depth of 180 m (Plate 2.2). Phelps Dodge also conducted a magnetic survey over the body, reporting a positive anomaly which did not continue far beyond the dimensions of the present quarry. The intrusion is presently exploited on a limited scale for gold. Due to the refractory nature of the ore, only weathered material is extracted. The gold grade is erratic but averages approximately 3.5 g/t with some samples assaying in the region of 10 g/t. According to the Consolidated Murchison Mining Company (per. com), records indicate a mercury soil geochemical anomaly related to the intrusion.

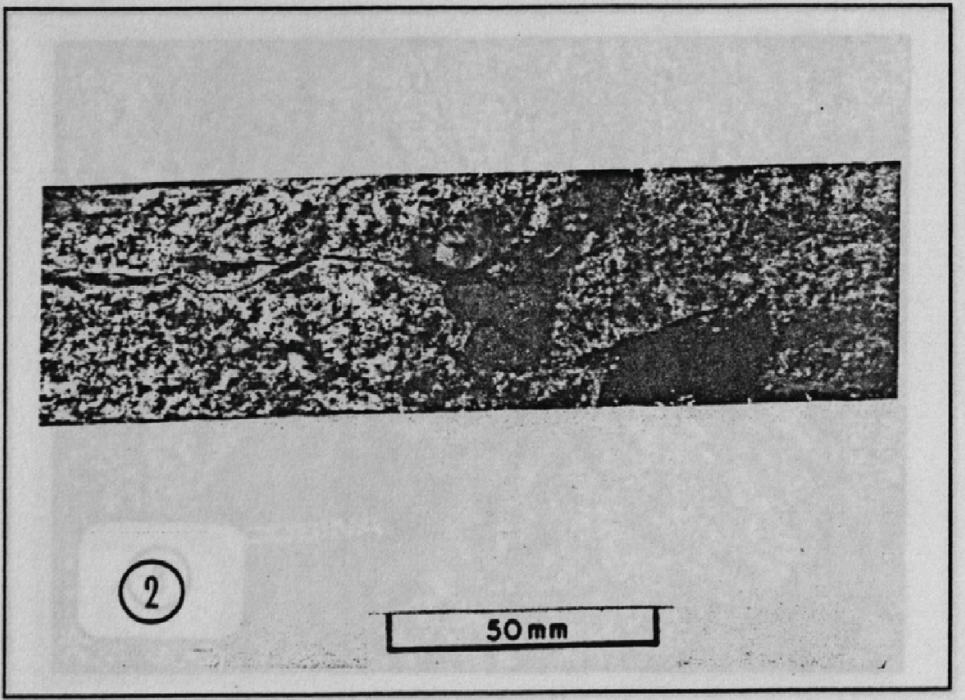

Plate 2.2. Mineralized albitized granodiorite. Malati Store intrusion.

The upper levels of the Malati Store intrusion have undergone intense sodium metasomatism, carbonate alteration and sulphidation. The intrusion is composed predominantly of equigranular, sugary-textured albite (70 - 90 %), quartz (10 - 30 %) and variable amounts of orthoclase and chlorite. Large laths of replacement albite (± 3 mm in length) give the body a sporadic porphyritic texture. A poorly developed steeply dipping fabric is present and has is developed parallel to the contact of the intrusive dolerite dyke. There is no evidence of regional fabric development within the intrusion. A minor relict fabric is observed running parallel to the intrusion contact, but generally no fabric has developed within the intrusion. A narrow (± 50 cm) north-east trending, steeply dipping ductile shear is present in the eastern portion of the intrusion and is terminated by the dolerite dyke (Figure 2.2). Gold sampling of this shear zone revealed little difference between the sheared and unsheared material.

The body exhibits extensive barren quartz stockwork development (Plate 2.3). Quartz impregnates the albite-rich material, resulting in intense silicification. The stockwork is generally confined within the intrusion, however, numerous irregular, clear quartz veins radiate into the country schists from within the intrusion. The altered schist xenoliths are also occasionally exhibit intense quartz stockwork development.