CHAPTER 9 SUMMARY AND RELATING PROCESSES

9.1 Related processes

In this chapter processes that had an influence on the petrogenesis and mineralization of the Uitkomst Complex will be discussed, both in comparison with examples from other similar intrusions and in relation to the observations made in the preceding chapters. The effects of assimilation of country rock and the resulting products on the magmatic evolution of the complex are discussed first. This is followed by a discussion of mineralization and formation models. An overview of assimilation- and external addition process is then discussed and reviewed in terms of the Uitkomst Complex. The fluid flow in a conduit system is investigated and related to observations in the study area, and finally, the development of solidification fronts and the effects these had on the physical development of the Uitkomst Complex is considered.

9.2 Magma interaction with dolomitic country rock

9.2.1 Contact mineralization

As could be expected, the dolomitic country rock to an intrusion such as the Uitkomst Complex suffers contact metamorphism resulting in the formation of skarn mineral assemblages and petrographic textures. The effects of this are well documented for the Ioko-Dovyren intrusion in Russia. The Ioko-Dovyren Intrusion is divided into (1) plagiolherzolite, (2) dunite, (3) troctolite and (4) gabbro-gabbronorite zones. Investigations here found that the dominant mineral in the skarns is brucite in pseudomorph form after periclase (Wenzel et al, 2001b). The skarn was also found to contain fosterite and Cr-poor spinels (Wenzel et al, 2001b). Fine grained fosterite-spinel skarns occur with the brucite skarns or as isolated schlieren in the magmatic host rock (Wenzel et al, 2001a).

Wenzel et al., (2001b) suggest that rapid heating of quartz-poor dolomite leads to the formation of minor olivine within the skarn, followed by the breakdown of such olivine to calcite and periclase. In the magma the partial melting of xenoliths results in the formation of a calcite melt with a low viscosity and low density, which can be easily squeezed out of the xenolith, leaving periclase and olivine behind (Wenzel et al, 2001b). This calcite melts

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reacts with the mafic magma to form a new olivine with an elevated CaO content of up to 1.67 wt % (Wenzel et al, 2001a, Wenzel et al, 2001b). The calcite melt is then assimilated into the mafic magma and this leads to the crystallization of Ca-Tschermak-rich interstitial clinopyroxene instead of plagioclase (Wenzel et al, 2001b).

It was found in the Uitkomst Complex that plagioclase is found exclusively, mostly as relict grains, in the wehrlite layers of the LHZBG unit with clinopyroxene (diopside) dominating in this unit. Plagioclase is absent from the PCR and even relict grains are absent. Olivine is also relatively rare in even the pristine parts of the LHZBG and completely absent from the xenoliths in this unit. Olivine is slightly more abundant in the pristine parts of the PCR unit, otherwise only "ghost" pseudomorphs of talc-chlorite are preserved. This is sufficient to propose that the effect of assimilation of dolomite in the PCR was not as pronounced as in the LHZBG. Olivine was able to develop, without their composition being driven towards clinopyroxene composition.

Wollastonite, andradite, grossular, spurrite, rankinite, merwinite and melilite have been found to be the most common minerals to crystallize at the interface between the dolomitic xenoliths and the magma, while no melting of calcite was observed (Wenzel et al, 2001a). Owens (2000) suggests that a metastable phase of stable state pyroxene, olivine and oxides may nucleate under conditions of local cooling in the area immediatedly surrounding the xenoliths. The incorporation of the various inclusions into the magma results in the preferential nucleation of mafic phases at the xenolith-magma contact.

The intermittent development of pegmatite phases around calc-silicate xenoliths in the LHZBG would suggest that the effect of localized cooling may have been too short-lived for continuous development of pegmatite phases around the xenoliths. The development of large diopside and calcite grains at the contacts along with semi-massive pyrrhotite does however suggest that nucleation of mafic phases was able to occur preferentially around the xenoliths.

At the very high temperatures which existed in the Uitkomst Complex conduit, akermanite should have formed as a product in the xenoliths. It has been found to be stable at temperatures between 1385 and 500 °C at 4.8 to 6.7 kbar (Deer et al., 1992). The formation of akermanite is given in the following reaction (after: Fulignati, Marianelli, Santcroce and Sbaran, 2004):

$CaMgSi_2O_6 + CaCO_3 = Ca_2MgSi_2O_7 + CO_2$
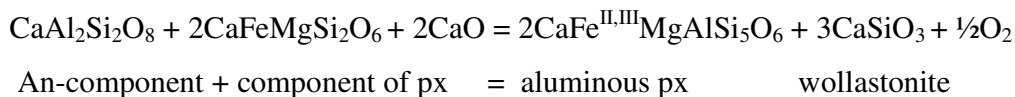Diopside + calcite akermanite
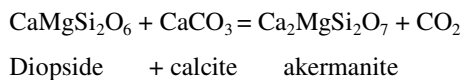
Another means of forming akermanite, by the reaction of impure dolomite suffering contact metamorphism and metasomatic exchange with magma, is proposed by Owens (2000):

Diopside + fosterite + monticellite = akermanite
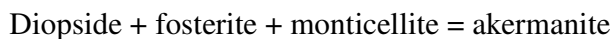
However, the lack of akermanite in samples from the Uitkomst Complex provides evidence that the temperature in the magma chamber did not attain temperatures high enough to lead to the formation of such minerals. This may be because the magma conduit was cooler than the required temperature, owing to the loss of heat during serpentinization of xenoliths and retrograde metamorphism.

9.2.2 Clinopyroxene formation due to the assimilation of dolomites

During the initial stages of limestone/dolomite assimilation into a mafic magma, wollastonite may precipitate due to the resorption of plagioclase (Baker and Black, 1980). The $CaAl_2Si_2O_8$ component is incorporated in pyroxene rather than in the crystallization of an anorthite-rich plagioclase. This process involves a desilicification of the primary igneous phases, without requiring the precipitation of nepheline (Baker and Black, 1980).

$CaAl_2Si_2O_8 + 2CaFeMgSi_2O_6 + 2CaO = 2CaFe^{II,III}MgAlSi_5O_6 + 3CaSiO_3 + ½O_2$
 An-component + component of px = aluminous px wollastonite

When Al substitutes in the tetrahedral sites of pyroxene, at the expense of Si, it effectively enriches the coexisting liquid in silica (Baker and Black, 1980).

The lack of wollastonite in especially the LHZBG unit would suggest that plagioclase was only developed in the wehrlite layer and did not develop in the main LHZBG magma. The preservation of relict plagioclase grains in an otherwise completely altered matrix suggest the plagioclase grains to be less susceptible to resorption. It was suggested in Chapter 4 that this may due to the presence of Al in the crystalline structure of the plagioclase.

Basic magmas are able to process the addition of Ca into the system by producing clinopyroxene and Ca-amphiboles (Barnes et al., 2005), owing to the high content of Fe and Mg in the primary magmas (Barnes et al., 2005). The conversion of olivine and orthopyroxene to clinopyroxene leads to the enrichment of the Mg content in clinopyroxene relative to Fe (Tilley and Harwood, 1931). High temperature phases of clinopyroxene, such as esseneite, indicate crystallisation in high fO_2 conditions, whereas at low fO_2 conditions iron-bearing calcic pyroxenes would be of a hedenbergite composition (Povoden et al., 2002). The early crystallization of clinopyroxene as observed in the Uitkomst Complex may be demonstrated to have taken place during the early stages of assimilation. This seems to confirm Bowen's suggestion that the mineralogy of the crystallising assemblage will not change during assimilation if the chemical imbalances could be accommodated within a solid solution series (Baker and Black, 1980). The point at which these imbalances can no longer be incorporated into the solid solution series will be marked by the crystallization of other phases such as wollastonite and garnet (Baker and Black, 1980), but the stability of these minerals depends on the CO_2-content of the system.

The presence of the minerals discussed above, demonstrates the assimilation of carbonate rocks. It also provides an indication of the amount of dolomite that may be assimilated, as demonstrated by the inability to further accommodate the imbalances of additional component during assimilation. The degree to which these different product minerals are

present or absent, also gives an indication of the conditions prevailing in the conduit at the time of their formation.

The dominance of diopside development in the LHZBG unit and lack of development of wollastonite and garnet suggest that the magma was able to accommodate the imbalances. It is suggested here that this is due to the continual influx of fresh magma capable of accommodating the additional Ca and Mg from the assimilated dolomite country rock.

Baker and Black (1980) also suggest that to produce a hybrid rock containing as much as 30% decarbonised limestone, most of the calcium would be incorporated into the hybrid melt before it intrudes as a calcite phase into a fracture system. Baker and Black (1980) speculated that if the depth of magma emplacement is shallow enough, the development of a circulating hydrothermal system and the formation of a late-stage hydrous mineral assemblage may occur.

The development of quartz-carbonate veins in both the LHZBG and PCR units suggest that a Ca-rich phase hybrid melt may have been present in the magma. The Ca-rich phase may have mixed with the additional Si in the magma, due to the substitution of Al in the clinopyroxene, to create these features during cooling of the system. The presence of a hydrous phase at this time may also have begun circulating leading to retrograde metamorphism of the primary magmatic mineral phases.

9.2.3. The significance of triple junction points in the LHBZG unit

Triple junction points observed between diopside grains in the studied rocks indicate that the present mineral assemblage in the LHZBG Unit formed due to metamorphic recrystallization of the precursor material. During a previous reconnaissance investigation of the LHZBG Unit (Steenkamp, 2004), it was found that some of the clinopyroxene-rich pyroxenites, could be classified as calc-silicate rocks and these rocks display classical metamorphic triple junction textures. The xenoliths also consist of calc-silicate rocks.

Triple junctions between clinopyroxene grains have been described for the parapyroxenite unit in the Platreef (Harris and Chaumba, 2001). In the Ioko-Dovyren Intrusion triple junction textures are also present, but with the difference that brucite replaces the precursor periclase associated with the triple junction intersections and some of the remaining grain boundries are lined with Fo-rich olivine and Mg-rich Cr-free spinel (Wenzel et al, 2001b). The occurrence of Fo-rich olivine in the junction points of clinopyroxene grains can also observed in samples of the LHZBG Unit (Figure 3.2).

These textural observations support the hypothesis that the interaction between the dolomite county rock and the intruding ultramafic magma, lead to the formation of the skarn and hybrid rocks. The olivine may be relict mineralization that segregated from the magmatic melt prior to sufficient assimilation of dolomite country rock, inhibiting the further development of olivine from the melt. The melt now effectively moved away from purely magmatic to a hybrid melt. The addition of Ca to the melt, and possibly hydrous fluids, would lead to the preferential development of diopside. This triple junction diopside would seem to indicate that the LHZBG unit suffered the effects of metamorphism shortly after of during development of the unit.

9.3 Models for the formation of sulphide deposits

9.3.1 General models

Several models have been proposed to explain the genesis of dunite-peridotite class Ni-S deposits (Edwards and Atkinson, 1986). The general consensus is that these deposits were formed by the segregation of immiscible sulphide liquid from an ultrabasic magma (Edwards and Atkinson, 1986). The "billiard ball"-model has been proposed to explain the close spatial association of massive, net-textured and disseminated sulphides, in which the formation of the textures is ascribed to gravitational settling of the sulphides within the cooling flow (Edwards and Atkinson, 1986). Another model is the "dynamic model" which assumes the segregation of sulfide and silicate components occurred during vertical flow, owing to a viscosity contrast (Edwards and Atkinson, 1986). Later modification of this model emphasizes the separation of sulfide liquid, silicate liquid and olivine crystals during

horizontal flow (Edwards and Atkinson, 1986). The lower viscosity sulphide phase tends to precede the silicate magma during flow, with partial crystallization having already occurred before the sulphide crystal mush is overwhelmed by the slower, more viscous silicate magma, effectively implying separate magma flows for sulphide and silicate melt (Edwards and Atkinson, 1986).

The development of net-texture sulphides in the wehrlite layer and the massive sulphide body suggest that such a segregation of sulphide liquid occurred from the melt. The development of these deposits in a conduit environment is considered in the following sections. It interesting to note that most other conduit deposits (Kabanga, Voisey's Bay etc.) exhibit the same relationship of net-textured sulphides in the lower units of the intrusion and a massive sulphide body near the bottom or in the floor underlying the intrusion.

9.3.2 Conduit model

It has been noted that a common trigger for the formation of sulphide deposits in conduit settings is the interaction between the intruding magma and the wall rock (Arndt, 2005; Arndt et al., 2005). Various physical properties influence the way in which magma will interact with crustal rocks, and these may be summarized as:

a) Density (the less dense the magma the further it can ascend),

b) Viscosity (magma with a low viscosity can thermally erode and assimilate wall rock faster),

c) Temperature (high temperatures enhance the extent of interaction)

d) Volatile content (Arndt et al., 2005)

e) High magma flux coupled with a turbulent flow regime

Staging chambers and conduits will usually develop at junctures where the crustal density drops, such as at an Archean granite – sedimentary basin contact (Ernest and Buchan, 1997; Arndt, 2005; Arndt et al., 2005). The upward migration of the magma will be influenced and guided by structures and the stresses present in the affected crust (Arndt, 2005). The

intersection between the magma and horizontally layered sedimentary strata may lead to the formation of either horizontal intrusions or sills (Arndt, 2005). In layer-parallel sills, magma flow may be rapid and even turbulent (Arndt, 2005). This type of flow will result in thermo-mechanical erosion and increased assimilation of wall rock. Arndt et al. (2005) stated that the best sulphide ore deposits forms when a highly S-undersaturated magma assimilates S-bearing wall rocks in the upper part of a volcano-sedimentary basin.

In sedimentary sequences, at shallow levels, the magma and wall temperature levels will be lower. If the magma flows through an easily fusible, S-rich rock stratum, the amount of assimilation may increase and a magmatic sulphide deposit may form (Arndt, 2005). In thicker parts of the sill, the flow rate will decrease, possibly leading to the sedimentation of the transported sulphides (Arndt, 2005).

The precipitation of sulphides in dynamic conduit systems owing to crustal contamination are suggested for Noril'sk and Talnakh (Li et al., 2003; Arndt et al., 2003; Arndt, 2005) and Voisey's Bay (Li et al., 2001).. In general, it is suggested that sulphide segregation in this deposit occurred in an open system where sulphur was introduced via circulating fluids that transported sulphur from the underlying evaporate-bearing sedimentary sequence or from the gneissic basement. The heat of the intrusion initiated fluid-flow in the crust, and the interaction of hydrothermal fluids and sediments may have led to the formation of sulphur-bearing brines. The sulphates were leached by the hydrothermal fluids and diffusive transfer of such S-rich material to the magma via the hydrothermal fluid occurred. The resulting immiscible sulphide liquid, which segregated due to the contamination, settled down in the wider parts of the conduit, while the magma continued to flow through the conduit. Successive pulses of new chalcophile- undepleted magma entered the conduit, which reacted with the sulphides already present and upgrading the sulphides with chalcophile elements as well as displacing much of the earlier magma in the conduit. In an open system the magma may leave the early sulphides in the conduit as it continues to travel to higher levels. Pulsed flow of magma may also result in the remobilization and redeposition of sulphide-crystal mixtures.

Disseminated sulphides will form if simultaneous cotectic crystallization of silicate and liquidation of sulphide takes place in the system (Naldrett, 1981). It is suggested (d'Ars et al., 2001) that the sulphide droplets grow during transport. This occurs due to cooling of the magma, which decreases sulphide solubility and crystallization, and reduces the volume of the silicate liquid. The assimilation of wall rock and the large interfacial tension of sulfide droplets have the effect of making coalescence unlikely during transport. The sulphides which segregate later in the magmatic process are likely to nucleate on pre-existing sulphide droplets, which will continue to grow until they become too large to transport (d'Ars et al., 2001). In a conduit, these disseminated sulphide droplets may become trapped upstream of irregularities or concentrated in the widening part of the conduit (Maier et al., 2001; d'Ars et al., 2001) or in depressions or riffles in the floor of the flow (d'Ars et al., 2001). The droplets of proto-ore will be remobilized and interact with the intruding surges of fertile magma, upgrading their metal content (Maier et al., 2001, Arndt et al., 2005). Droplets of non-coalesced sulphide have a large surface area/volume ratio and will effectively scavenge the chalcophile elements (Ni and PGE) from the flowing magma (d'Ars et al., 2001; Arndt et al., 2005).

9.3.3 Petrogenetic implications for the Uitkomst Complex

The formation of a massive sulphide deposit may result when the immiscible sulphide liquid has segregated and the sulphide droplets, initially dispersed throughout the magma, coalesce (Naldrett, 1981). In order to form a massive sulphide deposit, the sulphide droplets has to be locally concentrated without significant dilution due to silicate crystallization (Naldrett, 1981). This means that the segregation process has to occur extensively and quickly, during a period where little to no crystallization of silicate minerals is taking place (Naldrett, 1981). It is also reported by Arndt et al. (2005) that massive ores or ore-breccia locally transgresses their host rocks in a position near the base of the host intrusion. It is suggested that in this situation, the ore was injected as separate pulses of massive liquid sulphide or as a breccia rich in sulphide. In a conduit, the low viscosity of the host magma may allow the rapid

transformation of accumulated sulphide droplets into a massive sulphide layer, following deposition (d'Ars et al., 2001).

The process for the formation of a massive deposit is not clear, but it is suggested that either deformation along a fault or possibly the collapse by the roof of a magmatic body may expel the accumulated sulphide and a mixture of silicate liquid and cumulus mineral along with wall rock fragments from depth (Arndt et al, 2005). Alternatively the transgressive relationship may be due to mobilization of molted sulphide melts during a period of structural adjustment around the host intrusion (Arndt et al., 2005). The process envisaged by Hornsey (1999) for the Uitkomst Complex is discussed in section 2.2.1., but can be briefly summarised as being the result of a dense cloud of sulphide droplets that were able to penetrate into the basement rock underlying the main intrusion.

The Main Mineralized Zone (MMZ), hosted in the LHZBG Unit, is by far the most significant ore body in the Uitkomst Complex. Mineralization in this ore body includes net-textured mineralization located in the wehrlite layers. Similar mineralization has also been observed in the Kabanga intrusion (Evans et al., 1999), where the net-textured sulphides are seen to be representative of the accumulation of olivine and pyroxene together with immiscible sulphide liquid in a magma chamber or conduit (Evans et al., 1999). Evans et al., (1999) proposed that the accumulation was influenced by gravity and that the strata-bound sulphide bodies represent stratigraphically stacked units. Net-textured sulphides are also developed in the Jinchaun deposit, suggested to represent a deformed magmatic conduit (Lehmann et al. (2007). Barnes et al. (2001) suggested that sulphide droplets may settle out of the magma along with olivine crystals. The result would be an accumulation of olivine crystals with interstitial sulphide liquid.

It is suggested here that the hybrid rocks within the LHZBG Unit of the Uitkomst Complex represent the assimilation product after the reaction between the initial magma and the dolomite country rock. This is confirmed by the presence of less primitive diopside (depleted in Cr-content relative to diopside from the wehrlite layers) and metamorphic

textures. The wehrlite layers in the same unit with more primitive diopside (richer in Cr-content relative to the main LHZBG) and olivine represents fresh magma pulses that escaped the assimilation reaction. The presence of plagioclase in the wehrlite layers also suggests that the magma responsible for the development of these layers were of a slightly different composition that the surrounding host rock. The net-textured sulphides would also have only been able to form if it segregated from a melt. It is suggested here that olivine segregated from the melt first. Assimilation of dolomite triggered significant sulphide segregation from the melt to create the net-textures. Continued assimilation of dolomite led to the formation of a hybrid melt that led to the formation of the diopside rich mush that settled on top of the wehrlite layers. The transition of the composition from a magmatic phase to a hybrid phase may have been rapid as the contact between the wehrlite layers and the host rock is always sharp and no scouring of the top of the wehrlite layers is observed.

9.4. Assimilation

9.4.1 Assimilation models

An investigation of the effect the assimilation of the dolomitic country rock had on the Platreef led Gain and Mostert (1982) to propose a model for assimilation. In this model, dolomite rafts assimilated into the Platreef initially suffered prograde metamorphism, releasing CO_2, H_2O and probably S into the surrounding magma. The CO_2 was absorbed more readily than H_2O because the P_{H2O} of the Bushveld magma prevented large-scale addition. As a result, H_2O remained confined in the aureole around the xenoliths, changing the physiochemical parameters to favour precipitation of sulphides. Serpentinization and other retrograde metamorphic processes occurring in the xenoliths lowered the temperature within the xenoliths and immediate surroundings. Contributions of sedimentary sulphur to the cooling magma are derived by dissolution of evaporitic layers of anhydrite and disseminated iron-sulphides in the dolomite xenoliths. Some of the xenoliths are enclosed in an alteration halo of up to 20 m in width, while others are broken up. The sulphides were also affected by the retro-metamorphic processes, with magnetite replacing some of the grains. Erratic variations in PGE content at different localities in the serpentine zone may be due to post-consolidation processes that led to the redistribution of the PGE's. The

feldspathic pyroxenites at the bottom of the Platreef might have extracted sufficient PGE's, even if there is modally less sulphur than higher up in the stratigraphy.

This model provides a good analogue to what is seen in the Uitkomst Complex, where development of economic sulphide deposits are limited to the units hosted by dolomite country rock and the development of semi-massive sulphides around xenoliths. The entire economically important units were affected by late-stage retrograde metamorphism in both locations. The distribution of PGE does in both also appear to be the result of low temperature, post-consolidation, metamorphic processes.

Wallmach et al (1989), regarding the occurrence of extreme phase xenoliths in the Eastern Bushveld Complex, proposed the second model discussed here. Extreme phase xenoliths form in environments with a temperature around 1200 ºC. An influx of water into the xenoliths during decarbonation reactions ensured that the partial pressures of the fluid phase within the xenolith was equal to total pressure and the partial pressure of the fluid phase within the surrounding magma was much lower. In this case the H_2O was much more soluble in magma than CO_2. Since the xenoliths were completely enclosed in magma during metamorphism, any H_2O present in the fluid will tend to diffuse out of the xenoliths into the magma, leaving behind a fluid phase enriched in CO_2. Relatively fast heating and concomitant degassing during decarbonation not only result in loss of volume, but also prohibit magmatic fluids from invading the xenoliths. Fluid inclusions in high-grade metamorphic rocks thus contain high concentrations of CO_2 or almost pure CO_2.

The second model may not be applicable to the xenoliths of the Uitkomst Complex. Indications are that the H_2O did not diffuse into the magma, but may have remained in proximity with the xenoliths leading to the observed serpentinization in the LHZBG Unit. Assimilation of carbonate xenoliths have been recorded in the eastern lobe of the Bushveld Complex, e.g. Willemse and Bensch (1964) and Wallmach et al. (1995). However the vast difference in mineralogy and geological setting makes comparison with the Uitkomst Complex impossible.

The third model and most compatible with the inferred conditions in the Uitkomst Complex, is that of the Jinchaun intrusion, China. Lehmann et al., (2007) suggest that during the emplacement of the Jinchuan magmatic deposit, magma was emplaced along a thrust contact between a series of marbles forming the footwall and gneisses and minor marble form the hanging wall. This magma had earlier assimilated a high proportion of granitic material from the lower crust. The northern lowermost contact with marbles is sharp, but undulating and appears to be magmatic in origin. In places the crystal-laden magma invaded the floor rocks, and xenoliths of marble, transformed into diopside-rich rocks, were incorporated into the lowermost part of the intrusion. The chemical data presented by Lehmann et al. (2007), especially the major element and oxygen isotope compositions, provided evidence that the lowermost border of the intrusion assimilated marble. Xenoliths within the intrusion and some marginal rocks along the lower contact are partially to completely decarbonated, with the original mineralogy of the marbles being replaced by diopside and other silicates. This led Lehmann et al. to suggest that during its emplacement, the lowermost part of the intrusion interacted with the floor rocks and that this part of the intrusion was invaded by CO_2-rich fluids released by decarbonatization of the uppermost marbles and of marble xenoliths. These fluids would have percolated up into the crystal mush of the intruding magma.

It is further suggested by Lehmann et al. (2007) that heat from the magma may have partially melted the marble wall rocks or xenoliths, causing blobs of low-density and low-viscosity calcite-rich liquid to rise up through the olivine cumulate mush in the lower part of the intrusion. It is alternatively suggested by Lehmann et al. (2007) that the CO_2-rich fluids released by decarbonatization of the floor rocks and / or by the xenoliths could have percolated up through the cumulate mush. Upon reaching the cumulate-liquid interface, these fluids reacted with the magmatic liquid, thereby increasing its oxygen fugacity and causing sulphide liquid to segregate. If the magma were moving through the intrusion, the carbonate would oxidize and cause sulphide droplets to segregate from a constantly flowing magma stream. This would result in a large volume of sulphide that accumulated at the site

of this interaction. The denser sulphide liquid, relative to the silicate liquid, would percolate down through the crystal mush that formed the upper part of the cumulate pile, to just above the level where the rock was completely solid. The sulphide droplets accumulated at this level to form the net-textured ores that characterize the Jinchuan deposits.

This model has several common points with what is observed in the Uitkomst Complex. Both intrusions are hosted by carbonate country rock that developed a diopside selvage at the bottom of the intrusion. It is also suggested that increased oxygen fugacity, due to the addition of CO_2, led to the development of the economic sulphide deposits. The proposed mechanism of net-texture development may also be applicable to the wehrlite layers of the Uitkomst Complex. The major difference is that the Uitkomst Complex was not subject to severe structural deformation like the Jinchaun intrusion.

9.5. Assimilation characteristics

The assimilation of sedimentary rocks by magma has been described by McBirney (1993). If magma was contaminated by e.g. a shale or dolomite, the added components would be the same as those that would normally enter a crystallizing mineral at the same stage of cooling. Under these conditions the effect of assimilation may be concealed in the way in which the magma responds to the addition of large amounts of these components. As long as the crystal-liquid relationship control the course of differentiation, the major compositional elements of the evolving liquids are constrained to follow a liquid-line of descent that would not deviate from that defined by crystal fractionation.

The principal effect of assimilation of crustal material added to a crystallizing magma would be to change the proportions of the end-members of any crystals forming. The major-element composition of the liquid on the other hand would remain essentially unchanged. For example: if a basaltic magma was contaminated by shale, it would react with the xenolithic material and form more of the already present minerals, such as augite and anorthite. When equilibrium is approached during the process, the effect of country rock addition is absorbed by increased crystallization of minerals that remove the added

components. The liquid would evolve along a path that differs little from the one it would have followed, had assimilation not taken place. Although the proportion of the liquid and crystalline residue will be altered, the magma that erupts at surface would be consistent with normal fractionation. Thus evidence of assimilation would be reflected in the relative volumes of differentiated rocks.

9.5.1 Addition of carbonate rock

The assimilation of limestone or dolomite leads to the reduction of the stability field of olivine in favour of that of clinopyroxene (diopsidic) and orthopyroxene (Tilley and Harwood, 1931). The addition of lime and silica and the removal of oxides results in selective diffusion and enrichment of clinopyroxene in Mg relative to Fe, while the liquid becomes Fe-enriched (Tilley and Harwood, 1931). The addition of CO_2 during assimilation of carbonate rocks results in the decrease of viscosity of the melt and allows free growth of comparatively large crystals (Tilley and Harwood, 1931). Larger, uralized diopside grains have been observed near the contact of xenoliths and in the surrounding hybrid rock within the LHZBG Unit. This may be due to the addition of CO_2, during the assimilation of the country rock dolomite, which causes a decrease in viscosity around the xenolith, which also results in larger growth of diopside grains.

According to Barnes et al. (2005), the main features indicative of carbonate rock assimilation by magma are:

a. The abundance of Ca-rich minerals, such as clinopyroxene. In the Uitkomst Complex clinopyroxene (diopside) is present in the LHZBG and the PCR Units. The amphiboles are also dominated by calcic-amphiboles, suggesting that the diopside grains may have been the precursor mineral that resulted in the actinolite-tremolite after retrograde metamorphism of these units.
b. The evolution of the complex to alkaline compositions. Alkali enrichment is a function of Ca-depletion of melt due to clinopyroxene formation. It is suggested here that this may not be necessarily preserved in a dynamic system such as a magma conduit. Continued influx of fresh magma and assimilation of dolomite country rock would ensure that the melt never became Ca-depleted, even with continued crystallization of diopside.

c. The presence of interstitial calcite in apparent textural equilibrium with igneous silicates. Van Zyl (1996) found in her study that calcite is more prominent in the LHZBG Unit and to a lesser extent in the PCR Unit. She also found that there is a crude correlation between the mineralization and the occurrence of calcite and amphibole. The current investigation also confirms this weak correlation. The presence of calcite in apparent equilibrium with tremolite grains is demonstrated in Figure 3.48.

Barnes et al. (2005) suggest that the effect of assimilation would be pervasive because a calc-silicate contaminant would probably contain hydrous silicates. This would lead to the production of a hydrous, carbonate-rich partial melt. Such a melt would have a low viscosity and would be able to percolate as intergranular melt through the crystallizing mush of mafic magma. This may be demonstrated in the Uitkomst Complex by the actinolite-tremolite mineralization, especially where it has intergrown the interstitial sulphide minerals. The development of quartz-carbonate veins has been discussed earlier in this chapter.

The addition of calcium to the magma will initially be compensated for by the solid-solution of the crystallizing mineral phases (Baker and Black, 1980). Accompanying any solution of country rock (an endothermic reaction) there must be a corresponding crystallization within the magma of, for example, pyroxene. This reaction has the implication that the addition of sedimentary inclusions will add nothing in terms of mineralogy to the primary magma that is not already present in the primary magma (Baker and Black, 1980). The best example of this in the Uitkomst Complex may be the different ranges of diopside mineralization observed in the hybrid rock of the LHZBG Unit and the fassaite-diopside that is associated with xenoliths.

The order of metamorphic transformation of dolomite has been determined by Winkler (1974) to be firstly talc, followed by tremolite and then diopside. This progession is mainly heat driven as CO_2 concentration; fluid pressure and temperature increase simultaneously (Cui et al., 2003). Since tremolite and diopside forming reactions span a wide fluid composition range, these minerals can not be used to constrain the CO_2 concentration in the

system at the time of their formation (Cui et al., 2003). Initially talc has a higher growth rate than tremolite, but futher growth of tremolite eventually consumes the early produced talc. The LHZBG is dominated by tremolite, even though this unit is hosted by dolomite. The presence of dolomite would have led to an increase in the partial pressure of CO_2, leading to the stability of talc and other carbonate minerals. The lack of talc in the LHZBG unit suggests that it was consumed by tremolite. Talc is dominantly developed in the PCR unit, suggesting that conditions of higher CO_2 partial pressures did exist in the intrusion.

It has also been determined that dolomite is only an important reactant if quartz is also present in the original rock (Winkler, 1974). If dolomite is present in excess to the amount required for various reactions, it will persist to exist into higher grades (Winkler, 1974). Thus the mineralogy and the distribution of especially the alteration minerals may be influence by the proximity to the inferred margins of the intrusion (Section 4.5). Dolomite is found mostly in association talc-chlorite and appears to be secondary, but it may represent unconsumed dolomite.

The presence of calcite in siliceous dolomitic sediments is not necessary for thermal metamorphic reactions; the calcite taking part in these reactions has been produced by previous reactions starting with dolomite and quartz only (Winkler, 1974). Any calcite present in excess over the amount necessary for various reactions will also persist into higher metamorphic grades (Winkler, 1974). Calcite in the LHZBG Unit is only observed associated with minerals indicative of low metamorphic grades (section 3.7). Magnesite in siliceous dolomite is completely consumed in metamorphic reactions (Winkler, 1974). No magnesite was found in the Uitkomst rocks during the current investigation.

9.5.2 Addition of carbon dioxide

During thermal metamorphism of dolomites, it dissociates into periclase (MgO), carbon dioxide gas and calcite ($CaCO_3$) at the high temperature, low pressure conditions of contact metamorphism (Winkler, 1974). Together with water released the CO_2 will be able to leave the system when the overpressure created by the formation of gases within the rocks causes

cracks to form, allowing part of the gas mixture to escape, the fluid pressure is thereby approximately equalized with the load-pressure (Winkler, 1974). The metamorphism of carbonate rocks will release CO_2, but the composition of the fluid phase is not constant as the molecular ratio of H_2O to CO_2 will vary (Winkler, 1974). The presence of H_2O and CO_2 has the effect of reducing the density of the magma (Arndt et al., 2005).

Experimental investigations have shown that the fluid phase must have had a high CO_2 mole fraction at the time of metamorphic reactions. No noticeable dilution of the CO_2-rich fluid took place even though water is liberated in the surrounding rocks. The view was thus advanced by Winkler (1974) that during the relatively short time required for reactions to proceed, the fluid phase remains essentially unchanged.

It is suggested that in very high temperature volcanic-magmatic fluids, with temperatures exceeding 400°C, that Cl is present as HCl and partitions together with CO_2 into vapour phase (Giggenbach, 1989). The relative proportions of CO_2 lost through either (a) boiling or (b) conversion to calcite, depends on the order these processes occur (Giggenbach, 1989). Neutralization of acid fluids through interaction with county rock, causes some of the CO_2 to be deposited as calcite (Giggenbach, 1989). During further rising, or decrease in pressure, the fluids start to boil, leading to the loss of variable, but generally a minor (<2%) fraction of vapour (Giggenbach, 1989). Up to half the CO_2 in a system may be lost in this way (Giggenbach, 1989). It is important to note that CO_2 dissolves solely as carbonate (CO_3^{2-}) groups in basaltic melts, in contrast with the solely molecular form of CO_2 in rhyolites while intermediate melts like andesite will contain both species (Lowenstern, 2001).

An investigation into the reactive flow of a mixed CO_2–H_2O fluid and the progress of calc-silicate reactions in contact metamorphic aureoles by Cui et al. (2003) gives insight into the flow pattern of a CO_2-H_2O fluid in a conduit system with significant calc-silicate xenoliths. It is suggested that CO_2-rich fluids are driven upward thermally in the inner aureole and a CO_2-poor dense fluid flows downward in the outer aureole. The progression of devolatization reactions causes local fluid expulsion what is termed reacting fronts. The

progress of decarbonation reactions may be strongly influenced by the dynamics of the CO_2 transport away from the reaction fronts (Cui et al., 2003).

A water-rich fluid could be derived form either the crystallizing magma or sedimentary rock-pore fluids or as metamorphic water derived from dehydration reactions (Cui et al., 2003). The thermodynamics of each specific fluid may have different impacts on mineral reactions, consequently resulting in differing characteristic distributions of mineral assemblages as demonstrated here in section 4.5 (Cui et al., 2003). The CO_2 may be advected away by the flow of these fluids.

The assimilation of carbonates in a closed system is limited by the solubility of CO_2 (Barnes et al., 2005). The solubility of CO_2 increases with pressure and magma alkalinity (Lowenstern, 2001). This author found experimentally that the solubility of CO_2 increases with pressure at a near linear rate, while the temperature effect on solubility is very small compared to composition and pressure. In comparison, the solubility of CO_2 in natural melt is about an order of magnitude less than that of H_2O and the addition of H_2O to a melt-CO_2 system will decrease the solubility of CO_2 further (Lowenstern, 2001). Solubility of CO_2 depends further on the nature and abundance of various cations, in particular Ca, K, and Na where the effect of Ca^{2+} is most pronounced, followed by K^+, Na^+, Mg^{2+} and Fe^{2+} (Lowenstern, 2001). Carbonate is therefore more soluble in alkaline basalts than tholeiites (Lowenstern, 2001).In contrast CO_2 does not react with a felsic melt as it dissolves in molecular form, resulting in little variation of CO_2 solubility in felsic magmas (Lowenstern, 2001).

Carbonate assimilation reactions will proceed only when heat for assimilation is available in a system where the CO_2-rich fluids are lost as soon as they evolve (Barnes et al., 2005). Cui et al., (2003) suggests that the release of metamorphic fluids is controlled by the progress of mineral reactions. The progress of each reaction is a kinetic process defined by the rates of heat input and the rate of flow of chemically disequilibrium fluid. Other rate-limiting

processes identified include dissolution and growth of minerals and mass transfer into or out of the reacting sites.

The mechanisms suggested for the removal of CO_2 from a system, by Barnes et al. (2005) can be either:

a. CO_2 is removed upward from the complex in a mixed H_2O-CO_2 fluid entrained in, or steaming through the magma.

b. CO_2-rich fluids caused formation of an immiscible carbonate melt, which may be removed by upward migration. Evidence for such a process is found in the fact that it only operates at high temperatures, and that it is not a late stage phenomenon. No calcite veins or carbonatite dikes will be present in such a situation. In the Uitkomst Complex quartz-carbonate veins are present in both the LHZBG and PCR Units and the Units above (pers. comm. H.F.J. Theart, 2008). The siliceous nature of these veins suggests that a late stage siliceous fluid was enriched in carbonate products.

Cui et al. (2003) propose that the CO_2-rich fluid will only prevail in the early stage. Due to the greater buoyancy of the CO_2-rich fluid, upward flow is enhanced and the CO_2 is transported away from the reaction fronts and displaced by H_2O-rich fluid, diluting the CO_2 concentrations further.

If $P_f = P_{CO2} + P_{H2O}$ the equilibrium temperature is not uniquely determined. The greater the mole fraction of CO_2 in the fluid phase, the lower the equilibrium temperature. As a result the equilibrium becomes bivariant in nature (Winkler, 1974). Even if P_f could be estimated on the basis of depth, nothing is known about the probable composition of the fluid phase (Winkler, 1974).

Low grade metamorphic rocks are predicted to record the presence of CO_2-rich fluids where as high grade metamorphic rocks record the presence of CO_2-poor fluids (Cui et al., 2003). The interaction of the magma with the carbonate country rock may lead to high CO_2 partial pressure and Ti mobility (de Waal and Gauert, 1997). The presence of CO_2 and H_2O in

magma is indicated by the presence of phlogopite and magmatic amphibole in the groundmass (Arndt et al., 2005).

Gomwe (2000) concluded that the release of CO_2 caused the increase in oxygen fugacity along with a decrease in FeO resulted in sulfur-supersaturation (due to decreased S-carry capacity) and sulfur-segregation followed by chromite crystallization. Waal (1977) suggested that carbon dioxide and water from metamorphic reactions may serve as agents for the precipitation of sulphide and spinel in mafic magma.

The effect of the CO_2-rich deuteric fluid, as well as the possible direction of fluid flow in the Uitkomst Complex is discussed in section 5.4.

The main influence on the Uitkomst Complex, where sulphide mineralization took place, was the assimilation of Malmani dolomites. Gomwe (2002) found that the sulphides of the mineralized units have δ^{34} S values between -8 and -2 similar to the isotopic signature of the pyrite-bearing shaly intervals in the Malmani dolomites in the Fochville area. In turn the sulphides of the sulphide-poor units have a mantle signature. Gomwe (2002) therefore discards the possibility of the sulphide-rich units being derived from the Timeball Hill shales, which has a δ^{34} S values of between -12 and -18, that is too divergent from the Uitkomst Complex sulphides. In turn the sulphides in the BGAB Unit are compositionally more heterogeneous, with δ^{34} S values between -20 and +2 (Gauert et al., 1996: In Maier et al., 2004) and +0.2 and +2.7 (Li et al., 2002: In Maier et al., 2004). This might be because the rapid cooling of this unit prevented isotopic mixing (Gauert et al., 1996). The sulfur isotope (δ^{34}S) for country rocks around the Uitkomst Intrusion is presented in Table 9.1.

Table 9.1. Sulfur isotope (δ^{34}S) for country rocks around the Uitkomst Intrusion (Li et al., 2002).

Group	Timeball Hill	Penge Iron Formation	Upper ¾ Malmani *	Lower ¼ Malmani*	Black Reef Quartzites
δ^{34}S ($^o/_{oo}$)	-12 to -18	-3 to -6	0 to -8	+3 to +10	Near +3

*For Malmani, all samples from pyrite-bearing shaley intervals, no chert analyses

It has been found that using mass balance calculations and assuming that mixing took place between B1-type magma and dolomite, that only about 10% mass assimilation of dolomite is required to obtain the observed isotope ratio (Gauert et al., 1996; Li et al., 2002). Isotope analyses of oxygen and hydrogen by Sakar et al., (2005) indicate the ranges of δ^{18}O in pyroxene to be 5.3 to 6.3‰ and 5.9 to 6.5‰ for plagioclase in what they term as the "harzburgite unit". A simple two component mixing calculation involving a crustal component (assumed δ^{18}O = 18‰) and magmatic component (δ^{18}O = 6‰) done by them, suggests that 10 to 20% assimilation is required to produce a magma with δ^{18}O values between 7 and 10‰.

In turn Harris et al., (2001) calculated, from oxygen isotope data, that the Platreef assimilated approximately 18% dolomitic material.

Both the sulphide-rich and sulphide-poor units have similar incompatible trace element values, suggesting that the assimilation of external sulfur was not accompanied by significant silicate assimilation, which in turn suggests the assimilation of sulfur took place by means of devolitization that may be associated with the decarbonation of the dolomite country rock (Gomwe, 2002). All of this supports the concept that a degree of carbonate assimilation may have served as a source for the sulphur.

Contamination of the mafic magma with either siliceous crustal -rocks or –sulphides can result in sulphide over-saturation (Maier et al, 2003). The assimilation of S-bearing country rocks or the transfer of S from sulphide mineral-bearing country rock into the magma by

volatiles in response to contact metamorphism may raise the S-content of the mafic magma and lead to S-supersaturation (Maier et al, 2003).

The contrasting S isotopic composition found by Maier et al. (2004) in the sulphides of the ultramafic and mafic rocks of the Uikomst Complex, is interpreted as a result of assimilation of S from different country rocks. The implication is that the BGAB Unit assimilated S from the basal parts of the Malmani dolomites and the Black Reef Quarzites as it has positive δ^{34} S values (Maier et al., 2004). Whereas the overlying ultramafic units could have derived S from the upper portions of the Malmani dolomites preserved in this area and/or Timeball Hill shales that has negative δ^{34} S values (Maier et al., 2004). It was also conceded by Maier, Li and de Waal (2001) that the source of the sulphides was unclear as the Complex is hosted by S-rich and S-poor rocks. This is considered a more likely scenario than isotopic heterogeneity in the original magma source, considering the scale of the Uitkomst Complex (Gauert et al., 1996). It is also considered unlikely that the sulfide isotopes may have been altered by redox reactions and/or concomitant degassing (Gauert et al., 1996), as effective sulphur fractionation is only feasible at very low temperature conditions.

The current investigation supports a scenario where the magmas that formed the Basal Units of the Uitkomst Complex were only able to interact with the dolomite country rock for a limited time, due to the formation of solidification fronts asdiscussed in section 5.5. It is thus suggested that the Malmani dolomites were the principal source of assimilated sulphur, forming the proto-ore.

9.6. Direction of hydrous hydrothermal fluid flow

Baker and Black (1980) suggested that a shallow intrusion may lead to the formation of a circulating hydrothermal system and the formation of hydrous late stage mineral assemblages. Ferry et al. (2002) investigated the direction of fluid flow during contact metamorphism of siliceous carbonate rocks by various intrusions, and came to the following general conclusions. The peak pressures were between 500 and 3 500 bar (2 to 13 km) and

had peak temperatures of between 400 and 750 ˚C. The reactive flow in the systems was found to have a large vertical upward component with a significant horizontal component, directed away from the aureole. This is based in part on the occurrence of reactants and products of decarbonation reactions occurring together in the contact aureole. The occurrence studied indicates arrested retrograde carbonation reactions rather than prograde metamorphism.

Ferry (2000) also suggests that partial equilibrium during retrograde metamorphism (as has been established for the basal units of the Uitkomst Complex) with the preservation of reactants and products may alternatively be interpreted as arrested retrograde reactions. In this case fluid flow must have been in the direction of decreasing temperature as the aureole cooled. The co-existence of reactants and products of a retrograde mineral-fluid reaction is explained by Ferry et al. (2002) as being the result of continues fluid flow as the aureole cools in the same direction as during prograde metamorphism. Fluid flow will thus be in the direction of decreasing temperature, either vertical or horizontal.

The reactive flow of mixed CO_2–H_2O fluids and the progress of calc-silicate reactions in the contact metamorphic aureoles are described by Cui et al. (2003). The CO_2-rich fluids are indicated to be driven upward thermally in the inner aureole and the CO_2-poor dense fluid flows are driven downward in the outer aureole.

An idealized fluid flow regime that operated in the Uitkomst Complex is presented in the final interpretation. Here all the factors that influenced the flow regime are taken into consideration, as well as the effect that this deuteric fluid has on the host rock it moved through.

Ferry et al. (2002) also suggest that the infiltration of meteoric water is controlled by the mechanical properties of the rock. Meteoric-hydrothermal systems will develop in highly fractured competent rocks (e.g. volcanic) where the fracture system will assume hydrostatic pressure and surface water may be drawn downward towards the thermal anomaly created

by the cooling pluton. Carbonate rocks in contrast are more ductile during the period of metamorphism with the result that the fluid flow will be closer to lithostatic pressure. Flow systems near or at lithostatic pressure will not have a significant downward component. However, as the aureole cool, it will pass through the brittle-ductile transition. This may cause the rock to fracture and assume hydrostatic pressure, allowing meteoric water to flow toward the pluton. Channeled fluid flow may take place along bedding, but likely along permeable structures, including dykes, faults, fold hinges and fracture zones.

The mentioned paper does not discuss the mechanical properties of thermally metamorphosed shale. It may however be assumed the fissility of the unaffected shale may allow the infiltration of meteoric water to the contact with the hornfels which forms as a result of thermal metamorphism of shale. This may lead to the entire outer hornfels contact area being subjected to the effects of hydro-chemical processes. The breakdown of the hornfels or increase in permeability of the hornfels may depend on the thickness of the hornfels zone and the physio-chemical properties of the hornfels.

The effect of ground water is also considered. A de-watering study for Pit 3 was undertaken and reported on by Smith and Kotze (2010). It was found that the only potential de-watering problems for Pit 3 are:

- The northwest-southeast trending Pit 3 shear zone
- The north-eastern contact zone with the Transvaal rocks
- Adit Stream fault

As part of the study the depth of the water table to extent from 10 meters to a maximum depth of 60 meters. The confined to semi-confined aquifers that occur in the area are associated with the weathered and fractured rocks. There is also little to no evidence that the upper purely inter-granular aquifer, associated with weathering 20 to 30m deep, yield high volumes of water. The average depth to rest groundwater level is 23m. The majority (73%) of test boreholes indicate a depth to groundwater of between 10 and 30m (Smith and Kotze, 2010). It is therefore suggested here that ground water could not be responsible for the alteration products observed at depth in the study area. It is also suggested here that the coincidence of the higher ground water flow rate, at the north-eastern contact of the

intrusion and the "high talc" is due to the rock types developed prior to weathering to the current level and not as a result of the ground water movement.

Channeled fluid flow along the diabase sill intrusions in the Uitkomst Complex is considered unlikely. The sills show a chill zone along their contacts (Strauss, 1995) and fresh, unaltered mineralogy towards the center of the sill (Theart, Personal communication, 2007).

It is also suggested here that the irregular distribution of both CO_2- and H_2O-rich fluid in the melt may be responsible for the irregular development of secondary minerals such as amphibole, chlorite, serpentine and talc. In locations of higher CO_2-fluids, the partial pressure increase would stabilize the development of talc, replacing the precursor primary magmatic minerals. It is suggested that the CO_2-rich fluid may have been more acidic, aiding the dissolution of the precursor magmatic minerals. The locations where the fluid was dominated by a H_2O-rich fluid the precursor magmatic minerals would suffer retrograde metamorphism.

The fluid composition would also influence the bulk composition of the rock through which it migrated. The inconsistent effect of mobilization of elements was demonstrated with the isocon diagrams. No specific circulation regime could be established. The only elements that clearly show the effect of being transported and deposited by a CO_2-rich fluid is U and Th that is depleted in the narrow part of the intrusion and enriched in the broader part of the intrusion

It is suggested here that upward migration of the CO_2-rich fluid was constrained by the development of a skarn selvage along the contact of the intrusion and later emplacement of the MCR unit. This resulted in the situation where the CO_2-partial pressure in the PCR unit would have been higher than in the underlying LHZBG unit. Still, no specific lateral or vertical fluid component regime existed. Later cooling of the system led to a H_2O-

dominated fluid regime. This resulted in preferential development of chlorite along the center of the intrusion. These ideas are further expanded on in the following section.

9.7 Solidification fronts

Following an investigation to determine the type of magmatism and the type of host-rock interaction taking place in the magma chambers of Vesuvius, it was inferred that different solidification fronts may exist in a magma chamber (Fulignati et al, 2004). A solidification front may be described a feature that develop due to the assimilation of carbonate wall rocks by the magma and consequent exsolution of CO_2-rich vapour and complex melts from the contaminated magma that reacted with the carbonate wall rocks to form skarns (Gilg et al., 2001). At the reaction front the reactants and products will coexist along the flow path only at a sharp interface, provided the hydrodynamic dispersion is negligible and that reaction kinetics are not excessively sluggish (Ferry, 2002). It should be noted that the Vesuvian volcanism is rhyolitic, thus lower temperatures and higher viscosity than anticipated in a mafic to ultramafic magma.

Three types of skarns may form due to reaction between dolomitic host-rock and magma, as considered by Fulignati et al (2004), magmatic-, endo- and exoskarn.

Magmatic Skarn: this is the main type of solidification front that may form in a magma chamber (Fulignati et al, 2004). The strong crystallization occurring in this zone supplies energy for endothermic decarbonation reactions that destroy wall rocks, increasing the porosity and enhancing infiltration of melts (Fulignati et al, 2004). Addition of CaO and MgO to differentiated melt has the effect of lowering viscosity to about 30 and even 7 Pa.s and thus enhancing the mobility and infiltration of melts into the host-rocks (Fulignati et al, 2004).

Hulley (2005) found that the major and trace elements show two distinct patterns, during the calc-silicate xenoliths' interaction with magma in the Uitkomst Complex. It was found that the elements: Al, Fe, Cr, Ti, Si, As, Co, Cu, S, Ni, Ba, Zn, V showed increasing

concentrations near the contact of the xenolith relative to the centre. This would seem to indicate the infiltration of these elements into the xenolith from the magma. It was found that the elements: Ca, K, Mg, Na_2O, P, C, Sr and Mn show a decrease in concentration from the contact with the xenolith to the ultramafic rock. This would seem to suggest that these elements were lost from the xenolith to the magma.
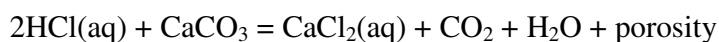
The viscosity of magma is influenced by the addition or removal of certain elements in magma (Hall, 1996). Addition of Si, Al and K contribute to a high viscosity, while Na, Ca, Fe and Mg contribute to a low viscosity (Hall, 1996). The normal viscosity of basalt melt at 1200ºC is $10-10^2$ Pa.s (Hall, 1996). The viscosity of basalt on eruption is 10^2-10^4 Pa.s (Hall, 1996).

During the formation of Endo- and Exoskarn, the circulation of a hypersaline fluid phase in the peripheral upper parts of the more evolved magma chamber induces carbonate melting through sintectic reactions (Fulignati et al, 2004). This complex fluid (Na-K-Ca-carbonate-chloride-rich hydrosaline melt) metasomatizes the rigid crust (Fulignati et al, 2004).

The expected reactions are:

$FeCl_2(aq) + CaCO_3 + SiO_2(aq) + H2O = CaFeSi_2O_6 + CO_2 + 2HCl(aq)$

        Calcite   hedenbergite
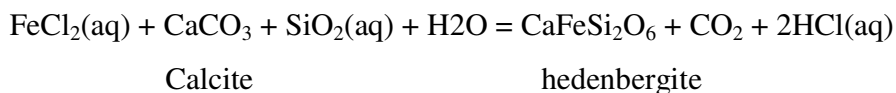
The HCl(aq) further reacts with the remaining calcite as follow:

$2HCl(aq) + CaCO_3 = CaCl_2(aq) + CO_2 + H_2O + porosity$

All of the above evidence seems to indicate that the interaction between the magma and the xenoliths, along with the exchange of elements, lead to the formation of solidification fronts in the magma conduit, lowering of viscosity, increasing the efficiency of mixing.

Del More (2001) suggests that the endoskarn, the solidification front and skarn shell in the Vesuvius chamber effectively isolate the interior from new inputs of contaminants, as mass

exchange occurs at the boundary between the crystallizing magma and the wall rocks. It is reported by Cui et al. (2003) that during the process of devolitization, local fluid expulsion takes place at the reaction fronts. The presence of reaction rims (pegmatoidal veins) at the contact between calc-silicate xenoliths and the magma, consisting of retrograde metamorphic minerals, may indicate the remobilization of fluids towards the margins of the xenolith (Hulley, 2005).

Hulley (2005) states that hydrothermal alteration and fluid flux in the calc-silicate xenoliths are proven by the disequilibrium of S-isotopes in sulphide minerals and the in the oxygen and carbon isotopic fractionation. Owens (2000) also suggested that the clinopyroxene reaction zones, observed in his study, once formed, would have served as an effective barrier to diffusion. Thus, any contamination effects (isotopic contamination of magma) would have been achieved prior to reaction zone formation. This may have the implication that in the area upstream from the reaction front the decarbonation reactions would have gone to completion and downstream from the reaction front no further reaction/interaction may take place (Ferry et al., 2002).

In the Uitkomst Complex the initial interaction between the intruding mafic magma and the dolomitic country rock would have led to the release of a CO_2-rich fluid and a hydrous fluid enriched in elements, such as Ca, Mg, Fe and Al. The CO_2-rich fluid may have brought about the physio-chemical conditions (increased oxygen fugacity, etc.) needed to segregate sulphide from the magmatic melt. At the same time however, the dolomitic rocks would be affected by thermal alteration leading to the formation of skarn minerals. The extensive development of diopside, a more refractory mineral, would start to decrease the amount of interaction taking place between the remaining xenolith and the intruding mafic magma. After the collapse of the xenolith, with resultant expulsion of calcite melt, the contamination effect of the xenolith would be significantly decreased. If the development of a skarn consisting of refractory minerals is extensive enough, it may stop the influx of more magma into that specific stratigraphic position.

This decrease in interaction between the xenoliths and intruding magma may lead to a decrease in the amount of CO_2-rich fluids being released into the lower parts of the conduit. As the CO_2-rich fluids are migrated upward, the hydrous fluid may remain in the lower parts of the conduit, and become dominant. The addition of the CO_2-rich fluid, enriched in elements that favour an increase in viscosity, would also affect the magmatic melt, probably increasing the ability to transport xenoliths out of the system, in the upper parts of the conduit.

The hydrous fluid, which remains in the system, may now start affecting the precursor minerals. The hydrous fluid led to the serpentinization of the remaining xenoliths and the adjacent hybrid rock. This caused wide-spread retrograde metamorphism and late-stage hydrothermal alteration products being formed. Late-stage fluids may also have intruded the xenoliths, affecting the original skarn minerals. As the system cooled further, the fluid system operating in the system, may have become completely hydrous dominated. This cooler hydrothermal fluid may have led to the amphibole-chlorite assemblages forming. The hydrothermal alteration system may have been strongest in the central parts of the Complex, away from the margins, as the occurrence of chlorite is dominant in the central parts of the Complex. This may have been due to a longer retention of heat, required for driving the system, and not suffering the moderating effect of the cooling margins or being able to escape from the system.

The skarnification of the country rocks along the margins of the Complex would also have resulted in the formation of a solidification front along the edges of the Complex. This may have served a containment mechanism, inhibiting interaction between the fluids in the conduit and infiltration of meteoric water, especially after cooling of the Complex. It would also contain the fluids in the conduit, possibly aiding in the intense alteration of the Basal Units.

The effect of the solidification fronts along with the fluid flow regime and the effect this had on the development of the Uitkomst Complex are further discussed in the interpretation section.

9.8 Effect of county rock on the shape of the Complex

The Uitkomst Complex is interpreted as being a conduit feeding into an unexposed or eroded layered intrusion (Gauert et al., 1995; Maier et al., 2004). This is based on the tabular shape, the large proportions of sulfide and chromite relative to silicate, and the absence of fractionation trends in the conduit part of the ultramafic units (Gauert et al., 1995; Li et al., 2002; Maier et al., 2004). Apart from indications that the Uitkomst Complex represents a magma conduit, the nature of the surrounding country rock undoubtedly also had an effect on the shape of the intrusion. As noted in the section on the country rock, the main lithologies intruded by the Complex are the Malmani dolomites, with interstitial layers of sulphidic shale and chert, and Timeball Hill graphitic shales with minor iron stones and quartzites.

The "anvil-shape" geometry of the Uitkomst Complex has been noted before (van Zyl, 1996; Gauert et al., 1996; de Waal and Gauert., 1997; de Waal et al., 2001; Li et al., 2002; Maier et al., 2004). The "foot" of the anvil is formed by the central trough, the sides of the central trough have been found to be formed by a very irregular contact, where sedimentary sidewall rocks protrude into the complex (Theart, 2000). The transition of the "foot" to the "head" of the anvil is controlled by a bench that is formed by the Bevets Conglomerate Member of the Rooihoogte Formation (Theart, 2000). The "head" of the anvil is formed where the Uitkomst Complex stoped out large volumes of the Timeball Hill shales above the central trough feature (Theart, 2000).

Gauert et al., (1996) suggested that the shape of the intrusion was controlled by a major fracture and fault system which strikes in a northwesternly direction. de Waal et al., (2001) postulated that the tabular shape is the result of the intersection of a near-horizontal bedding fault-plane with an existing vertical fracture zone under tension conditions.

Due to the thermal metamorphism of dolomites and limestones to skarns during intrusion of mafic bodies, the composition of the carbonate rocks change. It has been found that the intrusion of siliceous fluid into limestone ordinarily result in the formation of Ca-rich minerals such as wollastonite and idocrase (Park and MacDiarmid, 1975). The intrusion of the same fluids in dolomites results in Mg-rich minerals such as serpentine and diopside (Park and MacDiarmid, 1975). Gauert (1998) suggested that the tabular shape of the lower part of the intrusion might be due to the dolomites being more resistive due to its massive nature. During the present investigation it was found that the "clean" xenoliths, consisting of pyroxenes, amphibole, chlorite and carbonate, appear to be more resistive to further assimilation. Owens (2000) also suggests that the formation of a clinopyroxene reaction zone effectively inhibit any further reaction of the carbonate rock with the intruding magma.

It is suggested that the intrusion of the mafic magma reacted with the dolomitic country rock until a sufficiently thick pyroxenite solidification front is formed that would prevent any further interaction and assimilation of the dolomite by the magma. This feature is best explained as a combination of the structural controls, determining the orientation of the intrusion, along with the properties of the skarn preventing large scale thermo-chemical erosion of the country rock. Due to the more evolved nature of the basal gabbroic magma, there was not enough Mg and Fe present in the magma to accommodate the addition of Ca, and resulting formation of Ca-rich minerals. Thus no solidification front was formed, causing the greater lateral intrusion of the BGAB Unit into the dolomites than seen in the overlying LHZBG Unit.

The Uitkomst Complex has been found to be broader, forming the head of the "anvil", where it intersects the Timeball Hill shales. This part of the Uitkomst Complex might be compared to the Kabanga conduit that also intruded into shales. Evans et al., (2000) interpret the internal layering of the Kabanga intrusion to be broadly conformable with the sedimentary bedding structure due to utilization by the intrusion of earlier layer-parallel structures within the basin as the planes of intrusion. Alternatively, since the body has been

emplaced predominantly within shales, adjacent to quartzite units, the layering may be due to the more fissile nature of the shales.

The fact that the MHZBG Unit is laterally more extensive than the underlying LHZBG and PCR Units, led Li et al., (2002) to suggest that the Timeball Hillshale and minor Rooihoogte sediments were more amenable to thermal-mechanical-chemical erosion than the underlying dolomites. Alternatively it is suggested that the fissile nature of the shales might enhance the emplacement and expansion of the magma conduit relative to the dolomite-skarn and quartzite, leading to the "anvil-head" of the intrusion.

The main elements found in shale are Si and Al. Partial or total melting of shale may occur and the Al-content of the magma would increase. The addition of these elements (Si and Al) may not be as easily accommodated by the mafic magma as Mg and Ca. It is also suggested that the skarn products that forms due to thermal metamorphism of shale is not as resistant to thermal erosion and will continue to be broken down and may be completely assimilated by the intruding magma. This may prevent the formation of a reaction front and continual thermal-mechanical-chemical erosion will continue to advance into the side walls of the shale country rock. The lack of xenoliths in the upper part of the conduit stage, as reflected in the upper parts of the LHZBG and the PCR Units, may also indicate that all xenoliths was flushed out of the conduit system by the magma pulses, removing evidence of interaction between the magma and shale country rock.

It was suggested by Chandrasekharam et al., (2000) that magma of gabbroic-basaltic composition would on contamination with shaley sediments form a norite containing anorthite-rich plagioclase. Maier et al., 2004 proposes that the UGN Unit rocks represent roof crystallization from the initial magma pulses. Further investigation is needed to confirm this interpretation.

Wallmach (1988) suggested that the quartzite and calc-silicate xenoliths in the Eastern Bushveld Complex, only survived due to the more refractory nature of these rock. It is

suggested that the pelitic and greywacke rocks were melted and assimilated due to the minerals and mineral assemblages of these rocks having much lower melting points.

It is suggested here that the LHZBG Unit formed a solidification front at the end of its intrusion, from which only late stage CO_2-rich acidic hydrothermal fluids may escape upwards resulting in a secondary alteration assemblages in the PCR Unit, under the MCR Unit layer. The formation of which effectively sealed the lower part of the conduit and forced the new influx of magma to intrude and run through a larger conduit stoped out of the Timeball Hill shale.