7. Evolution of the Bushveld granites.

7.1. Differentiation trends and mechanisms.

The geochemical study suggests that the Nebo Granite and the Klipkloof Granite are closely related and it appears that the latter is an apical phase of the former. Most of the variation diagrams presented indicate that the Klipkloof Granite forms an extension of the Nebo Granite differentiation trend although there are noteable differences in their TiO_2 and Al_2O_3 contents. The difference in TiO_2 values is probably due to the chloritization of biotite, whereas the higher Al_2O_3 values may have resulted from an increase in volatile pressure.

Post-magmatic changes have played a major role in the geochemical signature of the Klipkloof Granite. These include late hydrothermal alteration and albitization of the feldspars. Albitization had a major effect on the trace element geochemistry of the rock, wherein trace elements normally present in perthite (Ba) were lost in solution.

The granites of the Groblersdal area are not as altered as the granites of the Zaaiplaats area, which is evident from Figure 6.5 and 6.6. The first differentiates of Nebo Granite in the two areas have the same composition. Only the later differentiates are different in the respect that the rubidium content is higher in the granites of the Zaaiplaats area. The albitized Klipkloof Granites have similar rubidium contents compared with the Lease Granite of the Zaaiplaats area. It is well known that a high degree of alteration took place at Zaaiplaats (Strydom, 1983 and Coetzee, 1984), which is also reflected in the tin mineralization in the area. The plots of Sr against Rb and Ba against Rb are therefore a good exploration tool, because an increase in rubidium due to late-stage alteration, could be associated with mineralization. If, on the other hand, the rubidium content in the rocks remains constant after an initial increase during differentiation, the possibility for mineralization seems low. The Lebowa Granite Suite in the study area would therefore be unfavourable for tin mineralization because no increase in rubidium took place. Only the albitized Klipkloof Granite could have some potential, but it was mentioned earlier that the economically significant roof zone of this altered granite was lost by erosion.

The majority of the diagrams used indicate that the Lebowa Granite Suite, the Stavoren Granophyre and Rooiberg Felsite could be related. Whether there is a definite comagmatic relationship, or whether the relationship is only due to the fact that these granitic rocks are derived from a common zone of source-region melting, is debateable.

7.2. The "A-type granite" characteristics of the Bushveld granites.

Many contributions to the classification of granitic rocks exist in the literature (e.g. Tuttle and Bowen, 1958; Streckeisen, 1973; Chappel and White, 1974; Hine et al., 1978; Ishihara, 1981; Collins et al., 1982; Lameyre and Bowden, 1982; White and Chappel, 1982).

If the properties of I-type, S-type (Chappel and White, 1974) and A-type (Collins et al., 1982) granites are compared with the properties of the Bushveld Granites it appears that the latter represent typical A-type granites.

The following properties of the granites of the Lebowa Granite Suite correspond to those of A-type granites (Collins et al., 1982):

1) The abundance of MgO is very low and the concentration of CaO in undifferentiated Nebo Granites is only 1,5 per cent. The fluorite content of the later

differentiates is generally high.

2) Concentrations of V,Ni,Co and Cr are low, whereas the content of highly charged elements, e.g. Nb,Ga,Y,REE,U and Th, are high (Fig.7.1).
3) The Ga/Al_2O_3 ratio is always high, especially in the Klipkloof Granite (Fig.7.2).
4) According to the Shand diagram (Fig.7.3) the composition of the Bushveld Granite varies between metaluminous and peralkaline. The proposed field of A-type granites coincides with a field defined by Loiselle and Wones (in press).
5) The magma was dry, as evidenced by late precipitation of amphibole and biotite.
6) The An content of plagioclase is low with values between An-10 and An-0,8 (Appendix 1).
7) High Zr content and peralkaline affinities.
8) CIPW normative alkali metasilicate or acmite (Appendix 2).
9) Bushveld Granites are hypersolvus granites.

It therefore appears that the Nebo and Klipkloof Granites have the same characteristics as the A-type granites of Collins et al. (1982). In particular, the high Ga content and Ga/Al_2O_3 ratio are in accordance with those of A-type granites.

The high Ga/Al_2O_3 ratios are considered by Collins et al. (1982) to be due to preferential retention of An-rich plagioclase in the source region during partial melting. The Ga-oxygen bond is longer than the Al-oxygen bond, which suggests that Ga will be slightly excluded relative to Al in earlier products of magmatic crystallization and will tend to concentrate in later products of differentiation and residual minerals (Burton, 1972). This explains why the Ga content increases in the Lebowa Granite Suite from

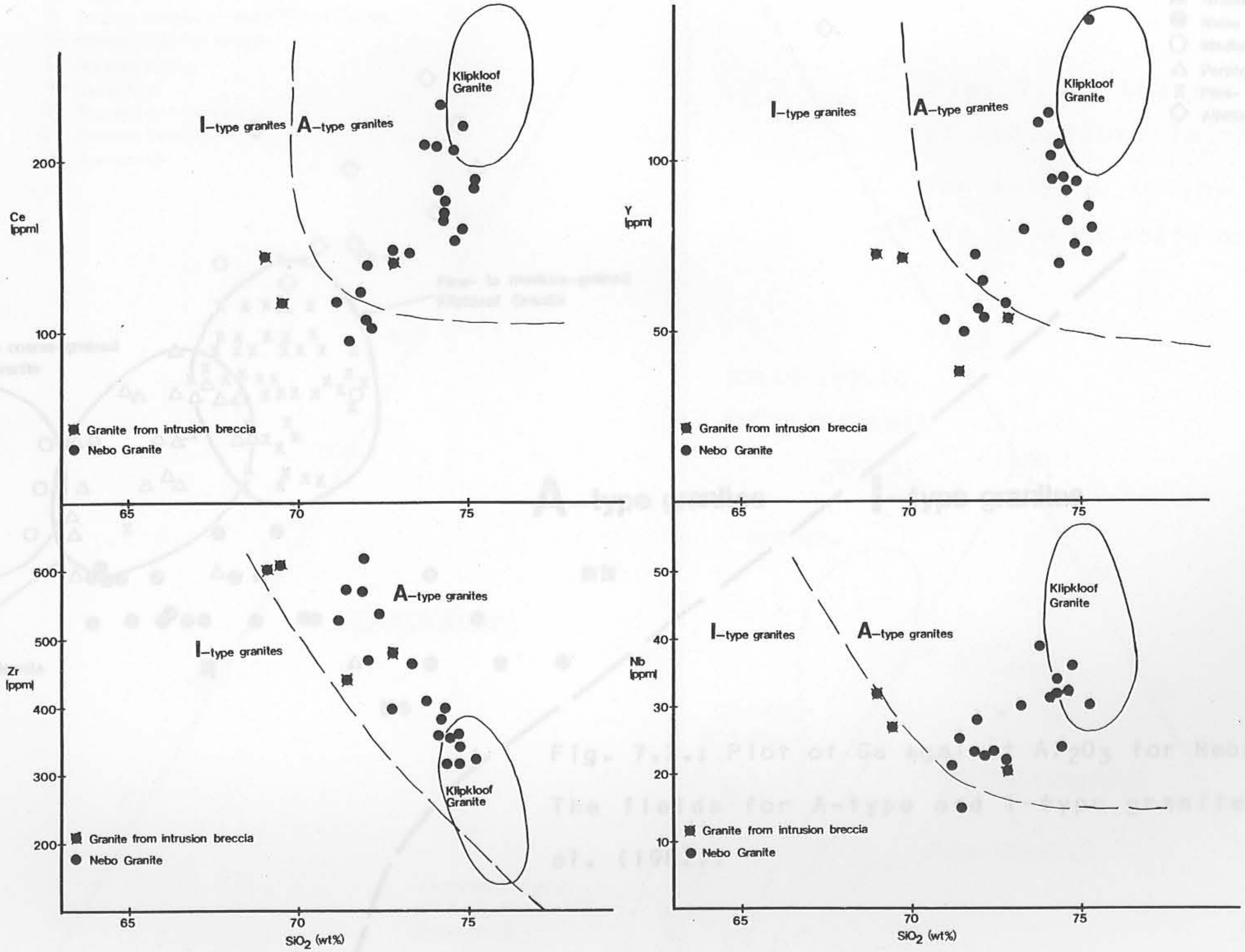

Fig. 7.1.: Harker diagrams for Ce, Y, Zr and Nb concentration in Nebo and Klipkloof Granite. The fields for A-type and I-type granites are from Collins et al. (1982).

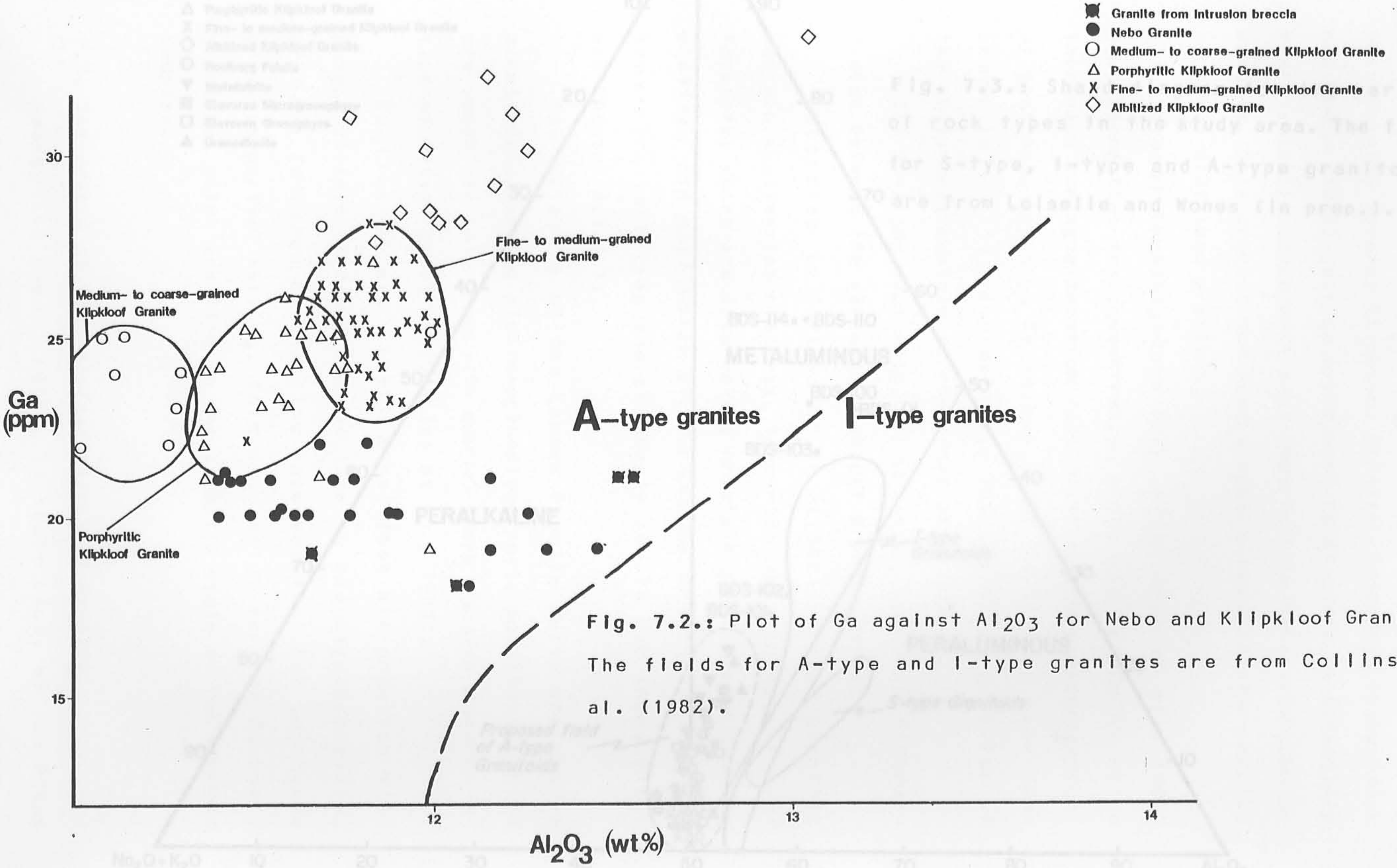

Fig. 7.2.: Plot of Ga against Al_2O_3 for Nebo and Klipkloof Granite. The fields for A-type and I-type granites are from Collins et al. (1982).

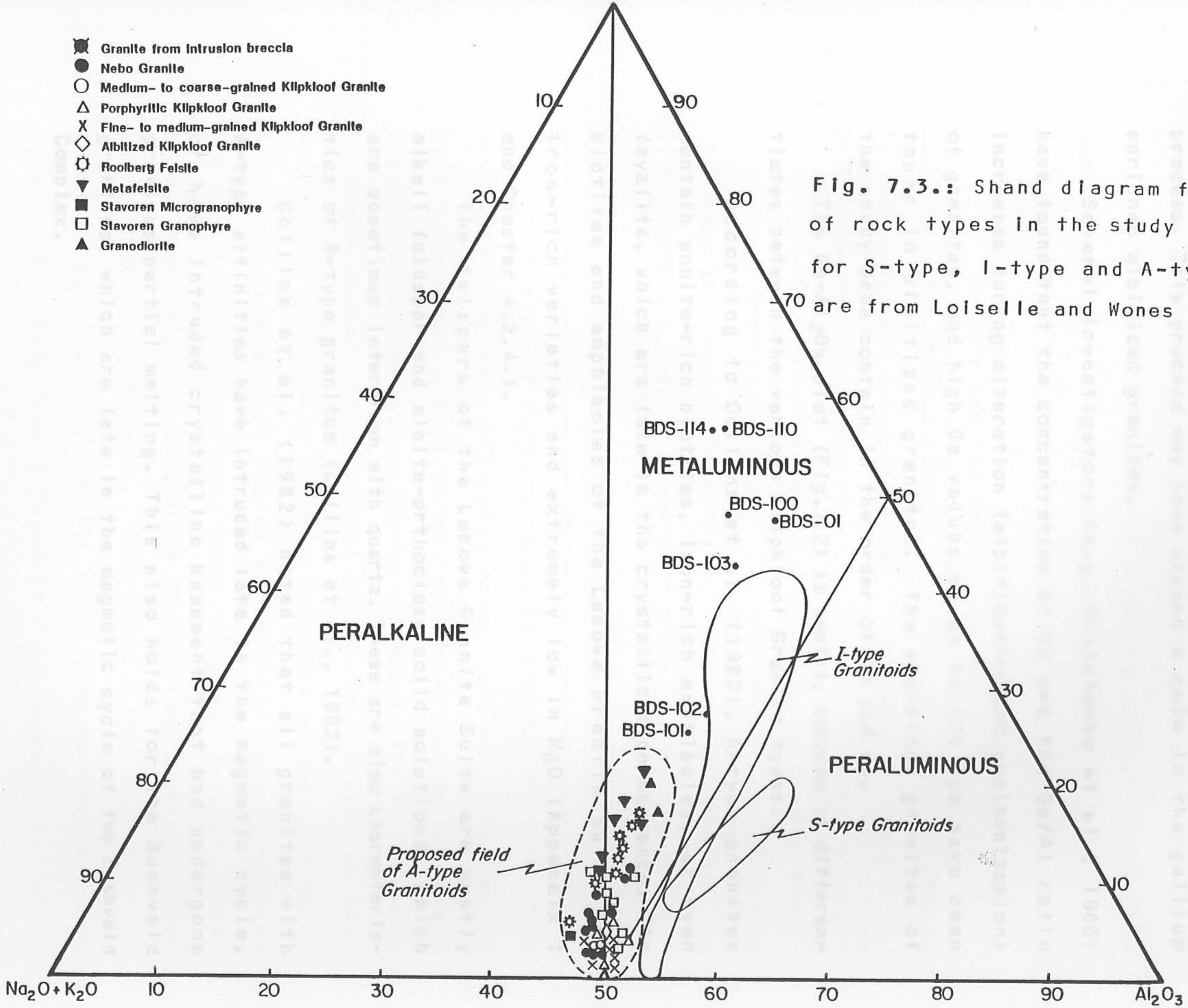

Fig. 7.3.: Shand diagram for the variety of rock types in the study area. The fields for S-type, I-type and A-type granitoids are from Loiselle and Wones (in prep.).

Nebo Granite towards Klipkloof Granite. According to Borisenok and Saukov (1960) gallium enrichment takes place in situations where volatile components were important in the crystallization process. This process may have played a role in the gallium enriched albitized granites.

Several investigators (e.g. Mishchenko et al., 1966) have found that the concentration of Ga and the Ga/Al ratio increases during alteration (albitization and greisenization) of granites, and high Ga values of up to 170 ppm have been found in albitized granites. The albitized granites of the study area contain in the order of 30 ppm Ga.

The Ga-Al_2O_3 plot (Fig.7.2) is useful, because it differentiates between the various Klipkloof Granite types.

According to Collins et al. (1982), A-type granites contain annite-rich biotites, iron-rich amphiboles, or even fayalite, which are late in the crystallization sequence. The biotites and amphiboles of the Lebowa Granite Suite are iron-rich varieties and extremely low in MgO (Appendix 1 and Chapter 4.2.4.).

The felspars of the Lebowa Granite Suite are mostly alkali feldspar and albite-orthoclase solid solutions, which are sometimes intergrown with quartz. These are also characteristics of A-type granites (Collins et al., 1982).

Collins et al. (1982) noted that all granites with A-type affinities have intruded late in the magmatic cycle, or have intruded crystalline basement that had undergone previous partial melting. This also holds for the Bushveld granites, which are late in the magmatic cycle of the Bushveld Complex.

7.3. The origin of fine-grained Klipkloof Granite.

Hawley and Wobus (1977), in their study of the Pikes Peak and Redskin Granites of Colorado, found a decrease in grain size from the oldest to the youngest granite. Their classification bears close comparison to that of the granites of the study area (Table 7.1.). The Pikes Peak Granite is considered to represent an A-type granite suite (Collins et al., 1982) and the present study has shown that the Nebo Granite is also an A-type granite suite.

Table 7.1. Comparison between the Pikes Peak and Redskin Granite and the Nebo and Klipkloof Granite.

Pikes Peak and Redskin Granite	Nebo and Klipkloof Granite
1) Coarse-grained subequigranular Pikes Peak Granite. 2) Coarse-grained porphyritic Pikes Peak Granite. 3) Medium- to coarse-grained Pikes Peak Granite.	Coarse-grained equigranular Nebo Granite in sheet-like body. Decrease in grain size from bottom to top in the granite sheet.
4) Granular Redskin Granite.	Medium- to coarse-grained Klipkloof Granite.
5) Porphyritic Redskin Granite.	Porphyritic Klipkloof Granite.
6) Fine-grained Redskin Granite. 7) Granite aplite (Redskin).	Fine- to medium-grained Klipkloof Granite consisting of sills and aplite dykes.

Grain size of igneous rocks is controlled by the rate of crystallization, diffusion rate, rate of formation of crystal nuclei, viscosity of the crystallizing magma and time-span of crystallization (Hawley and Wobus, 1977). According to these authors fine-grained border facies plutons show no evidence of chilling and more important neither the local fine- grained border facies nor similar interior facies are of quenched composition. They represent unusual rocks, whose chemistry and mineralogy suggest late crystallization from volatile-rich magma. This sums up the characteristics of the Klipkloof Granite which also represents a late phase crystalizing from a volatile-rich magma as evidenced by the high fluorite content, exploding bomb textures and the presence of tourmaline spheroids.

A commonly accepted view of the origin of fine-grained granites involves rapid crystallization after emplacement and loss of volatiles. The process, as detailed by White (1940), involves a late-stage build up of volatiles, resulting in increased vapour pressure and finally boiling off of volatile constituents with associated heat loss and more rapid crystallization.

Following Jahns and Tuttle (1963) three mechanisms exist for the formation of igneous aplites, namely:

1) temperature quenching or chilling
2) pressure release quenching
and 3) compositional quenching.

Jahns and Tuttle (1963) believed that pressure release quenching was the probable mechanism for the formation of granite aplites. This involves loss of volatiles and may have occurred in the case of the Klipkloof Granite aplites due to pressure release along structural weaknesses (faults and cracks) formed during the cooling of the Nebo Granite magma.

Another hypothesis proposed by Hawley and Wobus (1977) involves the gradual decrease of grain size, affected by a gradual increase in viscosity caused by a complex relation of bulk and volatile element composition and hence temperature of crystallization. They plotted compositions of Pikes Peak and Redskin Granite on sections through the thermal minima at different water-vapor pressures. Figures 22 and 23 of Tuttle and Bowen (1958) were used to construct the diagram with a range of SiO_2-K+Na feldspar compositions on the x-axis and temperature on the y-axis (Fig.7.4.). Hawley and Wobus (1977) found that the granular Redskin Granite (corresponding to the medium- to coarse-grained Klipkloof Granite) has much more of a thermal minimum composition than does the coarse-grained Pikes Peak Granite (Nebo Granite).

Tuttle and Bowen (1958, p17) found that viscosity is

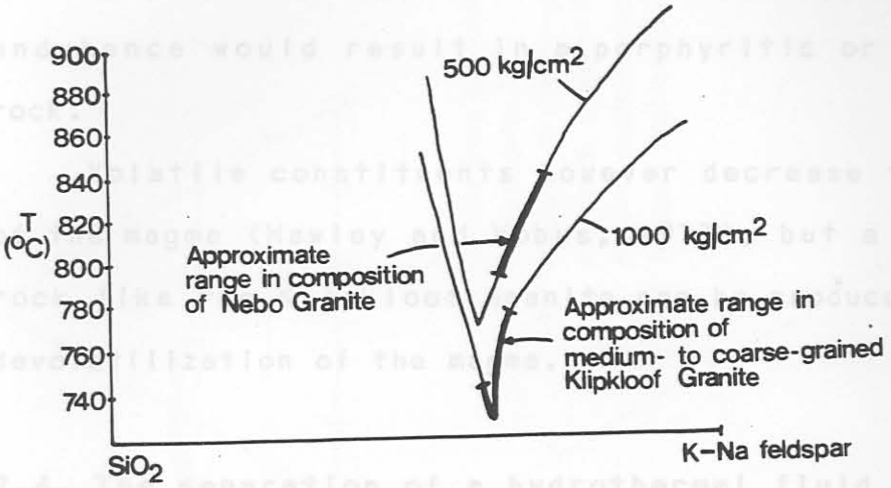

Fig. 7.4.: Compositions of Nebo and Klipkloof Granite plotted on sections through the thermal minimum at different water vapor pressures. Figures 22 and 23 of Tuttle and Bowen (1958) were used to construct the diagram.

related to ease of crystallization and that mixtures whose compositions lie along the Ab-Or sideline of the Qz-Ab-Or diagram (Fig.7.5) are the least viscous, whereas those compositions near the quartz-orthoclase eutectic and the ternary minimum are the most viscous. The Klipkloof Granite would therefore be more viscous than the Nebo Granite (Fig.7.5.) and hence would result in a porphyritic or fine-grained rock.

Volatile constituents however decrease the viscosity of the magma (Hawley and Wobus, 1977), but a fine-grained rock like the Klipkloof Granite can be produced by a sudden devolatilization of the magma.

7.4. The separation of a hydrothermal fluid from the Nebo Granite magma.

If aluminium is present in excess of that required to form Na- and K-feldspars, it occurs as corundum in the CIPW-norm. If, however, alkalis are in excess of that necessary to form Na- and K-feldspars, it occurs as acmite and/or alkali metasilicate in the CIPW-norm. From the CIPW-norm calculations (Appendix 2) it follows that no corundum is present in the granites of the study area, but that most of the samples contain CIPW normative acmite and/or alkali metasilicate. Tuttle and Bowen (1958, p89) concluded that a continous gradation from magma to hydrothermal solution exists if the alkali to aluminium ratio is such that crystallization results in concentration of alkali metasilicates. This is therefore taken as an indication that a hydrothermal fluid could have separated from the Nebo Granite magma.

7.5. Water content of the Nebo Granite magma.

It was concluded before that the Nebo Granite represents an A-type granite suite. According to Collins et al.(1982)

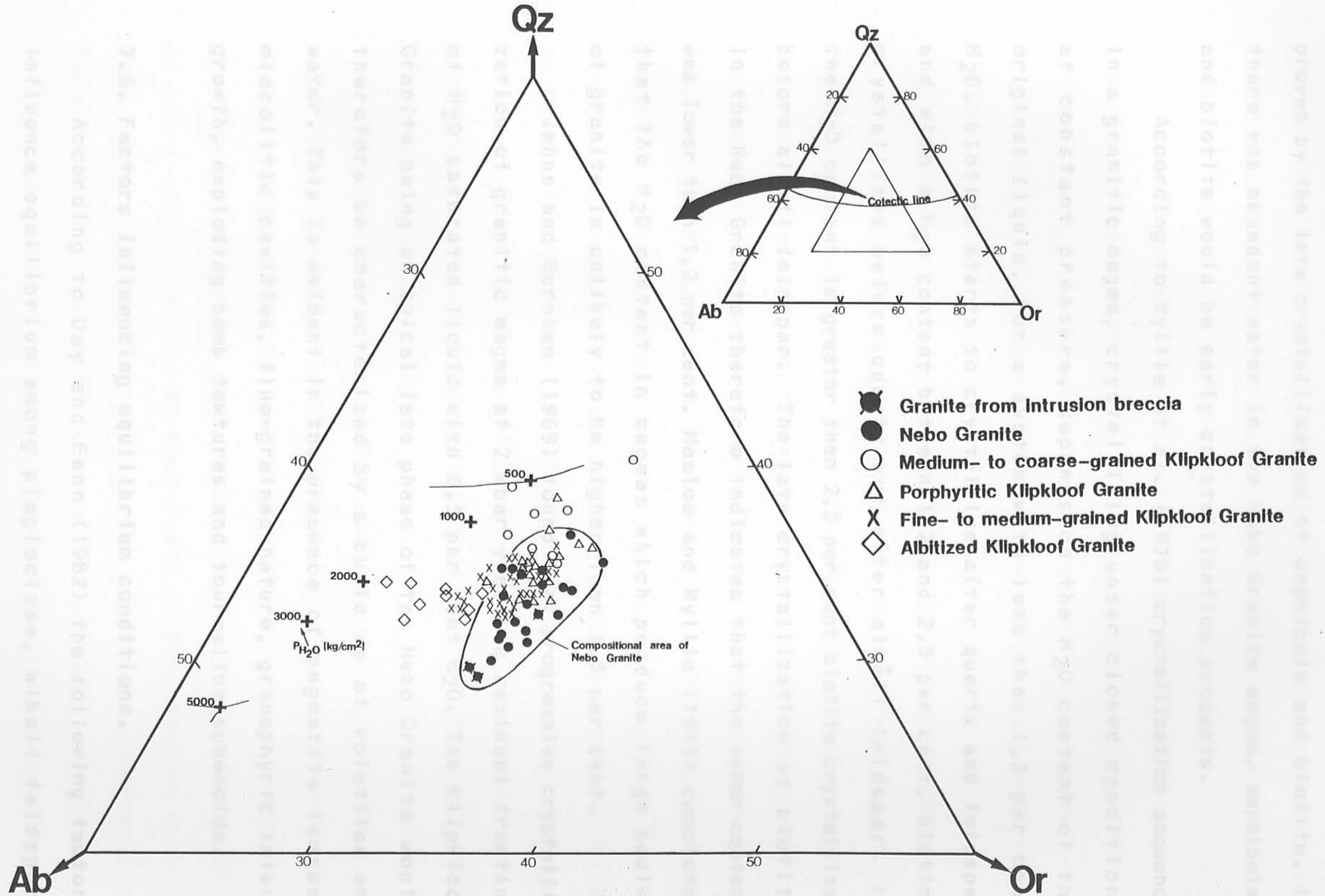

Fig. 7.5.: CIPW normative compositions of Nebo and Klipkloof Granite in the Qz-Ab-Or diagram. The pressures indicated are in kg/cm^2 and taken from Tuttle and Bowen (1958) and Luth, Jahns and Tuttle (1964).

A-type granite magmas are dry if not anhydrous, which is proved by the late crystallization of amphibole and biotite. If there was abundant water in the Nebo Granite magma, amphiboles and biotite would be early crystallization products.

According to Wyllie et al. (1976) crystallization sequence in a granitic magma, crystallizing under closed conditions at constant pressure, depends on the H_2O content of the original liquid. For a system with less than 1,2 per cent H_2O, biotite starts to crystallize after quartz and feldspar and with a H_2O content between 1,2 and 2,5 per cent, biotite crystallizes before quartz but after alkali feldspar. If the H_2O content is greater than 2,5 per cent biotite crystallizes before alkali feldspar. The late crystallization of biotite in the Nebo Granite therefore indicates that the water content was lower than 1,2 per cent. Maaloe and Wyllie (1975) concluded that the H_2O content in magmas which produce large bodies of granite is unlikely to be higher than 1,5 per cent.

Jahns and Burnham (1969) found that progressive crystallization of granitic magma at 2 kbar yields a residual fraction of H_2O saturated liquid with 6,5 per cent H_2O. The Klipkloof Granite being an apical late phase of the Nebo Granite would therefore be characterized by a build up of volatiles and water. This is evident in the presence of pegmatite lenses, miarolitic cavities, fine-grained nature, granophyric intergrowth, exploding bomb textures and tourmaline spheroids.

7.6. Factors influencing equilibrium conditions.

According to Day and Fenn (1982) the following factors influence equilibrium among plagioclase, alkali feldspar, quartz and water:

1) With increasing total pressure the two-feldspar liquidus boundary curve is shifted markedly towards more albite-rich compositions and therefore the composition field

of K-feldspar is expanded.

2) James and Hamilton (1969) found that increasing calcium in the liquid stabilizes plagioclase as the liquidus phase at the expense of K-feldspar.

3) Steiner et al. (1975) presented data which indicates that if the water content of liquids in the system Ab-Or-Q is decreased, the two-feldspar boundary curve moves so as to decrease the liquidus field of K-feldspar and stabilizing albite.

Fluorine (Bailey, 1977; Manning, 1981), rubidium (Glyuk et al., 1977) and boron (Chorlton and Martin, 1978) are capable of lowering the granite solidus by several hundred degrees centigrade. According to Manning (1981) the position of the quartz-alkali feldspar field boundary moves away from the quartz apex with increasing fluorine content. One per cent F lowers the minimum liquidus temperature of the fluorine-free system from 730°C (Tuttle and Bowen, 1958) to 690°C. With four per cent F the minimum liquidus temperature is lowered to 630°C. Addition of two per cent B_2O_3 lowers the minimum liquidus temperature from 730°C to about 650°C (Chorlton and Martin, 1978).

The combined effect of fluorine, boron, rubidium and other volatile elements would therefore lower the crystallization temperature of the Klipkloof Granite to about 550°C. The presence of tourmaline spheroids with a high concentration of boron would indicate an even lower crystallization temperature. Desborough et al. (1980) gave a crystallization temperature of 500°C and lower for the Redskin Granite, which has similar properties as the Klipkloof Granite (see Chapter 10.1).

Day and Fenn (1982) concluded that the Scituate Granite, a low Ca-granite, central Rhode Island, started to crystallize at a temperature of at least 750°C. The undifferentiated low-Ca Nebo Granite has the same composition as the Scituate Granite on the Q-Ab-Or diagram with 3 per cent An (James and Hamilton, 1969). An initial liquidus temperature of about 800°C is therefore proposed for the Nebo Granite, with the solidus at a temperature of about 650 to 700°C.

7.7. Hypersolvus and subsolvus granites.

According to Tuttle (1952), hypersolvus granites represent water-poor magmas, whereas subsolvus granites represent water-rich magmas. He also points out that hypersolvus granites are poor in alumina, with diopside, acmite, wollastonite or alkali metasilicate in the CIPW norm and that subsolvus granites are enriched in alumina, which is represented by corundum in the CIPW norm.

Luth, Jahns and Tuttle (1964) found that hypersolvus granites plotted in the Ab-Or-Q diagram, cluster in the thermal valley leading from the isobaric minimum for low values of P_{H_2O} (<0,5 kb) to the feldspar side line (the boundary separating the liquidus fields of Ab and Or), whereas subsolvus granites plot more closely to the isobaric minimum of the granite system. They further pointed out that occurrence of all plagioclase in perthite rather than as separate grains is evidence of development from a magma containing very limited amounts of water or other dissolved volatiles. According to Martin and Bonin (1976) granitic liquids will not yield a hypersolvus mineralogy at water pressures above 2,5 kbar.

The granites of the study area are hypersolvus, because they conform to all the criteria given above. The contents of plagioclase occurring as separate grains is low in the granites and the perthites are not cross-hatched microclines, which is characteristic of subsolvus granites (Martin and Bonin, 1976).

7.8. A model for the origin of Nebo and Klipkloof Granite.

Pitcher (1979) believes that plutons formed as great sheets are rather thin and emplaced forcefully. According to him the Main Donegal Granite, a sheet-like body, has a thickness of about four kilometres. According to Hyndman (1981) granitic magma must have been emplaced at a depth less than about 17 kilometres if breakdown of muscovite supplied all of its water, at less than 4 kilometres if biotite supplied the water, and at still shallower depths if hornblende supplied the water. Partial melting of a residual source containing F- and Cl-rich biotite and amphibole was suggested by Collins et al. (1982) for the production of A-type granite melts. Consequently the Nebo Granite was evidently generated by partial melting of a source that permitted emplacement at relatively shallow levels.

The Nebo Granite intruded under a cover sequence of Stavoren Granophyre, which in turn underlies Rooiberg felsites. After most of the Nebo Granite magma had crystallized, a late-stage volatile-rich liquid separated and crystallized to form the thin sill-like bodies of Klipkloof Granite in the upper part of the Nebo Granite. From Ba-Rb-Sr distribution it was concluded that the more differentiated sills occur at higher levels in the Nebo Granite. Late stage liquids from both the Nebo Granite and the Klipkloof Granite intruded into higher levels to form fine-grained Klipkloof Granite dykes. Some of these dykes had a high volatile and ore element content. Under an impermeable Klipkloof Granite sill or Stavoren Granophyre mineralization of the Varschwater type could occur (Fig.7.6).

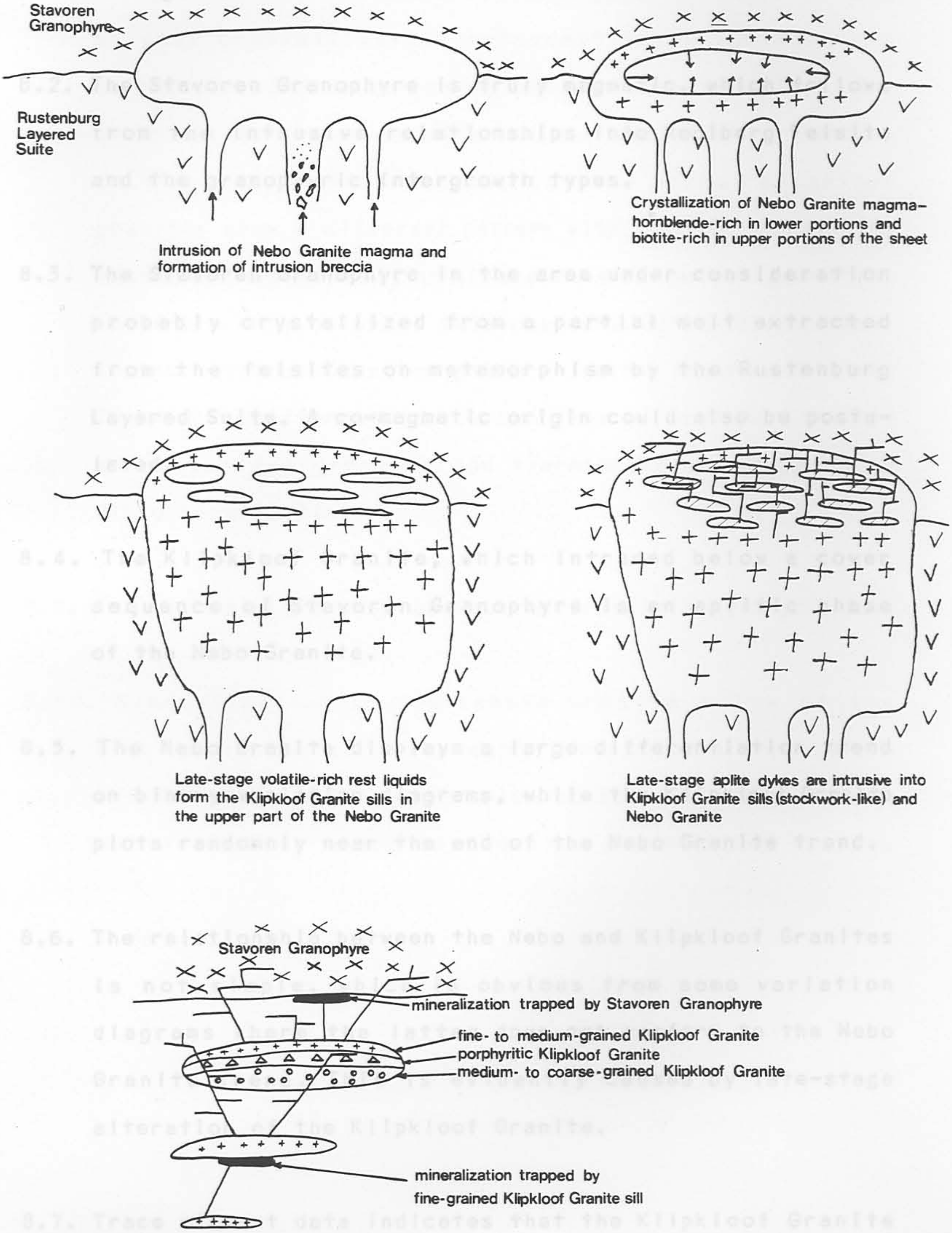

Fig. 7.6.: A model for the origin of Nebo and Klipkloof Granite.