Mineralogy and cryptic layering of the Kunene anorthosite complex of SW Angola and Namibia

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Abstract

The gabbro–anorthosite complex of SW Angola and Namibia (Kunene Complex) is dominated by anorthosite–troctolite cumulates. Other broadly gabbroic rock types are subordinate. An-rich plagioclase (max. An_{85}) and Fo-rich olivine (max. Fo_{79}) are common in the western area of the complex with plagioclase becoming gradually less anorthitic (min. An_{45}) and olivine less forsteritic (min. Fo_{62}) toward the east. This cryptic change is more pronounced in the northern half of the complex where rocks are darker, fresh, and the rhythmic layering is also more conspicuous. Within the white 'massive' anorthosite type, which is largely restricted to the southern half of the intrusion, cryptic layering is less pronounced. Textures indicate that rocks cooled very slowly and the co-existing mineral compositions indicate re-equilibration to usually low temperatures.

KEYWORDS: layering, layered anorthosite, 'massive' anorthosite, Kunene, Angola, Namibia.

Introduction

THE exposed portion of the Kunene Complex of Angola and Namibia (Fig. 1) is the middle part of a layered igneous body equivalent to the Main Zone of the Bushveld Complex. Anorthosite and troctolite are the dominant lithologies although other gabbroic rocks do occur (Silva, 1988). Layering is more evident in the northern half of the intrusion where rocks are usually fresh and dark coloured. Cryptic variation is evident in the composition of both plagioclase (An_{85-45}) and olivine (Fo_{79-58}), the two principal mineral phases occurring in the complex. There is a systematic variation of the chemistry and mineralogy of the rocks from west to east indicating that the top of the intrusion is to the east.

The 'white' anorthosite which occurs in the southern portion of the body is lighter in colour, and 'massive' in appearance. It was also studied by Kostlin (1967), in Namibia.

Analytical data presented in this paper were obtained during research performed towards a PhD. dissertation at the University of Lisbon, Portugal.

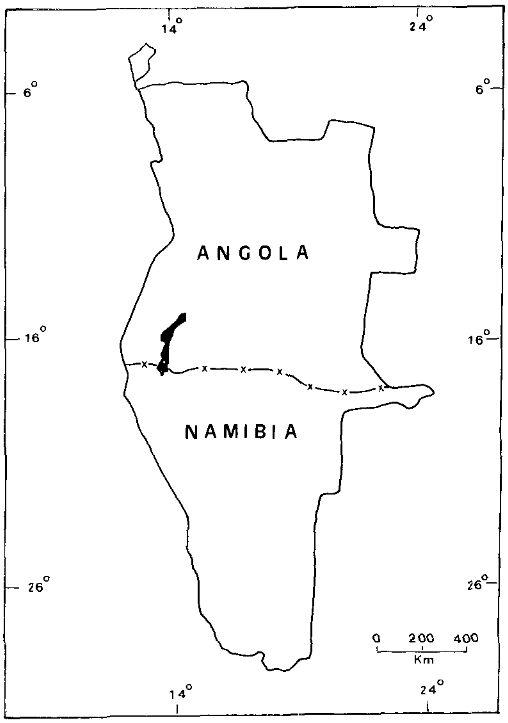

FIG. 1. Location map of the Kunene Complex.

Sampling and stratigraphy

This investigation was carried out on samples collected in 1964, by E. Loureiro, E. S. W. Simpson and C. A. M. Alves, covering the entire

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area of exposure of the intrusion in Angola. Microprobe analyses were performed for pair of elements in a JEOL JCXA 733 by using a 5 μm beam at 15 kV. Adularia was the standard for K, kyanite for Al, wollastonite for Si and Ca, olivine for Mg and Fe, rhodonite for Mn, kaersutite for Na and Ti and pure elements for Cr and Ni. Dip and strike are not readily determined in the field. As the specimens collected were not oriented, they could not be used to determine these features by microscopic methods. Nevertheless, all rock types occurring in the area were sampled, making it possible to detect small variations in the mineralogy and chemistry and to determine the general orientation of the intrusion, as will be described herein. Information obtained by the author while working in Angola was a valuable help during this research. Field work in the area has not been possible in the last 16 years, but this problem will be overcome enabling a more systematic study of this very large mafic intrusion.

Petrography

The complex is dominated by anorthosites and troctolites as defined by the modal classification of Streckeisen (1976). Plagioclase and olivine are the dominant minerals with subordinate clinopyroxene and minor orthopyroxene. Minor interstitial Fe and Ti oxides occur in most rock types. Rocks are typical plagioclase and olivine cumulates (pC and poC in the Irvine classification, 1982) and clinopyroxene is the most common intercumulus mineral. Texturally most rocks are usually extreme adcumulates or mesocumulates as defined by Wager *et al.* (1960).

Anorthosites (pC). Anorthosite is the most abundant rock type and occurs throughout the complex. Their modal composition varies from almost pure plagioclase (>98%) to anorthosite containing up to 10% interstitial pyroxene. The fresh rocks are dark coloured, grading from dark gray through greenish gray to black. The rocks are equigranular and the grain size ranges from medium (3–4 mm) to coarse (1 to 3 cm). Texturally they are mostly adcumulates or mesocumulates. Within each specimen plagioclase is unzoned but ranges in composition from labradorite to andesine in the intrusion as a whole. As a rule, the decrease in An content of the plagioclase can be followed from west to east in the complex. Augite is almost invariably the postcumulus phase (augite to ferroaugite). Exsolution lamellae are common in the augites, both wide ||(001) and fine ||(100). The anorthosites are almost devoid of oxide phases.

'White' anorthosites. This type of anorthosite is light green in colour, coarse grained, massive in appearance and occurs south of parallel 16°S in Angola. The occurrence of this rock has also been reported to the south of the Kunene River, in Namibia, by Kostlin (1967, 1974). Kostlin regarded the white type as being older than the dark, layered type, which is more common in the northern area of the Complex. They are adcumulates and mesocumulates with strongly altered plagioclase (An_{61}) as the only cumulus phase. Altered Ca-rich pyroxene and, less commonly, ilmenite and magnetite are the postcumulus phases. Exsolution lamellae are preserved in the altered pyroxene. Olivine, where present, is more Fe-rich than olivines from other rock types occurring in the area. These petrographic data, combined with geochemical and isotopic data (Silva and Kruger, and Kruger and Silva, in preparation) indicate that the white anorthosite is an altered variant of other fresh rocks of the complex. This alteration is probably of Kibaran age (Silva, 1987, 1988, 1990).

Gabbroic anorthosites (paoC). All specimens of this rock type were collected from the eastern part of the intrusion. They do not differ substantially from the anorthosites described above, except that olivine and rare oxide are also cumulus phases. This rock type resembles parts of the Upper Zone of the Bushveld Complex, notably with respect to the presence of magnetite concentrations. The plagioclase composition ranges between labradorite and andesine (An_{60} to An_{49}). Olivine varies from Fo_{55} to Fo_{71}. Fe-rich biotite is a minor component, usually associated with olivine.

Gabbros and anorthositic gabbros (poabC). Macroscopically these rocks resemble the anorthosites. They are similar in colour and are generally coarse grained. They have adcumulate, mesocumulate and heteradcumulate textures. Besides plagioclase and olivine, pyroxene and ore minerals are also cumulus phases. Both bronzite and augite occur in these rocks. Orthopyroxene occurs also as kelyphitic rims and is occasionally intergrown with ilmenite and magnetite. Clinopyroxene and ilmenite symplectites were observed, as well as good examples of pyroxene exsolution lamellae. Olivine composition varies from Fo_{74} to Fo_{59} and is also dependent upon the location of the rock in the complex.

Troctolites (opC). Next to anorthosites, the troctolites are the most common rocks. Most of the samples are greenish gray with dark gray to almost black patches. As this colour range is similar to that of the anorthosites, colour is not a valid criterion for field identification.

In general the troctolites have adcumulate, mesocumulate and heteradcumulate textures. In some rocks plagioclase exhibits lamination and an interesting olivine harrisitic texture is present in one sample. Plagioclase and pyroxene are poikilitic in the heteradcumulates where clinopyroxene is the intercumulus phase. Composition of the plagioclase ranges from bytownite to labradorite (An_{80} to An_{51}) becoming poorer in An towards the east. Orthopyroxene occurs mainly as rims on olivine. Olivine is usually fresh, any alteration being restricted to grain borders. In general olivine is richer in Fo in the western part (Fo_{74-63}) than in the eastern part (Fo_{69-57}) of the intrusion, although oscillations in composition do occur. Magnetite, Cr-magnetite and ilmenite are also cumulus phases in these rocks.

Norites (pboC). Norite is the least common rock type in the complex and seems to be restricted to its edges. It is possible that in the west it forms the Marginal Lower Zone of the complex. The rock is dark greenish, medium to fine grained and has a heteradcumulate texture. Olivine and chromite are also cumulus in addition to plagioclase, chromite occurring also as inclusions in both plagioclase and olivine. Interstitial biotite is more common than in the other rocks of the complex. In these rocks the systematic variation in mineralogical composition evident in the other rock types does not hold.

Plagioclase ranges between andesine and labradorite (An_{49} to An_{68}) and within the orthopyroxenes the range in composition is from bronzite ($Mg_{77}Fe_{17}Ca_6$) to ferrohypersthene ($Mg_{48}Fe_{50}Ca_2$). Fine exsolution lamellae of the Bushveld type, as described by Hess and Phillips (1940) are a common feature. The augite composition ranges from $En_{41}Fe_{15}Wo_{44}$ to $En_{48}Fs_{13}Wo_{39}$. Microprobe analyses of olivine from three rocks give Fo_{79}, Fo_{64} and Fo_{61}. Biotite is a minor phase in the norites.

Mineralogy

Plagioclase. This mineral is a cumulus phase in all rocks. Wavy extinction, mortar texture and bent twinning are rare features. The compositional range is from bytownite to andesine and in general the more albitic plagioclase is also more K-rich.

Representative data from 50 plagioclase microprobe analyses are shown in Table 1. There is a complete overlap in the plagioclase composition among the rock types described above, but the histograms in Fig. 2 clearly show that plagioclase from the base of the exposed area is more An-rich than that from the top of the intrusion. The mean composition for plagioclase from the base is $An_{65.8}$ (standard deviation = 9.3) whereas plagioclase from the top has a mean composition of An_{54} (standard deviation = 4.7). This cryptic layering, which here is also displayed by olivine, was first observed by Stone and Brown (1958). Albite enrichment of plagioclase towards the top of an intrusion is a common feature in layered intrusions, as shown in the Bushveld, Skaergaard and Stillwater Complexes (e.g. Wager and Brown, 1968).

The compositional variation displayed by the plagioclase from the Complex matches the com-

TABLE 1. Representative microprobe analyses of plagioclases

Analysis No.	1	2	3	4	5	6	7	8	9	10	11	12
Sample No.	377-84	389-10	389-3	337-4	356-5	378-2	357-12	357-9	357-13	357-15	357-19	377-24
SiO_2	49.43	56.28	54.70	48.30	50.88	53.96	55.70	53.94	51.51	49.25	48.16	55.36
Al_2O_3	32.02	27.41	27.91	32.34	30.84	28.22	27.55	28.58	30.47	31.90	32.16	27.81
FeO*	0.33	1.21	0.10	0.26	0.83	0.21	0.11	0.21	0.12	0.26	2.46	0.14
CaO	15.43	9.92	10.74	15.93	14.11	11.20	10.01	11.34	13.69	15.26	15.45	10.55
Na_2O	2.66	5.44	5.14	2.17	3.13	5.10	5.29	4.79	3.58	2.80	2.06	5.34
K_2O	0.01	3.54	0.23	0.11	0.24	0.20	0.63	0.27	0.09	0.05	0.07	0.35
Total	100.01	99.80	98.82	99.11	100.13	98.89	99.29	99.13	99.46	99.52	100.36	99.55
Cations on the basis of 32 oxygen												
Si	9.056	10.159	9.976	8.922	9.289	9.864	10.101	9.833	9.409	9.047	8.866	10.025
Al	6.916	5.826	5.999	7.041	6.636	6.080	5.889	6.140	6.560	6.906	6.978	5.936
Fe''	0.054	0.032	0.015	0.040	0.127	0.032	0.017	0.032	0.018	0.040	0.300	0.021
Ca	3.024	1.917	2.099	3.153	2.760	2.194	1.945	2.215	2.679	3.003	3.047	2.047
Na	0.943	1.902	1.818	0.777	1.108	1.808	1.860	1.693	1.268	0.997	0.735	1.875
K	0.028	0.124	0.054	0.026	0.056	0.047	0.146	0.063	0.021	0.012	0.016	0.081
An	75.7	48.6	52.8	79.7	70.3	54.2	49.2	55.8	67.5	74.9	80.2	51.1
Ab	23.6	48.2	45.8	19.6	28.2	44.7	47.1	42.6	32.0	24.9	19.4	46.8
Or	0.7	3.2	1.3	0.7	1.4	1.2	3.7	1.6	0.5	0.3	0.4	2.0

* Total Fe as FeO

1. Anorthosite (base) 2. Anorthosite (top) 3. "White" anorthosite 4. Gabbro (base)
5. Anorthositic gabbro (base) 6. Anorthositic gabbro (top) 7. Gabbroic anorthosite (top)
8. Norite (base) 9. Norite (top) 10,11. Troctolite (base) 12. Troctolite (top)

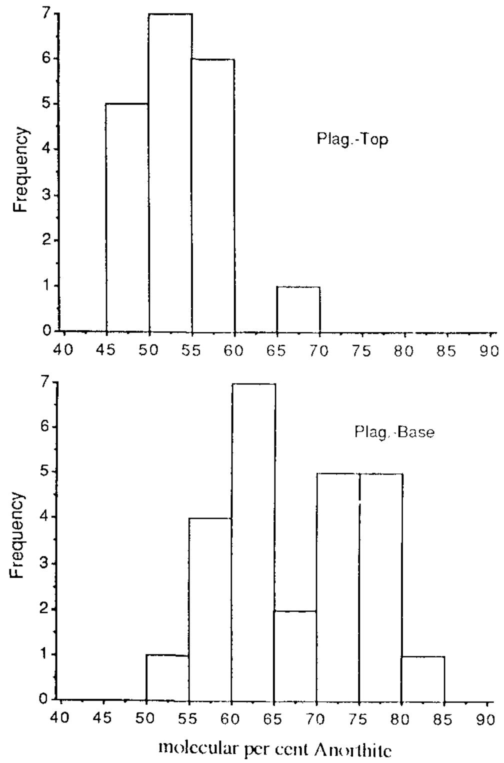

FIG. 2. Histogram showing frequency of plagioclase composition (44 analyses) related to their stratigraphic position.

position of plagioclase in the gabbroic or noritic parts of the Bushveld, Stillwater and Skaergaard Complexes. In the Bushveld Complex it is matched in the Upper Critical, Main and part of the Upper Zones; in Skaergaard by the Lower and Main Zones and in Stillwater by the Anorthositic Zone, and up to the Upper Gabbroic Zone.

The plagioclase in all these intrusions has a low-temperature, ordered structural state and in the case of the Kunene Complex, plagioclase from both layered and 'white' anorthosite types show this characteristic. Data from 12 samples were compared with data from the Bushveld, Skaergaard and Stillwater Complexes (Smith and Gay, 1958) and from Morin, a massive type (Philpotts, 1966) by using the parameters of Smith and Gay (op. cit) as shown in Fig. 3. Parameters Γ and B were obtained from diffractograms between 20 and 29 degrees using Cu*K*α radiation (Table 2). In Fig. 3 two populations (high and low An) are evident from clusters formed (1) by the layered type plus samples from the base and (2) by the 'white' type plus samples from the top of the intrusion. The latter population includes the samples from Morin.

Olivine. Next to plagioclase, olivine is the most common mineral and occurs as a cumulus phase in all rock types. Grains are generally fresh, and homogeneous in composition. Pyroxene rims or altered borders consisting of orthopyroxene–hornblende or orthopyroxene–chlorite are not uncommon.

Representative microprobe analyses of olivine from all rock types are presented in Table 3. The variation in composition of olivine is not regular as that of plagioclase across the complex, but in general olivine from the western part of the intrusion is more magnesian than olivine from the eastern area. The variation in composition across the intrusion can be illustrated as follows:

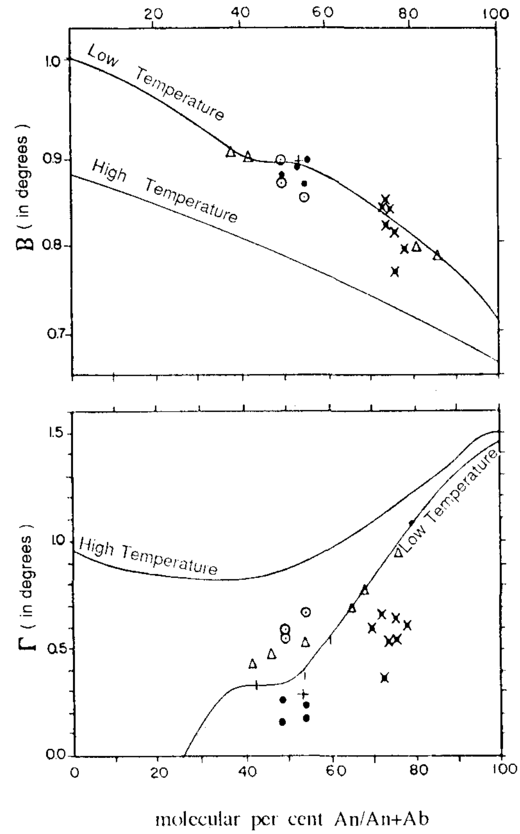

FIG. 3. Plot of the structural state of the plagioclases from the Kunene Complex. $\Gamma = 2\theta\,(131) + 2\theta\,(220) - 4\theta\,(1\bar{3}1)$; $\beta = 2\theta\,(1\bar{1}1) - 2\theta\,(\bar{2}01)$. Symbols are as follows: Angola: × 'base'; ● 'top'; + 'white' anorthosite. △ = samples from Bushveld, Skaergaard and Stillwater; ⊙ samples from Morin; temperature curves after Smith and Gay (1958).

TABLE 2. Γ , B and An/(Ab+An) of selected plagioclase

Sp. No.	1	2	3	4	5	6	7	8	9	10	11	12
Sample No.	357-1	357-21	377-84	377-90	378-10	398-10	377-80	377-136	377-148	378-13	398-6	398-3
Origin	b	b	b	b	t	t	b	b	b	t	t	(w)
Γ	0.54	0.62	0.66	0.67	0.21	0.15	0.56	0.34	0.60	0.19	0.27	0.28
B	0.83	0.80	0.77	0.85	0.90	0.88	0.82	0.85	0.82	0.87	0.88	0.90
An/(Ab+An)	74	78	76	72	56	50	76	73	71	55	50	53

$\Gamma = 2\theta(131) + 2\theta(220) - 4\theta(1\bar{3}1)$; $B = 2\theta(1\bar{1}1) - 2\theta(\bar{2}01)$
b = base ; t = top of exposed part of the Complex ; (w) = "white" anorthosite

	Fo mean value	std. dev.	minimum	maximum
Top	62.9	6.0	54.7	71.0
Base	68.1	5.7	58.6	79.1

Mg-rich olivines are present in rocks with higher magnetite contents, possibly as a result of empoverishment of iron in the liquid caused by higher f_{O_2} and earlier nucleation and rapid growth of magnetite.

Olivine from the complex compared with olivine from the equivalent portions of the Bushveld (Critical Zone), Skaergaard (Lower and Middle Zones) and Stillwater (Gabbroic Zone) shows a wider range in composition for the complex (Fo_{79-55}) contrasted with values of Fo_{81-79}, Fo_{77} and Fo_{69-52} for the other complexes, respectively. In all these three intrusions the precipitation of olivine is interrupted over certain composition ranges (Eales *et al.*, 1986; Wager and Brown, 1968), due to iron enrichment with fractionation, while in Angola such a break in composition does not occur.

Pyroxene. Both ortho- and clinopyroxene are present in the anorthositic rocks from Angola. Representative data from 50 microprobe analyses of selected samples are given in Table 4. Augite is the common intercumulus phase. The composition is variable within a certain range in all rocks, but no systematic variation could be traced across the intrusion. Ca-poor pyroxene occurs as rims to olivine and more rarely as an intercumulus phase.

Pyroxene composition shows that, in general,

TABLE 3. Selected microprobe analyses of olivine

Analysis No.	1	2	3	4	5	6	7	8	9
Sample No.	377-80	398-2	337-4	356-5	378-2	357-9	357-13	357-15	377-24
SiO_2	38.52	35.08	37.89	38.25	37.29	36.00	36.66	37.40	35.52
TiO_2	0.01	0.00	0.01	0.03	0.01	0.01	0.00	0.07	0.00
Al_2O_3	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.02	0.01
NiO	0.10	0.05	0.10	0.12	0.12	0.07	0.11	0.19	0.01
FeO*	24.04	38.73	26.32	23.57	28.57	33.52	31.93	24.34	37.43
MnO	0.34	0.47	0.34	0.28	0.28	0.53	0.48	0.30	0.41
MgO	37.42	26.24	36.05	38.01	34.07	29.67	32.11	38.12	27.44
CaO	0.00	0.00	0.03	0.03	0.00	0.02	0.02	0.00	0.01
Total	100.42	100.57	100.74	100.29	100.35	99.82	101.31	100.44	100.83
Cations on the basis of 4 oxygen									
Si	1.005	0.988	0.998	0.998	0.997	0.995	0.988	0.081	0.989
Al	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000
Ti	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.001	0.000
Fe"	0.525	0.912	0.580	0.514	0.639	0.774	0.720	0.534	0.872
Mn	0.008	0.011	0.008	0.006	0.006	0.012	0.011	0.007	0.010
Ni	0.002	0.001	0.002	0.003	0.003	0.001	0.002	0.004	0.000
Mg	1.455	1.101	1.414	1.478	01.357	1.222	1.290	1.490	1.139
Ca	0.000	0.000	0.001	0.001	0.000	0.001	0.000	0.000	0.000
Fo	73.5	54.7	70.9	74.2	68.0	61.2	64.2	73.6	56.6

* Total Fe as FeO
1. Anorthosite (base) 2. Anorthosite (top) 3. Gabbro (base)
4. Anorthositic gabbro (base) 5. Anorthositic gabbro (top) 6. Norite (base)
7. Norite (top) 8. Troctolite (base) 9. Troctolite (top)

TABLE 4. Selected microprobe analyses of pyroxenes

Analysis No.	1	2	3	4	5	6		7		8	
Sample No.	357-21	337-4	378-2	443-2	419-13	357-9		357-13		420-9	
Mineral						opx	cpx	opx	cpx	opx	cpx
SiO_2	52.49	51.57	53.15	52.27	49.99	51.76	51.55	53.77	52.26	52.99	51.95
TiO_2	0.48	0.82	0.15	0.05	1.60	0.21	0.53	0.18	0.49	0.20	0.43
Al_2O_3	1.75	2.75	2.33	3.15	4.10	1.55	2.83	1.55	2.55	0.86	1.80
Cr_2O_3	0.03	0.00	0.00	0.00	0.44	0.00	0.09	0.07	0.17	0.03	0.00
FeO*	8.68	8.54	17.80	18.90	8.76	20.17	8.74	18.43	7.15	22.70	9.38
MnO	0.27	0.21	0.30	0.24	0.19	0.50	0.27	0.49	0.24	0.64	0.34
MgO	13.58	14.24	25.80	25.08	15.07	24.28	14.10	25.24	14.50	22.13	13.62
CaO	22.69	21.37	0.43	0.24	18.95	0.61	21.49	0.49	22.08	0.95	20.95
Na_2O	0.24	0.32	0.01	0.00	0.51	0.06	0.45	0.05	0.46	0.02	0.35
K_2O	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.00	0.02	0.02
Total	100.21	99.82	99.97	99.93	99.61	99.14	100.05	100.27	99.90	100.54	98.84
Cation on the basis of 6 oxygen											
Si	1.954	1.919	1.931	1.907	1.858	1.922	1.912	1.958	1.934	1.967	1.961
Al	0.046	0.081	0.069	0.093	0.142	0.068	0.088	0.042	0.066	0.033	0.039
Al	0.031	0.040	0.031	0.042	0.038	0.000	0.036	0.024	0.045	0.005	0.041
Ti	0.013	0.023	0.004	0.001	0.045	0.006	0.015	0.005	0.014	0.006	0.012
Cr	0.001	0.000	0.000	0.000	0.013	0.000	0.003	0.002	0.005	0.001	0.000
Fe'''	0.004	0.018	0.030	0.049	0.039	0.060	0.051	0.009	0.022	0.018	0.000
Fe''	0.266	0.247	0.511	0.528	0.234	0.566	0.220	0.552	0.199	0.687	0.296
Mn	0.009	0.007	0.009	0.007	0.006	0.016	0.008	0.015	0.008	0.020	0.011
Mg	0.753	0.790	1.397	1.363	0.835	1.344	0.780	1.370	0.800	1.224	0.766
Ca	0.905	0.852	0.017	0.009	0.755	0.024	0.854	0.019	0.875	0.038	0.847
Na	0.017	0.023	0.003	0.009	0.037	0.004	0.032	0.004	0.033	0.001	0.026
K	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.001	0.001
En	38.9	41.3	71.1	69.7	44.7	66.9	40.8	70.1	42.0	61.6	39.9
Fs	14.4	14.2	28.0	29.9	14.9	31.9	14.6	29.0	12.0	36.5	16.0
Wo	46.7	44.5	0.9	0.4	40.4	1.2	44.6	1.0	46.0	1.9	44.1

* Total Fe as FeO ; opx = orthopyroxene ; cpx = clinopyroxene
Cations used to calculate proportions of En, Fs and Wo, were: Mg, Fe''+Fe'''+Mn and Ca respectively
1. Anorthosite 2. Gabbro 3. Anorthositic gabbro 4. Gabbroic anorthosite
5. Troctolite 6, 7, 8. Norite

the Al_2O_3 content is low (<3%), similar to that in pyroxenes from the Bushveld (Atkins, 1969; Markgraaff, 1976; Eales *et al.*, 1986) and Skaergaard (Brown, 1957; Brown and Vincent, 1963).

The relation Si–Al in the clinopyroxenes from the Kunene Complex was investigated by Silva (1988) who plotted the atomic proportions of Si and Al obtained from all data available in Kushiro's diagram (Kushiro, 1960), where magmas show higher Si–Al ratios with fractionation. Pyroxenes fall in the tholeiitic field, but show no fractionation trend similar to that of pyroxenes from the Stillwater and Skaergaard Complexes (Kushiro, 1960).

This 'antipathetic' relation Si–Al is shown in Fig. 4. Pyroxene compositions plotted in a Si–Al diagram (LeBas, 1962), clearly define a non-alkaline field, as also do pyroxenes from the Bushveld Complex. The occupation of *Z* sites by Al in these pyroxenes is also comparable with tholeiitic pyroxenes.

No significance in the variation of other cations was detected. In general Ti is quite low and in coexisting pairs, Ca-rich pyroxene has higher contents (average $Ti_{cpx}/Ti_{opx} = 2.66$). Ti is also higher in pyroxene from rocks where ilmenite and magnetite are absent, in contrast to Cr which is higher in pyroxene from rocks where Cr-magnetite or chromite occur. Fe^{3+} shows an irregular pattern and in coexisting pairs there is no preference for Ca-rich pyroxene, as observed in pyroxenes from the Bushveld (Atkins, 1969; Cawthorn *et al.*, 1991). However, clinopyroxenes from the Kunene Complex have higher magnesium and calcium contents than clinopyroxenes from the corresponding zones of the Bushveld, Skaergaard and Stillwater Complexes.

Coexisting pairs of cumulus ortho- and clinopyroxene from three rocks are plotted in a Ca–Mg–Fe pyroxene diagram in Fig. 5 where the crystallisation trend is compared to those of the Bushveld and Skaergaard Complexes. The pyroxenes from Angola appear to have re-equilibrated to lower temperatures than pyroxenes from the other two intrusions, as indicated by their Ca content (Lindsley, 1983).

The distribution coefficients (K_D) between Mg and Fe'' calculated for three ortho-clinopyroxene

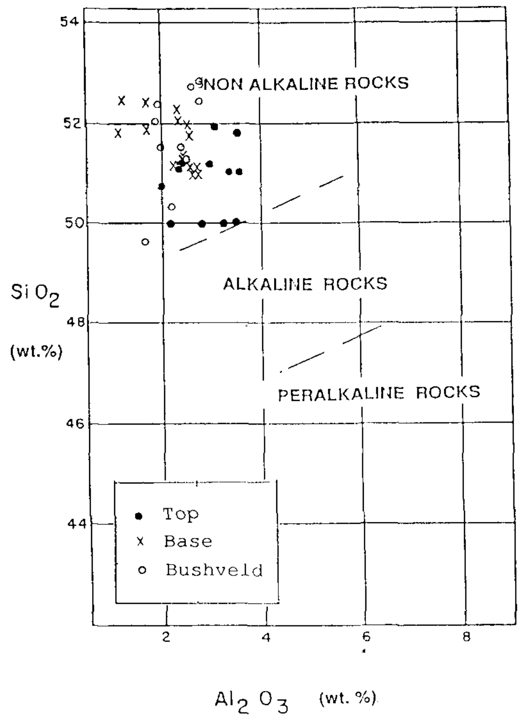

FIG. 4. Relationship SiO_2 *vs.* Al_2O_3 in the pyroxenes from Angola (after LeBas, 1962).

pairs by using the Ramberg and DeVore (1951) equation give values of 0.667, 0.621 and 0.685. These values fall in the range found by Atkins (1969) for Bushveld pyroxenes (0.64 to 0.70) and are close to the values expected for associations of igneous rocks (Kretz, 1961, and Bartolomé, 1961). Higher values are reported for Skaergaard (0.708 to 0.748) and Stillwater (0.712 to 0.731) which are accounted for by higher crystallisation temperatures than those of the Bushveld pyroxenes (Atkins, 1969).

The position of pyroxene plots on the diagram of Fig. 5 is similar to that of pyroxene pairs equilibrated at lower, subsolidus temperatures. Subsolidus features are found in pyroxenes from the complex, such as exsolution lamellae of Bushveld and Stillwater types, as defined by Hess and Phillips (1940), and reaction rims of pyroxene and olivine.

Ore minerals. Magnetite, ilmenite and rare chromite occur as cumulus and intercumulus phases in many rock types in the whole area. Magnetite and ilmenite also occur as monomineralic concentrations at several levels of the intrusion (Beetz, 1933; Santos, 1969; Simpson, 1970; Paixão, unpublished).

Discussion and conclusions

All rock types described, except the norites and the 'white' anorthosites, occur throughout the area. The occurrence of norites near the border of the intrusion may be meaningful. Norite layers or horizons are common features in anorthositic bodies of different origins (Romey, 1968) and in a layered intrusion like the Bushveld, marginal norite occurs beneath the Lower Zone (Cameron, 1978). In the Stillwater Complex, the norite zone is a transition between the Transition Zone and the Lower Gabbro Zone and is characterised by the beginning of the crystallization of plagioclase as a cumulus phase (Hess, 1960). In Angola both chromite and olivine started crystallising as a major phase in these rocks.

Olivine-bearing norite was reported by Beetz (1933) near the Kunene river and his description coincides with that of sample 420-11. Another type of norite, brownish in colour, and hypersthene-bearing was described in Angola by Oliveira and Mata and by the author (unpublished) in the area covered by sheet 398 of the map of Angola. This type of rock was referred to by Kostlin (1967) as occurring concordantly with the dark anorthosite, near Oronditi, close to the Kunene river. The olivine-bearing norite might correspond in Angola to a transition zone between a Marginal Zone, undefined yet, and the exposed gabbro–anorthosite. The brown, hypersthene-bearing norite may correspond to the transition zone between the Gabbro-anorthosite (Main?) and the Upper Zone, of different composition.

Kostlin (1967) and Simpson (1970) reported the occurrence of troctolite in Namibia as an intrusive rock in the white anorthosite, but such a relationship does not hold for Angola. White anorthosites in Angola seem to have resulted from alteration of the layered, dark anorthosite type. This assumption is supported by the type of occurrence, the mineralogy and the texture of these rocks, as well as by the chemistry and recent isotopic data (Kruger and Silva, in preparation).

The typical cumulate texture exhibited by the rocks in the complex, including the white anorthosite (relict cumulate) supports the idea that cooling and crystal settling took place at a slow rate, allowing the composition of grains to become fairly homogeneous. Small amounts of intercumulus (5–25%) phases are also typical of these rocks and constitute a good indication of slow cooling (Chalokwu and Grant, 1990) as is the presence of exsolution lamellae in the intercumulus pyroxene. Internal details of the complex are still unknown and more extensive work is necess-

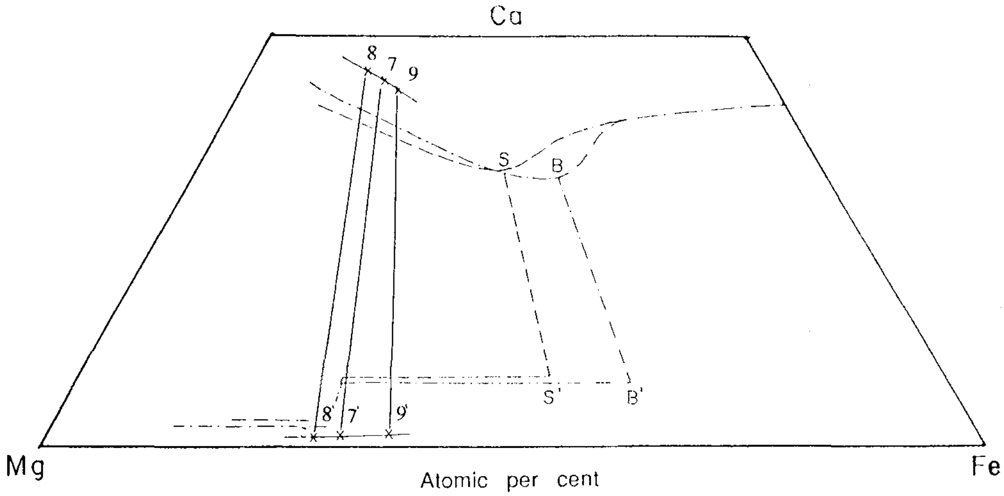

FIG. 5. Crystallisation trend of pyroxenes of the Kunene Complex in Angola. The trends for Bushveld and Skaergaard are given for comparison. (Data for the Bushveld from Atkins, 1969 and for Skaergaard from Brown and Vincent, 1963).

ary before a comprehensive model of crystallisation can be proposed. Fractional crystallisation and crystal settling might have been the dominant processes in the development of the cumulates, as suggested by the co-variation of plagioclase and olivine compositions. Other mechanisms such as multiple influxes of magma and associated fluid dynamic processes may account for the development of rhythmic layering in these rocks, as has been proposed for other intrusions such as the Bushveld Complex (Kruger and Marsh, 1982; Eales *et al.*, 1990), Skaergaard (McBirney and Noyes, 1979), Stillwater (Irvine *et al.*, 1983) and the Duluth Complex, which is also dominated by anorthosite and troctolite (Weiblen and Morey, 1980; Chalokwu and Grant, 1990; Miller and Weiblen, 1990). The repetition of alternate layers of anorthosite-troctolite-anorthosite and the development of harrisitic textures also support this concept.

The cryptic variation which is shown by the albite enrichment of the plagioclase towards the top of the intrusion is a common feature of any fractionating basaltic magma and seems also to characterise the Kunene Complex. The extensive crystallisation of orthopyroxene before the appearance of Ca-rich pyroxene, a distinct feature of the Bushveld Complex (Cameron, 1978; Barnes, 1989) did not occur. Instead, the first phases to crystallise were olivine and plagioclase, the two minerals that control the chemistry of the complex (Silva and Silva, 1990).

Finally, most data point to a tholeiitic magma which underwent slow fractional crystallisation and reequilibration to low temperature allowing the development of structurally ordered plagioclase and subsolidus features as exsolution lamellae in pyroxenes and symplectitic intergrowth of ore minerals with pyroxene.

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