ECONOMIC GEOLOGY RESEARCH UNIT

University of the Witwatersrand
Johannesburg

LOW-POTASH PILLOW-BASALTS IN THE PRETORIA GROUP, TRANSVAAL SUPERGROUP

A. BUTTON

INFORMATION CIRCULAR No. 76

UNIVERSITY OF THE WITWATERSRAND

JOHANNESBURG

LOW-POTASH PILLOW-BASALTS IN THE PRETORIA GROUP, TRANSVAAL SUPERGROUP

by

A. BUTTON

(Research Fellow, Economic Geology Research Unit)

ECONOMIC GEOLOGY RESEARCH UNIT

INFORMATION CIRCULAR No. 76

April, 1973

LOW-POTASH PILLOW-BASALTS IN THE PRETORIA GROUP, TRANSVAAL SUPERGROUP

ABSTRACT

A basaltic extrusive formation, previously mapped as a sill intrusive into the Pretoria Group, is described from the Transvaal Supergroup in the eastern Transvaal. The volcanic nature of the formation has been indicated by the pillow structures found in the basalts in some key exposures. Three chemical analyses of the pillowed lava are presented. The lavas are basaltic and, chemically, bear a very strong resemblance to the family of oceanic tholeiites which have been dredged off the present-day ocean floor. The presence of volcanics with this chemistry is puzzling, since they are found in a sedimentary pile deposited in a basin which rests on an older sialic crust. The lavas must have been injected through the crust with little or no contamination from this source.

* *

LOW-POTASH PILLOW-BASALTS IN THE PRETORIA GROUP, TRANSVAAL SUPERGROUP

CONTENTS

* *

LOW-POTASH PILLOW-BASALTS IN THE PRETORIA GROUP, TRANSVAAL SUPERGROUP

INTRODUCTION

Recent fieldwork in the Transvaal Supergroup of the eastern Transvaal has revealed the presence of an horizon of low-potash pillow-basalt. This unit, which has been traced from near Carolina in the south to the north of Burgersfort, has, in the past, been mapped as a basic sill (Hall, 1918; Schwellnus and others, 1962). Key exposures have proved that the formation has an extrusive origin. This discovery is a partial vindication of the contention of Cousins (1962), who held the view that most of the stratiform igneous bodies in the Pretoria Group (presently accepted as sills) were, in fact, of extrusive origin.

In this paper, the stratigraphy, field-geological characteristics, petrology, and major-element chemistry of the lava are briefly documented.

GEOLOGICAL SETTING

The area in which the volcanic rocks to be described were found is situated in the eastern Transvaal (Figure 1). The volcanics have been traced from near Carolina in the south, through Machadodorp, Lydenburg, and Burgersfort, to near Penge in the north. To the northwest of Penge, fine-grained igneous rocks petrologically similar to the volcanics (but without the diagnostic volcanic structures) have been followed in their correct stratigraphic position to the vicinity of the Olifants River.

The volcanic rocks to be described form portion of the Pretoria Group. Figure 2 (Column 1) illustrates the stratigraphic setting of these extrusives. In essence, the Pretoria Group is a cyclical alternation of argillaceous and arenaceous rocks with three volcanic formations. It is the uppermost of the broad subdivisions of the Transvaal Supergroup. The Pretoria Group, together with the underlying formations of the supergroup, were deposited in a sedimentary basin situated on a continental platform. Interpretations of the origin of the magmas extruded during Transvaal times must take into account the presence of the stable sialic crust which was already developed during these early times.

Deposition of the Transvaal Supergroup took place during the interval of geologic time extending back from around 2100-2300 million years ago (Davies and others, 1969; van Niekerk and Burger, 1963). Recently, the lowest volcanic unit of the Pretoria Group has yielded a Rb-Sr date of 2224 ± 21 million years (D. Crampton, Bernard Price Institute for Geophysical Research, personal communication).

STRATIGRAPHIC AND FIELD DESCRIPTION

The details of the stratigraphic setting of the volcanic rocks under discussion are shown in Figure 2 (Column 2). The Machadodorp pyroclastic rocks were recognized during the pioneer mapping program of Hall (1913, 1918), and have been subsequently described by Visser and others (1961), by Schwellnus and others (1962), and by de Waal (1969). Contrary to the mapping of Hall, the Machadodorp pyroclasts are not present in laterally discontinuous occurrences. Recent field-work has established that these rocks can be traced more-or-less continuously from Carolina in the south to Potgietersrus in the northwest.

The Machadodorp Volcanics have a gradational contact with the underlying Boven Shale and with the overlying Silverton Shale. The pyroclasts of the Machadodorp unit commence at the base with very fine-grained and laminated water-laid tuffs (some show small-scale cross-bedding). Some 100-110 metres up from their base, these fine pyroclasts give way to coarse agglomerates which, in certain areas, carry bombs up to about 1 metre in size. These boulder agglomerates pass upwards to bedded lapilli tuffs, which, in turn, grade upward to fine-grained tuffs with widely scattered

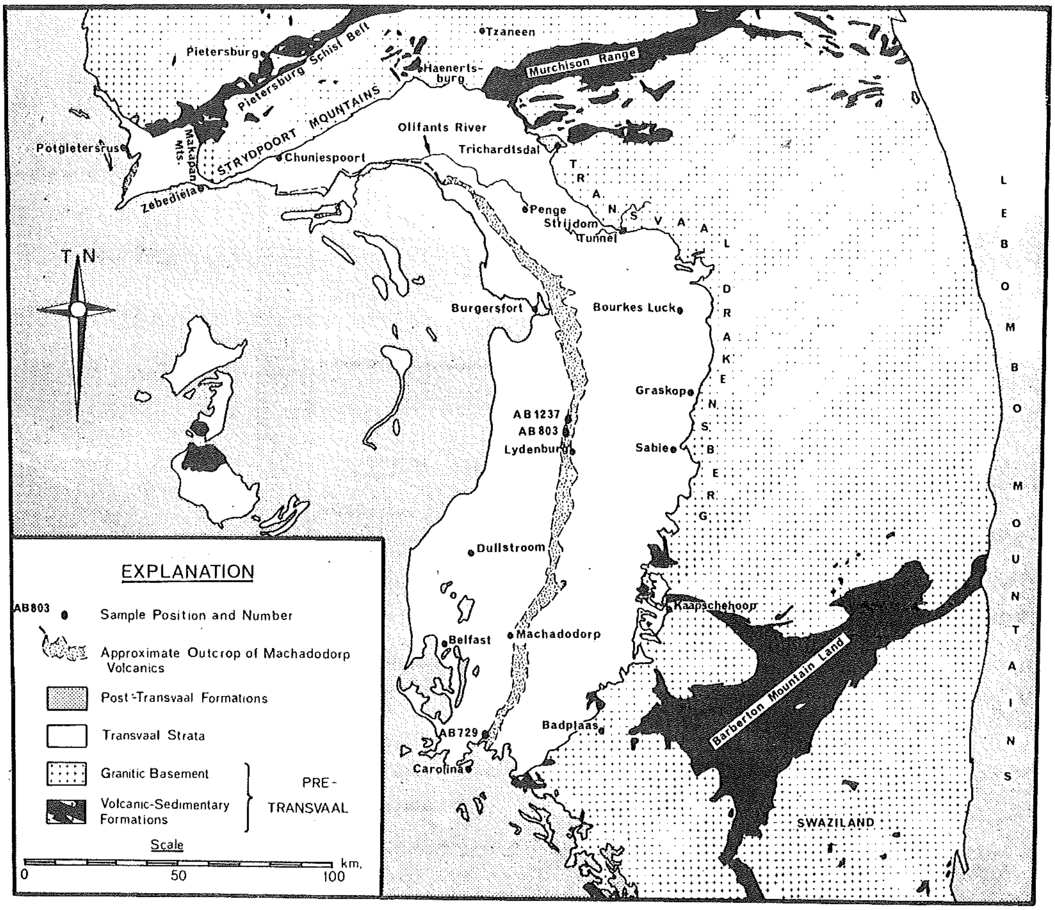

Figure 1 : Map showing the approximate outcrop of the Machadodorp Volcanics and the positions of the Chemically-analyzed samples.

small bombs. Very fine tuffs, in which pyroclastic fragments can barely be made out with the aid of a hand lens terminate the basal pyroclastic member of the Machadodorp Volcanic. This pyroclastic succession constitutes a near-perfect cycle with respect to particle size of pyroclastic fragments.

The basal pyroclastic phase of the formation is succeeded by a puzzling group of rocks which were originally regarded as a sill by Hall (1913, 1918) and by Schwellnus and others (1962). This igneous rock displays conspicuous differences from the normal family of sills which invade the Transvaal Supergroup. In the first instance, these igneous rocks are fine-grained or aphanitic over their entire thickness, whereas normal sills are only chilled for a few metres adjacent to their contacts, being medium-grained elsewhere. In the second case, sills tend to give rise to large spheroidal boulders on weathering, while the igneous rock in question weathers to cobbles and small boulders, often angular to sub-angular in shape (Plate 1A). Thirdly, the sills tend to support a vegetation of small scattered bushes in the highveld, while this rock supports only a lean grass-cover (Plate 1A). It must be stressed that, like all other formations in the Pretoria Group, the

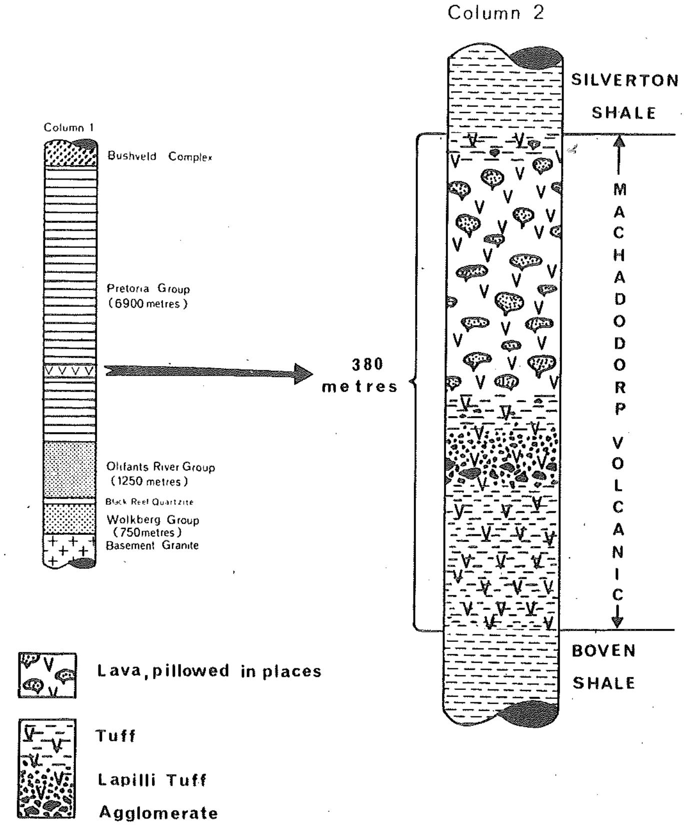

Figure 2 : Diagram showing the stratigraphic setting and internal stratigraphy of the Machadodorp Volcanics.

hitherto-unrecognized lava unit is also intruded by some diabasic sills. In places, adjacent to these sills, intrusion breccias are found. These consist of angular lava fragments in a somewhat coarser-grained diabasic groundmass (Plate 1B).

The outcrop of the lava unit is generally poor, being represented by a red soil with scattered boulders and cobbles on the surface. Examination of river-bed exposures has revealed the true nature of the rock, which is prominently pillowed in a number of places (Plates 1C, D, and E). Elsewhere, considerable thicknesses of lava show no diagnostic textures other than a uniformly fine grain-size.

The long axes of the pillows are usually in the range of 0,2 to 1,0 m. The pillows show most of the usual features, including downward protuberances, tricuspate void-fillings, and a concentric structure related to cooling of pillows from their margins towards their centres. (Plates 1C and D). Amygdales are anomalously rare in the pillows.

Some of the pillow structures in the Machadodorp basalt have irregular cores composed of vein quartz (Plate 1E). These are analogous to the tubular voids found in some recent pillow structures (Macdonald, 1967). According to this author, they are formed by draining out of liquid magma from the cores of partially-solidified pillows. In the case of the basalts under discussion, it is inferred that the tubular pillow-voids became filled with quartz in much the same way as vesicles are filled with secondary minerals to form amygdales. Radial jointing, related to cooling and contraction, is a feature typically found in pillow structures (Macdonald, 1967). Silica-filled radial cracks in a pillow are shown in Plate 1C.

The tricuspate voids between individual pillows are generally filled with a milky-white vein quartz or cherty-textured silica. On weathering of the pillowed horizons, the white quartz fragments are liberated, and serve as a valuable indicator of the presence of underlying pillowed lavas when found in the overlying soil.

The Machadodorp lavas are overlain by a few metres of fine-grained tuff with rare occurrences of chert. In one instance, domed stromatolitic structures were noted in a bed of chert (Button, 1970). The tuffs grade upwards to the shale of the overlying formation. In the zone of gradation, beds of tuff are found alternating with beds of shale.

PETROLOGY OF THE LAVAS

In the hand specimen, the Machadodorp lavas are fine-grained, dense, tough rocks, generally shades of dark greenish-grey in colour. Their appearance is remarkably uniform across the area studied. North of Lydenburg, where the lavas fall within the metamorphic aureole of the Bushveld Complex, minute needles of a metamorphic amphibole can be made out on careful examination of the rocks with a hand-lens.

Under the microscope, the lava is seen to be made up of numerous disoriented needle- or lath-like crystals of plagioclase, set in a groundmass of actinolitic amphibole with some ill-defined patches of chlorite. Scattered small grains of an ore mineral are present, as are some small grains of leucoxene. The felspar has an intermediate composition as judged from extinction angles.

When traced to the north, the lava becomes progressively more strongly altered by thermal metamorphism associated with the Bushveld Complex. In the first instance, a few small flakes of biotite and some epidote grains are developed. With increasing grade, the rock tends to become richer in blades of actinolitic amphibole, which appear to grow partly at the expense of felspar. Higher grades of metamorphism result in the complete destruction of chlorite and an appreciable increase in the grain-size and percentage of actinolitic prisms making up the rock. The actinolite assumes a more intense colouration, and the original felspar laths assume a very minor rôle. At the highest grades, in the area around Burgersfort, the felspars present in the rock have re-crystallized into larger blades, some of which show exsolution blebs of quartz, and others of which exhibit a cryptoperthitic texture.

CHEMISTRY OF THE LAVAS

Three specimens of the lava have been analysed for their major components. In addition, the trace elements Rb and Sr have been determined. The analysed samples were taken from pillow-structures in perfectly fresh river-bed exposures. In each case, the lava was free from macro-scopically-visible amygdales.

Table 1 shows the results of the analyses and an average analysis for the three specimens. The three analyses are remarkably similar, considering that they were selected from sample positions separated by a distance of over 100 km. The major element chemistry indicates that the lavas are basaltic in nature. The basaltic composition is surprising; in South African geologic literature, the green-grey lavas which characterize the Proterozoic basins are usually passed off as andesites on their appearance alone. It is becoming increasingly apparent that true andesites are rarely found in the Archaean or Proterozoic of southern Africa.

None of the analyzed volcanics from the Barberton Mountain Land (Viljoen and Viljoen, 1969a and b), Ventersdorp Supergroup (B. Wyatt, personal communication), Waterberg Supergroup

(O. B. Barker, personal communication) or Transvaal Supergroup (present investigation) show the combination of high SiO_2 (58-60 percent), high Al_2O_3 (17 percent) and very low MgO (3 percent) which (according to Chayes, 1969) typify the Cenozoic andesites. The majority of rocks previously termed andesites, on analysis, turn out to be tholeiitic basalts or basalts with andesitic affinities.

The Machadodorp lavas, on close scrutiny, cannot be compared with the normal continental tholeiitic magma. The first and most obvious discrepancy is in the proportion of K_2O in the Machadodorp lava. Engel and others (1965) (quoting Walker and Poldervaart, 1949) state that most continental tholeiites contain more than 0,5 percent K_2O and that they average 0,9 percent of this oxide. Manson (1967) gives an average value of 0,86 percent K_2O for continental tholeiites from a compilation involving 946 samples. The Machadodorp lava contains an average of 0,15 percent K_2O, which is very similar to the average K_2O content of oceanic tholeiite (0,16 percent according to Engel and others, 1965; 0,22 percent, according to Cann, 1971).

The K_2O content of the Machadodorp lava is also comparable to that in rocks regarded as being representative of the parent magma of the Bushveld Complex (analyses 5 and 6, Table 1). The latter rocks contain 0,19 and 0,14 percent K_2O (Wager and Brown, 1968).

A third close comparison may be made between the Machadodorp lava and the Archaean meta-tholeiites of the Barberton Mountain Land. Analyses 8, 9, and 10 (Table 1) indicate K_2O contents of 0,26, 0,16 and 0,54 for these basaltic rocks (Viljoen and Viljoen, 1969 a, and b). The last analysis is, stratigraphically, the uppermost of the three. Viljoen and Viljoen (1969b) speculate that the relatively high K_2O content of this basalt was caused by contamination from a thickening sialic crust.

A second fundamental feature of the Machadodorp basalts is the extremely low Fe_2O_3/FeO ratio, which averages 0,10. This figure is comparable to the 0,15 ratio for the average oceanic tholeiite (Engel and others, 1965), but is significantly lower than the 0,35 value calculated from Manson's figures for the average continental tholeiite (Manson, 1967, Table IV). According to Engel and his co-workers, this ratio is an index of fractionation in basaltic rocks. The low ratio in the Machadodorp lavas is an indication of the relatively "primitive" or unfractionated state of the magma.

The Na_2O/K_2O ratio is a third critical parameter in the evaluation of the chemical nature of the Machadodorp lava. The ratio of average Na_2O to average K_2O is just over 12. This figure falls well within the 10-15 range for abyssal (oceanic) tholeiites (Anhaeusser, 1972, quoting Jǎkes and Gill, 1970), and is directly comparable to the mean values quoted for the Onverwacht tholeiitic basalts, where ratios calculated from Viljoen's and Viljoen's (1969 a and b) data are in the range from 11 to 12,6.

A measure of the individuality of the South African ocean-floor-type meta-basalts lies in their relatively low Al_2O_3 contents. Estimates of the average Al_2O_3 content of ocean-floor basalts vary from 17,04 percent (Engel and others, 1965) to 16,01 percent (Cann, 1971). None of the average analyses for either the Machadodorp or Onverwacht meta-tholeiites contains more than 14,5 percent of this oxide. This difference, though small, has a strong influence on the normative mineralogy of the basalts.

Only a small amount of trace element work has been carried out on the Machadodorp lava, the elements Sr and Rb having been determined (Table 2, Columns 1-3). The average Sr content of the Machadodorp basalt is 113 ppm, and the average Rb content 3,3 ppm. These values indicate, once again, the similarity of the Machadodorp lava to oceanic tholeiite (Table 2, Column 5), where average values of 130 and <10 are quoted for Sr and Rb, respectively (Engel and others, 1965). Prinz (1967) has compiled trace-element data for basalts from around the globe, but his data are heavily weighted towards continental tholeiites. Prinz quotes Sr and Rb averages of 544 and 18-33 ppm, respectively.

	1	2	3	4	5	6	7	8	9	10	11	12
SiO_2	50,85	50,31	50,55	50,57	50,55	51,45	52,13	49,86	50,07	49,34	51,5	49,61
TiO_2	0,84	0,87	0,88	0,86	0,66	0,34	1,09	0,70	1,22	1,49	1,2	1,43
Al_2O_3	14,36	14,33	14,43	14,37	15,23	18,67	13,33	14,25	13,34	17,04	16,3	16,01
Fe_2O_3	0,95	1,12	1,26	1,11	1,04	0,28	2,24	2,65	2,31	1,99	2,8	11,49
FeO	10,48	10,66	10,21	10,45	10,07	9,04	9,94	7,67	9,10	6,82	7,9	
MnO	0,21	0,20	0,20	0,20	0,23	0,47	0,21	0,17	0,19	0,17	0,17	0,18
MgO	7,43	7,55	7,76	7,56	8,30	6,84	6,35	7,32	6,10	7,19	5,9	7,84
CaO	10,84	9,94	11,12	10,63	11,30	10,95	8,98	10,69	9,47	11,72	9,8	11,32
Na_2O	1,49	2,22	1,84	1,85	2,24	1,58	2,97	2,54	3,34	2,73	2,5	2,76
K_2O	0,11	0,15	0,19	0,15	0,19	0,14	0,26	0,16	0,54	0,16	0,86	0,22
P_2O_5	0,12	0,12	0,05	0,10	0,12	0,09	0,07	0,05	-	0,16	0,21	0,14
H_2O^+	2,29	2,32	1,41	2,01	0,24	0,34	1,97	2,70	2,95	0,69	0,81	-
H_2O^-	0,01	0,04	0,07	0,04	-	-	0,11	0,11	0,06	0,58	-	-
CO_2	0,11	0,10	0,04	0,08	-	-	0,07	0,48	0,23	-	-	-
TOTAL	100,09	99,93	100,01	100,00	100,17	100,19	99,72	99,35	98,92	100,08	99,95	101,00

1. Sample AB729, Machadodorp pillow basalt, Kwaggafontein 8IT, Carolina District [Analysts - General Superintendence Co. (S.A.) (Pty.) Limited].
2. Sample AB803, Machadodorp pillow basalt, Kleinplaas 26KT, Lydenburg District [Analysts - General Superintendence Co. (S.A.) (Pty.) Limited].
3. Sample AB1237, Machadodorp pillow basalt, Boomplaas 24KT, Lydenburg District [Analysts - National Institute for Metallurgy, Milner Park, Johannesburg].
4. Average composition of Machadodorp pillow basalt (average of analyses 1, 2 and 3).
5. Fine-grained hypersthene gabbro (SA1087), Marginal Group, Bushveld Complex [Analyst - Miss M. Hedges, Oxford University]. Quoted from Wager and Brown (1968).
6. Fine-grained hypersthene gabbro, Marginal Group, Bushveld Complex [Analyst - E.G. Radley]. Quoted from Wager and Brown (1968), originally from Daly (1928).
7. Average meta-tholeiite from the lower formations of the Onverwacht Group (Viljoen and Viljoen, 1969a, p. 78).
8. Average of pillowed meta-tholeiites from the Hooggenoeg Formation (Viljoen and Viljoen, 1969b, p. 142).
9. Average of meta-tholeiites from the Kromberg Formation (Viljoen and Viljoen, 1969b, p. 146).
10. Average oceanic tholeiite (Engel and others, 1965, p. 721).
11. Average continental tholeiite (Manson, 1967, p. 223).
12. Average ocean-floor basalt (Cann, 1971, p. 497).

Table 1 : Major Element Geochemistry of Machadodorp Basalts and Related Basaltic Rocks

	1	2	3	4	5	6
Rb (ppm)	5,2	2,0	2,7	3,3	<10	18-33
Sr (ppm)	100,4	112,9	125,6	113,0	130	544

1, 2 and 3 - Machadodorp pillow-basalts (see Table 1 for localities and sample numbers).

4 - Average of analyses 1-3.

5 - Average oceanic tholeiite (Engel and others, 1965, p. 721).

6 - Average basalt (Prinz, 1967, p. 307 and 310).

Table 2 : Rb and Sr in Some Basaltic Rocks

	1	2	3	4	5	6	7	8
Quartz	2,25	0,00	2,74	3,18	1,87	0,00	0,00	2,99
Orthoclase	0,94	1,16	0,86	1,64	1,01	3,44	0,98	5,33
Albite	17,12	20,15	14,27	27,59	23,65	31,40	24,74	22,85
Anorthite	31,39	30,99	43,70	23,03	28,00	20,70	34,07	31,19
Diopside	17,51	19,61	8,39	17,79	18,90	21,65	18,95	13,61
Hypersthene	27,94	20,38	29,09	22,45	21,33	16,01	12,55	18,93
Olivine	0,00	5,45	0,00	0,00	0,00	1,89	4,20	0,00
Magnetite	1,19	1,09	0,29	2,42	2,87	2,52	2,10	2,97
Ilmenite	1,23	0,92	0,48	1,57	1,01	1,78	2,09	1,70
Apatite	0,21	0,25	0,19	0,15	0,11	0,00	0,33	0,44
Calcite	0,21	0,00	0,00	0,18	1,26	0,61	0,00	0,00
TOTAL	99,99	100,00	100,01	100,00	100,01	100,00	100,01	100,01

1. Average for Machadodorp pillow basalt
2. Fine-grained hypersthene gabbro (SA1087), Marginal Group, Bushveld Complex (Wager and Brown, 1968).
3. Fine-grained hypersthene gabbro, Marginal Group, Bushveld Complex (Wager and Brown, 1968; originally Daly, 1928).
4. Average meta-tholeiite from lower formations of Onverwacht Group (Viljoen and Viljoen, 1969a).
5. Average of pillowed meta-tholeiite from the Hooggenoeg Formation (Viljoen and Viljoen, 1969b).
6. Average meta-tholeiite from Kromberg Formation (Viljoen and Viljoen, 1969b).
7. Average oceanic tholeiite (Engel and others, 1965).
8. Average continental tholeiite (Manson, 1967).

Table 3 : CIPW Molecular Normative Minerals of Selected Basaltic Rocks

The CIPW molecular normative mineralogy of the Machadodorp and other selected basalts is shown in Table 3. The similarity of the Machadodorp magma to ocean-floor basalt, to the parental Bushveld magma, and to the Onverwacht meta-tholeiites is striking in respect of the small percentages of normative orthoclase, apatite, magnetite, and ilmenite contained in these rocks. The plagioclases in these rocks are all intermediate-to-calcic in composition. All contain normative hypersthene and diopside as their dominant mafic minerals.

The most significant differences reflected by Table 3 lie in the presence of normative quartz in some of the basalts and of normative olivine in others. The chemistry of the selected analyses are all delicately balanced with respect to silica saturation, containing only small percentages of normative quartz or olivine. The chemical differences between quartz- and olivine-normative magmas are subtle, and are due to complex chemical interrelationships. An olivine-normative mineralogy may be caused by relatively higher amounts of alkalies, CaO and Al_2O_3 (which use up SiO_2 to form felspars, leaving an excess of FeO and MgO) or by higher percentages of FeO and MgO. Thus, for example, the slightly larger amounts of Al_2O_3 and Na_2O in Engel's average oceanic tholeiite (Column 10, Table 1), in comparison to the average Machadodorp basalt (Column 4, Table 1), probably accounts for the olivine-normative nature of the former.

THE SIGNIFICANCE OF THE MACHADODORP BASALT GEOCHEMISTRY

The similarities between the Machadodorp lava, the Bushveld parent-magma, the Onverwacht meta-tholeiite, and ocean-floor basalts has been stressed. The four groups are chemically so similar that a common origin seems probable. There is considerable evidence to suggest that the ocean-floor basalts were derived by a partial melting of an upper mantle "pyrolite". Hart and others (1970), from their study of trace-elements in Archaean basalts, suggest that these rocks were formed at shallow depths (less than 50 km) by high degrees of partial melting (over 30 percent) of an ultramafic source-rock in the upper mantle. Kushiro (1972) has experimentally produced a basaltic partial melt from a naturally-occurring spinel lherzolite at 10 to 20 kilobars (anhydrous). Further experimental studies (Kushiro and Thompson, 1972) on abyssal tholeiites from the Mid-Atlantic Ridge indicated that a plagioclase-tholeiite magma (similar to the Machadodorp basalt) could form by partial melting of a more mafic material or of a mantle peridotite at depths of 15 to 25 km in the presence of small amounts of water.

To summarize, modern thinking supposes that ocean-floor basalts formed by partial melting of an ultramafic upper mantle material at relatively shallow depths (estimates are in the range from 15 to 50 km). There is apparently no logical reason to suppose that the Machadodorp magma was not generated in the same way.

Sub-crustal melting in Archaean greenstone environments is considered to be comparable to the partial melting presently taking place beneath the oceanic crust. The close similarities of Archaean meta-tholeiites and ocean-floor basalts has been used as evidence for the absence of a significantly-developed sialic crust in these early times (Engel, 1968; Viljoen and Viljoen, 1969b; Anhaeusser, 1972). These authors reasoned that tapping of a low-potash melt through a sialic crust would result in a characteristic sialic fingerprint to the basalt chemistry. While this argument is by no means invalidated by the present findings (especially in the case of the extremely primitive and distinctive komatiite basalts), it must be coupled with the realization that oceanic tholeiitic magma can be passed through a sialic crust with insignificant contamination from that source.

The possibility exists that the sialic crust was much thinner during Transvaal times than it is at the present. At the present level of erosion in the eastern Transvaal, no geological or geochronological evidence exists for crustal additions at times younger than about 2550 million years ago (Allsopp and others, 1969). Any sialic additions which occurred must have been plastered onto the base of the crust from below.

The question arises that, if oceanic basalt magma can be passed through a sialic crust without contamination, what mechanism can be called on to explain away the compositional pecularities of continental tholeiite? One alternative is to suppose that Machadodorp-type extrusives are exceptional, and can be explained by lining of feeder-channels by chilled basalt. This argument is countered by the growing evidence from the Proterozoic of South Africa, that low-potash magmas are not exceptional. They have been found in both the Ventersdorp and Waterberg Supergroups (personal communications by B. Wyatt and O.B. Barker, respectively). The remaining alternatives are that a thickening sialic crust between the Proterozoic and the present is a reality, or that some sub-sialic mechanism (other than contamination) must be called on to explain the relatively high potash concentrations in continental basalts. If the first alternative is correct, it provides powerful support to the theory of sialic underplating (Engel, 1968), since there is no evidence of younger sialic additions in the eastern Transvaal at the present level of erosion.

* *

Acknowledgements

The writer is indebted to the South African Geological Survey for the analytical service used in this study. Mr. D. Crampton (Bernard Price Institute of Geophysical Research) carried out the Rb and Sr determinations. Dr. C.R. Anhaeusser is thanked for bringing much of the relevant literature to the writer's notice and for helpful discussions. The norm calculations were performed on a computer using a programme devised by Mr. D.H. Lenthall. Mrs. B.M. Button typed the draft copies of this paper.

* *

List of References

Allsopp, H.L., Davies, R.D., de Gasparis, A.A.A. and Nicolaysen, L.O., 1969, Review of Rb-Sr Age Measurements from the Early Precambrian Terrain in the South-Eastern Transvaal and Swaziland : Geol. Soc. S. Afr., Spec. Pub. No. 2, p. 433-444.

Anhaeusser, C.R., 1972, The Evolution of the Early Precambrian Crust of Southern Africa : Econ. Geol. Res. Univ, Inf. Circ. 70, 31 p.

Button, A., 1970, Early Proterozoic Algal Stromatolites of the Pretoria Group, Transvaal Sequence : Trans. geol. Soc. S. Afr., V. 74, p. 201-210.

Cann, J.R., 1971, Major Element Variations in Ocean-Floor Basalts : Phil. Trans. Roy. Soc. Lond., A.268, p. 495-505.

Chayes, F., 1969, The Chemical Composition of Cenozoic Andesite : Proceedings of the Andesite Conference, Oregon. Dept. Geol. Mineral Ind. Bul. 65., p. 1-11.

Cousins, C.A., 1962, The Stratigraphy, Structure and Igneous Rocks of the Transvaal System at the Western Areas Gold Mine : Trans. geol. Soc. S. Afr., V. 65, p. 27.

Daly, R.A., 1928, Bushveld Igneous Complex of the Transvaal : Bull. Geol. Soc. Amer., V. 39, p. 703-768.

Davies, R.D., Allsopp, H.L., Erlank, A.J. and Manton, W.I., 1969, Sr-Isotopic Studies on Various Layered Mafic Intrusions in Southern Africa : Spec. Pub. No. 1, Geol. Soc. S. Afr., p. 576-593.

De Waal, S.A., 1969, Interference-Folding of Bushveld-Igneous-Complex Age in the Transvaal System North of Marble Hall, Transvaal : Spec. Pub. No. 1., Geol. Soc. S. Afr., p. 283-298.

Engel, A.E.J., 1968, The Barberton Mountain Land : Clues to the Differentiation of the Earth : Trans. geol. Soc. S. Afr., Annexure to Volume 71, p. 255-270.

Engel, A.E.J., Engel, C.G. and Havens, R.G., 1965, Chemical Characteristics of Oceanic Basalts and the Upper Mantle : Geol. Soc. Amer. Bull., 76, p. 719-734.

Hall, A.L., 1913, The Geology of the Country South-West of Lydenburg : An Explanation of Sheet 11 (Lydenburg), Geol. Surv. S. Afr., Pretoria, 38 p.

Hall, A.L., 1918, The Geology of the Country Round Belfast : An Explanation of Sheet 16 (Belfast), Geol. Surv. S. Afr., Pretoria, 56 p.

Hart, S.R., Brooks, C., Krogh, T.E., Davis, G.L. and Nava, D., 1970, Ancient and Modern Volcanic Rocks - A Trace Element Model : Earth and Planetary Science Letters, V. 10, p. 17-28.

Jakes, P. and Gill, J., 1970, Rare Earth Elements and the Island Arc Tholeiitic Series : Earth and Planetary Science Letters, V. 9, p. 17-28.

Kushiro, I., 1972, Partial Melting of Synthetic and Natural Peridotites at High Pressures : Carnegie Institution Year Book 71, p. 357-362.

Kushiro, I. and Thompson, R.N., 1972, Origin of Some Abyssal Tholeiites from the Mid-Atlantic Ridge : Carnegie Institution Year Book 71, p. 403-406.

Macdonald, G.A., 1967, Forms and Structures of Extrusive Basaltic Rocks : p. 1-61 in Hess, H.H. and Poldervaart, A. (Eds.) - Basalts : Interscience Publishers, New York, 862 p.

Manson, V., 1967, Geochemistry of Basaltic Rocks - Major Elements : p. 215-269 in Hess, H.H. and Poldervaart, A. (Eds.) - Basalts : Interscience Publishers, New York, 862 p.

Prinz, M., 1967, Geochemistry of Basaltic Rocks - Trace Elements : p. 271-323 in Hess, H.H. and Poldervaart, A. (Eds.) - Basalts : Interscience Publishers, New York, 862 p.

Schwellnus, J.S.I., Engelbrecht, L.N.J., Coertze, F.J., Russel, H.D., Malherbe, S.J., van Rooyen, D.P. and Cooke, R., 1962, The Geology of the Olifants River Area, Transvaal : An Explanation of Sheets 2429B (Chuniespoort) and 2430A (Wolkberg), Geol. Surv. S. Afr., Pretoria, 84 p.

Van Niekerk, C.B. and Burger, A.J., 1964, The Age of the Ventersdorp System : Annals, Geol. Surv. S. Afr., 3, p. 75-86.

Viljoen, M.J. and Viljoen, R.P., 1969(a), The Geology and Geochemistry of the Lower Ultramafic Unit of the Onverwacht Group and a Proposed New Class of Igneous Rock : Geol. Soc. S. Afr., Spec. Pub. No. 2, p. 55-85.

Viljoen, R.P. and Viljoen, M.J., 1969(b), The Geology and Geochemical Significance of the Upper Formations of the Onverwacht Group : Geol. Soc. S. Afr., Spec. Pub. No. 2, p. 113-151.

Visser, H.N., Spies, J.J., Fourie, G.P., Viljoen, J.J., Söhnge, A.P.G. and Venter, F.A., 1961, Die Geologie van die Gebied Tussen Middelburg en Cullinan, Transvaal : An Explanation of Sheets 2528D (Bronkhorstspruit) and 2529C (Witbank) : Geol. Surv. S. Afr., Pretoria 71 p.

Wager, L.R. and Brown, G.M., 1968, Layered Igneous Rocks : Oliver and Boyd, Edinburgh and London, 588 p.

Walker, F. and Poldervaart, A., 1949, Karroo Dolerites of the Union of South Africa : Bull. Geol. Soc. Amer., V.60, p. 591-706.

*

Key to Figures

Figure 1 : Map showing the approximate outcrop of the Machadodorp volcanics and the positions of the chemically-analyzed samples.

Figure 2 : Diagram showing the stratigraphic setting and internal stratigraphy of the Machadodorp Volcanics.

*

Key to Plates

Plate 1 A : The contact of the Machadodorp basalt (foreground) with a diabase sill (background). The lava, which is characterized by angular cobbles and a lean grass cover, may be differentiated from the diabase, which weathers to round boulders and supports a vegetation of scattered small bushes (Kwaggafontein, north of Carolina).

Plate 1 B : Intrusion breccia, consisting of fragments of Machadodorp basalt (outlined in chalk) in a diabase matrix (Vlakfontein, north of Carolina).

C : Pillow structure in Machadodorp basalt, showing radial cracks and a concentric structure related to cooling (Boomplaas, north of Lydenburg).

D : A river-bed exposure showing cross-sections and plan-views of pillowed basalt (Kwaggafontein, north of Carolina).

E : A group of pillows, one of which shows a quartz-filled core (Kwaggafontein, north of Carolina).

* *

PLATE 1