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ALKALINE ROCKS AND THE OCCURRENCE OF URANIUM

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SAMEVATTING

Talle alkalikomplekse bevat lae konsentrasies van uraan en ander minerale en word as waardevolle potensiële reserwes beskou. Sekere ingewikkelde metallurgiese probleme moet egter nog in hierdie verband opgelos word.

Alkaligesteente wat gedurende tydperke van geologiese kalmte ontwikkel het, kom in verskillende vorme en omgewings voor en is hoofsaaklik in stabiele aseismiese gebiede afgeset. Heelwat hiervan is in ver= lengings van see-omvormingsverskuiwings onder die vastelandkors ver= vat en die toepassing van hierdie begrip op gebiede wat tans, na ons wete, nie alkalikomplekse bevat nie, kan nuttig blyk om potensiële gebiede vir prospektering af te baken.

ABSTRACT

Many alkaline complexes contain uranium and other minerals in low concentrations and are regarded as constituting valuable potential reserves. Certain complex metallurgical problems, however, remain to be solved.

Alkaline rocks occur in a number of forms and environments and it is noted that they are generated during periods of geological quiescence emplaced mainly in stable aseismic areas. Many occur along the extensions of oceanic transform faults beneath the continental crust and the application of this concept to areas not currently known to host alkaline complexes may prove useful in identifying potential target areas for prospecting operations.

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1. INTRODUCTION

Alkaline complexes are one of the most fascinating group of geological phenomena because of their uniqueness, brought about by the variability of the rock types and minerals, modes of emplacement and associated structural relationships.

Certain of these complexes contain valuable potential reserves of different minerals and elements usually in low concentrations. For example in South Africa phosphates, vermiculite, copper, zircon, niobium and a small amount of uranium, are being obtained from carbonatites and asso= ciated alkaline rocks. In the Republic of Bophuthatswana the Pilanes= berg Alkaline Complex has large reserves of uranium, niobium, zinc, rare earths and zircon associated with nepheline syenites. Other complexes in the world may also have a high uranium potential, such as the Ilimaussaq Complex in Greenland and Pocos de Caldas in Brazil.

Uranium in alkaline complexes usually occurs in a form generally not amenable to current extraction techniques. However, should the predicted shortfall in demand by the turn of the century materialise, these types of deposits will of necessity be forced into the category of economic viability.

Two approaches are essential for the evaluation of the economic uranium potential of alkaline complexes. The first is the delineation of target areas in those parts of the world which have no or very few known complexes. Secondly, once a complex has been found which may be partially or totally buried, it must be evaluated for its uranium potential using geological, mineralogical and geochemical hypotheses based upon known criteria from other similar deposits.

In reviewing the uranium potential of alkaline rocks it is necessary to discuss the evaluation of such rocks in terms of their distribution, classification, mineralogy, geochemistry and tectonics. Many works have been devoted to this subject, the most important of which are Heinrich (1966), Tuttle and Gittens (1966), Verwoerd (1967), Sørensen (1974) and Murphy *et al* (1978).

There are many other papers and books of noteworthy value in the literature. However, a comprehensive listing of most of that which has been written on this subject can be found in the abovementioned works and will not be repeated here except for the purpose of highlighting certain aspects of the discussion.

2. OCCURRENCE AND ABUNDANCE

Alkaline rocks occur in a number of different geological forms as listed below (Sørensen, 1974, p.34):

(a) Sills and laccoliths - commonly formed in *in situ* differentiated alkali basalt sills such as the Shonkin Sag Laccolith in the USA.

(b) Dykes - large and small.

(c) Central intrusions - includes necks, plugs and stocks varying in size from a few metres to several kilometers.

(d) Ring intrusions - composed of ring dykes, e.g. Spitskop and the Pilanesberg in Southern Africa.

(e) Layered intrusions - funnel shaped intrusions which are differentiated *in situ* to form layering, e.g. Lovozero in the USSR and Ilimaussaq in Greenland.

(f) Conformable bodies - syntectonically emplaced and folded during orogenesis, e.g. Ilmen and Vishnevogorsk in the USSR.

(g) Simple homogeneous intrusions - bodies composed of only one rock type, e.g. the Serra de Monchique foyaite of Portugal.

(h) Marginal syenite in granite massifs - tended to form during a feldspar crystallisation of a granite magma such as at Cape Ann in the USA.

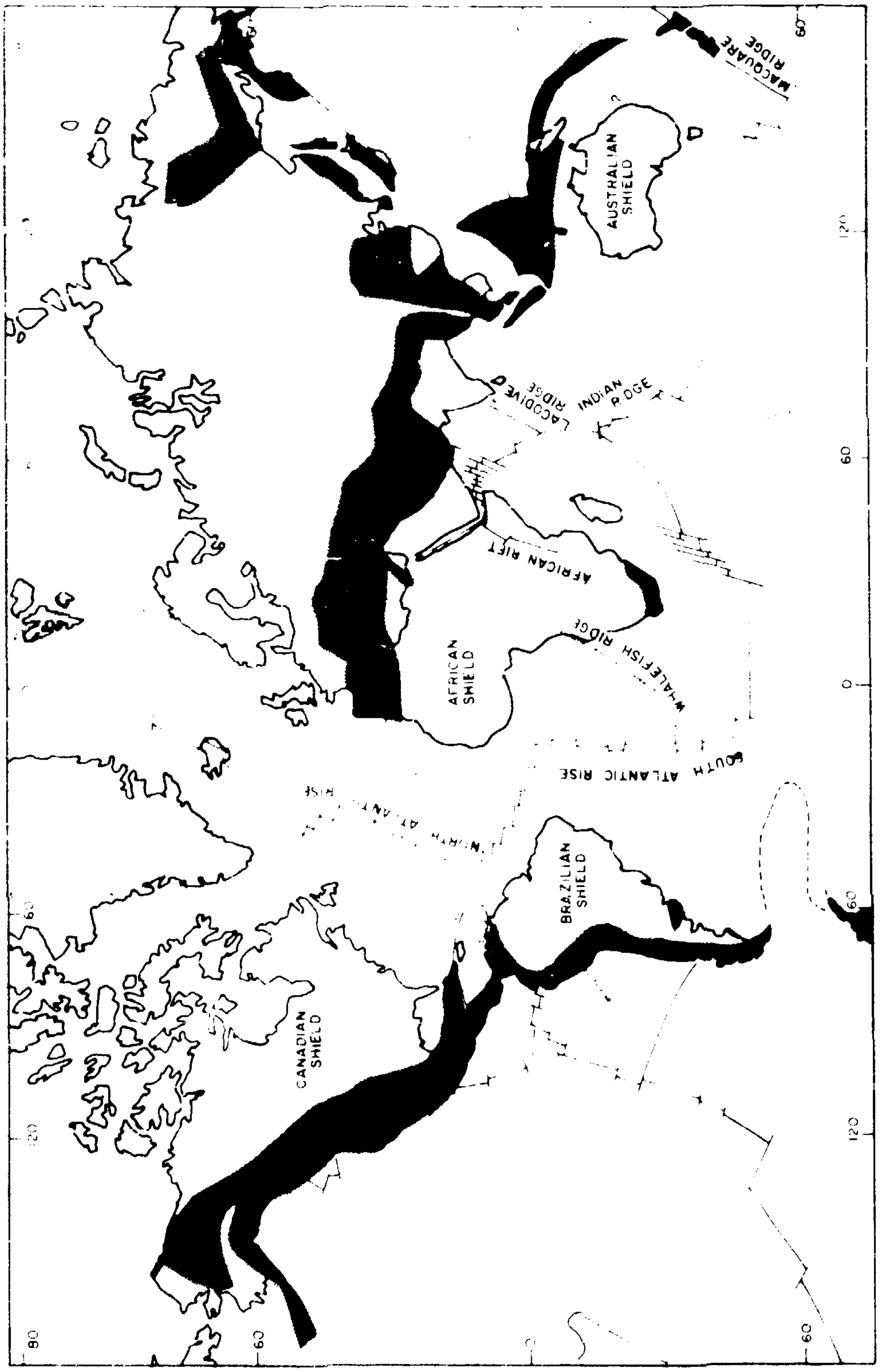
The most important geological forms, with respect to size and uranium distribution, are the ring and layered intrusives.

Geochronologically, alkaline rocks span the time gap from 2 050 Ma for Phalaborwa (Verwoerd, 1967) to the present time with the eruption of Oldoinyo Lengai in Tanzania (Heinrich, 1966). Alkaline rocks of widely different ages are closely associated indicating a reactivation of mag= matic activity over a long period of time.

Heinrich (1966) provided the following listing of the abundances of carbonatites on the globe which in order of magnitude are Africa, USSR, North America, South America, Eastern Europe and India. He further stated that none have been found in Australia but other likely areas for finding carbonatites are Argentina, Venezuela, Guianas, China and North America, particularly in the Rocky Mountains, Western Texas, Wyoming, Western Canada, Eastern Canada and Northern Mexico. Since then, two carbonatite occurrences have been reported from Australia. Mud Tank complex in Central Australia, Northern Territory dated at 730 Ma (Moore, 1973; Black and Gulson, 1978) and the Laverton complex in the Yilgarn Archaean Shield of Western Australia being early Proterozoic in age (Utah Development Company, Annual Reports - personal communication R.A. Binns). Murphy *et al* (1978) have provided a listing of some of the most prominent occurrences in the world.

3. ASSOCIATED TECTONIC STRUCTURES

The consensus amongst most researchers (Sørensen, 1974) is that alkaline complexes were generated during periods of geological quiescence but a relatively small number (i.e. synorogenic) were emplaced syntectonically in mobile environments. Alkaline rocks tend therefore to be mainly located in aseismic zones of the continental crust within shield and cratons subsequent to folding having taken place (i.e. epidiastresic). It is in these situations that alkaline magmas are able to differentiate in an enclosed system without the loss of the volatile constituents, thereby facilitating the development of alkaline conditions. A tectonic map of the world (Fig. 1) indicates zones of major movement which cor= respond to the world seismicity pattern. The stable areas are charac= terised by shields and cratons, the most important being east of the Rocky Mountains, east of the Andes, Greenland, Africa, Arabian Peninsula, India, Europe and Asia north of the Alpine-Himalayan Belt and Australia.


MACQUARE RIDGE
AUSTRALIAN SHIELD
LACCADIVE RIDGE
INDIAN RIDGE
AFRICAN RIFT
AFRICAN SHIELD
WHALEFISH RIDGE
SOUTH ATLANTIC RISE
NORTH ATLANTIC RISE
BRAZILIAN SHIELD
CANADIAN SHIELD
60
120
0
80

The South American, Arabian, Indian and Australian regions contain few alkaline complexes but exploration may lead to the discovery of new occurrences.

An important feature concerning the distribution of alkaline rocks is their apparent close association to deep-seated fractures which pene=trate the continental crust and upper mantle.

There are six major tectonic categories into which alkaline rocks can be classified. Only typical examples in each category are briefly discussed. Some of the alkaline provinces may contain one or more of the listed tectonic features, for example, doming and rifting are commonly associated.

3.1 Cratogenic Rifting

Bailey (1974) noted the relationship between rifting and alkali magma=tism in the continental crust. He concluded that these cratogenic rifts occurred as a result of crustal warping taking place mainly in the crests of the doming. Typical examples are:

(a) Rhine-Oslo Graben - Northern Europe (Wimmenauer, 1974)
(b) Gardar Rift - Greenland (Upton, 1974)
(c) East African Rift - (Bailey, 1974)
(d) Kola Peninsula - Russia (Gerasimovsky *et al*, 1974)
(e) Monteregian Province - Canada (Philpotts, 1974; Gold, 1967; Murphy *et al*, 1978)

The Monteregian Alkaline Province occurs at the intersection of the E-W-trending Ottawa Graben and the NNE-trending St Lawrence Graben with several of the alkaline intrusives actually occurring at fault inter=sections. The intrusive activity of the province spans four major tectonic episodes starting at 1 000 Ma and ending at 110 Ma (Philpotts, 1974) with the youngest rocks occurring in the east.

This long intermittent period of igneous activity cuts across tectonic provinces such as cratons, shelf, mio- and eugeosynclinal facies, sug=gesting that the events were controlled by a deep-seated fault system (Gold, 1967).

3.2 Intersection of Fault Zones not Rift-Related

Alkaline complexes can occur along fault zones which are transverse to the regional structural trend:

(a) Monteregian Province - Canada (Philpotts, 1974)
(b) Gardar Province - Greenland (Upton, 1974)

The Gardar alkali province occurs in an E-W-trending zone, 180 km long and 80 km wide. Intrusions took place during a magmatic episode referred to as the Gardar Cycle, spanning a period of 400 Ma with mag=matism reaching a peak between 1 150 - 1 250 Ma.

Large-scale faulting with both vertical and horizontal displacements of up to 15 - 20 km occurred. Two main groups of fault strikes are found, those trending ESE and E having left-lateral displacements and those that trend NNW and NNE being right-lateral wrench faults. Consequently, there appears to have been a conjugate set of trans=current faults intermittently active throughout the formation of the Graben, that may be explained in terms of a tensional stress along a NW-SE axis (Upton, 1974). Block faulting and rifting is thought to have occurred near Ilimaussaq.

3.3 At Bends in the Strike of Monoclines or Flexures

Deformation and bending of previously folded rocks, along zones of structural weakness, could cause further weakening and, if extended to depth, could create favourable loci for the emplacement of alkaline rocks. Such examples are:

(a) Kangerdlugssuaq Complex - E. Greenland (Kempe *et al*, 1970)
(b) Nuanetsi Province - Zimbabwe (Cox, 1970)
(c) Monteregian Province - Canada (Philpotts, 1974)

3.4 Updomed or Arched Structures

The fundamental characteristics of rift formation are tensional features resulting in updoming and arching having fractures extending into the mantle. Major crustal flexuring and the intersection of anti- and syn=clinorium folding have been postulated by Ferguson (1973) as being an important foci for the emplacement of the alkaline Pilanesberg Province in Southern Africa. Examples within this category are:

(a) Rift Valley occurrences in general (Bailey, 1974)
(b) Siberian alkaline Province (Butakova, 1974)
(c) Nigeria - Niger Alkaline Province
(d) Transvaal Alkaline Province - South Africa (Verwoerd, 1967; Ferguson, 1973)

3.5 Mid-Oceanic Transform Faults

Some major structures within the continental crust are thought to re=present the lateral extension of oceanic transform faults which have resulted from differential plate tectonic movements. Alkaline com=plexes in certain areas have been emplaced along such postulated zones of weakness. Examples of alkaline complexes thought to owe their origin to this hypothesis are listed below:

(a) Basin and Range - USA (Bailey, 1974)
(b) White Mountain - USA (Rhodes, 1971)
(c) Sutherland, Van Rhynsdorp, Kuboos - South Africa
(d) Luderitz and Damaraland Provinces - South West Africa / Namibia (Martin *et al*, 1960; Rhodes, 1971; Marsh, 1973)
(e) Sao de Bandeira - Henrique de Carvalho Province - Angola (Lapido-Loureiro, 1973)
(f) Cameroun Lineament (Bailey, 1974; Marsh, 1973; Rhodes, 1971)
(g) Jos Plateau - Nigeria Province (Rhodes, 1971)
(h) San Sabastian and Pocos de Caldas Provinces - Central Brazilian Province (Heinrich, 1966; Marsh, 1973; Murphy *et al*, 1978; Ulbrich and Gomes, in press)
(i) Northern Brazilian Province (Ulbrich and Gomes, in press)
(j) Mariscala and Piratini - Uruguay - Southern Brazilian Province (Marsh, 1973; Ulbrich and Gomes, in press)
(k) Cerro Cora - Paraguay (IUREP, 1977)
(l) Mount Dromedary - Australia (Boesen and Joplin, 1972)

The regions from (c) to (k) are situated along the Atlantic Ocean conti=nental margins on the west coast of Africa and the east coast of South America (Fig. 2).

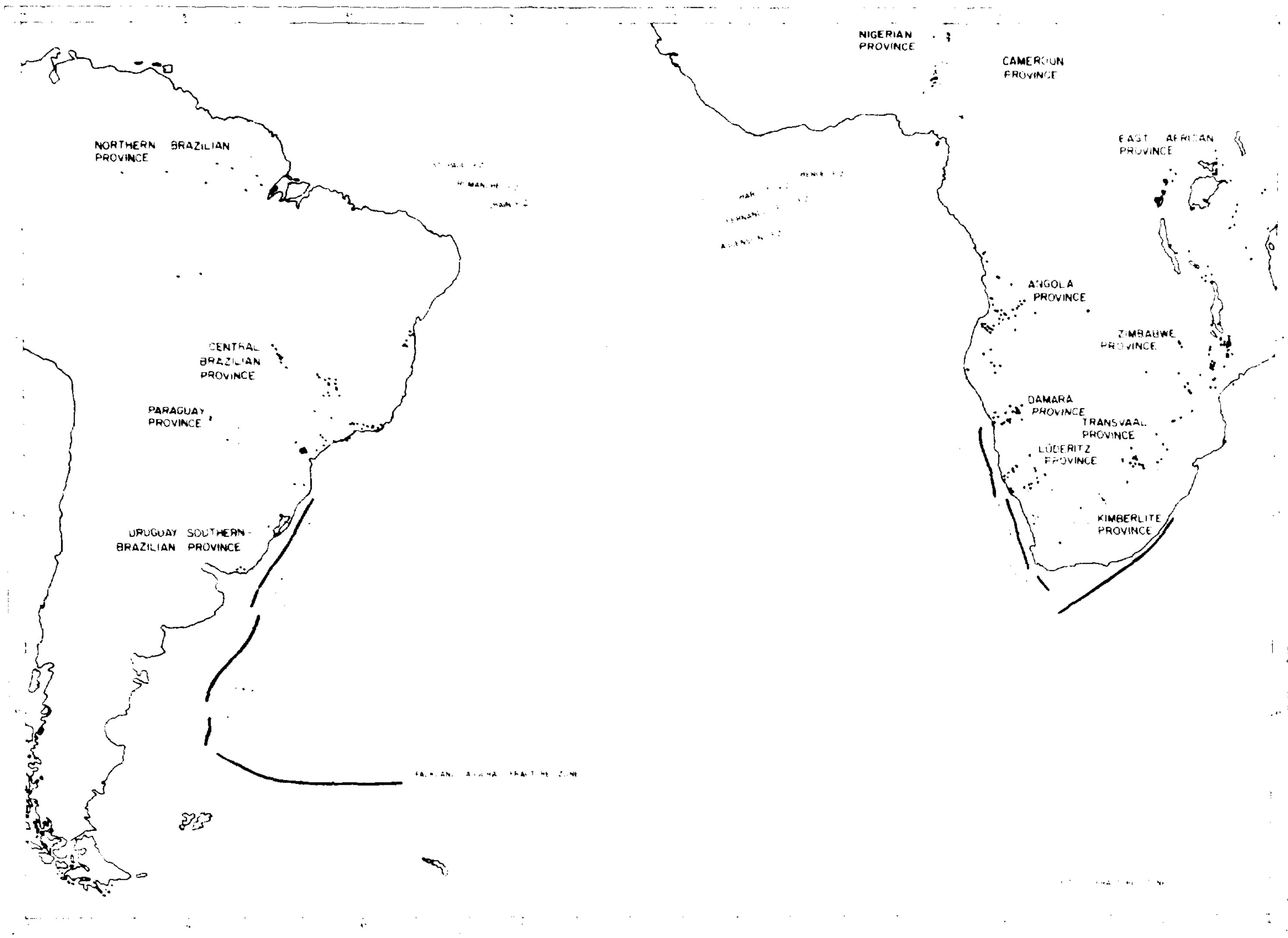


FIG. 2

THE SOUTH ATLANTIC SHOWING MID-ATLANTIC RIDGE CREST (DOUBLE LINES), TRANSFORM FAULTS AND FRACTURE ZONES (CURVED QUASILATITUDINAL LINES), MESOZOIC AND CENOZOIC MAGNETIC ANOMALY ISOCHRONS (NEARLY LONGITUDINAL LINES) ALKALINE COMPLEXES ● AND KIMBERLITES. THE HEAVY LINES REPRESENT THE OCEAN-CONTINENT BOUNDARY ALONG THE CONTINENTAL MARGINS OF SOUTH-WESTERN AFRICA AND SOUTH-EASTERN SOUTH AMERICA. THE FALKLAND ESCARPMENT AND AGULHAS MARGIN. ALKALINE COMPLEXES ARE POSTULATED TO OCCUR ALONG THE EXTRAPOLATION OF THE TRANSFORM FAULTS. (MODIFIED AFTER SIMPSON 1977)

It has been recognised for a long time that the alkaline provinces in Angola and South West Africa/Namibia lie along lines orientated in a NE direction (Martin *et al.*, 1960). More recently this tendency has been confirmed by several researchers (Rhodes 1971, Marsh 1973 and Lapido-Loureiro, 1973).

Rhodes (1971) pointed out that alkaline complexes of White Mountain, USA, and those of the Nigeria-Niger Province follow structural trends different from those in which they are located. In the case of the former, they follow a NNW structural direction continuous with the Kelvin Seamounts which is different from the older Appalachian trend. On this evidence and that of the structural positions of the above=mentioned complexes, Rhodes postulated that they tend to fall along extrapolated extensions of the transform faults associated with the Mid-Atlantic Ridge and the plate motions of the spreading Atlantic Ocean. Marsh (1973) plotted the positions of the complexes on both sides of the Atlantic relative to the present pole of rotation and showed that the Angola Province corresponds with the northern and southern arms of the Central Brazil Province. The Damaraland Province Province has equivalents in the southern portion of the Central Brazil Province and the Luderitz Province could be correlated with the Uruguay - Southern Brazilian Province as shown by the data given by Ulbrich and Gomes (in press). The Nigerian Province has equivalent uraniferous alkaline complexes in the Northern Brazil Province centered around the Amazon River (Ulbrich and Gomes, *ibid.*) (Fig. 2).

The most up to date map showing the Mid-Atlantic Ridge, the associated transform faults, magnetic anomaly isochrons and ocean continent bounda=ries of the South Atlantic was presented by Simpson (1977) and is shown in Fig. 2 with the alkaline provinces added to indicate their relation=ships to the transform faults.

From an inspection of Fig. 2 the following significant features can be inferred:

(a) Extensions of the transform faults confirm the Nigerian - Northern Brazilian, Angola - Damaraland - Central Brazilian - Paraguay and Luderitz - Uruguay - Southern Brazilian associations.

(b) The ocean-continental boundaries and the magnetic anomalies have distinct breaks and displacements in their trends and extensions of the transform faults pass through these anomalies. In the western part of South Africa three alkaline provinces can be inferred to be associated with the breaks and transform faults. The alkali granites near the Orange River in the NW part of South Africa and alkali complexes 300 km N and NW of Cape Town.

(c) The alkali complexes in the Nigeria-Niger Province and the asso= ciated Benue Rift also fall along lineaments, thus confirming Rhodes' (1971) speculation. The same applies to the Cameroun Province and associated alkaline rhyolites, including the islands islands of Fernando Po and Sao Tome.

(d) The remainder of the transform fault extensions are not asso= ciated with known alkaline rocks but in some cases they may still have to be discovered.

3.6 Mobile Belts - Synorogenic

As previously stated, most alkaline rocks were emplaced within stable shield areas of the continental crust. There are, however, exceptions where emplacement took place during orogenesis. Butakova (1974) drew comparisons between those alkaline rocks occurring within stabilised mobile belts and those that are very much younger. The former tend to be richer in alkalis with no quartz whereas the reverse applies to the younger belts having certain rocks saturated with silica. Examples are:

(a) Eastern Otago Pliocene Province - New Zealand (Turner and Verhoogen, 1960)

(b) Ural Mountains - USSR (Sørensen, 1974)

4. URANIUM POTENTIAL

4.1 General

Uranium mineralisation in alkaline rocks has been reviewed by several workers (Sørensen, 1970; Semenov, 1974 and Murphy *et al*, 1978). From his work, Sørensen (1970) concluded that the most promising geological, petrographic and geochemical relationships for the development and the locating of uranium- and thorium-rich deposits are:

(a) The presence of agpaitic* and peralkaline nepheline syenites having a high abundance of late fractionate elements such as uranium, thorium and rare earths.

(b) Although there are exceptions, the youngest rocks of a sequence generally have the higher concentrations of the rare elements.

(c) Late- or post-magmatic hydrothermal activity is important.

4.2 Target Selection

In the selection of target areas for locating possible occurrences of alkaline rocks certain criteria are of primary importance. For example, the relationship between the structure of the earth's crust and the occurrence of alkaline complexes appears to be fairly consistent. Structures such as grabens, updoming, intersection of faults, bends in monoclines and flexures, mobile belts and mid-oceanic transform faults are the most important potential host localities.

The positions and extensions of oceanic transform faults beneath the continental crust and the applications of this concept to areas not at present known to host alkaline rocks, may prove to be useful in identifying, more precisely, potential target areas. For example, the regions in South America corresponding to the Nigerian, Cameroun, Damaraland and other alkaline provinces along the eastern continental margin of South America from Venezuela down to Patagonia are considered favourable (Fig. 2).

**The terms agpaitic and miaskitic are defined as follows in molecular proportions:*

Miaskites where $Na + K < Al$
Agpaites where $Na + K > Al$

There are several areas in the world where alkaline complexes are not found and from Fig. 1 some predictions can be made regarding favour=ability criteria for their occurrence in the following areas:

(a) Northerly-trending tensional transform faults west of the Macquarie Ridge associated with spreading of the Tasman Sea can be extrapolated into the eastern portion of southern Australia. This area contains extensive Tertiary alkali basaltic vulcanism and the Mount Dromedary Cretaceous plutonic complex of alkaline affinity (Boesen and Joplin, 1972).

(b) The southern portion of the Arabian Peninsula.

(c) In India where large N-S transform faults west of the Lacodive Ridge extend into SW India.

4,3 Evaluation

Once target areas have been selected, geophysical airborne magnetic surveys, for example, are ideal for pinpointing actual occurrences. This is followed by an evaluation of their economic potential, in=volving detailed petrological and geochemical studies.

The largest uranium occurrences found in alkaline rocks are usually associated with the agpaitic suite with only accessory amounts in the miaskitic suite. Petrologically the agpaitic coefficient should be greater than one which is typical of most nepheline syenites and per=alkaline rocks. The mafic minerals are rich in alkalis such as aegirine and Na-amphiboles. Nepheline and sodalite are the main feldspathoidal minerals. Alkaline-earth-element and carbonate content is low, but that of volatiles such as F, Cl and H_2O is generally high. Pyrochlore has been shown to have compositions characteristic of the alkali-rich petrological associations within which it occurs (Semenov, 1974). This feature may be a useful criterion for exploring in regions where occurrences are unknown and in particular those areas of deep weathering where little outcropping occurs. For instance, the composition of pyrochlore the heavy mineral fraction of soil may be important in this regard.

Other diagnostic factors are high Th/U ratios and enrichment of lighter rare earths.

5. CONCLUSIONS

It is likely that alkaline complexes will in all probability constitute a valuable source of uranium and other minerals in the future. Major problems pertaining to extraction metallurgy remain to be solved and present an important field for research demanding interaction between the extraction metallurgist and the geologist.

It would appear that the finding of potential target areas will have to be based on fundamental studies along continental margins and shields with a view to locating extensions of transform faults into these zones. The continental margins of the South Atlantic represent promising target areas for such an investigation.

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