

REVIEW PAPER

CARBONATITE KIMBERLITE COMPLEXES OF INDIA*

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I am very grateful to Dr. B. P. Radhakrishna and the conveners of this symposium for inviting me to present this key paper on the carbonatite kimberlite complexes of India.

Since the first descriptions of carbonatites by Hogbom (1909) in Alno and by Brogger (1921) in Fen, the subject has been one of continuing controversy and increasing interest among geologists the world over. Some of the controversies were resolved by later work, especially experimental work, but many new problems were added. This will no doubt be settled by further sustained research. The controversial nature of these rocks as well as the fact that they are the repositories of many economic minerals have helped to generate and sustain an enduring interest among both exploration and academic geologists. To one who has been personally involved in research on carbonatites for the past decade and half, it is really heartening to see so many geologists from various fields assembled to discuss the different aspects of the subject. The conveners have wisely arranged the programme in such a way that the discussions follow two days of field work in carbonatite localities. Much as I would have desired to join these excursions, my health did not permit me to undertake this pilgrimage. I have no doubt that each one of us will return with a greater and more profound understanding and insight into the problems of carbonatites, and also an inspiration to continue or diversify our work on these rocks.

With the recent discoveries of carbonatites in Australia (Moore, 1973) and New Zealand (Cooper, 1971) it may safely be concluded that these complexes are found in all the continents of the world. One of the most significant features of carbonatite complexes the world over is their genetic association with alkaline silicate rocks, typically miassicitic (nepheline syenites, nephelinites and ijolites). Kimberlites are found in association with carbonatites at only a few localities, e.g., Alno (von Eckermann, 1966), Fen (Saether, 1957 in Mitchell, 1970), Ngualla (James, 1965), Tundulu (Garson, 1966) and Central Australia (Moore, 1973). The possibility of a genetic link between carbonatites and kimberlites arises mainly from the common characteristics of these two rock groups: (i) both are emplaced under similar cratonic conditions with volatiles playing an important role; (ii) both originate from the mantle; (iii) geochemically they are similar, being enriched in niobium, barium, strontium and rare earth elements; and (iv) both are rich in carbonates of primary origin.

Although kimberlite is of little consequence in terms of volume, it has attracted the attention of geologists for the following reasons: (i) it is the only definitely known source of diamonds; (ii) this rock probably originates at greater depths than any other rock; and (iii) it carries inclusions which are believed to be the direct samples of the mantle. Amongst the different types of xenoliths carried by the kimberlites, are rounded ultrabasic rocks consisting of varying combinations of olivine, rhombic and clinó pyroxenes, chrome-pyrope, spinel, picro-ilmenite and phlogopite. Some

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geologists regard these as cognate xenoliths from the kimberlite magma, whilst others consider them to be xenoliths of mantle material. (Dawson, 1967).

EMPLACEMENT

Until quite recently, the concept of a carbonatite magma did not find a general acceptance among geologists because of the high melting temperatures of anhydrous carbonates (calcite melts at 1340°C at 1000 bars pressure of CO₂). But the work of Wyllie and Tuttle (1959, 1960, 1962) on the system CaO - CO₂ - H₂O puts the minimum liquidus temperature at between 685°C and 640°C in the pressure interval of 27 bars to 4000 bars. This temperature is lowered further by about 50°C over a wide pressure range through the addition of MgO. Many other components present in the magma may still lower the temperature of crystallization of the carbonatite magmas. Experimental work on these lines is likely to throw more light as it happens with silicate magmas. Wyllie and Tuttle (1962) have confirmed the existence of these melts down to pressures of 10 bars (equivalent to rock overburden of about 45 meters). Crystallization temperatures determined experimentally are found to be in close accord with those predicted from field observations.

Wherever the carbonatite bodies (including the Indian carbonatites) in different parts of the world have been mapped, it is found that they assume the forms of dykes, sills, plugs and cone-sheets as in the cases of igneous silicate rocks. Further, an idea that carbonatites could erupt as vesiculating lava can well be understood from the soda-bearing carbonatite flows at Oldoinyo Lengai in Africa. Thus the field and laboratory studies leave no doubt in our minds that carbonatite can and does occur as any other silicate magma. The magmatic genesis of carbonatite is now a proven fact. It is gratifying and heartening to note that the geologists of the Geological Survey of India have been able to unravel the existence of one more non-silicate magma, 'the unique iron-oxide lavas' in the Cuddapah Basin (Rajaraman and Sood, 1976).

In 1960 when I first visited Amba Dongar in connection with fluorite prospecting for an industrial concern, I was baffled by the intrusive nature of the carbonate rocks, later identified as plugs of ankeritic carbonatite, and also their radioactive character. These features, further substantiated by geochemical data, helped us to establish the area as carbonatite-alkalic complex, the first such find in India (Sukheswala and Udas, 1963).

With the known magmatic source of carbonatites one would like to enquire about the exact composition of the primary carbonatite magma. Basing their experimental work (Na₂CO₃ - K₂CO₃ - CaCO₃ system) after the observed sodium, potassium, calcium mineralogy of the Oldoinyo Lengai lavas of 1960-61 eruptions, Cooper *et al* (1975) came to the conclusion that alkalic carbonate magmas of both sodic and potassic nature develop commonly, but do not in general retain their alkalis. The latter in aqueous solutions are often used up in fenitizing the wall rocks. If, however, the alkalis remain in the magma, minerals such as biotite, phlogopite, sodic-amphiboles and sodic-pyroxenes develop in the carbonatite. Compilations of average carbonatite compositions suggest that the total alkali content rarely exceeds 2 percent with K > Na (Pecora, 1956).

That the carbonatite complexes involve both carbonate and silicate fractions is very much in evidence from field and laboratory studies. Most of the carbonatite areas have in association alkaline silicate rocks. The experimental work of Koster

van Groos and Wyllie (1963, 1966) bears testimony to the co-existence and immiscibility relationship of carbonatite and silicate magmas. The above facts about the carbonatite-alkalic magmas are amply borne out by our findings in Amba Dongar and surrounding areas (Deans *et al*, 1972, 1973; Sukheswala and Borges, 1975; Sukheswala and Viladkar, 1976).

STRUCTURAL ASPECTS

A study of the ages of the carbonatites of the world does not show that they were particularly abundant in any one period. They seem to have erupted at various times from the Precambrian to the present day (Oldoinyo Lengai). The first discovery of carbonatite in India was reported in 1963 (Sukheswala and Udas), and since then many more occurrences in Peninsular India have been put on record. The ages of all the Indian carbonatites fall in the Precambrian, except for the Chhota Udaipur complex which is Eocene in age (Deans and Powell, 1968).

The locations of carbonatite-alkalic complexes around the world show that they occur in regions of crustal stability or rifting, and are absent from orogenic belts. However, opinions differ on the mode of eruption of carbonatite magmas. King and Sutherland (1960, p. 299, in Verwoerd, 1966) emphasise that volcanoes and plutonic centres in East Africa are 'common only in general distribution with the pattern of rifting, but in detail, alignment of centres rarely coincides with the faults', and that faulting and volcanism were not simultaneous. Carbonatite type volcanism in Tanzania is related to block faulting rather than true rifting (James, 1958 in Verwoerd, 1966); while there are instances in which possible connections are suggested between faulting and eruptive activity (Verwoerd, 1966, p. 131). Kaiserthul lies in the Rhine graben. Verwoerd (1966) comments: 'It seems possible that the carbonatites may have a genetic connection with structures more fundamental than rift faults: abyssal fractures in the earth's crust'. How interesting to relate this with the observations of Rajaraman and Sood (1976) who suggest that 'the alkaline rocks, kimberlite and carbonatite are of a deep-seated origin and safely assume the existence of a deep fracture passing through Chelima and Zangamrajupalle where there are dykes of micaceous kimberlite. Near Giddalur there are riebeckite syenites and it is possible that they are emplaced along fractures that are connected to the Chelima—Zangamrajupalle deep fracture'. The Chhota Udaipur carbonatite-alkalic district is situated a little to the north of the Narmada fault zone. It is also interesting to note that the carbonatite-alkalic complexes, the major mineral deposits and the Wajrakarur kimberlite pipes of South India are also connected along or in the vicinity of major fault zones (Grady, 1971).

From the data presently available, we may conclude that the younger (Tertiary) Amba Dongar carbonatite-alkalic complex is of volcanic to sub-volcanic type. In this complex we notice not only the structural disturbances attendant upon emplacement of carbonatites, such as doming and radial faulting, but also the explosive activity in the form of large circular outcrops of volcanic fluidized breccia in between the sovite and the central core basalt (Sukheswala and Udas, 1963, 1964; Deans *et al*, 1972, 1973; Sukheswala and Viladkar, 1976). We can also realise that the three major carbonatite bodies, viz., Amba Dongar, Newania and Sevathur, are now at vastly different erosional levels. Consequently Amba Dongar carbonatite retains many of the original characters, but such is not the case with the deep-seated Newania (Phadke & Jhingran, 1968) and Sevathur carbonatites (Borodin *et al* 1971). These

older (Precambrian) dolomitic carbonatites were perhaps emplaced at high pressures at deep levels in the crust. This suggestion emerges from Wyllie's (1966) experimental work in which he concludes that at low pressure calcite is formed, and with increasing pressure dolomite and ankerite are formed. Also, a moderate amount of FeO in the magma favours the formation of ankerite rather than dolomite.

The geotectonic situation of kimberlites is similar to that of carbonatites; they are restricted to stable continental areas or cratons. Important diamond-bearing kimberlites in Africa are situated within the older nuclei of these cratons, i.e., those sectors which have been free from orogeny and metamorphism for over 1500 m.y. Kimberlites located in the younger portions of the cratons are generally poor or barren in terms of diamond content (Clifford, 1966). Vinogradov and Tugarinov (1961, in Verwoerd, 1970) have stated that kimberlites were emplaced in Proterozoic times, i.e., after about 1900 m.y. ago. This means that they appeared quite late in the geological history of the earth, and the reason for this, according to Odinstov *et al* (1968) is, that the formation of kimberlite requires the presence of a thick continental crust. However, Bardet and Vachette (1966, in Verwoerd 1970) have reported kimberlites older than 2100 m.y. from West Africa. Thus it would appear that a very thick continental crust is not a pre-requisite for kimberlite formation.

The fact that kimberlites are generally associated with deep fractures suggests that their intrusion into the crust was governed by rifts extending to the mantle, although their final emplacement might be guided by structures in the upper crust (Verwoerd, 1970). In the light of these observations we should make a concerted effort to locate kimberlites in the cratonic areas of Peninsular India.

GEOLOGY AND STRUCTURE OF INDIAN CARBONATITES

Carbonatite-alkalic complexes have been located in four widely separated states of India, viz., Rajasthan, Gujarat, Andhra Pradesh and Tamil Nadu. The Chhota Udaipur alkaline district in Gujarat is situated in the midst of Deccan Trap basalts; the carbonatite-alkalic rocks have penetrated through a thick pile of basement gneisses and schists, Bagh sandstones and limestones, and basalts. All the others have invaded Precambrian terrain and are associated with deep crustal fractures.

Carbonatites are found as large masses forming mappable outcrops at (i) Chhota Udaipur in Gujarat, (ii) Newania in Rajasthan, (iii) Sevathur and Samalpatti in Tamil Nadu. The others occur as small lenses, dykes and veins in the surrounding country rocks. Only two of these Indian carbonatites have been studied in some detail, viz., (i) the Chhota Udaipur carbonatite-alkalic district (this includes the Amba Dongar ring complex, the Siriwasan brecciated sill, and the dykes and plugs of Panwad-Kawant area), and (ii) the Sevathur carbonatite.

Like their counterparts elsewhere, the Indian carbonatites are associated with other igneous rocks, viz., basic or ultrabasic alkaline rocks or even kimberlites, and/or nepheline syenites, nephelinites, phonolites and lamprophyres. In the Chhota Udaipur carbonatite-alkalic district, the chief igneous associates are phonolitic nephelinites, tinguaite and plagioclite. The most common ultrabasic rock associated with the Sevathur-Samalpatti carbonatites is pyroxenite, which occurs in the form of plugs and arcuate dykes. No igneous rocks are associated with the Newania carbonatite.

Although this symposium has been entitled 'carbonatite-kimberlite complexes of India', the suites of Indian carbonatites could be more appropriately referred to

as carbonatite-alkalic complexes. This sort of rigid distinction may help us eventually to understand the genesis of these rocks in a better perspective,

PETROLOGY AND MINERALOGY

With the exception of the Chhota Udaipur district, the bulk of the Indian carbonatites is of the rauhaugite/para-ankerite type. In Chhota Udaipur it is mainly sovitic in nature.

The most varied mineral assemblage among the Indian carbonatites is the one found at Sevathur. I could mention here only the salient features (details given elsewhere, Sukheswala and Viladkar, 1976) of their mineralogy. Next to the carbonates of calcium, magnesium and iron, apatite and magnetite are the most common minerals. Workable deposits of fluorite are associated with the carbonatites of Amba Dongar. Uran-pyrochlore is common in the dolomitic carbonatite of Sevathur. The mineral contains appreciable amounts of uranium and tantalum, but lesser amounts of niobium, calcium, fluorine and thorium as compared to the pyrochlore from Oka carbonatite (Gold, 1966). Pakkanadu carbonatite is rich in monazite which has also been reported in the Sevathur rauhaugite, and in the ankeritic carbonatites of Amba Dongar and Samalpatti. The Newania carbonatite has well-developed apatite veins.

There are three known kimberlite areas in India, Majhgawan in Madhya Pradesh, including diamond mines of Panna (Sinor, 1930; Mathur, 1962). Wajrakarur in Andhra Pradesh (Sinor, 1930; Satyanarayana Rao and Phadtre, 1966), and Jungal Valley, Mirzapur in Uttar Pradesh (Chhatopadhyay and Venkataraman, 1976). The Majhgawan kimberlite pipe is diamondiferous, whilst the Wajrakarur pipe is barren in this respect. Sinor (1930) has given a topographical map indicating areas of diamond mines of Panna in Madhya Pradesh, which seem to lie along two (NE-NSW, and almost N-S) intersecting lineaments. The rocks of these areas are described critically by Sinor, with a description of Majhgawan agglomeratic tuff by A. L. du Toit, who provisionally identified it as limburgite tuff (p. 145) with a suggestion that 'the Majhgawan tuff has a very close resemblance to certain types of 'blue ground' (p. 61). Core samples from the mines are chemically analysed and compared with kimberlite blue ground (pp. 147, 149, 150). Sinor believes that 'the Majhgawan deposit is a true volcanic pipe'. (p. 59).

Comparing the Majhgawan tuff with the Wajrakarur rocks (chemical analyses, p. 68) in Bellary district, Sinor remarks: 'the mineral composition of the Wajrakarur rock differs considerably from that of the Majhgawan tuff. Though no diamonds were found in the Wajrakarur pipe it is interesting to relate that diamonds had frequently been found in localities close to Wajrakarur. In the year 1881 a large diamond weighing 67 $\frac{3}{8}$ carats (cf. recent find of a 90 carat rough diamond by the geologists of the Geological Survey of India, Southern Circle) in its rough state was found near Wajrakarur (pp. 67-69)'. Though the Wajrakarur pipe remains barren, two diamond-bearing pipes in the Wajrakarur area have been discovered lately by the geologists of the Geological Survey of India, Southern Circle (Personal talk, Shri Ch. Narsimha Rao). It may therefore be said that Majhgawan in Madhya Pradesh and Wajrakarur in Andhra Pradesh are the only two known occurrences of the diamond-bearing kimberlite pipes in India. However, the diamond recovery is much less in the former, and the latter is just a new find. All the known areas of kimberlite will have therefore to be critically investigated structurally and petrographically, before considering the feasibility of their commercial exploitation.

Generally the kimberlites contain a wide variety of minerals such as olivine, phlogopite, ilmenite, pyrope, chrome-pyrope, magnetite, perovskite, sphene, diopside, pyroxene, pyrite, apatite and zircon set in a groundmass consisting of a mixture of calcite, serpentine and magnetite. Calcite is quite common and may even exceed 50%, and is of primary origin. Ilmenite usually has a high content (30–50%) of geikielite (MgTiO_3), and may also be enriched in niobium. The Majhgawan and the Wajrakarur kimberlite (?) rocks may therefore be re-examined in the light of such mineralogical and chemical details.

GEOCHEMISTRY

Carbonatites are recognised from sedimentary carbonate rocks by their distinctive contents of niobium, strontium and rare earth elements, and by their strontium isotope ratios ($\text{Sr}^{87}/\text{Sr}^{86}$). In carbonatite these ratios range between 0.702 and 0.705, with an average of about 0.7035. In sedimentary limestones and marbles, the ratios gradually exceed 0.706. The difference in the $\text{Sr}^{87}/\text{Sr}^{86}$ ratios also shows that carbonatites are not derived from original limestones either by partial melting or by mobilization. The higher values (0.7055 for Sevathur, and 0.7065 for Amba Dongar sovite and Panwad beforosite respectively) are attributed by Deans and Powell (1968) to contamination by wall rock. However, limestone and marbles with ratios less than 0.706 are extremely rare, and the low ratios for known carbonatite complexes is quite significant (Verwoerd, 1966). These facts in conjunction with field and geochemical data help to distinguish a carbonatite from a sedimentary carbonate rock.

Geochemically, kimberlites are enriched in aluminium, titanium, phosphorous, hydrogen, sulphur and calcium among the major elements, and in lithium, boron, copper, chromium, strontium, yttrium, zirconium, niobium and tantalum among the trace elements, compared to ultrabasic rocks. The fractionation of the lighter rare earth element lanthanum relative to the heavier member yttrium is particularly noticeable. Kimberlites are also richer in aluminium and calcium in comparison to other ultrabasic rocks. Also, the residual elements viz., carbon, potassium, rubidium, caesium, barium, lanthanum, lead, thorium, and uranium are concentrated by a factor of 200 as compared to normal ultramafic rocks (Dawson, 1967a; Harris and Middlemost, 1969).

FENITIZATION

Fenite aureoles are a common feature of carbonatites. The fenitized country rocks are generally granites, gneisses or sandstones. Such is also the case with the Indian carbonatites. With the exception of Amba Dongar where potash fenitization is predominant (Deans *et al*, 1972), all the other localities show varying degrees of soda-fenitization. Many of the Indian carbonatites still remain to be worked for fenite aureoles.

A review of the literature on this subject shows that there is a difference of opinion regarding the source of the fenitizing solutions, i.e., whether they are derived from the silicate or the carbonate fraction of the magma. Cooper *et al*, (1975) investigated the system $\text{Na}_2\text{CO}_3 - \text{K}_2\text{CO}_3 - \text{CaCO}_3$, and came to the conclusion that 'fenitization is associated both with some types of silicate magmas and some types of carbonatite magmas. It simply is not an either/or situation'. From my own work in Amba Dongar and surroundings, I am convinced that perhaps both the

immiscible fractions of the magma, silicate and carbonate, were responsible for the fenitization of the country rocks.

CARBONATITE KIMBERLITE RELATIONSHIP

I may conclude with a few remarks on the relationship between carbonatites and kimberlites. Dawson (1966) observes that the two are closely associated both in space and time, and good examples of this are found in Africa, North America, Russia and Sweden. In the carbonatite-kimberlite complexes the other associates are mainly alnoite, olivine melilitite, nephelinite and monchiquite. The intimate spatial, temporal and chemical relationships between kimberlites and the rocks of the carbonatite suite cannot be fortuitous, and so there must exist some genetic relation between the two. Some geologists (Verwoerd, 1970; Mitchell, 1970) deny the possibility of such a genetic link, since the carbonatites are not differentiation products of kimberlite magma, and also, the two are separated both geographically and tectonically. Mitchell (1970, p. 698) states: Generally, kimberlites are confined to uplifted centres of continental platforms and are commonly related to large-scale structural features. In contrast, carbonatites and associated alkaline rocks occur in peripheral parts of shield areas or closely related to large scale rift structures'. According to him, the mere fact that the two are manifestations of non-orogenic magmatic activity or that they might have been parts of the same magmatic activity does not prove their genetic link up. Although Dawson (1966) has shown chemical gradation between kimberlite and carbonatite, and also similar geochemistry, Mitchell (p. 698) argues: 'the similar geochemistry does not imply a genetic connection unless all the rocks of such geochemistry are genetically related; and further contends: 'a stronger case might exist for the association of kimberlite and basalt than for kimberlite and carbonatite' since basalt and possibly kimberlite also originate in the mantle. In support of this contention he cites the constant association of kimberlite provinces with rocks of basaltic composition, viz., Stormberg basalts of South Africa and the plateau basalts of Siberia which preceded the intrusion of kimberlite. (p. 699).

As pointed out earlier, carbonatites and kimberlites are confined to stable continental areas. All the important diamond deposits of Africa are situated within the older nuclei, and many kimberlite intrusions within the younger parts of the cratons are largely barren or have a very low diamond content. Since the Majhgawan and Wajrakarur kimberlite pipes have yielded diamonds, it would be worthwhile to determine their ages and that of the craton, and search for such areas in other parts of the Peninsular shield. The presence of detrital diamonds has helped to locate diamond-bearing kimberlite pipes. The augite-andesite or basalt claimed to be the parent rock of the diamonds of India (Wadia, 1975, p. 117) needs careful examination.

We have noted that the majority of African kimberlites are of Upper Cretaceous age, and also the fact that they are associated with epeirogeny and deep fractures. This brings to my mind the block faulting movements of the Gondwana period and also the intrusive mica peridotites of Jharia coalfield. These areas and the rocks therein need a careful scrutiny. Also, upwarp along the Narmada belt (Glennie, 1932) may be surveyed in detail. I may add that Rajaraman and Sood's (1976) recent observations 'Were the volcanoes that poured out lavas extremely rich in barium sulphate, sulphides, carbonates and iron oxide located on this deep fracture, then these unique non-silicate magmas would probably proclaim that they were the harbingers from great depths of the carbonatite, kimberlite and alkaline rocks' open

up a new field of research in the study of these new-found interesting but unusual types of rocks. They demand careful field and laboratory tests by geologists. The recent development in the idea of continental drift, viz., the idea of plate tectonics and its application in the location of ore deposits is quite significant. In light of his study of the Quaternary volcanic rocks Ryuichi Sugisaki (1976) has been able to conclude that 'the chemical composition of volcanic rocks is related to plate dynamics', and goes on to comment: 'It is of geological significance to consider whether the empirical regularities and their interpretation can be applied to the igneous rocks of the Pre-Quaternary'. The student of global tectonics has much to look for in these new ideas. Herein lie the seeds of new research and growth of new ideas.

May I be permitted to express my sense of joy and feelings of gratitude, and to thank the organisers for making it possible for me to meet so many geologists, and to participate in the 125 years Anniversary celebrations of one of the internationally known organisations in the country, the Geological Survey of India? I would also like to take the opportunity to make a special request to the Director-General to renew the good old practice of sending all the publications of the Geological Survey of India to the University and College Departments in the country. This may help teachers and students to keep abreast of the geological work done by this great organization. I am goaded to make this suggestion for there has been quite some difficulty in procuring these important and useful publications.

In the preparation of this address I received the help of my colleagues Professor Sethna, Professor Borges and Dr. Viladkar, as well as I drew much information from the writings of several authors on this subject; to all of them and to those whom I may have failed to mention by name in the text, I owe a debt of gratitude. If any faults have crept in, they are mine.

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