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Untapped Niobium and Vanadium Mineralization and Exploration Potential of Amba Dongar Carbonatite Diatreme, Gujarat, India

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ABSTRACT

Niobium and Vanadium are classified as "critical elements" and have wide applications in present-day industry. In Amba Dongar, both of these elements are widely distributed over the sövite ring dike and in some parts of ankeritic carbonatite, albeit pyrochlore is more abundant than vanadinite (and wakefieldite). Pyrochlore is a primary source of niobium in carbonatite complexes. This article discusses the mineralogy and mineral chemistry of these minerals and questions why these "critical elements" remain untapped in the Amba Dongar carbonatite diatreme.

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1. Introduction

Pyrochlore and columbite are the primary minerals exploited for Nb production. Brazil and Canada are the main countries producing Nb ore, and global production in 2022 was 79,000 tons (Oliveira et al., 2023). Besides, the following countries also contribute to a small-scale production:

Congo (Kinshasa), Russia, China, Rwanda, Argentina, Spain, Saudi Arabia, Malaysia (Tian et al., 2024). Unfortunately, India does not figure in this list of countries. In India, in three major carbonatite occurrences-Amba Dongar, Newania and Sevathur (Viladkar and Bismayer, 2010; Viladkar and Bismayer, 2014; Viladkar et al., 2017)-pyrochlore is found in all types of carbonatites. However, exploitation is possible only in Amba Dongar because in Newania and Sevathur, pyrochlore contains high concentrations of uranium (U_3O_8, up to 20–24%), which led to the metamictization of Pyrochlore. Exploitation of such a Pyrochlore would pose radiation risks. Moreover, the Nb reserves are considerably lower in Newania and Sevathur than in Amba Dongar.

Vanadium occurs in all types of Amba Dongar carbonatites. In alvikite, V ranges from 390 ppm to 1055 ppm (Viladkar and Wimmenauer, 1992; Viladkar, 2012), while in sövite it is up to 935 ppm. A recently published paper by Magna et al. (2020) reports even higher V content in some sövite, around 2840 ppm. Vanadium is associated with magnetite or ilmenite; however, independent vanadinite and wakefieldite grains are also located near ilmenite (BSE images, Magna et al., 2020).

2. Geological Setting

The Amba Dongar carbonatite–nephelinite subvolcanic diatreme consists of a major sövite ring dike that has an inner rim of carbonatite breccia (Fig. 1). Sövite constitutes most of the total volume of exposed carbonatite, and appears to have been emplaced in several phases leading to the formation of the ring structure. This multiphase emplacement is indicated by the presence of xenoliths of older sövite in successively younger phases of sövite. The sövite also forms small, circular-to-oblong plugs in the surrounding sandstone. Sövite is heterogeneous in composition. However, it hosts several minerals, including REE- and Nb-bearing minerals. In Fig. 1, the Nb-rich areas are marked with circles. Some of these areas have already been investigated, and the results have been published in several publications (Viladkar and Wimmenauer, 1992; Viladkar and Bismayer, 2010; Viladkar and Sorokhtina, 2021). In the western part of the

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ring dike, good mineralization was observed during the earlier field visits. However, most of these outcrops have been destroyed during extensive agriculture in this part of the ring dike. Nevertheless, some Nb-rich boulders remain available for investigation.

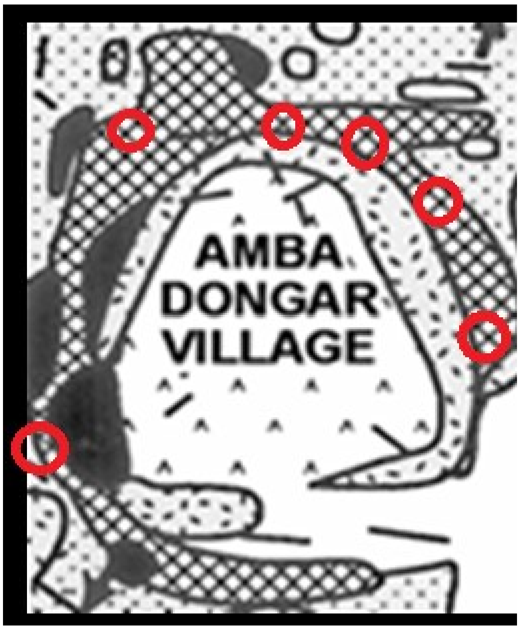

Fig. 1. Nb-enriched areas within the sövite ring dike in the Amba Dongar diatreme.

3. Nb mineralization

Pyrochlore is the main niobium mineral in the Amba Dongar carbonatite diatreme with a minor amount of fersmite. The other Nb-bearing phases are Betafite, Nb-zirconolite, columbite, and Nb-bearing perovskite. The magmatic Pyrochlore is mainly calcio- and niobium-dominant in composition, which shows hydrothermal alteration to various degrees.

Pyrochlore occurs in variable amounts in all intrusive phases of carbonatite, alvikite (I), alvikite (2), sövite and ankeritic carbonatite. However, it is more abundant in sövite than in the rest of the phases of carbonatite. It varies from pale golden-yellow, translucent to dark brown, almost opaque crystals. Zoning is very common in large grains; they consist of a dark core and a light margin. Even carbonatite breccia hosts a good amount of pyrochlore (Schulzki et al., 2024).

Pyrochlore in Amba Dongar carbonatite shows a wide range of crystallization from cumulate to the later phases of sövite and ankeritic carbonatite. Cumulate pyrochlore and crystals contained within the sövite suite are relatively homogenous and unzoned, and common associated minerals are apatite and magnetite. All these magmatic pyrochlores are calcium-niobium-dominant (Figs. 2 and 3). However, each phase appears to possess a distinct chemical composition. Only in the late-stage ankeritic carbonatite does pyrochlore show extreme zoning, mechanical disturbance, and alteration.

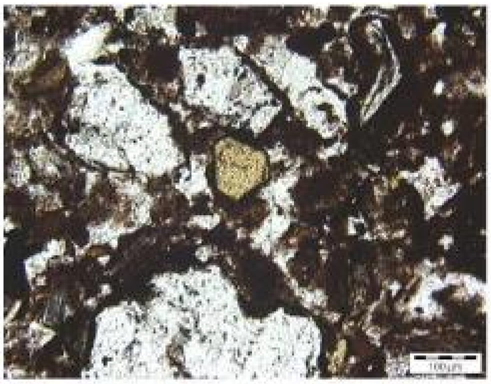

Fig. 2. An idiomorphic pyrochlore in a matrix of carbonatite breccia, northern part of the ring of carbonatite breccia.

Nb content of different sövite phases varies widely from 300 ppm to 5000 ppm with an average of 1900 ppm. It appears that the early pyrochlore generations crystallized in a highly alkaline environment at a temperature near 600^0 C. The secondary alteration of pyrochlore began in the hydrothermal environment with the gradual decrease of pH and the fluid temperature below 350^0 C. (Viladkar and Sorokhtina, 2021).

It is very pertinent to note here that (b) in Fig. 2 consists of only calcite and pyrochlore with a small proportion of magnetite. This is from the eastern part of the ring dike of sövite, and all the samples from this part have a modal pyrochlore content of almost 50%. The whole-rock analyses show almost 5000 ppm Nb; in some sövite samples, it reaches 8000 ppm. Such a cutoff grade is definitely minable.

The pyrochlore associated with ankeritic carbonatites has been extensively altered by hydrothermal fluids, resulting in vacancies at the A site. In this process, F in the primary pyrochlore is replaced by OH-groups. Simultaneously, Ca and Na are replaced by Th, U, REE, Sr and Ba. All these chemical characteristics are well represented in different analyses in Table 1. The representative analytical data for the Pyrochlore analyses are taken from the previous papers: (Viladkar and Wimmenauer, 1992; Ghose et al., 1997; Viladkar and Bismayer, 2010; Magna et al., 2020).

Amba Dongar Nb ore is comparable to the Araxa (Brazil) and Niobec (Canada). At the Araxa carbon-

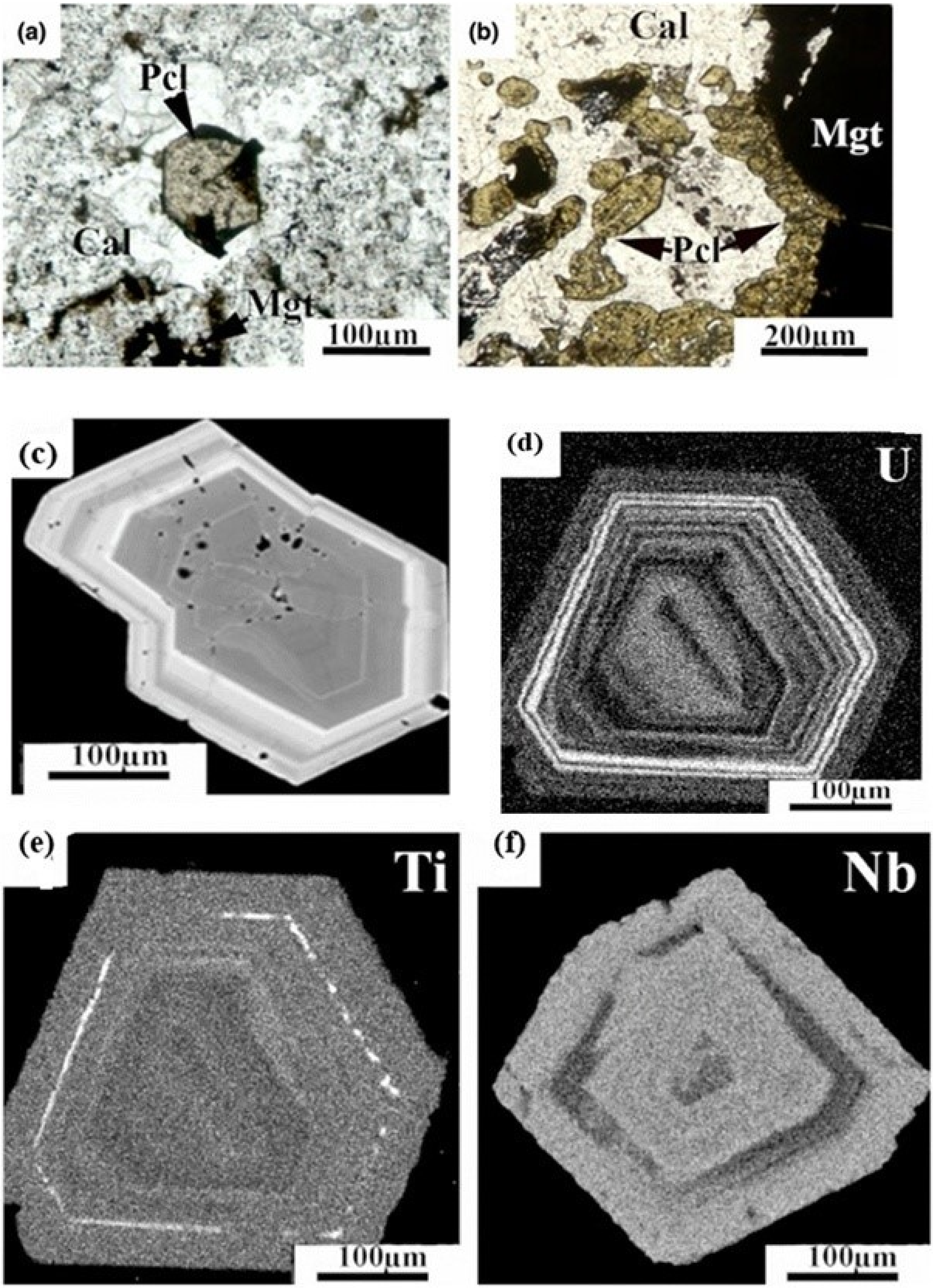

Fig. 3. (a, b) Transmitted-light images of calcite (Cal), pyrochlore (Pcl) and magnetite (Mgt) in calcite carbonatites. (c) zoned pyrochlore from coarse sövite, (d,e,f) Element maps showing the distribution of U, Ti and Nb in rhythmically zoned pyrochlore from ankerite carbonatites (Ref: Viladkar and Sorokhtina, 2021).

Table 1. Magmatic pyrochlores from the sövite and carbonatite breccia samples, a metamict one from ankeritic carbonatite.

	1	2	3	4	5	6	7	8	9	10	11
Nb_2O_5	64.68	64.89	69.69	70.66	44.19	48.45	40.45	46.15	54.94	61.69	52.500
Ta_2O_5	0.31	0.05	0.00	0.00	0.17	0.00	0.06	0.03	0.00	0.00	0.000
SiO_2	0.33	0.04	0.11	0.08	0.06	0.09	0.03	0.10	0.04	0.88	4.141
TiO_2	6.18	5.10	3.62	3.18	29.37	24.99	7.60	7.68	0.18	5.88	9.608
ZrO_2	1.36	1.26	0.12	0.04	0.86	2.14	3.28	3.57	2.01	1.40	
ThO_2	0.33	0.77	0.12	0.14	0.00	0.06	0.14	0.00	4.35	0.00	1.205
UO_2	0.17	0.40	0.06	0.07	0.00	0.00	0.27	0.08	0.00	0.00	4.001
Al_2O_3											
Y_2O_3	0.02	0.04			0.13	0.34	0.06	0.08			0.080
La_2O_3	0.46	0.35	0.32	0.31	4.61	3.52	0.73	0.72	0.45	0.24	0.133
Ce_2O_3	0.97	1.58	0.51	0.59	3.03	2.60	17.92	17.98	2.72	0.60	1.882
Pr_2O_3											
Nd_2O_3	0.17	0.17	0.00	0.08	0.95	1.10	0.37	0.37	0.00	0.00	0.014
Sm_2O_3											
Gd_2O_3											
Dy_2O_3											
Er_2O_3											
Yb_2O_3											0.000
MgO	0.01	0.03	0.08	0.22	0.05	0.29	0.84	0.25	0.00	0.02	0.045
CaO	19.22	18.50	18.11	19.03	15.00	14.15	20.33	18.48	17.98	18.72	12.514
MnO											
FeO	0.16	0.05	0.11	0.04	0.72	0.60	3.45	3.43	0.28	0.29	1.968
SrO	0.09	0.46	1.72	0.60	0.50	0.16	0.42	0.32	0.38	0.73	2.950
BaO	0.06	0.10	0.00	0.00	0.34	0.35	0.15	0.13	0.00	0.00	2.413
PbO	0.06	0.00	0.00	0.00	0.28	0.07	0.40	0.57	0.00	0.00	0.352
Na_2O	5.17	5.24	5.24	4.91	0.00	0.00	0.04	0.08	4.85	6.04	1.340
K_2O											0.054
F	0.03	0.02	0.02	0.01	0.00	0.00	0.02	0.01	3.76	5.49	0.026
SUM	100.77	101.02	102.83	103.94	105.26	104.91	96.56	100.03	102.47	102.30	106.23

1-4 from different sövite ring dike outcrops, 5 and 6 high TiO_2 pyrochlore from banded sövite, 7 and high Ce pyrochlore 9 and 10 are from a carbonatite breccia ring dike (9 is light honey brown couloured while 10 is dark colored) 11 is metamict pyrochlore from ankeritic carbonatite plug, SW of Amba Dongar village

atite complex in Brazil, the world's largest producer of Nb, even ore with a cut-off grade of 0.2% is being mined. The Nb ore is derived mainly from regolith formed by the weathering of carbonatites and phlogopitites (Biondi and Junior, 2023). While in Niobec mine, Quebec, Canada, the cut-off grade is o.55-0.71% Nb_2O_5 (Tian et al., 2024).

Recently, the Atomic Minerals Division (AMD), based on its REE exploration in Amba Dongar, also estimated 10,000 tons of Nb_2O_5 at an average grade of 0.08%. This estimate is based on exploration within a limited area of 0.04 sq. km. in the Southwestern part of AmbaDongar (Nagabhushanam et al., 2018). 0.04 sq. km is a very small area compared to the vastness of the sövite outcrops in the ring dike of the Amba Dongar diatreme. Consequently, the reserves of Nb mineralization are many significantly larger than those estimated by Nagabhushanam et al. (2018).

According to Mitchell (2015), about 115 Nb-bearing minerals have been identified by the International Mineralogical Association (IMA). The different pyrochlore types occurring in Amba Dongar carbonatite are presented in Table 1. In general, the major Nb deposits are hosted in lateritic soil overlying carbonatite. However, in the Amba Dongar complex, no lateritic soil has developed. Weathering of sövite and ankeritic carbonatite has produced soil around the outcrops, but it is not a major part of the Nb-bearing one.

4. Vanadium

Vanadium metal is highly corrosion-resistant and known for its high strength. It has a wide range of applications in modern industries and forms stable alloys with other metals. It occurs as magmatic, sedimentary, and hydrothermal deposits. Vanadium is usually found to be an integral part of magnetite, ilmenite and titano-magnetite.

In carbonatites, high vanadium concentrations are uncommon and typically occur as trace amounts in spinel, titanite, magnetite, and certain ferromagnesian silicate minerals. V-minerals (vanadinite, wakefieldite) have not been reported from magmatic carbonatites, barring some volcanic carbonatites of Italy. In Amba Dongar sövite, however, both these minerals occur abundantly, particularly in the eastern part of the sövite ring dike. It is noted that vanadium in low concentration is found in the magmatic stage, while its concentration reaches high enough in hydrothermal solutions to form vanadinite and wakefieldite. So far, perhaps Amba Dongar is the only carbonatite complex having such high vanadium activity

Sövite samples from these outcrops are generally coarse to medium grained dark coloured rocks due to their high amount of Fe and Fe+Ti oxides. In places, these dark-coloured minerals are oxidized, giving the rock an oxidized appearance. Calcite makes up the main carbonate minerals along with apatite, magnetite, pyrochlore and vanadinite. Barite, fluorite and quartz are frequent secondary vein minerals (Figs. 4–7).

Fig. 4. Sövite with vanadinite (associated with magnetite).

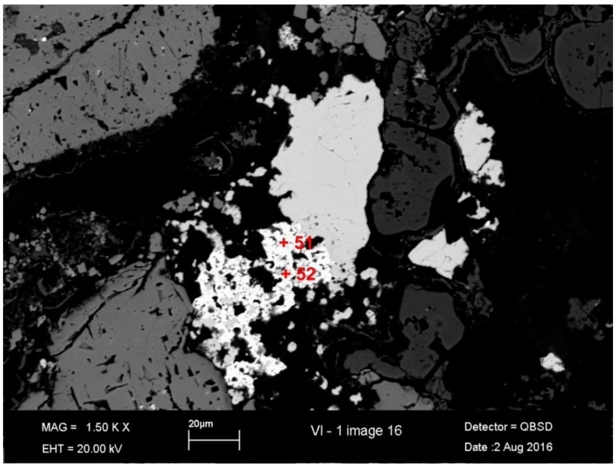

Fig. 5. Vanadinite (51) and Barite (52).

Sövite exhibits parallel banding, which is quite normal in the northern and western part of the ring dike. The bands are usually rich in magnetite, apatite and pyrochlore. Some banded sövite samples show vanadium concentrations as high as 935 ppm (Viladkar and Wimmenauer, 1992). Thin veins containing secondary hydrothermal minerals are randomly ori-

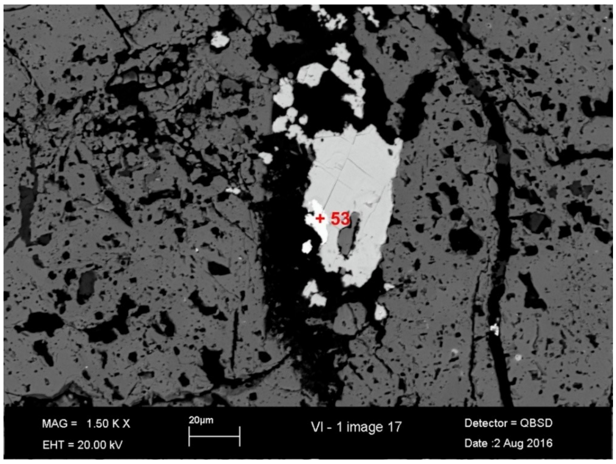

Fig. 6. Cluster of Vanadinite in BSE, No. 58, is analysed.

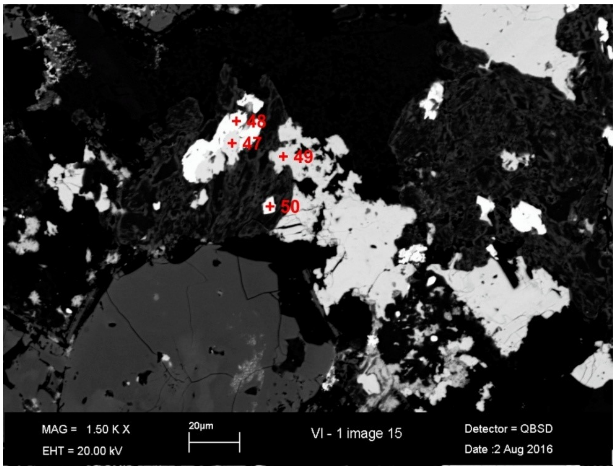

Fig. 7. Wakefieldite-Ce (47), Vanadinite (48 and 50) and barite (49).

ented all over the outcrop. These veins are rich in barite, REE minerals, and vanadinite. The presence of ilmenite and titanite in these samples is conspicuous. The following BSE images show vanadinite, wakefieldite and associated minerals.

Wakefieldite (Ce) is also rare in carbonatites; however, it appears in some sövite samples of the ring dike. The presence of both vanadinite and wakefieldite (Ce) points to the high concentration of vanadium in the carbonatite magma and later in the hydrothermal solution emanating from the carbonatite magma. The most common associate of vanadinite and wakefieldite is barite. In addition to the independent mineral phases, vanadium also occurs in the vanadium-bearing titanite. Wakefieldite is not a common mineral in carbonatites and has been reported only from Pianciano, Italy (Stoppa et al., 2016), and Wasaki, Kenya (Jones et al., 1996),

In Tables 2–4, mineral analyses of titanite, magnetite, vanadinite, and wakefieldite are presented.

Table 2. Representative analyses of Titanite and Magnetite.

	Titanite	Titanite	Magnetite	Magnetite
F	0.00	0.00	0.00	0.00
Na_2O	0.00	0.40	0.00	0.00
MgO	0.71	0.60	1.82	0.00
Al_2O_3	0.00	0.00	0.00	0.00
SiO_2	12.54	24.56	0.00	0.00
P_2O_5	0.00	0.00	0.00	0.00
SO3	0.00	0.00	0.00	0.00
Cl	0.00	0.00	0.00	0.00
K_2O	0.00	0.00	0.00	0.00
CaO	9.43	27.62	0.00	0.41
TiO_2	37.11	12.63	0.00	1.42
V_2O_5	1.57	1.07	0.00	0.73
MnO	8.91	0.39	3.91	2.41
FeO	16.52	22.17	75.14	79.22
CaO	0.00	0.00	0.00	0.00
NiO	0.00	0.00	0.00	0.00
ZnO	0.26	0.00	2.55	2.35
As_2O_3	0.00	0.00	0.00	0.00
SrO	0.00	0.00	0.00	0.00
Nb_2O_5	2.89	0.00	0.00	0.00
Rh_2O	0.00	0.00	0.00	0.00
Ag_2O	0.00	0.00	0.00	0.00
BaO	0.00	0.00	0.00	0.00
La_2O_3	0.00	0.00	0.00	0.00
Ce_2O_3	0.00	0.00	0.00	0.00
Nd_2O_3	0.00	0.00	0.00	0.00
WO_3	0.00	0.00	0.00	0.00
PbO	0.00	0.00	0.00	0.00
Rn	0.00	0.00	0.00	0.00
Total	89.94	89.44	83.43	86.54

Table 3. Representative analyses of Vanadinite and Wakefieldite.

	Vanadinite	Vanadinite	Vanadinite	Vanadinite	Vanadinite	Wakefieldite
F	0.00	0.00	0.00	0.00	0.00	0.00
Na_2O	0.66	0.00	0.00	0.00	0.00	0.00
MgO	1.49	0.41	0.00	0.00	0.00	0.00
Al_2O_3	0.00	0.00	0.00	0.00	0.00	0.00
SiO_2	3.00	0.00	0.00	0.00	0.00	0.00
P_2O_5	0.00	0.00	0.00	0.87	0.00	0.00
SO_3	0.00	0.00	0.00	0.00	0.00	0.00
Cl	2.48	0.00	2.80	3.29	3.05	0.00
K_2O	0.00	0.00	0.00	0.00	0.00	0.00
CaO	2.43	7.72	0.00	2.41	0.42	0.74
TiO_2	0.00	0.00	0.00	0.00	0.00	0.00
V_2O_5	17.91	23.64	20.32	21.80	20.69	39.68
MnO	0.00	14.62	0.00	0.00	0.00	0.00
FeO	0.48	2.01	2.69	0.00	0.67	0.00
CaO	0.00	0.00	0.00	0.00	0.00	0.00
NiO	0.00	0.00	0.00	0.00	0.00	0.00
ZnO	0.00	1.90	0.00	0.00	0.00	0.00
As_2O_3	0.00	0.00	0.00	0.00	0.00	0.00
SrO	0.00	0.00	0.00	0.00	0.00	0.00
Nb_2O_5	0.00	0.00	0.00	0.00	0.00	0.00
Rh_2O	0.00	0.00	0.00	0.00	0.00	0.00
Ag_2O	0.00	0.00	1.07	0.00	0.00	0.00
BaO	0.00	0.00	0.00	0.00	0.00	0.00
La_2O_3	0.00	0.00	0.00	0.00	0.00	26.79
Ce_2O_3	0.00	0.00	0.00	0.00	0.00	34.10
Nd_2O_3	0.00	0.00	0.00	0.00	0.00	7.14
WO_3	0.00	0.00	0.00	0.00	0.00	0.00
PbO	62.51	49.20	75.57	73.58	74.48	0.00
Rn	0.00	0.00	0.00	0.00	0.00	0.00
Total	90.95	99.50	102.45	101.95	99.31	108.45

Table 4. Wakefieldite analyses (Ref: Magna et al., 2020).

V_2O_5	33.01	33.63	33.99	34.17	33.77
La_2O_3	26.19	25.90	24.57	25.52	22.56
Ce_2O_3	27.46	27.36	27.62	28.11	27.43
Pr_2O_3	0.43	4.83	5.11	4.38	4.59
Nd_2O_3	6.41	5.88	7.03	5.65	8.32
Total	97.50	97.60	98.32	97.83	96.67

This paper presented an overview of field data collected by the author over the last five decades in the Amba Dongar diatreme, along with the Nb and V mineralogy of carbonatites and the mineral chemistry of Pyrochlore, vanadinite, and wakefieldite. The detailed investigation indicates that this carbonatite diatreme has notable potential for niobium and vanadium mineralization; however, no intensive exploration has been carried out, and thus the Nb and V resources have remained untapped. This review should encourage further detailed exploration across the entire Amba Dongar sövite ring dike exposures.

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