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Restoring the past glory of diamond mining in south India- A plausible case of diamondiferous Wajrakarur kimberlite pipe clusters with geochemical evidences

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ABSTRACT

A plausible case of collective and economical mining of diamondiferous kimberlite deposits of Wajrakarur and adjoining places in Andhra Pradesh, southern India, along with the whole-rock geochemical evidences in support of their diamond potentiality are discussed in this article. The kimberlites/lamproites are mantle-derived ultrabasic rocks which rarely carry diamonds from mantle to the earth's surface through carrot-shaped intrusions referred to as pipes. Even though few hundreds of diamondiferous kimberlite pipes were discovered in India so far, there is no other production unit than Panna diamond mine in the country where primary rock is mined. In ancient India, diamond mining in south India in the Krishna river valley was well-known to the world fascinated by famous gemstones like *Koh-i-Noor, Hope, Darya-e-Noor, Noor-ul-ain* etc. which were mainly extracted from alluvium or colluvium in Krishna river valley. Having bestowed with more than 45 kimberlite pipes, the Wajrakarur kimberlite field (WKF) forms a favourable region for initiating diamond mining in the country. Geochemically, majority of the WKF show low TiO_2 content and considerably high diamond grade (DG) values (>3) except some pipes viz., P-5 (Muligiripalli), P-13 (Tummatapalli) and P-16 (Pennahobilam) are barren due to high TiO_2 and ilmenite contents. The TiO_2 content (0.66-6.62 wt %) is inversely proportional to the DG (3.33 to 22.13). The DG value of some of the WKF pipes is close to that of Panna (8.36). The cationic weight% values clearly portray the diamondiferous nature of these deposits. The WKF pipes were also proved to be diamondiferous by exploratory drilling and bulk sample processing results by the government and multinational organisations. In southern India, due to several reasons, diamond mining has not seen its initiation and impetus till now although it records a considerable number of fertile kimberlite pipes at Wajrakarur, Lattavaram, Chigicherla, Timmasamudram etc. Though the majority of WKF diamondiferous kimberlite deposits in Wajrakarur are small in their areal extent (0.06-4.48 Ha) some of them are large (>10 Ha up to 120 ha). They occur in close proximity to each other offering feasibility for collective mining and winning the precious stone through a central processing unit by deploying the latest processing technologies. The geographic conditions of this region such as availability of human resources, water resources, vast open lands, wind power generation etc. also support to initiate mining of kimberlite pipes in this area. The availability of rough diamonds produced from local mines will make the polishing industry to meet its business needs during circumstances of the shortage of rough stone influx from foreign. Hence, although it demands liberal investments, reviving diamond mining in southern India can be materialised with a meticulous evaluation of these deposits ascertaining profitability. This will certainly help to restore the past glory of diamond mining in the southern part of the subcontinent.

Keywords : *Diamond, Economic Mining, Kimberlite, Southern India, WKF*

1. Introduction

The diamond, king of gemstones, is rare and its value is forever. The diamond was introduced to the world by India. Diamond mining in India is known since 800-600 B.C. [1]. Diamond exploration involves searching for either primary rocks (kimberlites or lamproites) or secondary deposits (alluvial deposits or conglomerates). Ever since the primary rock has been discovered at Kimberley, South Africa, the focus of diamond explorationists has shifted towards unravelling such deposits elsewhere [2]. Diamond incidence in kimberlites depends on depth of origin of kimberlitic magma, sampling of diamonds by ascending kimberlitic magma, degree of preservation, pressure and temperature (P&T) conditions, magma ascent velocity, magmatic transport efficiency, oxygen fugacity, residence time etc. [3]. Today, the major production of diamonds in the world comes from mining of kimberlites/ lamproites. The present paper brings out a possible case of collective mining of diamondiferous kimberlites of the Wajrakarur (77°23'5.00"E, 15° 1'43.00"N).

The primary source rocks of diamond, kimberlites, lamproites, lamprophyres and related clan of rocks sometimes carry diamond from mantle to the earth's surface. The foremost step in diamond exploration is initiated with searching for kimberlites and lamproites; hence kimberlite exploration is synonymous with diamond exploration. India was the only producer of diamonds in the world, until another source was found in Borneo (Kalimantan, Indonesia) in 1728, subsequently in Brazil and South Africa. The '*Periplus of Erithræan Sea*' provides information on the availability and production of gemstones in South India [4]. Marco Polo, Ibn Batua and Jean Baptiste Tavernier described the diamond mines of the Krishna valley in the Golconda Kingdom [5, 6, 7, and 8]. The Portuguese writer da Orta stated that the sovereigns in south India claimed all gems above 30 *magnelins* (37.5carat). Availability of diamonds and their mining in India was also discussed by Cesar Fredrick [9]. The ancient Indian scriptures and other treatises like *Artha Sastra (Economics), Brihat Samhita* (*Encyclopaedia or Mega treatise*) and travel reports of Marco-Polo and Tavernier act as evidences to the

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glorious panorama of the ancient Indian diamond industry. Due to this, India was a dreamland for merchants, sailors and kings of different countries in fond of diamond. Some ancient treatises like *Ratna Sastra (Science of Gems), Rasajalanidhi (Treatise of Hydrochemistry), Agastya Mata (Biography of Saint Agastya), Yukti-Kalpataru* (*Tree of Wisdom*) describe various aspects of diamonds and many other gemstones [8, 9]. In the seventeenth century de Late mentioned that stones of ten carats had been preserved in the old Golconda mines [10].

In ancient India, there were many active alluvial diamond mines in the earlier part of the 19th century but in later times, the mining has completely died out due to several reasons [11, 12]. The city, *Golconda* was the capital of the Hyderabad state, formerly called the ancient Kingdom of the Deccan. Golconda was not a mining region, but rather a market for the cutting, distribution and selling of diamonds from neighbouring areas. The most significant alluvial mines in the Golconda district are along the Penner (Pennar), Krishna (Kristna, Kistna), and Godavari (Godivari) rivers that flow eastward and merge into the Bay of Bengal. The principal localities are Cuddapah, Anantapur, Bellary, Kurnool, Guntur, Mahbubnagar, Kollur, Parital, Golapailly (Gollapalli), Eluru (Ellore), and Nandyal (Nandial). All this information was compiled for the first time by Pingali Venkaiah, the first Indian kimberlite explorationist, who was popular as '*Diamond Venkaiah*', to work on the WKF [13]. Later, his son, Parasuramaiah continued research on this subject. In the ancient India, alluvial diamond mines were located in the geographical map of 1600 A.D. at Kollur area of Guntur district, Andhra Pradesh and at Ravvalakonda area of Raichur in Karnataka state (Fig. 1). A Portuguese traveller and diamond explorationist who lost all his properties in diamond searching at Wajrakarur and determined to commit suicide out of gloom, found on the last day a large stone of substantial weight (90 carats) [14]. This history of ancient diamond mining at Wajrakarur thoroughly authenticates potentiality of this region.

The eastern Dharwar craton (EDC) has been proved to be fertile for emplacement of kimberlites [14, 15]. Ever since kimberlite was discovered by the Geological Survey of India (GSI) and exploration for the primary host rock of diamonds has begun in India in 1960, more than 300 kimberlites/lamproites were discovered in the country, majority of which occur in southern India. It was opined by some workers that the chances of discovery of outcropping kimberlite pipes in India are remote and the exploration geologists should now concentrate on searching concealed kimberlites [16]. This statement was probably made owing to the past experience of regional scale mapping at that time in India due to which many outcropping diamondiferous kimberlites, were missed and/or unknowingly merged in the Peninsular Gneissic Complex (PGC) or the country rock. Furthermore, some researchers have opined that Indian organisations lack in the expertise of effectively adopting and implementing latest technologies in diamond exploration [17]. Nevertheless, many occurrences ignored or overlooked or missed by Indian organisations in the past were unveiled by multinational companies like Rio Tinto, De Beers etc. with conscientious and uncompromising exploration investments in recent times. With that advent, government organisations like GSI, National Mineral Development Corporation Ltd (NMDC) etc. have also adopted latest techniques and reported considerable number of kimberlite and lamproite occurrences in the country. A major break-through in India was the discovery of world class Bunder (*Bunder- monkey in Hindi language*) diamondiferous lamproite deposit with a resource of 27 million carats in Chattarpur district of Madhya Pradesh by strenuous efforts and massive investment by Rio Tinto group [18, 19, 20]. As the deposit is situated in an environmentally sensitive area, the Bunder deposit is yet to see the mining stage. Due to several reasons, Rio Tinto has left the deposit along with all assets gifted to the Government of Madhya Pradesh in 2016 [19]. Thus the hope of establishing a world class diamond mine first-of-its-kind in the country and a premier diamond production centre that can place the country among top ten diamond producers of the world has become remote or despaired.

Kimberlite occurs in the form of cylindrical or cone/carrot-shaped intrusions called pipes while lamproites are so far known to occur as dykes. These rocks originate from mantle at a depth of more than 150 km sometimes capturing diamonds from the mantle and carry forward towards the earth's surface through deep-seated fractures by a violent ascent [23]. These rocks are highly enriched in ferromagnesian minerals such as olivine and its altered product serpentine along with mantle derived xenocrysts like pyrope, ilmenite, Cr-diopside, spinels. Due to predominance of olivine and serpentine, these rocks are vulnerable for surficial weathering and generally form geomorphic lows in a terrain.

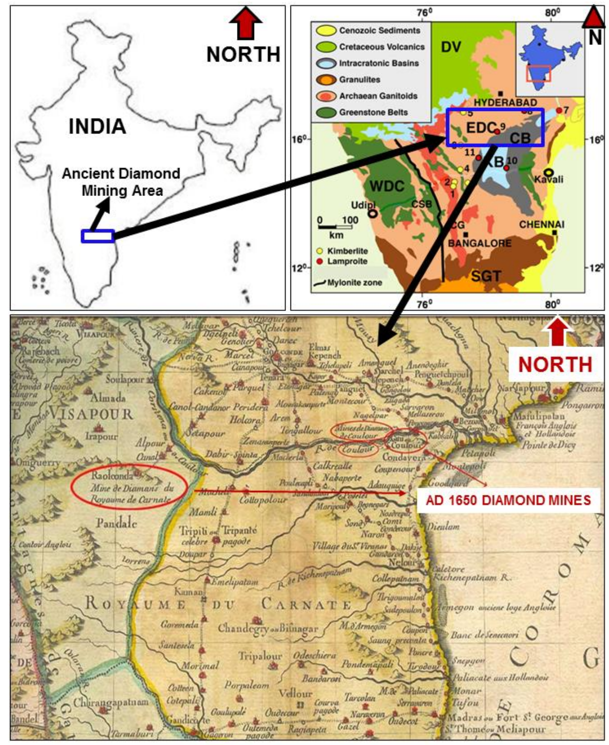

Fig. 1. Above- A regional geological map of southern India showing locations of kimberlite/lamproite clusters [21].

Legend: CB-Cuddapah Basin; CG-Closepet Granite; CSB-Chitradurga Schist Belt; DV-Deccan Volcanics; EDC-Eastern Dharwar Craton; EGGT-Eastern Ghats Granulite Terrain; GG-Godavari Graben; KB-Kurnool sub-Basin; SGT-Southern Granulite Terrain; WDC-Western Dharwar Craton. Kimberlite clusters: 1-Kalyandurgam and Timmasamudram; 2-Brahmanapally; 3-Chigicherla; 4-Wajrakarur; Lattavaram and Anumpalli; 5-Mahabubnagar; 6-Raichur; 11- Gooty. Lamproite clusters: 7-Ramannapeta; 8-Vattikodu; Ramadugu, 9-Somasila; 10-Chelima and Zangamrajupalli. Inset box (blue) shows ancient diamond mine localities. Below- Ancient geographical map showing locations of ancient diamond mines. Encircled portions show Coulur (Kollur), Golconda diamond mines of present Guntur district and Raolconda (=Ravvalakonda- *ravvala* meaning diamonds, *konda*- hill) of Raichur of Karanataka [22].

If the kimberlite is diamondiferous, the stones thus liberated from weathering of parent kimberlitic rock get transported and deposited in streams as placer concentrations forming alluvial diamond deposits (Fig. 2). The mantle derived minerals present in kimberlites released due to weathering accumulate as indicator minerals in the streams or low lying areas through sediment transport at favourable trap-sites and act as path finders in kimberlite exploration [24].

In southern peninsular India, the kimberlite rocks occur in four distinct fields viz., Wajrakarur (WKF), Narayanpet (NKF), Raichur (RKF) and Tungabhadra (TKF), among which the WKF is the largest kimberlite field in the craton as well as in India [26]. More than 45 kimberlite pipes are so far reported in the Wajrakarur Kimberlite Field [27]. With reference to the drilling results and diamond incidence assessment carried out by the GSI in the WKF, majority of the pipes are reported to be diamondiferous [28]. Several world famous diamonds were extracted from the gravels of Krishna and Penna rivers in ancient times (Fig. 3).

Even though ancient diamond mining has been reported from many places in southern India and to some extent at Panna, Bundelkhand in Central India as well [29], the diamond mining has not seen its ecstasy in the country. Despite flourishing past mining history in southern India, currently the only operating diamond mine exists at Panna. The southern part of India is yet to witness its past diamond mining glory in spite of having endowed with several diamondiferous pipes. From its status of pioneering importance in the production of natural diamonds, India has lost its pre-eminent position and primary source of large size diamonds could not be traced out till now.

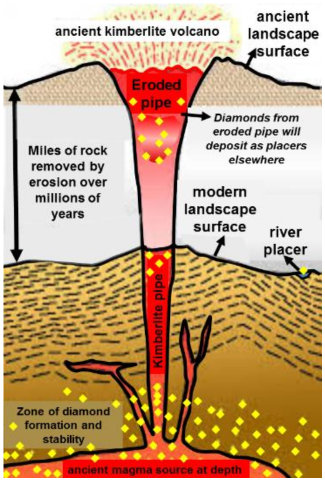

Fig. 2. Cartoon showing kimberlite pipe eruption, subsequent weathering and erosion giving rise to present day landscape [25].

Fig. 3. Some world famous diamonds originated from river gravels at Golconda Mines, Kollur, Guntur district, Andhra Pradesh [22].

On the contrary, the other countries in the world possessing similar geotectonic setting have witnessed an exponential development in diamond production during latter half of last century [30]. At this juncture, the question is can south India regain its past glory of diamond mining. The answer would be yes, considering the clustered occurrence of Wajrakarur diamondiferous pipes. The Wajrakarur pipes (1, 2 and 6), Lattavaram pipes (3, 4, 8 and 9), Venkatampalli pipe (7), Dibbasanipalli pipe 11 and 3021, Anumpalli pipes (10, 3055 and 3016) [31, 32] pipes are situated close to each other within a distance of 15 km from Wajrakarur (Fig. 4a). The kimberlites form small outcrops or sub-crops with distinct khaki green colour, mottled texture, typical mineral assemblage etc. in contrast with the country rock granitoid (Fig. 4b to d). Majority of the WKF pipes are diamondiferous and deserve to be developed as small open-pit mines owing to several favourable factors. A holistic summary of salient features of the WKF diamondiferous kimberlite deposits is presented in Table 1.

The WKF pipes are of different shapes in their surficial extent. The pipe-7 at Venkatampalli occurs as a linear body while all other pipes are circular to semi-circular or ovoid in shape (Fig. 5).

2. Geochemical evidences for Diamond prospectivity

Based on exploration conducted by several organisations, it can be stated that majority of the WKF pipes are diamondiferous [28, 36]. Right from the reconnaissance surveys, several approaches are being followed by exploration geologists to assess the diamondiferous character of the suspicious geological samples. In the reconnaissance diamond exploration, chemistry of mantle xenocrysts known as kimberlite indicator minerals (KIMs) has been widely used to obtain an initial idea of the diamond potentiality of kimberlite targets [39, 40, 41, 42]. Once discovered, the exploration advances with the evaluation of diamond potentiality of a kimberlite pipe thorough investigation of different lithological facies is preordained, evidenced through multidirectional drilling within the kimberlite intrusion. To ascertain the diamond incidence in each type of kimberlite facies, adopting processing technique such as caustic fusion is a common methodology used in diamond exploration [39]. As it is an expensive affair, many researchers have attempted to reveal relations between the chemical composition of kimberlites and their diamond potentiality before opting for caustic fusion. Certain geochemical parameters like K_2O/Na_2O ratio [43], the elevated concentrations of Cr and Mg and the decreased concentrations of Ti, Fe, and Al were considered as gauges of diamond potentiality of kimberlite [44]. The enrichment of these elements is attributed to the presence of primary kimberlite mineral constituents like chromite, Cr-diopside, pyrope, olivine, ilmenite etc. which also act as indicator minerals in stream sediments [24]. Furthermore, a methodology using regression statistical analysis to correlate bulk rock geochemistry and diamond potentiality has also received wide application [45]. An attempt has been made here to envisage the diamond potentiality of some of Wajrakarur kimberlite pipes, with emphasis on Lattavaram and Anumpalli kimberlites, using whole rock geochemical data [46, 47, 48] (Table 3). This method makes use of cationic wt% of major elements to prognosticate diamond content of kimberlites [49] In the binary diagram of Ti versus Al (%), the Wajrakarur pipes plot in the zone of diamondiferous to few diamonds field (Fig. 6a). The binary plots between cationic weight percentages of other major elements (K versus Al, K versus Fe and Ti versus K %) also show that the Wajrakarur pipes are undoubtedly diamondiferous in nature (Fig. 6b to d). Evidences from exploration activities involving assessment of Anumpalli, Dibbasanipalli and Chigicherla kimberlites, the GSI has recovered 81 diamonds weighing 20.74 carats from a kimberlite material of 200 tons [50].

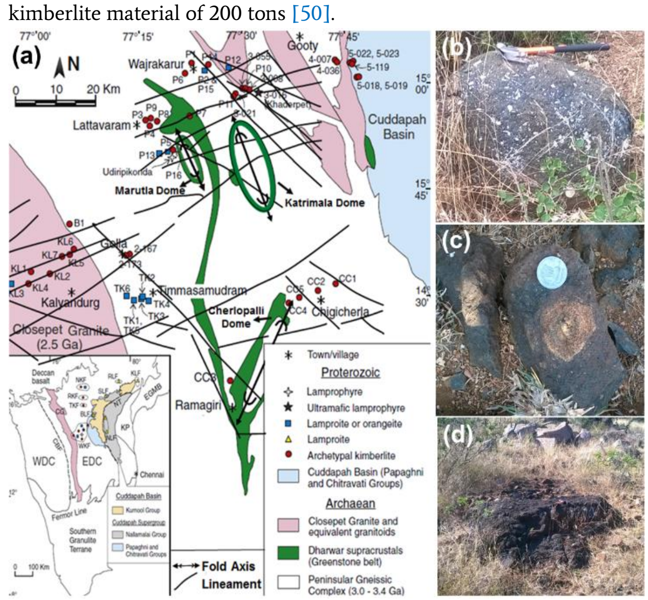

Fig. 4. (a) Regional geological map showing clusters of kimberlite pipes of Wajrakarur Kimberlite Field [33, 34] showing interpreted lineaments [35]. Inset: regional geological map of south Indian peninsula.

Legend for kimberlite clusters: Wajrakarur- P1-P16; Chigicherla- CC1-CC5; Kalyanadurgam- KL1-KL7; Timmasamudram- TK1-TK6; Dibbasanipalli and Khaderpet- 3021 and 3016; Brahmanapalle- B1; Golla- 2-167 and 2-173; Gooty- 4-007, 4-036, 5-022, 5-023, 5-119, 5-018, 5-019 and 5-028 (not shown in map). For kimberlite and lamproite fields (KF and LF) and other abbreviations refer Fig. 1. CBF- Chitradurga Boundary Fault, EGMB- Eastern Ghat Mobile Belt. (b) Pipe-11, Dibbasanipalli represented by a single boulder. (c) Granite xenolithic clasts in pipe-5, Tummatapalli. Coin diameter 25 mm. (d) pipe-5, Muligiripalli. Note granitoid country rock in the background.

Table 1. Salient deposit characteristics of Wajrakarur kimberlite pipes (Compiled from various sources).

Rock type		Kimberlite
Host rock		Granite, granodiorite, granite gneiss, dolerite dykes, amphibolite, greenstone etc. [36].
Chronological Range		WKF Kimberlites range in age from 1100 Ma to 90 Ma [36]
Deposit emplacement environment		Hypabyssal to diatreme facies [36].
Plate Tectonic Setting		Emplaced in stable Archaean craton except some of Gooty pipes [36]. Emplaced closed to contact of TT gneisses with TGA granitoids at the intersection of an ENE-WSW fracture with a NW-SE fault. Closely associated with younger alkali syenite intrusions [28].
Other associated Mantle rocks		Carbonatite in case of Khaderpet (3-021) pipe [37, 32]
Structure		Vertical deep-seated intrusions. Surficial outline generally circular to semicircular to oval. Located at the intersection of lineaments striking in multiple directions (NE-SW, NNE-SSW, NW-SE, WNW-ESE, ENE-WSW) [28].
Overburden		Capped by 1-5 meter thick calcrete/regolith/alluvium cover. Outcrops peep through the surficial cover [28].
Associated Deposits		Gold in Greenstone Belts within the province.
Primary Ore Mineral		Diamond
By products		REE, MgO, PGE
Mineralisation Structure/Texture		As sparsely disseminated discrete mantle xenocrystic diamonds.
Gangue Characteristics	**Xenolith/Clasts**	Granite, granodiorite, granite gneiss, dolerite dykes, amphibolite, greenstone etc. [36].
	Mineralogy	Within kimberlite: Serpentinised olivine, phlogopite, spinel, chromite, perovskite, rutile, pyrite, chrome diopside, garnets (Cr-pyrope, Ca-pyrope, almandine, etc.), magnetite, ilmenite, apatite, calcite [36].
		Crustal xenolith mineralogy: Quartz, feldspar, pyroxenes, biotite, muscovite, amphiboles, iron oxides [36].
Weathering		Kimberlite outcrops are vulnerable for weathering than host rocks forming topographic depressions [38].
Stability		These deposits are vertical intrusions hence developing benches for open-pit mining is not complex like elsewhere in the world. Also, the WKF deposits occur in seismologically stable cratonic domain, hence it is safe for mining activity.

The diamond grade (DG) has been calculated for Wajrakarur kimberlites, involving cationic weight percentages of Fe, Ti, Al, K and Na, using the empirical formula given below [51].

$$DG = Fe{:}Ti/[\log(Fe+Ti)+2\log(Al+K+Na)] \quad \text{Eq. (1)}$$

The ratio of cationic weight percentages (Fe:Ti) plays a major role in diamond content of a kimberlite [51]. The pipe-7 at Venkatampalli is reported to be superior among in terms of deposit size and diamond potentiality. Using published data [47], DG values for Panna (Majhgawan) kimberlite are calculated for comparison purpose. The pipes at Venkatampalli, Lattavaram and Dibbasanipalli possess DG values close to Panna pipe (Table 2). The TiO_2 content is inversely proportional to the DG. The high TiO_2 content in some of the WKF kimberlites is ascribed to the presence of enriched ilmenite proportion. The factors that influence the DG values in addition to the high TiO_2 content are crustal contamination, ilmenite entrainment, oxygen fugacity etc. However, these factors have no impact on the whole rock geochemical composition of the kimberlite rock [52, 53]. Further, wide variation in the proportions of macrocrysts and phenocrysts-matrix ratios are believed to be causative factors for the fluctuations in compatible element abundances [53]. Thus the low DG values in some of the Anumpalli kimberlites of the WKF (Dibbasanipalli, Khaderpet) are attributed to presence of crustal contamination by granitic rocks during the ascent of kimberlite magma from mantle (Fig. 7). Moreover, the Khaderpet pipe is represented by a heavily chloritised kimberlite granite breccia and is unique in possessing association of carbonatite (sovite) phase [37, 32].

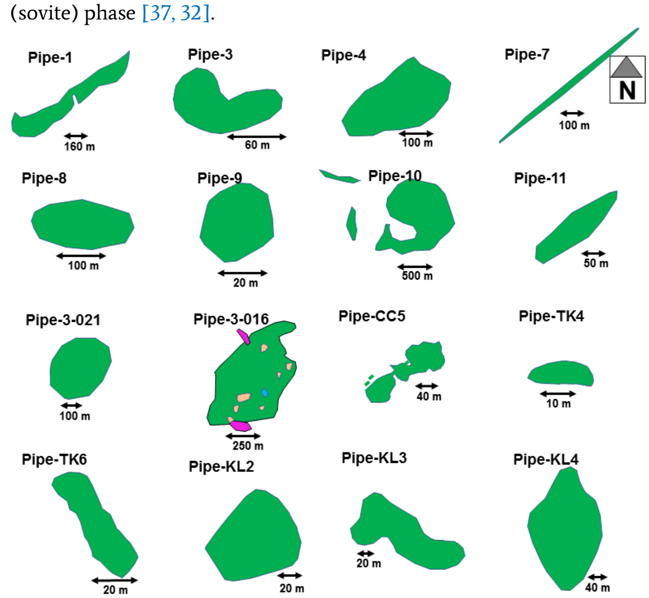

Fig. 5. Surficial outline of some of diamondiferous kimberlite pipes within the WKF [28, 36]. In pipe-3-016, Magenta- alkali syenite/younger pink granite, pink-granite- chloritised kimberlite breccia and blue- carbonatite. In all diagrams, green refers to kimberlite.

Table 2. TiO_2 and cationic weight% of kimberlites of the WKF. Panna data for comparison. See text for data sources.

Pipe	TiO_2	Fe	K	Ti	Al	Na	Diamond Grade (DG)
3	1.58	6.34	0.74	0.95	1.71	0.08	8.34
4	1.56	6.6	1.02	0.94	1.9	0.11	7.37
5	5.36	8.12	0.8	3.21	2.04	0.18	2.73
7	0.79	3.53	0.49	0.47	1.52	0.17	10.68
8	2.57	5.6	0.4	1.54	2.85	0.26	3.33
9	0.71	4.81	0.19	0.42	1.58	0.04	22.13
10	2.2	7.44	0.77	1.31	2.22	0.27	5.53
11	1.27	4.91	0.15	0.76	2.33	0.22	7.48
13	6.62	8.01	1.87	3.96	1.64	0.07	1.82
3-021 (Dibbasanipalli)	1.19	2.93	1.61	0.71	2.15	0.22	3.43
3-016 (Khaderpet)	0.66	2.78	2.46	0.39	7.33	2.48	3.52
Panna	0.74	2.88	0.66	0.44	0.55	0.14	8.36

The bivariate diagram involving Ta and Sc (ppm) portrays that the kimberlites of Lattavaram, Anumpalli, Chigicherla of the WKF are diamondiferous Fe-Ti varieties (Fig. 8a and b). The diamond incidence values given by the GSI [50], calculated from excavation and drilling material also align with the inferences made from whole rock geochemistry. However, some pipes (e.g. pipes- 5, 13 and 16 of Muligiripalli, Tummatapalli and Pennahobilam respectively) are reported to be barren which is attributed to high concentration of TiO_2 which is in turn due to high ilmenite content in the kimberlite [54, 34, 36].

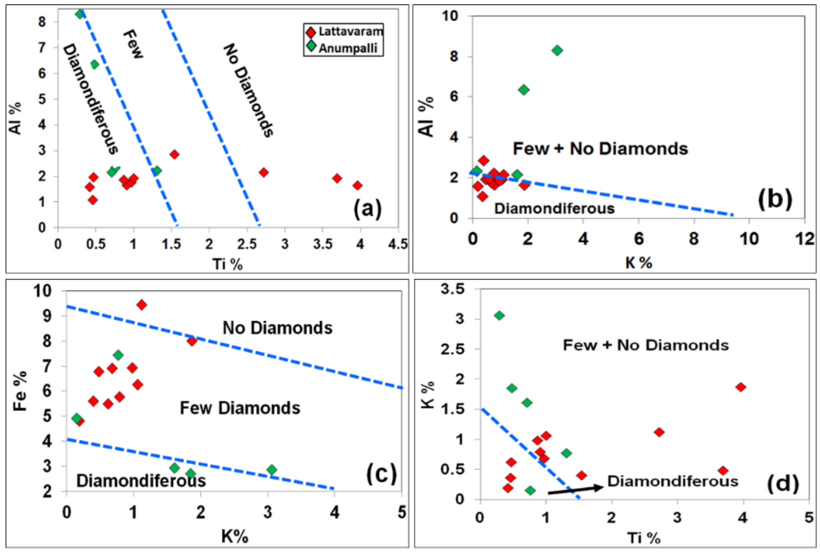

Fig. 6. Bivariate diagrams showing cationic weight percentages of kimberlites of Lattavaram and Anumpalli clusters in Wajrakarur field. For data sources, see text.

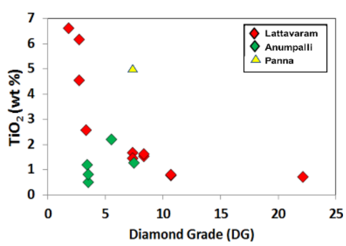

Fig. 7. Diamond Grade (DG) versus TiO_2 (wt %) in Lattavaram and Anumpalli kimberlites. See text for data sources.

3. Development of diamond mining industry

In India, mineral exploration programmes by government organisations persisted through more than a century and half ever since the GSI has been established. In the independent India, the GSI has been conducting diamond exploration since 1950s and has pioneered to be a stalwart organisation, by initiating 'National Diamond Project' in the WKF in 1980s [57]. Nonetheless, the diamond exploration was conducted with minimum financial and strategic support of concerned ministries.

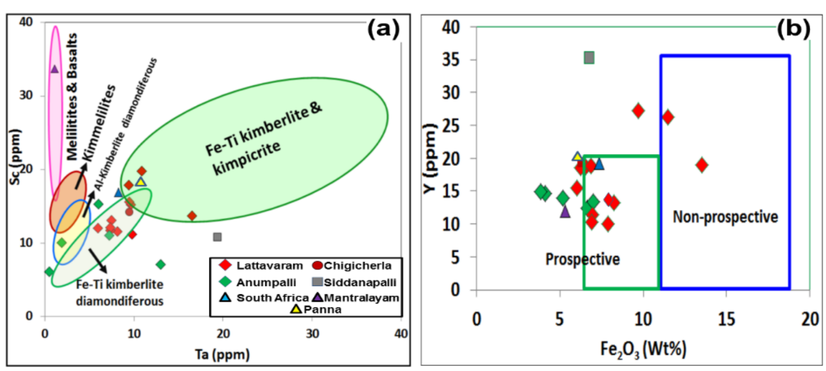

Fig. 8. Diamondiferous nature of Wajrakarur kimberlites. (a). Ta versus Sc (ppm) plot [55]. (b) Fe_2O_3 (wt %) versus Y (ppm) plot [56]. For data sources, see text.

Most of the kimberlite discoveries have received good quantum of research in terms of petrology and geochemistry, however, their economics were not substantially investigated. Furthermore, most of Indian private mining companies are interested and confident on investing on risk-free or less-risk oriented visible mineral deposits like coal, iron ore, bauxite etc. than invisible deposits like diamonds, gold, precious or base metals. Hence, only government organisations were active in diamond exploration. Even though some private companies obtained reconnaissance permits (RP), they could not reach up to prospecting license (PL) or mining lease (ML) stage. As a consequence, the survey reports by the Indian government organisations were the only resort to use as knowledge sources, which in most cases, have ended up with publishing a paper of the finding, helping to fulfill the personal goals of the project geologists and/or associated academicians. In the same lines, prior to the year 2000, economic assessment, though not comprehensive, has been meagre and conducted for only couple of pipes. Though some very recent pipes were systematically discovered by the Indian organisations, it appears that some of the past discoveries were accidentally found during conventional geological mapping or geophysical traverses or while searching for other mineral deposits. This was mainly due to lack of technical know-how on kimberlites during those times. Yet, pipe-7 of Venkatampalli was perhaps the first pipe discovered using systematic KIM survey in the year 1986 [36]. During the decade 2000 to 2010, with the advent of liberalisation of economic policies by the Indian government, several multinational companies like Rio Tinto, De Beers etc. have embossed their foot print and impetus with latest methods in diamond exploration in the country and actively carried out prospecting for new kimberlites in India. This has led to the discovery of several diamondiferous pipes of better grade than previous deposits [58, 59, 60]. All these discoveries warrant detailed feasibility studies and some of them may be reasonable to develop as small-scale diamond mines. India has a potential ground for discovering many more kimberlites than what have been discovered so far, provided a strategic exploration plan is exercised [61]. This is well endorsed by recent new additions in the WKF. It has to be noted that thorough economic assessment of all the kimberlite pipes is not in the pace with the global technological advancement happening in the rest of the world. While the production statistics are available for the Panna mine, resources of the south Indian pipes are limited to few pipes of the WKF. However, preliminary investigations in the WKF and results obtained from excavations at Panna reveal that the resources are substantial (Table 3), which still to be reassessed. India has gifted many amazing diamonds to the world as in Fig. 3. Some of beautiful diamonds acquired from the Wajrakarur kimberlites by the GSI are shown in Fig. 9.

Table 3. Diamond Resources in the WKF, Andhra Pradesh and resources in Panna diamond Mine. Units are in carats. Codes refer to UNFC System of mineral resource classification [62].

		Proved STD111	Probable STD122	Total 'A'	Pre-feasibility STD221	Measured STD331	Indicated STD332	Inferred STD333	Inferred STD334	Total 'B'	Total (A+B)
By grade	Gem	0	0		1017	234148	0	521600	0	756765	756765
	Industrial	0	0	0	223	58200	0	782400	0	840823	840823
	Unclassified	605577	600000	1205577	0	6290	1523077	245359	4022	1778748	2984325
By region	Andhra Pradesh (Wajrakarur)	0	0	0	1240	298638	1523077	0	0	1822955	1822955
	Panna	605577	600000	1205577	0	0	0	245359	4022	249381	1454958

Fig. 9. Diamonds extracted from the Wajrakarur kimberlites [28].

While diamond exploration has deteriorated in India currently, on the other hand, the diamond polishing industry is growing day by day, with a history of nearly 2000 years has continued to thrive till today. Approximately 80-90% of diamonds produced from elsewhere in the world are getting a refined shaped in India [58, 59]. The polishing industry has to be technologically modernised, with healthy and safe living conditions to the artisan workers. According to the Southern Gujarat Chamber of Commerce, about 3500-4500 small scale diamond polishing units are surviving in Surat alone offering employment to about 1.5 million people [62]. It is inevitable for the country to import or purchase large quantities of rough diamonds from multiple producers. The production of diamond from Panna mine is limited to meet the cutting and polishing industry's requirement [63]. As per the Indian Bureau of Mines (IBM), the production statistics from Panna diamond mine are gradually increasing (Table 4). The revenue incurred from Panna has been doubled from the year 2012 to 2017. However, production of diamonds from additional local mines, if developed, will undoubtedly ease the shortage and offer some solace to rough stone buyers in terms of cost which is currently a business risk for polishing industry.

Table 4. Production details of Panna diamond mine. Units in carats. [64, 65, 63].

Year	Production (carats)		Value (US$)
	Gem (rough & uncut)	Industrial	
2012-2013	10564	21424	4821.99
2013-2014	11599	25916	8080.05
2014-2015	12031	24976	8072.42
2015-2016	12784	23260	8176.86
2016-2017	13488	23028	8415.74

While in India, diamond exploration is limited to identifying the primary rock or at the most to obtain an initial idea of its field relations, geochemical aspects and diamondiferous nature, the western world has achieved a great success in proving world class discoveries. The success in diamond mining in the western world is mainly due to the involvement of top-notch private sector international companies or consortia of companies and their huge investment though it is risk-prone. At present, Russia produces 40 million carats and stands in the top most position in the world, followed by DR Congo with 23 million carats and then by Australia and Canada with 13 million carats each. Currently India's position in rough diamond production is much low with a production of 0.033 million carats [66]. Some of the richest diamond mines in South Africa have yielded the stones at the rate of 14 to 19 carats per 100 loads (each load weighing 1600 lbs) which amounts to 0.0000052% or approximately 0.2 carat/ton. However, the production rate has been increased in due course of time. When the world average is poor, it is quite possible that the investment and amount of investigation at Wajrakarur is very negligible and much more has to be assessed. The diamond content of the ascending kimberlite magma depends on the final empalcement processes involving multiple pulses of kimberlite that result into a single intrusive body. The diamond distribution within single kimberlite body can be highly complex [67]. If the planned drill holes puncture the zone where no diamonds are localised, the kimberlite might be declared barren. The practice in India till now has been based on a couple of shallow drill holes and thus the decisions were not unbiased. For instance, localisation of diamonds in the Bunder pipe was in southern portion of the pipe; had it been drill-tested in the northern or other portions, Rio Tinto could have left with a feebly diamondiferous pipe but an extraordinarily detailed investigation using multi-directional drilling spread all over the deposit has led to delineate the actual order of magnitude of the deposit. This has fortified a jubilant world class deposit portraying a classical example of exploration success which was resultant of no compromise on investment [68] and zeal to discover a mineable deposit instead of culminating the finding to a report or research paper. Therefore, all the WKF deposits need to be thoroughly investigated by additional multidirectional deep drilling to delineate the 3-dimensional structure of the intrusive bodies to arrive at an authentic diamond grade of each lithological entity through a methodical assessment. If government organisations do not have expertise to perform that task, skilled professionals are available in the private sector to whom it can be auctioned or outsourced. The historical exploration data of WKF should only be used as an initial reference however, while proceeding for mining, techno-feasibility studies need to be carried out meticulously. This will not only enhance the knowledge of kimberlite geology to appropriately evaluate the economic potential of the pipe but also helps improving the confidence in making decisions on exploration and effective mine planning.

Of late, the GSI have conducted detailed studies on WKF pipes such as Muligiripalli (P5), Pennahobilam (P16), Venkatampalli (P7), Timmasamudram (TK4) etc., however, most of this data is available with the GSI as confidential reports. Despite a history of 70 years in diamond exploration by the GSI, no kimberlite has been studied in terms of its geotechnical aspects other than initial investigations. The detailed geotechnical analyses are vital for proceeding for mining. Perhaps, the Wajrakarur pipe-1 (P1) was the only pipe so far on which detailed assessment of diamond potentiality has been carried out. About 670 stones, from Wajrakarur, Chigicherla, Anumpalli, Kalyanadurgam and Timmasamudram, have been tested for morphological and FTIR (Fourier Transformation Infrared) analysis. A major portion (80%) of these stones corresponds to Timmasamudram (TK4) pipe [36]. However, a recent preliminary assessment, with the aid of historical data, revealed that the diamondiferous nature of WKF pipes is not so encouraging (<2 cpht). Among the 65 stones collected from the WKF pipes, colourless type stones dominate among the population (51%) followed by brown colour stones (35%) while the least population is of yellow tinge stones (8%), transparent green coated (3%), grey (1.5%) and black (1.5%), An analysis using infrared spectroscopy shown that the total nitrogen content (N_{total}) for the WKF diamonds ranges from 0 to 586 at.ppm. One stone was reported to possess 1718 at.ppm. Majority of the WKF stones belong to IaAB, IaA and II class (58%, 25% and 17% by population respectively) with concentration of platelets ranging from 0 to 9.2 cm^{-1} [69]. Nevertheless, these inferences were based on a high-level reconnaissance approach and presumably generated from few available stones of historical exploration which involved shallow (10m) pitting at regular intervals. As diamond incidence is not distributed evenly in a kimberlite pipe, a thorough detailed diamond content analysis using core from large diameter drilling (LDD) is very much necessary so as to define the magnitude of diamond content of the WKF pipes. With the available knowledge and equipment during the period 1980-81, GSI has carried out processing of the kimberlite material was subjected to crushing, wet grinding, sizing and concentration at the Wajrakarur Processing Plant which can process about 30-40 tonnes per day. A detail of pitting/drilling activity and diamond incidence in some of the pipes assessed by the GSI is listed in Table. 5. The minimum concentration of diamonds must be substantial enough to achieve economic extraction. In general, as low as 0.1 carats (1 carat=0.2 grams) per a ton of kimberlite rock is feasible to mine as on today. However, a concentration of 0.5 carats or more per ton is generally preferred to consider a diamondiferous kimberlite to be mined. A concentration of 2-4 carats per ton is the most profitable case. At present, the production of pink diamonds from Argyle mine of Australia reaches only a production of 6 carats/metric ton (1 metric ton= 2200 lb) [70]. The WKF pipes all put together present a total caratage of 10.01 cpht with highest being the Venkatampalli pipe while the average caratage of the WKF pipes is 2.5 cpht (Table 5). This inference is based on available reports but if these pipes are meticulously assessed, there is every chance that grade may have betterment. It is significant to note that the source of this data is obviously the government reports and there exists a difference in these values in reports published by same organisation lacking in consensus among their own reports.

The Siberian kimberlites with less than 0.5 ct/mt of diamond were considered barren in the past while the mineable economic grade was greater than 2 ct/mt [71]. Elsewhere in the world, the Argyle lamproite is the only primary deposit that consistently meets this criterion even today (however, as per the latest news, by the time this article was published, the Argyle mine will be closed in late 2020). Therefore, the possibility exists that kimberlites considered to be barren in the past, may be reassessed to be economically viable in future by implementation of new technology and substantial investment.

The processing plant of the GSI at Wajrakarur is now disused either due to outdated manual process or unrepairable condition of equipment. This plant needs to be upgraded to state-of-the-art technology like caustic fusion that can minimise time and errors in manual intervention and gain faster dividends. Nevertheless, all the WKF pipes need to be thoroughly and systematically tested for their actual diamond content. The WKF thus forms most favoured area for targeting a detailed investigation to ascertain the feasibility of initiating diamond mining operations. An ideal case of a diamond mine is initially an open pit, upon advancement of mining activity while the mine progresses deeper, it may be upgraded to a level of an underground mine (Fig. 10).

Table 5. Bulk processing results of Wajrakarur Kimberlites [50]. Units: ct- carat, cpht- carats per hundred tons. ʃ[31], *[47].

Pipe No.	No. of Pits	Material processed	No. of Stones	Grade
1 (Wajrakarur)	14 +many trenches	13780 tonnes	384	80.88 ct or 0.78 cpht
2 (Wajrakarur)	9	16 tonnes; 540m³	nil	nil
3 (Lattavaram)	5	907 tonnes, 320 m³	12	2.55 ct or 0.3 cpht
4 (Lattavaram)	13	1400 tonnes	28	0.3 ct or 0.02 cpht
5 (Muligiripalli)	5	482 tonnes	nil	nil
6 (Kothakunta)	25	8471 tonnes	371	0.67 ct or 0.008 cpht
7 (Venkatampalli)	10	1515 tonnes	1142	119.52 ct or 7.9 cpht
10 (Anumpalli)		1434 tonnes	48	0.78 cpht
11 (Dibbasanipalli)	10	225 tonnes	2	2.15 ct or 0.95 cpht
3-016 (Khaderpet)ʃ	-	100 kg	58	-
3-021 (Dibbasanipalli)ʃ	-	100 kg	47	
Panna*	-	-	-	10 cpht

Not only just diamonds, kimberlites are reported to be sources for several other products and by-products. Kimberlites act as repositories of PGE, REE, Nb, Ta, Zr, Rb and other large ion lithophile elements (LILE) and high field-strength elements (HFSE) [39]. Tailings produced from kimberlite processing from diamond mine have been used for extraction of magnesium oxide (MgO) [72] and also can precipitate silica, sodium silicate, zeolite-A and titanium dioxide (TiO_2) [73]. Hence, production of such by-products from the excavated waste rock will add to the revenue influx to meet the operation costs of mining and diamond extraction to some extent.

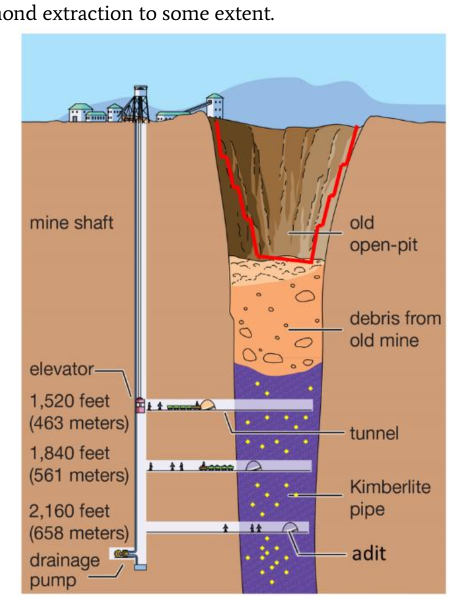

Fig. 10. Schematic cross-sectional view of an ideal diamond mine [74].

Diamond mining is a complex and exorbitant business. Once an economic viability of a diamond deposit is declared, the next stage is to study the feasibility for mining. Recent studies indicated that a financial budget of 400 million US$ is required to develop an economical kimberlite to a diamond mine [75]. A recent example is the contemplated budget for Misery open pit of Ekati, Canada where the initial development capital alone was 94 million US$ with sustaining capital and unit operating costs per tonne as 9 and 71 million US$

respectively total amounting to nearly 200 million US$ [76]. While the Indian government organisations may not come forward to invest such a risk-driven and high capital venture, the only resort is inviting participation of internationally renowned private companies who have proven technical track record of successful diamond mining. Further, the goal of a private organisation is always to discover a mineable diamond deposit with an expenditure of millions of dollars whilst the government organisations hold meagre and limited budgets granted annually. However, in India, as the cost of manpower, logistics etc. are comparatively cheaper than elsewhere; the total estimated cost may be much lesser. Once the mines are established and production takes off, operational costs will be stabilized at a much lower level by adopting cost-effective technologies.

4. Feasible geographic conditions

As majority of diamondiferous WKF pipes occur in close proximity, they can be developed as open pits adjoined with a centralized processing unit, diamond recovery and production units. Most importantly, the Wajrakarur pipes are not situated in environmentally critical zone and geographic conditions of the region offer feasibility for mining. The required processing unit may be setup at a central location which should be accessible from all the mine pits at Pandikunta-Tatrakal village area (14°56'40"N 77°22'52"E) where a perennial water source is available from Penna Reservoir at a distance of 7 km due south (Fig. 11). Another option for processing facility would be the renovation and modernisation of the existing processing plant at Wajrakarur established by the GSI, by increasing its capacity and incorporating latest kimberlite beneficiation technology like large scale caustic fusion, to beneficiate approximately 1000 tons of rock per day. The district being inactive in agriculture and drought-prone, ample and favourable ground is available for storing stock piles and waste dumps with the consent of local land owners. The tailings can be used for extraction of useful by products as well. All the pipe locations are well connected by a good road network and the available human resources are ample. The area is known for wind-mill based power generation, which can meet the electricity requirements for mining, transportation, processing etc. The vast plain lands are viable for developing township and other social infrastructure for the working personnel of the mines. The Kalyanadurgam- Timmasamudram pipes are located at a distance of 50 km due SW and the Chigicherla pipes are at due south from Anantapur town, for which a similar setup may be planned. The WKF area is close (~250 km) to major cities like Bangalore or Hyderabad where a variety of certified laboratories are available for day-to-day management of quality control. This scenario of collective mining is similar to the case of Diavik diamond mines of Canada, wherein a cluster of four closely spaced kimberlite pipes are being effectively mined (Fig. 12); nonetheless the diamond incidence may be much smaller in WKF pipes when compared to Diavik pipes. Of late, a new mine has been opened on the A21 pipe in the Diavik cluster to meet the production targets [77]. This demonstrates progressive development of mines to meet the production requirements.

The open-pits in the WKF may be developed sequentially so that there could be an uninterrupted production and raw material supply to processing plant. There is no reason why southern India should not regain its past glory of diamond mining, being the store-house of and having introduced the most exquisite and dazzling gemstone to the world. Even after decades of independence, the country has been futile to regain its lost grandeur and leadership position in diamond production. There is a need to bring reforms and changes its approach to place diamond mining back on track and compete with the present global market [78].

Indeed, a highly transparent bureaucratic governmental setup in achieving the goal of reviving the diamond production is preordained for significant growth in the diamond mining industry in India. In this context it is even more imperative to plan and execute a strengthened diamond exploration strategy with ample indigenous investment in all the potential areas in the country to augment diamond resources. With their vast experience, the public sector organisations may look into the feasibility of collective mining of WKF pipes or the government may invite foreign investment which would be an easy approach if the country vehemently desires to witness a revived diamond mining industry in southern India.

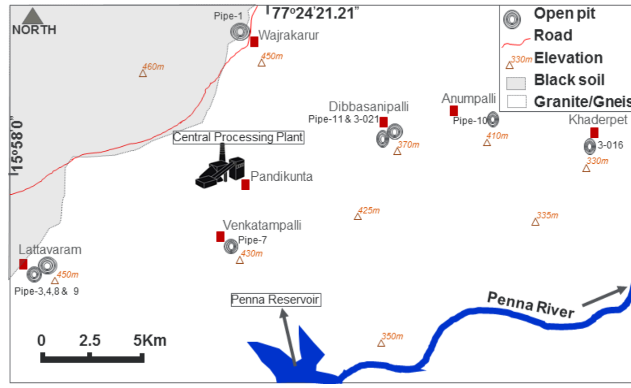

Fig. 11. Simplified geographic plan of possible open pit mines of some kimberlite pipes in Wajrakarur and centralised processing plant.

Fig. 12. Aerial view of Diavik diamond mine cluster [75].

5. Conclusion

Based on geochemical assessment supported by published field exploration results, the kimberlites of the WKF are undoubtedly diamondiferous and offer a feasible opportunity for extraction of diamonds in an economical way by adopting collective mining despite the smaller size of deposits. The closely situated kimberlite deposits of the WKF can offer ~10 cpht if collectively mined. The DG values calculated using whole rock geochemical data are high for the WKF pipes ranging from 3.33 to 22.13. It is observed that higher the TiO_2 content, lower is the DG value. The DG value of some of the pipes is higher or close to the pipe rocks of Panna mine. As the WKF pipes are situated within a radius of 15 km, a tremendous cost reduction in ore-processing and time saving is possible through collective mining, leading to efficient utilization of the local human resources. Such a conceptual collective mining plan, in accordance with a proper environmental strategy, will not only help the socioeconomic status of the region and in turn the country to grow but generate employment opportunities to the local people. Local production of diamonds will also offer a helping hand to the small to medium scale diamond polishing industry. It is indeed, the methodology of collective mining attracts huge investment but can be proved successful; however, needs to be abided by strict implementation of environmental and mining policies along with bureaucratic transparency. However, if this methodology is proved to be successful, it can be implemented for other smaller diamondiferous pipe clusters such as Chigicherla, Timmasamudram, Kalyanadurgam etc. in the southern India and others present elsewhere in the country with a long term mission and sanguine vision.

Acknowledgment

This article is written in commemoration of two unseen premier geologists of India, Late Pingali Venkaiah (1876-1963), the first Indian kimberlite exploration geologist, freedom fighter and designer of the Indian national flag and his son Late Pingali Parasuramaiah (May 24th 1919-1990), a diamond geologist cum journalist who pioneered the research on diamond-bearing rocks in India much before the GSI. Coincidentally, 2019 is the birth centenary year of Late Pingali Parasuramaiah. His monograph on diamonds inspired the author to develop interest in kimberlite exploration geology. The author thanks the organisers of the 'Mining Today-2018' International Conference, Hyderabad, India where he has presented a talk on a broadly related topic. Critical comments by anonymous reviewers have immensely improved the manuscript quality. The opinions in this article are of the author, based on his learnings as an exploration geologist in the field of diamond exploration from 2002 to present, and not necessarily of the affiliated organisation.

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