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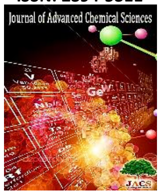

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Area Selection for Diamond Exploration Based on Geological and Morphostructural Set-Up: Examples from Wajrakarur Kimberlite Field, India

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ABSTRACT

As kimberlites/lamproites act as hosts for diamonds, exploration for those rocks is regarded as diamond exploration. In the world, kimberlite/lamproites are associated with cratonic areas where there is a conspicuous congenial tectono-structural set-up. Occurrence of kimberlitic rocks is considered as a geological anomaly and kimberlite exploration involves many geological, geophysical and geochemical aspects. Success of exploration for kimberlitic rocks is achieved in selecting favorable prospects in the first stage by thoroughly studying the existing maps, geological literature by taking reported pipe rocks into account. This paper high lights significance of geological aspects such as morphostructural, tectonic and style of geological set-up in selection of prospective areas for kimberlite search, presenting Wajrakarur Kimberlite Field (WKF) as an example, in comparison with some important similar cases elsewhere in the world. Three areas were suggested for further exploration in the WKF.

1. Introduction

As in the case of any other mineral commodity, diamond exploration also includes two or three broad stages viz., area selection, prospecting and exploration. In the initial stage, prognostication may be carried out on desktop remotely by using geological, geophysical maps, satellite imagery and existing mineral inventory data. The most effective approach to area selection is preliminary study of regional geology, geochemistry and geophysics of the area and thereby determining the most favorable and prospective areas, thus portending the possibility of further exploration. As an initial step, all available relevant geological maps need to be compiled, analyzed and areas of high priority need to be picked up where future prospecting is to be planned. Depending on the extent of previous studies and available literature, the following stages of prognostication can be defined; each corresponding to appropriate map scales (Table 1).

Table 1 General schema of area selection in kimberlite exploration [1].

Stage	Scale
1. General regional prognosis of geologic and tectonic provinces of diamond potentiality the country.	Regional (1Milion, 1:250,000)
2. Local prognosis scale aimed at delineation of the most prospective areas within defined kimberlite/Lamproite fields and pipe clusters within known or recently discovered fields, thereby narrowing down the area of interest.	Large (1:50,000, 1:25,000)
3. Detailed large scale or local prognosis on using modern web tools like Google Earth or Arc2Earth.	High-resolution (1:25,000 or larger)

Each stage stated above carries a different set of procedure depending on geology and feasibility and availability of published literature and degree of historical exploration.

Kimberlite/lamproite intrusions within cratons usually are localised in zones of high magmatic permeability, as defined by the repeated intrusion of various types of igneous rocks. This results in a linear distribution of kimberlite fields within individual provinces. The kimberlite-bearing zones are usually highly permeable and form a system of contiguous long-lived deep-seated major faults, controlling the intrusion of mantle (mafic and ultramafic) magmatism in cratons. These zones have been formed under a regime of uplift and compression and is characterised by well-developed block structure. Such mobile zones are characterized by the following features which can be divided into geological and structural [1].

1.1 Geological Features

In a cratonic terrain, kimberlite/lamproite emplacement is associated with many geological features. Basic, ultramafic, granitic intrusions, volcanics are ubiquitous. Due to the effect of intrusions, the proximities are fenitised moderately if not intensely. If basic volcanics are present within the adjacent craton cover, they are observed to increase in their thickness towards the mobile zone. The mobile zones exhibit typical horst-graben structure and the basement blocks often occur as outcrops. Across the strike of the mobile zone, the uplifted and subsided blocks occur in alternation. The central part of a mobile zone is generally characterized by widespread shear-thrusting and linear folds within the cover. The cover rocks may sometimes be metamorphosed from greenschist- up to amphibolite facies within a mobile zone. These mobile zones characteristically show elongated, discrete magnetic and gravity anomalies that have sharp contrast with the background. Dispersion halos of diamond-indicator minerals may relate the above-mentioned structures to the kimberlite/lamproite field. Finds of diamonds within these dispersion halos indicate a diamond-bearing field. Some indirect criteria of a kimberlite field are cluster distribution of local pipe-like magnetic anomalies within the above-mentioned structures, and geochemical halos of elements (Cr, Ni, Co, Ti, Nb etc.) characteristic for alkali-ultramafic magmas.

The 'Clifford's Rule' which states that the economically viable primary kimberlite deposits in general primarily occur on Archaean Cratons (Archons) and Proterozoic Cratons (Protons) and older mobile belts accreted to the cratonic areas [2, 3, 4 and 5] also holds good in guiding during the area selection for kimberlite prospecting.

In general shield areas of world comprise Precambrian cratons and mobile belts. Likewise the Indian peninsular shield consists of cratonic blocks viz., Dharwar, Bastar, Singhbhum and Bundelkhand. Further the Dharwar Craton is devided into two tectonic blocks (i) Western Dharwar Craton (WDC) and (ii) Eastern Dharwar Craton (EDC), based on

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differences in the schist belt characters, their interrelationships with the surrounding gneiss/or granite and the prevalent metamorphic facies [6]. For diamond exploration on a regional scale Archaean cratons are the most promising areas and includes both primary (Kimberlites/ Lamproites) and secondary source rocks (conglomerates and gravels). It is well-known fact that the Graniotid terrain of EDC, Granitoid- Greenstone belt comprising domal structures and Granitoid terrain in the proximity of Kadapa Proterozoic Basin and Western and Eastern margins of the Kadapa Basin stand as promising areas for further exploration [7]. As far as the Indian context is concerned, based on known diamond occurrences, diamond-host rocks and geotectonic setup, potential and promising areas hosting Wajrakarur, Raichur and Narayanpet kimberlite fields of the EDC, were among significant areas in addition to several others.

1.2 Structural Features

Common structural features that are associated with kimberlite emplacement are described below. These mobile zones described above are structurally divided into (a) transcurrent intra-cratonic and (b) rift-related ones, depending on their geological position [1].

The geological model reflects the existence at depth of a crust-mantle irregularity, from 30 to 90 km in diameter. It includes the following elements [1].

1. Intersecting highly permeable transverse structures, which usually are deep-seated faults. Such faults are usually detected by remote sensing techniques followed by ground truthing.
2. A dome- or block-shaped uplift 30-100 km in diameter (in relation to the field disposition) with an elevation from a few tens to a hundred meters, and gradually decreasing depth.
3. Minor domal uplifts and blocks within the main dome, including intrusion-related domes and blocks, corresponding to pipes.
4. Radial and parallel fault systems, with different orientations and centred near the apex of the dome-like or block uplift.

Recognition of all the above criteria considerably increases the possibility of distinguishing and outlining favourable provinces proposed kimberlite/lamproite fields and, consequently, enhances the effectiveness of the prognostication and subsequent prospecting. Dome-shaped uplifts are usually displayed in fairly plastic sedimentary cover rocks, while block-shaped uplifts are formed in more rigid cover rocks or within outcrops of basement on cratons. The uplifts exhibit structural complexity and intense jointing of the slopes or a complex block-framework combined with domes, flexures, and narrow trench-like grabens. The sizes of these uplifts are revealed during ground truthing where sedimentary cover is present.

Kimberlite/Lamproite fields can be distinguished into two types, based on their structure [1]. The first type is most typical of platforms composed of brittle rocks where the distribution of kimberlites and lamproite and their shapes is controlled by structures such as faults. In such fields, pipe bodies exist within contiguous fault zones and tend to occur as clusters in either medium-size elevated medium-size blocks or fault intersection nodes, which form borders between elevated and subsided blocks. Linear dykes and long axes of pipes are typically oriented parallel to kimberlite enclosing subzones of fault systems.

The second type of kimberlite/lamproite fields is mostly characteristic of old platformal plastic sedimentary rocks. The pipe distribution and structural orientation is controlled by faults and folds and overall field structure is displayed as a dome-shaped uplift. Within this field pipe bodies occur as clusters as in the first model in subzones of contiguous faults with structural and tectonic relation to other basic rocks. Among the kimberlite bodies subcircular-shaped pipes are dominant, and these pipes are located in the cases, when the zones of contiguous faults show centre of medium-amplitude (15-30 m) domes rather than in the blocks. Such domes are most commonly disposed along the kimberlite-enclosing subzones or above the fissures formed by the feathering of these zones (e.g. Little Botuobiya Kimberlite Field in Yakutia. The sizes of the domes enclosing the pipes are typically 3-5 times greater than the diameters of the pipes. In addition to the structures mentioned above, larger domes of 5-10 km in diameter are rather commonly met within such fields; however, this effect on the distribution of kimberlites remains to be explored. Possibly, these domes might determine the disposition of individual kimberlite clusters.

The pipes of Wajrakarur Kimberlite Field (WKF) belong to the class of morphostructurally controlled occurrences described above. The WKF kimberlites occur as clusters in the proximity of Kathrimala, Cherlopalle, Marutla and Cherlopalle/Ramagiri domal structures. These cases are similar to those observed elsewhere in the world whereas pipes occurring in Kalyandurgam and Timmasamudram areas are aligned in an ENE-WSW linear trend.

The occurrence of kimberlite magmatism on a regional scale is in general hypothesized to be in relation with the following aspects.

1. Eperiogenic faulting [3, 8]
2. Mantle diapirs [9, 10]
3. Continental extensions of transform faults [12, 13]
4. Flat subduction zones [13]
5. Mantle hot spots [14, 15] and
6. Concentric and radian anteclises and syneclises [16]

2. World Examples of Morphostructural Features

Diamondiferous provinces of different size and economic value are distinguished within ancient cratons. It is well known that majority of kimberlite pipes are localized in the cratonic parts of the world, which can be grouped into three major classes' viz., kimberlite provinces, belts and structures that control the emplacement of kimberlite pipes. Using satellite imagery it is easy to identify circular or semi-circular morphostructures and associated major structural trends that control the emplacements.

Deep-seated structures reflect morphostructural relief on the surface which show conspicuous structures recorded in topographic contour maps, large scale aerial photos and satellite imagery. Kimberlite and lamproite fields show large concentric-radial structures extending a diameter of few to several 100 km. The individual kimberlite fields reflect as local ring structures of radial and concentric features which are devided into ring, dome, dome-ring, flat ones based on morphostructural expressions. The structures are generally localised within long-lived deep-seated faults in the points of intersections with other structural trends. Large arch uplifts or arch-ring structures in the central parts exist extending for 200-300 km in diameters complicated by systems of several minor ring structures. According to Kaminsky and others kimberlite bodies occur in concentrations at points of intersections between concentric and radial elements of ring structures and cross-cutting faults showing certain fracture patterns without any geological expression [1]. Morphological lineaments usually coincide with faults established by geological and geophysical data. They form a complicated structure of concentric-radial (thick lines), transitional (medium lines) and local (thin lines) lineaments. Kimberlite clusters are located within separate morphostructural blocks.

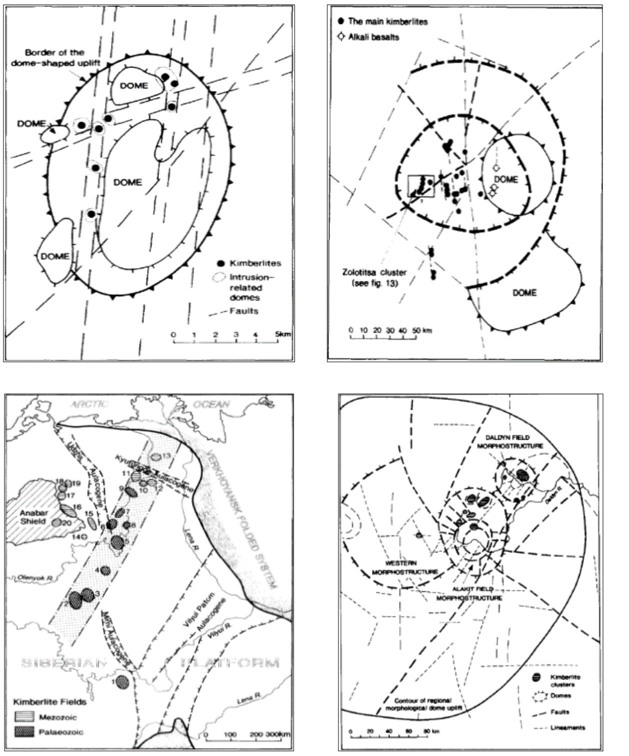

Fig. 1 From left to Right. Morphostructural features a) Little Botuobiya kimberlite field, Yakutia. b) Zimni Bereg Field, Arkhangelsk region. c) Kimberlite fields in Siberian craton and d) Daldyn-Alakit kimberlite region, Yakutia.

Kaminsky et al. reported that morphostructural features have strong affinity to kimberlite emplacements at various locations viz., Daldyn-Alakit kimberlite region and Little Botuobiya of Yakutia, Zolotitsa of Zimni Bereg Field, Siberian craton forming promising prospective zones [1]. In Little

Botuobiya kimberlite field, Yakutia, dome shaped uplift includes all the known pipes, which are controlled by zones of contiguous faults (Fig. 1a) whereas in Zimni Bereg Field, Arkhangelsk region, the kimberlite field is located within a morphological depression, in the central part of a larger morphological dome structure. Radial patterns are well seen in radial (thick lines), regional (medium lines) and local (thin lines) lineaments (Fig. 1b). In this case, kimberlites tend to occur near radial lineament zones and are controlled by submeridional local faults. The morphostructure of the Zolotitsa kimberlite cluster within the Zimni Bereg Field, the existence of one more prospective ring structure to the NW of the Zolotitsa cluster is clearly seen where diamondiferous pipes were reported. In the Siberian craton, kimberlites of Palaeozoic and Mesozoic age are distributed in linear fashion transecting all lineaments, dolerite dyke swarms which are considered to be ancient rift systems (Fig. 1c). In case of Daldyn-Alakit kimberlite region, Yakutia, Alakit and Daldyn Fields are well distinguished in morphological structures; as well they indicate prospective terrain to the west (Fig. 1d).

3. Examples from Wajrakarur Kimberlite Field (WKF)

The area selected for this comparative study forms part of the EDC falling in Anantapur district, Andhra Pradesh (Fig. 2). The WKF is located in the Wajrakarur area, north-west of Anantapur in Andhra Pradesh.

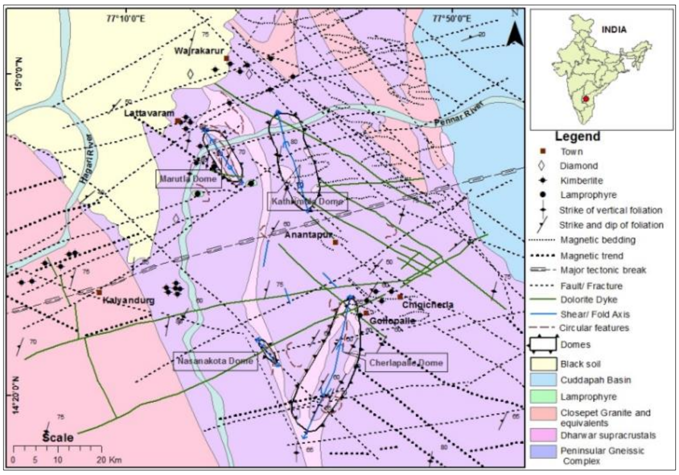

Fig. 2 Showing the WKF area in EDC, South Indian Shield [17].

3.1 Geological Set-up

The WKF is emplaced within the NS to NNW-SSE trending older gneisses, metavolcanics -metasedimentary rocks of the Ramagiri-Penakacherla schist belt and younger deformed granitoids over an area of 120x60 km. The WKF contains more than 28 kimberlite pipes, spread over clusters [18, 19]. In recent years this number has been increased to 40+ with the help of modern technology and better investments by various MNCs. The structural control for emplacement of the pipes is believed to be represented by intersection zones of ENE-WSW to NE-SW trending faults with NW-SE faults. The elliptical to circular and dyke bodies show diatreme and hypabyssal nature [20]. Precise age of 1100 Ma for the Wajrakarur pipes has been obtained [21, 22] from different systematics. These occurrences occur within the basement-supracrustal terrain of the EDC.

The general geological succession of the WKF area comprising various litho units is shown in Table 2.

The EDC comprises N-S and NW-SE trending thin linear greenstone belts and surrounded by gneisses and granites of different ages. In the EDC, basement- cover relations are practically absent in the greenstone belts. The EDC greenstone belts are narrow, linear and intruded by syn- to post-tectonic granitoids and mafic dyke swarms. Basic volcanics, acid to intermediate volcanics, granitoid-clast volcanic conglomerate and chemically originated sediments form the major lithology of these belts, with typical absence of continental sediments. The emplacement of granites resulted in to low pressure and high temperature metamorphism in the EDC, which is a characteristic feature. The EDC comprises major schist belts viz., Ramagiri-Penakacherla-Hungund-Kustagi and Veligallu-Raichur-Gadwal-Deodurg-Mangalur and Peddavuru. Among these the Ramagiri-Penakacherla Schist Belt (RPSB) occurs in the WKF area and comprises intensely deformed and metamorphosed basic and acid volcanics and banded iron formation rocks with thin intercalations of carbonate rocks. Three suites of granitic rocks, the Kammuru tonalite-trondjhemite gneiss, the Atmakuru granodiorite/Tonalite- Granodiorite-Adamallite (TGA) suite of rocks and the younger Kuderu and Venkatapuram granitoids are the associated granites seen in and around RPSB. The RPSB litho-units and the older two suites of granitoids had undergone penetrative deformation whereas the younger suite of granitoids appears to have suffered only brittle deformation. The kimberlite emplacements occur in close association with younger alkali rich granitoids.

Table 2 General geological setting of the WKF environs [23]

Middle Proterozoic	Mafic & ultramafic intrusives	Kimberlite, mica-lamprophyre
Late Achaean to Early Proterozoic	Mafic dykes	Gabbro, dolerite and rare ultramafic dykes
Late Archaean	Venkatapuram Granite & late-magmatic phases	Minor pegmatite and quartz veins Alkali feldspar granite- quartz syenite
	Kuderu Granite & late magmatic phases	Quartz reef, quartz and quartz ankerite veins with sulphide and gold Granodiorite- adamallite-granite. Tonalite (proto-orbicular)
	Somravandlapalli ultramafic-mafic Complex	Gabbro-granophyre associations. Pyroxenite, gabbro & minor anorthosite, Serpentinite, peridotite ± chromite cumulates
	Atmakuru Granodiorite	Tonalite- granodiorite- adamallite
	Intrusive contact	
	Bhadrampalle Formation	Banded ferruginous chert (BIF-II) Metachert with calc-silicate bands. Metarhyolite, tuff and pyroclastic/quartz-sericite schist
	Yeppamana Formation	Metabasalt (amphibolite/chlorite schist)
	Marutla Formation	Banded magnetite quartzite ± garnet± grunerite with minor tourmalinitte (BIF-I) ; Calc-silicate rocks ± garnet ± anthophyllite Amphibolite ± garnet
	Tectonic Contact Kammuru Gneiss Tonalite -trondhjemite- granodiorite gneiss with enclavial amphibolite and ultramafic schists	

In the EDC, the WKF kimberlites occur in discrete clusters in a discontinuous NS trending array along the western margin on the convex side of the Cuddapah basin. They occur in the intervening areas between the RPSB and Raichur schist belt, between Raichur and Gadwal Schist belts and to northeast of the Gadwal schist belt. Regionally the RTP anomaly map represents deep crustal and crustal scale geological features. Presence of Meso- to Neoproterozoic intracratonic alkaline-ultramafic activity in the area supports magmatic accretion and inter-cratonic amalgamation [24, 25]. The deep layer RTP map brings out that EDC clearly dominated by NW-SE trends. These NW-SE trending magnetic anomalies in the EDC may represent the former 'arc' traces of the 3.0-2.5 Ga arc-batholith evolution and the Closepet granite is regarded as a part of the Dharwar Batholith [26]. Due to miniature sizes of the pipe rocks, though regional geophysical studies are not successful in discovering kimberlite anomalies, they can be very well correlated with the modeled aeromagnetic data and also lithological contacts between different units are well represented in the maps derived from aeromagnetics. The EDC kimberlite fields occur in the area marginal to the Kadapa basin cover sediments whereas lamproites occur in marginal to craton-amalgamation areas (EDC-EGMB contact). In addition kimberlite magmatism in association with carbonatite is also reported at Khaderpet area [27]. The kimberlite/Lamproite/carbonatite magmatism in EDC appears to confirm coeval to significant period of global ultrapotassic and alkaline magmatism during 1.4 to 1.0 Ga. The timing of this Mesoproterozoic kimberlite and lamproite magmatism in EDC coincides with the development of several large igneous provinces (basic volcanism, alkaline magmatism and mafic dyke activity in the Kadapa) and attendant intercontinental rifting including formation of Proterozoic basins of EDC similar to Kalahari and Pilbara cratons [28]. This type of intersecting structural trends is proved to be congenial for emplacement of kimberlite bodies.

3.2 WKF Pipes and Major Structural Trends

It is noted that kimberlite pipes in WKF occur in the intersections of major lineaments and also in the peripheries of domal structures. Major structural controls of kimberlite pipes in WKF are listed out in Table 3. In recent years, world class companies like De Beers, Rio Tinto etc. discovered many diamondiferous pipes within Proterozoic sediments for the first time in India, on the eastern side of Kathrimala dome (Table 3). These new occurrences were discovered in the proximity of the domal structures where incidence of kimberlite pipes coincides with anomalous geochemical and geophysical signatures.

Table 3 List of WKF pipes and associated emplacement structures [7, 27, 29-30].

Cluster	Pipe No.	Emplacement & Structural Control
Wajrakarur	P1	ENE-WSW fault along contact of TT gneisses & TGA granitoids
	P2 P15	In TGA granitoids close to TT gneisses along NE-SW to ENE-WSW veering fracture. P15 exists north of P2.
	P3, P4, P8 & P9 P5	In TGA granitoids close to an ENE-WSW fault passing through Marutla dome closure.
	P6	At the contact of the TT gneiss and TGAs along NE-SW fault.
	P7	In granitoids occurring within RPSB and younger granitoids along NE-SW fault.
	P10 & 4 new pipes [30]	In younger granitoids at intersection of an ENE-WSW fracture and NW-SE Singanamala fault.
	New Pipe [27]	Intruded by a late stage carbonatite plug within granitoids.
	P11 P14	In TT gneisses & TGA granitoids at the intersection of an ENE-WSW fracture with a NW-SE major fault. P14 occurs NW of Dibbasanipalle.
	P12	In younger granitods along NE-SW fracture at its intersection with a NE-SW fault.
	P13	In TGA granitoids along ENE-WSW sinistral fault that displaces the Marutla dome.
	P14	In younger granitoids at the intersection of an ENE-WSW fracture with NW-SE Singanamala fault.
Chigicherla	CC1	In granitoids gneisses close to the intersection of WNW-ESE fracture with NW-SE lineament in the proximity of Cherlopally dome.
	CC2	In TGA granitoids at intersection of ENE-WSW fractures with the NW-SE shear.
	CC3	At contact of the Ramagiri schist belt and the younger granitoids along an ENE-WSW fracture.
	CC4 CC5	At intersection of ENE-WSW fault with WNW-ESE fractures.
Kalyandurgam	TK1 to 6	In Archaean granitoids and PGCs along a major ENE-WSW sinistral fault intersecting with NNW-SSE basic dykes.
	KL1 to 6 [30] New pipe [31]	In Closepet Granite close to the NNW-SSE and ENE-WSW fractures intersection.
Gooty	8 new pipes [31, 32]	In younger granitoids at ENE-WSW fracture and NW-SE Singanamala fault intersection in Proterozoic strata.

3.3 Morphostructural Features

Morphostructurally controlled kimberlite emplacements as described in previous sections, are conspicuously observed in the WKF in the vicinity of domal structures. From observed surface correlation of reported kimberlite occurrences with intersecting lineaments within regions of domal morphology, regions with such configuration were delineated as potential kimberlite bearing zones. Using this observation as a criterion, three potential kimberlite zones were delineated: 1. Area surrounding Kathrimala and Marutla domes (south of Wajrakarur, between Marutla and Kathrimala domes, between Kadapa Basin western margin and Kathrimala dome) 2. Around Cherlopalle and Nasanakota domes and 3. Linear zones comprising pipe clusters of Kalyandurgam and Timmasamudram areas. In all these areas, occurrences of kimberlites were found to be localized at intersections of lineaments and in surroundings of the domal peripheries. However the prospects are not bounded to the limits of these three areas shown here, but due to occurrences of known pipes, surrounding area can also be considered.

Pipe clusters concentrated around Kathrimala dome, Marutla dome, and Cherlopally dome in southern part confirm favorability for unknown concealed pipes in the proximity of the domal structures (Fig. 3) A cluster of >7 kimberlite pipes occur around Kathrimala dome. Chigicherla kimberlite cluster occurs on the peripheries of Cherlopally dome. In the Wajrakarur field, magnetic and gravity data shows conspicuous domal structures with discrete contrast with the background thereby leaving favourable zones for deep-seated magmatism. The kimberlite fields show a discrete relationship with the background.

Though several pipes are discovered so far in the proximity of these domal structures, still it is to be noted that many more pipes lie hidden and yet to be unveiled. A proper conjunctive usage of different survey methods like geochemistry and ground geophysics may bring out more number of pipes in this part of the country. The area close to these circular-ring structures forms the promising province for a much more detailed exploration (Fig. 3). Hence the area between Kathrimala dome and western margin of Kadapa Basin forms a favorable terrain for searching new pipe rocks.

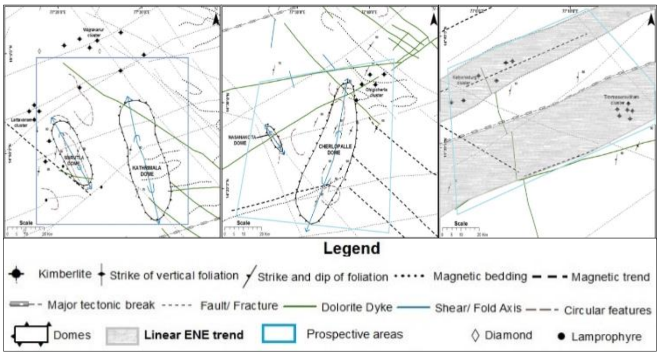

Fig. 3 Morphostructural features and kimberlite occurrences in WKF. From Left to Right. a) Wajrakarur Cluster b) Chigicherla Cluster and c) Kalyandurgam Cluster

4. Conclusion

Morphostructural features have strong affinity to kimberlite emplacements at various locations in the cratonic shields of the world. WKF also constitutes such favorable morphostructural features that are congenial for kimberlite emplacements which make this province promising for further exploration in search of kimberlite/lamproite pipes. The conjugation of linear structural features in WKF area is in correlation with the major global structural events elsewhere. Earlier discoveries were mainly surface pipe exposures; however with the advent of modern tools several international companies have discovered new concealed pipes utilizing advanced software data analytics technology. Integrated studies using satellite image, lineament patterns and kimberlite occurrences may reveal that further investigations in the vicinity of defined morphostructural features will probably be a favorable zone for advanced exploration in search of new pipes. About three zones were identified where further search can be carried out. The uplifted morphostructural and domal structures Marutla, Cherlopalle dome and Kathrimala are found to be encircled with kimberlite emplacements and these locales are inferred to be more favorable for emplacement of kimberlite bodies in this part of the EDC. The morphostructural method of prediction is not the only primary investigation for kimberlites/diamonds, since sometimes the same features could be associated with other deep-seated structures, but for gold and other metals. However, when used in conjunction with the geological and geophysical models it may be rather useful in finding new pipes and also gives more confidence in establishing deep-seated structures associated with kimberlite magmatic chamber. Hence it can be envisaged that there is a possibility that many more hidden pipes can be unveiled in the WKF area, which deserves exploratory search and research with the aid of modern technology.

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