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Prognosticating buried potential mineral deposits in virgin areas of Odisha and adjoining regions, India, using 3D Euler's deconvolution technique on gravity data for detailed exploration in future

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ABSTRACT

The paper deals with an attempt to draw a blue print of 'Fast Track Mineral Targeting' at a reasonably cheap cost around Odisha and adjoining regions, India.

Taking clues from known structural controls of ore deposits, mineralogical, lithological, metamorphic histories, actual as well as proven mineral deposits, occurrences and assuming probable shape and size of ore deposits, we have used 3D Euler's deconvolution solutions on gravity data for locating different ore groups, viz ferrous group, base and noble metals, diamond and gemstones, over a virgin and buried terrain.

3D Euler's deconvolution solutions indicate that there are four sets of apparently unknown faults aligned in E-W, N-S, NW-SE and NE-SW directions, related to different tectonic events. In addition to the above, we mapped several circular to elliptical shaped structures. Taking guidelines from different controls of ore deposits for various kinds, as mentioned above, we have prognosticated several hitherto unknown areas for the search of the above minerals from the 3D Euler's deconvolution solutions and known mineralized zones. This is primarily an attempt to explore those areas which are otherwise written off forever, as there are not sufficient clues available from either geological or geochemical data set or their synergy.

This concept of mineral targeting, we believe, will usher to new thinking hypothesis for the future researchers, which is reasonably fast and economic.

1. Introduction

The need for rapid industrial revolution for a quicker economic growth in a country like India is beyond any doubt. Such industrial growth would in turn help the growth of basic infrastructure and consequent downstream industrial development. Supply of raw material through exploration and mining of hitherto unknown minable resources is prime target for all countries. This needs to be fast tracked, efficient, eco-friendly and provide sustainable aid to an estimate of additional mineral resources.

The days are gone when mere knowledge of the Obvious Geological Potential (OGP) was the primary reporting standard. By OGP, we mean the one which is based on preliminary thematic geological/geochemical outcrop pattern and limited pitting, trenching or drilling (if considered necessary). Geological Survey of India (GSI) classified such zones in India. These zones played important role until the potential field maps (Bouguer gravity anomaly and total magnetic intensity) were not available for consultation. Subsequently, with the availability of these maps at our hand and along with some additional effort of processing such map, one can add the necessary directional scanning and view the unseen within the buried ground. One has to upgrade the OGP to the indicated resources, followed by indicated mineral reserve to probable mineral reserve and finally to proven mineral reserve determined with high degree of confidence. Bouguer gravity anomaly map and its interpretation can add much hitherto unknown knowledge for deciphering potential mineralized zones.

To draw a blue print of the intended 'Fast Tracks' under this scope, we choose Odisha state and the adjoining region of Eastern India, as an

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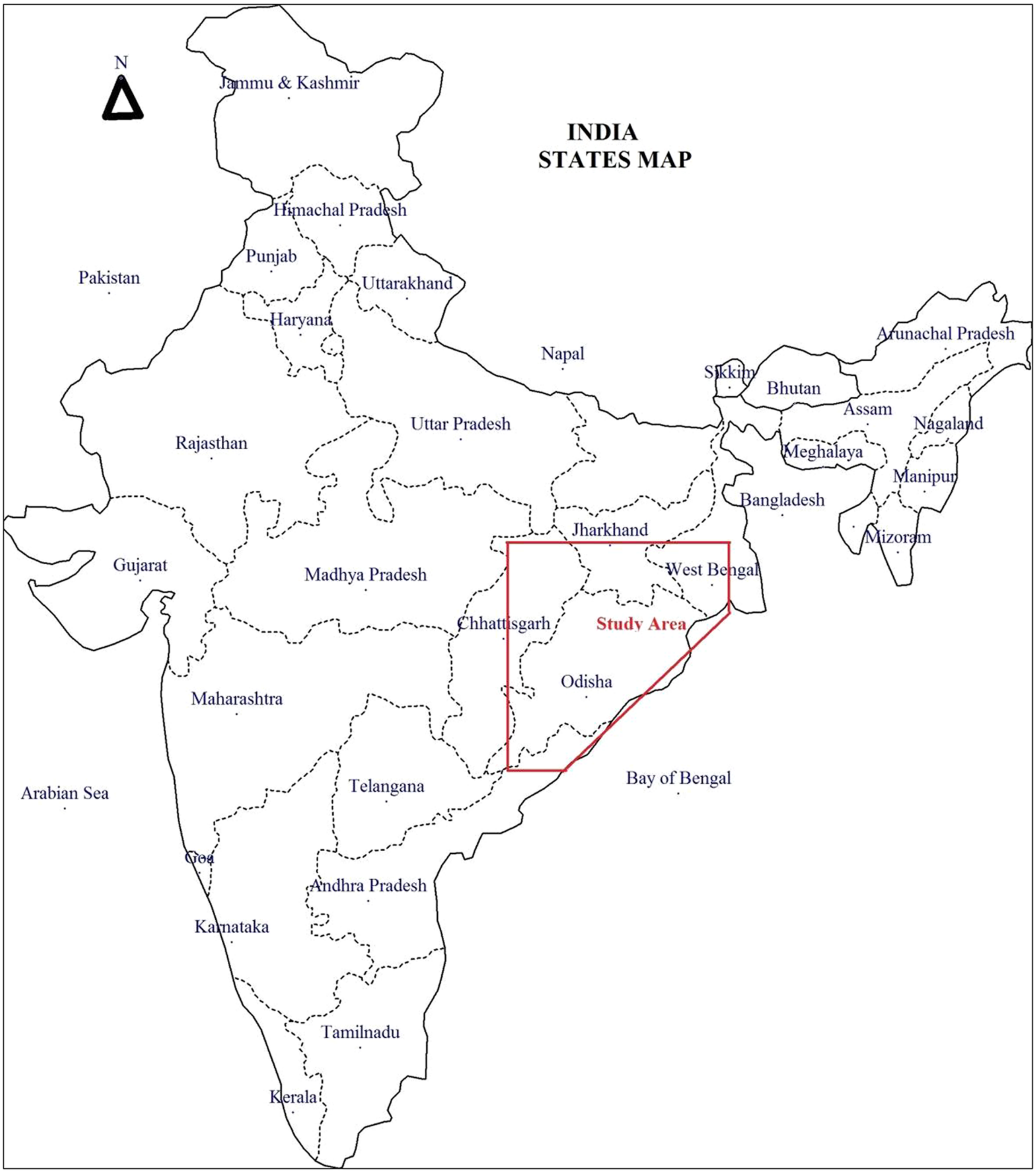

Fig. 1A. Location map of India with state boundaries.

example. We need not be cynical at the failure of every drill target and try to find fault with one another, especially when we have more innovative ideas and tools to fill-in the data gaps which may push us further.

In the present study, 3D Euler's deconvolution solutions of Bouguer gravity data i.e. second generation Bouguer gravity map (after GSI et al., 2006) of Odisha state and its surrounding region has been used for locating potential targets of different ore groups, viz ferrous group (Fe, Cr and Mn), base and noble metals (BM, Au and Ag), diamond (D) and gemstones (Ges), over a virgin and buried terrain of Odisha state and its adjoining area of Eastern India. In support to the Euler's deconvolution solutions we have taken clues from known structural controls of ore deposits, mineralogical, lithological, metamorphic histories, actual as well as proven mineral deposits, occurrences and assuming probable shape and size of ore deposits. This is an attempt to explore such buried mineral resources in study area as an example. This is primarily an attempt to upgrade the OGP to the next stage of detailed exploration in 1:10,000 scale for identification of indicated resources in a virgin area.

In our study we have prognosticated several hitherto unknown areas for the search of the specific minerals from the signatures of Euler's depth solutions and known mineralized zones. We have also prepared a template of association of mineral bodies with structural controls of deposition.

3D Euler's deconvolution solutions for fault contact have been generated from the Bouguer anomaly map. Further, it is worthwhile to mention here that 3D Euler's deconvolution solutions may be generated for different geometric shapes and sizes of the causative sources looked

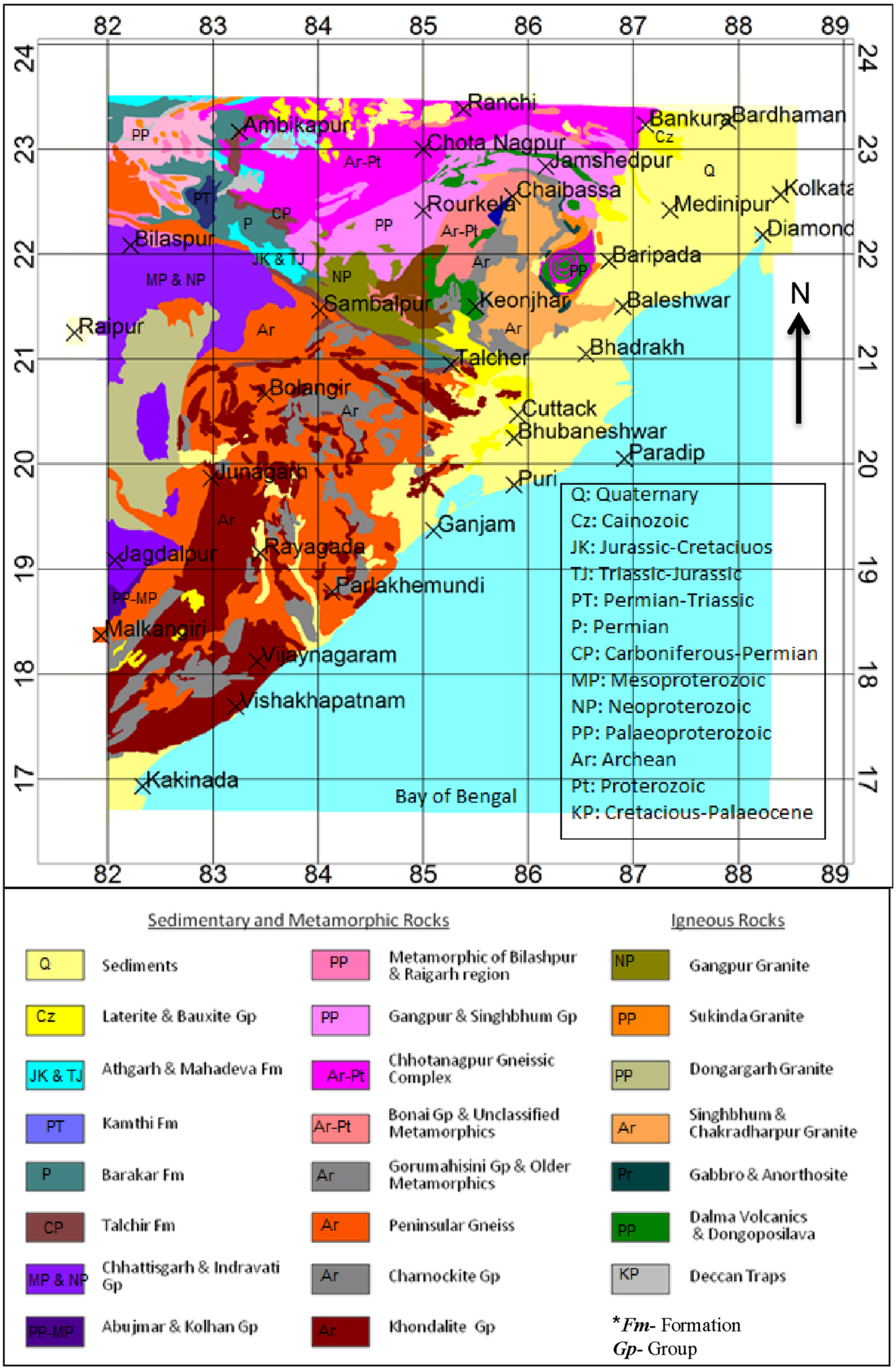

Fig. 1B. Geology map of study area (after GSI, 1998).

for, using different structural indices. Even structural indices may also be determined from the anomalies and the geological information. But since our objective has been primarily to map 2D faults in the study area, we have selected Structural Index (SI) as zero. The resultant solutions limited to a depth of 3 km have been plotted over the regional geology map (after GSI, 1998). The synergy of both these maps provides us an idea of tectono-structural features associated with mineralized zones in the presence of a suitable geological environment and litho association. Such structures provide conduits to hydrothermal solutions and can potentially control tectono-thermal history.

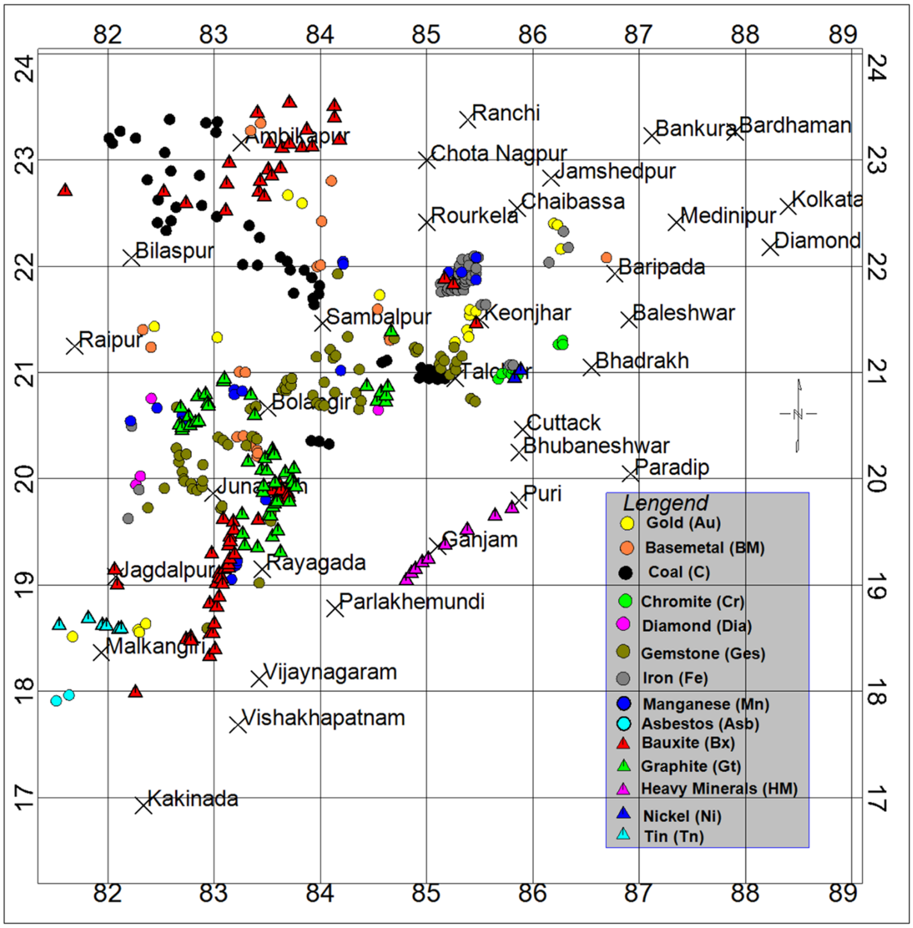

Fig. 2. Metallogenic map of the study area (after Directorate of Geology, Odisha, 2008).

2. Previous work

2.1. Geology as well as minerals of odisha and adjoining region

The study area (Fig. 1A) is bounded by latitudes 17^0N–23^0N and longitudes 81^0E–88^0E and covers almost 700 km of coast line, bordering the Bay of Bengal. The study area includes the Odisha, southern part of Jharkhand, northern part of Andhra Pradesh, eastern part of Chhattisgarh and south western part of West Bengal.

The study area contains rocks of various ages, which ranges from Archean to the Cenozoic. The geology map is shown in Fig. 1B.

About 73% of the study area in Odisha is dominated by Precambrian metamorphic rocks (Archean/Proterozoic), the primary host for mineral deposits in the state (GSI, 2012). The Gondwana formation, accommodating the coal resources, is present over about 8% of the land mass. The Tertiary and Quaternary formations occupy the rest of the 19% area and host aluminous/nickeliferous laterite and heavy minerals, (GSI, 2012). Nickel ore does not form any economically viable deposit in study area.

The Archean rocks in northern Odisha and Jharkhand areas include the metasedimentary supracrustals, including the Iron Ore supergroup, which host important deposits of iron, manganese, gold, and base metals (copper, lead, zinc). The host rocks include gneisses, granites and migmatites (Singhbhum, Bonai, Keonjhar and Mayurbhanj Plutons). The mafic/ultramafic intrusives within this terrain host occurrences of chromite, titaniferous-vanadiferous magnetite and platinoid group of elements (PGE).

The platformal Proterozoic rocks of western Odisha contain limestone and host small lead-zinc deposits. In the northwest the Precambrian rocks of the Gangapur series host manganese, limestone and deposits of lead-zinc. The central and southern parts of Odisha are occupied by the Eastern Ghat Granulite Belt that includes khondalite, charnockite, migmatite, anorthosite and alkaline rocks and contain bauxite, manganese, graphite and gemstones.

The Mesozoic rocks of Gondwana super group host coal deposits in north-central Odisha. The Cenozoic of eastern coastal plain host ash beds, low level laterite, heavy minerals in beach sand. The deltaic fans, extending into the offshore, host oil and gas resources.

The adjoining Bastar region of Archaean age hosts strontium-tantalum-niobium bearing pegmatite and deposits of tin, iron ore including gemstones and diamond. The metallogenic map of this region is shown in Fig. 2. Many of these are commercial deposits; while some are yet to be proven from prospect to deposit stages.

From the above, it is clear that the state contains substantial resources of ferrous group of metals, namely, Iron (Fe), Chromite (Cr) and Manganese (Mn); base metals, namely, Copper (Cu), Zinc (Zn) and Lead (Pb); noble metals, namely, Silver (Ag) and Gold (Au); Platinoid Group of Metals (PGM); Diamonds (D); Gemstones (Ges) and Graphite (Gt), apart from the energy minerals such as coal, oil and gas. For the present we restrict ourselves to the exploration strategy of ferrous group, base and noble metals, diamonds and gemstones only.

2.2. 3D Euler's deconvolution

Several contributions demonstrate that the 3D Euler's deconvolution solutions of potential field data is useful for understanding structurally controlled mineralized and other prospective ore zones (Slack et al., 1967; Thompson, 1982; Roy et al., 2000; Mushayandebvu et al., 2004; Gimez et al., 2009). Application and detailed methodology of Euler's deconvolution solutions for the estimation of source depth have

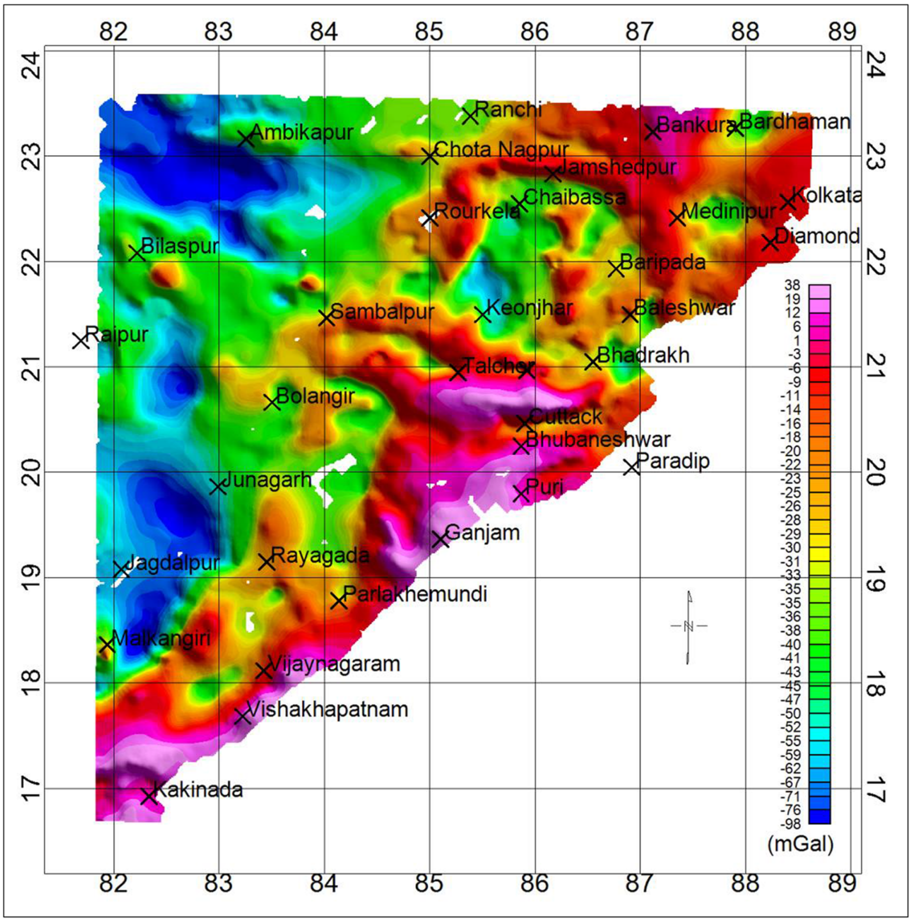

Fig. 3. Bouguer Anomaly map of study area (after GSI et al., 2006).

been explained (Reid et al., 1990, 2003; Stavrev, 1997) by using potential field data. Euler's deconvolution technique delineates the horizontal boundaries (Corner and Wilsher 1989, Huang et al., 1995). Euler's deconvolution method is at best an approximation for more complex bodies. A comparison between Euler's deconvolution technique and modelled gravity data was done at the Comet Gold mine (Chenrai, 2009).

3. Data sets and methods

The second generation Bouguer gravity map (after GSI et al., 2006) of Odisha state and its adjoining regions (Fig. 3) has been used for calculation of the 3D Euler's deconvolution solutions with structural index (SI = 0) for fault/contact as a standard practice. This analog gravity map has been digitized at 3.3 km × 3.3 km grid spacing for further processing and interpretation. Kumar et al. (2016) has proved that such grid spacing is suitable for understanding crustal gravity anomalies; tectono-structural settings and horizontal/sub-horizontal planner structures. Oasis Montaj (Geosoft) software has been used to generate 3D Euler's deconvolution solutions. The resultant solutions were limited to the depth of 3 km and have been plotted in Fig. 4A on the geology map of the area for easy comprehension.

The 3D Euler's deconvolution equation for gravity data, as given by Reid et al., (1990) is:

$$(x-x_o)dg/dx + (y-y_o)dg/dy + (z-z_o)dg/dz = N(g'-g) \quad (1)$$

where (x_o, y_o, z_o) is the position of an anomalous source whose total gravity (g) is detected at location (x, y, z), g′ is the regional gravity value and N is the structural index (SI) related to the geometry or nature of the source. Usually it has a significant control on the interpretations.

Further, it can be defined as the rate of attenuation of the anomaly with distance to estimate the depth and location of the source, applied to the gridded map or profile data. Structural index should be selected according to a prior knowledge of the source geometry. For example, SI = 0 for fault, SI = 1 for a horizontal cylinder and SI = 2 for a sphere (FitzGerald et al., 2004). The vertical derivative (dg/dz) and two horizontal derivatives (dg/dx, dg/dy) are used to compute anomalous source locations.

The solutions were calculated for fault/contact structure to understand the location and disposition of the palaeo tectono-structural crustal fabric of the study area which act as excellent structural control for ore bodies. It is well known that such fault structure provides easy pathways to uprising molten magmas and associated hydrothermal solutions, Kimberlite Clan of Rocks (KCR) and control the tectono-thermal history to produce different metallogenic provinces (Hagerty, 1986). Regional fault features extending over hundreds of kilometers provide the ideal tectono-magmatic pathways for mafic/ultramafic intrusions as well. Upwarpment of Moho and creation of associated rift/graben structure is ideal for deposition of minerals, metallic or non-metallic within a volcano-sedimentary assemblage in the graben (Koide and Bhattacharya, 1975). Regions traversed by such older and younger generation faults in different directions point to multiple reactivations in the geological history (Condie, 1982). These are ideal sites for multiple metamorphic episodes resulting in polyphase melting, remobilization and recrystallization of minerals. Such areas, if Archean to Proterozoic in age, are ideal sites for polyphase metamorphism creating a Barrovian zone, hosting many gemstone and high temperature refractory grade minerals like kyanite, sillimanite, tremolite, actinolite, etc. Rift zones with sufficient sedimentary, volcanic, mafic, ultramafic

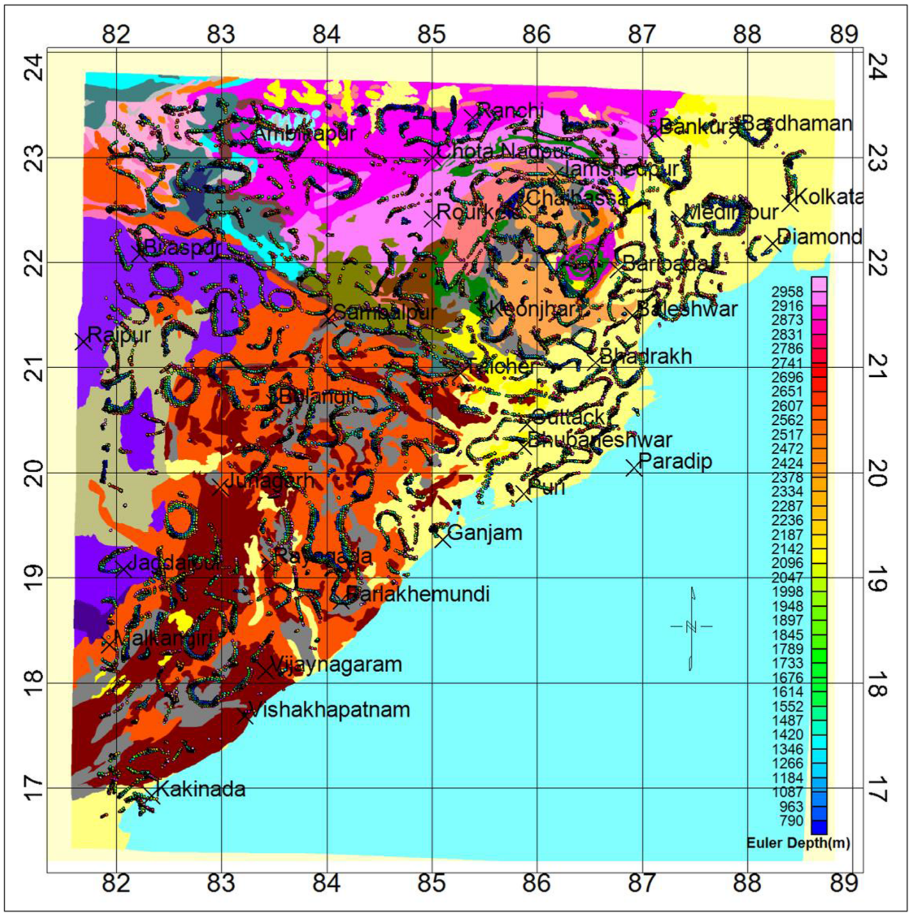

Fig. 4A. Euler's depth solutions up to 3 km depth (SI = 0; for fault/contact) over geology.

rocks and greenstone assemblages are good sites for Fe, Mn and Cr ores. Au is also found in such settings. Different Au deposits in Proterozoic rifted schist belts are examples of such deposits. Intersection of two or more fault planes creates ideal locations for base metals and gold. These intersections act as traps to the ascending hydrothermal fluids and help the fluid to deposit metals in suitable host rocks when physico-chemical condition for deposition is ideal. Elliptical to circular fracture zones are indicative of plug type intrusive bodies at depth. If such plug type intrusion come from depths below the lithosphere (greater than 200 km approx.), this may bring Kimberlitic Clan of Rocks (KCR) to near surface levels, where the crustal thickness is relatively higher particularly in areas where cratonic boundary meets mobile belt (Hagerty, 1986).

3.1. Results and discussion

Fig. 4B shows that there are four sets of faults aligned in E-W, N-S, NW-SE and NE-SW directions which are extending over hundreds of kilometer. Structural features with wavelength as high as several hundred kilometer would certainly indicate deeper roots. Normally these are expected to run several tens of kilometers in depth and may be even connected to Moho depth. Proximity to Moho would eventually allow upwelling thermal fluxes from time to time. Eventually such faults would be the ideal sites for uprising magma, hydrothermal solutions and tectono-thermal fluxes which are carriers for metallic and non-metallic mineralization. Circular/elliptical shaped fault structure may hint at pathways of kimberlitic clan of rocks from depth beyond 200 km. Among the above mentioned four sets of faults, the first two are over the Archean and Proterozoic terrain and therefore are possibly the oldest of the set in the crustal architecture. The E-W is the oldest regional trend in central India. The N-S structural trends are many. These encompass the Dhanjori, Simlipal basins and the western iron ore basin of Singhbhum region (Das et al., 1997). They opine that these are boundaries of Proterozoic rift basins in the area. In the western part of the study area these are seen bordering seven strings of circular to elliptical structure running through Malakangiri-Jagdalpur-Junagarh-Bilaspur areas bordering the contact of the peninsular gneiss and Indravati group of metasediments in Baster craton. These could be old cratonic boundaries. Kimberlitic Clan of Rocks in circular to elliptical shapes normally is found in cratonic boundaries (Hagerty, 1986). We also find three such parallel structures over the Eastern Ghat Mobile Belt (EGMB). One of these passes over Vijaynagaram-Junagarh and the second passes through Parlakhemundi. The third one occurs in between the above two and passes over Rayagada-Bolangir. In North of Bolangir, each one of these three swings in the NE-SW direction is eventually found to lose their identity below the NW-SE trending Gondwanas, the third tectonic event.

The other three N-S trending major faults are over the alluvial tracks of the Cenozoic Bengal basin. One of these passes through Bhadrakh-Baripada; the second one is to the west of Midnapur and the third one is over Diamond harbour-Kolkata area. Obviously, the first one represents the basin margin fault; the second one, the fault scarp zone and the third represents the Kolkata-Ranaghat-Syhlet hinge zone of the pericratonic Bengal Basin (Ghosh et al., 1993). These are the youngest of the lot and represent the fourth tectonic event.

The NW-SE trending Gondwanas are however related to the third tectonic event in the area. We believe that the NE-SW trends mostly seen in the coastal block and over EGMB granulitic terrain along with the NW-SE ones are the products of rotation of two ancient micro terrains as discussed later in the chapter.

Several trend lines have been drawn looking at the dispositions of

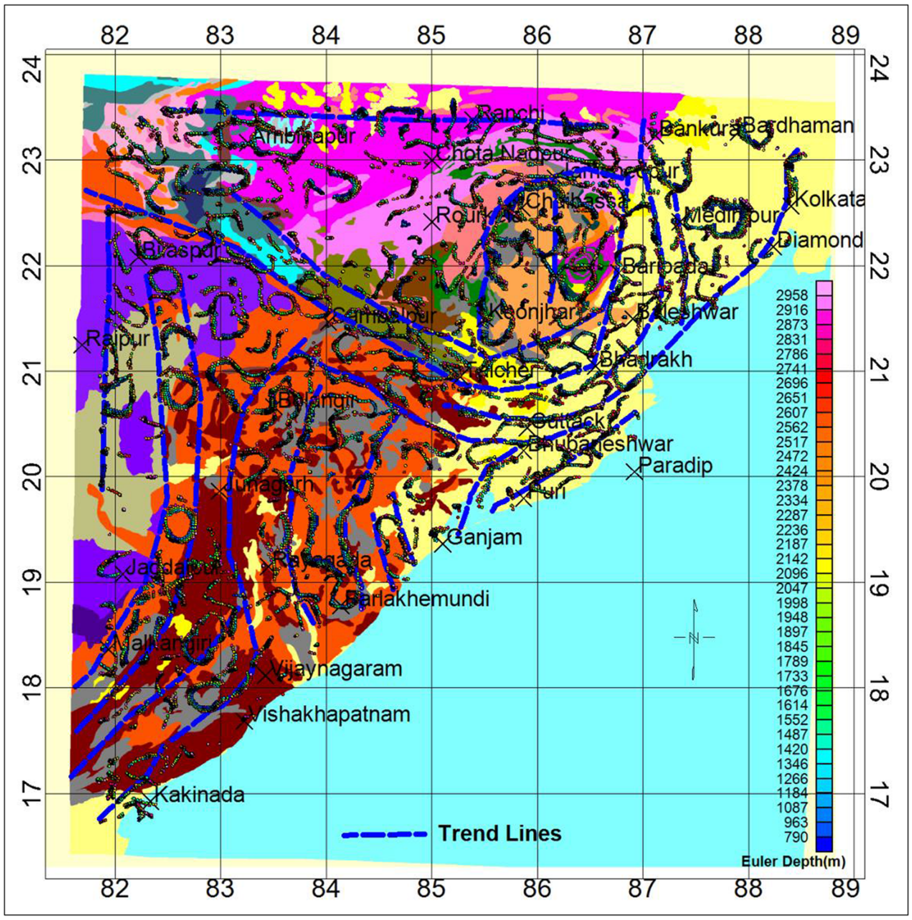

Fig. 4B. Geological trend lines from Euler's depth solutions over geology.

the Euler's depth solution trends, primarily for easier comprehension of the movement of the crustal block in the study area. The western N-S trends enveloping primarily the circular contours around 82.7°E longitude represents a northward motion and gradual younging of the circular anomalies southwards. The landward convex bending over the EGMB and concave disposition near Keonjhar probably hints to two different Euler poles of rotation in two different geological eras. However, we admit that there may be some subjective bias based on the known geological features of the area and interpreted faults from gravity data.

3.2. The predictive models

Let us now have a look at the known metallogenic provinces in parts of Singhbhum, Odisha and Chhattisgarh regions, which are known till date vis-à-vis the locations of these interpreted fault structures mapped in the study area. Our objective is to create a template of association of mineral bodies with these structural controls of ore deposits.

3.2.1. Predictive model: ferro-chrome group

In Fig. 5A, we have plotted the locations of ferrous group metallogeny (Fe, Mn & Cr) on the 3D Euler's depth solutions generated for fault/contact up to a depth of three kilometer.

The northern cluster of the iron ore (Fe) occurrences are bounded by two intersecting fork like faults that join together in the north and continues farther north as the third arm. The iron ore group of meta-sediments is contained well within this zone. The southern tip of iron ore occurrences are again surrounded by two faults closing to the south of the occurrence. Both of these closures indicate a triple arm geometry that leads to probable centers of volcanism and found to pour the lava into the valley creating ore deposits. Precambrian iron ore in the Singhbhum and North Odisha region occurs as part of a horse shoe-shaped broad synclinorium known as Iron Ore Group (IOG), which host many iron ore deposits (Gua, Kiruburu, Noamundi, etc.).

The Manganese (Mn) occurrences are seen over far flung regions away from the meta-sediment pile, but invariably in the Proterozoic terrain. More often than not, these are controlled hydrothermal genetically as evidenced in black smokers over oceanic setting. At a few locations these are near the deep seated faults (Fig. 5A); at other locations, they do not show any clear relationship with such features. Manganese being detached lensoid shaped bodies formed in marine environment ranging from shelf to abyssal plane and also in bog and lake, which have hence been metamorphosed several times, are very much disturbed from their original place of occurrence (Roy, 1968; Kevin et al., 1993). This is probably the reason that manganese occurrences apparently do not bear any relationship with the present day fault structure prepared from the Bouguer anomaly map.

The Chromite deposits in general are located once again along the intersections of E-W and N-S faults. The E-W and N-S faults are the oldest in the area. NW-SE and NE-SW disturbances have obliterated and destroyed much of the original ore, a part of which may be under the alluvial cover down south. We believe that relict of the old terrane hosting chromite may still be there below the younger cover rocks.

Drawing analogy to our basic axiom of structural control of ore deposits vis-à-vis the favorable rock types of preferred age and lithological composition we have prognosticated several areas for the search of Fe, Cr and Mn ores. These have been marked by rectangle with Fe and Mn annotated inside the boxes. Both Fe and Cr have been marked as Fe. As per the differentiation history, those stratigraphic sequences with mafic/ultramafic rock types, comparatively older in age, layered

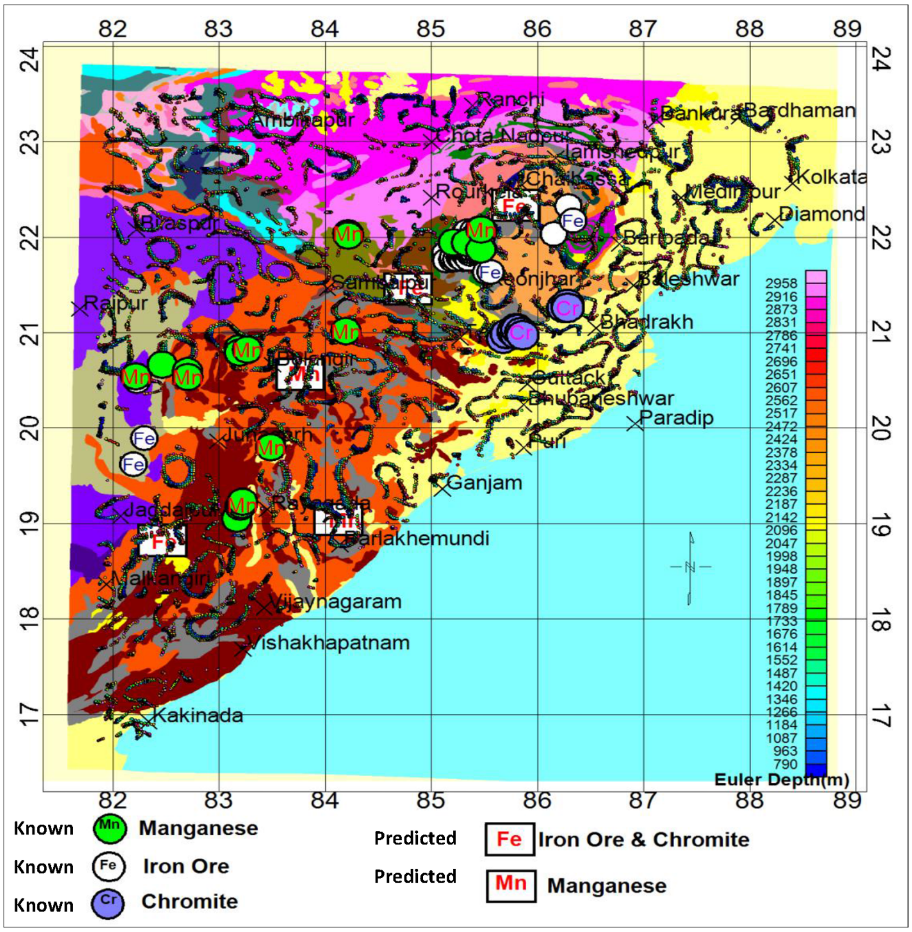

Fig. 5A. Fe/Mn/Cr zones with Euler's depth solutions (upto 3 km depth) over geology.

igneous complexes are good for Cr investigation. Comparatively younger volcano-sedimentary sequences need to be explored for Fe.

3.2.2. Predictive model: base-metal and gold group

We have plotted the known locations of occurrences of base-metals (BM) and gold (Au) in Fig. 5B along with 3D Euler's depth solutions up to a depth of three kilometer. Using the hypothesis as explained earlier for the control of similar ore deposits, we have selected several new areas for future search of BM and Au (Agarwal et al., 1999; Holiday and Cooke, 2007) in the study area. These have been marked by close rectangle with BM and Au annotated inside the boxes. Following similar ideas/hypothesis we have successfully traced the extension of gold veins in South Kolar Gold Fields (Kolar Gold Ltd, 2012). Discovery of new veins in Kolar district, Karnataka and also around Ganajur area in Haveri district, Karnataka are two examples. Several areas in Kolar have yielded high value of gold in drilling. Apart from these, more than thirty different horizons of sulphides associated with copper and gold in Dhanjori basin, East Singhbhum have been proved by drilling within 700 m depth of lava pile in the basin (Das et al., 2012).

3.2.3. Predictive model: Diamond

From our past experiences (Das et al., 2005) and the global examples of occurrences of Kimberlite Clan of Rocks (KCR) (op.cit), reasonably well known as Kimberlite Clan of Rock with a possibility of hosting diamond that mostly occur over circular/plug type of intrusive bodies. These bodies may or may not be associated with gravity or magnetic highs. These also occur below elliptical closures of 3D Euler's depth solutions representing sills hidden under cover. From 3D Euler's depth solutions, we have demarcated several circular, semicircular zones at the ancient cratonic margin of Odisha and Chhattisgarh. In Fig. 5C, the known locations of diamond and gemstone occurrences have been plotted along with the interpreted circular/semicircular faults. The interpreted locations of new diamond bearing zones have been prognosticated. We have marked few areas with inscription of 'D' in the closed rectangle to represent future sites of diamond exploration in the area.

3.2.4. Predictive model: Gemstones

Gemstones are product of multiple metamorphism, where several episodes of melting, recrystallization and change of mineral phases are involved. Higher the grade of metamorphism more is the chance of formation of gemstone in an ancient terrain. For reference, we have plotted the known locations of gemstones in the study area. Taking clue from our own hypothesis, we have selected several zones where we find criss-cross pattern of four different generation of tectono-thermal reactivation. Such zones have been marked with 'G' in the closed rectangle to represent future sites of gemstone exploration in the area (Fig. 5C).

3.2.5. The predictive template

Any predictive model must satisfy the existing ground truths. These are the different geological domains as are revealed in the area with their respective geologic connotations like rock type, age, structural details, mineralogy etc. The mineral shows, existing operational mines and old mining districts need to be considered in right earnest. We have considered these facts. We have followed the established norms of plate tectonic setting in the study area. Moreover, we have also given due credence to the well-established norms of structural and tectonic controls of ore deposits.

Through the 3D Euler's deconvolution solution of gravity data, and

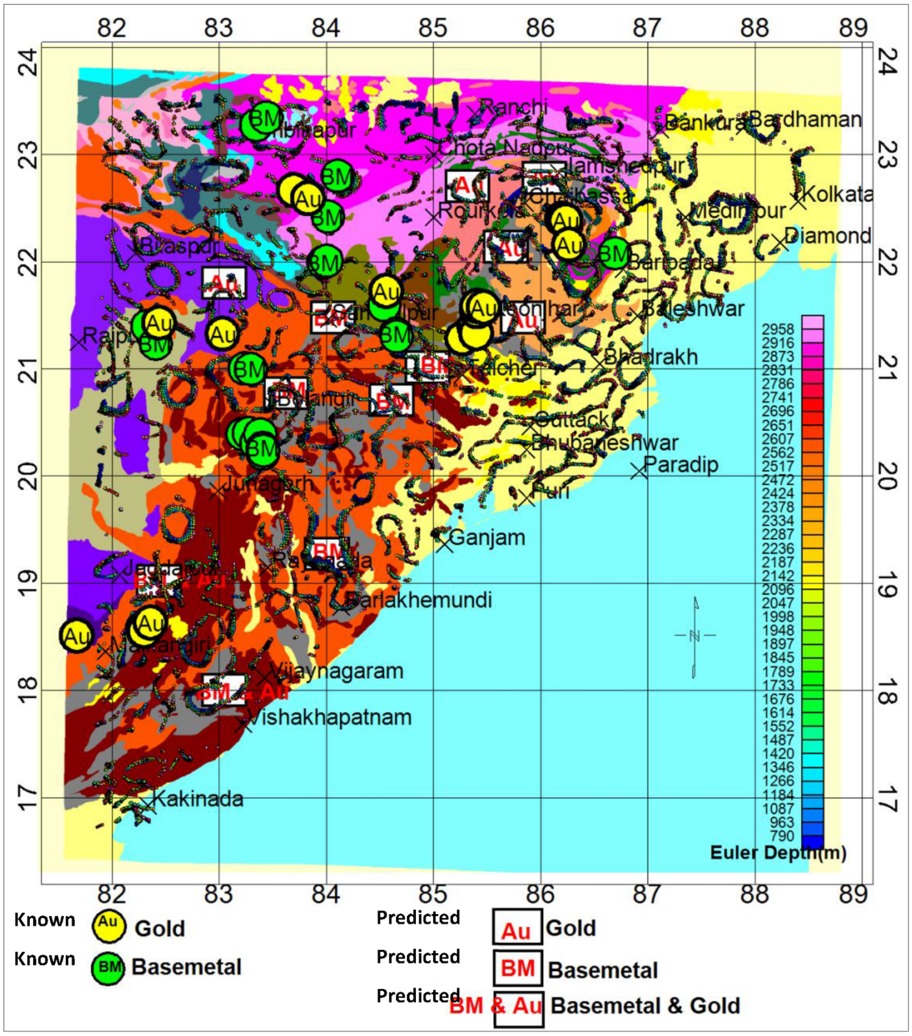

Fig. 5B. BM/Au zones with Euler's depth solutions (upto 3 km depth) over geology.

assuming the causative sources as faults and plugs, we have interpreted the hitherto unknown faults and mapped their attitude and depth continuity. This has helped us towards understanding the structural controls of different ore deposits like ferrous group (Fe, Cr, and Mn), the base metal group (Cu, Pb, and Zn), the noble metals (Ag, Ag) and the Platinoid group of elements (PGE) along with diamonds and gemstones.

The patterns of faulting have revealed distinctive features like a trijunction ('Y' or inverted Y), in a criss-cross pattern both in acute and obtuse angles and in circular to elliptical features. These faults did bring out the different tectonic domains which are characteristics to the particular tectonic episode. The rotations of the different blocks of the craton along with resultant transgression (strike slip faulting) in principally E-W & N-S directions have been brought out through this study. Even the gradual younging of the plug type bodies around the Indravati basin in Chhattisgarh, to the south, has been very clear. Indirectly this indicates a northward push of the craton as a whole. Even the fault systems over the Bengal basin margin and the coastal Odisha are very clearly depicted in the study. These have far reaching consequences on the Tertiary history of the area.

Such divergent facts have indirectly revealed the earth's palaeo tectono-structural and thermal history in different forms. The 'Y' or 'inverted Y' trijunction cautions us about outpouring of basic/ultrabasic lava sources, which may give rise to ferrous group of metallogeny in an ideal geological environment. The 2D metabasites and sheet dykes, the layered igneous complexes arising out of such a tectono-structural setting may produce chromite and PGE mineralization at depth. In the same spirit a 3D anticlinal shaped body may indicate volcanogenic massive sulphide (VMS) deposit which may host Ni and Co, along with other minerals.

2D faults and intersections of fault structures reveal easy pathways for ascending hydrothermal solutions carrying Cu-Pb-Zn, as also Ag and Au from deeper interior. These are deposited in favorable host rocks at shallower depths.

Circular to semi-circular and elliptical fault structure may indicate favorable hosting sites of kimberlitic clan of rocks in the boundaries of two ancient cratons. These may produce diamond.

Intersections of several fault segments of different ages in criss-cross fashion or trapezoid setting may induce polyphase metamorphism and association of gemstone in such setting.

The template also includes the melting (solidus) temperatures of different metals which is another indicator of depth of genesis, though presently these are at much shallower depths. This guides us through the differentiation process of liquid immiscibility and deposition of metals in a phased condition.

Such a template is definitely an indicator to the hidden wealth in the earth's crust. We name it the 'Dhanlakshmi' template, in its new version. The template is shown in Table 1.

The proposed template like any other gives a Standard Check List (SCL) of the different parameters listed under 'Type of Setting' for individual commodities listed in the left side of the Table 1. In total there are ten standard check list identified by us. Among these the geologic identities are generally available from geological map, listed petrology,

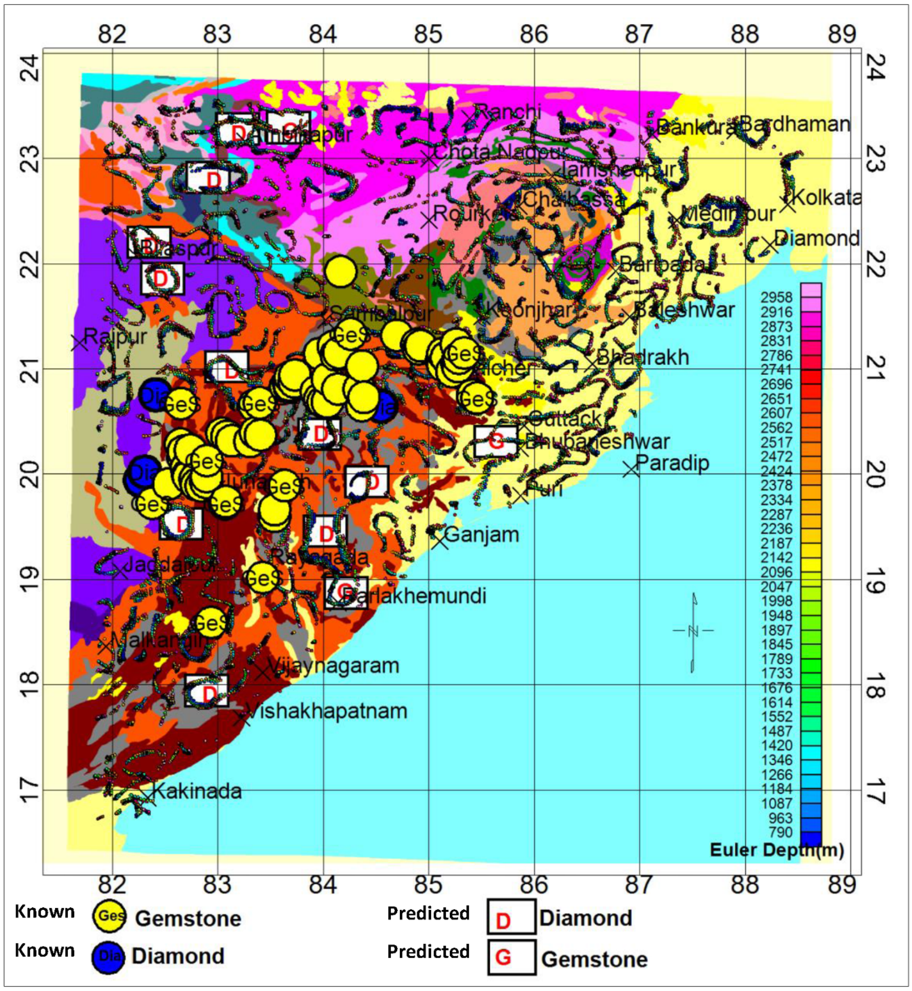

Fig. 5C. Dia/Ges zones with Euler's depth solutions (upto 3 km depth) over geology.

Table 1
Suggested Template for Prognostication.

Sr. No.	Type of Setting	Minerals							
		Fe	Cr	Au/Ag	Cu/Pb/Zn	Gemstone	Pt	Mn	Diamond
1	Sedimentary/meta-sedimentary (non-volcanogenic and volcanogenic)	✓	✓	✓	✓			✓	✓
2	Hydrothermally connected with faults (vein type)*			✓	✓		✓	✓	
3	Connected with basic lava (failed Y type rifting tri-junction) mostly sill type*	✓		✓	✓				
4	Connected with ultramafites & layered complexes*		✓				✓		
5	Connected with acid volcanics (layered complex)			✓	✓				
6	Associated with Komatiites and ultramafic effusive (layered igneous complex)*		✓	✓			✓		
7	Complex structural style with more than one generation of faulting in pre-Cambrian terranes*			✓	✓	✓			
8	Circular to elliptical fault bounded areas with Kimberlite Clan of Rocks in ancient cratonic boundaries*								✓
9	Solidus (melting) temperature (°C)	1538	1907	1064/961	1085/328/420	2000	1768	1246	4726
10	Placers		✓	✓		✓			✓

* Identified through analyses of gravity or other potential field data.

mineralogy, stratigraphy and structural studies. At a few instances one may be lucky to have some exploratory wild cat borehole data as well as collateral truth. But the limited version of fault/dykes/contacts seen on the geological map may not be sufficient to decide on the detailed exploration. Gravity allows us to have a lateral and vertical density differentiation in the area allowing us to understand the lateral and vertical changes in rock/litho units. Further, it also helps us to map the length and attitude (dip) of concealed 1D or 2D faults and dykes helping us to understand the possible 3D model (Kumar et al., 2018) of the potential area. One can model for dome/anticline/syncline etc. assuming 2D horizontal cylinder. Even the podiform/lensoid/limited stratiform deposits can be identified assuming sill like geometry for the causative sources at depth. The assumption of source geometry controls the solution; better the initial choice less ambiguous is the result. Moreover, gravity survey done over 3° × 3° area can generate 2D/3D crustal model up to Moho depth. Once such deeper information is available on a regional scale, one can assess the tectonic setting of the area as well.

If the SCL parameters for a particular commodity match well with geological, lithological, mineralogical, structural style and tectonic setting, then the potential of the area increases. The 2D/3D structural setting and tectonic implications that control the movement of magma/mineralogical fluids, deposition through differentiation can be mapped through potential field data in a quick and cheap way.

4. Conclusions

i. Any earth science predictive model is never guided by a theory or an established law. Like any other predictive science, we have developed our own template based on global examples, personal experience and local occurrence of metallogeny and mining districts in the study area. This is a modest attempt that could be only presented with humility.
ii. Actual exploration scale is about hundred times the scale of the regional map. Thus, unless we have data in 50 m × 50 m grid, actual exploration scale map is not possible. Therefore the present work is only a guide for future exploration sites to evaluate new resources and not to an indicated mineral resource.
iii. Tectonic events could be mapped through the synergy of geology and Euler's depth solutions.
iv. The movement of crustal block has been mapped at the dispositions of Euler's depth solutions shown by tracing the trend lines in the study area.
v. Such large grid spacing 3.3 km × 3.3 km of potential field data is good enough to delineate tectono-structural features associated with mineralized zones.
vi. 3D Euler's depth solutions have helped to demarcated criss-cross pattern of four different generation of tectono-thermal reactivation, several circular, semicircular zones at the ancient cratonic margin of Odisha and Chhattisgarh for plausible locations of future gemstones exploration.
vii. In other areas in India we have successfully completed several exploration projects for Uranium, gold, chromium, iron, manganese, copper, lead, zinc as mentioned in the text. We feel that our sincere effort in Odisha would be fruitful in detailed exploration of these minerals and should be undertaken in future.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.oregeorev.2018.11.014.

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