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ARTICLE

Diamonds from the Coromandel Area, West Minas Gerais State, Brazil: an update and new data on surface sources and origin

Diamantes da região de Coromandel, oeste de Minas Gerais, Brasil: atualização e novos dados sobre sua origem

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ABSTRACT: Important diamond deposits southeast of Coromandel and the local geology have been studied in an attempt to understand what surface source provided the stones. River gravels of Pleistocene to Recent age from this region have supplied most of Brazil's large diamonds over 100 ct. The upper cretaceous Capacete Formation of the Mata da Corda Group, composed of mafic volcanoclastic, pyroclastic and epiclastic material, has been worked locally for diamonds, nevertheless considered non-economic. The authors present results of their study of a deactivated small mine, representing the first report with description and analyses of two gem diamonds washed from this material. Hundreds of kimberlites, discovered in the last half century in the region, are sterile or non-economic. We propose that the surface source of the diamonds is the Capacete "conglomerado". The volume of this material is enormous representing a potential resource for large-scale mining. The authors suggest detailed studies of the volcanic facies of this unit focusing on the genesis, distribution and diamond content. As to the question concerning the origin of these diamondiferous pyroclastic rocks, the authors exclude the kimberlites and point towards the large Serra Negra and Salitre alkaline complexes which are considered the primary source for the pyroclastic units of the Mata da Corda Group. They propose that early eruptive phases of this alkaline complex brought diamonds from a mantle source to the surface, much as happens with traditional kimberlites, to explain the association of such huge carbonatite complexes and diamonds.

KEYWORDS: diamonds; Coromandel; surface source; origin.

RESUMO: *Importantes depósitos diamantíferos aluvionares a sudeste de Coromandel e sua geologia foram estudados, com o intuito de encontrar sua fonte. A maioria dos grandes diamantes Brasileiros acima de 100 ct foram recuperados de tais depósitos. A Formação Capacete do Grupo Mata da Corda do Cretáceo Superior, composta por material vulcano-clástico máfico, piroclástico e epiclástico, já foi alvo de garimpagem, entretanto considerado como sendo não econômico. Os autores descrevem os resultados de seus estudos de uma pequena mina desativada nestas rochas e apresentam o primeiro relato com descrição e análises de dois diamantes recuperados deste material. Centenas de kimberlitos descobertos nos últimos 50 anos são estéreis ou não econômicos. Nossa proposta é que o "conglomerado" Capacete é a fonte principal dos diamantes nos cascalhos aluvionares. O volume deste material é enorme e representa um recurso com potencial para mineração de maior porte. Os autores sugiram um estudo pormenorizado da fácies vulcânica desta unidade, enfatizando a gênese, distribuição e conteúdo diamantífero. Com relação à origem das rochas piroclásticas diamantíferas, os autores excluem os kimberlitos e apontam para o complexo alcalino-carbonatítico Serra Negra – Salitre como sendo a fonte destas rochas. Eles sugerem que fases iniciais eruptivas de tal complexo carregaram diamantes do manto à superfície, semelhante como os kimberlitos conhecidos, para explicar a associação de tal complexo alcalino-carbonatítico e diamantes".*

PALAVRAS CHAVE: *Diamantes; Coromandel; origem.*

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INTRODUCTION

Brazil had been the principal diamond producer of the world for over 150 years, when it was surpassed by the South African production (Karfunkel *et al*. 1994). The precious stones were discovered in Minas Gerais (Fig. 1, lower part) near Diamantina, in 1714 (Calógeras 1904); however, 1729 is the official "discovery year" when the notice reached Europe.

Because of the discovery of diamonds in alluvial gravels of the Abaeté and other rivers in the mid-18th century (Barbosa 1991), garimpeiros (artisan diggers) migrated towards the West (Fig. 1) to a region called the Triângulo Mineiro. In the 19th century, scientists (e.g. Derby 1882; Pires 1885) described the diamond occurrences and provided the first geological descriptions of the region. In the 20th century, scientists were attracted by the geology of diamonds and tried to explain their genesis, depositional environment and regional geological setting.

For over 250 years, the Triângulo Mineiro supplied a major amount of Brazil's diamonds. Surprisingly, almost all diamonds over 100 ct came from this region (e.g. Reis 1959; Liccardo & Svisero 2005; Hoover & Karfunkel 2009). By the 1960s almost all major diamond companies came to the Triângulo Mineiro to explore the primary diamond sources. After over half a century of extensive investigation they have abandoned further exploration leaving the region to small mining firms and to the garimpeiros. Although much of the exploration data remain proprietary, they have revealed the discovery of hundreds of kimberlites and related intrusive bodies in the region. Nevertheless, the primary diamond source remains an enigma to this day.

The present paper reviews the known surface sources and proposed models about the origin of diamonds in the Triângulo Mineiro, and reports new data including analyses of two diamonds from the studied area, which suggest a primary source in large epiclastic volcanic apron deposits.

GEOLOGICAL SETTING

A problem arises concerning the geological terminology of the southwestern part of the Triângulo Mineiro, because it covers the border of Minas Gerais and São Paulo. Diamonds and the interesting geology caught the attention of scientists from both states decades ago, leading, in part, to different terms for similar sequences. As the scope of the present article is diamonds, their surface sources and origin, the geology will be focused on the S-SE region of Coromandel (Figs. 1 and 2) where most of the large diamonds have been found.

In Upper Cretaceous time (90 – 80 Ma), a large region in the Triângulo Mineiro, called the Alto Paranaíba Arch (Fig. 1), was formed giving rise to two huge hydrographic basins in South America: (i) the Paraná Basin to the S-SW of the Arch, with a sedimentary-magmatic character covering 1.5 million km^2 in Brazil, Paraguay, Argentina and Uruguay; and (ii) the São Franciscana Basin to the N-NE, with an extension of 1100 km and 200 km wide (Haralyi & Hasui 1982; Hasui & Haralyi 1991). According to Gibson *et al*. (1995), this arch had its origin with the Trindade Mantle Plume, and has been accompanied by magmatic manifestations such as kimberlites, carbonatites, kamafugites and related rocks. Many of these are distributed in a N35°W direction, seen in magnetometric maps and known as the mega-lineament AZ125 (e.g. Leonardos & Meyer 1991).

The sedimentary-magmatic sequences of both basins laid mainly on Precambrian rocks belonging to the Araxá, Canastra, Ibiá and Bambuí Groups.

In the present article, the authors focus on the Mesozoic sedimentary-magmatic sequences, which are of Lower- and Upper Cretaceous age (Sgarbi *et al*. 2001). In the São Franciscana Basin the former is represented by the Areado Group, formed in alluvial fan, wadi, lacustrine, fluvial, deltaic and eolic environments (Sgarbi *et al*. 2001). The latter, the Upper Cretaceous Mata da Corda Group, is an association of alkaline, mafic rocks of kamafugitic nature with volcanoclastic and sedimentary rocks in the southern part of the basin. More to the north occur the Urucuia Group with fluvial, lacustrine and eolic sediments, chrono-stratigraphically equivalent to the Mata da Corda Group.

The Mata da Corda Group has been divided into the Patos Formation, mainly intrusions and flows of alkaline and kamafugitic nature, but kimberlites and related rocks also occur, and the Capacete Formation, composed of pyroclastic rocks and epiclastic sediments. Both formations are about the same age (Sgarbi *et al*. 2001).

In the Paraná Basin only the upper cretaceous Bauru Group, Uberaba Formation is of interest for this article, since it represents an equivalent to the Capacete Formation in the São Franciscana Basin. It is composed of sandstones with a high content of perovskite and apatite, as well as (locally) diamondiferous conglomerates incorporating magmatic–sedimentary-metamorphic rock fragments (e.g. Campos 1891; Svisero *et al*. 1981). Paleogeographically the source area is probably within the Alto Paranaíba Arch to the N-NE (Gravina *et al*. 2002).

During late Tertiary time regional peneplanation processes in South America and Africa (King 1956) led to the formation of "chapadas" (peneplains) often capped by the Mata da Corda. These have since been laterized down for several tens of meters. This process in a tropical climate with deep weathering often hampers geologic interpretations due to lack of fresh outcrops, making it difficult to distinguish multiple episodes of volcanism.

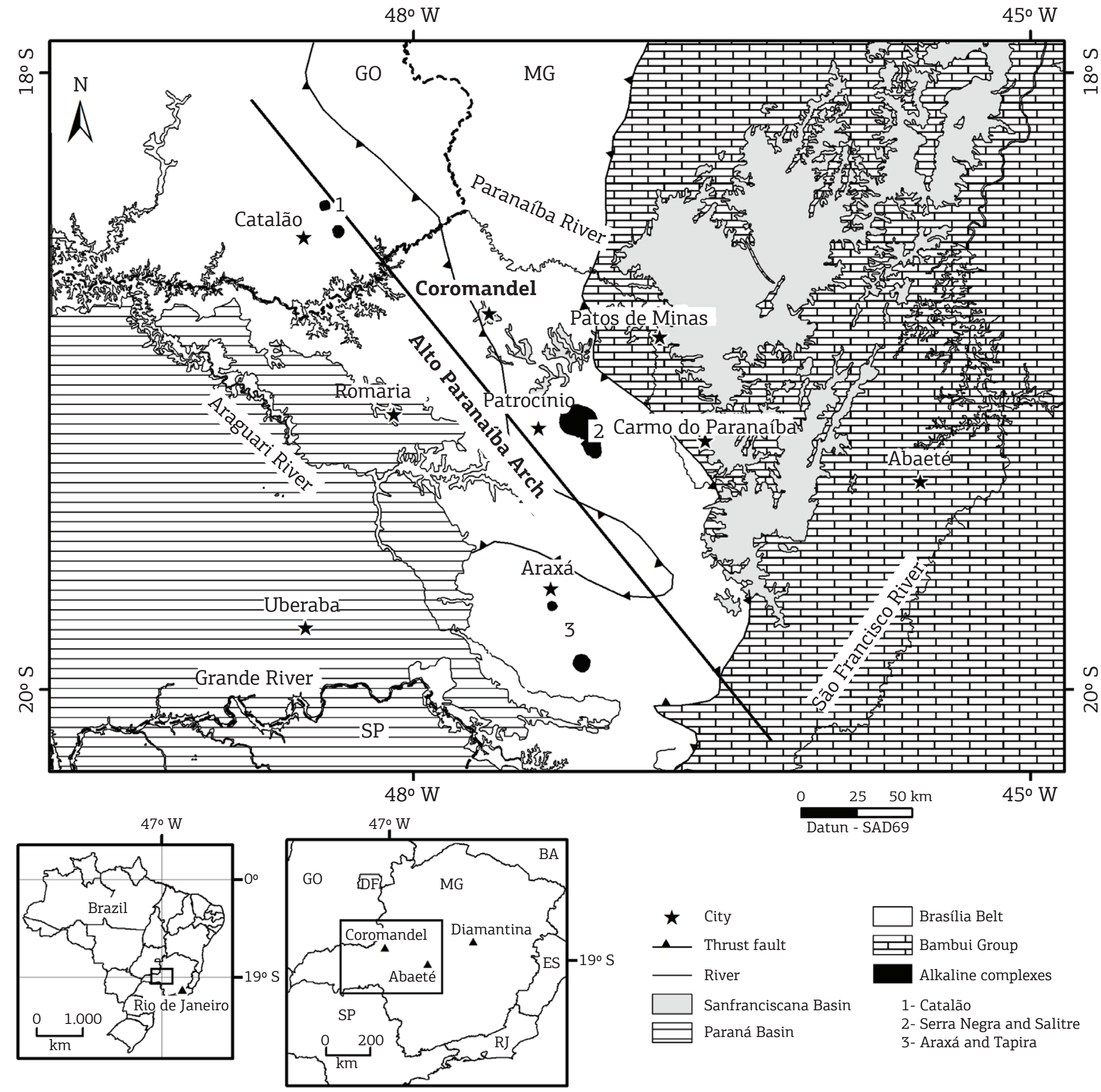

Figure 1. Part of the Triângulo Mineiro region in Minas Gerais showing the Alto Paranaíba Arch and the Paraná and Sanfranciscana basins, as well as the most important alkaline complexes (modified from Heineck *et al.* 2004).

River gravels of Pleistocene and Holocene age are diamondiferous in several localities in the Triângulo Mineiro. Topographically river gravel terraces show dozens of meters differences in altitude, a consequence of their different formation age.

Triângulo Mineiro Mafic Rocks

Several ultramafic alkaline complexes have been described in the Triângulo Mineiro, like Araxa, Tapira, Serra Negra, Salitre and Catalão (Fig. 1). The magnetic map (Fig. 3) shows the large Serra Negra (right arrow) and Salitre alkaline complexes as the dominant mafic rocks in the region along with the series of linear mafic dikes aligned along the 125° mega-lineament. These dikes, prominent in the scale of the magnetic map, have little evidence from field mapping due to their surface width and deep weathering. More important for the present article is the expression of the (reduced) Mata da Corda volcanic units in the magnetic profile. Typical of mafic

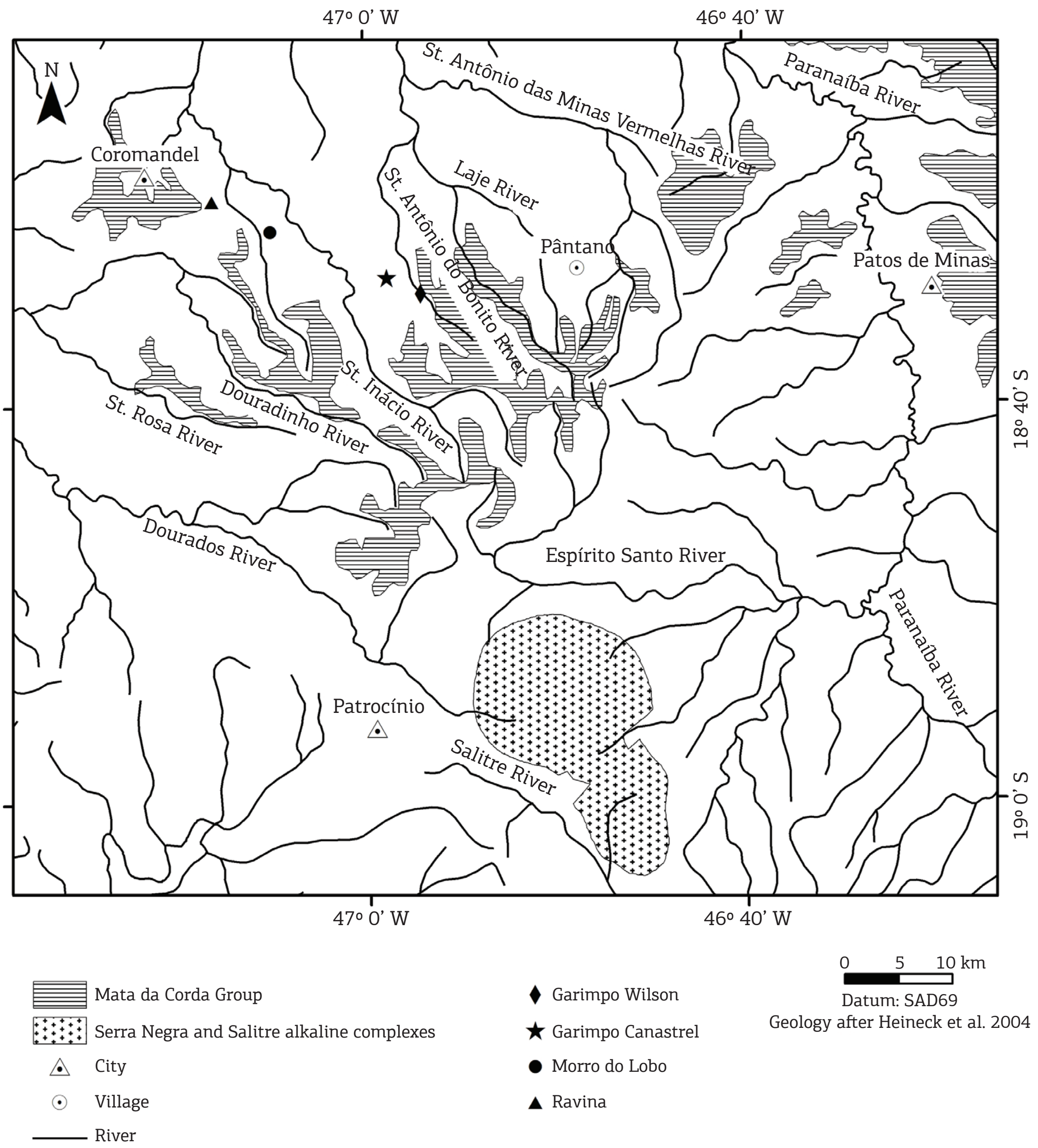

Figure 2. Distribution of the Mata da Corda conglomerates and associated rocks southeast of Coromandel with the location of Garimpos Wilson and Canastrel, as well as Morro do Lobo and Ravina.

extrusives, much of the Mata da Corda has a clear magnetic expression shown by an irregular magnetic pattern. Figure 3 shows that the mapped units of the Mata da Corda capping the ridges SE of Coromandel also have a clear expression.

The known kimberlites can be just a couple of meters in diameter or (seldom) represent large bodies. The small kimberlite plug near garimpo Wilson, mentioned in the next section (Study Targets) has a magnetic signature too weak to be seen at this scale. Remarkable is that erosion did not reach a lower level in most bodies, since majority show crater facies. This point will be discussed further in the text. The enigma concerning the origin of diamonds in the Triângulo Mineiro led the authors to select two study targets, which were considered promising as to the contribution for the solution of the enigma. The authors chose a case study from both gravel and conglomerate typically worked by the garimpeiros.

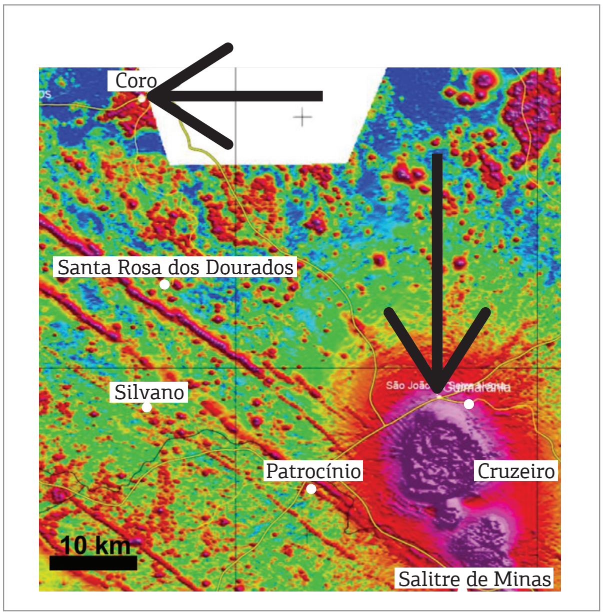

Figure 3. Magnetometric map (analytical signal) of the same area shown in Fig. 2 (after CODEMIG/CPRM, 2006); upper arrow: Coromandel; right arrow: Serra Negra and Salitre alkaline complexes.

SURFACE SOURCES OF DIAMONDS

Diamonds have been washed in the Triângulo Mineiro since their discovery from "cascalhos" (river gravels). This source remained the only one till the end of the 19th century, when garimpeiros started to wash "conglomerados" as well, but with no economic importance. These two sources, called here "categories of washing material", will be discussed, since they led to hypotheses about the origin of diamonds in the region.

Gravels: the first category, the "cascalhos" can be recent deposits, found in the actual river beds, or sub-recent, representing paleochannels today lying dozens of meters above the first. Their ages have never been discussed, nevertheless, compared with other localities in Minas Gerais, the actual gravel horizons formed around 7000 – 5000 yBP. During the climax of the last glaciation (Wisconsin) only small ice caps covered the Andean mountains in South America (Flint & Fidalgo 1969). About 100,000 yBP the average annual temperature has been 8°C – 11°C lower than today (Herd & Naeser 1974). The decreased humidity and lower average annual temperatures in the order of 5°C – 7°C led to arid conditions (Karfunkel *et al.* 1998). At the beginning of the Holocene, about 10,000 yBP, temperature and humidity increased drastically and, consequently, pluvial index too (Bigarella & De Andrade 1965). However, that time period showed oscillations in precipitation (Deevey & Flint 1957). Thus, humidity and precipitation reached their maximum around 5000 – 7000 yBP (the Altithermal stage according to Deevey and Flint 1957), leading to incisions of the drainage systems and formation of the actual gravel horizons, in the Triângulo Mineiro, some of them being diamondiferous. There are no data concerning the higher gravel levels, but they should be of Pleistocene age. Diamond populations from both gravel horizons (recent and sub-recent) do not show any differences and certainly shared the same source rock.

Conglomerates: the second category of washed material is the so called "conglomerado", which is geologically a "mixture of different terms"; however, it is highly important due to genetic aspects, and could give hints as to the origin of the diamonds. The following among them are described below.

The Abaeté conglomerate is described in the São Franciscana Basin near the Serra do Cabral as being probably diamondiferous (Karfunkel & Chaves 1995). Geologically, it is a "true conglomerate in the sedimentological sense", and the above authors suggest that Precambrian (secondary) diamondiferous rocks from the Espinhaço Range to the East may be the surface source. They were distributed in a braided system during Lower Cretaceous time in a western direction.

The Romaria conglomerate located near the homonymous city (Fig. 1), at the base of the Bauru Group in the Paraná Basin (Uberaba Formation), proved to be a source of diamonds. It has been described by many authors for over 100 years in detail (e.g. Campos 1891; Svisero *et al.* 1981) and there is no doubt as to its diamond content. Nevertheless, the location of the source rock was still not known. Based on provenience analyses some authors (e.g. Gravina *et al.* 2002) postulated the Alto Paranaíba Arch to the N-NE as being the supplier region.

A quite different model is suggested by Tompkins & Gonzaga (1989). A Neoproterozoic diamictite of glacial origin, distributed over huge areas on and around the São Francisco Craton was often called just "conglomerado". According to them the original diamondiferous rocks were intruded during Precambrian time in the cratonic area. The craton was covered by thick ice sheets of continental dimensions that eroded pre-existing diamondiferous kimberlites in the cratonic area and scattered the stones in the so called "conglomerados" (Macaúbas, Jequitaí, Ibiá sequences, among others). Modern fluvial systems, they believe, concentrated the diamonds in river gravels.

Of more interest for the present article as to the source of the Triângulo Mineiro diamonds is a "conglomerado" and associated rocks, widely distributed in the São Franciscana Basin over an area of more than 20,000 km^2 (Fig. 1). Barbosa *et al.* (1970) classified the conglomerate as belonging to the base of the Bauru Group, which can be over 10 m thick. Nowadays on geologic maps of the area the term Mata da Corda replaces the term Bauru. This conglomerate, we believe, is extremely important as the probable surface source of diamonds, a point that Barbosa (1991, p. 102) already recognized: "these conglomerates are the more important rocks as to the finds of big stones, because without any doubt, they were the original rocks, that supplied these gems to the river gravels" (translation by the authors).

STUDY TARGETS

Target 1: gravel from headwaters of the Santo Antônio do Bonito River (Figs. 2 and 4), which is one of the most famous rivers in the Triângulo Mineiro for the supply of stones over 100 ct. Liccardo & Svisero (2005, Fig. 3) show a map of the main diamondiferous rivers in the Coromandel area with numbers pointing towards the finds of large diamonds. Surprisingly, over one fifth of stones larger than 100 ct came from Santo Antônio do Bonito gravels, and the

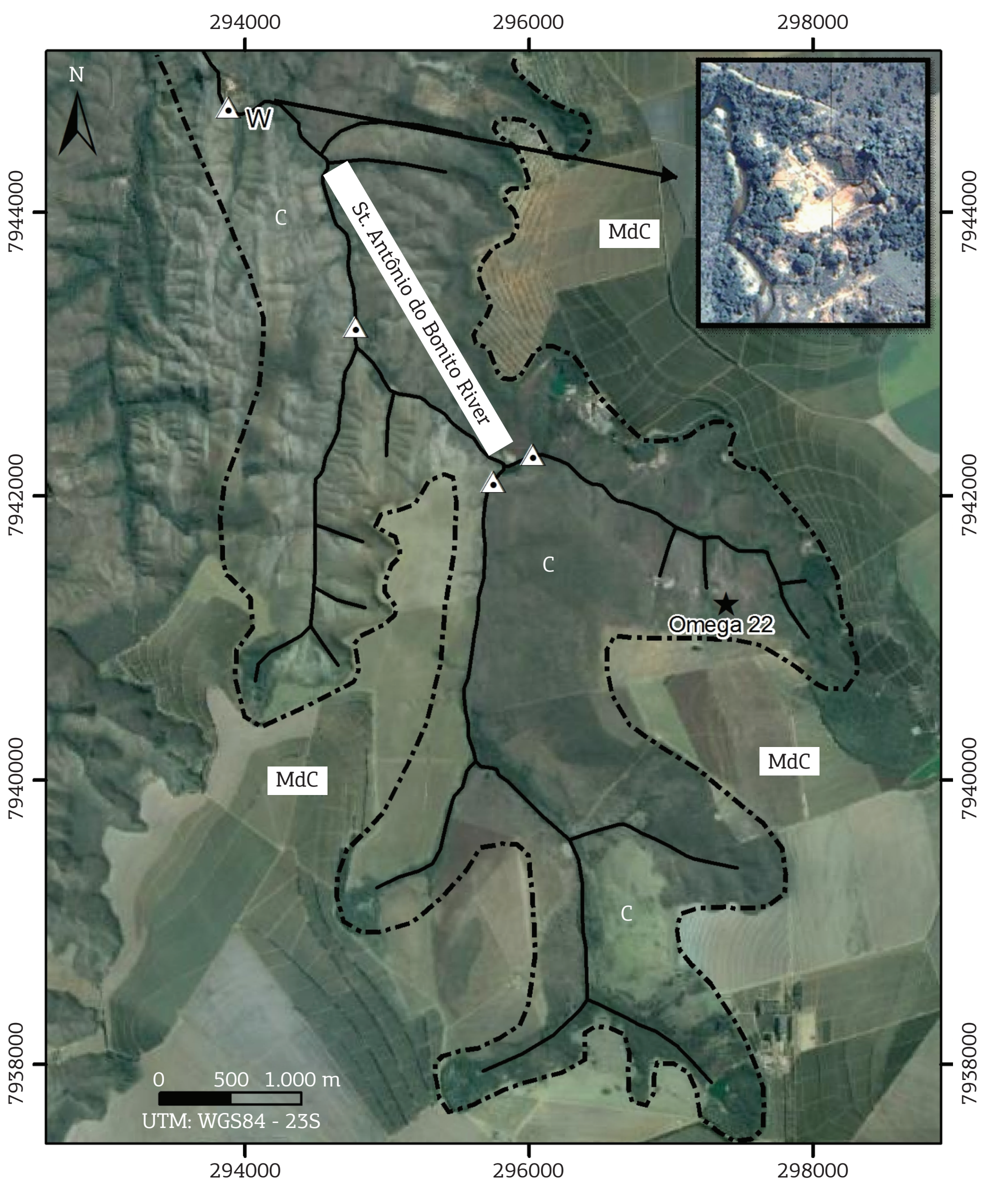

Figure 4. Headwaters of the Santo Antônio do Bonito River (dashed line), showing the Garimpo Wilson (W) and the sampling sites (triangles), as well as the kimberlite Omega 22 (star). C: Canastra Group; MdC: Mata da Corda Group.

three largest Brazilian gem diamonds came from this river (Pres. Vargas 726.7 ct, Santo Antônio 602 ct and Darcy Vargas 460 ct). Combined with the nearby Santo Inácio, the two rivers have provided about 50% of the large stones. Interesting to note is that these two rivers are also the two closest to Serra Negra of all the producing rivers.

A large mechanized garimpo called "Garimpo Wilson" (UTM Projection, Datum SAD 69, E293856/N7944782; Figs. 2 and 4) is situated in alluvial deposits at the headwaters of the river (Santo Antônio do Bonito). It was active for many years and supplied hundreds of carats of diamonds, among them pink stones too (verbal report of garimpeiros and owners of the mine). The authors' estimation point towards 8000 m^3 of material that had been washed. Due to environmental problems it was closed a couple of years ago. The authors examined the abandoned operation, confirming that a 30 – 60 cm thick package of river gravels had been worked with the aid of bulldozers. The overlying laterized colluvium of about 4 – 8 m is assumed sterile. The only possible source for the diamonds is the small basin itself and overlying sediments upstream.

From the map (Fig. 4), the only surface rocks which could supply diamonds to the Garimpo Wilson are the overlying Mata da Corda sediments. The underlying Canastra quartzites and schists are sterile. Because the topography is relatively steep, and most geological contacts are hidden by colluvial deposits and deep weathering, small lithologic units can be overlooked, such as the small known kimberlite (Omega 22). That the known kimberlites in the region were abandoned suggests that they were not a source.

To test for diamond indicator minerals the authors washed at four sites of the upper Santo Antônio do Bonito with over 100 liters per washing site. Only ilmenite has been found in two of them. The ilmenites have been analysed (Micro-Probe) and plotted in the diagram of Wyatt *et al.* (2004). Fernandes (2013) described and compared them to the occurrence of other ilmenites in the region. In the diagram, it can be seen that they are clearly of kimberlitic origin. This result is not considered as hard evidence, nevertheless, corroborates the hypothesis of the Mata da Corda sediments being the surface source for the Santo Antônio do Bonito diamondiferous gravels.

Target 2: conglomerate from the eastern slope of the ridge, dividing the diamondiferous rivers Santo Antônio do Bonito and Santo Inácio (Fig. 3). Both rivers are famous for finds of many large diamonds. A small mine (called Garimpo Canastrel, UTM Projection, Datum SAD 69, E291126/N7946476), had been working "conglomerados" of the Mata da Corda rocks (Capacete Formation) for some years, but has been deactivated. The last owner, Ingo Wender, has provided the authors with some valuable information, which have been confirmed by other prospectors who worked there during that period.

The mined outcrop (Fig. 5) is composed of tuffaceous material, alternating with conglomerates ranging in thickness from 20 to 100 cm (locally up to 5 m) and cross-bedded sandstones. The clasts, up to 20 cm with no preferential orientation, are composed of well-rounded sandstones, similar to those of the Areado Formation and a few clasts of volcanic material, as well as Precambrian lithologies. In the brownish-beige conglomerate matrix, altered feldspars occur and phlogopite has also been identified. These materials are covered by a lateritic soil up to 10 m in thickness. According to Fernandes (2013), the conglomerate belongs to the lower part of the Capacete Formation. The authors calculated the volume of the worked material in the Garimpo Canastrel and estimated 850 m^3, which corroborates the verbal information of "less than 1000 m^3" (Ingo Wender). Moreover, three diamonds have been recovered with a total weight of about 2 ct (0.8, 0.750, and 0.497 ct); the first was of very low quality and was sold at the time. The other two are of good gem-quality (H-J/Vs-Si), and were kindly loaned to the authors by Mr. Wender for study (Fig. 5). From the

Figure 5. Garimpo Canastrel (upper photo) and contact between conglomerate (Cngl.) and tuff (lower left). The two gem quality diamonds from this outcrop are shown on the lower photo to the right.

information obtained, the conglomerate at the Garimpo Canastrel has an average content of 0.0025 ct/m^3.

From the above described diamondiferous conglomerate, the authors recovered several ilmenites and garnets with kelyphitic rims (cf. Fernandes 2013). Mr. Wender confirmed the occurrence of Cr-diopside as well. The ilmenites and garnets show no fluvial wear, pointing towards the absence of, or extremely short, surface transport.

Microprobe analyses (SEM) of both indicator minerals have been compared to others from the region by Fernandes (2013) and plotted in the diagram of Wyatt *et al.* (2004) and Grütter *et al.* (2004) (for ilmenite and garnet, respectively). The ilmenites are classified as kimberlitic and the garnets as pyropes belonging to the groups G4 and G5. The G4 and G5 garnets are associated with diamonds from eclogitic and peridotitic sources.

The Garimpo Canastrel was compared to other Mata da Corda outcrops from the area composed of tuffs and conglomerates. The tuffs of Morro do Lobo (UTM Projection, Datum SAD 69, E279584/N7950829, Fig. 2) and the nearby (3 km to the W) clay mine show several small clasts in the fine matrix (tuff), magnetite layers of some centimeters thick, cross-stratification in the coarser sandy parts and gas pipes (Fernandes 2013). The fine tuff is used for the ceramic industry. Phlogopite and smectite have been identified in the tuff. At the conglomerate outcrop called Ravina (UTM Projection, Datum SAD 69, E271992/N7952698; Fig. 2) the contribution of volcanic material is much higher (Fig. 6). This outcrop, located a few meters west of the paved road from Patrocínio to Coromandel (Fig. 2), represents one of the best outcrops showing the epiclastic nature of these rocks, as well as the cyclic deposition. The outcrop is the consequence of gully erosion that probably started due to garimpo activities. It is clear from the comparison of these and other Mata da Corda outcrops that the Mata da Corda rocks show lateral and vertical variations.

Gravels near a small creek between Morro do Lobo and the clay mine have been worked for diamonds some years ago (verbal communication of Mr. Don Haynes). At this site the authors have found a tuff underlying the gravel horizon, thus the latter probably represents a paleochannel. The topographic difference between Morro do Lobo – clay mine (about the same height) and the tuff underlying the gravel is about 80 m. In many other localities south of Coromandel, these differences in topography of the Capacete Formation probably represents a paleorelief during the deposition of the epiclastic material on a highly irregular topography, which explains the thickness of the sequence south of Coromandel with an average of 20 – 30 m.

In all three occurrences described above, most clasts are well rounded except for some which are angular; the coarser sand grains are rounded and represent Areado sandstone

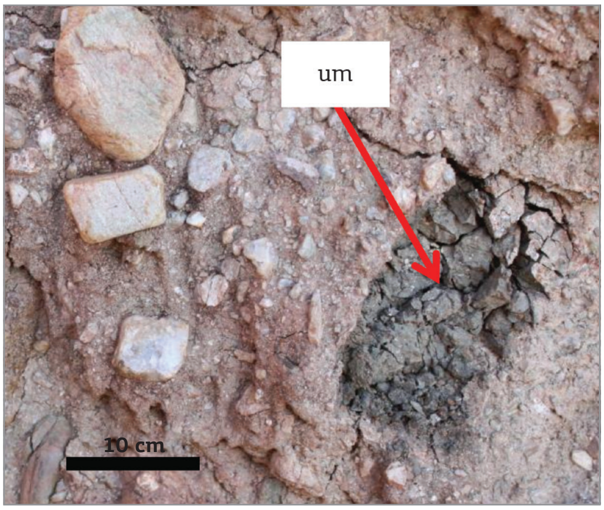

Figure 6. The outcrop called “Ravina”: conglomerate with different types of rock fragments, rounded and angular, in a sandy/clayish matrix; um: ultamafic, decomposed fragment.

transported by the erupting magma, and blown into the air. Other garimpos south of Coromandel have been reported by garimpeiros to have large diamonds in Mata da Corda conglomerate, however, none have yet been documented. The Garimpo Canastrel is the first documented one.

Description and analyses of the two diamonds from the Garimpo Canastrel

Physical characteristics of diamonds have been described in many papers (e.g. Harris *et al.* 1975; Robinson 1979; Otter *et al.* 1991). These authors in their classification schemes distinguish between primary (growth) and secondary (resorption) morphologies. The authors of the present article suggest to add a third feature originating in the sedimentary environment (Karfunkel *et al.* 2001), since they can give hints as to the surface transport conditions and deposition. The short description that follows has no statistical value, nevertheless, together with all other information, can help to elucidate some points in this enigmatic subject.

Both the diamonds provided by Mr. Wender are nearly equidimensional, the larger one (0.750 ct) being slightly distorted (Fig. 5) with only discrete inclusions (Vs). Of the two, the smaller stone (0.497 ct) is white (H), whereas the larger one is slightly yellowish in color (J). The secondary (resorption) morphologies lay between categories 3 and 4 of Otter *et al.* (1991). The authors suggest calculating the primary mass (or weight) divided by the percent preservation factor. In the Garimpo Canastrel case, the stones would have primary masses of about 1.3 ct (larger stone) and 0.8 ct (smaller stone).

Diamonds recovered from xenoliths commonly show characteristic surface features (Robinson 1979). Both the Canastrel diamonds show uniform resorption. Lamination lines on two adjacent tetrahexahedral surfaces are well developed, passing the edge of surfaces (Fig. 7A), indicating glide plane dislocations during plastic deformation in the mantle.

Elongated hillocks of different sizes on adjacent tetrahexahedral surfaces have been noted (Fig. 7B). On one surface, hexagonal terraces (Fig. 7C), described by Robinson (1979), gradually turn into elongated hillocks. Small oriented etch pits (Fig. 7D) are probably oriented corrosion sculpture pits (Fig. 7E).

As to the tertiary features, both the diamonds do not show severe wear features. This observation is important since a comparison between the sedimentary wear features of the Triângulo Mineiro diamonds with those of the Diamantina region (e.g. percussion marks, severe breakages;

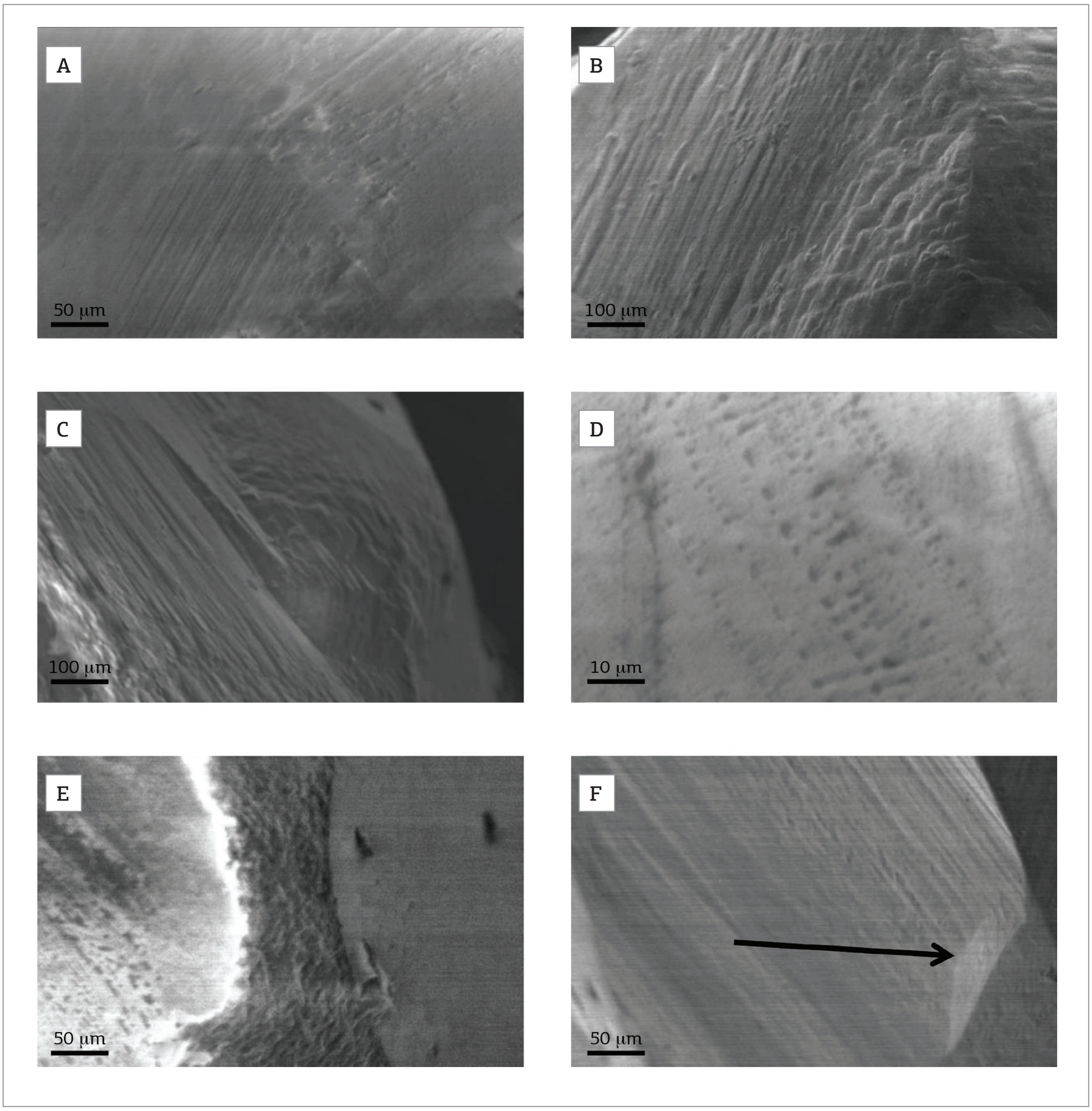

Figure 7. Microprobe analyses images of the diamonds. (A) lamination lines on two adjacent surfaces; (B) elongated hillocks of different sizes on adjacent tetrahexahedral surfaces; (C) hexagonal terraces gradually turn into elongated hillocks; (D) small oriented etch pits; (E) corrosion sculpture on the tetrahexahedroidal crystal faces; (F) small breakage marked by arrow.

cf. Karfunkel *et al.* 2001) reflect a different transport and depositional history. Only one of the Garimpo Canastrel diamonds show a single, small breakage (Fig. 7F), reflecting the relatively smooth transport history. The above described lamination lines represent glide planes due to deformation in the mantle and predate resorption (e.g. Robinson 1979; Robinson *et al.* 1989; McCandless *et al.* 1991; Otter *et al.* 1991). The Triângulo Mineiro is known for the occurrence of fancy colored diamonds, pink and brown being predominant — a fact that corroborates the deformation mentioned and enhancement by resorption.

Analyses by infrared absorption spectroscopy (IR) and photoluminescence (PL) of both diamonds have been carried out. Figures 8 and 9 present the results. Although the IR spectrum of the larger diamond (Fig. 8) shows partial saturation effects in some parts of the one phonon region (400 – 1.400 cm^{-1}), the spectra of both diamonds could be normalized at 2000 cm^{-1} to an absorption coefficient of 12.3 cm^{-1} (Woods 1986; Clark & Davey 1984; Breeding & Shigley 2009). After normalization, the nitrogen content in the two samples could be determined. Both diamonds belong to class Ia. The larger diamond has less nitrogen content and belongs to class IaAB with about equal concentrations of nitrogen aggregates A (1.285 cm^{-1}) and B (1.175 cm^{-1}) with concentrations of about 50 ppm. The smaller diamond has higher nitrogen contents with dominant B aggregates (~ 650 ppm) and less A aggregates (~ 200 ppm). Therefore, the smaller diamond belongs to class IaB. Both diamonds have low hydrogen concentrations which is manifested by a low intense IR band at 3.107 cm^{-1}.

The photoluminescence spectra of both diamonds excited by a solid state laser at 375 nm (16 mW) are shown in Fig. 9. According to Eaton-Magaña *et al.* (2007), both the diamonds can be distinguished by their photoluminescence spectra. While the smaller diamond belongs to category I with dominant photoluminescence bands at ~ 450 and 490 nm originating from N3 centers — three nitrogens in a [111] plane surrounding a carbon vacancy, the larger diamond belongs to mixed category I/II with an additional photoluminescence band at about 525 nm. In addition, the larger diamond shows the N3 zero-phonon line at 415 nm and also the H3 band at 503 nm was detected.

DISCUSSION

It is believed that the diamondiferous rocks recent to sub-recent "cascalhos" south of Coromandel have their surface source in "conglomerados" — not directly from kimberlites and related rocks. The quantity of diamonds washed in the last 250 years in the Triângulo Mineiro is not compatible with the relatively shallow erosion level of the kimberlites (mostly crater facies). The authors estimated that 40 (± 10) million carats have been recovered, which is approximately in accord with data from Barbosa (1991). If we suppose an average of 0.2 ct/t, like in South Africa, it means that the original re-worked kimberlites in the Triângulo Mineiro would be about 8 million tons, a number that is not acceptable for the kimberlite volume (crater facies). Moreover, if these and other kimberlites would be so extremely rich in diamonds, why did all major companies left this region? The case study of Garimpo Wilson including the headwaters of the Santo Antônio do Bonito point clearly towards the Mata da Corda rocks as being the only source for diamonds in this area.

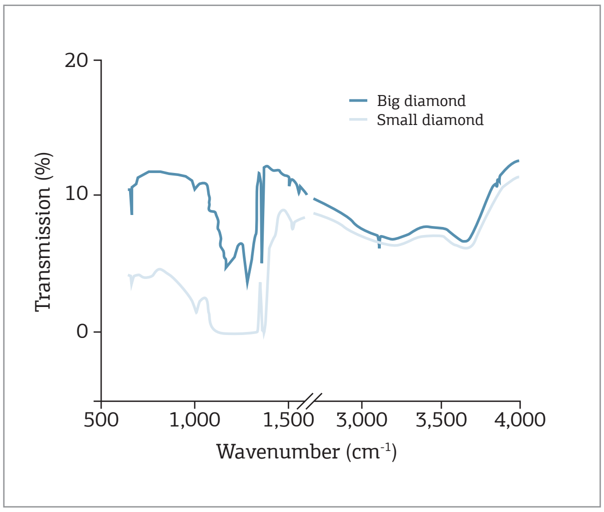

Figure 8. Infra-red spectroscopy of both diamonds.

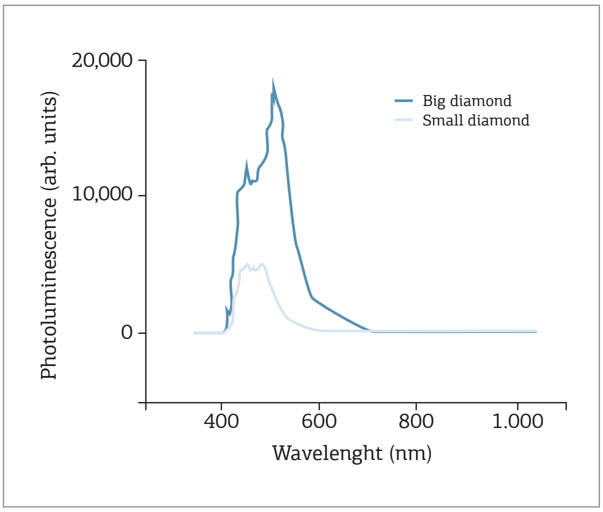

Figure 9. Photoluminescence of both diamonds.

The first discussed "conglomerado", the Abaeté Conglomerate, is proved to be sterile in outcrops south of Coromandel. The Serra do Cabral source lies far away from Coromandel (350 km to the NE) and paleogeographic studies showed their provenience from the east in the Espinhaço Range. Therefore, it is plausible to discard the Abaeté Conglomerate as the surface source for the alluvial diamonds in question.

Although the second type of "conglomerado" from the base of the Bauru Group in the Paraná Basin is diamondiferous, it was not the source for the Coromandel diamonds because of the topography between the states of Minas Gerais and São Paulo.

The model of Tompkins and Gonzaga (1989) is also rejected, since there are diamondiferous hydrographic basins in the Triângulo Mineiro (e.g. Santo Antônio do Bonito) with no Precambrian tillites. Moreover, there are hydrographic basins which comprises of Ibiá tillites, with no diamondiferous gravels.

The fourth described "conglomerado" was mapped in detail by Fernandes (2013) as belonging to the Capacete Formation and shows alternations between fine to extremely coarse material, composed of a large variety of sedimentary, magmatic and metamorphic components. When examining the Capacete sequence the reader has to distinguish between two geologic processes:

- The magmatic process (cf. Sgarbi *et al.* 2001), that brought huge quantities of magmatic material, as well as lithologies incorporated by the ascending magma to the surface, and blew the components through the chimney high into the atmosphere. These volcanoclastic rocks are believed to have formed over time from numerous eruptive episodes in order to have deposited such an enormous amount of rock. After all this mixture of material was deposited on a highly irregular relief, the second process started.
- Sedimentary fluxes redistributed this mixture of pyroclastic-volcanoclastic and associated rocks. As a result of these fluxes, conglomeratic rocks were formed in several places, and as the process was repeated several times, nowadays geologists find alternating sequences. According to Fernandes (2013), the more important as to the diamondiferous source is the lower, thicker conglomerate.

Several authors already mentioned these processes. Schobbenhaus *et al.* (1984, p. 241) say that "… Caotic and welded tuff and associated rocks… locally conglomeratic due to the presence of ejecta in the tuffaceous matrix… granules of magnetite… cross stratification in sandstones… the sandstones incorporate extraformational, epiclastic, polymictic conglomerate with clasts of Cretaceous and Precambrian rocks…" (translation by the authors). However, they did not mention the Mata da Corda epiclastics as the surface source for the "cascalho" diamonds.

The case study of Garimpo Canastrel "conglomerado" is, to the authors' knowledge, the first-reported diamond finds in such conglomerates of the Mata da Corda Formation with photographs, descriptions and analyses. The verbal notice of isolated garimpeiros locally washing these rocks for diamonds south of Coromandel has been rumored for a long time, and likely to be true. However, the low diamond content, as shown from the Garimpo Canastrel, does not justify any investment at the moment.

Considering the wide spatial distribution of Capacete epiclastics in the region, with an average thickness of 15 – 20 m (Fernandes 2013) yields a huge volume of about 400 – 600 km^3. If we compare these data with the Krakatoa explosion in 1883, that blew 21 km^3 of material into the atmosphere, one can easily imagine the size of eruptions south of Coromandel. These studies leave no doubt as to the surface origin of diamonds in "cascalhos" south of Coromandel: "conglomerados" belonging to the Capacete Formation.

The character, composition and distribution of the "conglomerados", point towards the epiclastic nature, and are, without any doubt, as Barbosa (1991) and few others have already suggested, the surface source of the "cascalho" diamonds. Nevertheless, the question is: where is (are) the conduit(s) that supplied the huge amount of pyroclastic material? Kimberlites and related rocks in the region are not diamondiferous (or non-economic). Nevertheless, the huge alkaline complexes shown in Figs. 1 and 2 are outstanding, mainly the Serra Negra and Salitre situated about 60 – 70 km to the SE of Coromandel. The association of carbonatites and other rocks like kamafugites has already been discussed by several authors (e.g. Brod *et al.* 2000). The possibility that these alkaline complexes brought the diamonds from the mantle to the surface cannot be discarded.

Meyer (1985), Mitchell (1993) and Nixon (1995) have reviewed the nature of primary diamondiferous occurrences. Two factors are of importance: a fertile source of diamonds within its stability field in the mantle (peridotites or eclogites) and a very rapid emplacement of magma, ~ 7.0 km/h, from the mantle source to the final site at the surface. Anderson (1979) has discussed the necessity for a gas drive in the brittle lithosphere in order to have crack propagation rapid enough for magma to reach the surface and be cooled for effective preservation of diamond. This requires a large supply of gas, for example CO_2, be present in the mantle and associated with the diamond source rock. The exit velocity of magma from the volcano is at the velocity of sound, Mach 1 or greater, so that material may be thrown for large distances. How exsolved volatiles, water and carbon dioxide, can form in sufficient quantities to raise the massive load of kimberlite or lamproite rock which acts as the express elevator bringing diamond to the surface has been a problem for understanding the emplacement of diamonds. A recent paper by Russell *et al*. (2012) appears to have provided answers, although the idea has been discusses shortly in other papers too (e.g. Ukhanov 2005). The mechanism requires an initial carbonatite-like partial melt in the mantle, which then begins to migrate upward. These silica-undersaturated melts assimilate orthopyroxene which causes a drop in CO_2 solubility, producing vapor which then drives a rapid and accelerating ascent of diamond-bearing magma. They suggest that all kimberlites may start life as carbonatitic melts.

Recent studies of the mantle have shown that carbonatites may play a more important part in diamond crystallization and emplacement than previously recognized. Gaillard *et al*. (2008) note that low resistivity zones within the upper mantle probably are caused by low volume partial melts of carbonatitic magma because of its very high conductivity, 1,000 times more than molten silicates. They also have very high wetting properties which help in forming interconnecting networks between grain boundaries. Extensive conductive anomalies in the oceanic upper mantle are attributed to low degrees of partial melting of a carbonatitic melt and may extend to depths of 300 km.

Cartigny *et al*. (1998) studying the carbon isotope content of eclogitic diamonds from the Jwaneng pipe concluded that diamonds crystallized from carbonatitic mantle melts, and that differences between the $\delta^{13}C$ distribution of peridotitic and eclogitic diamonds is due to the presence or absence of olivine in the host rock. Cartigny (2005) notes conflicting ideas of whether the carbon source for diamonds is from mantle carbon or from crustal carbon recycled by subduction. Based on his stable isotope studies he concluded that conflicting evidence is reconciled if carbon is introduced into mantle eclogites or peridotites by a fluid. He cites evidence which show that diamonds in eclogites are confined to metasomatic veins, showing that carbon-bearing melts or fluids are involved in diamond crystallization. Highly mobile carbonatitic melt appears to be a reasonable agent. This idea is further supported by Jacob *et al*. (2000) in studies of polycrystalline diamonds, framesites, from the Orapa, Jwaneng, Premier, and Venutia pipes in South Africa. Based on mineral inclusions, trace elements and isotope studies, they concluded that a carbonatitic melt remobilized material stored for considerable time and interacted with a host eclogite to rapidly form framesites just prior to eruption.

Further to the association of diamonds and carbonatites, Djuraev and Divaev (1999) have identified diamonds in a melanocratic carbonatite in the Chagatai Complex, Uzbekistan. These are transitional forms between true kimberlites and carbonatites. Russian researchers have followed up with experimental investigations of diamonds from such melts (e.g. Litvin 2011). They have conducted field work of other carbonatites in an effort to develop exploration techniques. That work has resulted in the finding of micro diamonds in the Montaña Blanca-Milocho rare-metal type carbonatite, Canary Islands, Spain (Shumilova 2005).

Because carbonatites have their origins within the mantle there would be no reason that they also might be sources of diamonds, provided that their emplacement was rapid enough for the preservation of any diamonds that might become entrained in the magma. We believe that the evidence presented suggests that magmas from the Serra Negra and Salitre complexes were the probable sources for the diamonds of the Coromandel region. It seems probable that the diamonds were erupted early in the development of the volcanic edifice, before too great an enlargement of the feeder system. The gravity and magnetic data (Rugenski 2006) indicates that a large mafic body of 1,907 km^3 with roots of 30 – 50 km depth is present below the complex.

An important aspect is wind directions during the settlement of the ejecta from the atmosphere for the geographic distribution of this material. Nevertheless, there is no possibility to determine this (or these) direction(s). Moreover, as has been shown in the text, the eruption was not a unique event, but a sequence of events probably over a long time span. Therefore, such paleo-meteorological research is of little importance. We do not discard the possibility of other alkaline complexes as feeders for the Mata da Corda rocks; however, the geographic position of the Serra Negra and Salitre complexes, their deep roots and large size makes them favorable as the primary source.

CONCLUSIONS

The enigma concerning the surface source of the diamondiferous gravels south of Coromandel is, in part, resolved, since the authors do not want do exclude other possibilities with minor contributions. Nevertheless, the Capacete Formation rocks are scattered over a huge region in the Triângulo Mineiro, as one can observe on geologic maps (e.g. Heineck *et al*. 2004). The region includes the diamondiferous rivers Abaeté, Borrachudo and Indaiá too, as mentioned in the introduction, situated to the east of Coromandel. Geological peculiarities are similar as in the described area south of Coromandel. Thus, the pyroclastic and epiclastic rocks have a much larger distribution, limited not just to the area south of Coromandel. On the VEI scale (Volcanic Explosivity Index) they certainly belong to a source with category 8 (> 1,000 km^3 of tephra) and represent a major supervolcanic explosion event in Mesozoic/Cenozoic time.

Diamonds in this distribution region of the Capacete Formation are scattered over a huge area and, therefore, economically (apparently) of no interest. Most large diamonds over 100 ct came, as Barbosa (1991) wrote, from this epiclastic material. Nevertheless, if Barbosa *et al*. (1970, p. 100) observations corroborated by Svisero *et al*. (1981) concerning Romaria's grade are correct (0.12 – 0.2 ct/m^3), grades can locally be better than the described "cascalhos". If this grade is representative for certain localities, then the epiclastic diamondiferous rocks are, in some places, the consequence of enrichment processes during their redistribution and would be quite economic for a large scale operation, and could provide an enormous reserve.

Since mining activity is not a gambling activity, it should be left, at the moment, to the dreams of garimpeiros. Geologists should study these deposits in more detail, mainly the nature and processes that have been responsible for the formation of the epiclastic deposits — only after this research work it may be possible to invest in a large-scale enterprise.

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