Sri Lanka–Madagascar Gondwana Linkage: Evidence for a Pan-African Mineral Belt

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ABSTRACT

Sri Lanka occupies a unique geologic position in Gondwana. Recent age and isotopic data suggest that the high-grade basement rocks of Sri Lanka are more closely associated with the southeastern part of Madagascar than with the Archean granulites of southern and eastern parts of India. The occurrences of gem minerals and graphite in the centrally located Highland Complex of Sri Lanka can also be correlated with those of the Kerala Khondalite Belt (KKB) at the southern tip of India and of southeast Madagascar south of the Ranotsara Shear Zone. These geological and mineralogical features indicate the juxtaposition of Sri Lanka with Madagascar and also with the Lützow-Holm Bay area in Antarctica. The very close juxtaposition of Sri Lanka with Madagascar suggested here, which has hitherto been given only passing reference, implies that there exists a distinct mineralized belt running from Antarctica through the Highland Complex of Sri Lanka into Madagascar, Mozambique, Tanzania, and farther north. This mineral belt is clearly of Pan-African origin and is now considered to be an important geosuture associated with the main Mozambique Belt. The position of Sri Lanka in Gondwana is of particular significance because Sri Lanka acts as a bridge across the main East African and Antarctica crustal fragments.

Introduction

The supercontinent of Gondwana had been marked by collisional events between the component cratons of West Gondwana (Africa and South America) and East Gondwana (Australia, Antarctica, India, Sri Lanka, Madagascar), as well as by deformational events along the East Gondwana paleo-Pacific margin (Grunow et al. 1996). Within Gondwana, the Mozambique Belt (fig. 1) is of special importance because it is one of the largest orogens known. As reported by Jacobs et al. (1998), the closure of the "Mozambique Ocean" and the formation of the Mozambique Belt has been the subject of extensive studies (Shackleton 1993, 1996; Stern 1994; Grunow et al. 1996; Unrug 1996; Dalziel 1997).

The continuation of the Mozambique Belt southward across Africa and into East Antarctica has been the focus of attention of several researchers (Kriegsman 1993; Shiraishi et al. 1994; Rogers et al. 1995; Jacobs et al. 1998). Kriegsman (1993) studied in detail the geodynamic evolution of the Pan-African lower crust in Sri Lanka and compared the geology of Sri Lanka, South India, East Africa, and Madagascar. The position of Sri Lanka in Gondwana, though enigmatic, has evoked great interest in view of the island's remarkable geology and mineralogy, particularly in relation to its Gondwana neighbors (fig. 1). A proper understanding of Pan-African tectonics in East Gondwana therefore requires correlation of geologic features of South India, Sri Lanka, and Madagascar.

The German–Sri Lankan Consortium on the Crystalline Crust of Sri Lanka, under the International Geological Co-operation Programme Project 304 on Lower Crustal Processes (Kröner et al. 1991), has amassed a wealth of new geological information on Sri Lanka's high-grade metamorphic terrains, making them among the best studied of the East Gondwana fragments for their geology and isotopic characteristics. Special characteristics of Sri Lanka, South India, and Madagascar are the presence of nearly all the important high-grade metamorphic features, such as an abundance of

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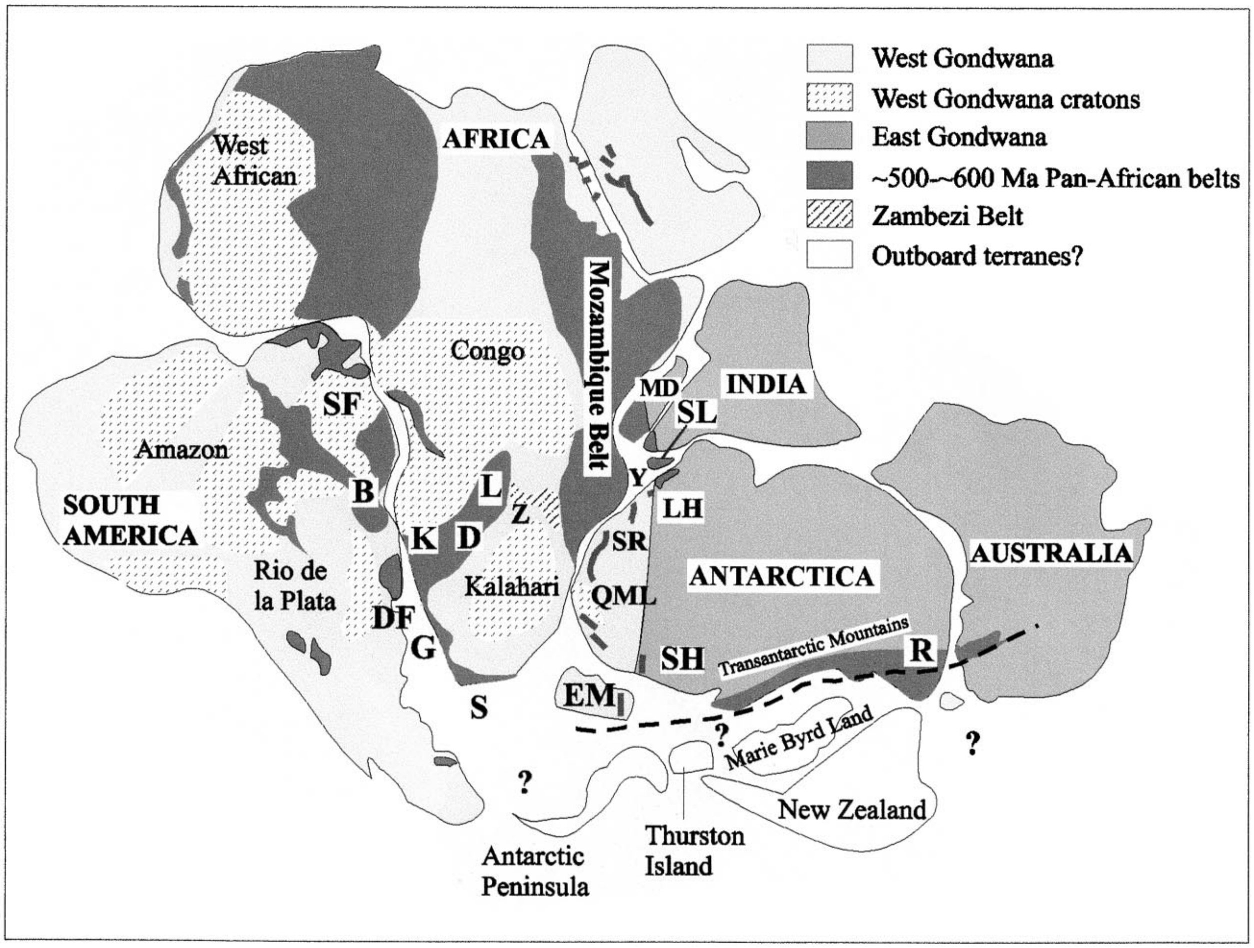

Figure 1. Gondwana assembly reconstruction showing location of Pan-African events (after Grunow et al. 1996). Older cratonic blocks of West Gondwana and possible outboard terrains. Pan-African belt: *B*, Brasiliano; *DF*, Dom Feliciano; *D*, Damara; *G*, Gariep belt; *K*, Kaoko belt; *L*, Lufilian arc; *LH*, Lützow-Holm Bay; *MD*, Madagascar; *Y*, Yamato mountains; *R*, Ross orogen; *S*, Saldanian belt; *SH*, Shackleton Range; *SL*, Sri Lanka; *SR*, Sor Rondane mountains; *Z*, Zambezi belt. Other features: *EM*, Ellsworth-Whitmore mountains; *QML*, Queen Maud Land; *SF*, São Francisco craton.

charnockites, a variety of amphibolite and granulite facies metamorphic rocks of igneous and sedimentary heritage, the special phenomenon of in situ charnockitization, the possibility of a tilted section of former lower-to-middle crust, and well-documented ages ranging from Archean to Early Paleozoic (Hofmann 1991; Raith et al. 1991). The similarities of geological, petrological and mineralogical features in Sri Lanka, South India, and Madagascar warrants further investigation into their interrelationships from the point of view of their Gondwana affinities. Several studies in Madagascar (Agrawal et al. 1992; Paquette et al. 1994; Milisenda and Henn 1996), in addition to those of Windley et al. (1994), Ackermand et al. (1989), and Nicollet (1985, 1986), have provided new information on the geology and mineralogy of Madagascar that enable a comparison between Sri Lanka and Madagascar to be made. The recent work of Sacks et al. (1997, 1998) and Rajesh et al. (1998) has brought new light onto the Pan-African orogenesis in South India with possible implications for deformation in Madagascar and Sri Lanka. New information on the mineral occurrences in South India and the affinities of these occurrences to the Sri Lankan mineral exposures (Radhika and Santosh 1995, 1996) enable a comparison of Sri Lanka, South India, and Madagascar on the basis of their mineral occurrences.

This article attempts to synthesize the new information concerning the Sri Lanka–Madagascar linkage and to put forward a more plausible suggestion concerning the position of Sri Lanka in Gondwana, hitherto neglected by many geologists on account of the earlier views that the Precambrian basement of Sri Lanka is an extension of the high-grade gneiss terrain of South India (Newton and Hansen 1986; Shackelton 1986; Katz 1989). It is the aim of this article to discuss the comparative mineralizations of Sri Lanka, South India, and Madagascar within the broad framework of the geology of the Mozambique Belt. The latter has already been studied extensively by several researchers and their studies are used to highlight the importance of the Sri Lanka–Madagascar linkage in Gondwana geology.

The General Geology of Sri Lanka

The geology of Sri Lanka is mainly that of high-grade metamorphic rocks in a Precambrian terrain. These rocks form three major lithotectonic units (fig. 2), namely, the Highland Complex, the Vijayan Complex, and the Wanni Complex. Among these, the Highland Complex is the largest unit and forms the backbone of the Precambrian rocks of Sri Lanka. Included in this unit are the supracrustal rocks of the former Highland Series (Group) and the Southwestern Group (Cooray 1962, 1984), together with a variety of igneous intrusions of predominantly granitoid composition that now occur as banded gneisses. The rocks comprising the Highland Complex are mainly of granulite facies metamorphites, predominantly varieties of granulites including charnockites, quartz-feldspar-garnet-sillimanite-graphite schists, quartzites, marbles, and calc-gneisses. On the basis of field and petrological evidences, Kröner et al. (1991) infer that a significant proportion of the rocks in the Highland Complex are of granitoid origin. Widespread arrested charnockite formation has been observed within this unit (Hansen et al. 1987). These rocks are dated at about 550 Ma (Baur et al. 1991).

The Vijayan Complex, lying to the east of the central Highland Complex (fig. 2), consists of biotite-hornblende gneisses and scattered bands of metasediments and charnockitic gneisses. Among the other prominent geological features of the Vijayan Complex are the small plutons of granites and acid charnockites near the east coast (Jayawardena and Carswell 1976) and the north-west-trending suite of dolerite dikes at Kallodai. Milisenda et al. (1988) and Milisenda (1991) have described the gneissose granitoids of the Vijayan Complex as having compositions ranging from tonalite to leucogranite. The Vijayan Complex is mostly of amphibolite-facies grade, and the fact that it has not been subjected to granulite facies metamorphism has been interpreted by Kröner et al. (1991) to mean that the charnockitic bodies within the Vijayan domain are klippen and/or unfolded or intersliced fragments of the Highland Complex. These are similar to the Kataragama klippe (fig. 2), of which the derivation from the latter complex has been established (Cooray 1978; Vitanage 1985).

The Wanni Complex consists of a suite of granitoid gneisses, charnockitic gneisses, and granites, along with a variety of amphibolite- to granulite-facies rocks such as metasediments of predominantly pelitic to semipelitic composition (Milisenda et al. 1991). Studies of detrital zircons from metapelites have shown that the Wanni Complex is younger than the Highland Complex, even though the boundary between these two lithotectonic units is still poorly defined.

The Geology of Madagascar

The Precambrian of Madagascar, as shown in figure 3 (Windley et al. 1994), is divided into two sectors by the north-west-trending sinistral Ranotsara Shear Zone, known to continue in the Mozambique belt, probably as the Surma Shear Zone (Windley et al. 1994). It has been suggested that the Ranotsara belt continues in southern India as the Achanakovil Shear Zone. On the basis of recent field data, however, Sacks et al. (1997) suggest that dextral shear along the Achanakovil Shear Belt is opposite to the sinistral shear reported for the Ranotsara Shear Zone in southern Madagascar; hence, these two shear zones cannot be correlated in reconstructions of this part of Gondwana.

The center of Madagascar is traversed by a 100-km wide, north-south-trending shear zone of possible Pan-African age transecting the Proterozoic and Archean basement (fig. 3). This high-grade zone consists mainly of granulites and amphibolite facies rocks, migmatites, conformable granite sheets, and granite plutons quite similar to those in Sri Lanka. The north-west-trending Ranotsara Shear Zone separates southern Madagascar, where paragneisses predominate, from central-northern Madagascar, which consists mainly of granitic orthogneisses.

Links with East Antarctica

The granulites and amphibolites in East Antarctica have been correlated with the Sri Lankan Precam-

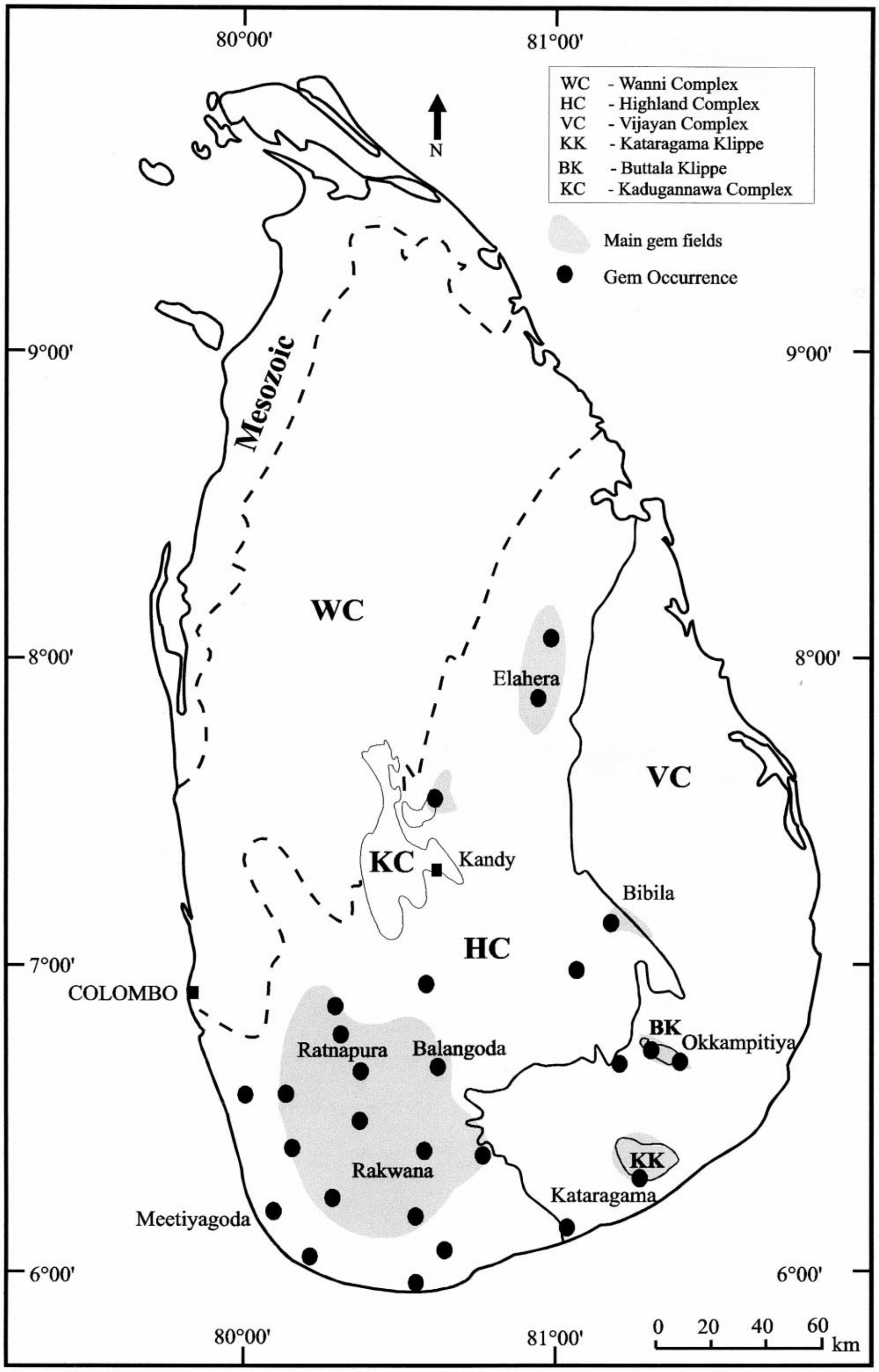

Figure 2. Simplified and generalized geological map of Sri Lanka showing major lithotectonic units (after Kröner et al. 1991). The dashed line gives only the proposed boundary.

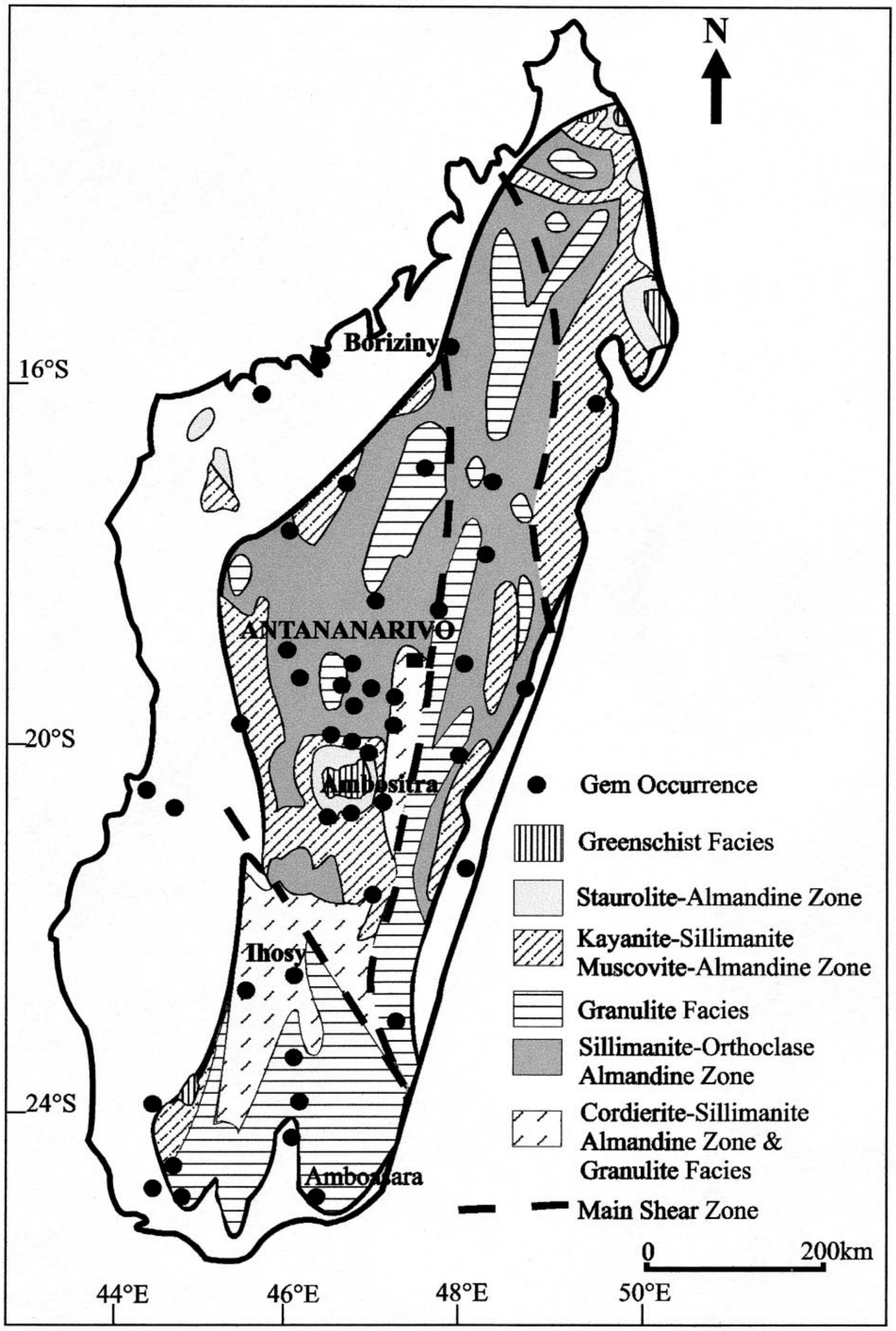

Figure 3. Map of the metamorphic zones and facies of the Precambrian of Madagascar (modified after Windley et al. 1994). Locations of gem deposits (after Chikayama 1989).

brian by several geologists (Katz 1974; Collerson and Sheraton 1986; Yoshida et al. 1992; Kriegsman 1993). The lithologies of the Skallen Group of the Lützow-Holm area of East Antarctica and the Highland Complex (highest pressure) of Sri Lanka are strikingly similar and show a complex composed of orthogneisses, metabasites, quartzites, metapelites, and marbles (Yoshida and Vitanage 1993).

Yoshida (1978) has shown that structures in the

Lützow-Holm Bay area show a similar tectonic evolution as the granulites of Sri Lanka. Yoshida et al. (1992) suggested a comparison of the Prince Olav Complex with the Wanni Complex of Sri Lanka and the Yamato-Belgica Complex with the Vijayan Complex.

The Sri Lanka–Madagascar Gondwana Linkage

Kröner (1991), on the basis of new age and isotopic data, suggested that the high-grade basement rocks of Sri Lanka were not linked to the Archean granulite domain of southern India but that they experienced their main structural and metamorphic development during the Pan-African event, about 950–550 Ma. The isotopic data reported by Kröner (1991) conclusively demonstrates that the high-grade metamorphic event in the Sri Lanka basement is of Late Proterozoic age and is therefore considerably younger than the ~2.5 Ga high-grade metamorphism of the Nilgiri Hills in the Dharwar Craton and adjacent terrains in southern India (Buhl et al. 1983; Peucat et al. 1989). It is now known that the granulites of the Eastern Ghats Belt of India, with which the high-grade rocks of Sri Lanka have also been correlated, are distinctly older than the Sri Lankan granulites (Kröner 1991). The work of Srikantappa et al. (1985) and Buhl et al. (1983) has also indicated that the charnockite formation in granitic gneisses south of the Palghat-Cauvery Shear Belt in southern Kerala, India, occurred at about 550 Ma. The above findings have indicated that a considerable and as yet undefined part of the high-grade basement in southern India is most likely part of the same crustal province as the basement of Sri Lanka (Kröner 1991).

This new view that the basement of Sri Lanka, the southern tip of India, and southeast Madagascar together formed part of a broad zone in the late Precambrian to early Paleozoic is also borne out by the recent work of Kriegsman (1993) and Grunow et al. (1996). Sacks et al. (1997) investigated the Tenmala Shear Zone, which forms the southwestern margin of the Achanakovil Shear Zone, one of several major Pan-African shear zones in South India. Because the Achanakovil belt also coincides with a major change in the aeromagnetic pattern (Reddi et al. 1988), Sacks et al. (1997) considered it likely that the Tenmala Shear Zone formed part of a significant crustal break that formed during Pan-African orogenesis.

The fact that the Ranotsara shear in the southeast of Madagascar is sinistral, in contrast to the dextral shear along the southwest of the Achanakovil Shear Zone, precludes these two units from being a continuation of each other; hence a correlation might be made between the Achanakovil Shear Zone and the north-trending, dextral shear belt in Madagascar north of the Ranotsara Shear Belt (Windley et al. 1994). Sacks et al. (1997), however, were criticized by Rajesh et al. (1998), who suggested sinistral movement exists in parts of the shear zone. Sacks et al. (1998) replied that their studies covered a wider area and that they preferred dextral shear along the Tenmala Shear Zone, even though it may be sinistral at certain minor locations. It could therefore be possible that the Ranotsara Shear Belt continues into the southwestern part of Sri Lanka, where rocks similar to those of the Trivandrum block are found. Further detailed work in the southwestern part of Sri Lanka is, however, necessary to confirm the structural continuity of the Ranotsara Belt in Sri Lanka.

Occurrence of a Pan-African Sri Lanka–Madagascar–Tanzania Gem Belt

The close geological correlation between Sri Lanka, the southern tip of India, and southeast Madagascar is further evidenced by the presence of a mineral belt that runs through Antarctica, Sri Lanka, Madagascar, Mozambique, and Tanzania. This mineral belt also passes through the southern tip of India in the Kerala Khondalite Belt.

Whereas Sri Lanka has been well known for over 2500 years for its wide variety of gem minerals, new gem discoveries are being made in Madagascar (Nicollet 1990; Milisenda and Henn 1996) and in Tanzania (Henn and Milisenda 1997). Among the gem minerals common to Sri Lanka and Madagascar are corundum, spinel, topaz, zircon, aquamarine, amethyst, gem varieties of quartz, and tourmaline. Figures 2, 3, and 4 illustrate the gem occurrences in Sri Lanka, Madagascar, and Tanzania. It is also of interest to note that gem minerals have been found in eastern Antarctica, confirming the presence of the mineral belt there (Grew and Manton 1979, 1986). As in the case of Tanzania and Madagascar, Sri Lanka has a wide verity of gem minerals, corundum, tourmaline, aquamarine, spinel, chrysoberyl, zircon, beryl, garnet, sphene, and topaz being prominent. The similarity of the geological features of these gem-bearing lithologies with those in Tanzania and Madagascar is clearly evident.

In southern Madagascar, granulite-grade rocks crop out over a large area. These are known to form part of an Archean crust that had experienced its main thermotectonic evolution during the pan-African event. These rocks mark the eastern limit of the Mozambique Belt regarded as a compression

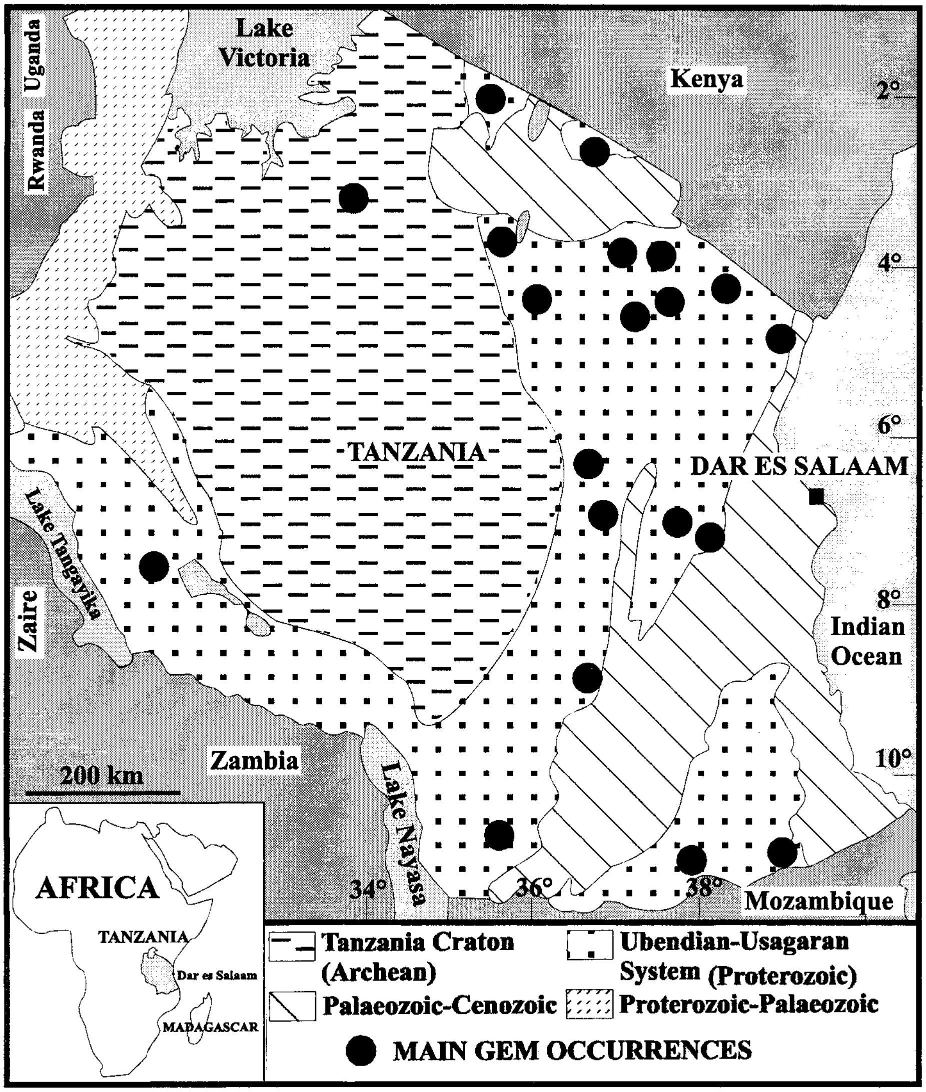

Figure 4. Simplified geological map of Tanzania showing the main gem occurrences (modified after Henn and Milisenda 1997).

structure resulting from a collision of East Gondwana (India-Antarctica-Australia) and West Gondwana (Africa–South America) at ~600 Ma (Kröner 1991; Milisenda 1991). In a recent article, Milisenda and Henn (1996) concluded that the Tanomaro Belt, in which new sapphire deposits have been located, closely resembles the supracrustal sequence of the Highland Complex of Sri Lanka (Milisenda et al. 1988, 1994) and which included Archean and Early Proterozoic rocks that had been extensively reworked in Pan-African times. They assigned the corundum formation to a Neoproterozoic age of ~600 Ma.

The continuation of the Mozambique Belt in Tanzania also yields spectacular gem occurrences (fig. 4). Among the gem minerals are blue and fancy-colored sapphires, color-changing sapphires, padparadschas, rubies, variously colored spinels, garnets such as rhodolite, hessonite, and color-changing types, chrysoberyls, including cat's-eyes, alexandrite and alexandrite cat's-eyes, various quartz and beryl varieties as well as tourmaline, zircon, kyanite, scapolite, peridot, and diamond (Henn and Milisenda 1997).

Geologically, these gem occurrences are located in the Tanzanian part of the Mozambique belt and are of Proterozoic age. The gem formation event is of Pan-African origin and has affected not only the entire eastern part of Africa and southern India but also Sri Lanka. The geological features associated with gem-mineral formation during the Pan-African episode are also evident in Sri Lanka (fig. 2). Dissanayake and Rupasinghe (1993), using the criteria of lithology and topography, stream drainage density, presence of alluvium, and the nature and abundance of heavy minerals, determined that approximately 20% of the land mass of Sri Lanka may be gem bearing. The most noteworthy feature of the gem occurrences of Sri Lanka is the fact that nearly all of them are found in the centrally located Highland Complex, clearly a continuation of the main gem belt that runs across Madagascar, Mozambique, and Tanzania and possibly eastward into Antarctica.

Evidence from Graphite Formations

Apart from the occurrence of gem minerals in the eastern part of the Pan-African Mozambique belt, graphite formations within this belt are also prominent. The continental fragments of Sri Lanka, South India, and Madagascar are particularly well known for their occurrence of high-quality graphite. Although some graphite occurrences have been reported in East Antarctica (Yoshida 1979), thick ice has presumably covered such graphite formations.

As shown in figure 5, the vein graphite deposits of Sri Lanka are mainly concentrated in the southwest sector (Dissanayake 1981). The graphite is extremely pure (>99%) and occurs in the form of fracture fillings. The graphite is found mostly within rocks of the granulite-facies grade.

In Madagascar, toward the south of the Ranotsara Shear Zone, several tectonic belts have been recognized that are made up of gneisses intruded by pegmatites. Among them is a 20-km-wide belt consisting of graphite-bearing hornblende-biotite gneisses that are part of the "System du Graphite" (Windley et al. 1994). Madagascar has one of the world's largest reserves of flaky graphite. The graphite deposits lie along a north-south axis across the island within the central and eastern parts of the mobile belt (fig. 5).

In the southern part of India, the Kerala Khondalite Belt (KKB), a large supracrustal sequence of metamorphosed pelitic and psammitic sediments, was studied by Chacko et al. (1987). Apart from the graphite occurrences in the Eastern Ghats, the KKB contains graphite deposits (fig. 5) associated with metasedimentary rocks of granulite and amphibolite facies (Radhika and Santosh 1995). Garnet sillimanite and garnet biotite gneisses belonging to the Khondalite suite of rocks (similar to that in Sri Lanka) constitute the most important source for graphite (Radhika et al. 1995).

It is evident that the presence of graphite deposits in southwest Sri Lanka, the southern tip of India, and southeast Madagascar supports the juxtaposition of these crustal fragments in a Gondwana reconstruction. The similarity of the distribution of graphite deposits and their occurrences in similar lithologies also support this view.

It appears probable that these graphite-bearing areas may have been part of a large Precambrian basin that had abundant primitive microorganisms (Radhika and Santosh 1995). These sources of carbon may well have been the precursors of the graphite that formed subsequent to subduction and high-grade metamorphism (Dissanayake 1981, 1994). The hypothesis that the Late Proterozoic Gondwana supercontinent was separated by an ocean extending from Antarctica and continued through Sri Lanka and southern Indian peninsular to Madagascar and possibly beyond is supported by the existence of the geological features mentioned above.

Position of Sri Lanka in the Mozambique Belt

Figure 6 illustrates a Pan-African mineralization zone in a possible reconstruction of the Gondwana setting, with Sri Lanka adjacent to Madagascar. This relatively new position of Sri Lanka in Gondwana has important implications because it acts as a bridge across East Antarctica and East Africa and as a small yet significant part of the Mozambique belt (fig. 6). The tectonic and metamorphic evolution of the Sri Lankan basement is explained within the framework of a major Pan-African continental collision event between West Gondwana and East Gondwana (Kröner 1980, 1991; Kriegsman 1993). A major implication of this view is that during the collision resulting in the formation of the Mozambique belt, one of its major suture zones became exposed in Sri Lanka in the form of Highland Complex. This suture zone in Sri Lanka shows characteristics of a mineralized belt (Munasinghe and Dissanayake 1982; Dissanayake 1985) with gem- and graphite-bearing formations. This mineral belt shows marked similarities in lithology and mineralogy to the KKB of South India, Madagascar, and Tanzania. The mineralization has now been dated as Pan-African, and the mineral belt runs across East Antarctica, Sri Lanka, Madagascar, Mozambique, Tanzania, and farther northward, confirming the important position of Sri Lanka in the context of Gondwana.

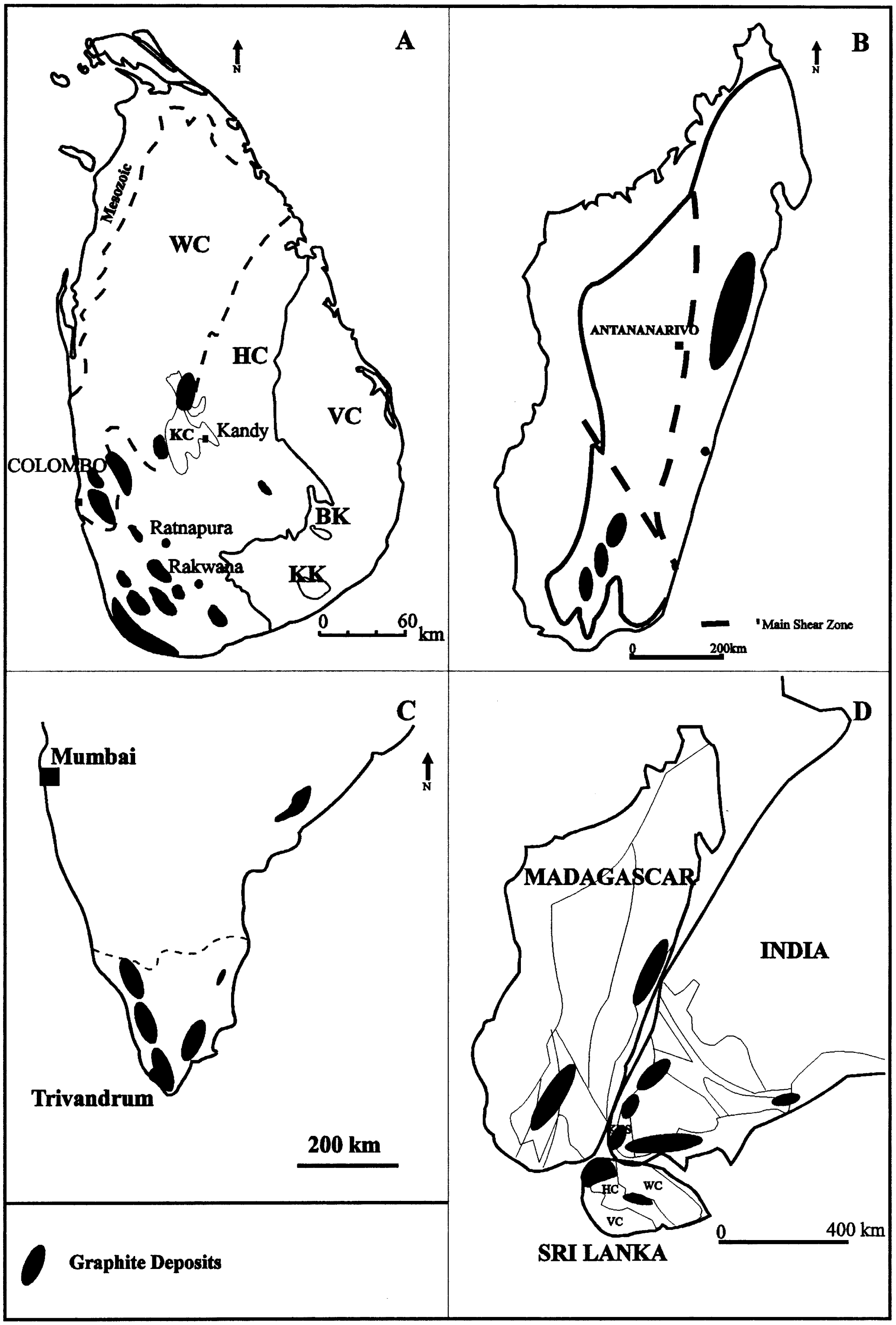

Figure 5. *A*, The main graphite occurrences in Sri Lanka (modified after Dissanayake 1994). *B*, Main graphite occurrences in Madagascar (modified after Radhika and Santosh 1995). *C*, Main graphite occurrences in South India (modified after Radhika and Santosh 1995). *D*, The graphite belt in East Gondwana.

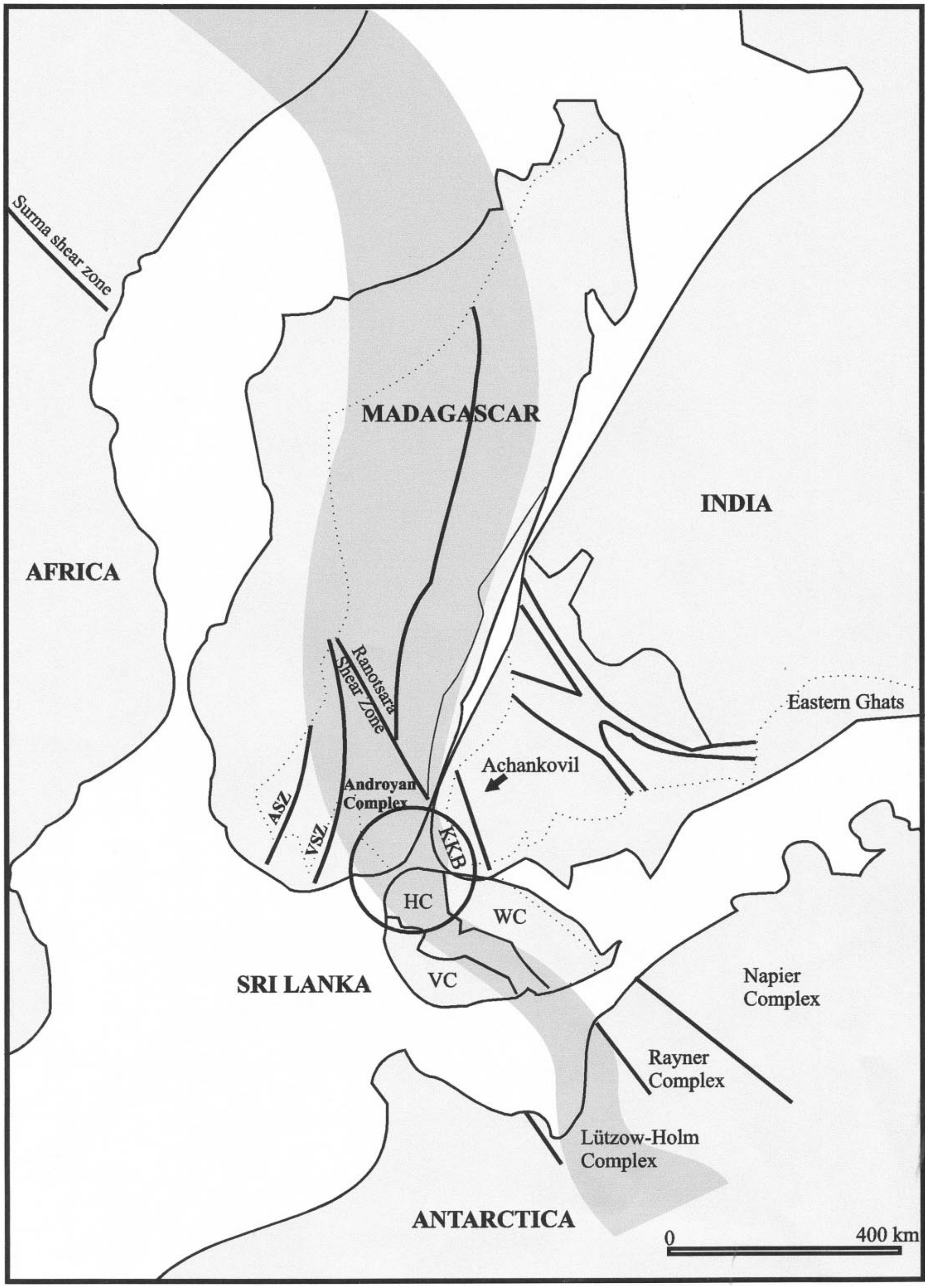

Figure 6. The new juxtaposition of Sri Lanka, the southern tip of India, and Madagascar (encircled) in Gondwana, as suggested by the authors. *ASZ*, Ampanihy Shear Zone; *VSZ*, Vorokafotra Shear Zone; *KKB*, Kerala Khondalite Belt; *HC*, Highland Complex; *WC*, Wanni Complex; *VC*, Vijayan Complex. The central shaded belt indicates the mineral belt within the geosuture.

Conclusion

In the final analysis, the comparison of the mineral occurrences, mainly gems and graphite in Sri Lanka, South India, and Madagascar, in this study indicates that the fit of Sri Lanka with Madagascar is far closer than hitherto postulated by other researchers, who had juxtaposed Sri Lanka mainly with southern India. This close fit of Sri Lanka with Madagascar has, therefore, important implications for the collision tectonics between East and West Gondwana.

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