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Origin of vein graphite in high-grade metamorphic terrains

Role of organic matter and sediment subduction

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Abstract. The role of CO_2 in the creation of a refractory base of granulite by metamorphism has received increasing attention by geologists investigating sub-crustal phenomena. A voluminous source of mantle-derived CO_2 has been postulated for the phenomenon of granulite formation. Recent studies on the granulite terrain of Sri Lanka has clearly shown that it is only an upper crustal section and that it had been subjected to a much smaller influx of CO_2 than hitherto envisaged. The close association of graphite with the granulites and the recent discovery of grain-boundary graphite in the lower crust implies graphite as a major source of CO_2. Recent reports on the discovery of alluvial diamonds within the granulite belt of the Highland Complex of Sri Lanka where graphite is abundant possibly indicates penetration of the graphite-diamond inversion line.

The origin of Archaean granulites has recently been the subject of much controversy and interesting debate. Theories on crustal evolution and high-grade metamorphism have been centered on Archaean granulitic terrains in many parts of the world (Windley 1977). Granulite terrains are often regarded as possible models for the deep crust (Newton and Hansen 1986), because granulites are H_2O-deficient and formed possibly at pressure ranges of 7–12 kbars (i.e. at a depth range of 25–40 km). The pyroxene-bearing granulites of granitic composition, termed charnockites, are abundant in many granulitic terrains and are thus extensively studied (Hansen et al. 1987; Pohl and Emmerman 1991). Many mechanisms for the large-scale removal of water during granulite metamorphism have been put forward (Wendlant 1981; Harris et al. 1982; Valley and O'Neil 1984; Srikantappa et al. 1985; Harris and Jackson 1991), and the role of CO_2 and the creation of a granulite front (Newton et al. 1980) is now being widely investigated. Carbon dioxide-rich and H_2O-poor fluid inclusions have been clearly observed in ancient high-grade rocks including charnockites (Touret 1971; Santosh and Yoshida 1991).

Even though an influx of CO_2 from the mantle along shear zones in the lower crust may well provide a plausible mechanism for the dehydration of amphibolite to granulite with accompanying large ion lithophile element removal to higher crustal levels, many problems still remain concerning the actual sources and location of the voluminous source of CO_2, and, if present in a deep crust–mantle region, the form and nature of such a carbon source.

An intriguing problem that could be linked to carbonic metamorphism is that of the origin of graphite in granulite terrains and also of diamonds in deep-seated high-pressure rock types (Boyd and Gurney 1986). Both require a ready source of carbon for their formation. Whereas the questions of the origin of graphite though still debated is much better understood, the process by which carbon is precipitated in the mantle in elemental form is not known to any degree of certainty (Cox 1978; Boyd and Gurney 1986).

The interrelationship between the occurrence of graphite and CO_2 and the deep crust has assumed greater importance recently as illustrated by the work of Frost et al. (1989) and Mareschal et al. (1992), on grain-boundary graphite as a cause of high electrical conductivity in the lower crust. Their observation that grain-boundary graphite may occur in many rocks in the lower crust enhances the importance of graphite as a source of carbon for the CO_2 that plays a significant role in the formation of granulites, bearing in mind the considerable amount of graphite present, particularly in Precambrian rocks (Windley 1977).

The close geological association of granulites including charnockites, graphite and various sources of carbon such as carbonate minerals and organic matter, encompasses interrelated geochemical phenomena that could be best studied using a model for carbon cycling under sub-crustal conditions. As shown by Nisbet and Kyzer (1988), such a model should necessarily consider the mapping of CO_2 pathways under deep crustal conditions, and the passage of biospheric carbon into deep crustal regions.

Sri Lanka provides an ideal case study for the following reasons.

1. Ninety percent of the island consists of metamorphic rocks of granulite and amphibolitic facies, with well-developed charnockites in a granulitic terrain.

2. The large-scale vein graphite, found confined to the granulite terrain is of extreme purity (~ 99%) and is ranked among the purest in the world. Disseminated graphite is also found confined to the same granulite terrain, though not in economic quantities.

3. The discovery of alluvial diamonds within the granulite belt (Gunaratne 1965) indicates penetration of the graphite–diamond inversion line and the existence of a possible mantle carbon source. Diamonds have been reported in the Balangoda and Polonnaruwa areas. It is the aim of this paper to discuss some aspects of the carbon cycle of the deeper crust and their relationships to the origin of lower crustal graphite and granulite formation.

The Precambrian granulite terrain of Sri Lanka

In a Priority Project aimed at studying the detailed geology, geochemistry, petrology and to a small extent geophysics in a major Precambrian granulite terrain, the Deutsche Forschungsgemeinschaft in 1985 selected Sri Lanka as the terrain of choice (Hofmann 1991). The reasons for this choice were the presence of nearly all of the important high-grade metamorphic features. This includes an abundance of 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, abundant structure and deformation, with age estimates ranging from Archaean to early Palaeozoic etc. (Fig. 1).

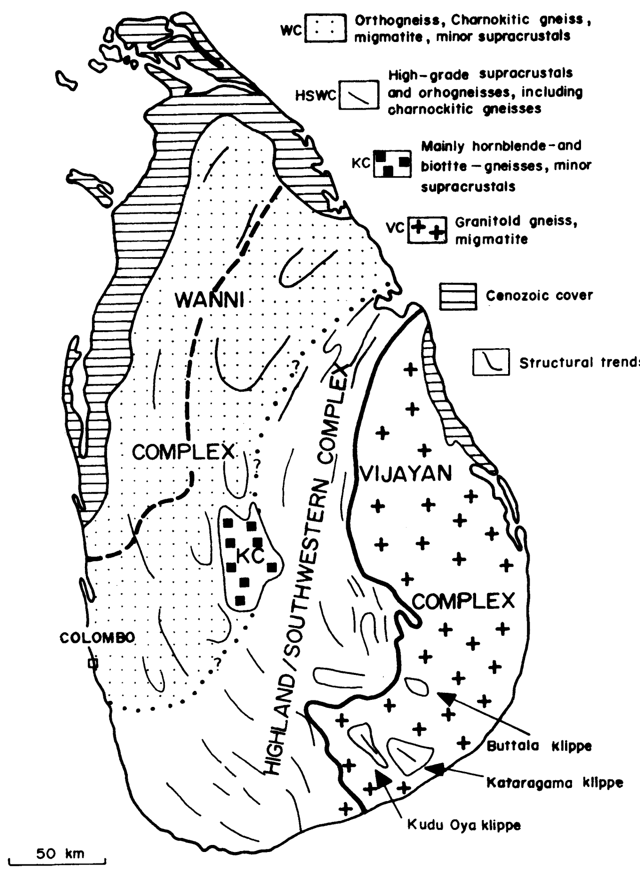

Fig. 1. Generalized geological map of Sri Lanka. *WC* Wanni Complex; *HSWC* Highland/South Western Complex; *KC* Kadugannawa Complex; *VC* Vijayan Complex (after Kröner et al. 1991)

The Highland/Southwestern Complex (HSWC)

The Highland/Southwestern Complex (HSWC) (Kröner et al. 1991) is the largest unit forming the backbone of the Precambrian rocks of Sri Lanka. Included in it are the supracrustal rocks of the former Highland Series (Group) and Southwestern Group (Cooray 1962, 1984) together with a variety of igneous intrusions of predominantly granitoid composition that now occur as banded gneisses. This is the granulite terrain of Sri Lanka, the prominent rocks present being varieties of charnockites, undifferentiated metasediments, quartz–feldspar, garnet–sillimanite–graphite–schists quartzites, marbles, calc-gneisses and granulites. Based on field and mineralogical information Kröner et al. (1991) infer that a significant proportion of the rocks in the Highland/Southwestern Complex (HSWC) are also of granitoid origin.

Widespread arrested charnockite formation has been observed in the Central Highland regions in the districts of Colombo, Kurunegala and Galle (Hansen et al. 1987).

The Vijayan Complex (VC)

The eastern Vijayan Complex consists of biotite/hornblende gneisses and scattered bands of metasediments and charnockitic gneisses. Small plutons of granites and acid charnockites also occur close to the east coast (Jayawardena and Carswell 1976). A prominent feature in the area is the NW-trending suite of dolerite dykes. Millisenda et al. (1991) have described the gneissose granitoids of the Vijayan Complex as having compositions ranging from tonalite to leucogranite. Kröner et al. (1991), commenting on the fact that the Vijayan rocks have not experienced granulite facies metamorphism, interpret the charnockitic bodies of the Vijayan domain as tectonic clippen and/or infolded or intersliced fragments of rocks of the Highland Southwestern Complex (HSWC) similar to the Kataragama Complex of established HSWC derivation.

The Wanni Complex

The rocks earlier termed Western Vijayan Complex have a poorly defined boundary with the HSWC. The rocks of the Wanni Complex consist of a suite of granitoid gneisses, charnockitic gneisses and granites.

Evolution of the Highland Basin

Munasinghe and Dissanayake (1982) and Dissanayake and Munasinghe (1984) suggested a subduction zone type of sedimentary environment for the basin of the present Highland Southwestern Complex (HSWC). They termed this basin the Highland Basin (Fig. 2A). The presence of siliceous and carbonate pelagic sediments, extensive igneous activity (basaltic volcanism), submarine and subaerial volcanoclastic debris all suggest a subduction zone type of sedimentary environment (Siever 1979). The petrochemistry of these rocks, indicative of igneous activity (Munasinghe and Dissanayake 1980; Dissanayake and Munasinghe 1984), also provides further evidence for subduction-related processes.

Recent work by Kröner (1991), Milisenda (1991) and Liew et al. (1991) have helped in the further development of such a model. Milisenda (1991) interpreted the Vijayan province as a continental margin intruded by subduction-associated I-type plutons. The juxtaposition of the juvenile Vijayan province and the ancient Highland Southwestern Complex (HSWC) was interpreted as the result of a post-Vijayan collision event that resulted in the uplift of deep crustal rocks. These observations are in conformity with the model of Munasinghe and Dissanayake (1982) that the Sri Lankan high-grade units constitute a collision-related granulite terrain. Considering the Nd-isotope data and the presence of ultramafic bodies along