FELDSPAR AND VEIN QUARTZ MINERALIZATION IN SRI LANKA: A POSSIBLE POST METAMORPHIC MID-PALEOZOIC PEGMATITIC-PNEUMATOLITIC ACTIVITY

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ABSTRACT

High grade metamorphic rocks ranging from upper amphibolite facies to granulite facies cover more than 90% of the island of Sri Lanka. The rest is mainly sedimentary and sometimes contain valuable mineral resources such as Miocene limestone of the northwest. Even though the grade of metamorphism is high, a significant primary and secondary mineralization occurs throughout the island. Exposed mainly in the crystalline rocks of the Highland (HC), Wanni (WC) and Vijayan Complexes are few multitudes of pegmatites contain industrial minerals such as feldspar, quartz and mica with occasional occurrence of other minerals of beryl, corundum, topaz and tourmaline.

The primary mineralization is mainly fracture controlled vein type or shear zone mineralization. Graphite is the major economic mineral that occurs in large quantities in a fracture controlled vein system in Sri Lanka. The mineralization in the Kandy-Matale area includes quartz veins with high purity SiO_2 and pegmatites bearing K-feldspar, fluorite, muscovite and gem minerals such as tourmaline, topaz, beryl etc. Quartz of gem-quality occurs in vugs and fissures of the country rock. Late stage ductile and shear fractures are commonly filled with disseminated sulphides.

The pegmatites, quartz veins and the fracture and shear-controlled mineralization in the Kandy-Matale area can be attributed to an intensive pegmatitic and pneumatolitic stage of magmatic activity during a series of relatively young ductile and brittle deformation stages. Considering the temperature and pressure depicted by the depth of formation of pegmatites, vein quartz deposits and changes such as skarnification and other types of alteration zones presently exposed on the surface have been emplaced during mid Paleozoic at least 250 Ma after the pan-African, 610 - 550 Ma peak metamorphism.

Keywords: pegmatites, vein quartz, feldspar, gem minerals

INTRODUCTION

The ancient mining for minerals in Sri Lanka can be dated back to more than 2000 years including extraction of metals such as iron and copper. Use of clay to make various objects, pottery, pipes, ornamental ware etc. has a lengthier history. Even though the rocks of Sri Lanka have been metamorphosed up to high granulite grade a large number of mineral deposits occur in the country, out of which several deposits of economic importance are being commercially exploited. The types of deposits that are being mined at present include graphite, phosphate, feldspar, quartz (both vein quartz and silica sand), gemstones, clay, limestone and mineral sands. Figure1 is a generalized map showing the occurrences of important mineral deposits and the geological subdivisions of Sri Lanka. The annual mine output of some important minerals recorded within the period between 1995 and 1999 are as follows: Kaolin16,000 - 20,000 tonnes, ball clay 12,000 - 24,000 tonnes, feldspar 22,000 - 26,000 tonnes, vein quartz 10,000 to 21,000 tonnes, silica sands 25,000 to 37,000 tonnes, limestone 620,000 - 90,000 tonnes, apatite 30,000 - 37,000 tonnes, graphite 5,000 - 6,000 tonnes, mica 2,000 - 5,000 tonnes and mineral sands 40,000 - 80,000 tonnes (Sri Lanka Minerals Year Book, 2000).

Within the crystalline rocks of the country (Figure 2) occurs a great number of commercially viable non-metallic mineralization, which include graphite, phosphate, vein quartz and pegmatites with simple mineralogy of feldspar, quartz and mica, occasionally containing gem minerals such as beryl, chrysoberyl, konerupine, corundum, topaz, tourmaline and moonstone, and metallic mineral deposits such as iron ore. In the sedimentary areas, valuable industrial mineral resources are the Miocene limestone, clays and mineral sands. In the sediments of central, south and south-western parts of the island, the most important types of mineral deposits are the gem deposits that has brought highest income of mineral export of the country amounting to Rs.195 billion - Rs.325 billion within the same period indicated above (Lankathilake, 2001).

Out of the intrusive bodies of economic importance, the most important ones are the vast microcline bodies in the Rattota-Matale area and vein quartz bodies around Kandy (e.g. Galaha) and other places (Figure 2). Pegmatites containing muscovite occur in many parts of the country. Some of which with economic quantities and phlogophite occurs in marble around Kandy (e.g. Digana) and other places associated also with serpentinite. Mining of mica continues from 1970s and at present mining is carried out in Talagoda, Madumana, Pallekale, Talatu-oya, Badulla, Maskeliya, Madugoda, Udumulla, Naula, Haldummulla, Mailapitiya, Kebithigollewa, and Madampe areas, the importanit types being muscovite and phlogophite. (Sri Lanka Minerals year book, 2000).

Feldspar and vein quartz are mined for porcelain and other industries. Vein quartz which is a valuable raw material is exported without value addition. Moonstone deposits at Meetiayagoda in the south western part of the country occur as inclusions in kaolin deposits that have been derived from the decomposition of moonstone bearing pegmatites and granites in the area. Fluorite deposits occur at Kaikawala near Rattota, Matale and some occurrences at Gatambe (Coomaraswamy, 1905).

Magnetite deposits of several kinds, some of which are of economic importance, have been discovered at Panirendawa, Wilagedara, Deltota (Herath, 1995), Buttala, (Senaratne, *et al.*, 2001), Galgamuwa and Passara (Cooray, 1984). A magnetite-chalcopyrite deposit was found at Seruwila and hydrated iron-oxide deposits in the south and southwestern part of the country.

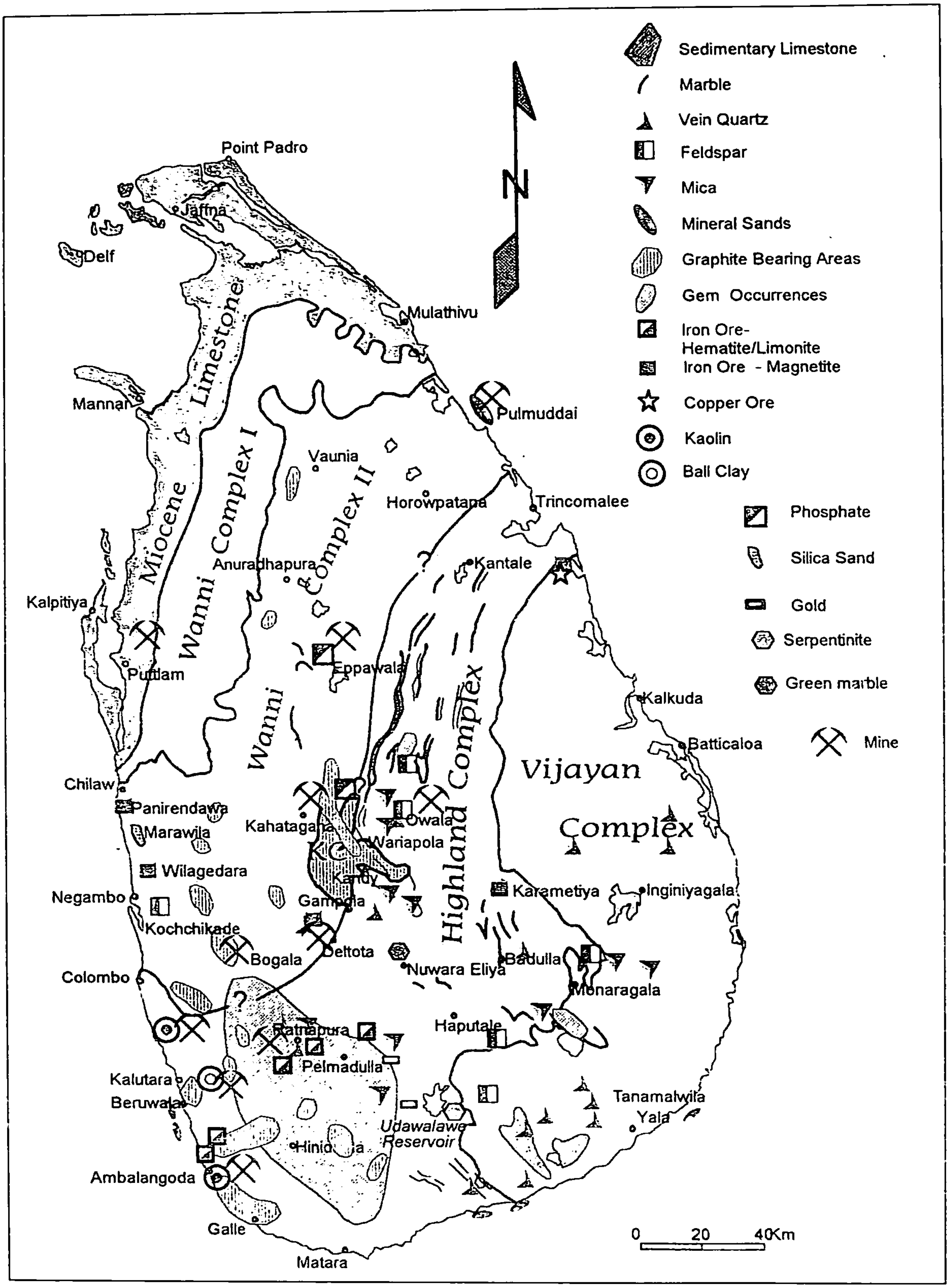
A number of granites and granitoid rocks of various sizes are found in Sri Lanka (Figure 2) including granitic bodies at Tonigala, Galgamuwa, Ambagaspitiya, Arangala, Haragama, Gallodai and Medavachchiya. Although they commonly exhibit intrusive nature (Katz, 1972; Abeysinghe, 1987; Mathavan and Hettiarachchi, 1989), some authors have interpreted the origin of some of them as conversion of pelitic gneisses to granitic bodies by postmetamorphic metasomatism (Perera, 1983). Abeysinghe (1987) indicates that the granites of Sri Lanka are fractionated S-type and are products of a single source. It is important to note that there have been several magmatic events up to the intensive Pan-African (or Pan-Gondwana) magmatic activity that influenced most of the Gondwana fragments including Sri Lanka.

Geological Setting

The crystalline Precambrian metamorphic rocks which have been subdivided into three major subdivisions, Highland Complex (HC), Vijayan Complex (VC) and Wanni Complex (WC), (Cooray, 1994) covers more than 90% of the island of Sri Lanka and the rest is mainly Jurassic and Miocene sedimentary rocks (Figure 2).

The rocks of the HC are generally metamorphosed to granulite facies and both VC and WC are metamorphosed to upper amphibolite facies. Granulite grade khondalite-bearing metasediments, migmatites and granitoid gneisses (Cooray, 1978; Vitanage, 1985) and charnockites form the HC, while orthogneisses and migmatites of amphibolite facies complexes form both the WC and the VC. Patches of charnockitization of the "arrested" stage, known also as incipient charnockites, occur mainly in the HC more towards the southwestern part.

Some fine examples of these can be seen in Digana near Kandy and at Kurunegala (Figure 1). Charnockitization is present along the fractures and sometimes the original banded features are still preserved in the charnockitzed part. In the plate tectonic model introduced by Munasinghe and Dissanayake (1982) for the formation of Sri Lankan rock sequences of granulite grade, the boundary between the HC and the VC has been interpreted as a mineralized belt.


Sedimentary Limestone
Marble
Vein Quartz
Feldspar
Mica
Mineral Sands
Graphite Bearing Areas
Gem Occurrences
Iron Ore-
Hematite/Limonite
Iron Ore - Magnetite
Copper Ore
Kaolin
Ball Clay
Phosphate
Silica Sand
Gold
Serpentinite
Green marble
Mine
N
Point Padro
Jaffna
Delf
Mulathivu
Mannar
Miocene Limestone
Wanni Complex I
Wanni Complex II
Wanni
Pulmuddai
Vaunia
Horowpatana
Trincomalee
Anuradhapura
Kantale
Kalpitiya
Puttlam
Eppawala
Highland Complex
Kalkuda
Batticaloa
Vijayan
Complex
Chilaw
Panirendawa
Marawila
Kahatagaha
Owala
Wariapola
Wilagedara
Kandy
Karametiya
Inginiyagala
Negambo
Gampola
Kochchikade
Bogala
Deltota
Nuwara Eliya
Badulla
Colombo
Monaragala
Haputale
Ratnapura
Pelmadulla
Kalutara
Beruwala
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Yala
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Reservoir
Hiniduma
Ambalangoda
Galle
Matara
0 20 40Km

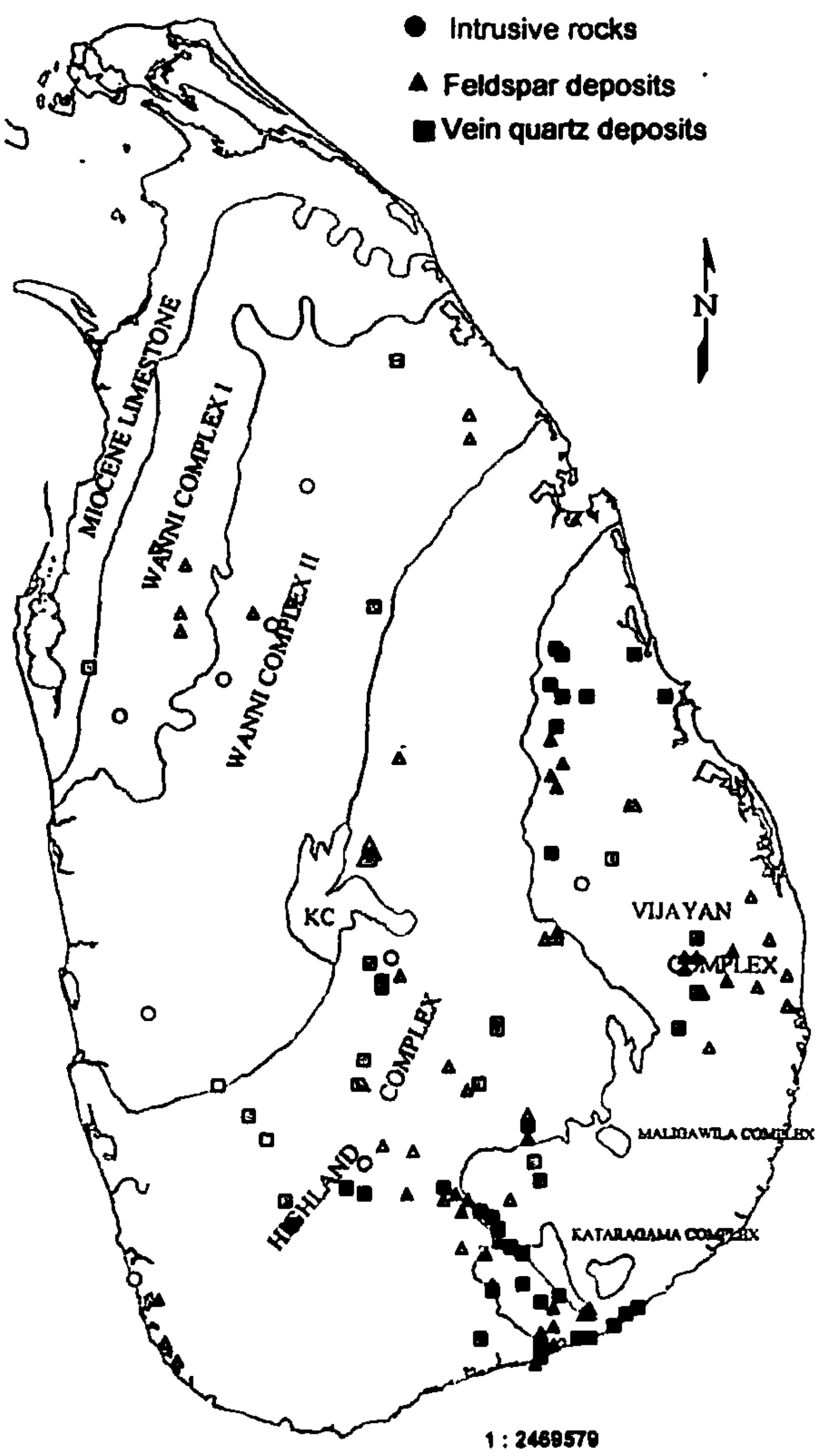
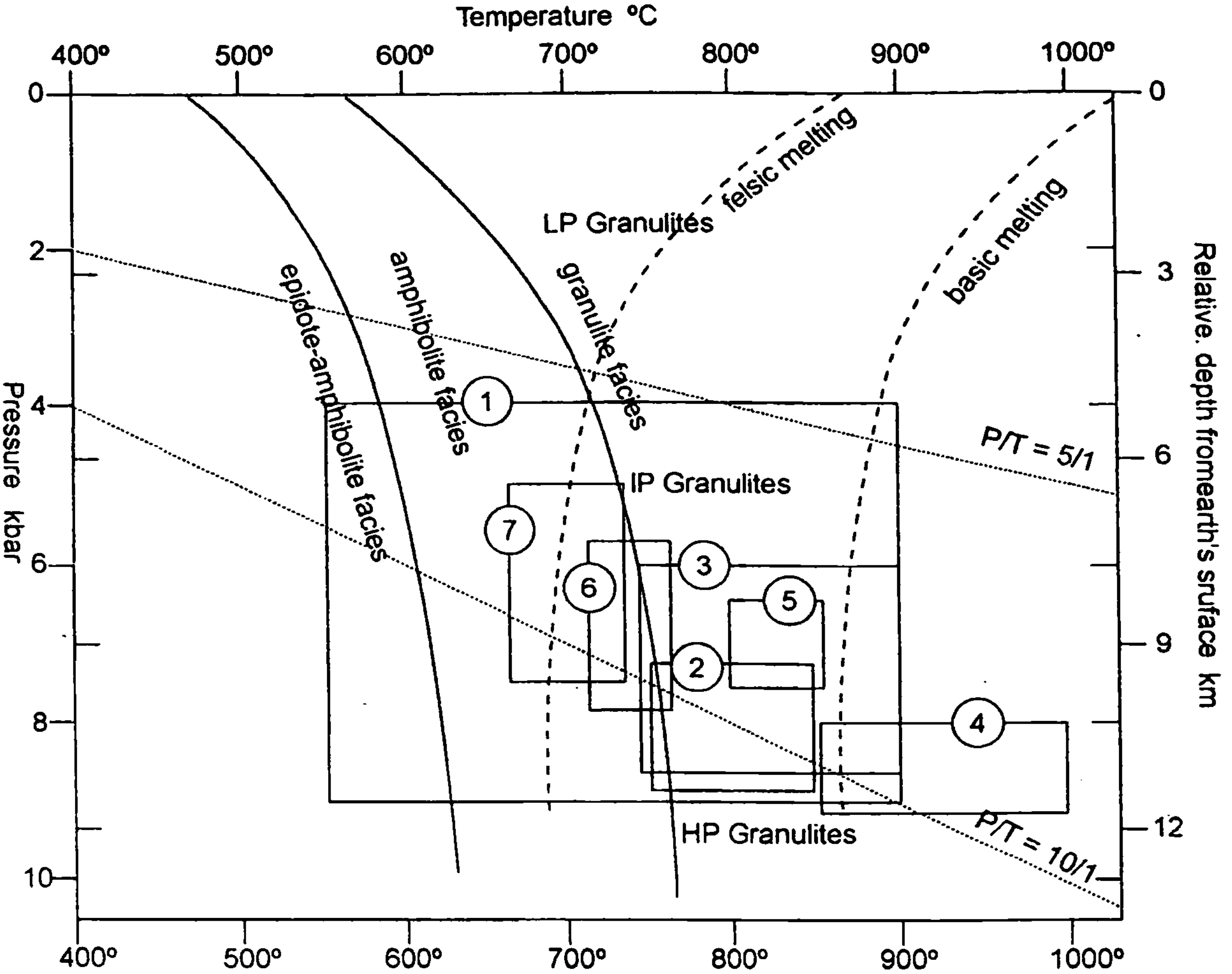


Figure 2: *Feldspar and vein quartz deposits of Sri Lanka*

They also postulate that the intense deformation resulted in large and sometimes tight folded features which in turn gave rise to fissures later filled by various types of multi component fluids. For the peak metamorphism of Sri Lankan rocks the pressure and temperature ranges calculated has a range depending on the locality, for example 5.5 - 7.5 kbar pressure range and about 650°-750°C temperature (Prame, 1987; Jayawardena and Carswell, 1976) and around 8.2-9.3 kbar and 860° - 980°C for sapphirine granullites of the HC (Osanai *et al.*, 1989) (Figure 3).

It should be noted that the pressure-temperature ranges calculated are not uniform throughout the crystalline complexes and they commonly exhibit different stages of metamorphism including later retrograde imprints such as the presence of cordierite bearing rocks and metasomatized zones.

Since 1987, the age of the high grade metamorphic events has been repeatedly revised: 1100 Ma (Kröner *et al.*,1991),720-650 Ma (Kröner, 1990), 611-550 Ma (Baur, *et al.*,1991; Hözl *et al.*, 1991) out of which 611-550 Ma event has been accepted as the peak metamorphism (Baur, *et al.*, 1991; Hözl *et al.*, 1991, Kröner *et al.*,1991), however, ages of the actual granulitic grade metamorphism is questionable (Perera, 1994).



1. Schenk et al, 1991 2. Schumacher et al, 1990 3. Bohlen, 1987 4. Osanai et al, 1989
5. Faulhaber and Raith, 1990 6. Sandiford et al, 1988 7. Jayawardena and Carswell, 1976

Figure 3: Significant granitoid rocks other than pegmatites of Sri Lanka

Hapuarachchi (1995), recognizing 13 metamorphic events named from M1 to M13 placed the peak metamorphic events from M10 to M13, i.e. the last two metamorphic events, in the different lithological subdivisions HC, VC and WC. He also suggests a skarn type intense metasomatic origin caused by high fluorine bearing fluids in connection with the Eppawala granite which was intruded around 550 Ma for the Eppawala (Figure 1) apatite deposit which also lies in close proximity to Tonigala and Galgamua granites (Hapuarachchi, 1995/1996) which have intruded around 552-556 Ma (Hözl *et al.*, 1994) and all these have been related to a major Pan-African magmatic activity. However, as shown clearly by its crosscutting nature, the host rock of Eppawala apatite mineralization can be identified as a post metamorphic intrusive carbonatite as confirmed by some other authors (Silva and Siriwardena, 1988), Weerakoon, 1999). It is also suggested that the Eppawala carbonatite is apparently affected only by the last deformational phase which took place approximately 560-550 Ma ago, therefore, its emplacement age should be between 610 - 550 Ma (Weerakoon, 1999), most probably around 550 Ma (Weerakoon, *et. al.*, 2000).

Intrusive Granites and Granitoid Rocks of Sri Lanka

The commonest intrusive rocks of granitic composition in Sri Lanka are granites, pegmatites and other granitoid rocks that occur in the form of plutons, sill like bodies and dykes (Cooray, 1984). The largest and the most known of these is the Tonigala (Figure 2) granite in the northwest of the island which has two sub parallel units, one with about 24km length and the other about 15km and the width ranging from 1km to about 3km. They are vertical or steeply dipping with boundaries parallel to the foliation of the surrounding rocks. Many other pink granitic sheet-like intrsions and pegmatites are also common in the area. In the southwestern part of the country, relatively small granitic bodies occur at Ambagaspitiya, Ruwanwella, Loluwa and Arangala. The Ambagaspitiya granite (south of Veyangoda) which shows a circular plan view, covers an area of about $40km^2$ with average diameter of about 7km. This rock is less uniform in composition having some gneissic patches within it and several other granite outcrops of smaller scale occurring around it.

The Arangala granite (Figure 2) seems to be circular pluton with an average diameter of about 2km intruded into the surrounding rocks. This is a coarse grained hornblende granite with hornblende crystals with more than 10cm in length and also contains purplish brown crystals of zircon. The Balangoda (Figure 2) zircon bearing syenitic intrusions, which were earlier called zircon granites, containing a large amount of zircon crystals are exposed on the surface as detached segments lying in a line of about ½ km with the striking feature of presence of large greyish and purplish brown zircon crystals up to 4cm in length (Nawaratne, 1974). The rock is exposed again about 2km from Balangoda on the Balangoda - Ratnapura road. Zircon granites have also been found in Beruwala and Loluwa (Cooray, 1984).

Numerous pegmatites throughout the island cross-cut the Precambrian rocks which commonly display a simple mineralogy consisting of pink feldspar, quartz and mica. Some of these deposits specially those in the Matale-Kandy area, form extensive commercial scale deposits of feldspar and mica. They are also commonly associated with vein quartz. The economic pegmatites of the Owala estate near Rattota contain huge deposits of fluorite as inclusions in the form of vertical to sub-vertical pipe like bodies (Figure 4), large blocks quartz and large books of biotite (Figure 5). White and pale-grey vein-like granitoid bodies, some parallel to the foliation and some cross cutting, occur within the arena gneisses in the Kandy area are probably of two generations. The cross cutting veins appear to be later generation linked with the incipient charnockitization (Almond, 1991). Perera (1983), showing conformable sheets of "pink granite" in the bases of arena gneiss sequences, suggests that they are metamorphosed arkosic sedimentary rocks, however, Almond (1991) suggests the possibility of them being metamorphosed rhyolitic pyroclastics, possibly ignimbrites of a volcano sedimentary association and this view explains also the igneous zircon morphology noted by Kröner et al, (1986). Some allanite bearing pegmatites occur at Alutpola and granitic pegmatites are present in the southwest (Cooray, 1984). Large bodies of vein quartz occur throughout the country with exceptionally large deposits like in the Galaha area near Kandy (Figure 1).

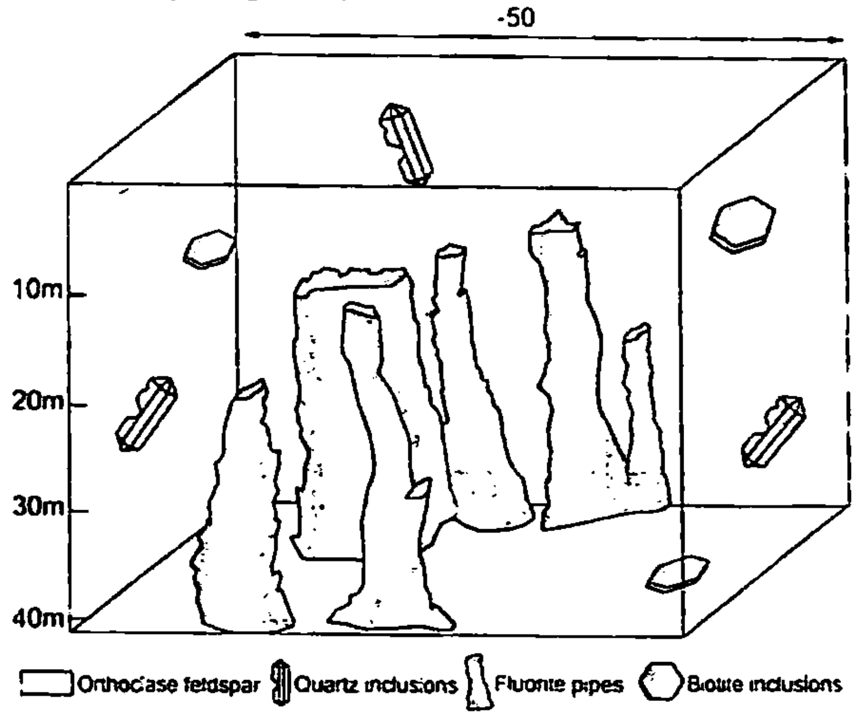


Figure 4: Vertical to sub-vertical pipe like bodies where huge deposits of fluorite occur (in Owala – Rattota)

Mineralization in the Matale-Kandy Area

Several major mineralizations occur in the Matale and surrounding area. Among them are the K-feldspar and vein quartz deposits in the Owala Estate in Kaikawala near Rattota, muscovite deposits in Kaikawala, the fluorite deposits in Kaikawala and the topaz deposits at Polwatte near Rattota. Occasionally large crystals of aquamarine (a gem variety of beryl) have been found in the Polwatta area.

The sizes of the pegmatites vary widely from small ones to extremely large deposits and the largest deposits which occur at Kaikawala are made of K-feldspar with minor inclusions of quartz, fluorite and biotite. All of the minerals occur in in-situ deposits, but corundum, topaz and occasionally baquamairine which have been derived apparently from pegmatites are recovered from eluvial and alluvial accumulations. The fluorite within and around the Kaikawala pegmatite (Figure 6), the K-feldspar deposit, occur in the form of several vertical and sub-vertical pipe-like bodies with oval to irregular cross sections (Figure 4).

Fluorite has developed as replacement mineralization due to invasion of high fluorine containing residual magmatic fluids into the pegmatite, subsequently. In the Kandy area several minor mineralizations such as chalcopyrite, pyrite, pyrrhotite, phlogophite, spinel in Digana and large crystals and massive beryl at Getambe are found. It is interesting to note that amazonstone (green microcline) occurs at Kaikawala in significant amounts (Figure 7) indicating addition of Cr. Phlogophite veins in Digana form various folded patterns within the marble. Marble has inclusions of basic rocks which appear like longitudinal blocks and large lumps of pyrite and chalcopyrite.

Age of Emplacement of Granitic Bodies in Sri Lanka

Out of the pegmatites of various scales that occur in all three crystalline sub-divisions of Precambrian metamorphic rocks mainly as cross cutting features, the largest pegmatites have been resulted as end products of magmatic processes and some of the others, mainly un-economic pegmatietes, by partial melting during high grade metamorphic activity.

Only a little work has been carried out on the emplacement ages of granites and granitoid rocks of Sri Lanka. Cordani and Cooray (1989) have evaluated Rb-Sr ages for several granites and granitoid rocks which include a leucogranite at Ganewalpola, granites at Haragama, near Gallodai (north of Weragantota), near Madawachchiya, and at Arangala and, a charnockitic pegmatite at Yatagalawatte (Figure 3). The granite at Haragama, near Kandy, belongs to the HC and has given the Rb-Sr age 966±32Ma. The Arangala granite and the Yatagalawatte charnockitic pegmatite belong to the southwestern part of the HC (earlier South West Group) and have shown ages 1560±68Ma and 1051±43Ma respectively.

The granite near Madavachchiya belongs to the WC and has given Rb-Sr age of 921±125Ma and the granite near Gallodai falls into the VC and has given the emplacement age of 930±42Ma. The ages of Ganewalpola, Haragama, Gallodai and Madavachchiya show somewhat similar emplacement ages of around 1050 - 920Ma which also coincide with age of the Tonigala granite (Crawford and Oliver, 1969), 985±30 Ma (Cooray, 1971). Using new U-Pb data, Hözl et al, have invalidated the above age for the Tonigala granite and shown that it was formed around 552-556 Ma ago synchronously with the Galgamuwa granite.

These ages can be attributed to the Vijayan orogeny. The Arangala granite is pre-Vijayan in age (Cordani and Cooray 1989). The Ambagaspitiya granite-syenite, one of the largest of such formations has been dated to around 1109 - 1118 Ma by Crawford and Oliver, (1969).

(Kröner and Jäckel, 1994) with mostly calc-alkaline, I-type granitoids, suggesting and Andian-type active plate margin in the WC at this time (Prame and Pohl, 1994). See Figure 2 for the locations of these granitoid rocks.

DISCUSSION AND CONCLUSIONS

The Precambrian basement rocks of Sri Lanka consist of metamorphosed rock series up to granulite facies mainly in the HC and to amphibolite facies mainly in the WC and VC with some granulite grade rocks in the southern WC. For these rocks as shown on Figure 8, Schenk *et al.* (1991), calculated the pressure range to be about 4 - 9 kbars at respective depths of 15 - 30 km at a temperature range of 550° - 900°C which is in a much broader range than some others, e.g. Schumacher *et al.* (1990); Osanai *et al.* (1989); Sandiford, (1988), for the peak metamorphism that took place around 550 - 600 Ma. The HC of Sri Lanka forms a part of the Pan-African metamorphic belt (Kröner, 1991).

The zircon ages suggest two important plutonic episodes by the emplacement of tonalitic to granitic plutons (now mangerites to charnockites) in the WC around 1000-1100 Ma (Kröner *et al.*, 1994b) which testifies widespread granitoid magmatism and around 750-790 Ma.

Figure 5: Photograph showing a part of the Kaikawala deposit with biotite inclusions

Figure 6: Massive block of beryl from Getambe quarry near Kandy

Figure 7: Fluorite occurrence in the K-feldspar deposit at Kaikawala

The rocks of granitic composition and granitic appearance apparently have been formed at least in three clearly defined time periods in Sri Lanka and other Gondwana fragments. These three time periods, 1100 Ma, 750-790 Ma and 550- 500 Ma, are related to intensive magmatic activities evidenced by the Gondwana fragments, India, Madagascar, Africa and Sri Lanka (Satish Kumar and Santosh, 1994). On the formation of rocks of granitic appearance in Sri Lanka several views prevail, which include, the metamorphism of felsic rocks of a volcano sedimentary formation (Almond and Gunatilake, 2001), S-type granites of the products of a single source (Abeysinghe, 1987) and post-tectonic metasomatism (Perera, 1983, Mathavan and Hettiarachchi, 1989, Kehelpannala, 1998).

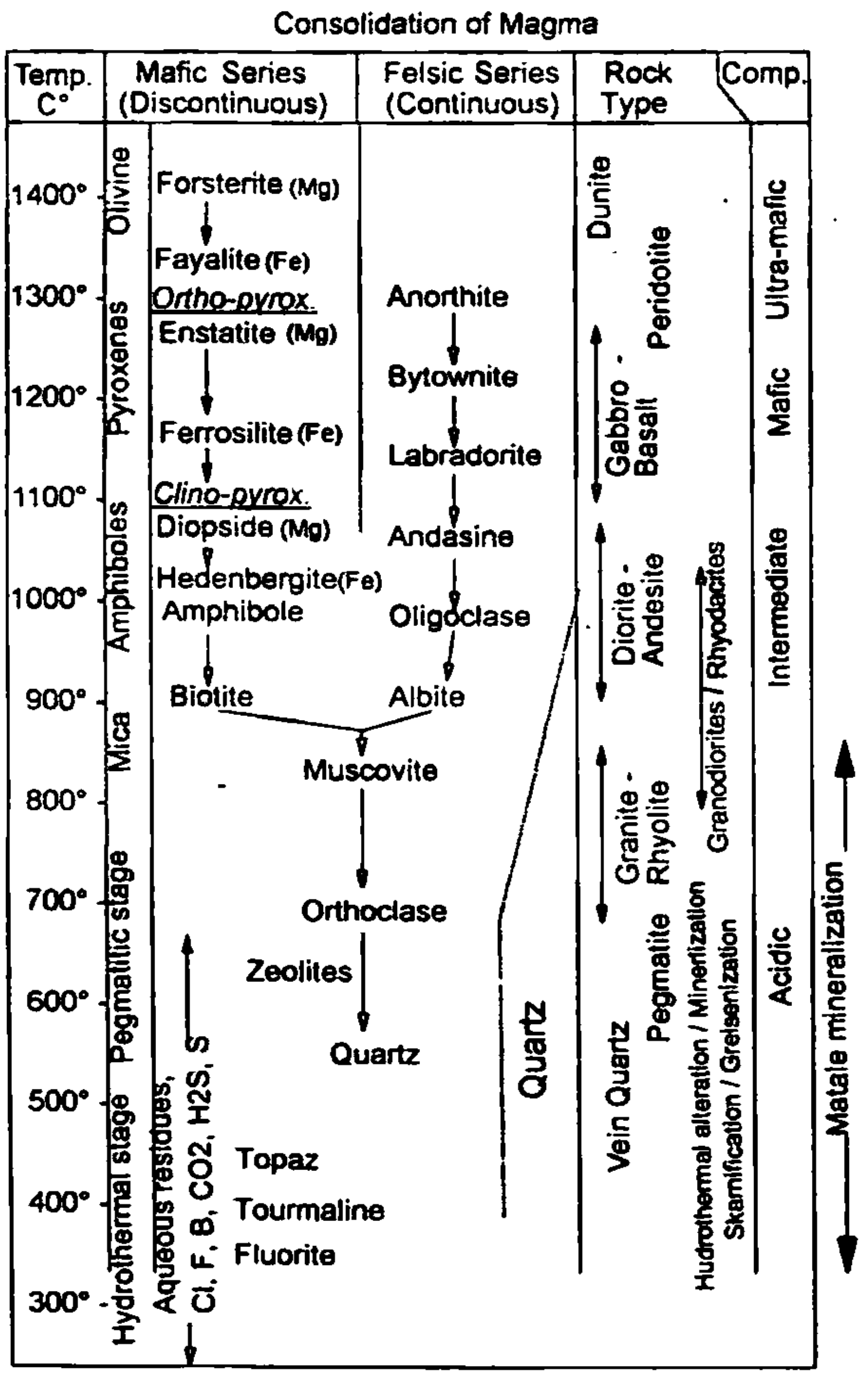


Figure 8: Pressure temperature diagram for the metamorphic rocks of Sri Lanka

The Tonigala and Galgamuwa granites are large felsic intrusive rocks that have intruded around 552-556 Ma (Hözl *et al.*, 1994) which is an Pan-African (Pan-African orogeny around 850 - 550 Ma (Kröner, 1980; Shackelton, 1986). On the origin of the Tonigala granite, Cooray (1971) explains that was formed by granitization of granodioritic to trondjhemitic rocks by widespread potassium metasomatis or microclinization, which was last major episode in plutonic history of the area. He also describes that certain features of the Tonigala granite resembles the syn-kynamatic granites and certain other features late-kinamatic granites comparable with similar events in Finnland and India.

The Ambagaspitiya granite-looking rocks of quartz deficient syenite to monzonite composition have been formed by high-temperature potassium-metsomatism on post-tectonic magmatic protoliths of granitic to granodioritic composition (Mathavan and Hettiarachchi, 1989).

Kehelpannala (1998) argues that the Ambasgaspitya granite looking rocks are more or less isotropic, have not undergone deformation and metamorphism and are the products of post-metamorphic metasomatism by externally derived K-rich fluids acted on once highly deformed and metamorphosed orhogneisses of the area. These metasomatic events including formation of incipient charnockites are post or syn D4 deformation and metamorphism that took place around 550-600 Ma. Development of certain other mineralizations such as gold, mainly in the Walawe Ganga region, are also in the discordant sulphide and quartz veins generated in relation to the latest ductile and brittle, D4, deformational structures (Nawaratne and Wijeratnе, 1995a and 1995b). Such mineralizations in the brittle D4 deformational structures including the fissure filled type graphite mineralization are synchronous or post-date the incipient charnockitization.

The local charnockitization took place at low-pressure conditions of CO_2 infiltration at shallow to intermediate depths and is distinct from the regional granulite facies metamorphism which took place at the bottom of the crust. Hapuarachchi (1995) explains that the skarn type intense metasomatic origin of the Eppawala apatite deposit triggered by high fluorine bearing fluids emanated from the Eppawala granite intruded around 550 Ma which lies in close proximity to Galgamua and Tonigala granites wich intruded synchronously. This also suggests that intense magmatic activity continued even after 550Ma which has produced huge amount of pegmatitic-pneumatolotic fluids.
Almond and Gunatilaka (2001) in connection with the formation of multispecies gemstone provinces

in the Gondwana continents, show that anatectic melts and related low density (gas-like) fluids could have reacted vigorously with the hot country-rocks of contrasting composition, producing skarns such as diopside, spinel, phlogophite, calcite and garnet rich skarn at Nawalapitiya and contaminated melts. They also suggest that the Pan-African thermal event continued even 50Ma after the peak metamorphism marked the most important period of surging temperature which led to the enhancement of multi-species gemstones in Sri Lanka, especially along the zones of former suturing in the heartland of the super continent. In these skarn associations, spinel and phlogophite are the extreme products of desilication (Almond and Gunatilaka, 2001). Corundum bearing skarns in Bakamuna and Elahera (Silva and Siriwardena, 1988) were formed by magmatic fluids (Silva, 1976), which is also evident in the marbles at Digana.

In India, the Eastern Ghats Granulite Belt (EGGB), the Periyar-Madurai Granulite Belt (PMGB) and Trivandrum Granulite Belt (TGB) belong to the Proterozoic, which can be correlated with Sri Lankan Proterozoic rocks of the HC. The late Precambrian- early Paleozoic of South India is marked with an episode of emplacement of a number of alkali granites and syenites associated with transcrustal fault systems (Santosh and Drury, 1988; Santosh and Masuda, 1991). One of the major intrusions, the Kalpatta granite of southern India which has intruded into the surrounding gneisses and charnockites has been dated to 765 Ma (Odom, 1982).

The granite has been intruded as a coarse to medium grained body with the microcline-albite-quartz-biotite assemblage, containing euhedral sphene as the major accessory mineral (Nair *et al.*, 1983). There are two types of pegmatites that cross-cut the granite body, one of which has simple mineralogy consisting of feldspar, quartz, biotite and accessory sulphides and the other has complex mineralogy with a well defined zoning with feldspar rich outer zone and quartz and fluorite rich inner zone (Satish Kumar and Santosh, 1994). In the second type, fluorite occurs both as purple and colourless varieties. Based on petrological and fluid inclusions studies, the emplacement of the Kalpatta granite and the cross cutting fluorite bearing pegmatites in southern India has been interpreted as consequences of the major Pan-African magmatic event (Satish Kumar and Santosh, 1994).

For the TGB of southern India, in which the rock types are more closely related to Sri Lankan HC rocks, three distinct metamorphic grades have been proposed; (M1) regional high grade metamorphism followed by incipient charnockitization and formation of garnet-bearing metasomatic rocks at contact between basic granulites and gneisses (540-600Ma), (M2) middle temperature retrograde stage: formation of secondary cordierite, change in composition at the contacts of cordierite and garnet (530 Ma) and (M3) low temperature retrograde stage: change in composition at the contacts of cordierite and garnet, biotite and garnet, crystallization of chlorite, amphibole (440-470 Ma) (Fonarev *et al.*, 2000). Santosh (1992) shows that the CO2 rich fluid activity took place as a younger Pan-African ca. 500-550 Ma forming charnockitic alteration in southern India and Sri Lanka. Incipient charnockitization to the north of Moyar shear zone in India took place around 2600 Ma in Late-Archean and to the south of Palghat-Cauvery shear zone in Kerala and Tamil Nadu around 550 Ma which is considered a Pan-African event can be directly correlated with the incipient charnockite formation in the HC in Sri Lanka (Harris and Jackson, 1991).

The metamorphic zoning in southern Madagascar is around 590-500Ma (Pan-African) and the main structural trends are wholly NS and EW in the granulite terraines. The high grade metamorphism in southern Madagascar took place around 556-560 Ma, similar to the HC of Sri Lanka, but ages of late Archean (ca. 2510-2550Ma) and paleo-Proterozoic (ca. 2330-1710Ma) are also observed, showing high geochronological heterogeneity of the high grade basement (Kröner *et al.*, 1999). Geochronological (U-Th-Pb) estimates on monazite intrusions have given ages with systematically lower ages for earlier tectono-metamorphic events giving 590-530 Ma and the later structural events such as major ductile shear zones giving ages around 530-500Ma. The major occurrences of widespread pegmatites in Tanzania and in Sri Lanka, which have not been studied with great details, could have some relationship to a major magmatic event.

All the above are indicative of several stages of metamorphism and deformation with the marked last stages of the processes being around 550Ma in all the Gondwana fragments with widespread thermal event at the same period of time. The 550Ma thermal event is clearly connected to the emplacement of a great number of extremely large granitic intrusions in the Gondwana fragments, especially in southern Madagascar, southern India and Sri Lanka.

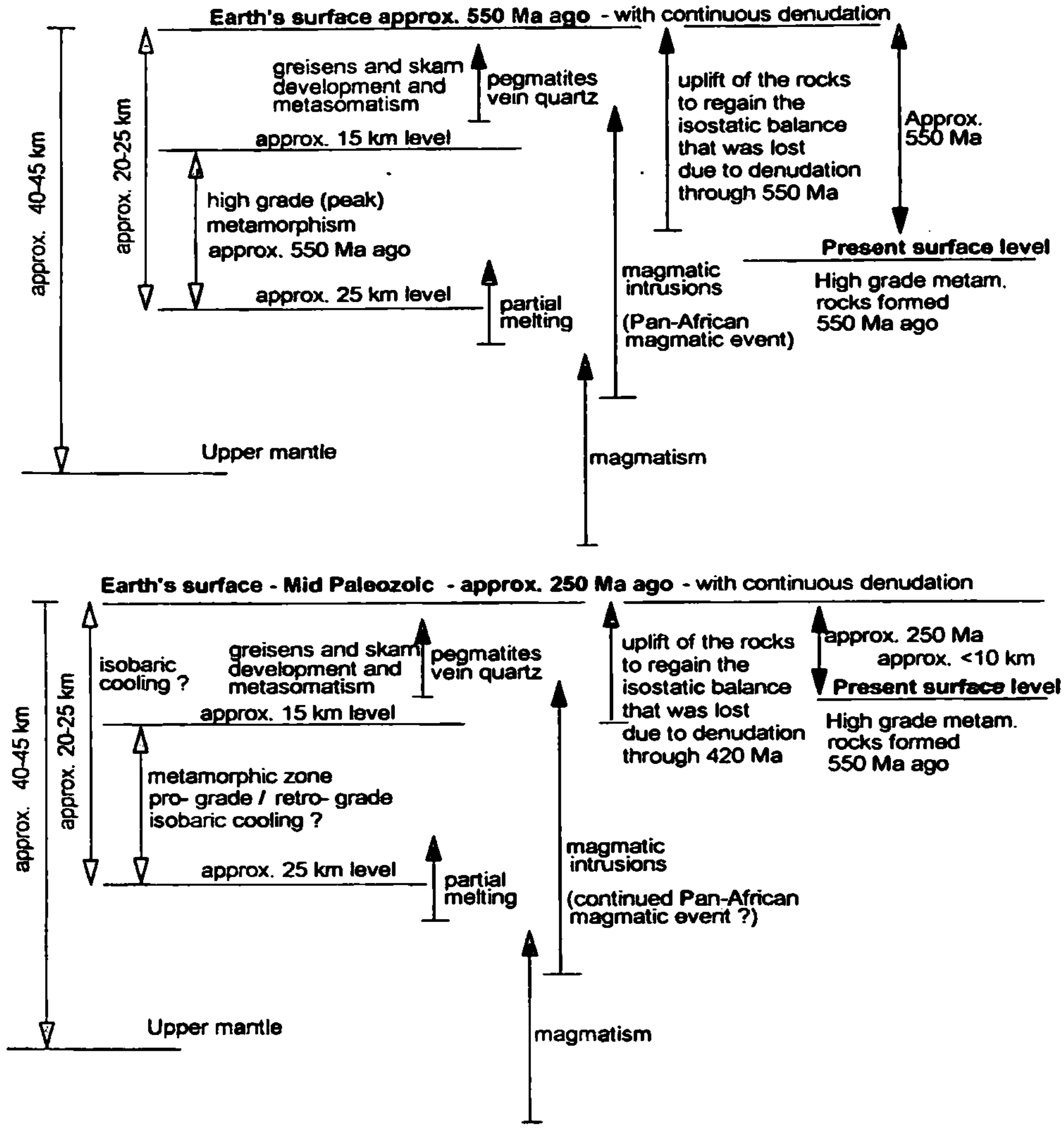


Figure 9: Exhumation and relative age gaps for the rocks of the Highland Complex

Various types of metasomatism including the alteration or the secondary development of the Ambagaspitya granite of Sri Lanka (Mathavan, 1989, Kehelpannala, 1997, Perera, 1983), development of mineralized skarns at various places in Sri Lanka, (Silva and Siriwardena, 1988, Almond and Gunatilake, 2001) including the well known metasomatized marble with skarnification at Rupaha and the formation of fluorine bearing apatite at Eppwala, Sri Lanka with huge influx of fluorine (Hapuarachchi, 1995, 1996) indicate that a vast amount of fluids have been produced during the thermal event and related magmatic activity. Formation of extremely large number of pegmatites as crosscutting bodies within the granites and the county rocks is a result of the development of huge amounts of pegmatitic-pneumatolitic fluids which formed the pegmatite and vein quartz deposits of commercial scale in Sri Lanka by this felsic magmatic event as its end product of magma solidification (Figure 8).

The estimated depth of the peak metamorphic events of granulite facies rocks in Sri Lanka is somewhere around 18-25 km with temperatures ranging up to 800° C and pressures of up to 20kbar during 600 - 550 Ma period. Skarnification, greisenization and many other types of alterations of country rocks during development of epigenetic mineral deposits and similarly formation of large pegmatites take place at low to medium depths in the earth's crust normally up to about 7 km with somewhat lower temperatures. The skarns, pegmatites, vein quartz and other hypothermal or mesothermal products in Sri Lanka, therefore, have been formed by the action of pegmatitic-pneumatolitic and hydrothermal fluids at the end phases of the magmatic consolidation at these depths and their exposure on the surface as seen today is due to the weathering and erosion of the overlying rocks up to 10 kilometres. A denudation rate of 10 - 100m per million year period has been estimated for the tropical climatic regions such as Sri Lanka (Saunders and Young, 1983) and the average denudation rate required for the exhumation of the rocks formed approximately at 20 km depth 550 million years ago within the HC can generally be placed around 45m per million year, which closely match the rates of Saunders and Young (1983).

Even though the rates of denudation may vary with time, depending on climatic conditions, at the above average rate of denudation in the HC rocks, the time required for exhumation of the rocks which were at 10km depth, will be somewhere around 200 - 250 million years. Studies on the actual exhumation history of the Sri Lankan formations are lacking, but the depths of the peak metamorphism and the depths of emplacement of the pegmatitic and vein quartz deposits and formation of skarns should show a large time gap. Alteration of the rocks around epigenetic mineralizations, widespread skarnification and development of commercial scale K-feldspar and vein quartz deposits in Sri Lanka, which are exposed on the surface today therefore, have taken place at much shallower depths than the high grade metamorphic rocks formed 600-550 Ma ago.

Therefore, these secondary formations within the granulite complexes such as the intrusive bodies of K-feldspar and their secondary inclusive formations of large fluorite bodies like in Kaikawala, that are exposed on the surface at present, has been caused by an intensive pegmatitic-pneumatolitic activity in Sri Lanka. Based on the calculations of gradual denudation, this has taken place in mid to late Paleozoic time that is around 250-300 million years after the Pan-African (600-550Ma) (Figure 9) peak metamorphic event. It should be noted that the rate of denudation and related up-warping in order to regain the isostatic balance is varying along a NNW-SSE axis with a maximum up-warping rate in the Highlands as shown by Vitanage, 1972.

Whether these pegmatitic-pneumatolitic and hydrothermal fluids that formed the mineralization in Sri Lanka was a result of continued thermal event of the Pan-African age into another 200 million years or a later magmatic event in the Paleozoic should be established by further work.

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