*Journal of Geological Society of Sri Lanka Vol. 17 (2015), 101-112*
*J.W. Herath Felicitation Volume*

# REVIEW ON NEW U-Pb AND Lu-Hf ISOTOPE SYSTEMATICS OF METAMORPHOSED MAGMATIC ROCKS: IMPLICATIONS FOR MULTIPLE MAGMATISM, SOURCE CHARACTERISTICS AND CRUST FORMATION BENEATH SRI LANKA

S.P.K. MALAVIARACHCHI

*Department of Geology, Faculty of Science, University of Peradeniya, Sri Lanka*
*e-mail: malavi@pdn.ac.lk*

## ABSTRACT

Numerous geological studies on Sri Lanka in the last three decades have provided data to evidence for tectonic amalgamation of its crustal units namely, Highland Complex (HC), Wanni Complex (WC), Vijayan Complex (VC) and Kadugannawa Complex (KC) during the assembly of Gondwana. These data are very recently supplemented with high resolution Lu-Hf and U-Pb isotope systematics on metamorphosed rocks of igneous origin, providing a better view of tectono-magmatic scenarios for the Sri Lankan basement. The garnetiferrous charnockites of the HC give the oldest Hf-crustal model age of ~3.5 Ga and highly negative εHf values (upto -30) inferring contribution of older subducting sediments and/or crustal components. This observation is well consistent with Nd-model ages previously discovered from other lithologies in the HC. The variable εHf of zircon from negative to positive values of dioritic to granodioritic gneisses indicate the involvement of both juvenile mantle components and old continental materials in the generation of the arc-related magmatic suite of the WC and KC. The meta igneous rocks of the VC have positive εHf data supporting entirely a juvenile origin. These new evidence suggest both the WC and the VC were coeval magmatic arcs during late Mesoproterozoic to early Neoproterozoic (ca. 1000-1100 Ma) whereas the HC represent a collisional suture during the late Neoproterozoic to Cambrian incorporating sediments and crustal fragments of the WC-VC arcs derived from melting of older continental fragments and/or subducted sediments (ages up to 3200 Ma). This suggests that the Sri Lankan terrains were juxtaposed at an active continental margin setting during the late Neoproterozoic to Cambrian collisional event (ca. 500-600 Ma) of the Gondwana metamorphosing the entire basement.

*Key words: Geochronology, Zircon, Highland Complex, Gondwana*

## INTRODUCTION

Unraveling geological history of a highly metamorphosed and deformed terrain like Sri Lanka is challenging unless petrological and structural geological studies are supplemented by high quality geochemical and geochronological data.

Recently, geochronochemical analytical techniques have been developed at a rapid pace globally (Dickin, 2005) and such uplifted technical knowledge in the fields of geochemistry and geochronology has enabled pathways to critical evaluation of existing data and compare with new, more recent data in order to reconcile geological evolution of a certain terrain. The Concordia upper intercept age of a zircon represents the time since it has been crystallized from a magma source, usually taken to equal the time of intrusion of an igneous body and hence generally accepted that U–Pb zircon geochronology is the most precise and accurate method for determining the time of igneous rock formation (e.g. Dickin, 2005). A model age, as the name implies, is model dependent, and is therefore only an estimate of age. However, the model age approach has the advantage that U–Pb dating method lacks, which is its ability to estimate the original age of formation of a crustal segment. However, U–Pb dating can provide a lower limit on the crustal formation age by dating younger plutonism, while Nd and Hf model ages can provide an upper limit on the formation age of a crustal segment (e.g. McNutt and Dickin, 2012).

The Sri Lankan Precambrian is one of the high-grade terrains with enormous international interest in all aspects of geology due to its pivotal position within the east Gondwana Supercontinent. This has made the island subjected to numerous studies by many experts during the last few decades (e.g. Meert, 2003 and references therein). These studies particularly after Milisenda et al., (1988) have presented various scenarios and models to understand tectonic amalgamation of so called 'crustal units' of Sri Lanka during the Gondwana assembly.

As presented in Kehelpannala (2004) mainly based on data of Kehelpannala (1997) and Kroner et al., (2003) two collisions have been suggested, for amalgamation history Sri Lankan crustal units. Ideally, if two collisions were there, two separate orogens with different ages along the collisional margins (e.g. HC-WC and HC-VC) should have occurred. In fact there are no field evidence to support such two separate collisional events, however, only the HC-VC collision is clearly evidenced in the field. This reality is overlooked by many studies sihmply with the notion that the WC-HC collisional evidences are totally 'obscured' by high-grade metamorphism and strong retrogression (e.g. Kroner et al. 1991, 2003, 2013; Wilbold et al. 2004). However, Kehelpannala (1997, 2004) suggested that a part of the HC-WC collision could be marked by crustal shear zone (e.g. Digana), which is generally considered as the boundary between the HC and KC (e.g. Cooray, 1994). Further, 'lack of sufficient geochronology data' is another reason for previous authors (e.g. Kroner et al. 2003, 2013; Kehelpannala, 2004) for placing the two complexes of 'unknown or exotic' origin. Nevertheless, unlike the last one or two decades recently Sri Lanka has a sufficient data set on petrology, geochemistry, structural geology and geochronology to conclude its tectono-magmatic evolution without many assumptions.

The majority of previous U-Pb geochronological studies in Sri Lanka incorporated conventional techniques for zircon analysis including zircon evaporation and dissolution by thermal ionization (TIMS) and only few studies incorporated SHRIMP dating (e.g. Kroner et al. 1987; Kroner and Williams, 1993). These conventional techniques have major drawbacks due to its failure to obtain 'core-rim' ages. Therefore, if a zircon with an old core metamorphosed producing a young rim, the overall age derived from conventional technique will be meaningless giving a 'mixed' age. The recent studies discussed in this paper present results of U-Pb and Lu-Hf isotope systematics from insitu analysis of core-rim zones of zircons at high resolutions by LA-ICPMS and therefore, the new age estimates should be more reliable and reflect individual growth events recorded in zircons compared to those derived by conventional techniques.

In consideration of these facts as the background, this paper attempts summarizing most recent U-Pb and Lu-Hf isotope systematics of metamorphosed magmatic rocks of Sri Lanka, in the lights of multiple magmatism, source characteristics and crust formation beneath Sri Lanka.

## HISTORICAL SUBDIVISIONS OF THE SRI LANKAN PRECAMBRIAN

The crystalline basement of Sri Lanka has been divided into different crustal or lithological subdivisions of basement units by Adams (1929), Coates (1935), Cooray (1962, 1984a,b) and Vitanage (1972). Later in early nineties, with Japanese and German consortium efforts on petrological, structural geological, geochemical and geochronological studies (e.g. Milisenda et al, 1988; Hiroi and Motoyoshi, 1990; Kröner et al., 1991; Raith and Hoenes, 1994; Milisenda et al., 1994) the classification of Sri Lankan basement rocks and their boundaries were revised extensively with addition of more geochronological data resulting in the current nomenclature presented in Cooray (1994).

Cooray (1994), based majorly on Kroner et al., (1991) classified the Sri Lankan Precambrian into four basement units: Highland Complex (HC) in the centre, Wanni Complex (WC) and Kadugannawa Complex (KC) towards the West with the Vijayan Complex (VC) to the east. Although the subdivisions of the HC – VC and HC-KC are discernible in the field with clear evidence from petrology, the HC and WC crustal domains lack obvious petrological and structural geological terrain markers. Thus, the HC-WC boundary is merely an isotopic boundary (i.e. a boundary defined by contrasts in isotopic values) based on entirely a regional sampling set of Nd model ages, which is physically unrecognizable in the field. Lithologies along the most part and on either side of this so-called 'inferred boundary' are petrologically and structural geologically more or less comparable and therefore serves a poor guide to define an absolute crustal boundary. Kehelpannala (1991, 1997) proposed that the HC-WC boundary should run over the top of the highest marble band of the HC in the north-central Sri Lanka and below the pink granitic gneiss of KC, which marks the lower limit of the KC. Such a modified boundary line would incorporate the KC also into the WC and would lie a few hundreds of metres tectonostraigraphically below the KC coinciding with the high-strain shear zone around Kandy (Digana) of the HC. Nevertheless, still there is no strict consensus on whether the KC should be included in the WC, and apparently it is found in the literature that different authors use or not the term 'KC' as they prefer.

## PROTOLITH CHARACTERISTICS AND THERMOBAROMETRY

Interbedded typical meta sediments such as quartzite, marble, calc-silicate gneisses, garnet-sillimanite bearing gneisses (khondalites) and psamo-pelites are dominant in the HC which forms a major part of the Sri Lankan metamorphic basement, with other rocks of meta igneous origin such as amphibolites, charnockites and meta gabbros. In the WC, meta igneous rocks are dominant ranging from granitic, granodioritic to dioritic composition together with subordinate amounts of meta sediments such as quartzites (Cooray, 2004). In the VC of Sri Lanka, only minor occurrences of quartzite and calc-silicate rocks are encountered close to its boundary with the HC (e.g. Dahanayake and Jayasena, 1983; Cooray, 1994). Granodioritic to dioritic and TTG gneisses with augen structures are dominant in the VC (Cooray, 1994; Kroner et al., 1991). The KC, which consists of doubly plunging synformal structures around Kandy contain minor and thin metasediments of quartzite, marble and calc-silicates (Kroner et al., 1991; Cooray, 1994).

In the HC, metamorphic pressures and temperatures show a decrease from 8-9 kbar and 800-900 °C in the East and Southeast to 4.5-6 kbar and 600-700 °C in the southwest (Faulhaber and Raith, 1994, Schumacher and Faulhaber, 1994, Raase and Schenk, 1994; Kriegsman and Schumacher, 1999; Dharmapriya et al., 2014; 2015). In the WC and KC, estimated P-T conditions are $P = 3.5–7.5$ kbar and $T = 600–900$°C (Schenk et al.,, 1991; Faulhaber and Raith, 1991). Predominantly amphibolite facies assemblages are found in the VC, except for localized granulite facies assemblages in the extreme East around Pottuvil area (Jayawardena and Carswell, 1976; De Maessclialck et al., 1990; Kroner et al., 2013).

## PROTEROZOIC CRUSTAL HISTORY AND CAMBRIAN METAMORPHISM

The pre-metamorphic crustal history of Sri Lankan high-grade terrains has been inferred on the basis of Nd-model ages and U-Pb zircon ages and show a prolonged crustal residence times from ~3500 (both Nd-model and U-Pb zircon ages) to 670 Ma (U-Pb zircon age) (e.g. Kroner et al., 1987; Milisenda et al., 1988., 1994; Baur et al.,1991; Holzl et al., 1994). The HC represents the oldest terrain with respect to Nd-model ages, ranging from 3500-1850 Ma (Milisenda et al.,, 1988). U-Pb detrital zircon ages from para gneisses range from 3200-2400 Ma and U-Pb Concordia upper intercept ages of metamorphic zircons from metapelites define an age group of 2100-1900 Ma. These data imply that the minimum sedimentary deposition age of the HC could be considered as ~1900 Ma. Magmatic, mafic to intermediate protoliths of the HC show emplacement ages of 1950-1850 Ma (Holzl et al., 1991) and 921 Ma (Dharmapriya et al. 2015) with a single age of felsic magmatism at 670 Ma (Baur et al., 1991) is the youngest igneous intrusion.

Nd-model ages of the WC range from 2000-1000 Ma and the U-Pb ages for detrital zircons record a time span of 1329 - 750 Ma with Concordia upper intercept ages ranging from 1100-750 Ma (Milisenda et al., 1988; Liew et al., 1991; Kröner et al., 1994) suggesting a minimum depositional age of 750 Ma. However, in the western part of the WC, post-tectonic intrusive alkaline granites record the latest magmatic activity as ~550 Ma (Holzl et al., 1991; Pohl and Emmermann, 1991).

The VC rocks yield Nd-model ages of 1900 – 1000 Ma (Milisenda et al., 1988; Liew et al., 1991; Holzl et al., 1991) with detrital zircons from meta sediments having U-Pb ages of 1100 – 1000 Ma. Concordia upper intercept ages of magmatic zircons are found to be ~1020 Ma with distinctly positive epsilon Nd and Hf values (Milisenda et al., 1988; Kroner et al., 2013) suggesting a minimum magmatic crystallization age which represent the VC as a Mesoproterozoic juvenile addition (direct derivation from the mantle).

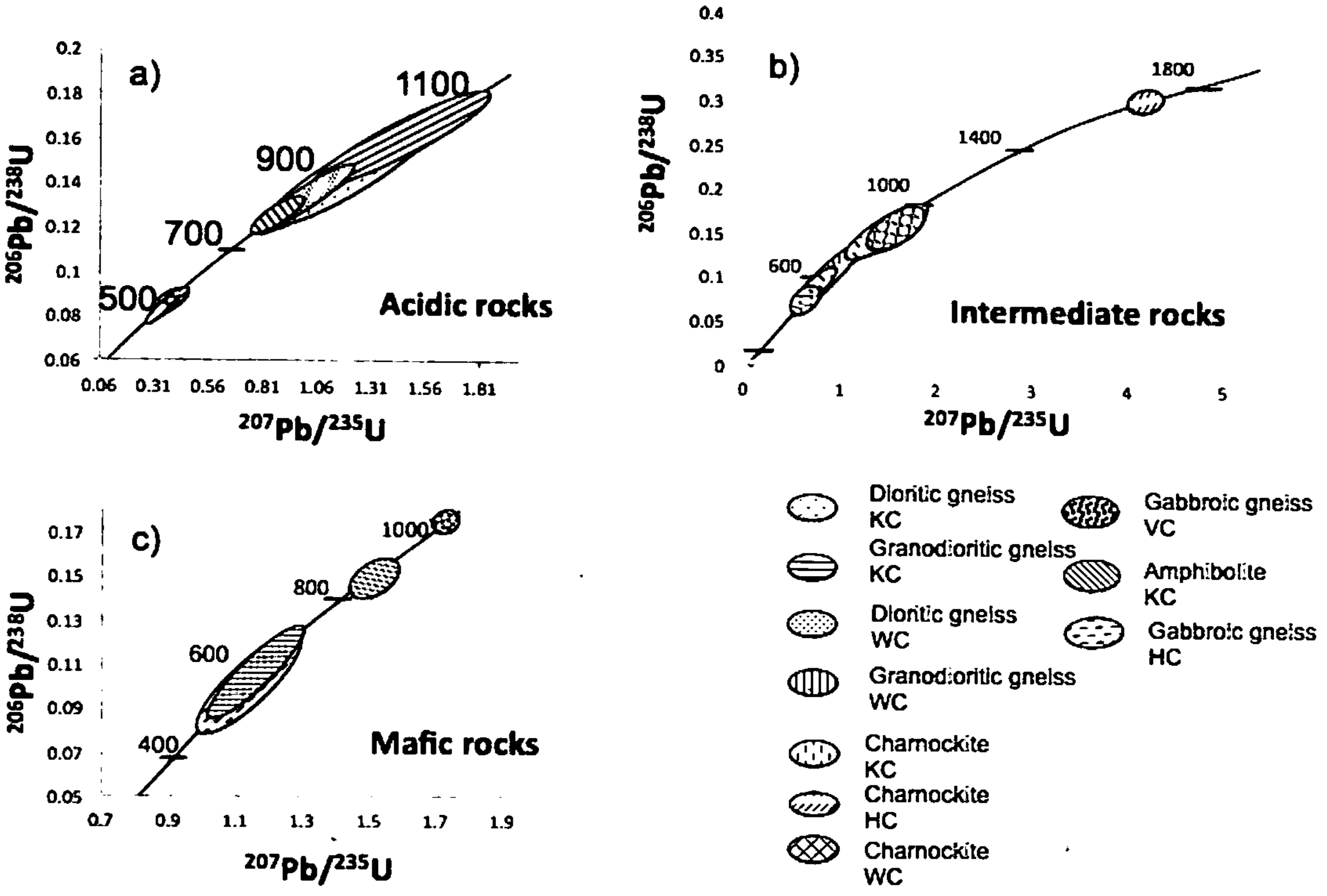

*Fig. 1 U-Pb ages of Zircon from metamorphosed acidic (a), intermediate (b) and (c) mafic rocks of Sri Lanka (see text for reference)*

The smallest unit, the KC which structurally overlies the HC, represents Nd-model ages of 1850-1000 Ma with U-Pb magmatic zircon upper intercept ages in the range of 1100 – 890 Ma (Kroner et al., 2003. Wilbold et al., 2004; Santosh et al., 2014; He et al., 2015), marking a minimum igneous crystallization age of 890 Ma (e.g. Kroner et al., 2003; Wilbold et al., 2004).

The metamorphism of the Sri Lankan basement is considered to be the result of collisions associated with the formation of the Gondwana super continent (e.g. Shiraishi et al., 1994). However, the nature of metamorphism in the four complexes is variable. The HC and WC show typical high-grade granulite facies metamorphism while the KC is characterized by upper amphibolite to granulite facies conditions. The VC is traditionally interpreted as a typical amphibolite facies terrain however, granulite facies rocks are also found at the eastern coast around Pottuvil-Akkaraipattu, first reported by Jayawardena and Carswell, (1976) and later studied by de Maesschalck et al., (1990). Early interpretations of age of metamorphism based on Rb-Sr data, reported ages of ~2000, 1250-1100 and 900-800 Ma by Crawford and Oliver, (1969), Katz, (1971, 1978) and De Maessclialck at al. (1990) respectively, while cooling ages of K-Ar were reported as 600 – 450 Ma (Holmes, 1955; Cooray, 1969; Cordani and Cooray, 1989). However, subsequent studies combining crust formation ages and U-Pb zircon ages protocols provided a solid data set for the age of metamorphism which is found to be mostly coeval in all the complexes of Sri Lanka. Accordingly the HC, both WC and KC, and VC record high-grade metamorphism at 610-550, 590-540 and 510-460 Ma, respectively (e.g. Kröner et al., 1991; Kröner and Williams, 1993).

## DISCUSSION

U-Pb (zircon) and Sm-Nd isotope systematics have been applied to Sri Lankan basement since late eighties (e.g. Milisenda et al. 1988). However recently, Lu-Hf systematics were also applied to understand the magmatic and protolith characteristics of Sri Lankan rocks (e.g. Kröner et al., 2013; Santosh et al., 2014; He et al., 2015). In these studies metamorphosed rocks of dioritic, granodioritic charnockitic, gabbroic and amphibolitic compositions (dioritic gneiss, granodioritic gneiss, charnockite, gabbroic gneiss and amphibolite, respectively) have been used extensively to unravel tectonomagmatic history of the basement of Sri Lanka (e.g. Kröner et al., 2013, Santosh et al., 2014; He et al., 2015; Takamura et al., 2015). Salient features and implications on geochronology with tectonic significance of these new studies is briefly reviewed in the following sections.

## EVIDENCE FOR MULTIPLE MAGMATISM: IMPLICATIONS FROM ZIRCON U-Pb AGES

### FELSIC MAGMATISM

Zircons from metamorphosed felsic to intermediate rocks of the HC record multiple late Neoproterozoic-Cambrian thermal events (Fig. 1a, b). Charnockites of the HC yield concordant multiple age populations of 565-1800 Ma as their emplacement ages. Particularly, the oldest and the youngest ages of (1800 and 565 Ma respectively) are observed from garnet-charnockite of the HC (Santosh et al., 2014). The metamorphic zircons of charnockites show age range of 511-543 Ma (Santosh et al., 2014; He et al., 2015).

U-Pb zircon ages of charnockites from the WC characterize several age groups (Fig. 1b) of which, the oldest upper intercept age is 1000 ± 52 Ma may represent the emplacement of the magmatic protolith (Santosh et al., 2014 and He et al., 2015). The younger age groups corresponding to lower intercepts indicate Pb loss during multiple thermal events between the periods of 565-576 Ma, and closely identical to the Neoproterozoic magmatism of charnockites in the HC. The dioritic gneiss of the complex has upper intercept age of about 980 Ma (Fig. 1a). et al.,U-Pb concordant zircon ages of granodioritic gneiss of the WC show multiple thermal events at ages of 805±12Ma (emplacement of the magmatic protolith), 734.0 ± 4.6 Ma (Cryogenian thermal event) and 546.0 ± 5.7 Ma (latest Neoproterozoic- Cambrian metamorphism) (Santosh et al., 2014).

Zircons in dioritic and granodioritic gneisses from the KC yield Concordia upper intercept ages of 890 ± 16 Ma to 1100 ± 57 Ma (Fig. 1a) marking early Neoproterozoic magmatism followed by metamorphism at 532 ± 18 Ma, given by Concordia upper and lower intercepts, respectively (Santosh et al., 2014; He et al., 2015). Charnockites of the KC yielded ages of 569 Ma and 958 Ma (Concordia upper intercept), respectively as the emplacement age while the concordant metamorphic age being 553 Ma and 543 Ma (He et al., 2015), respectively.

.Dioritic gneiss of VC records concordant U-Pb Concordia upper intercept age of 1049 ± 2 Ma (Fig. 1b) reflecting the time of emplacement of the protoliths (Kroner et al., 2013). Howeevr, zircons of rare charnockiteesamples around Pottuvil yield slightly younger ages of 999 (Concordia upper intercept) with metamorphic age of 537 Ma defined both by Concordia lower intercept and concordant grains (Kröner et al., 2013).

### MAFIC MAGMATISM

Mafic magmatism is evidenced manly by gabbroic gneiss in the HC and amphibolites (amphibolites differ from meta-gabbroic rocks as they do not contain two pyroxenes) in the KC (Fig. 1c). Zircons of the gabbroic gneiss of the HC yield several populations of zircon with weighted mean U-Pb ages in the range of 523 – 553 Ma while metamorphism is indicated by new zircon growth at 525 Ma defined by concordant grains. Zircons in the garnet-amphibolite from the KC show extensive metamorphic recrystallization yielding a weighted mean U-Pb age of 521 Ma. The incipient charnockite of the KC at Boyagama yields two concordant age groups of 784-661 Ma and 850-970 Ma, and the host hornblende biotite gneiss yields protolith age of 973 Ma defined by concordant zircons (He et al., 2015).

In the VC (Fig. 1c), gabbroic gneissesyield U-Pb Concordia upper intercept ages of ~1040 Ma (Kröner et al., 2013). An amphibolite dyke in dioritic gneiss records a concordant U-Pb age of 537 Ma (Kröner et al., 2013).

## SOURCE CHARACTERISTICS AND CRUST-MANTLE INVOLVEMENTS: IMPLICATIONS FROM Hf CRUSTAL MODEL AGES

The εHf values reported from the Sri Lankan crustal rocks (E.g. Santosh et al., 2014; He et al., 2015) provide evidence for magma generation from mixed sources involving both juvenile (mantle) and reworked (crustal) components. The summarized Hf crustal model ages (Santosh et al., 2014; He et al., 2015) and correlation of εHf values with U-Pb zircon ages are shown in the Fig. 2 and Fig. 3, respectively.

### SOURCE CHARACTERISTICS

The HC rocks preserve distinct imprints of reworking of older crust. The zircon εHf values in metamorphosed gabbroic rocks show a tight cluster from −20.5 to 1.6 with crustal model ages in the range of 1501–2790 Ma (Santosh et al., 2014; He et al., 2015) suggesting a mixed

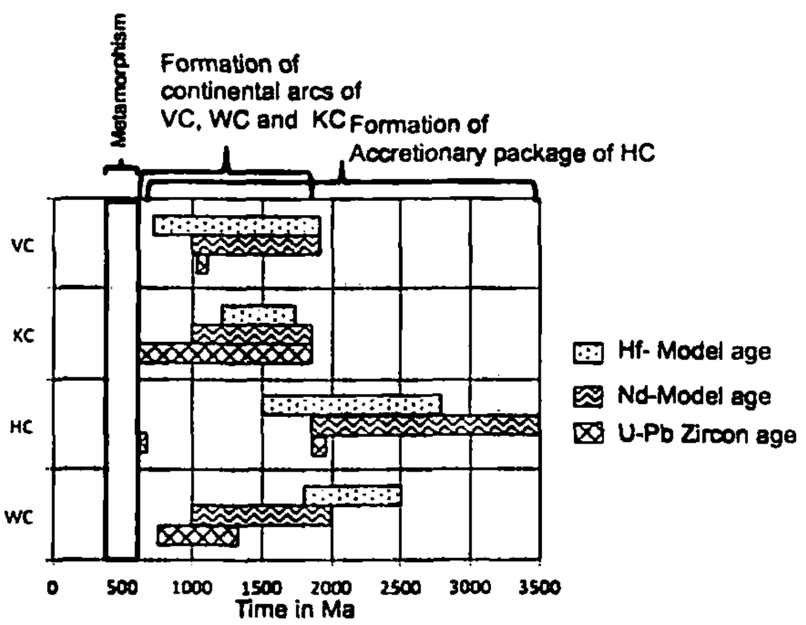

*Fig. 2 Summarized geochronology of Sri Lankan rocks. See text for references*

source from both juvenile Neoproterozoic and reworked Mesoproterozoic – Neoarchean components. Zircons in charnockites also display predominantly large negative εHf values from -33.3 to -6.7 and older crustal model ages from 2039 to 3580 Ma (Santosh et al., 2014; He et al., 2015) suggesting reworked Paleoproterozoic – Archean crust in the genesis of magmatic rocks.

Zircons in the charnockite of the WC possess all positive εHf values ranging from 4.4 to 13.1 with crustal model ages in the range from 709 to 2498 Ma (Santosh et al., 2014; He et al., 2015) suggesting highly juvenile components in the magma source.

The Lu–Hf data reveal dominantly positive εHf values for zircons of the KC in the metamorphosed rocks of dioritic and granodioritic composition from 0.4 to 7.2, with 1031 to 1662 Ma of crustal model ages, and amphibolites display εHf from -4.5 to 5.1 and Hf-crustal model ages of 1206–1733 Ma (Santosh et al., 2014; He et al., 2015) suggesting mixed sources from both juvenile and Paleo-Mesoproterozoic components. However, zircons in garnet amphibolites from this complex show dominantly negative εHf from -21.3 to -13.8 with crustal model ages in the range of 2356–2828 Ma (Santosh et al., 2014; He et al., 2015) suggesting reworked Paleoproterozoic-Archean crustal components in the magma source.

In the VC complex, metadiorites display markedly positive εHf values of 2.5-10. Metagranodiorites show εHf of 2-5.5 while charnockites have εHf values of 4.5-10, inferring predominantly juvenile origins (Kröner at al. 2013).

## CRUST-MANTLE INVOLVEMENTS

The distinct negative εHf values of the magmatic suites in the HC, with the Paleoproterozoic Hf crustal model ages suggest the involvement of older recycled continental crustal components. The oldest Hf crustal model age of about 3.5 Ga is obtained from zircons in a garnetiferrous charnockite from the HC (Zircon U-Pb age for crystallization of the rock is about 1.8 Ga) (Santosh et al., 2014). This is clearly consistent with melting of underlying older basement. Zircons in the metagabbro enclaves in charnockite in the HC (He et al., 2015) show negative to positive εHf values, indicating the input of juvenile components into the HC crust, possibly at a subduction setting. This is clearly indicated by arc-related geochemical features of the charnockites (Santosh et al. 2014; He et al. 2015). Thus, the variable Hf composition from negative to positive εHf of zircon with ages up to Palaeoproterozoic in the magmatic suite from Sri Lanka indicates the involvement of both juvenile mantle components and old continental materials in the generation of the arc-related magmatic suite. Accordingly, εHfranging from highly negative to positive values and older model ages can be correlated with contribution of either older continental crust or subducting oceanic sediments, or both in the source region of the HC, mixed with mantle melts.

The WC magmatic rocks including charnockite and metadiorite show similar zircon crystallization age of ca. 980 Ma (Santosh et al. 2014). The markedly positive εHf values (from +5 to +15) suggest depleted mantle source for magma origin in protoliths. In clear contrast, the εHf values of samples from the KC are plotted close to the Chondrite line, ranging from slightly negative to positive, with crustal model ages mainly from 1.5 Ga to 1.8 Ga (Fig. 3). This trend suggests that the protolith of the felsic rocks were derived from mantle sources with the input of minor crustal components within the arc setting. However, zircons in mafic rocks show dominantly negative εHf values with Hf crustal ages of Paleoproterozoic implying reworked Neoarchean-Paleoproterozoic crusts as the magma source. However, the KC has unique petrological and Hf-Nd isotopic identities (e.g. Fig. 3; Santosh et al., 2014; He et al., 2015) and hence it could be better interpreted not simply as a part of the WC (e.g. Kehelpannala, 1997; Kröner et al., 2003), but as a marginal arc magmatic terrain that was exhumed and

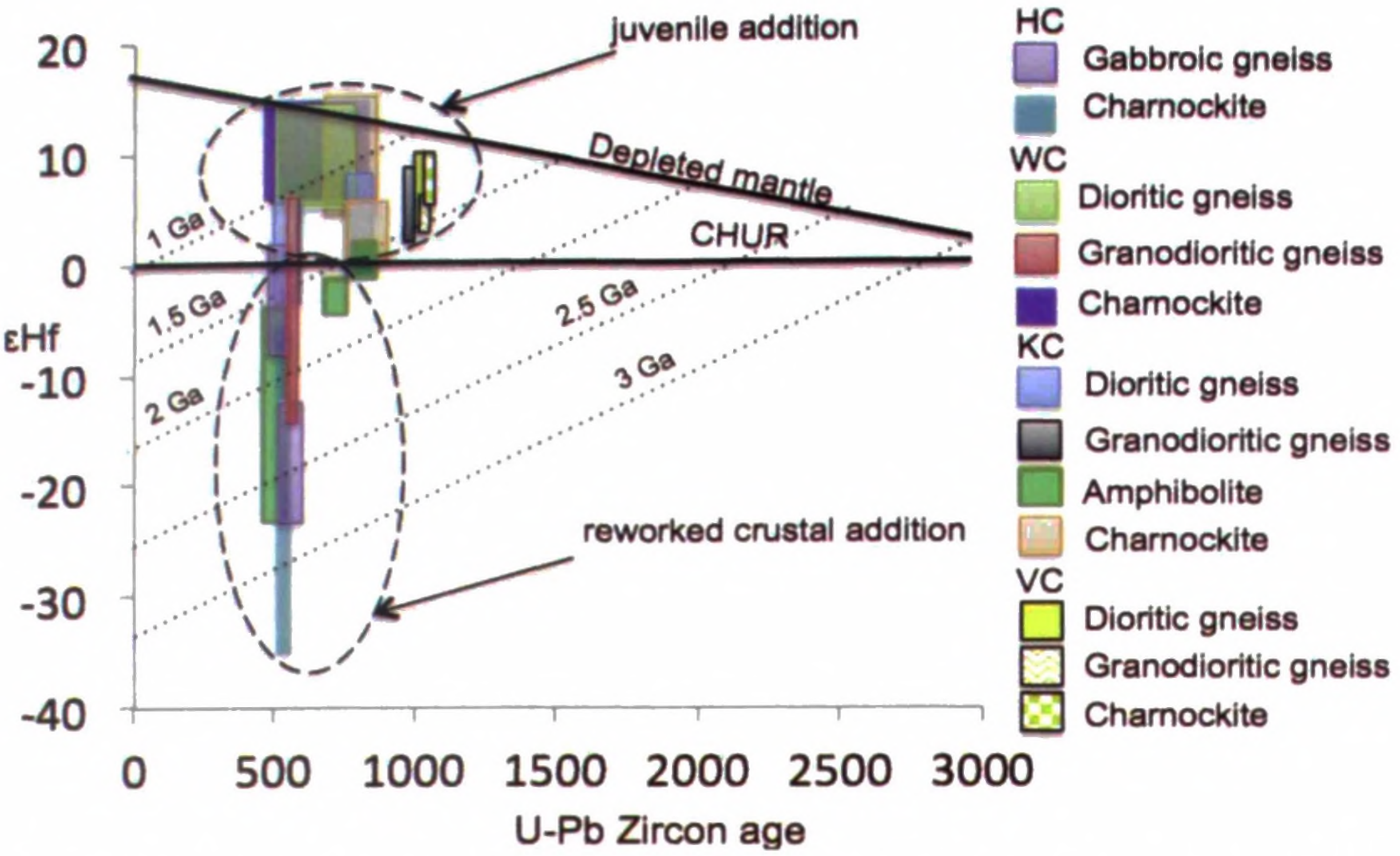

*Fig. 3 Epsilon Hf values against U-Pb zircon ages of Sri Lankan rocks showing possible source characteristics. See text for references*

transposed along the margin of the WC (Santosh et al., 2014; He et al., 2015).

Mostly positive εHf(t) data generally support predominantly juvenile origin of the VC gneisses, however slight negative εHf values may suggest that minor amounts of older continental material were involved in the generation of these rocks (e.g. Kröner et al., 2013). Thus, crystallization of melts derived from the mantle at ca. 1000-1100 Ma is suggested as the dominant crust-forming process in the Vijayan magmatic arc.

## COMPARISON WITH Nd ISOTOPE DATA

Studies on Nd isotope data reported highly heterogeneous εNd values of metamorphosed rocks of felsic and mafic composition ranging from -10 to +2 and -8 to +4, respectively for the KC and WC and +1.5 – 3.5 for the VC (e.g. Milisenda et al., 1994; Willbold et al., 2004; Kröner et al., 2013). These data imply variable amounts of crustal contamination of mantle-derived melts in a continental magmatic arc setting. However, in clear contrast, the HC rocks show dominantly negative εNd(t) values from −7 to −25 suggesting a different genesis or tectonic setting from that of the KC and the WC. This interpretation is highly consistent with negative εHf values (e.g. Kröner et al., 2013; Santosh et al., 2014; He et al., 2015), as depicted in the Fig. 3. Therefore, it is clear that the HC incorporates crustal components and material derived by melting of older (Paleoproterozoic to Archean) continental and oceanic components.

## IMPLICATIONS FOR CRUST FORMATION BENEATH SRI LANKA AND RECENT GEOTECTONIC MODELS

A plate tectonic model for Sri Lanka was first suggested by Pathirana (1980), who interpreted the HC - VC boundary as a subduction zone. Munasinghe and Dissanayake (1982) and Dissanayake and Munasinghe (1984) suggested the present HC as a sedimentary basin of a subduction zone where presence of siliceous and carbonate pelagic sediments in favour of forming quartzite-marble associations. The authors further suggested that the abundant and undisturbed development of these metasediments in the HC is indicative of a stable-shelf quiet water environment analogous to a present-day continental shelf zone with the present WC and VC derived as a single unit. The WC is proposed to have collided with the HC and subsequently, both WC and HC together collided and thrusted over the VC (e.g. Berger and Jayasinghe, 1971; Vitanage, 1972; Voll and Kleinschrodt, 1991; Kröner and Jaeckel, 1994; Kriegsman, 1995; Kröner et al., 2003;

Kehelpannala, 2004, Kroner et al., (1991; 2003) speculated two major collisions for independently derived VC, WC and the HC (see Kehelpannala, 2004 for summary), with the the VC constituting a Grenville-aged magmatic arc of unknown origin, whose original protoliths were predominantly emplaced between 1100 and 1000 Ma related to Rodinea breakup, and consisted largely of dioritic and tonalitic intrusives (e.g. Kröner et al., 2003 and Willbold et al., 2004). Kehelpannala (2004) used age interpretations of Holzl et al. (1994), Kroner et al., (2003) and Wilbold et al., (2004) to speculate that the WC and VC magmatic arcs were brought together to subduct beneath HC microcontinent of unknown origin resulting two collisions within a very short time span from 550 to 580 Ma. , Kröner et al., (2013) inferred that the mantle-derived melts have contributed as the dominant crust-forming process in the Vijayan magmatic arc implying an intra-oceanic subduction zone. Accordingly, most of these studies have concluded that the early Neoproterozoic magmatism in Sri Lanka is a result of passive continental margin tectonics and represent as the hallmarks of the breakup of the Rodinia supercontinent (e.g. Kröner et al., 2003; Wilbold et al., 2004; Kehelpannala, 2004; Kröner et al. 2013).

Nevertheless, Santosh et al., (2014), He et al., (2015) and Takamura et al., (2015) showed that various Neoproterozoic magmatic pulses as described above in Sri Lanka clearly reflect geochemical evidence for active convergent margin setting at ca. 1000-1100 Ma. Further, accretion of oceanic components and arc magmatism reported by the latest studies using both age and geochemical data (e.g. Santosh et al., 2014, He et al., 2015 and Takamura et al., 2015) all support an active convergent margin setting. Moreover, extensive U-Pb and Hf isotopic data (see results in Kröner et al., 2013; Santosh et al., 2014; He et al., 2015, Takamura et al., 2015) strongly suggests that the WC and the VC were coeval magmatic arcs formed during early Neoproterozoic at a double-subduction regime (e.g. Santosh et al. 2014; He et al. 2015) whereas the Highland Complex is the collisional suture in the setting of Gondwana. Subsequently, the WC and VC arcs have collided at late Neoproterozoic-Cambrian together with the accretionary sediments between the two arcs forming the HC as the collisional suture metamorphosing simultaneous with WC and VC (e.g. Santosh et al., 2014; He et al. 2015; Takamura et al. 2015; Dharmapriya et al. 2015), apparently closing a 'paleo HC' ocean. This tectonic scenario appears to be more or less similar to the situation of Palghat Cauvery Shear Zone of southern India, which represents the Neoproterozoic closure of the Mozambique ocean (e.g. Meert, 2003; Santosh et al. 2009).

The broadly negative εNd and εHf values and older model ages are consistent with melting of underlying older basement rocks of Sri Lanka. The mafic to intermediate suites in the KC are explained as input of juvenile components stored in a large magma chamber at the suprasubduction setting of the WC in the Neoproterozoic, while the HC is an accretionary suture with oceanic and continental components, fragments of older continental crust (see U-Pb and Hf model ages of with highly negative epsilon Hf in zircons described above) and accretionary remnants of the subducting oceanic lithosphere with trench sediments (e.g. see MORB remnants of Santosh et al. 2014 and Takamura et al. 2015). Thus, occurrence of dunites-serpentinites, anorthosites and Cu-magnetite deposits in association with chert bands and hot springs in the marginal zones of HC-VC also could be explained as evidence for active continental margin magmatism typical of a suprasubduction zone setting. In addition, subsequent slab-break off and asthenospheric upwelling could be a major heat source for UHT metamorphism within the HC.

## CONCLUDING REMARKS

Based on the results of new U-Pb zircon geochronology and Hf-Nd isotope data from recent studies summarized in previous sections, it is clear that the WC, KC and VC represent arc magmatism during early Neoproterozoic, followed by continuous thermal events with significant melting of older crustal components of ages up to the Archean. Further among all the crustal units of Sri Lanka, multiple thermal events during the Neoproterozoic in the VC characterize an ~1000-1100 Ma juvenile addition directly from the mantle (e.g. Kröner et al., 2013; Santosh et al., 2014; He et al., 2015; Takamura et al., 2015). The latest Neoproterozoic to Cambrian High-grade metamorphism with approximate mean age of ~550 Ma as discussed in previous sections have overprinted the previous magmatic event in all the basement rocks of Sri Lanka.

Importantly, there are several rock types associated with basement rocks in the HC, VC and close to HC-VC boundary, whose origin/petrogenesis is not clearly explained so far. For instance, these rocks include mantle derived rock sequences especially, dunite-serpentinite-websterite-magnesite sequences (e.g. Seruwila, Ussangoda, Indikolapelessa etc) and anorthosites (e.g. Seruwila), Cu-magnetite deposits (e.g. Buttala), chert bands (e.g. Bandarawela and Ussangoda) volcanic ash deposits, (e.g. south of Ussangoda, Pathirana, 1980; Cooray, 1984) and ultra high temperature (UHT) lenses of rocks (e.g. Gampola-Kotmale, Hakurutale, Nildandahinna-Welimada). However, the Previous tectonic models (e.g. Voll and Kleinschrodt, 1991; Kröner and Jaeckel, 1994; Kriegsman, 1995; Kröner et al., 2003; Kehelpannala, 2004, Kroner et al. 2013) have not considered the occurrences of these specific rocks apparently due to inconsistency of occurrence of such rock types into the given models. On the other hand, those specific rocks are not generally found in typical passive continental regimes whereas such sequences are commonly reported in active continental margins elsewhere in the world (e.g. see the review in Taylor and Natland, 1995), thus making it necessary to consider their possible origins in the context of WC-HC-VC tectonic setting. Therefore in this perspective, the dual convergent margin-related tectonic model involving active continental margin settings on either sides of the HC (e.g. Santosh et al., 2014; He et al., 2015) is reasonably able to explain the origins of the above important specific rock suits possibly in a supra-subduction zone setting (e.g. Fig. 4).

Further, it is clear that any tectonic model is not able to sufficiently reproduce the near surface structural trends observed in the field. However, this fact is not significant, because in all collisional belts the near surface structural patterns would be gently or nearly horizontal whereas in the deep they become more vertical, and both sides of the orogen, they diverge opposite directions (e.g. Harris et al. 1994; Maruyama et al. 2007; Rino et al. 2008; Santosh et al. 2009; Santosh, 2010). Thus, foliations and/or stretching lineations measured by strike and dip cannot comprehend deep processes on a plate tectonic scale and reflect only the near surface dynamics although either seismic data on crustal and lithospheric scale or mantle mineral (e.g. pyroxene and olivine) fabrics in mantle rocks help understanding deep structure or flow directions. Hence, traces of the deep crustal or mantle dynamics directly evidenced from surface rock exposures could only be inferred from field identification of petrology, geochemistry and spatial and temporal

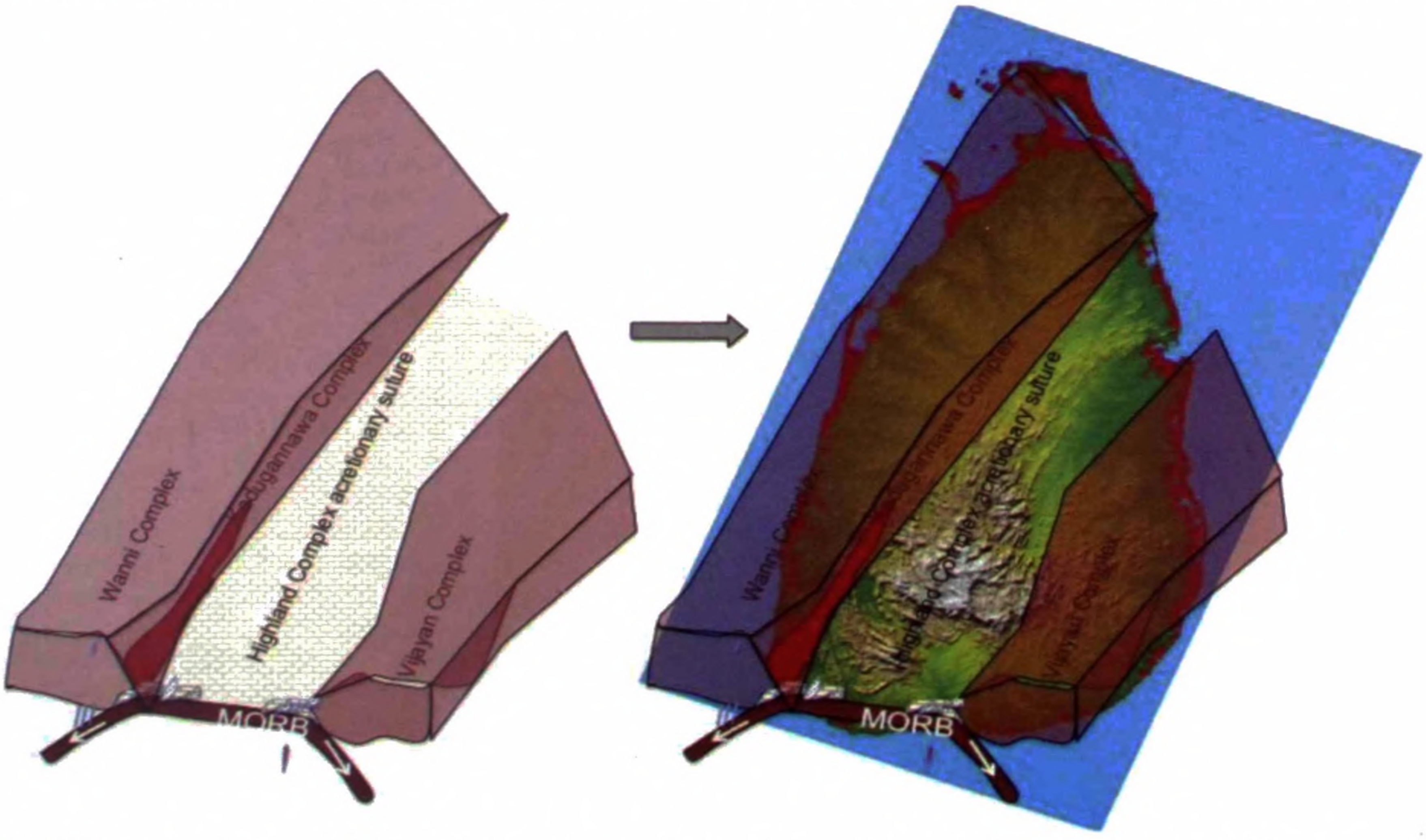

*Fig. 4 Tectonic fitting of Sri Lanka in active margin setting after collision of Wanni and Vijayan arcs forming Highland Complex as the acretionary suture (belt) (see text for description)*

interrelationships of rock types, which we may essentially bear in mind when interpreting lithotectonic history of deep-rooted terrains like Sri Lanka.

## REFERENCES

Adams, ED. (1929) The geology of Ceylon. Canadian J.Res., 1:425-511.

Baur, N., Kröner, A., Todt, W., Liew, T.C. and Hoffman, A.W. (1991) U–Pb isotopic systematics of zircons from prograde and retrograde transition zones in high grade orthogneisses, Sri Lanka. Journal of Geology, 99:527–545.

Berger, A.R. and Jayasinghe, N.R. (1976) Precambrian structure and chronology in the Highland Series of Sri Lanka. Precambrian Research 3:559–576.

Taylor, B. and Natland, J. (1995) Active margins and marginal basins of the western Pacific. Geophysical Monograph 88, American Geophicical Union.

Coates, J.S. (1935) The geology of Ceylon. Ceylon J. Science, 19:101-211.

Cooray, P.G. (1969) The significance of mica ages from the crystalline rocks of Ceylon. Geol. Assoc. Can., Spec. Pap., 5: 47-57.

Cooray, P.G. (1984a) Geology, with special reference to the Precambrian. In Fernando, C.H. (ed.) Ecology and biogeography in Sri Lanka. Dr. W. Junk, The Haugue, pp 1-34.

Cooray, P.G. (1984b) An Introduction to the Geology of Sri Lanka. National Museum Sri Lanka Publication, 340 pp.

Cooray, P.G. (1994) The Precambrian of Sri Lanka: a historical review. In: M. Raith and S. Hoernes (Editors), Tectonic, Metamorphic and Isotopic Evolution of Deep Crustal Rocks, With Special Emphasis on Sri Lanka. Precambrian Research, 66:3-18.

Cooray, P.G. (1962) Charnockites and their associated gneisses in the Precambrian of Ceylon. Q. J. Geol. Sot. London, 118:239-273.

Cordani, U. and Cooray, P.G. (1989) Rb-Sr ages of granites and gneisses from the Precambrian of Sri Lanka. J. Geol. Soc. Sri Lanka 2:35-43.

Crawford, A.R. and Oliver, R.C. (1969) The Precambrian geochronology of Ceylon. Geol. Soc. Aust, Spec. Pub., 2:283-316.

Dahanayake, K. and Jayasena, H.A.K. (1983) General geology and petrology of some Precambrian crystalline rocks from the Vijayan Complex of Sri Lanka. Precambrian Research 19:301–315.

De Maessclialck, A.A., Oen, IS., Hebeda, E.H., Verschure, R.H. and Arps, C.E.S. (1990) Rubidium-Strontium whole rock ages of Kataragama and Potuvil charnockites and east Vijayan gneiss : Indications of a 2 Ga metamorphism in the Highlands of South east Sri Lanka. Journal of Geology, 98: 772-779.

Dharmapriya, P.L, Malaviarachchi, S.P.K., Galli, A., Ben-Xun Su, Subasinghe, N.D. and Dissanayake, C.B. (2014) Rare evidence for formation of garnet + corundum during isobaric cooling of UHT meta-pelites: New insights for retrograde *P-T* trajectory of the Highland Complex, Sri Lanka. Lithos, 220:300-317.

Dharmapriya, P.L., Malaviarachchi, S.P.K., Santosh, M., Tang, L. and Sajeev, K. (2015) Late-Neoproterozoic ultra high temperature metamorphism in the Highland Complex, Sri Lanka. Precambrian Research, 271:311–333.

Dickin, A.P. (2005) Radiogenic isotope geology. Cambridge University Press.

Dissanayake, C.B. and Munasinghe, T. (1984) Reconstruction of the Precambrian sedimentary basin in the Granulite belt of Sri Lanka. Chemical Geology, 47:221-247.

Faulhaber, S. and Raith, M. (1991) Geothermometry and geobarometry of high-grade rocks: a case study of garnet- pyroxene granulites in southern Sri Lanka. Min. Mag., 55:33-56.

Harris, N.B.W., Santosh, M. and Taylor, P.N. (1994) Crustal evolution in South India: constraints from Nd isotopes. The Journal of Geology, 102:139-150.

He, X.-F., Santosh, M., Tsunogae, T. and Malaviarachchi, S.P.K. (2015) Early to late Neoproterozoic magmatism and magma mixing - mingling in Sri Lanka: implications for convergent margin processes during Gondwana assembly. Gondwana Research, doi:10.1016/j.gr.2015.02.013.

Hiroi, Y. and Motoyoshi, Y. (Ed.). (1990) Study of Geologic Correlation Between Sri Lanka and Antarctica' (1988-1989). Chiba University. 151 pp.

Hölzl, S., Hofmann, A. W., Todt, W. and Köhler, H. (1994) U-Pb geochronology of the Sri Lanka basement. In: Raith, M. and Hoernes, S. (eds.) Tectonic, Metamorphic and Isotopic Evolution of Deep Crustal Rocks, With Special Emphasis on Sri Lanka. Precambrian Res. 66:123-149.

Holmes, A. (1955) Dating the Precambrian of Peninsular India and Ceylon. Proc. Geol. Assoc. Can., 11:81-106.

Holzl, S., Kohler, H., Kroner, A., Jaeckel, P. and Liew, T.C. (1991) Geochronology of the Sri Lankan Basement. Geol. Surv. Dept. Sri Lanka, Prof. Pap., 5:236-257.

Hölzl, S., Köhler, H., Kröner, A., Jaeckel, P. and Liew, T.C. (1991) Geochronology of the Sri Lankan Basement. Geological Survey Department Prof. Paper 5, Sri Lanka, pp 237–257.

Jayawardene, D.E.D.S. and Carswell, D.A. (1976) The geochemistry of charnockites and their constituent ferromagnesian minerals from the Precambrian of south-east Sri Lanka. Mineralogical Magazine, 40:541—554.

Katz, M.B. (1974) Paired metamorphic belt in Precambrian granulite rocks in Gondwanaland. Geology, 2:237-241.

Katz, M.B. (1978) Sri Lanka in Gondwanaland and the evolution of the Indian Ocean. Geological Magazine, 117:237-316.

Kehelpannala, K.V.W. (1991) Structural evolution of high grade terrains in Sri Lanka with special reference to the areas around Dodangaslanda and Kandy. In : Kriiner, A. (ed.) The crystalline crust of Sri Lanka, Part I, Summary of Research of the German - Sri Lankan Consortium. Geol. Surv. Dept. Sri Lanka, Prof. Paper 5, pp 69-88.

Kehelpannala, K.V.W. (1997) Deformation of a high-grade Gondwana fragment, Sri Lanka. Gondwana Research, 1(1): 47-68.

Kehelpannala, K.V.W. (2003) Structural evolution of the middle to lower crust in Sri Lanka—a review. J. Geol. Soc. Sri Lanka 11, 45–86.

Kehelpannala, K.V.W. (2004) Arc accretion around Sri Lanka during the assembly of Gondwana. Gondwana Res. 7, 1323–1328.

Kr6ner, A. and Williams, I.S. (1993) Age of Metamorphism in the high-grade rocks of Sri Lanka. J. Geol., 101: 513-521.

Kriegsman, L. (1995) The Pan-African events in East Antarctica: a review from Sri Lanka and the Mozambique Belt. Precambrian Res. 75, 263–277.

Kriegsman, L.M. and Schumacher, J.C. (1999) Petrology of sapphirine-bearing and associated granulites from central Sri Lanka. J. Petrol. 40, 1211–1239.

Kröner, A., Cooray, P. G. and Vitanage, P.W. (1991) Lithotectonic subdivision of the Precambrian basement in Sri Lanka. In: Kröner,A. (Eds.) The Crystalline Crust of Sri Lanka, Part-1. Summary of Research of the German-Sri Lankan Consortium. Geological Survey Department, Sri Lanka, Professional Paper 5, 5-21.

Kroner, A., Jaeckel, P. and Williams, I.S. (1994) Pb-loss patterns in zircons from a high-grade metamorphic terrain as revealed by different dating methods: U-Pb and Pb-Pb ages for igneous and metamorphic zircons from northern Sri Lanka. Precambrian Res., 66:151-181.

Kröner, A. and Jaeckel, P. (1994) Zircon ages from rocks of the Wanni Complex, Sri Lanka. J. Geol. Soc. Sri Lanka, 5:41–57.

Kröner, A., Kehelpannala, K.V.W. and Hegner, A. (2003) Ca. 750–1100 Ma magmatic events and Grenville-age deformation in Sri Lanka: relevance for Rodinia super-continent formation and dispersal, and Gondwana amalgamation. Journal of Asian Earth Sciences, 22:279–300.

Kröner, A., Rojas-Agramonte, Y., Kehelpannala, K.V.W., Zack, T., Hegner, E., Geng, H.Y., Wong, J. and Barth, M. (2013) Age, Nd–Hf isotopes, and geochemistry of the Vijayan Complex of eastern and southern Sri Lanka: a Grenville-age magmatic arc of unknown derivation. Precambrian Research, 234:288–321.

Liew, T.C., Milisenda, C.C., H61zl, S., K6hler, H. and Hofmann, A.W. (1991) Isotopic characterization of the high grade basement rocks of Sri Lanka. Geol. Survey Dept. Sri Lanka, Prof. Pap., 5: 258-267.

Maruyama, S., Santosh, M. and Zhao, D. (2007) Superplume, supercontinent, and post-perovskite: mantle dynamics and anti-plate tectonics on the core–mantle boundary. Gondwana Research, 11(1):7-37.

Mcnutt, R. and Dickin, A.P. (2012) A comparison of Nd model ages and U–Pb zircon ages of Grenville granitoids: constraints on the evolution of the Laurentian margin from 1.5 to 1.0 Ga. Terra Nova, 24:7-15.

Meert, J.G. (2003) A synopsis of events related to the assembly of eastern Gondwana. Tectonophysics, 362:1–40.

Milisenda, C., Liew, T.C., Hofmann, A.W. and Kr6ner, A. (1988) Isotopic mapping of age provinces in Precambrian high-grade terrains: Sri Lanka. Journal of Geology, 96: 608-615.

Milisenda, C.C., Liew, T.C., Hofmann, A.W. and Kohlel, H. (1994) Nd isotopic mapping of the Sri Lanka basement: update, and additional constraints from Sr isotopes. In: M. Raith and S. Hoernes (Editors), Tec- tonic, Metamorphic and Isotopic Evolution of Deep Crustal Rocks, With Special Emphasis on Sri Lanka. Precambrian Research, 66: 95-110.

Munasinghe, T. and Dissanayake, C. B. (1982) A plate tectonic model for the geologic evolution of Sri Lanka Journal of the Geological Society of India, 23: 369-380.

Pathirana, H.D.N.C. (1980) Geology of Sri Lanka in relation to plate tectonics. J. Natl. Sci. Counc. Sri Lanka, 8:75–85.

Pohl, J.R. and Emmermann, R. (1991) Chemical composition of the Sri Lanka Precambrian basement. Geol. Survey Dept. Sri Lanka, Prof. Paper 5, pp 94-124.

Raase, R. and Schenk, V. (1994) Petrology of granulite facies metapelites of the Highland Complex, Sri Lanka : implications for metamorphic zonation and P-T path I'recambrian Ties., 66:265-294.

Raith, M. and Hoernes, S. (Eds.) (1994) Tectonic, Metamorphic and Isotopic Evolution of Deep-Crustal Rocks, with Special Emphasis on Sri Lanka. Precambrian Research.

Rino, S., Kon, Y., Sato, W., Maruyama, S., Santosh, M. and Zhao, D. (2008) The Grenvillian and Pan-African orogens: world's largest orogenies through geologic time, and their implications on the origin of superplume. Gondwana Research 14 (1):51-72.

Santosh, M., Tsunogae, T., Malaviarachchi, Sanjeewa P.K., Zhang, Z.M., Ding, H.X., Tang, L. and Dharmapriya, P.L., (2014) Neoproterozoic crustal evolution in Sri Lanka: insights from 1643 petrologic, geochemical and zircon U–Pb and Lu–Hf isotopic data and implications for Gondwana assembly. Precambrian Research, 255:1–29.

Santosh, S., Maruyama, M. and Sato, K. (2009) Anatomy of a Cambrian suture in Gondwana: Pacific-type orogeny in southern India? Gondwana research, 16 (2):321-341.

Santosh, M. (2010) Assembling North China Craton within the Columbia supercontinent: the role of double-sided subduction. Precambrian Research 178 (1), 149-167.

Schenk, V., Raase, P. and Schumacher, R. (1991) Metamorphic zonation and P–T history of the Highland Complex in Sri Lanka. Geological Survey Department Prof. paper 5, Sri Lanka, pp 150–163.

Schumacher, R. and Faulhaber, S. (1994) Summary and discussion o f T'-T estimates from garnet-pyroxene- plagioclase-quartz bearing granulites-facies from Sri Lanka. Precambrian Research, 66: 295-308.

Shiraishi, K., Ellis, D.J., Hiroi, Y. and Fanning, C.M. (1994) Cambrian Organic belt in East Antarctica and Sri Lanka; implication for Gondwana assembly. Journal of Geology, 102:47-65.

Takamura, Y., Tsunogae, T., Santosh, M., Malaviarachchi, S.P.K. and Tsutsumi, Y., (2015) Petrology and zircon U-Pb geochronology of metagabbro from the Highland Complex, Sri Lanka: Implications for the correlation of Gondwana suture zones, Journal of Asian Earth Sciences, doi: http://dx.doi.org/10.1016/j.jseaes.2015.07.001.

Vitanage, P.W. (1985) Tectonic and mineralization in Sri Lanka. Bull. Geol. Soc. Finland, 57:157-168.

Vitanage, P.W. (1972) Post Precambrian uplifts and regional neotectonic movements in Ceylon. 24th Int. Geol. Congr., Montreal, 3: 642-654.

Voll, G. and Kleinschrodt, R. (1991) Sri Lanka: Structural, magmatic and metamorphic development of a Gondwana fragment. Geological Survey Department, Sri Lanka, Prof. paper pp 22–52.

Willbold, M., Hegner, E., Kleinschrodt, R., Stosch, H.-G., Kehelpannala, K.V.W. and Dulski, P. (2004) Geochemical evidence for a Neoproterozoic magmatic continental margin in Sri Lanka-relevance for the Rodinia-Gondwana supercontinental cycle. Precambrian Research, 130:185–198.