Structure, Composition and Evolution of the South Indian and Sri Lankan Granulite Terrains from Deep Seismic Profiling and other Geophysical and Geological Investigations: A LEGENDS Initiative

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ABSTRACT

This is a proposal for a multidisciplinary, integrated geophysical/geological survey across southern India and Sri Lanka, part of the largest exposed Neoproterozoic high-grade metamorphic terrain in the world. The purpose is to undertake deep seismic profiling and other geophysical and geological investigations in order to better understand the structure, composition and evolution of a key segment Precambrian continental crust and the role it played in the amalgamation and subsequent break-up of the Gondwana supercontinent. Of particular importance is that this crustal segment records a 2 billion year long history of magmatism, sedimentation, deformation and metamorphism and now exposes rocks on the surface that once formed at crustal depths of 30-90 km and record unusually high metamorphic temperatures of up to 1000 °C. Geophysical data will help to find out what lies underneath these high-T rocks and whether the entire terrain consists of individual blocks separated by (now hidden) sutures. It is likely that crustal-scale structures were generated during the formation of this crust that may extend to other, now dispersed, segments of the Gondwana landmass and may help in reconstructing the process of supercontinent assemblage and break-up.

1. Deep Seismic Exploration of the continental lithosphere

Systematic exploration of the continental lithosphere by deep seismic reflection profiling, pioneered by the COCORP program in the U.S., has revolutionized our view of the deep crust and upper mantle over the past 30 years (Fig. 1). Major national programs such as COCORP, BIRPS, DEKORP, LITHOPROBE, ECORS, DRP (Fig. 2) have used the CMP (Common Mid Point) techniques developed by the oil industry to (a) trace important geological faults to lower crustal and even mantle depths, (b) demonstrate that the base of the crust, or Moho, is a complex interface representing, in turn, compositional contrast, phase changes and tectonic contacts; (c) identify hitherto unsuspected boundaries between crustal blocks and, in some cases, show that virtually entire mountain belts formerly considered as rooted in the Earth's mantle are actually allochthons riding above intact extensions of continental material at lower crustal depth; (d) discover seismic "bright spots" marking magma chambers in the deep crust; and (e) find deep laminated reflectors that may be relicts of lower crustal flow (e.g., Barazangi and Brown, 1986; Meissner et al., 1991; Matthews and Smith, 1987; Leven et al., 1990, Clowes and Green, 1994; White et al., 1996; Klemperer and Mooney, 1998, Carbonell et al., 2000).

Although multichannel reflection profiling has cored most of the above efforts, advances in technology in recent years have made it more feasible to record a richer array of seismological information in a deep lithospheric investigation (e.g. Brown, 2000; Fig. 3a). Thus, contemporary deep seismic surveys often collect not only reflection and refraction information from controlled sources, but also "passive" recordings of earthquake sources that can be used to image structures well into the mantle (e.g., Bostock, 1999; Fig. 3b)

2. The LEGENDS Initiative

Spectacular as these results have been, most of such surveys have been limited to national programs in those countries with the financial resources to mount expensive geophysical initiatives. Thus, whereas major networks of deep seismic profiles now span North America, Europe, Japan and Australia/New Zealand, much of the world's continents remain unsampled (Fig. 2). Although recent multinational efforts have led to deep geophysical transects of such key targets as the Himalayas/Tibet (INDEPTH), the Urals (URSEIS) and the Andes (ANCORP), most of Asia, Africa, South America and Antarctica remain *terra incognita* in terms of modern, high resolution deep seismic reflection imaging. Whereas there have been some notable investigations in these areas using other seismic techniques, such as refraction in the East African rift (KRISP project, Prodehl et al., 1997) and passive teleseismic analysis (the Kaapvaal Project in South Africa and Zimbabwe, James et al., 1997), deep seismic *reflection* profiles remain rare.

From a geological perspective, perhaps the largest expanse of unexplored continental lithosphere lies in those fragments that were once part of the supercontinent Gondwana (Fig. 4). With the exception of Australia, which has pioneered the use of deep reflection surveying since the 1960s, and India, where a number of DSS (Deep Seismic Sounding, a technique emphasizing wide angle reflection recordings) and some CMP-style reflection seismic surveys have been collected (see below), few modern seismic profiles exist to delineate the gross structure, much less the details, of the continental architecture of a region which played such an important historical role in the development of plate tectonic theory.

We suggest that the time is ripe for a comprehensive program of deep geophysical surveys, cored by seismic reflection profiling, to probe Gondwana. In particular, structural, petrological, geochemical and isotopic studies of the crystalline rocks in East Africa, Madagascar, southern India, Sri Lanka, and East Antarctica (termed East African Orogen by Stern, 1994, also commonly referred to as part of the broader late Neoproterozoic to early Palaeozoic Pan-African orogenic system, Kröner and Stern, 2004) now provide a firm basis for framing geotectonic questions that can be addressed by such surveys (e.g. Kusky et al., 2003; Collins and Windley, 2002). At the same time, new seismic technologies make surveys in previously remote areas more practical and powerful. Furthermore, the present-day dispersal of the fragments of Gondwanaland makes many of these geological problems accessible to marine deep seismic profiling, which is considerably less expensive than similar surveys on land.

The East African Orogen (EAO, Fig. 5) is now recognized as one of the great orogenic belts of the world exposing, in its southern part, deep products of what has so far been interpreted as a Tibet-Himalayan style continent-continent collision as well as considerable volumes of juvenile material. The EAO constitutes a broad mobile belt that is unique for the study of key processes of continental evolution, since among its many facets, the region exposes large areas of deep crust that were involved in the collisional amalgamation of Gondwanaland in Neoproterozoic to earliest Palaeozoic time (ca. 850-530 Ma).

The geological terranes that were produced during this amalgamation and collision are now scattered due to break-up of the Gondwana supercontinent. This break-up produced a range of continental crustal fragments offering an opportunity to investigate not only the structural controls that guided this break-up (and their relation to older structures of collision vintage) but our entire understanding of what constitutes continental lithosphere at depth (e.g. Jordan, 1975). From microcontinents such as Sri Lanka and Madagascar to mesocontinents like India (now sutured along its northern bounds to the contemporary Eurasian supercontinent), the region contains a remarkably diverse collection with which to probe the links between deep crustal/upper mantle structure and the Wilson cycle in the continental context (Fig. 6).

The LEGENDS Initiative has been accepted by the International Lithosphere Program as a Workshop/Sub-Committee under the existing CC-8 Committee and has organized workshops and conference sessions in Osaka, Japan (2001), Hyderabad, India (2002), San Francisco, USA (2002), Kandy, Sri Lanka (2003), Nice, France (2003), southern India (2004), and Singapore (2004).

3. Southern India and Sri Lanka

On scientific and logistical grounds, a most appropriate starting point for a program of deep lithospheric studies of East Gondwanaland is southern India and Sri Lanka. The Precambrian crystalline rocks of this region have been a focus of numerous geological and geochronologic studies by scientists from many countries (Shackleton, 1976; Naqvi and Rogers, 1987; Harris et al., 1996; Rogers and Giral, 1997, Paliwal, 1998, Meissner et al., 2002; Ramakrishnan, 2003; Kröner et al., 1991, 2003; Raith and Hoernes, 1994; Santosh et al., 2003). Moreover, certain portions of southern India have also been probed by both controlled source (e.g. Kaila and Krishna, 1992; Srikantappa et al., 1992; Mahadevan, 1994; Reddy et al., 1995; 2000; 2003, Gupta and Mahadevan, 2000; Vijaya Rao et al, 2000) and passive seismic surveys (Saul et al., 2000; Kumar et al., 2001; Sarkar et al., 2003; Rai et al., 2003; Gupta et al., 2003a,b) which, together with magneto-telluric (Harinarayana et al., 2003; Naganjaneyuhu and Hrinanaryana, 2003), gravity (Mishra, 1992; Mishra et al., 1999; Reddy et al., 2000; Singh et al., 2003) and magnetic (Ramachandran, 1990; Rajaram et al., 2001; 2003), coverage, provide a vital reference framework for the planning of new deep seismic surveys that are a focus of this proposal.

Serendipity has also played a role in putting southern India and Sri Lanka at the top of the list of potential LEGENDS operations. The southern part of India had already been earmarked for deep seismic surveys by Indian scientists even before the LEGENDS concept was floated for consideration. However, it was quickly realized that by bringing additional resources to augment the equipment that the National Geophysical Research Institute (NGRI) in Hyderabad has in place, a much more effective survey could be carried out. Also, by treating this survey not in isolation but as part of a larger program of surveys in East Gondwana, the potential scientific payoff would be markedly enhanced.

The major geologic structures and terranes of southern India include (Fig. 7) the Dharwar (East and West) craton in the north, the Southern Granulite Terrain (SGT) at the southern tip and the Eastern Ghats belt in the east. The SGT, the crystalline rocks of Sri Lanka and parts of the Eastern Ghats belt represent remobilization during the late Neoproterozoic (Pan-African event) associated with the collision and accretion tectonics that gave rise to the East African orogen (Fig. 5).

3.1 Geology of the Southern Granulite Terrain, India

The SGT consists primarily of a late Archaean granulite-facies domain along its northern part; the Nilgiri-Biligiri Rangan-Sheveroy-Madras blocks immediately south of the amphibolite-/ granulite-facies transition zone (TZ) (Fig. 7) and two units of Neoproterozoic granulite-facies rocks, namely the Madurai-Kodaikanal terrain or Madurai Block (MB) and the Kerala Khondalite Belt (KKB), consisting of the Nagercoil and Trivandrum blocks (NB and TB)(Drury et al., 1984; Harris et al., 1994; Jayananda et al., 1995; Bartlett et al., 1998; Ramakrishnan, 2003 and references therein; Braun and Kriegsmann, 2003; Santosh et al., 2003). In general, the basement lithologies of the SGT have experienced multiple deformation events and were subjected to high-grade metamorphism at about 550 Ma ago.

These granulite blocks are dissected by a number of late Neoproterozoic to early Palaeozoic ductile and brittle shear zones. The most prominent and important of these is known as the Palghat-Cauvery Shear Zone (Drury et al., 1984). This large shear zone system refers to a ~70 km wide tract characterized by a network of numerous narrow (typically 1-2 km wide) shear zones (Chetty et al., 2003b). Along these zones intense ductile- and/or brittle shearing and considerable retrogression and alteration of granulite-amphibolite facies rocks is common. Based on an interpretation of lithological assemblages and new geochronology, including U-Pb and Pb-Pb zircon and monazite ages, Sm-Nd and Rb-Sr whole-rock/mineral tie lines and Sm-Nd model ages (Bartlett et al.,1995; Jayananda et al., 1995; Ghosh 1999; Meissner et al., 2002; Bhaskar Rao et al, 2003; Collins and Santosh, 2004), it is suggested that the Archaean-Neoproterozoic boundary in the SGT lies along a line connecting the towns of Karur-Kambam-Painavu-Trichur (KKPT) (Ghosh et al.1998; Ghosh, 1999; Bhasker Rao et al., 2003; Naganjaneyulu and Harinarayana, 2003; Ghosh et al., 2004). This broadly matches the southernmost shear zone in the Palghat-Cauvery shear system (Chetty et al. 2003b).

Over the last five years, geochronological studies on the Palghat-Cauvery shear system (Bhasker Rao et al., 1996; 2003; Raith et al., 1999; Meissner et al., 2002; Santosh et al., 2003; Ghosh et al., 2004; Collins and Santosh, 2004) and the cratonic granulite blocks provided the following new results and interpretations:

(1) The Biligiri Rangan Highland massif includes the oldest rocks of the SGT with protolith and Nd model ages up to ca. 3.6 Ga.

(2) The Palghat-Cauvery shear system includes infracrustal associations such as 2.9 Ga layered anorthosite complexes and 2.5 Ga charnockitic gneisses with Nd mean crustal residence ages between 3.3 and 3.1 Ga. Anorthosites and mafic layered intrusions are widespread in the Palghat-Cauvery shear belt.

(3) In contrast, the Nilgiri highland massif is composed of distinctly younger material with crust-formation ages between 2.9 and 2.7 Ga but emplaced and metamorphosed around 2.5 Ga.

(4) The ductile shear zones separating the various blocks have a recurrent geologic history with the latest events occurring around 0.6-0.5 Ga.

(5) The Palghat-Cauvery shear system and the northern granulite blocks also include numerous alkali syenite plutons emplaced ~0.8 Ga ago, and granites that intruded between 0.6 and 0.5 Ga ago.

The Madurai block is bounded by the Palghat-Cauvery shear system in the north and the Achankovil lineament in the south. The predominant rock types include high-grade meta-sediments (biotite gneiss, quartzite, marble, khondalitic assemblage), mafic granulites, char-nockite massifs and massif-type anorthosite bodies such as at Oddanchathram, Kadavur and Perinthatta. Igneous emplacement ages are Neoproterozoic (~800 Ma), but the granitic protoliths have incorporated older crustal components up to ca. 3 Ga. Detrital zircon ages are as old as 3.2 Ga, whereas younger granites were emplaced at ~0.8-0.6 Ga (Ghosh, 1999; Santosh et al., 2003; Ghosh et al., 2004; Collins and Santosh, 2004). P-T-t estimates on sapphirine granulites suggest an ultra-high temperature (UHT) metamorphic event, accompanied by ductile deformation and granite intrusion (Choudhary et al., 1992; Mohan and Windley, 1993; Raith et al. 1997; Tsunogae and Santosh, 2003). This may relate to an early component of the pervasive late Neoproterozoic to early Palaeozoic (Pan-African) overprint as revealed by 0.45-0.6 Ga zircon rims, monazite and uraninite ages (Santosh et al., 2003). With more controlled sampling and dating it may be possible to delineate domains with different Pan-African thermal imprints and thus open up new research opportunities.

The Achankovil Lineament (AL, Fig.7) is a prominent morphologic feature (Fig. 8) separating the Madurai block to the north from the Kerala Khondalite Belt (KKB) to the south. The lineament has a prominent expression on magnetic anomaly maps of southern India (Fig. 9) and has long been considered to represent a shear zone (the Achankovil Shear Zone on many published maps), but with disputed shear sense between dextral and sinistral (e.g., Radakrishna et al., 1990; Sacks et al., 1997; Rajesh et al., 1998). However, the lineament has recently been reinterpreted as the high-strain, attenuated limb of a major fold (Ghosh, 1999; Ghosh et al., 2004). Many workers have correlated the AL with the Ranotsara shear zone in southern Madagascar, but this is disputed by others (Janardhan et al., 1997; Chetty et al., 2003a).

South of the AL the two major segments of the KKB are also described as the Trivandrum and Nagercoil blocks. These terrains reveal similar lithologies and metamorphic histories as the Madurai block but may also include Meso- to Palaeoproterozoic protoliths compared to the apparently younger units along the ASZ (Bartlett et al., 1998). Zircons from rocks of igneous and sedimentary derivation in the KKB range in age from 0.5 to 2.4 Ga, whereas metamorphic ages are around 500-550 Ma (Santosh et al., 1992; 2003; Bartlett et al., 1995; Collins and Santosh, 2004). Nd model ages suggest that the granulite protoliths were generated between 2.2 Ga and 1.2 Ga (Brandon and Meen, 1995; Harris et al., 1994; Bartlett et al. 1995), in line with the zircon age patterns reported by Santosh et al., 2003).

These terrains have assumed importance in terms of their potential Pan-African linkage with Sri Lanka, Madagascar and eastern Antarctica (Fig. 10).

3.2 The basement geology of Sri Lanka

The basement rocks of Sri Lanka (Fig. 11) are subdivided into three major lithotectonic units on the basis of rock type, metamorphic grade and isotopic characteristics (Kröner et al., 1991; 2003; Cooray, 1994). These are:

(1) The ***Highland Complex (HC)***, an association of interlayered, predominantly granulite-facies, granitoid (charnockitic to enderbitic) gneisses and clastic to calcareous shallow-water metasediments with ages, based on magmatic and detrital zircons, ranging between ~670 and <1900 Ma and intruded by ~550 Ma late- to post-tectonic granitoids. The gneisses were ubiquitously intruded by mafic dykes that are now structurally concordant with their host rocks.

(2) The ***Wanni Complex (WC)***, an upper amphibolite- to granulite-facies assemblage of ~770-1100 Ma granitoid, gabbroic, charnockitic and enderbitic gneisses, migmatites, minor clastic metasediments, including garnet-cordierite gneisses, as well as late to post-tectonic granites. A suite of upper amphibolite- to granulite-facies, calc-alkaline ~890-1006 Ma hornblende and biotite-hornblende orthogneisses of gabbroic and granitoid composition in the area around Kandy and previously described as *Kadugannawa Complex* is now included in the WC.

(3) The ***Vijayan Complex (VC)***, an upper amphibolite-facies suite of ~1000-1030 Ma calc-alkaline granitoid gneisses, including augen-gneisses, with minor amphibolite layers (derived from mafic dykes) and sedimentary xenoliths such as metaquartzite and calc-silicate rock.

The contacts between the above lithotectonic units are all considered to be tectonic. There is general agreement that the HC/VC contact is a shallow thrust with the HC thrust eastwards over the VC (Vitanage, 1985; Kröner, 1986; Kleinschrodt, 1994; Tani and Yoshida, 1996) with several HC klippen preserved in the VC terrain of SE Sri Lanka. The boundary between the WC and HC is a folded thrust in the Kandy area with the WC thrust over the HC (Kehelpannala, 1997). Elsewhere, however, the WC/HC boundary is ill-defined since there is no clear structural break between these two units. Distinct differences in zircon ages and Nd mean crustal residence ages suggest different origins for these two terrains, but the isotopically defined model age boundary appears incompatible with the structural trends in the SW part of the island.

3.3 Fundamental geological questions

The architecture of southern India and Sri Lanka, especially the relationship between several discrete crustal blocks and intervening shear zones or shear belts (e.g. Moyar-Bhavani, Palghat-Cauvery or the KKPT in India, HC/VC and WC/HC boundaries in Sri Lanka) that may mark collisional sutures, are clearly primary targets for deep geophysical studies. These take on special significance when viewed in the context of the region's keystone position in the geologic reconstruction of Gondwanaland (e.g. Fig. 1). For example, how do the major shear zones of southern India correlate with similar shear zones in Madagascar, Sri Lanka and East Africa? There is general consensus that the late Neoproterozoic metamorphism and deformation reflects Gondwana assembly and, therefore, there should therefore be sutures that mark the boundaries of the various blocks that assembled during this time. Much controversy exists over the location of such inferred sutures in the high-grade rocks of southern India, Sri Lanka, Madagascar, Mozambique and Dronning Maud Land of East Antarctica (e.g., Shackleton, 1996; Collins and Windley, 2002; Collins et al., 2004) with the exception, perhaps, of the Highland/Vijayan thrust in Sri Lanka. Sutures in such terranes are difficult to identify from surface geology since granulite-facies metamorphism, partial melting, and pervasive ductile deformation will mask many of the features used to identify sutures at shallower crustal levels, and suture zones are also more likely to correspond to areas of poor outcrop than to regions of good exposure that attract detailed geological work. Successful identification of such structures requires a combination of isotopic and geological techniques (Collins et al. 2003) and would be greatly helped by seismic reflection studies providing a third dimension.

Most of the exposed rocks in this region record peak temperatures of 850-950 °C at depths of only ~25 km, and some units indicate temperatures of more than 1000 °C at depths of about ~35 km. These temperatures are difficult to reproduce in standard models of collisional orogenesis, and in most cases are explained through some process of post-collisional lithospheric thinning, detachment or delamination, bringing the asthenosphere into close proximity with the lower crust (e.g., Harley, 1998). If so, evidence for this should be preserved at crustal levels below the current erosion surface (e.g. Moho topography, mafic magmatic underplating, etc.), making these regions a prime target for geophysical investigations.

Further questions to be addressed during this survey are: (i) did Pan-African collisional orogenesis result in significant subduction of lower continental crust and mantle as per recent, generalized geodynamic models? (ii) Are discrete crustal blocks still attached to their original, and possibly equally discrete, subcrustal mantle sections? (iii) Do the kinematics of major shear zones record the major accretion events or are these long-lived structures that only variably preserve fabrics from major events? (iv) how much crust was reworked and how much was newly-formed (juvenile) during the major tectono-metamorphic events? (v) Can marine seismic data from continental shelves help to resolve some of the Gondwanan correlation problems presented by subarial geology? Lastly, are the correlations suggested by surface geology and geochronology substantiated by geometric analysis of subsurface features or does lateral transport on intra-lithospheric detachments play a role in 3D reconstructions? It is this broader perspective that distinguishes the geophysical and geological collaboration proposed here.

The reasons for delineating deep structures in these related continental fragments goes well beyond resolution of spatial correlations. For example, the large areas of high-grade metamorphic rock suggests that enigmatic reflection features seen elsewhere may be "calibrated" by comparable surveys here, in which the geology responsible is more widely accessible to view in outcrop. The substantial coast lines of southern India and Sri Lanka provide a remarkable opportunity to evaluate the role of tectonic heredity in guiding continental collapse and break-up. The many "crustal pieces" of varying size and shape provide an opportunity to re-assess the thickness of present-day lithspheric plates by seismic studies (e.g. Jordan, 1975).

If previous experience with other programs is any guide, we fully expect that these discussions will result in recognition of a number of fresh issues that are worthy of seismological investigation. Moreover, such planning must recognize that many of the now famous discoveries of deep seismic profiling were largely serendipitous. Thus, the targeting in any major program of profiling must continually be updated in the context of new results.

4. Deep Seismic Sounding and Deep Reflection Profiling in India

As already mentioned, Indian geoscientists have been engaged in deep seismic surveys of the continental lithosphere for some time. Much of that work prior to the 1990's was focused on the so-called DSS methods, essentially a means of improving the resolution of classical refraction methods by recording detailed wide-angle reflections on closely spaced surveys (Kaila, 1982; Prasad et al., 1986; Kaila et al., 1987, 1990; Krishna et al., 1989; Reddy et al., 1995; Murty et al., 1998; Reddy et al, 1999; Vijaya Rao et al., 2000; Reddy et al., 2000; Reddy et al., 2003). These DSS profiles have provided a basic inventory of fundamental crustal properties across much of India, with the notable exception (until very recently) of the SGT (Reddy et al., 2003; Fig. 12). Indian scientists have recently expanded their crustal studies program to include deep seismic reflection surveys as well as wide-angle recording. Most notable among these deep reflection efforts are the following:

4.1. Proterozoic Aravalli-Delhi Fold belts

A deep crustal seismic reflection (DSR) study, accompanied by limited refraction work, was carried out in 1991-1993 as part of the Deep Continental Studies program of the Indian Department of Science and Technology (DST) along a 400 km profile (the Nagaur-Jhalawar transect) across the Proterozoic Aravalli-Delhi fold belts of the NW Indian shield (Fig. 12; Tewari et al., 1995,1997,1998,2003). The seismic surveys were carried out by the NGRI using a DFS IV, 120 channel seismic reflection system, and the resulting seismic reflection section (Fig. 13) reveals (a) a deeply penetrating, highly reflective thrust fault extending from near the surface to Moho depths that is interpreted as a palaeo-subduction zone (Prasad et al., 1999; Vijaya Rao et al., 2000); (b) variations in crustal thickness and Moho reflectivity and (c) significant lateral and vertical variations in interval velocity on parts of the profile (Satyavani et al, 2000, ; Reddy et al., 1995; Prasad et al, 1997). The quality of the Aravalli deep seismic profile (Fig. 13) is clearly comparable to that of other deep seismic profiles in Precambrian terranes collected by contract crews.

4.2. The Central Indian Suture (CIS)

A coincident seismic reflection/refraction survey was conducted by NGRI in 1994 across the Central Indian Suture (CIS) along the Mungwani-Katangi-Kalimai profile (Fig. 14). The resulting seismic sections revealed an upper transparent crust underlain by a distinct dipping reflectivity pattern down to 14 sec TWT (Reddy et al., 2000, Reddy and Satyayani, 2001). The Katangi-Kalimati section, where the Central Indian Suture (CIS) is inferred, indicates two adjacent fabric domains dipping towards each other with a Moho offset interpreted as a Palaeoproterozoic collision/suture zone (Reddy and Satyavani, 2001). A noticeable change in the reflectivity character N and S of the CIS also supports the above interpretation.

4.3. The Dharwar-Southern Granulite Terrain Transition Zone

Of particular interest to the program being proposed here is the seismic and other geophysical work recently completed along the Kuppam-Palani transect in southern India (Fig. 15). The transect extends from the southern Dharwar craton across the Palghat-Cauvery shear zone into the northernmost part of the Southern Granulite Terrain (SGT). A review of the various geophysical and geological studies carried out along this transect is given in Ramakrishnan (2003). Refraction/wide-angle reflection data along the transect indicate a thick mid-crustal low velocity layer (LVL) throughout the region (Reddy et al., 2003) which corresponds to a high conductivity zone (Harinararayana et al., 2003; Naganjaneyulu and Harinarayan, 2003). Such a correlation provides strong evidence for fluids or partial melts at middle to lower crustal depths. Crustal thickness increases from 36 km north of the Mettur shear zone (low-grade cratonic domain) to about 45 km south of this boundary. Significant changes in reflectivity on the seismic reflection sections have been associated with both the Mettur and Palghat-Cauvery shear zones. The reflection section indicates a striking Moho upwarp of the order of 4-5 km at Nagarasampatti and Chennimalai. A deeply penetrating south-dipping reflection band extending to Moho depth is interpreted as a thrust zone.

Modelling of the gravity field, constrained by the seismic data, supports the variations in Moho topography, and deep resistivity and MT surveys indicate distinctly higher crustal conductivities within the Mettur shear zone (Singh et al., 2003; Harinarayana et al., 2003).). New Nd model ages for rocks along the transect highlight that the southern margin of the Palghat-Cauvery shear system marks a terrane boundary (Bhaskar Rao et al., 2003) that may correlate with east Madagascar (Collins and Windley 2002; Collins et al. 2003).

The geophysical and geological results along the Kuppam-Palani transect are interpreted to indicate that a Precambrian crustal block was upthrust onto the Archean Dharwar cratonic block across the Moyar-Bhavani-Mettur shear zone, which is visualized as a late Archaean/Palaeoproterozoic suture (Raith et al., 1999; Chetty et al., 2003b). Subsequently the region became part of a large transpressional tectonic zone during the Neoproterozoic, when crustal reworking associated with magmatism and migmatization was localized mainly along the shear zones.

The seismic refraction and reflection data collected by the NGRI along the Kuppam-Palani transect are highly variable in quality (Fig. 16; Reddy et al., 2003). This variability is attributed, at least in part, to the "low fold" nature of the acquisition (500m shot-receiver spacing instead of the planned 100m spacing) and considerable gaps in refraction data acquisition (shot point interval of 50 km) due to logisticallyl difficult terrain. These factors reduced the data redundancy available for signal enhancement, especially for the upper crust. This sparse sampling approach was necessitated by the budgetary and logistical limitations. The situation was exacerabated by suspected problems with source coupling along the line.

5. Passive Seismic Studies of the Indian Lithosphere

Indian scientists have also implemented an aggressive program of passive seismic studies of the crust and mantle beneath India (Fig. 17). Receiver functions for the Dharwar craton have found that the crust beneath the western Dharwar craton is significantly thicker (ca 41 km) than that beneath the eastern Dharwar craton (ca 34 km) although the gross shear wave structure is essentially the same for both (Sarkar et al., 2003), with no evidence of a high velocity basal layer that might indicate mafic cumulates (e.g. Rai et al., 2003). Receiver functions indicate that crustal structure in Proterozoic crust north of the Dharwar craton is more complex, but structure at Tirvandrum in the southernmost part of the SGT is similar to that of the Archean (Kumar et al., 2001). Perhaps the most surprising result of passive seismic measurements to date in India is the indication of anomalously thick crust (up to 60 km) beneath the Nilgiri block of the SGT (Gupta et al., 2003 a,b). If this result stands up, it represents one of the thickest sections of continental crust outside an active mountain belt anywhere in the world.

Most of the broadband stations used for passive seismic estimation of crustal properties are located north of the SGT. However, the permanent station at Trivandrum (Fig. 17) and temporary stations at PCH and KOD (Fig 17) all sample the SGT and indicate crustal thicknesses of 35, 39 and 43 km respectively (Kumar et al., 2003; Gupta et al., 2003a).

6. The Proposed South India-Sri Lanka Transect

Studies on the deep continental crust assume great significance in terms of continental lithospheric geodynamics primarily because much of the upper crust has developed during processes that involved the deep crust. These studies are fundamental to the formulation of geodynamic models for the evolution of the Earth, to understand the juxtaposition of continents in the geologic past and also in obtaining information on potential mineral resources. The proposed southern Indian/Sri Lankan transect will probe one of the largest exposed deep continental sections on Earth and will thus provide general information on the composition, processes and evolution of the middle to lower crust.

We envisage that the Southern Indian-Sri Lankan LEGENDS Traverse will consist of seismic experiments, accompanied by integrated studies of international teams from several countries, formal field and laboratory workshops as well as informal research visits between the participating scientists. Also, the new data from the above traverse should be evaluated in terms of deep seismic reflection results and accompanying studies from other regions of the world which contain active analogues of the geologic processes involved. The example of Tibet comes to mind since recent deep seismic studies of the type under consideration here have revealed important new aspects of collisional structure that may relate to formation of the granulite terranes of southern India and Sri Lanka (e.g. Brown et al., 1996; Nelson et al., 2002).

The Dharwar craton of southern India was cratonized by the end of the Archaean whereas the high-grade SGT comprises a number of distinct crustal blocks, welded together probably in the Neoproterozoic and dissected by major transcrustal shear zones. With a variety of lithologic assemblages, structural patterns, spectra of textural and mineralogic features, diverse fluid composition and fluid-rock interaction, and distinct geochemical and age signatures, these granulite blocks, associated intrusives and the network of shear zones provide an excellent opportunity to understand deep crustal and crust-mantle interaction processes.

The Kuppam-Palani geotransect (section 4.3), executed in 2001, examined a crustal section from the Archaean low-to high-grade metamorphic transition in the north well into the Southern Granulite Terrain. This traverse transected a large part of the Archaean granulite domain of the southernmost Dharwar craton, including the crustal-scale Palghat-Cauvery shear zone system, consisting of discrete shear zones that reflect structural and petrological reworking of the Archaean crust in the Neoproterozoic. Based on this integrated study, some of these shear zones have been modelled as important terrane boundaries separating temporally distinct crustal blocks. This transect has also brought out the possibility that the Archaean-Neoproterozoic boundary in the SGT may extend up to the Karur-Kambam-Painavu-Trichur (KKPT) line (KKPT, see Fig. 7). It is therefore essential that the multidisciplinary studies conducted north of the KOSZ (Ramakrishnan, 2003) are extended to the region farther south.

Some major scientific targets of this new transect include: (1) The nature and subcrustal architecture of major shear zones such as the Palghat-Cauvery shear system, the KKPT and the Achankovil Lineament in southern India (Fig. 7) and their tectonic significance. (2) The nature and deep crustal configuration of the boundary between southern India and Sri Lanka, considering that these two crustal provinces are difficult to correlate by surface geology (Kröner et al., 2003). (3) The nature of crustal transition between southern India and Sri Lanka (oceanic, extended continental or transform). (4) The nature of the boundary between the Wanni and Highland, and between the Highland and Vijayan Complexes in Sri Lanka and their extensions into the lower crust. (5) The nature and composition of deep crustal fluids in southern Indian and Sri Lankan granulites and their role in high-grade metamorphism and retrogression in shear zones.

In a broader perspective, perhaps the most important unresolved problem in southern India and Sri Lanka concerns the tectonic relationships between the various crustal provinces and their potential continuation in other, now dispersed, parts of Gondwanaland. It is important to understand the nature and role of convergent versus extensional tectonic processes in space and time, which have contributed to the evolution and exhumation of the granulites. Even such basic questions as the location of sutures and subduction polarities remain unanswered. The proposal would also address several regionally important geologic problems that cannot be resolved by geophysical work, but where geophysical surveys will provide impetus for geological research, namely:

(1) The time frame of granulite-facies metamorphism: Do the granulites represent Archaean and Palaeoproterozoic rocks reworked during the Neoproterozoic or were there also new additions during the Neoproterozoic?

(2) Do the Kerala Khondalite and Madurai-Kodaikanal belts represent temporally different terrains?

(3) What is the relationship between the structural evolution of the high-grade terrains in southern India and Sri Lanka? Is there a common tectonic history and when did it begin?

(4) What do the sedimentary protoliths tell us? Are they passive margin sediments? Do they represent closure of ocean basins? What are the sources of the sediments?

(5) Do the major shear zones in southern India and Sri Lanka represent potential zones for mineral deposits and what is the role of fluids in shear zones?

7. Objectives

The study will help us to bring into focus lateral and vertical structural and compositional variations in the varied metamorphic terrains extending from north to south across segments of old cratonic blocks and surrounding mobile belts. The study should also help to fix the position of southern India and Sri Lanka in the vast expanse of the Gondwana supercontinent. Specific objectives of the proposed transect are:

(1) To delineate the crustal and upper mantle structure of the SGT and Sri Lanka in terms of seismic P and S-wave velocity structure, reflectivity characteristics, and velocity anisotropy. Interpretation of these results will be constrained by more detailed gravity, magnetic, magnetotelluric and resistivity observations. Of particular interest will be the detection and delineation of known and suspected shear zones and suture zones that are key markers for the structural evolution of this area. The details of lithospheric structure expected from these surveys will not only serve as guides to geological evolution of southern India and Sri Lanka, respectively, including the question of how UHT rocks were created in the lower crust, but will also provide a new 3D basis for evaluating the tectonic connections, if any, between these two key Gondwana blocks.

(2) To determine the thickness of the lithospheric keel beneath India and Sri Lanka from seismic tomography, as well as detail the geometry of the mid-mantle discontinuities (410-km and 660-km) as constraints on the mantle evolution of the region. Systematic variations in these deep parameters throughout East Gondwana should help assess the depth to which crust-mantle interactions are involved in collisional orogeny.

(3) Understanding the kinematics and geometry of key tectonic discontinuities such as major faults and shear zones and the boundaries separating distinct geologic terrains based on synoptic interpretation. Specifically, the geophysical work should help to identify potential suture zones that are likely to separate the various blocks making up the southern Indian-Sri Lankan high-grade terrain.

(4) Improve the existing geochronological data, which are scanty in both methodology and regional coverage, particularly in southern India. Multi-geochronometric age determinations by combining U-Pb and Lu-Hf on zircon and monazite with whole-rock and mineral Sm-Nd and Rb-Sr isotopic methods will be undertaken to determine the timing of crust-formation, deformation and metamorphism

(5) Integrate geological and subsurface data with satellite observations of regional structures and geophysical anomalies.

(6) Determine physical properties such as density, magnetic susceptibility, palaeomagnetic directions, electrical and thermal conductivity, compressional and shear wave velocities on a representative set of samples along the corridor to constrain interpretation of in situ observations.

(7) Modelling of crust-mantle evolution in space and time by integrating the geophysical and geological data sets, particularly in terms of the cratonic domain, the craton-mobile belt

interface, major crustal accretion along the geotransect and the question of whether extensive magmatic underplating played a role in the generation of UHT rocks.

(8) To contribute towards a more compatible geodynamic model that juxtaposes India and Sri Lanka with other continental fragments of the Gondwana supercontinent.

(9) To determine the nature and extent of gold, molybdenum, tin, tungston and REE mineralization along major shear zones.

8. Work Plan and Methodology

The geophysical surveys will be carried out by scientists of the NGRI in cooperation with Cornell University, Geoforschungszentrum Potsdam and CSIRO, Australia. The accompanying geological, petrological, geochemical, geochronological and palaeomagnetic work will be undertaken by an international consortium consisting of scientists from India, Sri Lanka, Germany, France, U.K., Australia, USA and China.

The project will try to implement a mixed seismic (termed SEISMIX) experiment. The core of the effort will be a series of deep seismic reflection profiles to provide the structural detail needed to relate surface geology to lower crust and upper mantle heterogeneity. The CMP style profiling will be complemented by wide-angle recording of both P and S waves to provide velocity estimates at depth. Offsets adequate to obtain Pn and Sn arrivals will be sought to allow unambiguous identification of the Moho. The controlled source effort will be matched by passive recording of earthquake sources in two modes: (a) high resolution passive profiles (using both broadband and short period instruments) across key features (e.g. shear zones, the gap between India and Sri Lanka) to provide detailed receiver functions to trace key markers such as the Moho across putative terrain boundaries and closely spaced estimates of crust and mantle anisotropy to evaluate kinematics of lithospheric deformation; and (b) a regional 2D array of broadband instruments to allow P wave and surface wave tomography delineation of lithospheric thickness in 3D.

A provisional deployment geometry for the active/passive seismic surveys is shown in Fig. 18. Instrumentation for these surveys will be derived from pools available to India, US and German participants. Key components include:

(a) Two 24-bit high dynamic range (144 db) seismic RF telemetry systems available at NGRI. This system is comparable to the industry reflection systems commonly used to collect multichannel deep seismic reflection data in other parts of the world This system is a substantial technical upgrade over the DFS IV used by NGRI in their previous deep seismic surveys. The large dynamic range and digital telemetry should greatly improve the signal to noise in reflection recording.

(b) Ca. 1000 portable single channel recorders (e.g. Texans) from the US IRIS instrument pool, to be provided through Cornell University (USA). These instruments can be used for both reflection and wide-angle recording, as well as special geometries such as wideline and crossline configurations for 3D control. They are especially useful in rough terrain.

(c) Ca. 100 three-component seismic recorders (REFTEKS and PDAS) from the IRIS (USA) and GFZ (Germany) instrument pools, to be equipped with short period (e.g. Guralp or Mark Products L-28) sensors for recording wide-angle/refraction data and teleseismic data for receiver functions.

(d) Ca. 50 broadband recording systems (e.g. REFTEK DAS with Guralp or STS2 sensors) from the instrument pools of IRIS (Cornell) and the GeoForschungsZentrum (GFZ), Potsdam, Germany, respectively. The broadband units will be used in both the detailed passive program and the 2D tomographic deployment.

(e) Explosive sources for the reflection/wide-angle/refraction program. NGRI has considerable expertise in supervising the drilling and shooting activities needed for this type of seismic work. It is expected that the seismic drilling will be carried out by local contractors under NGRI supervision. Since the quality of the seismic data depends heavily upon good source coupling, special attention will be placed upon source positions and quality control during source preparation.

Continuous high resolution seismic reflection coverage may not be feasible for the entire geotransect, so emphasis will be placed on key tectonic boundaries and shear zones. Source spacing of 100-200 m for 25-50 kg charges, with receiver spacing of 50-100 metres for 240 channels, is the nominal expectation for reflection recording. This corresponds to a nominal stacking fold of 30-60 (not including wide-angle contributions). These closely spaced sources will be augmented by larger shots (500 –2000 kg) at ca 50-100 km intervals to provide adequate signal at large offsets for refraction work. A recording spacing of ca 1 km is planned for the wide-angle component, with 3-component instruments interspersed with single-component Texans.

Given that many of the passive instruments (short period and broadband) will be located near coastal regions, where noise is known to be a serious problem, and that teleseismic source regions are limited, we expect that extended deployments will be needed to obtain satisfactory receiver function and tomographic results. Therefore we expect to use a minimum of 1 year for the high resolution passive profiles and 3 years for the 2D broadband array.

The channel between South India and Sri Lanka (Gulf of Mannar) suggests the possibility of using marine sources with the land stations to image (at least at wide angle) the crustal structure between these two landmasses. However, this marine zone is a sensitive area, and permissions for use of marine sources and receivers is currently uncertain. Likewise, possible instrument sites along Adam’s bridge, the thin strand of land between southeastern India and NW Sri Lanka, are an attractive option for spanning the zone between the countries. However, access to this region is currently limited due to political concerns. Deployment of ocean bottom instruments (including broadband) is also an option under consideration. These aspects will be pursued as circumstances allow. Details of instrument deployment is dependent upon careful scouting of routes, to be carried out during the preparatory phases of this work.

Gravity and magnetic data will be acquired simultaneously at a large number of stations (about 4000) within a ~100 km wide corridor. The station interval will be guided by the available gravity data. Magnetotelluric (100 stations) and resistivity (50 stations) experiments will be conducted along the transect, coincident with the seismic profile to derive the subsurface geoelectric structure. Sampling and determination of physical properties such as density, magnetic susceptibility, electrical and thermal conductivity, compressional and shear wave velocities palaeomagnetic directions and heat flow on representative sets of rock samples along the corridor will facilitate a better interpretation of the geophysical data.

Lacoste-Romberg (Model-G) gravimeters with an accuracy of 0.01 mGal will be used for the 4000 new gravity measurements along the geotransect. In order to minimize the error due to drift in the instruments, secondary bases will be established throughout the corridor, which will be tied to the base already established by NGRI. The gravity data will be collected along a 300 km long seismic line at an average interval of about 0.5 km and in a 100 km wide corridor on either side of this transect at a spacing of approximately 2 km located along roads. The geodetic survey team provides the position location and elevation of the gravity stations along the seismic line. The 1:50,000 toposheets of the Surveys of India and Sri Lanka will be used for locating the rest of the gravity stations along the corridor. For elevation control most of the stations are located at the Bench Marks and the Spot elevations, whereas elevation for the other stations will be derived from measurements made by GPS. Total intensity magnetic measurements will be made along with the gravity at all stations.

Synoptic geological and structural interpretations will be prepared from satellite images and field mapping of key domains and preparation of geological and structural cross sections. Geological mapping of the corridor will be undertaken, where required, with detailed structural mapping of the shear zone systems along the corridor and at key locations outside the corridor. Emphasis will be placed on understanding the geometry and kinematics of fault/shear movements at major terrane boundaries.

Sampling, petrography and electron microprobe mineral analysis (EPMA) will be carried out to decipher P-T-t paths of important metamorphic units. The currently available data only provide a broad overview and is limited to a few studies. The proposed study will employ

EPMA and geothermobarometric studies involving metapelites, mafic granulites, charnockites and granitoids. Keeping in mind that the terrain has probably experienced more than one granulite-facies metamorphic event, the P-T determination and study on fluid migration should focus only on carefully time-calibrated samples. Combined dating and P-T determination on core and rims of single garnet crystals may reveal P-T-t ancestry of the rocks. The nature and composition of fluids in charnockites, gneisses and granitoids will be studied along the traverse in order to assess the role of such fluids during metamorphism and fluid-rock interaction during lower crustal processes as well as to understand the influence of fluids in localization and initiation of shear zones.

Major and trace element geochemistry of representative and dominant lithologies will be determined along the corridor, combined with isotopic studies (O-, Rb-Sr, Sm-Nd, Pb-Pb) and modelling of petrogenetic conditions. The focus will be on the charnockites and granitoid gneisses.

Age determinations by a combination of U-Pb, ^{207}Pb/^{207}Pb, Sm-Nd, Lu-Hf, Rb-Sr and ^{40}Ar/^{39}Ar isotopic methods with an objective to determine the timing of rock and protolith formation, deformation and metamorphism in the major crustal blocks along the corridor are required. Dating major faults, shear zones and crustal uplift by whole-rock and mineral analysis using U-Pb, Rb-Sr, ^{40}Ar/^{39}Ar, U-He and fission track methods will contribute significantly to a better understanding of the exhumation and uplift history of the terrain.

The crustal growth and reworking history will be determined from a combination of age and isotopic tracer studies. The tectonic setting of the major crust-forming events will also be evaluated using these data and other geochemical information. Where available, lower crustal and mantle xenoliths will be studied to determine the composition and thermal history of deep, inaccessible parts of the lithosphere.

The field program proposed here is designed not only to address the specific issues related to southern India and Sri Lanka but to provide a basis of comparison for future data acquired in other parts of East Gondwana. This is an important aspect of the LEGENDS initiative: individual surveys are to be acquired in the context of their relevance to understanding the evolution of Gondwana as a whole. In addition the geophysical and field data will provide an important base for exploration of unexposed mineral resources.

9. Need for collaboration

International collaboration is called for, both on geological and geophysical grounds. With respect to geology, we have already argued, and here re-emphasize, that the investigation of lithospheric structure and processes in southern India and Sri Lanka cannot be completed without consideration of what is exposed in the adjacent parts of Gondwana (e.g., Kröner et al., 2003). Whereas a pan-Gondwana perspective is already extant among geologists, there has been no similar geophysical perspective, at least insofar as deep seismic studies are involved.

From the geophysical point of view, collaboration in planning of future surveys is virtually *de rigueur* given the complexity and instrumental requirements of a modern, hyperspectral geophysical profile. As substantive as is the geophysical acquisition equipment owned by the NGRI, a future experiment would gain immeasurably from the additional resources that could be provided by such countries as the United States, Germany, Australia, U.K. and France. For example, deployment of the multichannel profiling system of NGRI could be integrated with a deployment of portable reflection/refraction instruments (e.g. Texans/REFTEKS) available to U.S. researchers through the IRIS consortium. One candidate survey configuration would have the NGR multichannel system record structural details at near-vertical incidence whereas 800 channels of IRIS "Texans" provide wide aperture for physical property estimation and/or 3D control. Moreover, 3 component IRIS REFTEKS could provide critical shear wave information from the same source used for simultaneous CMP reflection and wide-angle recording. Alternatively, deployment of large numbers of recorders could reduce survey costs by providing recording redundancy (e.g. stacking fold) in place of source redundancy.

Modern seismic surveys of the lithosphere go well beyond the simple exercise of running an oil exploration system with longer recording times. In the INDEPTH project, for example, the seismic component involved simultaneous CMP profiling (as used in oil exploration), 3 component wide-angle recording, and passive broadband teleseismic recording (e.g. Brown et al., 2001). In addition, an extensive program of complementary magnetotelluric surveys and ground mapping was carried out. Such interdisciplinary approaches require careful, long-term planning and coordination of instrumentation pools and personnel.

Another aspect of the collaboration is the desirability of having different kinds of geophysical surveys, as well as additional geological observations, collected along the same route. The integration of seismic and magnetotelluric methods, for example, has been particularly fruitful in recent international lithospheric surveys. (e.g. Nelson et al., 2002).

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Figure Captions

Fig. 1. SNORCLE deep reflection profile in northwestern Canadian shield. After Cook et al., 1998.

Fig. 2. Global deep seismic reflection programs.

Fig. 3. (top) Deep Seismic reflection techniques. (bottom) Integration of deep reflection and receiver function imaging along SNORCLE transect in NW Canadian shield (After Bostock, 1998.

Fig. 4. Gondwanaland reconstruction. After Lawver et al. (1999).

Fig. 5. The East African Orogen. After Stern (1994).

Fig. 6. Relative sizes of the Gondwanaland fragments.

Fig. 7. Geologic terranes of southern India. From Geological Excursion Guide; Tectonics and evolution of the Precambrian Southern Granulite Terrain, India and Gonwanian Correlations.

Fig. 8. Topography of southern India.

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Fig. 10. Geological reconstruction of Gondawanaland. After Kroener et al., (2003).

Fig. 11. Geology of Sri Lanka (Courtesy of W. Kehelpanala).

Fig. 12. DSS and deep reflection profiles in India. From Reddy and Rao (2002).

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Fig. 15. The Kuppam-Palani geotransect (Reddy et al., 2003).

Fig. 16. Sample of seismic reflection data from Kuppam-Palani geotransect (Reddy et al., 2003).

Fig. 17. Seismic stations used for passive seismic studies of lithospheric structure. Circles indicate permanent stations; triangles indicate temporary deployments of broadband instruments. After Kumar et al. (2001).

Fig. 18. Proposed seismic deployments for detailing lithospheric structure in southern India and Sri Lanka.