Deep Seismic Exploration of East Gondwana:

The LEGENDS Initiative

Systematic exploration of the continental lithosphere by deep seismic reflection profiling over the past 20 years has revolutionized our view of the deep crust and upper mantle. National programs such as COCORP in the United States, BIRPS in Britain, LITHOPROBE in Canada, and many others have produced detailed seismic images that have addressed fundamental geotectonic questions**.** The result has been a string of important scientific discoveries about the deep geometry of major faults, the nature of the continental Moho, the existence of magma ”bright spots”, heterogeneity in the upper mantle as well as the crust and spectacular intrusive sequences deep within the Precambrian cratons.

Spectacular though these results have been, such surveys have been limited largely to North America, Europe and Australia. Although recent multinational efforts have produced important 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 imaging.

From a geological perspective, perhaps the largest expanse of unexplored continental lithosphere lies in those fragments that were once part of the supercontinent of Gondwanaland. With the exception of Australia, which has pioneered the use of deep reflection surveying since the 1960s, and India, where numerous older DSS style seismic surveys have been collected, relatively few seismic profiles exist to delineate the gross structure, much less the details, of continental architecture of this region which has played such an important historical role in the development of plate tectonic theory.

We suggest that the time is ripe to consider a comprehensive program (LEGENDS, for Lithospheric Evolution of Gondwana East from iNterdisciplinary Deep Surveys) to probe the structure of East Gondwanaland. Geological and geochemical/isotopic studies of the crystalline rocks in East Africa, Madagascar, southern India, Sri Lanka, and East Antarctica now provide a firm basis for framing geotectonic questions that can be addressed by such surveys. 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. At the same time, new seismic technologies make land surveys in previously remote areas more practical, and have greatly expanded our abilities to quantify physical properties at depth.

Why East Gondwana? Inspection of large scale geologic trends in East Gondwanaland suggest at least two principal corridors for deep geophysical surveys: one across the East African Orogen (LEMURS, for Lithospheric Evolution from MUltidisciplinary suRveys of a Supercontinent), and one already begun by Japanese scientists in East Antarctica (SEAL, for Structure and Evolution of the East Antarctic Lithosphere)

The East African Orogen (Figure 1) has been interpreted as the site of ocean closure and continental or terrane collision in the Neoproterozoic, when the Congo-Kalahari blocks converged with India and East Antarctica to form Gondwanaland. The site of the collision zone is defined by a broad belt, several hundred kilometers wide, of granitoids, gneisses and high-grade metamorphic rocks involved in the collision. Metamorphic assemblages clearly demonstrate that we are looking at ca 10 kbar rocks at the surface today; some 30 km of overlying crust has somehow been removed. Because 30 km or more of crust still underlies these belts, we are presumably looking at an exposed mid-crustal analogue for the Himalayan/Tibetan region. Thus the program suggested here should provide a test of concepts in modern as well as ancient orogeny, and help calibrate seismic character with deep crustal geology.

Madagascar is the keystone of this tectonic corridor because the suture between the Indian and Congo-Kalahara cratons potentially runs through the island. There are several models for where the suture might lie, and a real possibility exists that there may be more than one branch of the Neoproterozoic Mozambique ocean that closed during the collision. Also, there is a need to investigate whether the major crustal boundaries recognized by geological mapping extend to depth and continue across the Gondwana fragments. A north to south traverse in India would cross from the Archean Dharwar craton through its southern boundary to the Pan-African orogenic belt of southern India. At the boundary is a major shear zone, the Palhvat-Cauvery, several tens of kilometres wide, associated with other parallel shear zones and containing several mafic and ultramafic complexes. It is possible that this is one of the major suture zones, which continues northwestwards into the main Pan-African suture zone of eastern Madagascar.

Near the southern tip of India is the Achankovil shear zone, which has Pan-African high-grade rocks on both sides, and which may correlate with the left-lateral Ranotsara shear zone in southern Madagascar, which similarly has high-grade Pan-African rocks on either side. In so far as the Ranotsara shear zone can be reasonably extended northwestwards as one of the several left-lateral shear zones crossing the East African orogen, this shear zone in total must be many hundreds or even a thousand or so kilometres long. It is an important post-collisional shear zone, which may be related to some component of late indentation, perhaps like the transcurrent faults in Tibet today.

The suture zone in eastern Madagascar has an Archaean terrane on its eastern side, and a 700-800 Ma deep level continental magmatic arc on its western side. However the Palghat-Cauvery suture in southern India, whilst having an Archaean craton on its northern side, has a Pan-African orogen on its southern side, which does not have a subduction-related magmatic arc. It is likely therefore that the major bend in this suture zone from Madagascar to southern India is related to the westwards indentation of the Archaean Dharwar craton, which would have a suture zone on its frontal leading edge, comparable to the Indus suture zone of the Himalayas, but a transform boundary on its southern side, comparable to the Chaman fault on the western side of India.

The thrusts associated with the suture zone in eastern Madagascar dip shallowly to the west at the surface. They may continue at depth with this shallow westerly dip, in which case Madagascar represents a thin-skinned orogenic belt, an hypothesis which seismic surveys will clearly be able to test. It is also possible that the Archaean Dharwar craton was subducted westwards under the orogenic belt now in Madagascar, analogous to India being thrust under Kohistan and Tibet in the Himalayas today. Therefore it is possible that there could have been a major increase in crustal thickness to the 60 km level (considering the assemblages indicate some 10 kbar at the surface today) in central Madagascar, and the remnants of this increased crustal thickness could be detected and defined by the deep seismics.

Although there is evidence for the formation of new Neoproterozoic crust in the Mozambique Belt (MB) of Tanzania, the vast majority of gneisses appears to be of Archaean to early Proterozoic age and represents reworked equivalents of cratonic crustal elements now exposed farther west. There are also early Proterozoic (ca. 2 Ga) and Neoproterozoic eclogites. The traverse would shed light on the crustal architecture and structural evolution of the MB, help identify the Tanzania craton/Mozambique belt structural boundary, perhaps resolve the tectonic significance of the eclogite occurrences (cryptic sutures?) and contribute to defining the boundaries between Neoproterozoic and older crustal elements (major thrusts resulting from terrane amalgamation?). Anti-clockwise PT-paths in the MB of Tanzania have been related to processes of magmatic underplating, an hypothesis best tested by seismic imaging.

An E-W traverse across Sri Lanka from Colombo via Kandy to Batticaloa would cross all its major crustal units. The tectonic boundary between the Vijayan and Highland Complexes has long been regarded as a major shallow W-dipping thrust and terrane boundary, whereas the boundary between the Wanni and Highland Complexes is structurally ill defined. Seismic imaging would enable us to study the deep crust of what has been interpreted as the root zone of a Grenville-age magmatic arc (Vijayan Complex), an ancient passive continental margin (Highland Complex) and a late Mesoproterozoic to early Neoproterozoic magmatic arc with several mafic layered complexes (Wanni Complex), all caught up in collision tectonics during amalgamation of Gondwanaland. The basement of Sri Lanka is also the link between East Antarctica (Lützow-Holm Complex), southernmost India and the enigmatic Grenville-age gneisses of northern Mozambique.

Seismic surveys in East Antarctica will traverse geologic terranes that are believed to be corollaries of the East African Orogen. This corridor is already the focus of ongoing crustal seismic surveys as part of the SEAL (Structure and Evolution of East Antarctic Lithosphere) initiative of the National Polar Research Institute of Japan. The Japanese seismic team has thus far focused on deep refraction/wide-angle reflection profiles to produce a complete crustal section from Western Enderby Land to the Eastern Queen Maud Land, terranes spanning the Archean to early Paleozoic. Addition of reflection profiling and ultradeep passive seismic transects would provide a comprehensive basis for comparing lithospheric structures in related parts of Gondwanaland.

A synopsis of the fundamental questions that may be addressed by deep seismic profiling in East Gondwana might include:

- Where is/are the Neoproterozoic suture(s) between India and the Congo?
- Was one of the continental blocks thrust under the exposed granite-gneiss terrain, like India has been thrust beneath southern Tibet?
- Do the exposed granite-gneiss terranes in Madagascar and East Africa truly represent an analogue for the ca. 20 km deep crust beneath Tibet ?
- Are the younger Mesozoic breakup margins controlled by, or spatially related to, the older collisional crustal architecture?
- Does Neoproterozoic continental underthrusting involve delamination of the crust at mid-crustal or base-of-the-crust levels?
- Can the very broad zone of crustal reactivation of 2.5 Ga crust in the late Neoproterozoic be related to the degree or extent of crustal underthrusting?
- Is the suture between the East African and Indian Archaean cratons a flat-dipping or steep structure at depth?

- Is there any evidence for asthenospheric underplating of the East African orogen by mafic bodies (as is suggested by anticlockwise PT paths)?
- Do the late stage ca. 530–500 Ma transcurrent faults go down to the mantle, and do they juxtapose continental crust of different types?
- What is the lithospheric structure through a major transform margin (Eastern Madagascar and Western India)?
- Are the Mesozoic basins of western Madagascar and Somalia controlled by inherited Neoproterozoic structures?
- What is the origin of the Ultra High Temperature terranes of the Napier Complex?
- Is there a lithospheric keel beneath continental fragments the size of Madagascar or Sri Lanka?
- What role do Precambrian structures play in neotectonics (a question rendered more than academic by the devastating Guajarat earthquake of January, 2001)?

Seismix. The core of the proposed activities will be a series of modern, lithospheric-scale seismic surveys across key elements of the East African Orogen and its extensions (Figure 2). While such surveys face substantial challenges due to difficult terrains on land, they also benefit from the fact that the now-dispersed fragments of Gondwanaland are surrounded by oceans and thus many geological targets can be investigated by marine deep seismic profiling and onshore-offshore techniques. Most importantly, substantial economies of scale can be realized by approaching the deep exploration of Gondwana in the systematic, long-term manner so successfully employed by the major national programs like COCORP, BIRPS and LITHOPROBE.

The critical elements of a modern lithospheric seismic survey include:

Deep seismic profiling (land and marine), also known as multichannel (MCS) or common midpoint (CMP) profiling. Although the most expensive of the seismic techniques, it is the only method that can provide resolution comparable to surface geologic outcrop. Since marine seismics are generally an order of magnitude less expensive than land seismics, the extensive coastal exposure and submarine extent of geologic terranes in Eastern Gondwanaland is a major logistical advantage. On the land side, new portable seismic instrumentation (such as the PASSCAL "Texan") offer opportunities for land profiling at considerably lower cost than traditionally-used oil exploration contract crews. In general deep reflection profiling has been particularly effective in Precambrian terranes.

Wide-angle reflection and refraction profiling can provide estimates of physical properties (Vp, Vs, Q, anisotropy) to upper mantle depths. With Ocean Bottom Seismometers (OBS), wide-angle surveys can be extended across the ocean-continent boundary well into oceanic lithosphere.

Natural source techniques exploit seismic waves from earthquakes (local and teleseismic) to image lithospheric structure from below. Such recordings can be used to map deep velocity variations by tomographic methods, delineate major intralithospheric (e.g. Moho) and sublithospheric (e.g. 410 km, 670 km) discontinuities by receiver function techniques, and map deep anisotropy (SKS techniques) as a guide to modern and ancient shear orientations. A new generation of broadband OBS now make it possible to apply these techniques to water covered areas as well as land, and thus removes the ocean-land interface as a barrier to continuous lithospheric imaging.

A critical consideration in any major lithospheric seismic experiment is the availability of appropriate instrumentation. Deep reflection profiling can draw upon both oil industry resources (land and marine seismic crews) and/or academic facilities (seismic capable ships, portable land instruments). There are a number of institutional (e.g. ETH Zurich, Leicester, GFZ Potsdam, NGRI Hyderabad) and national (e.g. IRIS PASSCAL in the US, ANSIR in Australia, Japan) instrument pools, which can provide appropriate instruments. Although demand is high and scheduling tight, with proper planning the surveys envisioned here are feasible given both existing and projected numbers of instruments.

However, we also propose that, as part of this initiative, a dedicated instrument pool be developed to not only help support these surveys but to provide a long term resource for the countries hosting these activities. Such a pool could be critical to follow up and spin-off studies by scientists from the Pan-Indian Ocean region.

Although the focus in this document is on seismic methods, other geophysical techniques, especially magnetotellurics (MT), gravity and magnetics, are expected to make critical contributions as well. Special geological studies (e.g. strip maps, structural sections, geochronologic studies) are also expected to be needed to maximize the value of the new geophysical data.

Organizational Approach. The geology of Gondwanaland has been a theme uniting geologists from many countries for some years. The geological syntheses and collegial international relations from these activities are important resources for the initiative envisioned here. Conversely, just the planning of surveys such as those considered here can stimulate fresh approaches to identifying and clarifying key geological issues. The proposed surveys will certainly provide extensive access to modern equipment and associated training for scientists and students in region. Programs such as LITHOPROBE in Canada and EUROPROBE in Europe offer possible models for operating such an ambitious multinational endeavor. The International Lithosphere Program can serve to help organize such activities. Wherever possible, the surveys envisioned here should recognize, build upon and cooperate with other major geophysical programs in the area (e.g. KRISP activities along the East African Rift, the proposed EAGLE initiative in the Afar, the KAAPVAL Craton project in South Africa).

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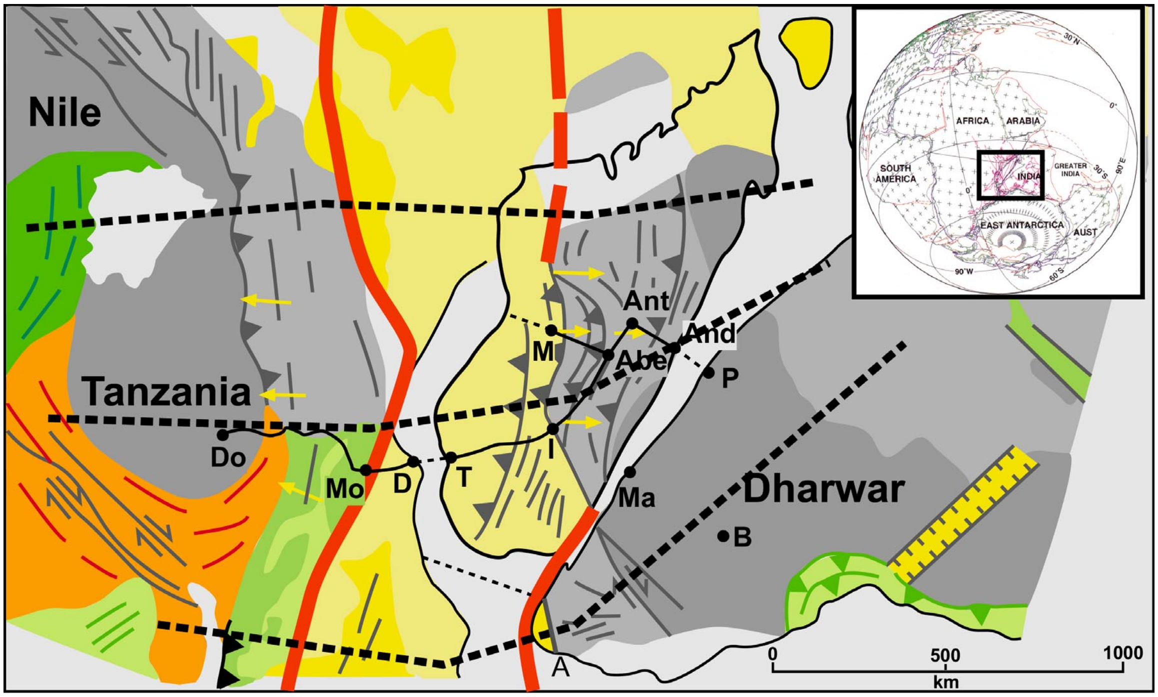

Do - Dodoma
Mo - Morogoro
D - Dar es Salaam

T - Toliara
I - Ihosy
Abe - Antsirabe
M - Miandrivazo
Ant - Antananarivo
And - Andevoranto

Ma - Mangalore
B - Bangalore
P - Panjim
A- Achankovil Shear zone

Figure 1. Tectonics elements of East Gondawana (India–Madagascar–Congo fit; courtesy of C. Powell). Archaean cratons are shown in dark gray; Palaeoproterozoic crust (commonly reactivated in the Neoproterozoic) in light gray; green represents areas of late Mesoproterozoic–earliest Neoproterozoic deformation and magmatism; yellow areas of Neoproterozoic magmatism, deformation and, in parts, juvenile crust. Together with coordinated surveys across Sri Lanka and East Antarctica (Figure 2), a systematic program of deep seismic profiling would reveal critical elements of lithospheric architecture in this critical nexus. Dashed lines are intended only to indicate the possible scale of seismic profiling. Solid line is an example of how an actual (land) survey route might look. Inset shows location of map relative to Gondwana fit of Lawver et. al. (Mem. National Institute of Polar Research Spec. Issue 53, 1998)

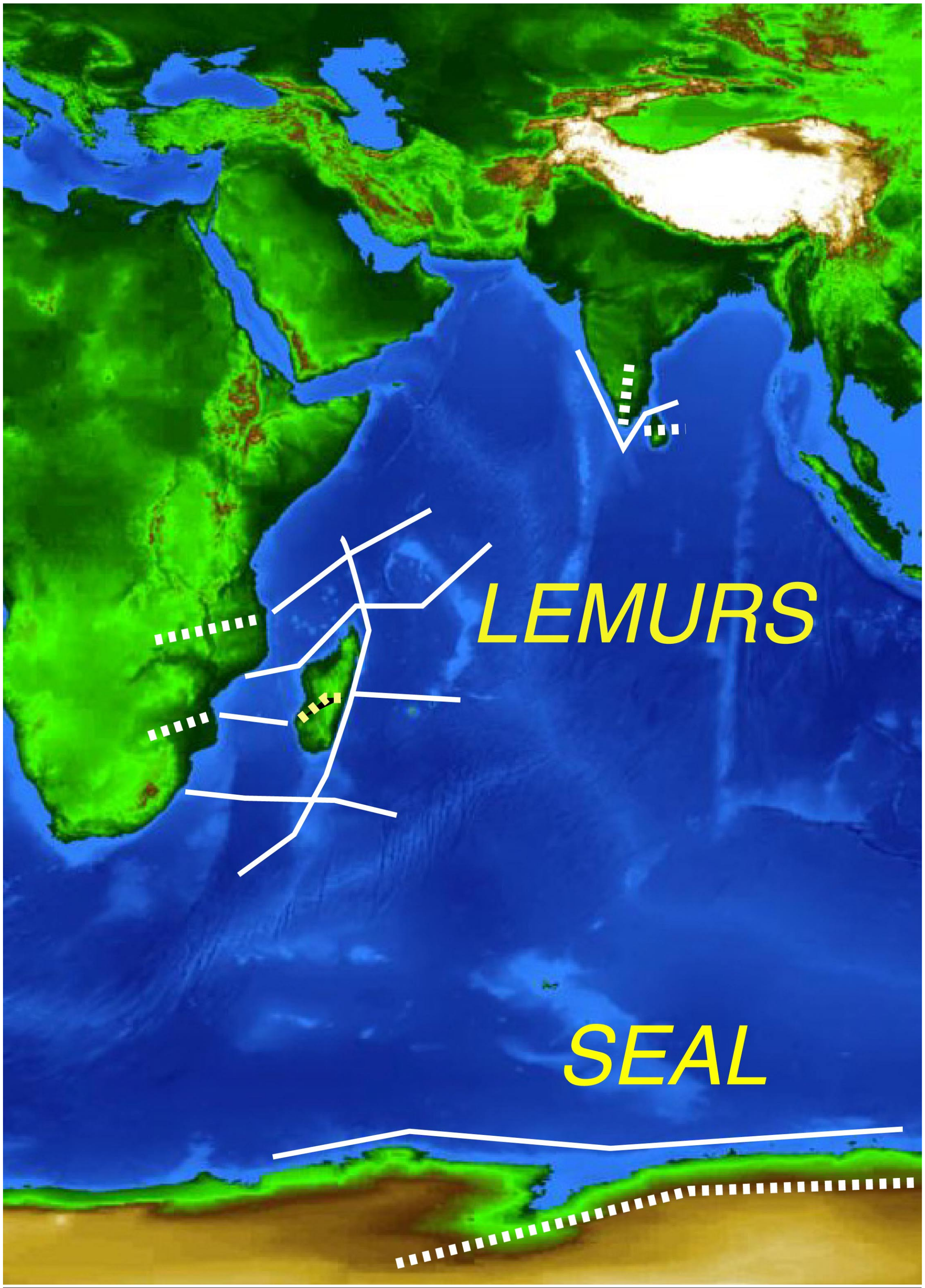

Figure 2. Present-day continental configuration, with example of a possible program for deep seismic surveys at sea (solid) and on land (dashed). Post-breakup dispersal of Gondwana fragments makes key elements of the former continental interior accessible to less expensive marine deep seismic reflection surveys. Actual survey routes will require careful scouting and planning, will exploit both active and passive methodologies and will take advantage of opportunities for integrated onshore-offshore data acquisition.