Deep Seismic Exploration of East Gondwana: A Proposal (LEGENDS)

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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. Major geological features have been traced to lower crustal depths. Certain deep crustal features have been traced into the underlying mantle (fossil subduction zones?). Some geotectonic boundaries, considered by generations of geologists to be major crustal sutures, have been shown to be merely splays off underlying lithospheric boundaries. Hitherto unsuspected boundaries to crustal blocks have been identified, and in some cases, virtually whole mountain belts formerly considered as rooted in the Earth's mantle have been shown to be allochthons riding above intact extensions of continental blocks at lower crustal depth. Seismic "bright spots" have mapped magma chambers in the deep crust and laminated reflectors have been interpreted as relicts of lower crustal flow.

Spectacular though these results have been, such surveys have been limited largely to National Programs in those countries with the financial resources to mount expensive geophysical initiatives. Thus, while 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. 1). 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 (Figure 2). 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, few seismic profiles exist to delineate the gross structure, much less the details, of continental architecture of this region which played such an important historical role in the development of plate tectonic theory.

We suggest that it is now time to consider a comprehensive program of deep geophysical surveys, cored by seismic reflection profiling, to probe Gondwanaland. In particular, 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. At the same time, new seismic technologies make surveys is previously remote areas more practical. 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.

Here we outline an initiative called LEGENDS (**L**ithospheric **E**volution of **G**ondwana **E**ast from i**N**terdisciplinary **D**eep **S**urveys). This concept is in its earliest stages, and the following is intended primarily to spur discussion and generate interest among the global geological and geophysical community. We hope that the scientific ideas will be refined by such discussion over the coming months, and that interested scientists will feel free to join in developing plans to implement such surveys, which we believe are now needed to advance our understanding of Gondwana in particular and continental evolution in general.

Key geotectonic questions

Today, after some 30 years of research since the inception of the application of plate tectonics to the continents, much is known about the geology and geophysical character of the upper crust, especially the major orogenic belts (e.g. modern and ancient island arcs, the Andes, the European Alps and the Himalayas). We also know a lot from multi-disciplinary studies about the geological and geophysical expression of intra-continental rifts, passive margins, subduction zones, sutures, accretionary wedges, island arcs, continental magmatic arcs, and collisional orogenic belts. Yet the geological community still knows comparatively little about the nature of the modern and ancient lower continental crust. Of course some studies have been made and are on-going of the geology of the lower crustal crust, but these represent something like a hundredth or a thousandth of what is known about the upper crust. Nevertheless, it is well established from, for example, rheological studies that the strength, structure and mode of tectonic evolution of the lower crust has a major, if not controlling, influence on the style of deformation of the upper crust.

In this proposed initiative, onland seismic traverses will cross a substantial expanse of deep crustal rocks of Neoproterozoic orogenic belts. Metamorphic assemblages clearly demonstrate that we are looking at ca 10 kbar rocks at the surface today, and thus some 30 km of overlying crust have been removed by some tectonic processes. Because some 30 km of crust still underlies these belts, we are probably looking at a crustal section which is about half way through the 60 km thick crust of a Himalayan/Tibetan type collisional orogen. Thus this project would contribute fundamental new knowledge and understanding of the crustal profile of collisional orogenic belts in general as well as those of the Neoproterozoic in particular.

Upper crustal sections for most of the continents are generally not well-correlated with structures in the lower crust. This project would provide the high-definition of structures in the lower crust which could be correlated with, and tightly constrained by, structures such as the sutures known at the present mid-crustal level. Therefore this project could help in the general interpretation of upper crustal portions of deep seismic surveys elsewhere.

Inspection of large scale geologic trends in East Gondwanaland suggest at least two principal corridors of interest for future geophysical surveys. One spans the East African Orogen (Figure 3a), the other is represented by that portion of Antarctica that borders the Indian Ocean (Figure 3b).

The East African Orogen (whose southern, high grade portion is also known as the Mozambique belt) 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 (Figure 3a). 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. It is an ancient example of the kind of continental collision currently in progress in eastern Asia, with the potential to provide important information about the processes and kinematics of the modern continental collision at a depth of ca 15-20 km below the Tibetan surface. Deep erosion has exposed at the surface rocks of the collision zone to middle and lower crustal depths, yet the region is still underlain by an apparently full thickness of continental crust.

Taken as a whole, the East African Orogen with its possible continuation in East Antarctica is more than 8000 km long, and the collision zone is in places 500 to 1000 km wide (Fig. 3). Gondwanaland reconstructions place the western margin of India adjacent to Madagascar, which, in turn, was situated adjacent to Somalia, Kenya and Tanzania (Fig. 3a). A complete traverse across the collision zone can be made at the latitudes of Dar-Es-Salaam in Tanzania, Antananrivo and Tulear in Madagascar, Panjim and Banglore in southern India and across Sri Lanka (Fig. 4). Such a corridor, ca. 2000 km long in the Gondwanaland reconstruction, crosses from undeformed Archean cratons on either end, though a broad zone of ca. 2.5 Ga continental crust heated and partially melted in the late Neoproterozoic and across the site of the now disappeared Neoproterozoic Mozambique Ocean (Fig. 3). Although specific routes for real surveys await detailed geophysical scouting and consideration of practical land and marine options, the schematic transects in Figure 4 represent a general “LEMURS corridor” (Lithospheric Evolution from MUltidisciplinary suRveys of a Supercontinent) which can address the geologic issues key to understanding the region.)

Madagascar is the keystone of this tectonic corridor because the suture between 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.

Passing southwards from this suture, the proposed geotraverse passes through the high-grade Pan-African orogen, where little is known about its structural evolution, but where detailed studies on metamorphic petrology and geochronology have been undertaken. Near the southern tip of India the geotraverse crosses 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 terrain on its eastern side, and an 700-800 Ma deep level continental magmatic arc on its western side. However the Palhvat-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 suturing in eastern Madagascar dip shallowly to the west. They may continue at depth with this shallow dip, in which case Madagascar represents a thin-skinned orogenic belt, an hypothesis which seismic surveys should 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 that the remnants of this increased crustal thickness could be detected and defined by the deep seismics.

The East-West traverse in Tanzania could follow the main road from Dar es Salaam via Morogoro to Dodoma and cross the high grade rocks of the Mozambique belt (MB), where most of the major structures are north-south, into the Archaean Tanzania craton (Fig. 3a). Although there is evidence for the formation of new Neoproterozoic crust in the MB, 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 in the MB of Tanzania. 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.

A short E-W traverse across the high grade basement of Sri Lanka from Colombo via Kandy to Batticaloa would cross all its major crustal units, namely the Wanni, Highlands and Vijayan Complexes. 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 strucurally 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.

Likewise, seismic and other lithosphere scale geophysical surveys in or near Droning Queen Maud land (Figure 3b) will traverse geologic terranes that are believed to 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; addition of reflection profiling and passive seismic transects would provide a new basis for comparing corollary lithospheric structures in these two regions of Gondwanaland.

A project entitled "Structure and Evolution of the East Antarctic Lithosphere (SEAL) " has been active since the 1996-1997 austral summer season within the framework of the Japanese Antarctic Research Expedition (JARE). The Japanese team has focused on deep seismic refraction/wide-angle reflection probing in East Antarctic Shield. The goal of the SEAL geotransect is to obtain, by seismological and the other geophysical/geological surveys, an entire crustal section encompassing the various geological terrains from the Western Enderby Land to the Eastern Queen Maud Land, spanning the Archean to early-Paleozoic time. In the austral summer season in 2000, the first deep seismic probe (JARE-41) was conducted on an ice sheet of the northern Mizuho Plateau in the Lutzow-Holm Complex (LHC).

Many fundamental scientific questions can be addressed along these complementary geotraverses:

- 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 as documented by deep seismic profiling in the Himalaya ?
- Are the younger Mesozoic breakup margins controlled by, or spatially related to, the older collisional crustal architecture?
- Do the exposed granite-gneiss terranes in Madagascar and East Africa truly represent an analogue for the ca. 20 km deep crust beneath Tibet ?
- Does 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 during the formation of Gondwanaland?
- 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 from anticlockwise PT paths (and as has been proposed to account for parts of the modern Tibetan uplift)?
- Do the late stage ca. 530–500 Ma transcurrent faults go down to the mantle, and do they juxtapose continental curst of different types?
- What is the lithospheric structure through a typical 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?
- Do continental fragments the size of Madagascar or Sri Lanka retain a lithospheric keel?
- What role do these ancient structures play in neotectonics (e.g. earthquakes)?

These are undoubtedly only a subset of the issues that may be addressed by systematic deep surveys in the East Gondwana nexus. Undoubtedly one could generate a comparable collection of important questions related to the dramatic submarine features (e.g. Mascarene Plateau, Laccadive Ridge and numerous passive margins) within the ocean basins that now separate the Gondwana fragments and that could be collateral targets of the proposed geophysical program. Certainly we expect that future discussion will lead to a more complete and compelling list.

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. 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 in this situation include both controlled source (active) and natural source (passive) techniques. Controlled source methods include:

<u>Deep seismic profiling (land and marine),</u> also known as multichannel (MCS) or common midpoint (CMP) profiling, can provide structural details from the upper crust to the lower lithosphere. 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 is 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 IRIS "Texan") offer opportunities for land profiling at considerably lower cost than traditionally-used oil exploration contract crews. Airguns at sea and explosives on land appear to be the most feasible sources at present.

<u>Wide-angle reflection and refraction profiling</u> (WARRP) ca provide estimates of physical properties (Vp, Vs, Q, anisotropy) to upper mantle depths. With the appropriate mix of instruments and sources, CMP and WARRP can be recorded simultaneously. WARRP is particularly effective in onshore/offshore experiments which can take advantage of high density airgun shots at sea. Both CMP and WARRP recordings can be

used in tomographic imaging of subsurface velocity structure. With Ocean Bottom Seismometers (OBS), wide angle surveys can be extended across the ocean-continent boundary well into oceanic lithosphere.

High resolution reflection profiling. New portable multichannel systems, traditionally used for shallow environmental surveys, when coupled with small explosive sources can provide even higher resolution (10’s of meters) imaging of geological structures in the upper crust.

Natural source techniques exploit lower frequency seismic sensors, usually deployed at much coarser spacing than in controlled source experiments, to detect seismic waves from distant earthquakes to image lithospheric structure from below. Such recordings can be used to:

Map deep lithospheric and sublithospheric velocity variations by tomographic methods.

Delineate major intralithospheric discontinuities (e.g. Moho) and sublithospheric discontinuities (e.g. 410 km, 670 km) by receiver function techniques (RF). RF analysis can also provide estimates of crustal Poisson’s ratio. High density (10 km station spacing) RF images resemble low resolution seismic reflection profiles; however, they typically sample much deeper than controlled source surveys.

Map lithospheric and sublithospheric anisotropy (SKS techniques) as a guide to modern and ancient rock fabrics and shear orientations.

A new generation of Broad Band (BB) OBS now make it possible to apply these techniques to water covered areas as well as land, and remove the ocean-land interface as a barrier to continuous lithospheric imaging.

The deployment of instrumentation for natural source imaging provides the additional, and significant, benefit of monitoring and accurately locating local earthquake activity. Detailed mapping of seismicity is obviously a powerful tool for identifying currently active tectonic structures and assessing the role of reactivation in the tectonic history of eastern Gondwanaland.

With careful scheduling, the instrumentation used for natural source imaging can also record the active sources as well. Integrated analysis of both controlled and natural source data can detail structure from the surface to mid-mantle depths.

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) and national (e.g. 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 of this effort is on seismic methods, other geophysical techniques such as magnetotelluric (MT), gravity and magnetic profiles) are expected to make critical contributions. Also, special geological studies (e.g. strip maps, structural sections, geochronologic studies) are 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. In a similar vein, a common geological interest in deep structure and shared logistical needs for future surveys can provide a fresh basis for international collaboration. 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 organizing both individuals and institutions in such an ambitious endeavour. 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, recent broadband studies in East Africa, the proposed EAGLE initiative in the Afar, the KAAPVAAL Craton project in South Africa).

We propose that details of geological targeting and geophysical design for this initiative should be formulated in a series of workshops during an initial planning phase. We expect that major field work can take place no earlier than 2003 or 2004, and that a serious program may take anywhere from 5 to 10 years to complete.

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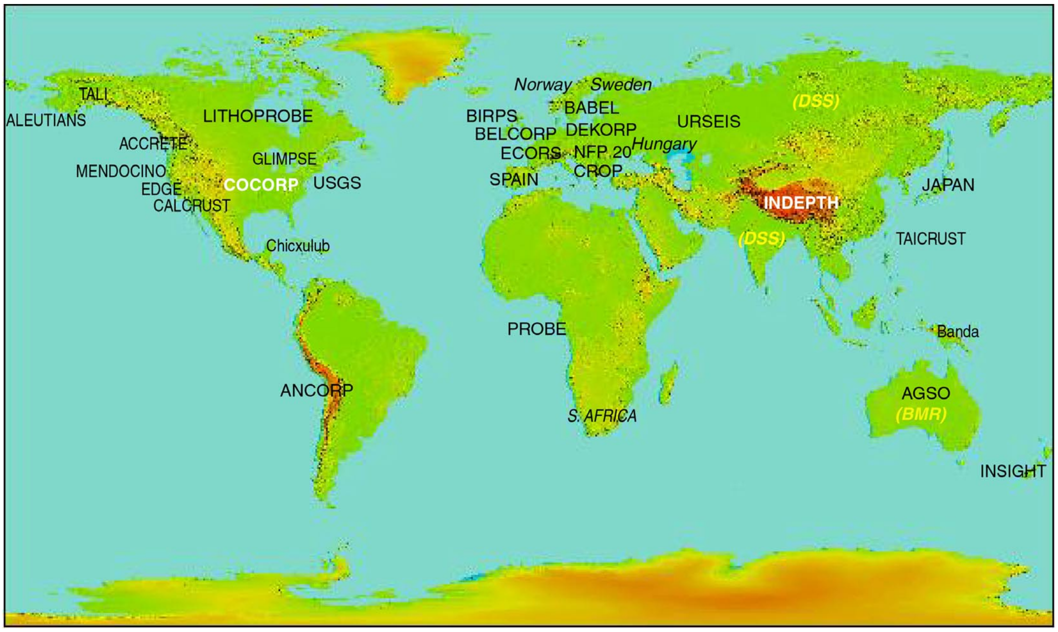

Figure 1: Deep seismic reflection programs around the world. Although the northern hemisphere has received considerable attention over the past 20 years, much of the southern hemisphere (Australia excepted) remains unexplored.

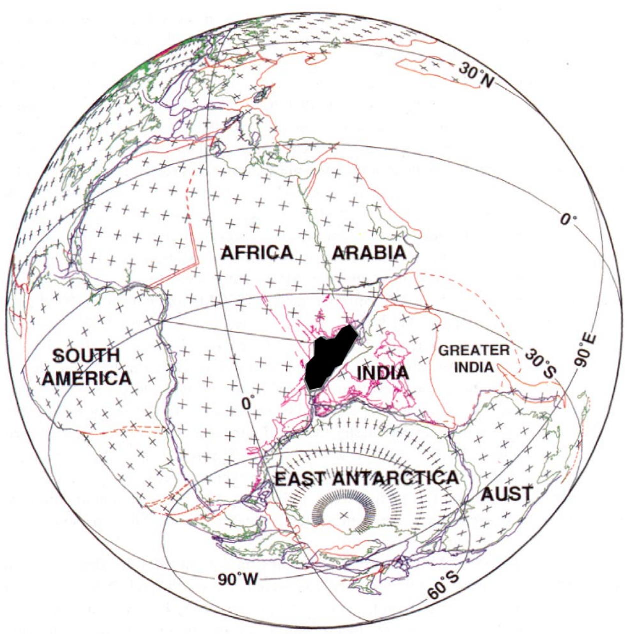

Figure 2: Gondwanaland (from Lawver et al., Mem.National Institute of Polar Research Spec. Issue 53, 1998). This supercontinent represents the largest expanse of continental lithosphere yet to be explored by modern deep reflection methods. Black indicates Madagascar, a keystone in such reconstructions and one focus for future deep seismic surveys.

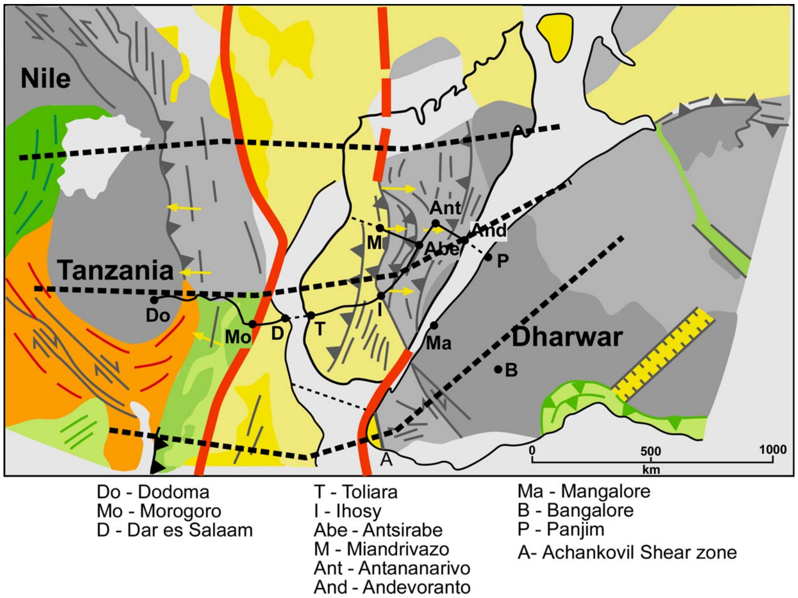

Figure 3A: Detail of the India–Madagascar–Congo fit (geotectonic map courtesy of C. Powell). Profile routes (dashed lines) are schematic and only intended to promote discussion. Actual routes must be guided by geological priorities, logistical constraints (ease of access on land) and opportunities (marine alternatives) and imaging requirements. Solid line is an example of how an actual (land) survey route might look. Archaean cratons are shown in dark grey; Palaeoproterozoic crust (commonly reactivated in the Neoproterozoic) in light grey; green represents areas of late Mesoproterozoic–earliest Neoproterozoic deformation and magmatism; yellow areas of Neoproterozoic magmatism, deformation and, in parts, juvenile crust. Note: Sri Lanka, another keystone element, is not shown here but is a critical target for seismic profiling (Figure 4).

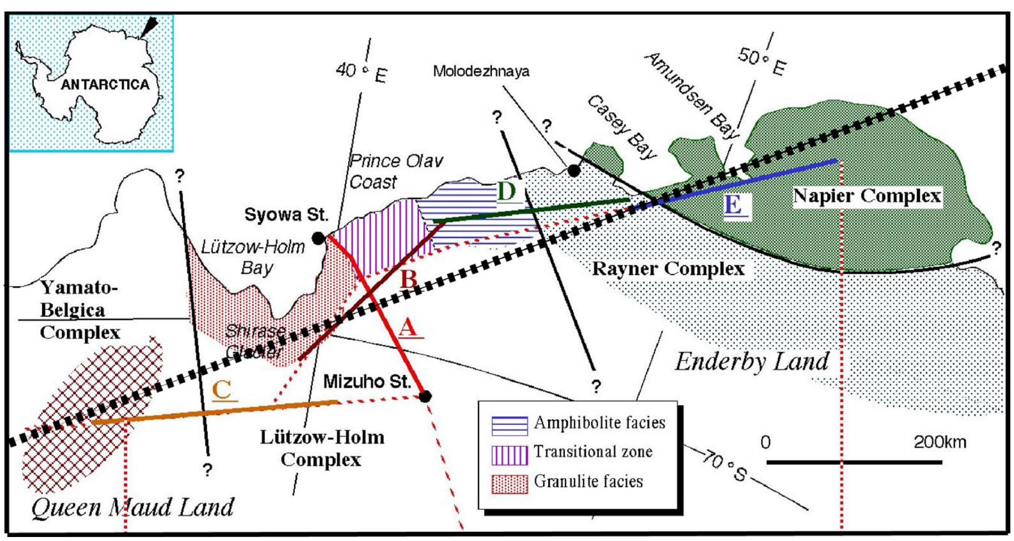

Figure 3B: Crustal terrains of Antarctica which represent the continuation of orogenic trends of the East African Orogen. Dashed line indicates conceptual transect for deep seismic profiling; actually surveys may include both land and marine segments. Solid lines represent seismic refraction surveys carried out or planned as part of the SEAL program (Figure courtesy of M. Kanao, NIPR, Tokyo).

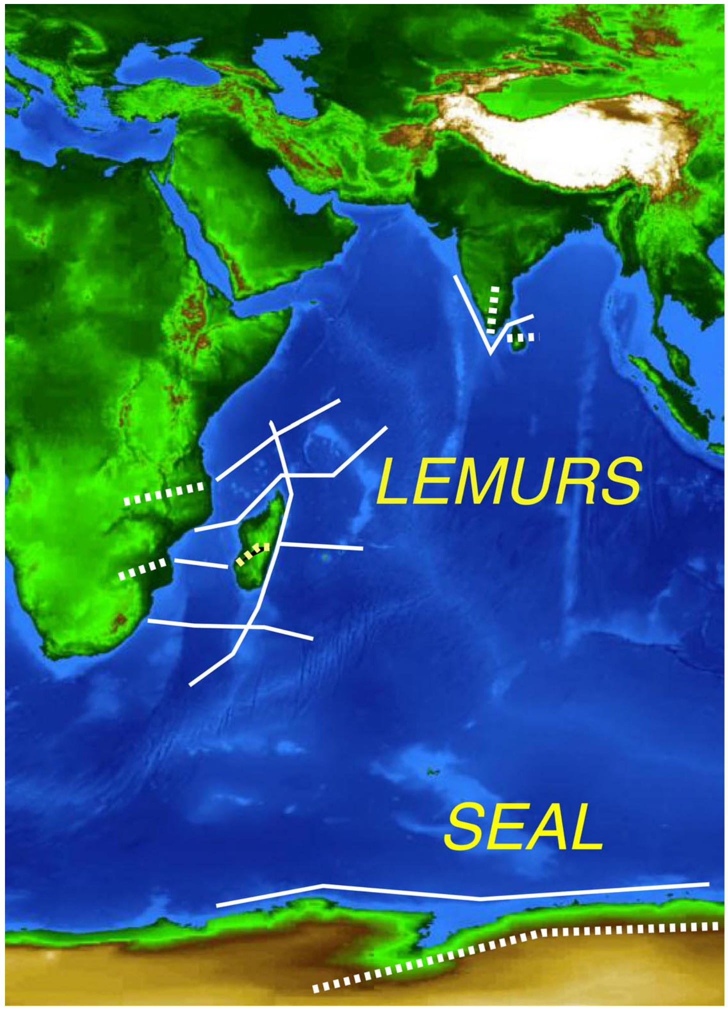

Figure 4: Present-day continental configuration, with example of a possible program for deep seismic surveys at sea (solid) and on land(dashed). Actual survey routes will require careful scouting and planning, and will exploit both active and passive methodologies and opportunities for integrated onshore-offshore acquisition. These routes, which are only loosely related to those in Figure 3, are primarily intended to convey the scale of such a program.

LEGENDS Appendix: Last Updated 6/21/01

Potential Funding Agencies

NSF (USA)- June 1 preproposal; Dec 1 main proposal; June 1 Start
Australia ARC Discovery Grants- close Feb; Nov. decision; Jan Start
European Funding Agencies- EU, ESF, individual countries
World Bank- (for instruments to be donated to developing countries, plus costs of training indigenous personnel in its use.
UNESCO- training funds
Commonwealth of Australia
Mining companies (?)- support could be in kind with use of drill rigs and vehicles in countries of interest
Oil companies- especially those with interests in western Madagascar and the Tanzanian-Somali continental shelf
France- Marine geophysical surveys emanating from Reunion base.

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