Lithospheric Structure of an ancient Extensional Basin within a Convergent Orogen: the Curnamona block and Flinders Ranges of South Australia.

**Summary**

Lithosphere-mantle interaction in the continental environment is important in the development of orogenic belts and sedimentary basins, though the details of this interaction are enigmatic. Replacement of mantle lithosphere by asthenosphere from the convecting mantle may be one of the key processes in the development of orogenic belts. Where such events happen, deformation occurs rapidly, mountain ranges and basins may be formed or destroyed within a few Myr or less. One important class of tectonic structure that provides a specific window on such events is the class of extensional basins that formed in the midst of convergent mountain belts. Examples of such structures are few, and those that are well documented, such as the Alboran Sea Basin and the Pannonian Basin, are relatively young, yet such basins have a remarkable affect on the structural evolution of the continental lithosphere because extension when it occurs is so rapid. The Curnamona Province of South Australia may be one of the best-preserved examples of an ancient sedimentary basin that formed by extension or tectonic collapse of an orogen, in this case the Cambrian Adelaideran orogen of South Australia. The comparison and contrast of this intra-orogenic basin with the above-mentioned Neogene examples should provide significant clues as to how such basins form, because the thermal signature of the formative event is by now completely dissipated in the former, but still significant in the latter. We propose here to acquire a seismological dataset that will define the lithospheric structure of the Curnamona Block and adjoining orogenic belts. These data will provide an important set of new constraints on theoretical models of how these orogenic events occur, by showing what is the long-term structural effect on the continental lithosphere. Concurrent with the seismological data processing, we will use computational methods to develop a self-consistent model that explains the formation of this type of orogenic basin systems in terms of extension and contraction driven by the dynamical and thermal interaction of mantle and continental lithosphere.

**Introduction**

The development of the plate tectonics paradigm has dominated the interpretation of large-scale geological processes in recent decades. Nonetheless it is clear that deformation within continental regions often does not fit comfortably within the plate tectonics framework. In particular, distributed deformation of the continents often is recognised in regions where mountain building or orogenesis occurs, and also where extension of the lithosphere causes sedimentary basins to form. Because these processes have been so important in the geological evolution of the continents, both have been studied extensively, using both field based measurements and theoretical studies. Yet there are still many aspects of these geological processes that are uncertain or poorly understood. The project proposed here focuses on one aspect of the internal deformation of continents by studying a specific class of structure that is now recognised as forming in regions where the continental lithosphere passes temporally and spatially from a convergent domain to an extensional domain. It has long been recognised that mountain belts formed by horizontal shortening may pass relatively quickly into phases of extension and erosion (Dewey, 1988, England and Houseman, 1989). More recently it has been recognised that extension may develop in one part of an orogen at the same time that convergence continues in adjacent regions (Vissers and Platt, 1995), and that the extension may occur very rapidly (Soto
Lithospheric stress domains that are defined by spatially coherent orientations of the stress field may be bounded by plate boundaries, by domain boundaries between separate regions of differing lithospheric strength, or by interaction with different flow domains in the convecting upper mantle.

Extensional basins bounded by convergent orogens may be difficult to recognise in the geological record, but perhaps the main criterion is that the basin is of limited horizontal extent and the fold belts that surround it on either side appear to develop an oroclinal structure along-strike, splaying apart and surrounding the basin, and if not interrupted by other structure, merging again on the other side of the basin. Perhaps the clearest example of the development of such basins in present-day landforms is found in the Pannonian Basin of eastern Europe, surrounded by the adjoining Carpathian, Dinaric and Alpine mountain chains (Cloetingsh et al., 2002). Another possible example of this type of basin is the Alboran Sea Basin in the western Mediterranean, a region of continental lithosphere that was thinned rapidly during the Miocene, synchronous with continuing convergence in the surrounding Betic and Rif fold belts (Vissers and Platt, 1995). This type of basin is, however, relatively unusual. It is difficult to identify many such structures in the geological record, if only because structures that form in the midst of an orogenic belt are likely to be short-lived by the nature of the processes that produce them.

One of the older and less recognised candidates for a large intra-orogenic basin in the ancient geological record is the Curnamona Province of eastern South Australia (Figure 1). The Curnamona province is a region of Proterozoic crust surrounded by early Paleozoic mobile belts of the Adelaide Geosyncline (Preiss, 2000). The Curnamona basement, which was intensely deformed, metamorphosed and altered in the mid-Proterozoic Olarian orogeny (1640-1580 Ma) is exposed in the Willyama inliers of the Olary-Broken Hill region to the southeast and the Mt Painter block to the northwest. The Curnamona province is bounded on the west by the Adelaidean sediments of the Flinders Ranges, and to the south-east by outcropping Olary-Willyama domains. Sedimentary and low-grade metasedimentary rocks of the NeoProterozoic and Cambrian overlie the basement. The Curnamona province is largely covered with Tertiary to Quaternary sediments, so data relating to its composition and structure are sparse. If the Curnamona Block is an example of an intra-orogenic basin, it is remarkably well-preserved for its age, and it therefore could provide a possibly unique insight into the internal lithospheric structure of such basins. While the Pannonian and Alboran Sea Basins are well past the major geological events in which they formed, they are relatively young, and presumably still evolving thermally as well as tectonically. The Curnamona Block on the other hand has persisted sufficiently long that we can be assured that any thermal transient associated with its formation has long passed. The key evidence needed to define this lithospheric structure will be provided by seismology, and specifically by lithospheric seismic tomography and crustal receiver functions.

Aims

This proposal then seeks funds to enable the acquisition of a seismic dataset, which will help to define the mantle and lithospheric structures that are associated with the Curnamona province, and the adjoining fold belts in South Australia. The data will be analysed to produce a 3D map of the structure of lithosphere and upper mantle beneath the Curnamona province and the adjoining Flinders Ranges and Olary-Willyama blocks. These results will be used to evaluate the predictions of geodynamical models of the formation of such basins. The aim of this project is to
obtain insight and understanding into how intra-orogenic basins form, and the stages in their structural evolution. An essential part of this aim is to determine whether the Curnamona block formed by the same kind of geological event that formed the Pannonian and Alboran Sea Basins. A second part of this aim is to document the state of the lithosphere for one such basin that is long past the point of thermal re-equilibration. The comparison with younger basins in which thermal equilibration continues will be important in separating the effects of thermal evolution from structural development.

The data-gathering activity will proceed in association with other groups who are working on related seismological projects. An Australian National University group (led by Prof B.L.N. Kennett) is currently undertaking a major project to record surface waves in order to study the large-scale structure of the Proterozoic - Paleozoic boundary in eastern Australia (loosely known as the Tasman Line). A group from Geoscience Australia (led by Dr P. Cummins) have also deployed a network to record local seismicity in the Flinders Ranges as a part of seismic hazard evaluation. The distinct goals of these three projects require different kinds of dataset, since the surface wave study requires much larger aperture (area covered) and the hazard survey requires higher frequency recording. If we can collect data in the same field season, however, the possibility of sharing data and support in the field offers tangible benefits. Nevertheless we clearly stand to gain from the synergy obtained by cooperation between the three groups even if it is not possible for the field projects to run simultaneously.

The analysis and interpretation of the dataset will be supported by dynamical models of the development of the lithospheric-scale deformation structures that we hypothesize are responsible for this type of basin. In a separately funded project (Leverhulme Foundation) we are presently developing the capability of a 3D finite deformation program based on the finite element method running on a multi-processor system. This capability should be available in 2005 for application to the Curnamona project. Until the 3D program is available, however, we have the use of the 2D finite deformation program basil (Houseman et al., 2002) that can be used to develop approximate 2D models of the Curnamona / Flinders region, either in plane-strain vertical section, or in thin sheet approximation.

Geological Background

Figure 1b shows a sketch map of the geographic relation of the Flinders Ranges, Olary and Willyama basement, which bound respectively the western and southern limits of the Curnamona Basin. The Willyama SuperGroup is an early Proterozoic assemblage of highly metamorphosed igneous and sedimentary rocks that have the distinction of hosting one of the larger AgPbZn deposits in the world in the Broken Hill Region further to the east. Multiple phases of deformation and metamorphism are recognised in the Willyama on outcrop and micro-scale. The Willyama is truncated to the southwest in the Olary region, largely by faulted contacts with folded upper Proterozoic sediments of the Adelaidean system that show east-north-east trending fold axes. With extensive sedimentary regions to north and south, the Willyama and Olary regions, though of greatly differing age, appear to represent a contiguous basement high that has some shared history. To the west of the Olary region, the fold axes of the Adelaidean sediments follow a more northerly trend, and run into the main north-south trend of the Flinders Ranges. The outcrop of late Proterozoic sediments in the Flinders Ranges shows a striking pattern of large-scale fold interference, produced primarily by E-W convergence in the Cambrian-age
Delamerian Orogeny. A similar pattern of fold interference is evident in the Olary block, differing primarily in the change of strike as these two belts separate to the North and East. Without detailed analysis, it is evident from the EW structural section taken through the 1:250,000 Ororoo sheet of the central Flinders Ranges (SADME, 1989) that shortening of the order of a factor of two across this convergent belt is plausible.

Both Flinders Ranges and Olary-Willyama belt stand out clearly on a geological map or a topographic map of South Australia (Figure 1a). They probably once were marked by high mountain ranges, but erosion has ensured that the remaining topographic relief is less than 1 km. The Stuart Shelf to the west, received early Paleozoic sedimentation. During the Delamerian, sedimentation in the Curnamona region occurred mainly in the Cambrian Arrowie Basin beneath present Lake Frome and further east. There are also extensive Mesozoic and Tertiary sediments that unconformably overlie the lower Paleozoic. The long hiatus could represent significant excision of the section by erosion. The basement has been sampled in a few places by drilling, intersecting Adelaidean-age sediments and Willyama basement highs. The Flinders Ranges today remain one of the more seismically active regions of Australia, though the seismicity is diffuse and large events (M > 5) are rare.

Figure 1 (a) detail from the Digital elevation map of Australia (Kilgour and Wyborn, 1998), showing regional elevation. (b) geological sketch map, with fine lines showing fold axis traces and bold dashed lines showing schematic locations of proposed seismograph array.

The working hypothesis of this proposal is that the Curnamona Block formed by extension of a previously much broader fold belt, of which both Flinders Ranges and Willyama block were constituent parts. In the course of this extensional phase the Willyama block rotated clockwise relative to the Flinders Ranges, in order to make space for extension in the Curnamona province of previously thickened lithosphere that was part of the same large fold belt. This hypothesis is new, untested, and could be controversial, but I think that it is a plausible, and perhaps the most probable explanation of the most recent phase of the geological evolution of this region. The significance of this study is more than regional however. If the hypothesis is correct the results of this study should help us to interpret and understand in more general terms how a particular class of extensional basins form in the midst of convergent belts.
Methods

The focus of this proposal is firstly on seismic measurement and data analysis. The plan is to deploy about 60 seismic stations for a period of 6 months, and record natural seismicity, mainly from the Australian plate boundaries. Large seismic events are frequent in the Java Trench - New Guinea region to the north, and in the Tonga Kermadec trench region to the east, both at distances of 30 to 50 degrees approximately. The sketch map in Figure 1b shows a conceptual plan for the deployment in the form of three lines of length 200-300 km, with seismographs spaced approximately at 15 km intervals. This map does not show actual planned station locations, which will require detailed survey of maps for accessibility by road, but provides an outline of the region of interest, and the sense that station spacing will be closer in the across-strike direction than along strike. The region under investigation clearly has a 3-dimensional structure, however, and it is essential that the deployment cover an area of order 300 by 300 km in order to obtain reasonable constraints on 3D structural variation to depths of a similar order.

SEIS-UK has available for loan the necessary recorders for a field survey proposed for the period March to September 2005. A proposal for the use of this equipment from the NERC Geophysical equipment facility is attached. These instruments are self-contained, solar-powered, 3-component seismographs with local storage for up to 3Gb of data and GPS timing. With 3-component continuous recording of 24-bit words at 25 samples per second, there is sufficient data storage for about 5 months of continuous operation. We propose to visit each seismograph once during the survey, for data download and restart after 3 months of operation, in order to guard against the hazard that a particular station could fail soon after installation, and yield little or no data.

The three-component waveform data to be collected by this survey will be analysed using the following techniques:

- receiver-function studies (ref), with particular emphasis on measuring the thickness of the crust from the arrival times of converted shear waves.
- teleseismic travel-time tomography, using arrival time residuals for P and S waves to obtain 3D maps of the sub-surface velocity structure in the upper mantle beneath the survey region, to depths of order 300 km.
- shear-wave splitting studies to interpret lithospheric anisotropy
- location of local seismic events.

These techniques are by now all well established, and the Geophysics Group at Leeds has considerable collective experience in these techniques. We do not envisage any major new developments in the way that the data analysis techniques are applied in the course of this project. The innovation in this study resides mainly in what we will learn about the tectonic structure of this region, and how it evolved.

Both PIs have significant experience in planning and directing previous major seismic investigations. Houseman planned and ran a major lithospheric seismic tomography survey over a broad swathe of south-east Australia including the relatively harsh environment of outback South Australia during the period 1998-2000 (Graeber et al., 2002). The PhD student assigned to this project will receive comprehensive training in all aspects of such a seismic survey, including planning, deployment, field operations, data analysis and interpretation. Prof S. Greenhalgh of the University of Adelaide has previously collaborated with the PI on the earlier projects and is able to offer limited logistical and base support for equipment storage and staging etc at Adelaide, the nearest port, depending on staff availability etc.
Dynamical Models of Lithospheric Deformation

The other major component of this project will focus on dynamical models of lithospheric evolution, and a program of numerical experiments designed to test and evaluate different hypotheses for the development of extensional basins in continental lithosphere that has been activated by orogeny. The continental plates are rigid in most circumstances, but where they deform, the stability of the dense mantle lithosphere is perhaps the most important determinant of the subsequent tectonic evolution of the lithosphere, as summarised in the recent review by Houseman and Molnar (2001). A complete dynamical model of the tectonic development of such basins requires that the mantle-lithosphere interaction be included. Clearly, the change from convergence to extension in a region that remains bounded by convergent belts cannot simply be explained by changes to the driving forces on distant plate boundaries. The argument developed by England and Houseman (1989) in relation to Tibet applies also to all the intra-orogenic basins discussed here and is perhaps even more self-evident: the change from convergence to extension in a local domain is most easily explained by altering the vertical stress balance, specifically by replacing cold mantle lithosphere with hot asthenosphere.

Forced convergence can trigger gravitational instability of the lithosphere in different modes. Houseman et al. (2000) showed that instability induced by lithospheric convergence in a restricted 2D domain can induce the instability to occur either by a single central downwelling, or by means of central upwelling and peripheral downwelling. Central downwelling is probably in evidence in convergent environments like the Transverse Ranges of southern California (Houseman and Billen, 2003) or the South Island of New Zealand, both cases where strike-parallel shear dominates. Central upwelling is predicted, however, if the crustal layer is significantly weaker than the mantle, and central upwelling is characterised by significant thinning of the mantle lithosphere above the upwelling and accompanying convergence on the peripheral regions. Lithospheric thinning in the central region is likely to be accompanied by a lesser crustal thinning. Royden et al. (1980) documented the lithospheric and crustal thinning in the Pannonian Basin that is consistent with this type of model. Preliminary experiments show that the same types of instability modes occur in models that have a vertical axis of symmetry, forming circular regions of local extension.

An initial goal of the computational part of this project will be to properly explore the dynamical implications of such axisymmetric orogenic instability models for a range of crustal and lithospheric physical parameters. A second aim will be to demonstrate that this model can be applied to the Cambrian extensional deformation of the Curnamona province (the central extensional region) during the Delamerian orogeny of the Flinders and Olary belts (the peripheral convergent belts). The seismic tomography analyses by then will hopefully have revealed whether the present-day lithospheric structure in this region still bears the scars of these Cambrian tectonic events in the form of lithospheric thickness variations, or whether such variations have been removed by the thermal re-equilibration of the lithosphere in the subsequent 500 Myr time period. A final aim will be to compare the Curnamona-Olary regional structure with that of the Miocene Alboran Sea and Pannonian Basins, where the thermal signature of extension is still strongly in evidence.

(maybe a diagram to be added here if text can be condensed enough)
**Timetable**

Two PhD students will be recruited for this project. Student X, commencing October 2004, will focus on the seismological part of the project (data acquisition, processing and analysis). Student Y, commencing October 2005 will focus on modelling of lithospheric dynamical models and interpretation of the seismological results in the light of model calculations. The PIs will be closely involved with the work, supervising all aspects including fieldwork, seismic inversion and dynamical modelling.

**October 04 - March 05:**
- Student X commences detailed planning of fieldwork logistics, including geological background, site permissions, transport requirements etc.

**April 05 to October 05:**
- Installation, recording and recovery of data, with 3 separate trips to Australia.

**October 05 - March 06:**
- Student X proceeds with data archiving and basic processing (event picking)
- Student Y commences work on this project, and begins familiarisation with mathematical theory, available modelling software, and review of tectonic models.

**March 06 - September 06:**
- X: tomographic inversion studies using travel-time data
- Y: begins software modifications as required for representation of lithospheric deformation models

**October 06 - September 07:**
- X: completes tomographic inversion studies, carries out receiver-function analysis on selected data, develops final structural model based on both datasets, writes up and submits thesis.
- Y: develops program of numerical experiments, focussing on lithospheric / upper mantle dynamical interaction, and incorporating results from seismological study

**October 07 - September 08:**
- Student Y: continues program of numerical experiments, develops further the geological interpretation, writes up and submits thesis.

**Budget Justification**

**Personnel**

The major item on the budget is stipend for two tied PhD studentships, commencing October 2004. One of the students (X) will focus on the seismological data acquisition, processing and interpreting. The other student (Y) will focus on numerical modelling experiments of lithospheric deformation that could be used to explain the tectonic events that produced the present-day geometry of the Curnamona block and surrounding regions. The student stipends and research support allocations are based on a fixed scale. The second personnel item is a request for 6 months technician salary to (a) support the field work, including at least one trip to South Australia, and (b) assist with technical issues relating to maintaining the data archive according to required standards. This technical post (not yet employed by the Department) will be shared by a number of projects of this nature.

**Travel**

Airfares: Leeds to Adelaide, 4 return fares for installation trip (PI, 2 students, and technician), 2 return fares for the data visit (PI, and student), 2 return fares for the equipment recovery trip (PI and student): fares can sometimes be got for as low as £600 (and will be if possible), but more often cannot be got for much less than £900. Allowing for ancillary costs such as train to London, request is £7,200. If it turns out
to be not feasible to send 4 people to Australia for the installation trip, it may be possible to obtain volunteer assistance with the installation of the array from either Adelaide or Canberra.

Truck rental (4WD): The installation of 60 seismographs in such remote areas will probably require two teams of 2 working for 10 days. Because of the amount of equipment to be transported, LandCruiser Troop Carriers or similar will be needed. Data and recovery trips can probably be managed by one team of 2 in a single vehicle, again allowing 10 days for an entire circuit of the array. Total vehicle rental is estimated at 40 vehicle days by A$300 per day = approximately £4,800. Fuel for estimated total distance of 10,000 km is estimated at A$1,500 or approx £600.

Accommodation and food (typically using low cost country hotels where possible) for 80 people-days in the field over the duration of the 3 trips is estimated at A$150 per day for a total of $12,000 or approx. £5,000.

Equipment

The main equipment cost will be for the transport of 60 recorders and associated equipment including portable computers, solar panels, batteries, and shipping containers, shipped to Adelaide and back. Estimated total cost: £3,500. Data analysis and modelling work at Leeds requires a new workstation for each student. Basic Linux workstations can be obtained for £80 each.

Other

Field supplies, and tools required for installation may need to be bought locally, unless they can be borrowed. A provision of £200 for field supplies is requested. Both students should attend one international conference (usually either AGU meeting in San Francisco in December (estimated cost £900), or EGU meeting in Nice in April (estimated cost £600). Total cost for both students over 3 years £4,800:

References


Houseman and Billen


Houseman, Neil and Kohler


Royden

SADME (South Australian Department of Mines and Energy), Olary 1:250,000 Geological Map Sheet SI-54-2, 1989.

Soto