Abstract

We give an overview of the range of observational data for the entire Australian plate, which are available to modelers. We introduce the discipline of geo-informatics, and discuss some examples of integration of data with models to illustrate the importance of a workflow that brings data, visualization, modeling and skilled geoscientists into a single loop. Geo-informatics’ tools under current development such as the data visualization tool, auSEABED, and plate tectonic modeling tool, gPlates, are explained. The idea of interactive inverse modeling is introduced as a way to incorporate the subjective judgment of experienced geoscientists into the process of finding well-fitting models for diverse observations.

Keywords: Lithosphere deformation, geo-informatics, marine geoscience

Australia: A large island surrounded by a vast ocean territory

The area of seabed under Australian jurisdiction far exceeds the Australian land area. Australia’s vast ocean territory is approximately 16.1 million sq km in area – the third largest in the world. In contrast, Australia’s land area “only” measures 7.8 million sq km, so in reality our land covered by oceans is twice as extensive as terra firma (Fig. 1). Eighty percent of Australia’s population lives within 50km of the sea. As such, Australia depends on sustainable ecosystem and species management, and the preservation of clean and healthy marine environments. Ecosystem-based oceans planning and management of coastal areas should aim to maintain ecological processes including water and nutrient flows, community structures, food webs, and ecosystem links.

One of Australia’s major strengths lies in its vast, relatively unexplored ocean territories and continental shelf system, which extends from the tropics to high latitudes, with its unique resources. In order to manage our maritime jurisdiction we need to have effective means of remotely sensing, imaging, classifying and modelling the seabed and sub-seabed at a wide range of spatial and temporal scales. The importance of Australia’s paired strengths in marine resources and political stability was underpinned in the year 2002 by a contract to supply China with liquefied natural gas from the

Figure 1: Australia’s marine jurisdiction. White lines denote 200 nautical mile Australian exclusive economic zone, with preliminary estimate of outer limit of Australia’s extended continental shelf seabed and subsoil regime beyond 200 nautical miles (magenta) and maximum extent of an extended continental shelf off Australian Antarctic territory (from Phil Symonds, Geoscience Australia).
Northwest Shelf worth $25 billion, the single biggest export contract for Australia. Figure 2 illustrates the marine geoscience issues that Australia’s wealth and health will depend upon in the future: They range from coastal and harbour management to maritime law, marine resource exploration and conservation issues and climate change.

Marine geo-scientific data are collected at various scales using a vast array of techniques. For example, recently the most comprehensive marine geophysical imaging and ocean drilling campaign in history around Australia was completed, carried out by Geoscience Australia and by the international Deep Sea Drilling and Ocean Drilling Programs (DSDP and ODP). The data set is now comprised of more than 600 drill sites in Australasia/Antarctica, and thousands of kilometres of marine seismic, gravity and magnetic data, as well as high-resolution images of the sea floor. These data hold an enormous amount of information on the evolution of ocean basins and margins through time and may help us unravel fundamental links between tectonics, sedimentation and marine resources. Marine geoscience data can be numerical or textual, map-oriented or time oriented, facies related or stratigraphically related. How do we analyse such diverse data sets as a whole, and model the processes involved? The methods for analysing and displaying geo-scientific data are necessarily diverse and complex. In most situations no single data set provides all the pieces necessary to solve a scientific problem. The solution to existing conundrums and the advancing of new frontiers can only come from the effective integration and computational analysis of several diverse data types – geo-informatics!

Geo-informatics

What is geo-informatics? Geo-informatics is a new field in the Earth sciences discipline that seeks to develop revolutionary tools that will facilitate the most effective use of geo-scientific data – and indeed, to bring these data alive. For many decades Geosciences has primarily been an observation science. However, readily available consumer computer hardware and software now allows many researchers to start modelling the complex processes that have shaped the Earth, ground-truthed by their observations. The earth has a complex record of the dynamic interaction of plates, earth materials and life that provide clues to the physical and chemical evolution of continents, oceans and the atmosphere. It has become clear that our understanding of the dynamic Earth can be vastly improved through the application of modern IT tools and the principles of physics to the geosciences. This field is in its infancy, and there is scope for advancement in all areas from novel techniques for data collection that maximizes the potential value of data at later stages, to new IT protocols for storing and accessing data, and new numerical techniques that are sufficiently generic to enable parallel processing of all forms of geoscientific data.

Thus the primary objective of geo-informatics is to extract knowledge from the rock and sedimentary records, as well as from current processes at the Earth’s surface and in the oceans, through construction of databases and the development of modelling tools. IT research in Geo-informatics will focus on knowledge-based mediation and information integration techniques for 4D data models; visualization of multi-scale, 4D information spaces; data-level interoperability; metadata modelling and interchange; and, metadata-based access to data and services. Issues of scale and time, observational versus analytical data, and interpolated versus interpreted data, pose unique challenges for Geo-informatics.
An important field of research applied to understanding coastal and marine environments is Geographical Information Science (GIS). GIS involves the capture, organization, analysis, modelling and visualization of geographically referenced data in a computer environment. GIS techniques allow the spatial and temporal relationships between different phenomena to be explored, described and predicted. For example, the degradation of coral reefs may be linked to the spatial proximity of land based pollution outfalls. Through GIS the association between the dispersion of these pollutants and reef condition can be modelled. GIS provides researchers and managers insight into the relationships between phenomena in the marine environment that vary spatially, such as water depth, coral growth and the distribution of fish species.

How can GIS be used to integrate diverse data relating to the coastal and marine environment, analyse spatial trends, and support environmental and resource management decisions? GIS data is stored in the computer as digital map layers that can be overlaid using a common geographical coordinate reference system. Remotely sensed images obtained from satellites or aerial photography and field data collected using Global Positioning Systems (GPS) are common sources of spatially referenced data used in GIS. For example, a GIS data layer defining the boundaries of seagrass beds can be generated from satellite imagery. This map can then be compared with the location of aquaculture farms that have been recorded in the field using GPS units, to determine the impact of commercial farming activities on the health of the seagrass communities. The GPS unit operated from a vessel in the field computes position based on distance measurements to satellites orbiting the earth. The grid reference coordinates recorded by the GPS (such as easting and northing values) is entered into the GIS as a point location which can be overlaid with habitat maps, depth charts, satellite images or any other marine data layers. Being able to access this spatial information, make predictions and visualise areas of resource interest or use conflict provides marine managers and stakeholders with a greater understanding in the decision making process. The value of GIS is not merely in the efficiency with which the technology can be applied, but rather it enables us to think differently about the way we organise, integrate, interpret and use spatial information.

A combination of spatial information technologies, including remote sensing, GIS and GPS are currently being applied to map the temperate seagrass beds in the nearshore waters of Tasmania. Substrate habitat is mapped using detailed scale aerial photography (between 1:5,000 and 1:25,000) and broad scale satellite imagery (Landsat 7). GIS data layers delineating the different habitat categories (such as sand, gravel, patchy seagrass) have been generated. The positional

Figure 3: Movement of a vessel during a seasonal seagrass mapping survey conducted in Blackman Bay. Discrepancies between the mapped habitat boundaries and the field observations were assessed using a range of spatial statistical techniques (such as error matrix, Kappa statistics and line intersect analysis). This provided an indication of the reliability of the mapped data (from Eleanor Bruce, School of Geosciences, The University of Sydney).
and descriptive accuracy of these maps are then verified in the field using GPS, underwater video and echo sounder equipment. The echo sounder and GPS are linked to the GIS, and provide a continuous record of the substrate traversed by the research vessel. Figure 3 depicts the movement of the vessel during a seasonal seagrass mapping survey conducted in Blackman Bay. Research findings demonstrated that high biomass seagrass beds were mapped from remotely sensed data sources with a high level of accuracy. However, the sparse or low biomass seagrass beds had a lower level of accuracy due to misclassification as a sandy substrate. These results provide marine managers with a measure of the uncertainty associated with the GIS maps on which they are basing decisions. In determining a suitable location for a proposed aquaculture lease in Blackman Bay, the marine manager would need to recognize that the GIS maps underestimate the presence of low biomass seagrass beds. GIS based site selection and uncertainty analysis techniques can be employed to facilitate this decision making process.

**Seabed characterization, dynamics and modelling**

To illustrate the need for a new geoinformatic paradigm, consider the problem of characterizing the seabed over an area the size of Sydney. To classify the roughness of the seabed for hydrodynamic modelling, for example, we would need to combine measurements of sediment size with measurements of rock-reef and submarine dune size. Scale issues dictate that the former would be sampled physically and the latter remotely, and probably acoustically. We would also need to sample through time as sedimentary beds in shallow water can be highly mobile. Integrating this seabed roughness data obtained with differing techniques and over a wide range of scales is not trivial! Yet this is one of thousands of similar problems faced by marine geoscientists.

In the last 10 years, enormous progress has been made in mapping the seafloor. Previously, the echosounding methods available to us relied on a single acoustic signal, whose travel time between the vessel to the seafloor and back gave us the depth at a single point, with numerous such soundings adding up to a depth profile. The development of multibeam sonar systems has resulted in a number of fairly sophisticated systems which map a swath of seafloor underneath a ship's track, typically at least as wide as two times the water depth. A typical medium/deep-water multibeam system emits a signal every 10ms at a frequency of say 13 kHz. The transmit beam generates a footprint on the seafloor with a width of 120-150° in the across-track direction and about 2° in the along-track direction. A total of at least 100-150 overlapping beams at a spacing of 1° receive the return signal. The signal is received with three important pieces of information: the depth, which is calculated from the elapsed time, the angle from which it is received, and the intensity of the signal. In Figure 4 we compare an old-fashioned seafloor topography (called bathymetry) map (Fig. 4a), which was hand-contoured from profiles of ship depth soundings, with a modern multibeam bathymetry map of the same area southwest of Tasmania (Fig. 4b). The multibeam image shows a nearly vertical cliff more than 1500m tall dropping down from the South Tasman Rise, a submerged continental plateau, to the abyssal seafloor to the west. Also shown are previously unmapped volcanic cones. This example demonstrates how much we have learned about the seafloor from multibeam data.

![Figure 4: (a) Hand-contoured bathymetry map of the western South Tasman Rise and adjacent abyssal plain, compared with (b) a modern multibeam seafloor image of the same area (from Phil Symonds, Geoscience Australia).](image-url)
However, collection of detailed remotely sensed images of the seabed is only a starting point. Now, we need to "ground-truth" these images. What do the features we see on these images really tell us? What is the geology and the benthic habitat of the seabed? We can only determine this, and ultimately model the processes that shape the seabed, by compiling data bases of seabed properties. The auSEABED data base is an example. The data base was compiled for the Australian Maritime Region by Dr. Chris Jenkins at the School of Geosciences at the University of Sydney. It is based on a diverse set of data collected based on different navigation methods, technologies, aims, standards, and formats. The research resulted in a data mining system designed especially for the seabed.

**Data Visualization**

The primary method of visualisation of data from auSEABED is via grids, which can be compiled at a variety of resolutions and with various selections of data. Visualization is accomplished using GIS and other software applications. The outputs of the auSEABED processing are designed to be importable into any GIS and/or RDB (Relational DataBase), and are also suited for use in mathematical packages such as Surfer or Matlab. A primary goal of auSEABED is to provide inputs of important seabed parameters to the community of ocean modellers, including wave damping, nutrient budgets, sediment erosion, object burial, acoustic propagation and backscatter, stratigraphy and carbon cycle. This is done mostly through grids of seabed properties in selected areas. Figure 5 shows the output from a similar database for the Bass Strait, including mean wave period, mean significant wave height, maximum tidal velocity, bathymetry, graminize, and parameters relating to sediment composition, such as carbonate and mud content, and how well the sediment is sorted. These maps are gridded from irregularly spaced individual observations from the seabed, based on sediment cores. Naturally, the resulting maps are quiet smooth, as we have interpolated data for many areas without observations. Of course the real seabed is much more complicated. Multibeam images may give us a better idea of the real textures and structures of the seabed. Figure 6 shows an assemblage of so-called seafloor backscatter images, displaying the amplitudes of acoustic energy back-scattered (as opposed to absorbed) by the seabed. Relative fine-grained and soft seabed surfaces will have low backscatter, whereas hard surfaces made up of rocks or coarse sand will have high backscatter. Much of the seafloor is composed of varieties of so-called organic oozes, made up of marine organisms called the Plankton (the wanderers). This includes single-celled marine plants (diatoms) and animals (foraminifera and radiolarians), which are mixed with inorganic mud and sand. By looking at backscatter images around sample sites, we can associate certain acoustic patterns with the "geology", or sediment composition, and can in fact use artificial intelligence such as artificial neural networks to train computer programs to automatically classify remotely sensed images of the seabed into seafloor geology and biological habitat maps, also called "facies" maps. Figure 7 illustrates an example for such a seafloor facies map for the Bass Strait, compiled by Geoscience Australia.

![Figure 5: GIS-based mapping of the seabed composition and other oceanographic parameters in Bass Strait (from Phil Symonds, Geoscience Australia).](image)
Figure 6: Seafloor backscatter patterns from multibeam mapping, and seafloor geology based on sediment cores.

Figure 7: Seafloor facies (sediment type) map of Bass Strait, based on data from Fig. 5 and seafloor images as in Fig. 6 (from Phil Symonds, Geoscience Australia).

A virtual journey through space and time: the gPlates project

Plate tectonic reconstructions have been an integral part of global tectonic research since the discovery of sea-floor magnetic anomalies and the advent of the plate tectonic paradigm. On the broadest scale, palaeogeography refers to the distribution of continents and oceans through time. At a smaller scale, palaeogeographic configurations may be obtained, for example, through the study of facies distribution. Both geographic scales can ultimately be combined to give a detailed pattern of the geography of an area through time. The display of reconstructions in sequential 'time slices' is a comprehensive method of viewing biogeographic, geologic, palaeo-climate and palaeogeographic information and is extremely useful in understanding local and regional geologic relationships in the ocean basins and margins as well as the fundamental driving forces of plate tectonics. Recently, the gPlates consortium has grown out of the desire to create a universal standard for plate reconstructions, linked both to commonly used data bases, as well as to geodynamic models, using open standards and open software. The development of gPlates is coordinated at the University of Sydney (D. Müller) and includes two other primary development nodes at the California Institute of Technology (M. Gurnis) and the Norwegian Geological Survey in Trondheim (T. Torsvik). gPlates will be not only a software tool but all available geodata sets from Planet Earth will eventually be compiled, evaluated and implemented in the system. Our aim is to use gPlates to simultaneously display models for plate motions and plate/mantle dynamics, and to track the time history of point, line and gridded data, thus representing a 4D data base, whose entire data set can be reconstructed spatially and temporally through geological history.
Figure 8: Global grids of topography, gravity anomalies and age of the ocean floor.
Throughout the past decade, a number of global gridded Earth data sets have become available, which are extremely valuable for constraining plate reconstructions and the history of ocean basins through time. Three of the most relevant data sets are global topography and bathymetry (marine topography), gravity anomalies, and the age of the ocean floor (Fig. 8). Once a set of plate reconstructions has been derived, then one of these global gridded data sets can in turn be separated by tectonic plate and rotated through time. Figure 9 shows an example where a digital continental topography grid has been rotated through time, with climate zones being restored based on a simple climate model within a geographic information system (GIS). As the next step, such reconstructions can be used as input for numerical ocean models, to improve our understanding of natural oceanographic and climate change through geological time. Figure 9 shows a sketch of how paleoceanographic circulation may have changed through time, from a system dominated by a circum-equatorial current, flowing between Laurasia in the north and dispersing Gondwana continents in the south, to a system of a circum-Antarctic current, created by the opening of the Drake-Passage between the southern tip of South America and Antarctica, and the passage between Tasmania and Antarctica. The circum-Antarctic current was the major driving force of Antarctic glaciation by causing its isolation from warmer water masses. Antarctic glaciation in turn resulted in the onset of deep water formation in the Weddell Sea, by a combination of sea-ice formation and cooling, which leaves behind cold, saline water that sinks and flows into the deep ocean basins (thick arrows in Fig. 9), thus starting an oceanic “global conveyor belt” (without which phenomena such as the Gulf stream and El Nino would not exist).

Figure 9: Reconstructions of continental topography for the Early Cretaceous at 100 Ma and in the Late Tertiary (Oligocene) at 30 Ma. Overlaid is a sketch of oceanic surface circulation. The bold arrows in the 30 Ma reconstruction show the onset of deep water formation off Antarctica, due to formation of extremely cold and saline water from sea ice formation.

The dispersion of Gondwana (Fig. 9) together with the seafloor spreading in the Pacific Ocean changed the paleogeography of southern Eurasia and Australasia substantially. However, what is not visible in Figure 9 is that the geometries and topography of the surrounding ocean basins also underwent major changes. However, much of the ocean floor that existed in the past has now been recycled (subducted) back into the Earth’s mantle. The large-scale patterns of mantle convection are believed to be mainly dependent on the history of subduction. Therefore, some of the primary constraints for geodynamic models are given by the locations of subduction zones through time, and by the age of now subducted ocean crust.

As one of the first applications of the gPlates approach, we have used a combination of methods and datasets in order to reconstruct vanished ocean basins. The Paleo-oceans are modelled by creating “synthetic plates” whose locations and geometry is established on the basis of preserved ocean floor, regional geological data and the rules of plate tectonics. The resulting oceanic palaeo-age can then easily be converted into oceanic palaeo-depth maps, as the depth of ocean crust increases as the square-root of its age, due to thermal cooling (Fig. 10). Global reconstructions of the age of the ocean floor through time will enable more accurate modelling of palaeo-ocean circulation, and thus improve our understanding or palaeo-climate through time.

**Exploration Geodynamics and Interactive Inversion**

In recent years it has become apparent that better knowledge of the large-scale, long time behaviour of the Earth can dramatically improve the way we understand and model smaller scale geological processes, such as faulting and sedimentary basin evolution. Geodynamic modelling and visualisation provides both industry and academia with tools to better understand the occurrence of marine resources such as fossil fuels and minerals, and the formation and evolution of ocean basins and margins. To do so requires the integration of models which span a very large range of time and space scales. Length scales range from mantle convection cells and plates (100000km) down to the size of small-scale geological structures such as faults and folds, whereas time scales range from the age of the Earth to the time for a fracture to form or a chemical reaction to turn dead buried microorganisms into a rich deposit of black gold.
This integration is already beginning, particularly in Australia, and has resulted in the emergence of a relatively new field of applied research, which we coined “Exploration Geodynamics” — the focusing of geodynamic modelling on resource exploration. However, these activities require highly skilled graduates, who have combined studying physics and information technology with an interest in marine geology and geophysics, to learn how to simulate Earth processes using high-speed workstations or parallel computers.

**Continental splitting: from rift to seafloor spreading**

The formation of an ocean basin starts with continental rifting, the slow stretching of continental crust driven by the forces that result in the fragmentation of land masses (Fig. 11). Continental rifting is the prerequisite to continental margin and basin formation, and is often stretched out over many tens of millions of years. When the crust eventually breaks, seafloor spreading starts, and the two conjugate, or opposite, margins become tectonically passive. The continental shelves formed by this process may be symmetric or asymmetric, narrow or wide, and accompanied by volcanism, reflecting the continuously evolving non-linear interaction of the structure and physical properties (“rheology”) of rocks at extremely large deformations. Initially the continental rift geometry might be relatively simple, e.g. horizontally layered, but during the course of its evolution, very intricate patterns will develop, including faulting at different scales, mantle exhumation, and superposition of several phases of rifting with different stretching rates and directions. Since the 1970’s enormous amounts of data have been collected to map and image continental margins, mostly in the search for hydrocarbons. Recently developed numerical methods provide a new set of tools to understand the physics behind the non-linear processes that facilitate the stretching and breaking of continental crust to form marine shelves and basins.

**From analogue to numerical modelling**

In the past, lithospheric extension in three dimensions has largely been modelled using analogue laboratory experiments, based on materials such as sand, clay and plasticene, long before computers were available for this purpose. Geological observations tell us that the continental crust and underlying mantle represents a “jelly sandwich”. The hot, lower crust is assumed to be viscous and weak relative to mechanically strong layers above and beneath with different mineral compositions. In a typical laboratory experiment sand is used for the high strength brittle layers and silicone putty for low strength layers. After stretching such artificial crust, researchers found that many features of real continental margins can be reproduced, such as a detachment between crust and mantle, resulting in the Earth’s mantle, normally at a depth of about 30-35 km, being exhumed at the surface.
However, there are several aspects of continental margin formation that could never be explored using laboratory models. These include melting and magmatism/volcanism that is often associated with continental breakup, and thermal cooling of the margin through time. Based on recently developed software, we can investigate for the first time the effects of time-dependent crustal stretching rate, mantle temperature and crustal thickness and rheology on margin architecture and evolution.

We have developed numerical models of a series of problems involving extension of the continental lithosphere. This constitutes one of the first applications of 3D particle-in-cell technology to a problem of geodynamic importance. Specifically, we model the Earth’s crust and mantle as a 3-layer system (with upper and lower crust, and upper mantle components), and incorporate phase changes via decompression melting. The rheological model is viscoplastic, where the plastic part of the rheology is set to mimic brittle deformation and the viscosity is temperature-dependent. In a 3D model that includes the brittle upper crust, the relatively weak lower crust and the mantle, we have explored the consequences of rifting above a mantle plume – this commonly occurs in the real world, as continental breakup is often triggered by a cylindrical hot mantle upwelling, called a mantle plume. Our model shows that heating of the crust by the plume can result in viscous flow in the mid-crust towards the plume, thereby causing a symmetric pattern of crustal thinning on both sides of the plume, where extension is focused initially (Fig. 12). For further information on the mathematical background and methodology see the Large Scale Modelling overview by Louis Moresi in this introductory section of the conference volume.

Figure 12: 3D lithospheric stretching simulation with an initial temperature perturbation, due to a mantle plume and intrusion of magma. Time = 2.8 million years after the onset of stretching with an extension velocity of ~2 cm/yr. The non-dimensional distance is converted to the modeled distance by multiplying by a scale factor of 20 km. The extension is ~ 55 km. a) 2D section showing amount of brittle failure (plastic strain, StrP) in the upper crust and mantle (lower crust is in-between, in white; b) 3D plot of the particles in the upper crust and mantle, with the black lines showing the location of the cross section in a). An inactive weak zone is seen as a darker area in the right brittle zone of the upper crust. The temperature anomaly has cooled significantly by this time. See text for details.
Interactive inversion

The idea behind interactive inversion is the development of a system that would allow geological models to evolve backwards in time. The method of interactive evolutionary computation (IEC) provides for the inclusion of geological knowledge and expertise in a rigorous mathematical inversion scheme, by simply asking an expert user to visually evaluate different geological models. The IEC method provides for the inclusion of user expertise in a rigorous mathematical inversion scheme. Model iteration is based on interactive user evaluation of model outputs and genetic algorithms, which progressively modify the solution set by mimicking the evolutionary behaviour of biological systems (selection, cross-over and mutation), until an acceptable result is achieved (Fig. 13). This allows the model to explore a wide range of parameters before selecting an optimal output, and reiterating with a bias towards similar outputs is computationally intensive, and is only viable with the advent of the high-speed numerical simulations available due to today’s technology.

![Interactive evolutionary computing diagram](image)

Figure 13: Interactive evolutionary computing. A geologist chooses a target geological section associated with certain observations, prepares forward code input template, runs generation 1 models, ranks output images, runs generation 2 models, ranks output images again, and repeats modelling until target is closely matched (from Chris Wijns, Univ. of Western Australia).

The concept of Interactive Inversion, coupled with the evolutionary process of Genetic Algorithm development has many possible uses in the field of geoscience. Constraints can be placed on models for the styles of mantle convection, patterns of crustal faulting and basin evolution. In general, all questions of the sort “What initial conditions may result in this geological response?” can be tackled.

The IEC technique considerably reduces the effort required to create realistic Earth models. The novel modelling approach would help industry to assess the hydrocarbon potential of marine sedimentary basins, as the models would simulate the accumulation of sediments and hydrocarbons, the deformation of basins, and the temperature-conditions everywhere in the basin through time.

The key strength of the method is that it allows the user to direct the inversion according to his or her judgement and requirements, without having to formally specify these requirements to the modelling software. This brings the power of inversion and high-speed modelling directly to the desktop of a user who has no prior training in the field of inversion, but who can distinguish between viable and unviable model outputs.

As an example, let us look at common extensional structures in a rifting environment, i.e. a small number of large-offset faults, which have accommodated much of the crustal extension (Fig. 14, top). The particle-in-cell finite element model is composed of two initially homogeneous crustal layers, namely the upper and lower crust, with a layer of air on top (Fig. 15). Extension proceeds by applying a uniform horizontal velocity to the right-hand boundary. The upper crust has strain-softening properties, which cause initial strain perturbations to localise. An initial weakness is included in the upper layer in order to control the location of the first fault. This perturbation is small enough that it does not affect the direction or depth of fault propagation. The fault geometry and successive fault spacing arise naturally from the initial conditions of the problem. Eight forward models are run at each step of the inversion. We allow six upper crustal strength parameters to vary: viscosity and five other coefficients which determine together how the material fails in extension. After a set of eight model runs, the user evaluates the outputs, and chooses the “best-fit” model, which is then used to spawn eight new models with slightly different parameter combinations, based on applying genetic algorithms. After six runs, our model converges, and we find a suitable combination of parameters (Fig. 16) that gives rise to the type of extensional faulting we observe. The best-fit parameters imply a high upper crustal viscosity, large strain weakening (i.e. once deformed, the material weakens substantially), a low limit for material failure in tension, a low to zero cohesion with weak pressure dependence, and that the “saturation strain” does not affect our results very much (Fig. 16).
Figure 14: Interactive evolutionary computing applied to modelling the formation of several large-scale faults in extended crust. After each modelling iteration, the geologist compares and ranks eight model outputs; then a genetic algorithm is used to spawn a set of new starting conditions for the next batch of eight models. After only six iterations, we converge on a best-fit model. The multi-dimensional parameter space is so large that an automatic search for the best-fitting parameters is not feasible (from Chris Wijns, Univ. of Western Australia).

Figure 15: Initial model setup, composed of an upper layer of air, and upper and lower crust. An initial weakness is embedded in the model to control the location of the first fault (from Chris Wijns, Univ. of Western Australia).

Without interactive inversion, we would have had to select parameters manually by trial and error, or an exhaustive coverage of the entire parameter space, i.e. all possible combinations of parameters. Trial and error may succeed with a limited number of parameters, but depends upon the user's knowledge of the coupling and feedback between parameters, which, in highly non-linear problems involving complex crustal rheologies, may be impossible. A parametric study quickly becomes unfeasible due to the sheer number of models, which must be run as the number of parameters is increased. Neither of these approaches takes full advantage of the expert knowledge of an experienced geoscientist.
Discussion

Australia largely remains data rich and information poor in marine geoscience as tens of millions of dollars have been spent on collecting data matched by a lack of data integration and ground-truthed modelling. In response to this situation, the discipline of marine geoscience is currently in a process of redefining itself as a multidisciplinary subject area that thrives on interacting with other sciences. Interaction with information technology and physics is essential to foster geodynamics, the study of the fundamental processes, which drive the evolution of the Earth, and processes shaping the ocean basins, continental shelves, and coasts. The field of geo-informatics is analogous to the role bio-informatics is now playing in the field of biology and gene-technology.

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