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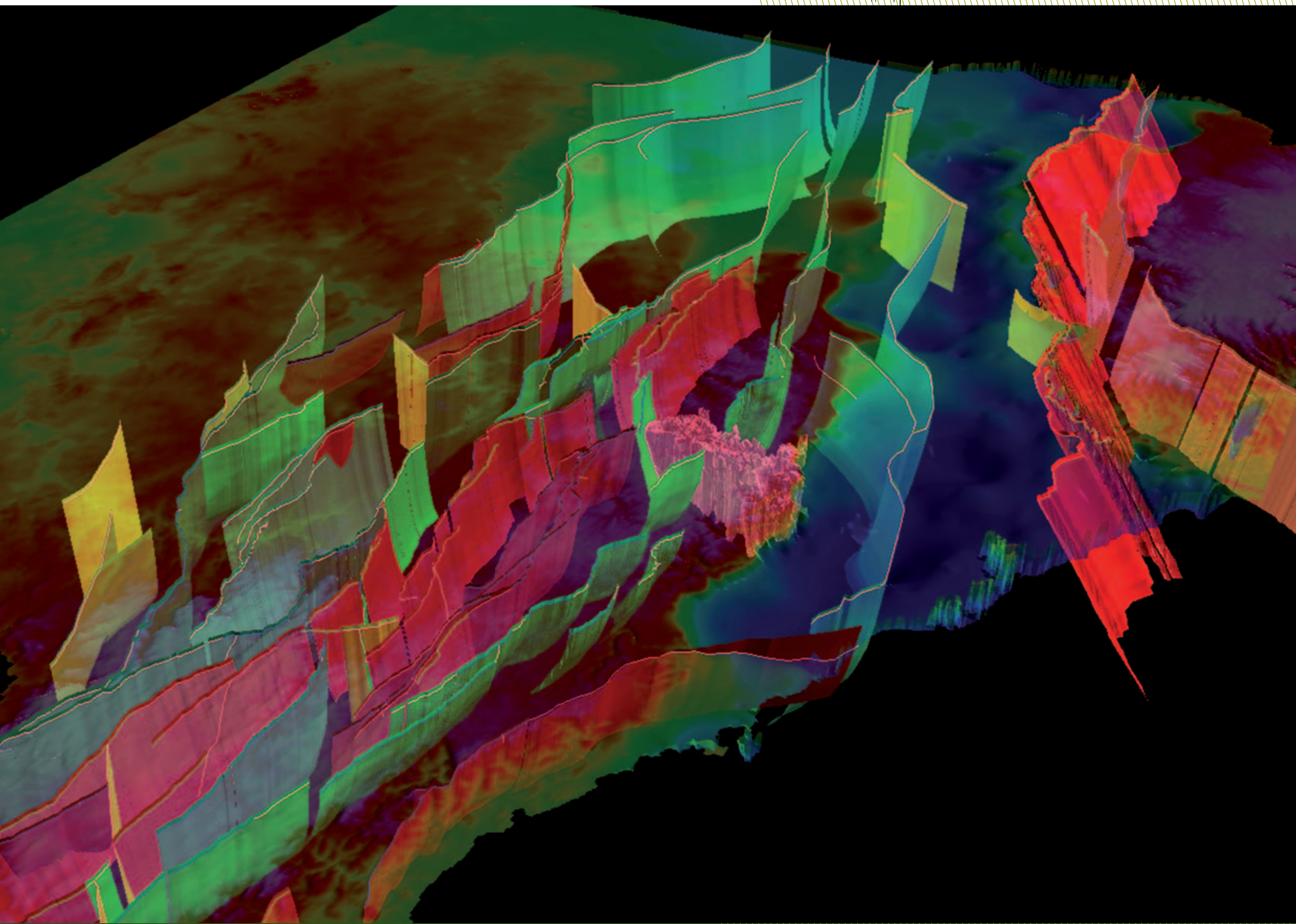
PREVIEW



NEWS AND COMMENTARY

FEATURES

Education matters

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In this issue of *Preview* it is my privilege to introduce an article by Professor Dietmar Müller and Associate Professor Patrice Rey and their team, bringing us an overview of work in progress by the Basin GENESIS Hub at the University of Sydney on plate tectonics and the evolution of sedimentary basins. There is an interesting historical antecedent here; in the 1930s it was a University of Sydney student, Sam Carey, who developed a fascination with the concept of continental drift, and completed a PhD and DSc on tectonics of the Sydney Basin and basins of Papua New Guinea. His fascination with geology was interrupted by war service as a commando (1942–45) but, from the start of his appointment as Professor of Geology at the University of Tasmania in 1946, he was a powerful advocate for continental drift for two decades, a time when 'drift' was a derided concept in geosciences of the western world. The theory of plate tectonics became respectable in the academic world during the 1960s.

Professor Carey's trademark was to teach his students to question published work (even that of supervisors!), and if he were to look down at his old Department in Sydney from wherever he may be now, he would nod with approval, and remind today's students of his favourite motto regarding established scientific wisdom, 'disbelieve if you can'.

Carey was famous in the 1950s for deforming plastic sheets in boiling water to create earth-shell segments for tracing and moving continental margins on a globe. Researchers of the Hub may be remembered in 2080 for their use of super-computers available within the National Computational Infrastructure. We can't guess what advances the five post-doc researchers who contributed to this article will see in the next 60 years, but we wish them well in a branch of geoscience that progresses as much by iconoclastic change as by evolution.

The ARC Basin GENESIS Hub: connecting solid Earth evolution to sedimentary basins

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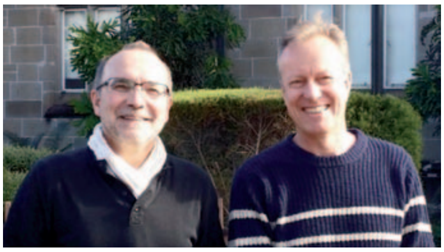

Dietmar Müller (right) and Patrice Rey (left).

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The ARC Basin GENESIS Hub (BGH) is a 5-year Industry Transformation Research Hub supported by the Australian Research Council (ARC) and 5 industry partners, aimed at developing and applying next generation computer models to fine-tune our understanding of the structure and evolution of sedimentary basins. The Hub is based at the University of Sydney's EarthByte research group (www.earthbyte.org), led by Dietmar Müller and Patrice Rey, with additional nodes at the University of Melbourne (led by Louis Moresi), Curtin University (led by Chris Elders), the California Institute of Technology (led by Michael Gurnis) and Geoscience Australia (led by Karol Czarnota). The Hub's unique strength is in connecting global plate tectonic and geodynamic models to models of the evolution of individual basins and their hinterlands. This requires linking disparate geological and geophysical data sets with several simulations and modelling codes and their outputs. A central theme in the Hub is understanding the origin, and destruction, of topography. Surface topography represents the source of sediments that ultimately end up in sedimentary basins. Therefore, we are trying to understand how surface topography or accommodation space is created or destroyed via combinations of lithospheric deformation, mantle convection, erosion and sedimentation, constrained by a range of observations. This article portrays the software and new basin modelling workflows being developed in this research centre, with particular emphasis on the Hub's early career researchers.

For this, we first need well-constrained solid Earth models, driven by mantle and plate tectonic processes. The global tectonic reconstructions created in our EarthByte group are a key to understanding this system. The basic rules of plate tectonics theory, first defined formally in the 1970s, describe first order surface lithospheric motions, but these rules are mostly kinematic and do not explain the time-dependent interaction between the convecting mantle and the tectonic plates. As a consequence, the increasing uncertainties in the geological record back in time make it difficult to constrain plate reconstructions before Pangea breakup.

One way to deal with these uncertainty estimates is to better understand the physics behind plate motions. Although it is generally agreed that convection in the mantle and plate motions are inextricably interconnected, the relationships between deep Earth dynamics and surface tectonics are still poorly understood. To make progress in this direction, BGH research fellow Claire Mallard uses recently-developed fully-dynamic global models using the code StagYY (https://github.com/the-life-tectonic/xsede/wiki/StagYY), which self-consistently generate Earth-like mantle currents together with plate-like surface tectonics. The virtual planets produced this way (Figure 1) provide access to a range of different evolving parameters representing plate-mantle evolution (Mallard et al., 2016).

Claire Mallard.

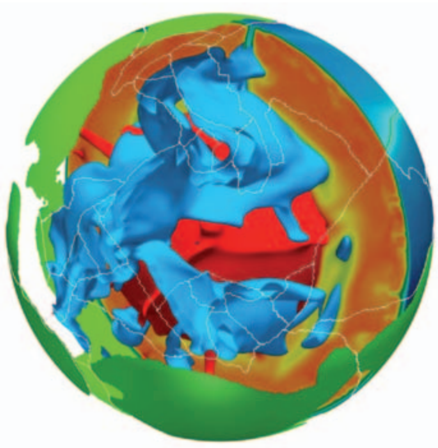


Figure 1. *Mantle temperature field and surface expression (in white) of a fully dynamic convection model, highlighting modelled plate boundaries. The Earth's interior shows hot up-wellings in red and sinking slabs in blue. At the surface, continents are shaded green.*

We are now able to qualitatively and quantitatively compare these virtual planet computations, such as their plate boundary evolution and reorganization, and estimate dynamic topography resulting from mantle flow, applying the rules of plate tectonics and geological observations. For instance, the definition and number of plates, as well as the length and evolution of past subduction zones, in the tectonic reconstruction is biased, and implies an increasing uncertainty of dynamic topography estimates deeper in geological time.

Our development of the open-source and cross-platform GPlates plate reconstruction software (Müller et al., 2018) is the enabling engine of our efforts to build and improve global plate tectonic reconstructions that we also share with the community. These plate reconstructions are typically constructed using a synthesis of continental geological constraints (e.g. palaeomagnetic, sedimentary/fossil evidence of prior tectonic affinity, metamorphic/volcanic chronologies, etc.) and marine magnetic anomalies and fracture zones (where they are preserved). To better understand the influence of the deep Earth on surface processes, we use our plate tectonic reconstructions as surface constraints for numerical models of mantle convection, using the well-established CitcomS code (https://geodynamics.org/cig/software/citcoms/). Recently, the capability to deform plates has also been added to GPlates (Gurnis et al., 2018), allowing us to use deforming plates as surface boundary conditions for geodynamic models and in basin modelling.

Sabin Zahirovic.

Our evolving 4D solid Earth models help us track the evolution of the mantle, as well as how convection influences vertical motions of the Earth's surface. All geologists are well-versed in tectonic topography (mountain-building in collisional settings, basin formation during rifting, etc.), but the role of the convective mantle in shaping regional topographic signals has been somewhat under-appreciated. A key observation is that plates move across different mantle domains, and so the dynamic topography acting on continents (and the basins they host) changes through time. For example, Australia's northward motion towards Southeast Asia in the last 50 million years has resulted in the northern margin of the continent overriding subducted slabs from Asia and the Pacific, leading to broad subsidence of the Arafura Shelf and New Guinea, leading to north-eastward tilting of the Australian continent at present-day. In addition, dynamic topography likely dominated the regional uplift of Southeast Asia in the Eocene, which was followed by broad regional subsidence towards the present, despite falling long-term sea levels. However, the influence from mantle flow is superimposed by tectonic and flexural topography in such complex regions, and work is under way to better quantify the relative roles of these signals. These global models, applied to the Southeast Asian and Papua New Guinea regions by Sabin Zahirovic and his students and collaborators (Figure 2), are an essential component of the infrastructure that helps track basin evolution across a wide range of spatio-temporal scales. More importantly, these modelling approaches help us better understand global and regional tectonics, as well as help us link global mantle flow to surface processes in frontier basin exploration areas.

GPlates is designed to visualize the outputs of mantle convection models with plate reconstructions and observational data attached to moving plates. To achieve this we had to explore and prototype various ways to render 2D raster data and 3D volume data with past configurations of tectonic plates, an effort led by John Cannon, the GPlates lead developer whose previous experience with graphics programming in the computer games industry comes in handy. Eventually we adopted an approach based on so-called hierarchical cube maps, accelerated by GPU graphics hardware. The cube map approach combined with a programmable ray-tracing capability of modern graphics hardware can be used to visualize arbitrary 3D geophysical data and geodynamic model outputs (Figure 2) together with plate reconstructions (Müller et al., 2018).

John Cannon.

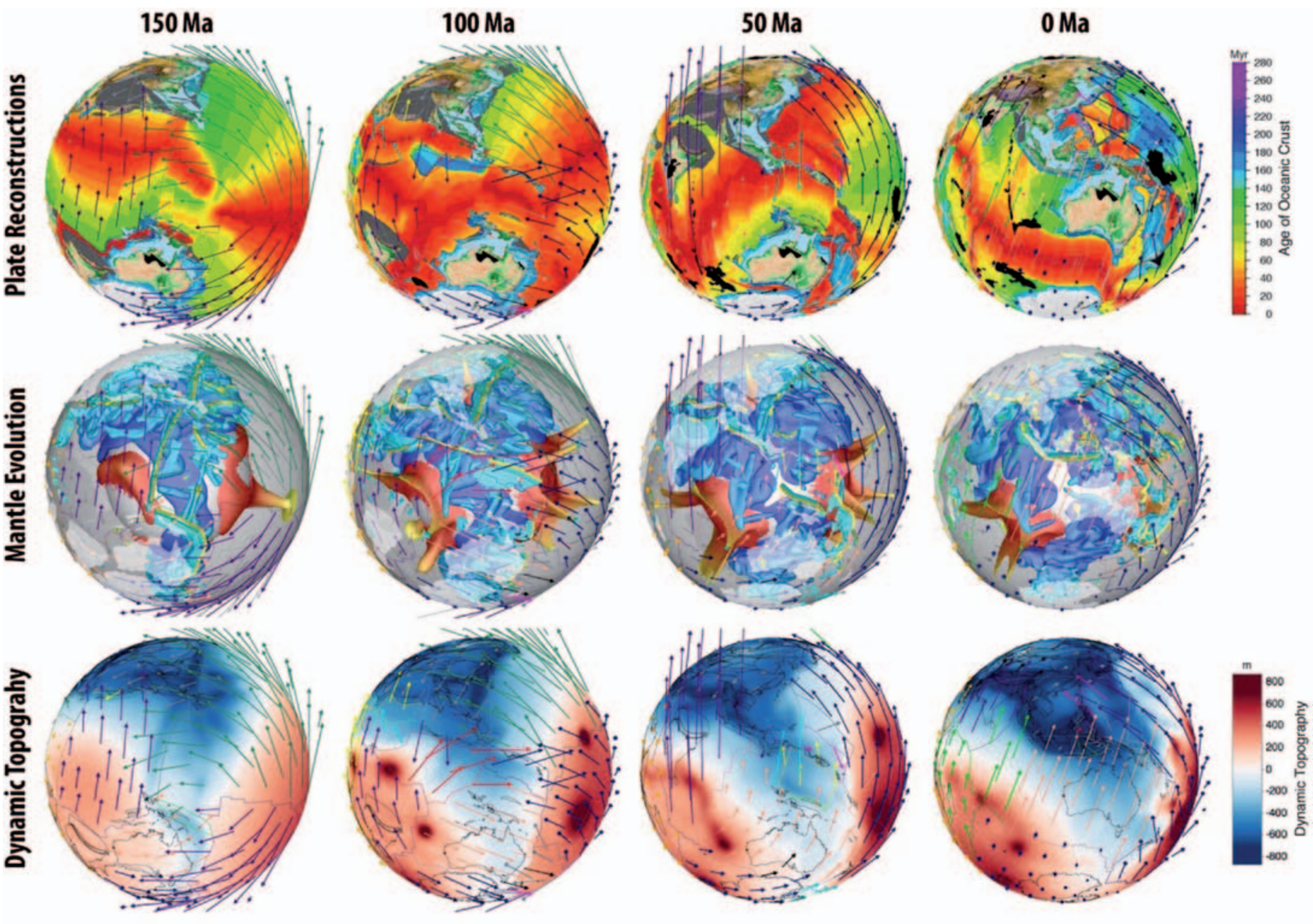


Figure 2. *Global plate tectonic reconstructions since the Jurassic in GPlates (www.gplates.org) (Zahirovic et al., 2016) with an Orthographic view of the Tethyan-Indian Ocean region. The plate motions (top row) from GPlates are used as surface boundary conditions for mantle convection models (middle row) in the CitcomS code, which help us estimate the dynamic topography (bottom row) acting on continental and oceanic basins as a result of mantle flow. This spatially- and temporally-evolving dynamic topography is typically regional in scale, with an amplitude of only several hundred metres, but is crucial in explaining the inundation or emergence of continents that may be out of sync with eustasy, as well as helping understand anomalous basin subsidence and uplift.*

Tristan Salles.

Our surface process models, driven by tectonic forcing of topography via mantle convection and plate deformation using the Badlands software (https://github.com/badlands-model/pyBadlands) (Salles, 2016), depend on a range of uncertain driving forces that we are exploring by experimenting with a range of input parameters (Figure 3). For instance, the erodibility coefficient of rocks at the surface is not well known and needs to be determined empirically, while the total uplift or subsidence rates through time are equally ill-constrained. Therefore, we run numerous forward models exploring parameter combinations to find the best-fit models constraining erosion and sediment accumulation (Figure 4).

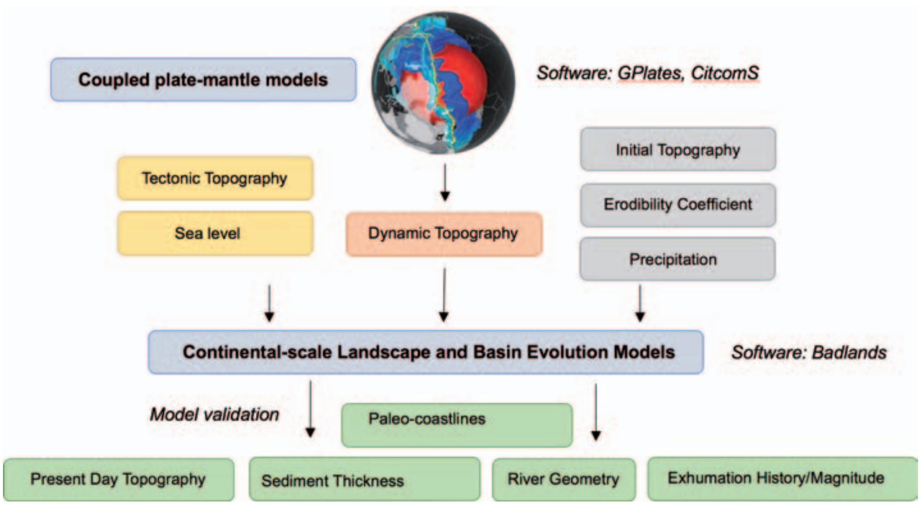


Figure 3. *Workflow to link geological and geophysical data to landscape and basin evolution models, constrained by tectonic and dynamic topography modelled via coupled plate-mantle geodynamic models.*

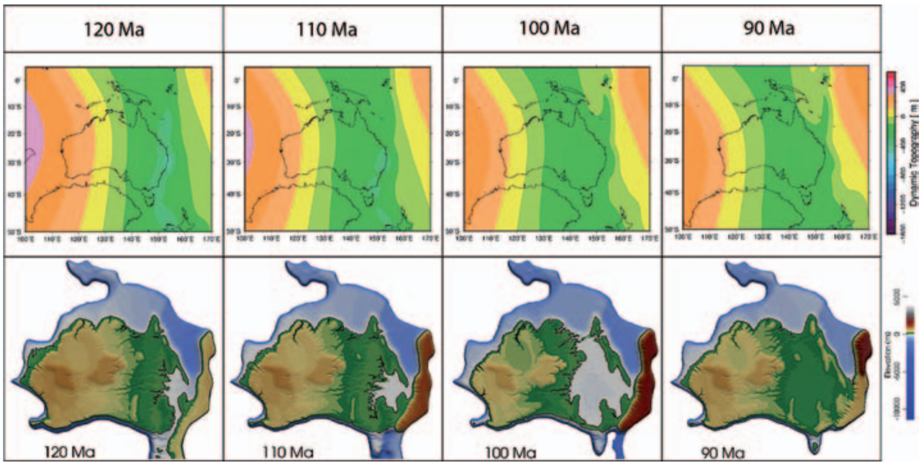


Figure 4. *Influence of change in mantle convection-driven dynamic topography (top row) on the transgression and regression of the Eromanga Sea from 120 to 90 Ma in the Cretaceous (Harrington et al., 2017). As Australia moves eastwards during this time period (not shown here) it overrides the East Gondwanaland "slab burial ground" drawing down eastern Australia and causing extensive flooding long before the Late Cretaceous global sea level high. Subduction becomes extinct around 100 Ma, resulting in slab material progressively sinking into the lower mantle, dimishing its effect on the surface, causing topographic rebound. Our Badlands surface process models can be used assess the effect of this westward wave of dynamic subsidence on landscape evolution. We can model the evolution of sediment fill in the Eromanga Basin, followed by uplift and exhumation after retreat of Australia's epicontinental sea. How deep Earth and surface processes interact, depends also on the interplay between rock erodibility, precipitation and global sea level change through time.*

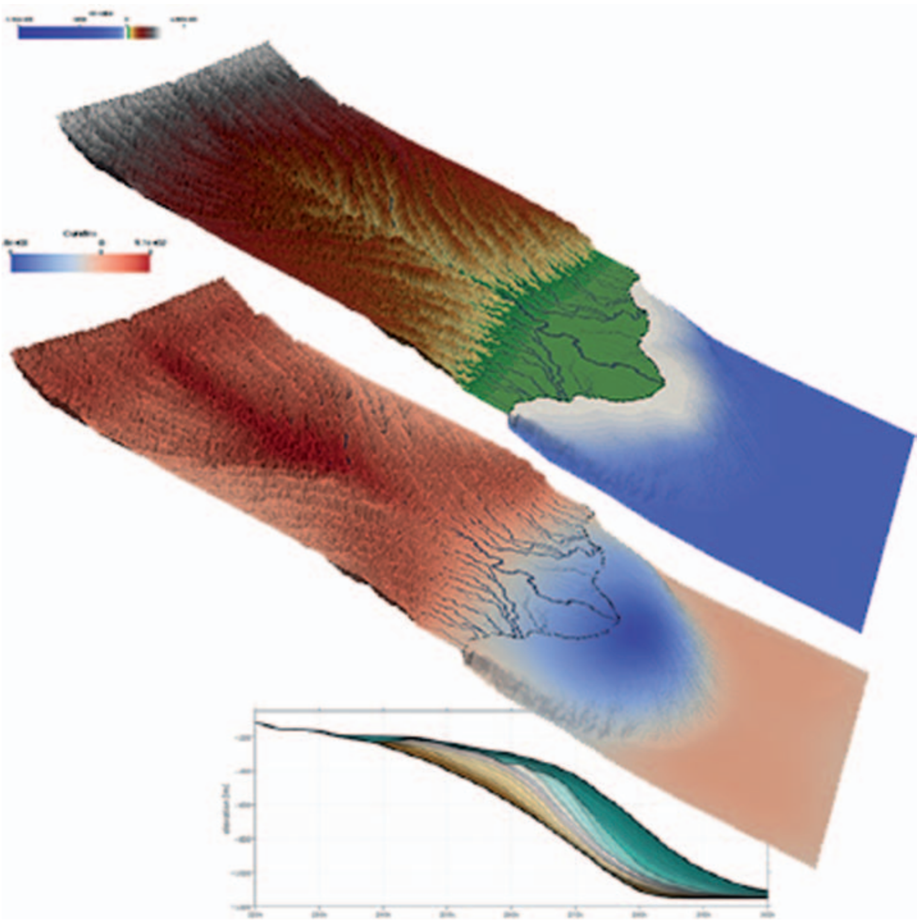


Figure 5. *Output of cutting-edge deltaic simulations generated in Badlands showing elevation and bathymetry, cumulative flexure and synthetic stratigraphy. Simulations are used to better understand the first-order controls that generate the sedimentary patterns we observe in ancient deltas. Improvements in understanding of fluvio-deltaic sequences are needed to unlock the vast amounts of hydrocarbons hosted in these types of reservoirs.*

These models have been applied to understand the interplay of the formation and disappearance of the Cretaceous Eromanga Sea and the subsequent uplift of the eastern highlands of Australia (Salles et al., 2017).

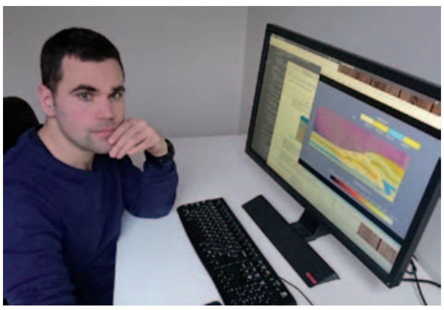
A particular emphasis of the Hub is the development of detailed models of the formation, preservation, and economic significance of deltas. Significant resources such as hydrocarbons and water are accumulated in deltaic deposits; prime examples are the Ceduna and Mungaroo deltas in Australia and the Paleo-Mississippi in the Gulf of Mexico. Improvements in understanding of fluvio-deltaic sequences are needed to unlock the vast amounts of hydrocarbons hosted in these types of reservoirs. Numerical modelling offers a cutting-edge process-based approach for unraveling controls in facies distribution and stratigraphic architecture in fluvial systems. In the Hub's team, Sara Morón uses the Badlands software to better understand the first-order controls that generate the sedimentary patterns that we observe in ancient deltas, by combining seismic, biostratigraphic, geochronological and thermos-chronological data to provide boundary conditions for our numerical simulations (Figure 5).

Sara Morón.

To formally evaluate model uncertainty, we have developed Bayeslands, which was created jointly with the recently established Centre for Translational Data Science at the University of Sydney. Bayeslands uses a Bayesian statistical framework to estimate model parameters by evaluating the outputs of thousands of forward models (Badlands) against observational data and prior knowledge. This approach, led by Rohit Chandra, has been successfully tested on simple basin models dependent on just three parameters (rock erodibility coefficient, annual rainfall and sediment thickness). This is being extended towards more complex models using high performance computing resources (https://www.earthbyte.org/bayeslands-resources/).

Rohitash Chandra.

Even though the resolution of our virtual planets allows us to better understand the mantle-lithosphere interaction processes as drivers of sedimentary basin evolution at the first order, a finer resolution is needed to capture faulting and crustal flow, as well as surface processes like river erosion and sediment transport. This additional challenge involves including our evolving understanding of mantle-lithosphere interaction in the feedback between mantle flow, crustal deformation, erosion and sediment transport at the scale of sedimentary systems. Patrice Rey, Tristan Salles, and research fellows Romain Beucher, Sara Morón, Claire Mallard and the Underworld/Badlands software teams have developed a range of different 3D thermo-mechanical models for different tectonic contexts using the Underworld (http://www.underworldcode.org/) numerical modelling framework. It is now possible to link these models with surface process models in order to model basin stratigraphy via our Badlands software (Figure 6a and Beucher et al., 2018). This 4D simulation of surface processes, enabled by a high-performance parallel computing approach, allows us investigate the effect of lithospheric rheology and extension speed/obliquity on the removal of up to several kilometres of material during rifting (Mondy et al., 2017) (Figure 6b), as well as associated sedimentary deposits. These models are starting to be applied to basins in a variety of tectonic settings around the world.



Romain Beucher.

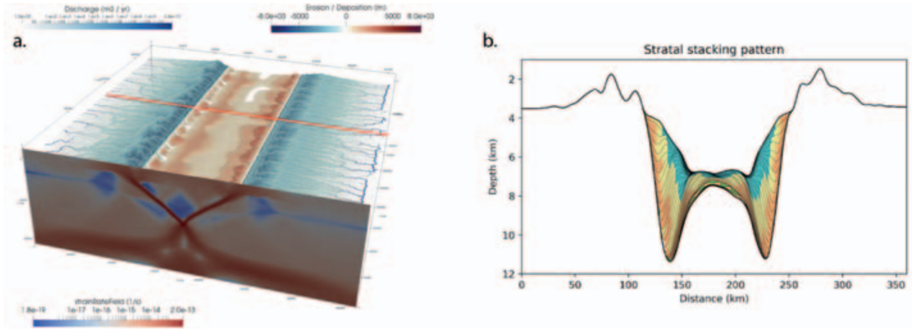


Figure 6. *Example of an Underworld thermo-mechanical model coupled with the surface process code Badlands. (a) The left panel shows a snapshot of the strain-rate in an extensional basin after 5 million years of rifting, while the surface illustrates the total erosion and sedimentation. (b) The right panel is a cross section of the stratal stacking pattern (along the red profile across the model), which can be compared to seismic reflection profiles.*

Figure 7. *Graduated and current Basin GENESIS Hub PhD students. From top left to bottom right: Xuesong Ding, Wenchao Cao, Amy I'Anson, Michael Tetley, Rhiannon Garrett, Ben Mather, Maelis Arnould, Carmen Braz, Sarah McLeod, Luke Mahoney, Amanda Thran, Omer Bodur, Luke Mondy, Nick Barnett-Moore, Andrew Merdith and Rakib Hassan.*

The Hub's PhD projects (see Figure 7 for past and current PhD students) cover a large range of spatial and temporal scales in solid Earth and surface processes. Examples include modelling syn-rift sequence stratigraphy using coupled thermos-mechanical and surface process models (Xuesong Ding), determining the role of asthenospheric flow and major plate motion speed changes on anomalous uplift and subsidence on sedimentary basins on leading and trailing edges of continents (Omer Bodur), and constraining upland erodibility in catchments delivering sediment to the Gulf of Papua (Rhiannon Garrett).

The work of these students will be described in more detail in the annual review of research by Australian students in geophysics that will appear in the December issue of *Preview*.

The Basin GENESIS Hub is enabled by the AuScope National Collaborative Research Infrastructure, Simulation project, whose Simulation and Modelling project, led by Louis Moresi, has supported software development since 2007. Another critical building block of the Hub is the Australian National Computational Infrastructure; without their high-performance computer Raijin we would not be able to execute our models. Lastly, we thank our industry partners, Statoil, Chevron, Oil Search, Intrepid Geophysics and 3D GEO, who support the development of open-source software for resource exploration. Our development of community software is a key aspect of the Hub, as it ensures that our software and workflows will live on long after the Hub's 5-year lifetime. All end-users, including industry, are able to access our software at no cost, and an open-source philosophy allows us and a network of global collaborators to educate the next generation of exploration geoscientists who are all able to use, and be trained on, the same software, share their experiences and contribute to improving these community codes; updates on progress appear regularly on ResearchGate and the EarthByte research group page on Facebook: https: //www.facebook.com/earthbyte/.

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