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From Paleogeographic maps to Evolving Deep-time Digital Earth models

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Major advances in computational power, as well as community modelling workflows and an improvement in data availability, has revolutionized Earth sciences over the last decade. Geological data has been synthesized into flexible and open access plate tectonic and paleogeographic reconstructions using the open-source and cross-platform GPlates (www.gplates.org) software since 2008 (Müller et al., 2018; Müller et al., 2008). These digital plate reconstructions have been revised both in spatial and geological detail (Fig. 1), as well as the temporal reach, with emerging models extending to cover more than one billion years of Earth history. Importantly, these reconstructions have been linked to numerical models of mantle flow using tools such as CitcomS (Bower et al., 2015;Fig. 2), which has improved the testability of plate reconstruction scenarios where mantle flow predictions can be validated using present-day P- and S-wave seismic tomographic constraints. These time-evolving 4D Earth models have also provided insights on the evolution of the plate-mantle system over supercontinent cycles, as well as shed important insights into the role of the churning planetary interior in vertical motion of tectonic plates and the continents they carry. This "dynamic topography" (Braun et al., 2013; Flament et al., 2013; Gurnis, 1990, 1993) (Fig. 2), which is in addition to isostatic (tectonic) and flexural topography, has influenced (and sometimes controlled) the long-term flooding and emergence of almost every continent.

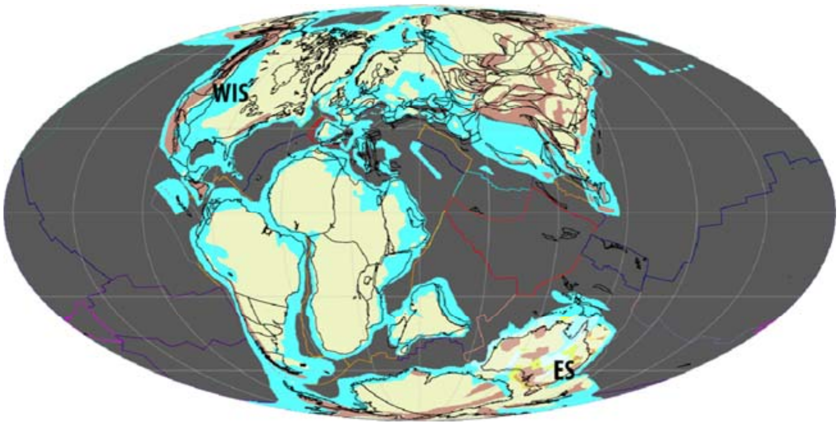

Fig. 1. Global paleogeographic and plate tectonic reconstruction at 110 Ma for the mid-Cretaceous in Gplates.
The global paleogeographic model from Cao et al. (2017), modified from Golonka et al. (2006) using constraints from the Paleobiology Database, is plotted on the global plate tectonic reconstructions of Matthews et al. (2016), highlighting the Western Interior Seaway (WIS) on North America. The Paleo-geographic Atlas of Australia from Langford et al. (2001) is superimposed to highlight the regional detail of the Eromanga Sea (ES) in the mid-Cretaceous.

The high eustatic sea levels, resulting from greenhouse conditions, in the mid-Cretaceous, in addition to dynamic subsidence from subduction along eastern Australia and western North America led to geologically-ephemeral regional flooding to create the Eromanga Sea (Fig. 3) and the Western Interior Seaway on these continents (Gurnis et al., 1998; Spasojevic et al., 2009), respectively. In addition, the northeastward tilting of Australia since the Eocene has been argued to be the result of the continent overriding sinking slabs in the mantle (DiCaprio et al., 2009; Sandiford, 2007; Tobin et al., 2018), leading to the ephemeral flooding of New Guinea that was out of sync with global eustasy (Harrington et al., 2017). Similarly, the subduction history along the Java-Sunda margin in Southeast Asia since the Cretaceous has shaped the long-term emergence and inundation of the continental promontory (Yang et al., 2016, 2018; Zahirovic et al., 2016a). Much of these broad topographic uplift and subsidence patterns become obvious in the regional stratigraphic record, and even in regional paleogeographic reconstructions,

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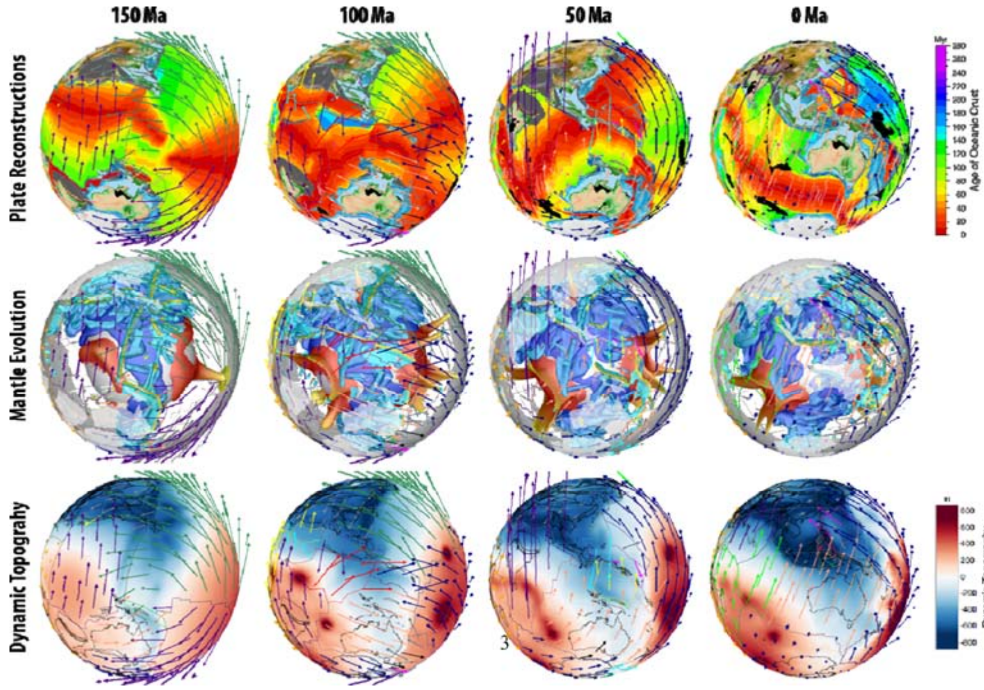

Fig. 2. Global plate reconstructions in GPlates (top row) are used to guide mantle flow models in CitcomS (middle row) allowing us to track the evolution of the plate-mantle system, including dynamic topography (bottom row).
Digital community plate reconstructions, in this case the model of Zahirovic et al. (2016b) (top row), is applied as a surface boundary condition following the approach described in Bower et al. (2015) with an Extended Boussinesq Approximation method in CitcomS (middle row) described in Hassan et al. (2016). The resulting mantle flow can be used to estimate dynamic topography (bottom row), which is an important component of Earth's paleogeographic evolution.

such as the global and Asia-focused reconstructions from Golonka et al. (2006), and the Paleogeographic Atlas of Australia from Langford et al. (2001) (Fig. 1).

The maturity of modelling and data approaches signals a new dawn in capturing the evolution of our planet over hundreds of millions of years. In particular, significant strides have been made in linking deep Earth and surface processes (Salles, 2016; Salles and Hardiman, 2016) that transcend spatiotemporal scales, capturing important interactions of the geosphere with other Earth systems (hydrosphere, atmosphere, biosphere, etc.). The open-source Badlands software (https://github.com/badlands-model/pyBadlands) enables a new generation of paleogeographic map-making (Fig. 3), where Earth's topographic evolution is captured through the interplay between lithospheric and crustal deformation, plate flexure, dynamic topography, eustasy, and the erosion and deposition of sediments on continental-scale models. These models run efficiently on desktop computers, but scale in efficiency also on high performance platforms through user-friendly Docker-Kitematic virtual machines. The challenge now is to generate realistic initial topography, as well as well-constrained time-evolving boundary conditions (including climate and rainfall), to produce robust models that provide unparalleled insights into the evolving surface and subsurface of our planet. The Paleogeographic Atlas of Australia (http://

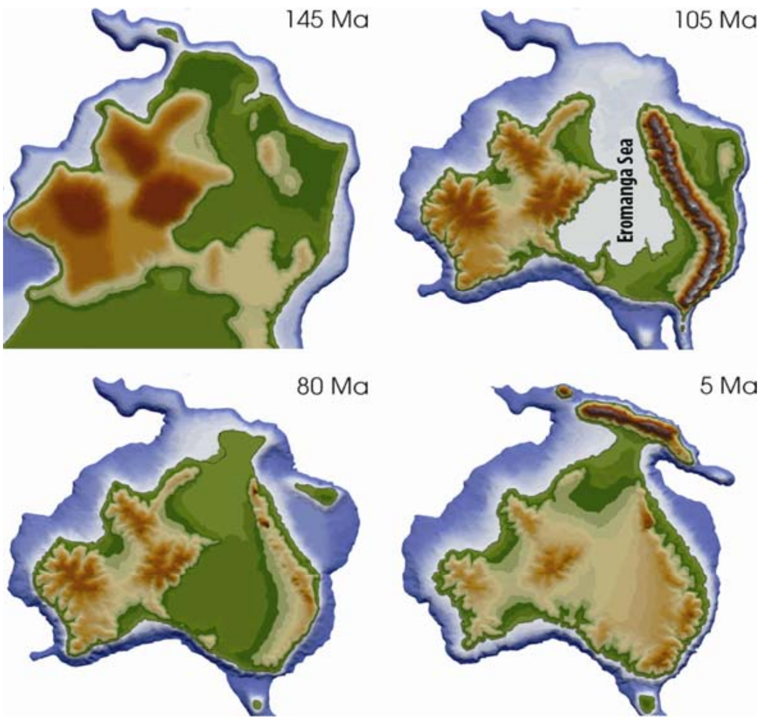

Fig. 3. Landscape evolution models using the Badlands code for the Australian continent.
The Paleogeographic Atlas of Australia (Langford et al., 2001) was converted to an initial estimate of topography for landscape evolution models run using Badlands (Salles, 2016; Salles and Hardiman, 2016). Time-evolving rainfall, sea level, tectonic uplift/subsidence, and mantle-driven dynamic topography is applied to track the evolving topography that includes erosion and deposition (Braz et al., in preparation). These panels show the evolution of the Eromanga Sea in Australia since the Cretaceous.

www.ga.gov.au/static/palaeo/palaeo.html), curated by Geoscience Australia, provides the best example of digital public paleogeographic maps that separate out the raw data and the interpretation. Similarly, Geoscience Australia provides a range of open access data, including sediment thickness models and interpretations that are vital to ground-truthing surface process models of the continent (e.g., http://pid.geoscience.gov.au/dataset/ga/79790). In addition, the Paleobiology Database (http://paleodb.org) provides the best example of a comprehensive and robust database that can be easily adapted for use in paleogeographic reconstructions. However, databases of paleo-altimetry, paleo-bathymetry, and exhumation/denudation from thermochronology remain the next frontier in community infrastructure to support deep-time digital Earth modelling. The next decade of work will provide unprecedented opportunities in modelling Earth processes across spatiotemporal scales to address critical research areas relating to energy and mineral exploration, climate and sea level change, as well as modelling ocean circulation and interactions between the solid Earth and the biosphere, atmosphere, and hydrosphere on geological timescales. Here we present an example of a new generation of 4D digital landscape evolution models that combine plate reconstructions, mantle flow, and eustasy in a community modelling framework.

Key words: paleogeography, tectonics, Tethys, GPlates, Digital Earth

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Sabin ZAHIROVIC, was born in 1986 in the city of Brcko in Yugoslavia, now Bosnia and Herzegovina. He arrived in Sydney, Australia, in 1997, and received his PhD from the University of Sydney in 2015, where he has since worked as a Post-Doc and Lecturer in global tectonics and geodynamics.