

Forward Modelling in the Geosciences

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Abstract

We describe how we use models of mantle dynamics to understand and test the controls and effects of plate tectonics, such as ocean basin volume, magma production and the formation of natural resources. Numerical modeling and geological ground-truthing were incorporated to test the hypothesis that vertical motion of the Australian continental plate, as observed from sediments deposited during a marine incursion, was linked to the effects of negative buoyancy due to the dynamics of a sinking subducted slab along the eastern margin of Australia. Different models with varying parameters and boundary conditions were developed and then compared with geological observations to develop a best-fit numerical model.

Keywords: Lithosphere deformation, Plate tectonics, Tectonic Reconstruction

Introduction

Planet Earth is an extremely complex system, partly because of the existence of plate tectonics. Plate tectonics is an expression of slow convection of the Earth's mantle over geological times, and the principle means by which the Earth loses its internal heat. On a geological timescale (i.e. millions of years), plate tectonics exerts major controls on global sea-level changes and geochemical cycles. We know that all continents aggregated during the Late Palaeozoic, about 250 million years ago, into a single supercontinent, Pangaea, and then dispersed during the Jurassic period, initially into Gondwana in the south and Laurasia in the north (Fig. 1). However, plate motions not only determine the distribution of land and sea, but also the volume of the ocean basins, which depends on the average global seafloor spreading rates (how fast tectonic plates are moving away from each other). The rates of plate creation at mid-ocean ridges and plate subduction in zones where plates converge exert major controls on the carbon cycle and other geochemical cycles, by means of seafloor weathering, mid-ocean ridge degassing, and subduction of sediments. Plate tectonic processes also control the production of magma, the generation and destruction of crust, and crustal deformation, driving the formation of basins and mountain belts with associated natural resources (Fig. 2).

Despite over 30 years of research in geodynamics, there are still many fundamental unresolved questions with regard to how the Earth has evolved since its accretion about 4.5 billion years ago. When exactly did plate tectonics evolve, and what triggered its inception? What exactly drives the plates and what determines the geometry of the plate tectonic system? Why do we have plate tectonics, as opposed to some other tectonic mode, which would remove planetary heat? What controls the time-dependence of mantle convection? Are sea-level variations entirely caused by the waning and waxing of polar ice-caps, or are there other mechanisms that may result in major fluctuations of relative sea-level?

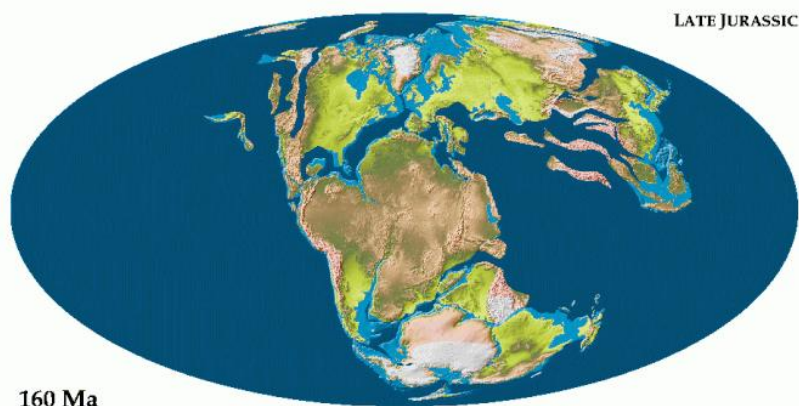


Figure 1: *Paleogeographic reconstruction of Gondwana in the southern hemisphere and Laurasia in the north after initial breakup of the supercontinent Pangaea. This reconstruction is based on a global digital elevation model, divided up into the different tectonic plates, which were restored to their position in the Late Jurassic at 160 million years ago. Climate zones were approximately restored based on a simple climate model within a geographic information system (GIS).*

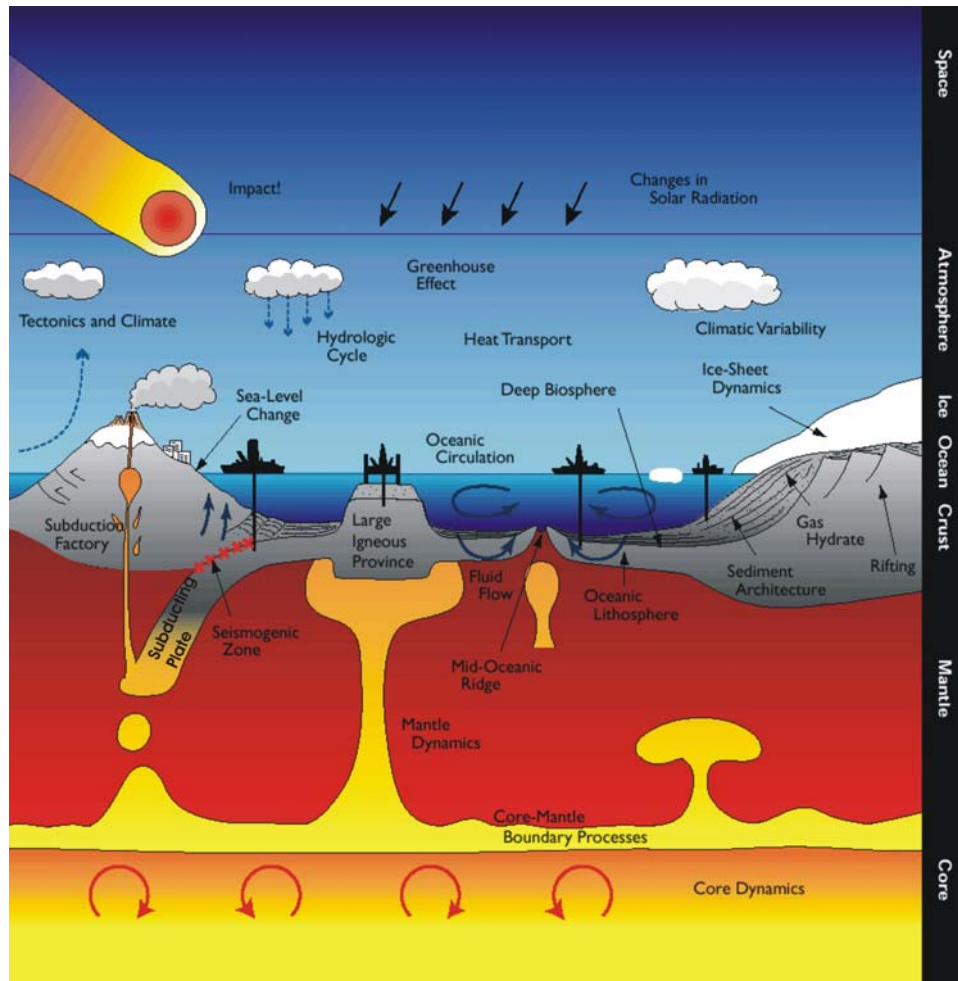


Figure 2: *Cartoon of the dynamic Earth. Complex links among tectonics, global biota, ocean chemistry and circulation, and atmospheric composition control the long-term evolution of the climate system. The most fundamental process controlling this system is plate tectonics. Plate motions not only determine the distribution of land and sea, but the volume of the ocean basins, which depends on the average depth of ocean basins. The rates of plate creation and subduction exert major controls on the carbon cycle and other geochemical cycles, by means of seafloor weathering, mid-ocean ridge degassing, and subduction of sediments. The rates of mass and energy transfer from the mantle to the crust and back again are not constant through time, but result in catastrophic events such as earthquakes, volcanic eruptions and tsunamis. Modified from Integrated Ocean Drilling Program initial Science Plan, unpublished report, 2000.*

Australia's Vertical Motion since the Cretaceous

Numerical Earth models running on supercomputers alone are not useful, unless we can “groundtruth” them with geological observations. This means we have to consider what observations can best be used to evaluate how realistic our computer models are. It turns out that considerable insight can be gained into the nature and evolution of mantle convection by looking at the vertical motion of continents. The downward vertical motion of a continent, also called subsidence, may result in flooding and widespread marine inundation, resulting in deposition of shallow marine sediments. Such sediments are extremely widespread and well mapped in eastern Australia, providing a record of the time-history of subsidence and possibly also uplift, resulting in erosion. The shallow marine sediments provide information about relative sea level change in a certain region, which we can compare with the average global sea level change documented on all continents. Vertical motion of the Earth’s surface associated with mantle convection is extremely slow, it typically has rates less than 100 m/million years, or 0.1 mm/year.

Australia shows many oddities in its distribution of inland seas through time. During the Cretaceous period (145-65 million years ago), the marine inundation of Australia and the global sea-level curve were out of phase. Maximum flooding of Australia occurred between 120-110 million years ago, when a large fraction of the continent, especially in

the east, was covered by a shallow sea (Fig. 3). This area has accumulated up to 3.5 km of Cretaceous and Jurassic sediments. During the Late Cretaceous, eastern Australia became progressively uplifted and exposed, with a flooding minimum 80-70 million years ago, when global sea-level was inferred to be near a maximum. Near the end of the Cretaceous, Australia, was approximately 250 m higher than it is today. Later, some time during the Tertiary period (after 65 million years ago), Australia appears to have subsided as a single unit by as much as 200 m, perhaps with very little tilting, as the continent moved northward after it separated from Antarctica.

Where plates diverge, seafloor spreading occurs, forming new ocean crust. The process of subduction recycles oceanic plates back into the convecting mantle where oceanic and continental plates converge. During the Cretaceous period, Australia, South America, Africa, India, Antarctica and New Zealand were assembled into a vast supercontinent called Gondwana, which had existed for more than 400 million years before it fragmented into the landmasses we know today, due to seafloor spreading. Prior to breakup, eastern Australia was bounded to the east by an enormous subduction zone where a cold oceanic tectonic plate plunged into the mantle, which was formed in the proto-Pacific Ocean (Fig. 3a). Together with geodynamicists Mike Gurnis from the California Institute of Technology and Louis Moresi from CSIRO (now at Monash University), a hypothesis that the dynamics of this subduction zone and the flooding of eastern Australia were intricately linked was developed. Maybe Australia had flexed like a giant wobble board, moving hundreds of metres down, and later rebounding, as the plate was drawn over a giant sinking subducted plate which later vanished nearly entirely into the deep, lower mantle. In other words, a sinking slab underneath Australia may have drawn the continent down, leading to submergence and flooding of the continental land mass. Beowulf computing allowed the creation of a 3D mesh with associated properties and a modeled time-history mimicking geological reality. A computer model was created in which plate motions were imposed at the surface, leading to subduction and seafloor spreading. The model starts with a long-lived subduction zone initially at the eastern Gondwana continental margin 130 million years ago. Based on geological information, subduction then becomes extinct in our model, and Australia is drawn over this "slab burial ground" as the continent moves east, and later north. The question we want to answer is: Can this conceptual model be turned into a realistic computer model, which creates flooding and emergence of Australia in accordance with our geological observations?

Model for Australia's geodynamic evolution since the Cretaceous

In making comparisons between computed model topography and observations, we have to subtract the normal thermal subsidence of cooling, contracting oceanic lithosphere from the observed seafloor topography, also called bathymetry. Another influence on topography is crustal thickness variations. Within our modeled continent, only sedimentation changes crustal thickness. In the oceans, we create lithosphere by seafloor spreading between the Australian and Antarctic plates, as a function of mantle temperature (the hotter the mantle, the thicker the ocean crust).

The model shows that first, just after 130 million years ago, there is a general motion toward the Pacific by the three plates that make up Gondwana at this time (Australia, Antarctica, Lord Howe Rise Plate) with velocities exceeding 5 cm/yr (Fig. 3a). Following a period of relative quiescence, during which time Australia rifts from Antarctica but moves only slowly northward, Australia starts moving away from Antarctica at about 45 Ma with nearly constant, fast velocities between 7 and 8 cm/yr. While the plates change their position, dynamic topography continuously evolves as the subducted oceanic plate, now underneath Australia, changes its structure and depth distribution. Inspection of the

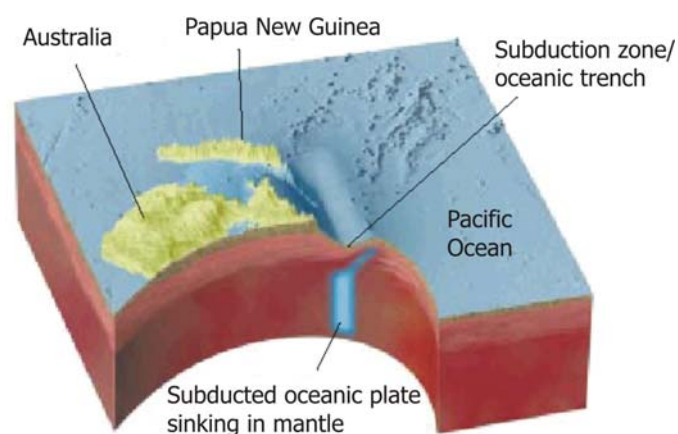


Figure 3a: In the Early Cretaceous, 130 million years ago Australia is bordered by a deep oceanic trench in the east, where an oceanic plate is being recycled (subducted) back into the Earth's mantle. The box shown comprises a depth of nearly 3000km, down to the boundary between the Earth mantle, shown in dark red, and the Earth's core (not shown). The vertically sinking oceanic plate in the mantle is shown in blue, representing cooler temperatures than the surrounding mantle. Modified from Gurnis (2001).

changing topographic signature as the imposed plate kinematics evolve reveals two fundamental features. During the first phase of plate motion, Australia migrates over the topographic depression generated by the slab. From 120 to 110 million years ago, the eastern interior of Australia is over the former position of subduction, which is still a downwelling with up to ~350 meters of overlaying dynamic topography (Fig. 3b). There is a continued slow migration of the topographic depression westward over the continent while the amplitude of the topography decays as the slab sinks through the mantle; this means the continent, mostly in the east, rebounds and is uplifted by about 200 m from 110 to 60 Ma.

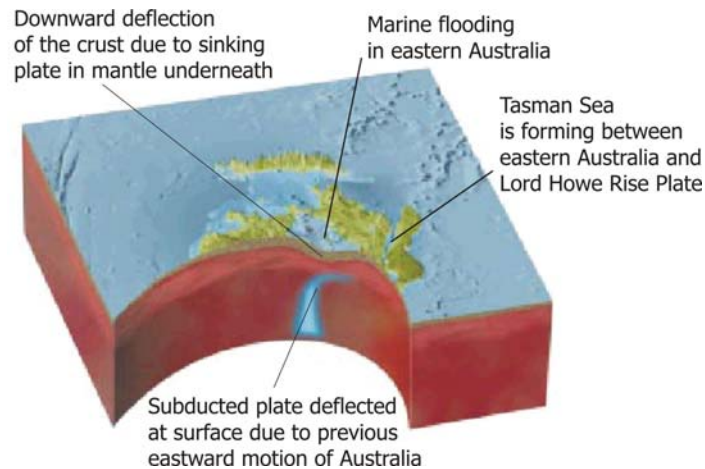


Figure 3b: *Reconstruction of Australia in the Late Cretaceous, 80 million years ago. Between 130 and 80 million years ago, the Australian plate moved east, overriding the sinking plate to the east. As a consequence, eastern Australia is drawn down by the “negative Buoyancy” of the sinking slab, resulting in marine inundation of large parts of eastern Australia by a shallow sea. After 80 million years ago, the downward drag of the subducting plate on the surface slowly diminished due to the increasing vertical distance between the sinking slab and the continent, resulting in a rebound and uplift of eastern Australia. Modified from Gurnis (2001).*

The more recent subsidence of the Australian continent as a whole, (less than 65 million years ago) is likely related to the motion of Australia toward the subduction zones to the north bounding Indonesia and Papua New Guinea (Fig. 3c). However, this extensive system of Southeast Asian subduction zones was not initially part of our regional geodynamic simulation, and therefore we could not model this effect. Published subduction driven global mantle flow models (references) show that Australia could have subsided by about 200 meters since 20 million years ago as it moved toward this extensive system of subduction zones at the intersection of the Pacific and Indian oceans. As Indonesia sinks, it pulls Australia down with it as the continent is moving north over a vast system of subducted sinking oceanic plates in the mantle. Indonesia itself is the best example for this process: only the highest mountain peaks form islands, as the largely submerged continent sucked down into the mantle by the enormous “negative buoyancy” of the sinking plates underneath it.

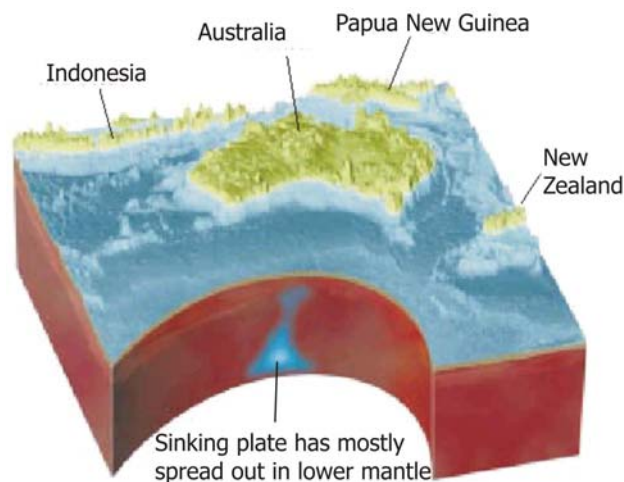


Figure 3c: *Present day location and topography of Australia. About 45 million years ago, Australia started moving north, resulting in convergence with Indonesia. The entire continent is now drawn down once again, but not as much as in the Cretaceous. This is caused by a system of subducting slabs around Indonesia and Papua New Guinea (not shown here), which Australia is approaching. Modified from Gurnis (2001).*

Ground-truthed modeling by iteration

Figure 4 illustrates the iterative nature of numerical computer models, ground-truthed by observed geological data. Our model is constrained by various boundary conditions and assumptions, whose possible variation we have to explore by running a set of different models, and then comparing the model outputs with our observations. Some of parameters, whose possible ranges have been explored are: (1) The initial location and dip-angle of the subducted slab east of Australia; (2) the assumed sedimentation rate in flooded continental areas; and (3) whether or not improved results are obtained by using a present day digital elevation model for the assumed topography of Australia, as it is modulated by dynamic topography originating from the sinking slab in the mantle. Figure 4 shows a few examples of dozens of models that were run to explore these “parameter spaces”, and illustrates how we converge on a “best-fit” model.

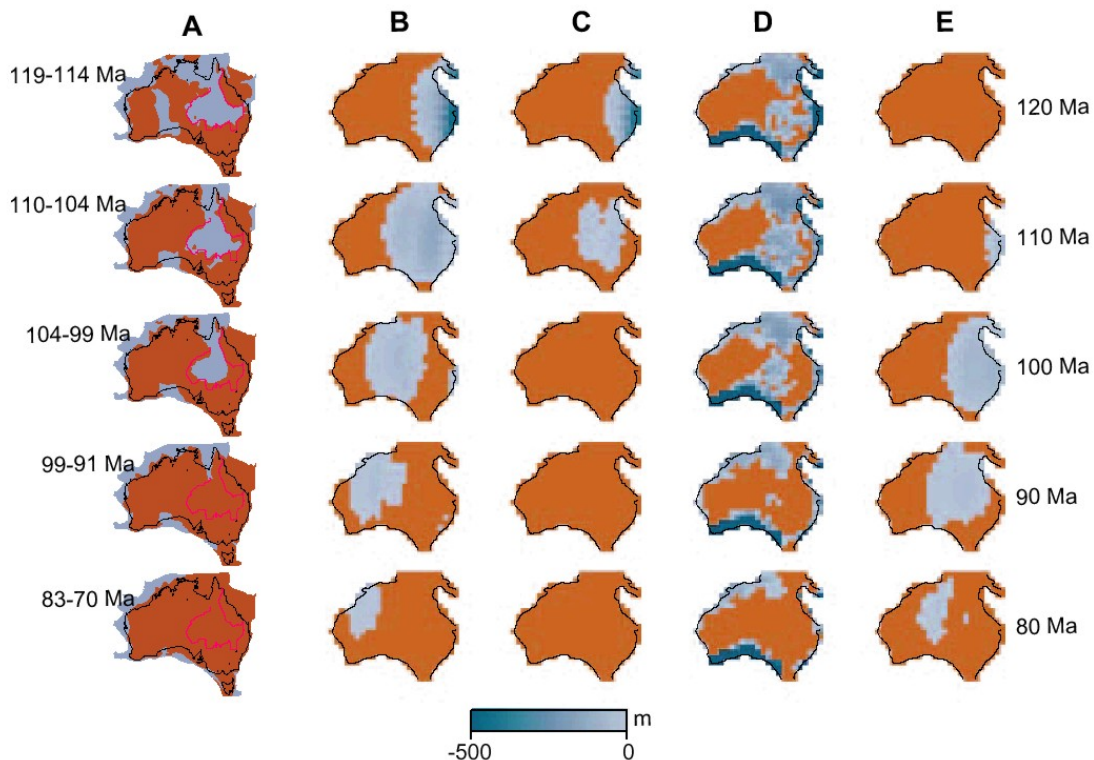


Figure 4: This figure illustrates the idea of “ground-truthed modeling”, namely the iterative “tuning” of a computer model to match the data. The first column of maps (A) shows paleogeographic reconstructions of Australia during the Cretaceous based on geological data; blue shading outlines marine inundation, and brown shading denotes land areas of the continent. The geological age ranges on the left refer only to the paleogeographic reconstructions, and are given in “Ma”, from “Megannum” in Latin, which here means “million years before present”. The faint red contour outlines the Eromanga and Surat basins. Figures B to E show the modelled marine inundation of Australia from our geodynamic models. Ages to the right refer only to these models. Blue areas are those areas covered by shallow seas; brown shading denotes those parts of the continent predicted to be exposed. Columns B to E show our model results, based on Australia overriding a subducting plate that initially dips at an angle of 30° and is located 1400km east of the present eastern Australian margin. (B) Initial model case with an assumed sedimentation rate of 5 m/million years. This model results in flooding in western Australia after 100 Ma, where none is observed. (C) The same as (B), except for a sedimentation rate of 10 m/million years. This model agrees quite well with the first-order observations. (D) The same as (B), except with the initial topography taken from a digital elevation model, improving the match with the data. This is our preferred model. (E) Subducted slab is assumed to have been located further east, 2400 km off the Australian margin with a sedimentation rate of 5 m/million years. This model results in too little flooding before 100 Ma, and in too much flooding after 100 Ma. Modified from Gurnis et al. (1998).

Conclusions

We tend to look at the present state of the Earth as a static system. Popular consensus in the face of global warming is that sea level should always remain as it is now, and we think of a vast continent as Australia as a stable geological feature, which probably always had an appearance more or less as it does today. It is extremely hard to fathom the meaning of geological, as opposed to human, timescales, and the powerful processes originating in the hot, churning interior of the Earth. These processes have changed regional sea levels by hundreds of metres, or even several kilometres, through geological time long before humans existed. A graphic example of the enormous magnitude of relative sea level variations due to geological forces is shown in Fig. 5, a photo of a sandstone with work burrows that

once formed near the sea surface in the southern Pacific Ocean, but is now found in 2.5 kilometers water depth. Such drowned, usually flat-topped seamounts were named “guyots” by Harry Hess of Princeton University during World War II, when he served as an officer aboard a naval vessel. Hess recognized that such seamounts must have undergone enormous subsidence, but he did not know the reason at the time. Today we know that oceanic crust subsides by several kilometers after it forms at mid-ocean ridges, simply because it cools and contracts.

However, such changes occur so slowly that we cannot observe them directly – only the geological record gives us some clues for vast pre-historic basins, floods, or mountains which may have existed at times when dinosaurs roamed the face of the planet. Most of us understand the idea that ice-ages may influence global climate and sea-level: melting ice caps may raise the global sea level, and a new ice age would lower it. However, a combination of detailed geological observations and sophisticated computer models running on parallel systems of off-the-shelf PCs, powered by the Beowulf variant of the free Linux operating system, are about to give us a glimpse into the dynamic past of our planet. Gigantic forces driven by sinking or rising branches of the global mantle convection system not only help drive the horizontal motion of tectonic plates, but they also lift and lower the continents, thereby resulting in dramatic regional sea-level changes that have nothing to do with the history of ice caps, or with human impact.



Figure 5: Worm burrows in sand composed of marine foraminifer shells, dredged up from a volcanic seamount part of the Louisville Ridge in the south Pacific Ocean in a depth of 2500 m by the German research vessel Sonne. The worm burrows show that this seamount was once in extremely shallow water near the sea surface – hence it has sunk by 2500m! This illustrates that natural relative sea level variations of enormous magnitudes have occurred in the geological past, long before humans existed. Photo: Dietmar Müller.

Our theory of the Earth has come full circle. Before the advent of plate tectonics, scientists believed that the history of the Earth’s surface could be understood entirely based on vertical motions. It was assumed that ocean basins are deep because they have sunken, and mountain belts exist because they have risen – without any involvement of horizontal motions. Then the theory of plate tectonics came along, introducing a framework to account for most geological observations by means of horizontal motions between plates, and the ensuing sea-floor spreading, subduction and collisions, accompanied by continental aggregation and dispersal. Changes in the elevation of continents were thought to be a direct consequence of horizontal plate motions, creating mountain belts that are subsequently eroded by physical and chemical weathering. Based on sophisticated geodynamic models, which include mantle convection and horizontal plate motions we have now learned that “elevator tectonics”, the vertical ups and downs of large landmasses, may be only indirectly related to plate tectonics, and not an immediate consequence of horizontal plate motions.

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