Gaina, C., Mac Niocaill, C., Conrad, C. P., Steinberger, B., Svensen, H. H. (2019): Linking plate tectonics and volcanism to deep earth dynamics – A tribute to Trond H. Torsvik. - *Tectonophysics*, *760*, pp. 1-3.

DOI: http://doi.org/10.1016/j.tecto.2019.03.002

Editorial

Linking Plate Tectonics and Volcanism to Deep Earth Dynamics – a tribute to Trond H. Torsvik

Carmen Gaina[1], Conall Mac Niocaill[2], Clinton P. Conrad[1], Bernhard Steinberger[1,3] and Henrik H. Svensen[1]

[1] Centre for Earth Evolution and Dynamics, University of Oslo, Norway; [2] Department of Earth Sciences, University of Oxford, UK; [3] GFZ-Deutsches GeoForschungsZentrum, Germany

The **Plate Tectonics** theory took shape in the 1960’s after paleomagnetism proved the existence of continental drift, as Wegener had suggested half a century before; and magnetic anomalies of oceanic crust attested to mantle convection as a mechanism for breaking and assembling continents and recycling oceanic lithosphere. The seminal paper of Jason Morgan in 1971 (“*Convection plumes in the lower mantle". Nature. **230***) established, for the first time, a link between deep mantle processes and surface volcanism. The first tomographic models of Dziewonski and collaborators (*Dziewonski et al., 1977; Dziewonski, 1984*) imaged degree two large-scale tomographic features on the core-mantle boundary, later named the LLSVPs (Large Low Shear-wave Velocity Provinces). We have since realized that these regions play an important role in the evolution of our planet.

The links between the Earth’s surface and deep mantle have been explored incessantly in the past decade, ever since Kevin C.A. Burke and Trond H. Torsvik published a series of papers (*Torsvik et al. 2006; 2008; 2010*) suggesting that large-scale volcanism is triggered by deep-seated mantle plumes that rise from the edges of LLSVPs at the core-mantle boundary. Torsvik immediately realized that this discovery – that plumes rise from the edges of the LLSVPs – provided a framework for understanding plate tectonics and mantle dynamics over the course of Earth history. In a series of popular science articles in both Norwegian and English (*Torsvik and Steinberger, 2006; 2008*), Torsvik and collaborator Bernhard Steinberger argued that this new framework for mantle dynamics represented a new scientific revolution in the Earth Sciences. A decade later, the intensity of scientific research surrounding this framework substantiates Torsvik’s vision (e.g., *Torsvik et al., 2016*).

This special issue provides an overview of our current understanding of how the evolution of plate tectonics and mantle dynamics are linked by better knowledge of paleomagnetic data from land and oceans, state-of-the-art tomographic models of Earth’s mantle, geodynamic modeling, and observations of volcanic eruptions, including Large Igneous Provinces (LIPs). Several contributions also aim to highlight how changes in Solid Earth structure and dynamics may have triggered environmental catastrophes in Earth History. This collection of papers addresses themes essential to our understanding of our planet’s evolution, but also links to topics in which Torsvik has made substantial contributions to the geoscientific community. Here we follow the course of Torsvik’s career, starting with paleomagnetic and geophysical observations that constrain Earth’s tectonic history, and then proceeding toward the dynamics of the deep mantle before linking these dynamics back to the surface through volcanism and a tight coupling to plate tectonics.

Given Torsvik’s major contribution to **paleomagnetism and paleogeography**, this special volume gathered several papers in which paleomagnetic data are used to better quantify the positions of continents from the Neoproterozoic to the Cenozoic, and studies that use paleomagnetism together with a wealth of other data to uncover past regional tectonic frameworks.

Pivarunas et al. (in this issue) report new paleomagnetic and geochronologic data from the Southern Granulite Terrane (SGT) of India, a collage of Archean to Neoproterozoic crustal blocks hosting several generations of mafic dykes, that permit a better-resolved reconstruction of Indian crustal elements of ca. 2Ga age. The study also unmasks a widespread late Neoproterozoic Ediacaran-age remagnetization associated with the final stages of Gondwana assembly. *Owen-Smith et al.,* (in this issue) provide an independent test for proposed pre-breakup fits between the continental margins of South America and Africa that uses new palaeomagnetic data from the African Etendeka volcanic province. The study presents a revised reconstruction for West Gondwana during the early Cretaceous. *Molina Garza et al.,* (in this issue) analyze the position of the Chortis Block in the Late Cretaceous and construct a new tectonic model that links Laramide deformation with back-arc extension at the southern tip of the Laramides prior to the rotation of the Chortis Block and the development of the North America-Caribbean plate boundaries. *Nemkin et al.,* (in this issue) use the secondary magnetizations of carbonate rocks to provide information on orogenic processes. In particular, they show that Lower Cretaceous formations from the Monterrey Salient in northeast Mexico were remagnetized at 48–52 Ma, an age that is concurrent with the frontal, remagnetized, folds in the central Sierra Madre Oriental.

Understanding the geodynamics governing subduction and the Himalayan orogeny is the main aim of *van Hinsbergen et al.* (in this issue), which reviews kinematic models and tests them against paleomagnetic data and seismic tomographic models. Based on kinematic constraints and sediment provenance, all Greater Indian lithosphere may have been continental, but from a geodynamic perspective, subduction with rates close to 20 cm/yr is incompatible with that scenario. They conclude that the Greater India Basin scenario is the only scenario that can fulfil paleogeographic, kinematic, and geodynamic constraints while also allowing absolute northward slab migration and overturning caused by flat slab subduction, Tibetan shortening, arc migration and arc volume decrease. *Gürer and van Hinsbergen* (in this issue) postulate that prolonged oceanic subduction and diachronous slab pull drew the adjacent terranes of the Eastern and Central Taurides into Central Anatolia, producing orogeny and oroclinal bending starting in the early Cenozoic. Estimates of the timing of collision in Central Anatolia are based on a forearc-to-foreland basin transition along the Eurasian margin. Their model, based on geologic observations, suggests that oceanic subduction continued much longer in Eastern Anatolia, perhaps well into the Miocene.

The **history of oceanic basins** and **microcontinents** is discussed in three contributions: one re-evaluates oceanic plate tectonics, one specifically looks at the North American plate and its neighboring oceanic basins, and the third unveils for the first time the stratigraphy of a microcontinent stranded in the North Atlantic ocean (the Jan Mayen microcontinent).

Crameri et al. (in this issue) reviews the life-cycle of an oceanic plate from its formation at mid-ocean ridges to its destruction at subduction zones, a journey that is intimately linked to the overturn of Earth's mantle. They note that the full range of dynamic behavior of an oceanic plate is not fully captured by the existing concept of Plate Tectonics, and they introduce a more specific and integral concept named **Ocean-Plate Tectonics** that describes tectonic plates like the Pacific plate, and that must have emerged on Earth at least 1 Billion years ago. *Gaina and Jakobs* (in this issue) employ a more regional focus by attempting to find a possible link between the destruction and formation of oceanic lithosphere along the western and eastern sides (respectively) of the North American plate in the Eocene. Both the interior and margins of the North American Plate were affected when subduction beneath western North America changed its behavior. The collision and incipient subduction of the early Eocene Siletzia Large Igneous Province in the Pacific Basin may have caused a sharp decrease in spreading rate in the Labrador Sea and north of the Charlie-Gibbs fracture zone. A subsequent, rapid, Farallon slab-break-off, and associated upwelling in the upper mantle, led to further variations in North Atlantic spreading rates. Tectonic stresses caused by changes to mantle-lithosphere interactions west of the North America plate may have triggered the emplacement of Eocene age kimberlite magma more than 1000 km from the western plate boundary of North America.

The Jan Mayen Microplate Complex (JMMC) in the NE Atlantic has been interpreted as a collage of continental fragments, mainly based on remote-sensing data. *Polteau et al.,* (in this issue) provide new evidence for the continental nature of JMMC using recently recovered rocks of Permian/Triassic to Eocene ages, including igneous samples related to early Eocene breakup volcanism. In addition, the rock samples carry evidence for active migration of Jurassic-sourced hydrocarbons.

The Mantle structure and dynamics theme is discussed in two contributions, with special attention to the Large Low Shear Velocity Provinces (LLSVPs), the two antipodal thermochemical piles detected by seismic waves at the core-mantle boundary.

Trønnes et al. (in this issue) present a comprehensive study that reviews planetary melting, core formation and early mantle differentiation in the terrestrial planets, with an emphasis on the Earth. In order to understand the origin of observed structures in the Earth's lower mantle, they discuss core-mantle chemical exchange, mainly during the solidification of a Basal Magma Ocean (BMO). *Trønnes et al.* postulate that bridgmanitic cumulates with elevated Fe/Mg ratios have been convectively swept into the African and Pacific LLSVPs, which have moderate excess density, high bulk modulus, and high viscosity. *McNamara* (in this issue) reviews the observations associated with the LLSVPs and the various conceptual models of their dynamics that the community is currently debating. Ultra Low Velocity Zones (ULVZs), features of an order-of-magnitude smaller scale than LLSVPs, are also reviewed, together with the dynamical linkages between the two as their relationship provides critical insight into global scale mantle convection.

Torsvik’s pioneering work linking the **Deep Earth, Plate Tectonics and Surface Processes** is honored by two studies: one that compares Earth’s observed topography with predictions from mantle flow models, and another that suggests a correlation between time-dependent subduction flux and geomagnetic reversal rate.

Steinberger et al., (in this issue) investigate the implications of postulated upwellings above the two LLSVPs. In particular, they compare observations of residual topography (the topography remaining after accounting for isostasy) to predictions of dynamic topography made using numerical models of mantle flow. They find that uplifted regions above the “superplumes” are barely seen in the observed topography, and the authors suggest that this implies extensive chemical heterogeneities in the lower mantle and/or laterally-varying or anisotropic lower mantle viscosity.
Hounslow et al., (in this issue) find a positive relationship between the time-dependent global subduction flux and the rate of magnetic reversals, which sheds new light on the dynamic connections between the surface and deepest Earth. This study takes a step further by presenting new models that link mantle convection, the thermal evolution of the lowermost mantle, and the geodynamo.

Linking the deep mantle back to the surface is tackled in three contributions that address **large-scale volcanism** in geological time. One of these reviews LIPs, while two others present new constraints on the rifting processes that are an essential part of plate tectonics.

Svensen et al., (in this issue) review the emergence and evolution of the LIP concept and terminology, originally presented in a series of seminal papers by Millard F. Coffin and Olav Eldholm in the early 1990's. They combined existing data and information from continental flood basalts with the emerging geophysical understanding of oceanic plateaus and rifted continental margins. However, the history of this field of research prior to the 1990’s has so far not been dealt with in detail. Who first realized that LIPs represent extraordinary events in the history of the Earth, what terminology was used, and why were geologists interested in this type of events? *Svensen et al.* conclude, based on the history of four different LIPs, that the past 150 years of LIP-related research was driven by the need to understand fundamental aspects of Earth evolution, including plate tectonics and the role of volcanism in driving mass extinctions and climatic change.

Jerram et al. (in this issue) report on new geochronologic data constraints from the African margin (Angola) that illuminate volcanic events younger than the main pulse of the Paraná-Etendeka (ca. 134 Ma) that led to the South America-Africa break-up. These events associated with relatively low volume volcanic pulses, document the development of volcanic passive margins and the evolution of South Atlantic breakup from south to north. Moving from the South Atlantic to the North Atlantic, *Abdelmalak et al.* (in this issue) investigate the tectono-magmatic evolution of the NW Atlantic using extensive geophysical datasets, complemented by seabed samples and fieldwork. Their study shows that most volcanism in the NW Atlantic occurred between ~62 and ~58 Ma, and exhibited a complex rift configuration that developed along the conjugate margins both prior to and during breakup.

Lastly, *Trond H. Torsvik* (in this issue) contributes a paper about how **Earth History** can be deciphered by quantitatively establishing ancient longitudes using markers from the Earth's deep interior that can be linked to its surface in geologic time.

To conclude, this special issue dedicated to Trond H. Torsvik's achievements in geosciences assembles a collection of 17 papers that demonstrate (1) how modern paleomagnetic data can improve our understanding of plate tectonics from deep time to recent; (2) when linked to other geologic and geophysical data, paleomagnetism is a powerful tool that allows us to build high-resolution regional and global geodynamic models that link the surface to the deep Earth; (3) state-of-the-art mineral physics and geodynamical modeling can now define more accurately the structure and dynamics of the deep mantle, including the LLSVPs and ULVzs at the core-mantle boundary; and (4) volcanism through time played an important role in continental break-up and the formation of oceanic and continental LIPS, which may, in turn, have influenced the dynamics of tectonic plates. Changes in subduction regimes may have affected remote plate boundaries, seafloor spreading and triggered intra-plate kimberlitic volcanism, and time-dependent global subduction flux influenced the rate of magnetic reversals.

We thank the Tectonophysics editorial board and staff, and we are especially grateful to Timothy James Horscroft and Editor-in-Chief Philippe Agard for supporting and helping with this special issue. We would like to express our appreciation to all contributing authors, and to the referees for providing critical reviews. We acknowledge partial support from the Research Council of Norway through its Centres of Excellence funding scheme, project number 223272.

References

Dziewonski, A. M., B. H. Hager, and R. J. O'Connell (1977), Large scale heterogeneities in the lower mantle, *Journal of Geophysical Research*, *82*(2), 239-255, doi:10.1029/JB082i002p00239.

Dziewonski, A. M. (1984), Mapping the lower mantle: Determination of lateral heterogeneity in P-velocity up to degree and order 6, *Journal of Geophysical Research*, *89*(B7), 5929-5952, doi:10.1029/JB089iB07p05929.

Torsvik, T. H., and B. Steinberger (2006), Fra kontinentaldrift til manteldynamikk, *Geo*, *8*, 20-30.

Torsvik, T. H., M. A. Smethurst, K. Burke, and B. Steinberger (2006), Large igneous provinces generated from the margins of the large low-velocity provinces in the deep mantle, *Geophysical Journal International*, *167*(3), 1447-1460, doi:10.1111/j.1365-246X.2006.03158.x.

Torsvik, T. H., and B. Steinberger (2008), From continental drift to mantle dynamics, in *Geology for Society for 150 Years - The legacy after Kjerulf*, edited by T. Slabstad and R. Dahl, *Gråsteinen, vol. 12,* pp. 24-38.

Torsvik, T. H., B. Steinberger, L. R. M. Cocks, and K. Burke (2008), Longitude: Linking Earth's ancient surface to its deep interior, *Earth and Planetary Science Letters, 276*(3–4), 273-282, doi:10.1016/j.epsl.2008.09.026.

Torsvik, T. H., K. Burke, B. Steinberger, S. J. Webb, and L. D. Ashwal (2010), Diamonds sampled by plumes from the core-mantle boundary, *Nature*, *466*(7304), 352-355, doi:10.1038/nature09216.

Torsvik, T. H., B. Steinberger, L. D. Ashwal, P. V. Doubrovine, and R. G. Trønnes (2016), Earth evolution and dynamics—a tribute to Kevin Burke, *Canadian Journal of Earth Sciences*, *53*(11), 1073-1087, doi:10.1139/cjes-2015-0228.