100 Influential Papers from *Geophysical Journal International*

The Royal Astronomical Society
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Front cover image: **Arenal Volcano in central Costa Rica**,
16 February 2013, cropped to fit the page and with adjusted brightness/contrast.
Arenal, the youngest stratovolcano in Costa Rica, last erupted in 2010.

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Contents

Introduction

In September 2022, the Editors of *Geophysical Journal International* (*GJI*) were asked to select their favourite papers from *GJI* for a virtual online collection. The response was tremendous. More and more papers were selected by the Editors and, as they scouted the back archives reflecting on the papers that impacted on their careers and those that have been highly influential in their fields, they provided personal and professional comments as to why they had selected these particular papers. Within a month, close to 100 papers had been chosen; an overwhelming number if presented to readers as a list within a collection.

The opportunity to create a series of issues within the collection arose. To provide readers with context to each issue, the Editors, who had made the suggestions, were invited to write an introduction to the issue containing the papers they had selected. Some wrote as individuals and others together where they had selected the same papers, or their fields of expertise overlapped with the papers in the issue.

It is from this acorn of an idea, that we have the pleasure of presenting to you the full collection of introductions and selected papers as a whole. Each paper is referenced including a doi which is hyperlinked in the PDF if you are reading online. The references to the 100 Influential Papers are highlighted in bold in each chapter.

We are grateful to our Editors who helped with this initiative, and we are proud of the RAS 100 year history of geophysics publishing and of its support, alongside the DGG, for launching a dedicated solid-Earth geophysics journal over 65 years ago.

The publication of this collection coincides with the decision by the RAS to make the whole back archive free to read, so whether the paper was originally published in the *Geophysical Supplement to the Monthly Notices of the Royal Astronomical Society*, or in *Geophysical Journal International*, all papers can be read in their entirety.

We hope you enjoy reading the introductions and the papers that have been highlighted, and that they inspire those early in their careers and provide a reminder, for those who have worked in solid-Earth geophysics for many years, of the many great papers that have been published.

Our special thanks go to Joerg Renner, the Editor-in-Chief, and Duncan Agnew, Deputy Editor-in-Chief of *GJI* for their vision, drive and inspiration for the 100 influential papers in *Geophysical Journal International* collection.

Elizabeth Baker and **Kim Clube**, Publishing Managers, RAS Journals
Louise Alexander and **Fern Storey**, Assistant Editors, *Geophysical Journal International*

Global Plate Tectonics

We open our centennial collection of papers in *Geophysical Journal International* with four publications covering the most important advance in the earth sciences in the twentieth century: the theory of plate tectonics. In 1960 geoscientists knew about the major features of the Earth's surface (mountains and oceanic rises, fracture zones, and trenches) but had no clear picture of why these existed. Now, all these are seen as aspects of a single model, of undeforming plates separated by different zones of deformation. And in all cases, we can assign precise values to the rates of deformation in these zones, values useful for studies ranging from geological analysis to seismic hazard estimates.

To get to this point required not just the basic concept of interacting plates, but systematic application of relevant data to determine their boundaries and relative motion. The first paper in our list, by **Clement Chase in 1972**, was also the first to set up a mathematical framework for finding the angular velocities of all the plates using data collected from ocean rises (spreading rates from magnetic anomalies), fracture zones (directions of plate slip from bathymetery) and trenches (earthquake slip vectors): in all, 235 data to determine the relative velocities of eight plates.

The next paper, published in **1974 by Bernard Minster, Tom Jordan, Peter Molnar, and Eldon Haines**, was in part the result of a collaboration between scientists who wished to learn more about plate tectonics and a colleague very familiar with it: a difference coming from one being at an oceanographic institution, and the others at a leading geoscience department not yet teaching this subject. This paper included a further development of the mathematical model relating plate motions to observations; a model for the motion of eleven plates determined from 236 data. These authors combined their plate-motion model with apparent tracks from hotspots to find that these did not appear to move relative to each other, and noted that the hotspot reference frame was very nearly equivalent to one in which averaging velocities gave no net rotation.

Chase, and Minster and Jordan, went on to publish "second-round" plate-motion models in 1978. Subsequent work in this area was done by two scientists at Northwestern University (NU), Richard Gordon and Seth Stein, with their graduate students Charles DeMets and Donald Argus. Through the 1980s the NU group examined new datasets and developed new methods for deciding (for example) if adding additional plates to a model was statistically justified. The culmination of this was the NUVEL-1 plate-motion model published in 54 pages of *GJI* in **1990 by DeMets and coauthors**. This model brought to bear three times as many spreading rates and a very much larger set of earthquake slip vectors than previously employed: 1122 data for a 12-plate model. Careful accounting of all plate motions greatly reduced a result relevant to any San Francisco AGU: how much larger the motion between the Pacific and North-American plates was than the slip rate on the San Andreas fault.

Finding better plate models might seem to be a case of diminishing returns; the final paper in this series, by the same group two decades later, (**DeMets, Gordon, and Argus 2010**) showed that this was not so. This model, MORVEL, introduced 25 plates, four times as much data with a nearly complete replacement of earthquake slip vectors by transform-fault bathymetry from multibeam sounding data, and the first use of geodetic measurements for plates that did not include a spreading center.

So in these *GJI* papers we can see the progression both of data (collected by many scientists and freely shared) and of concepts, leading to a detailed and accurate picture of how the Earth's surface has and continues to move, with uses throughout the Earth sciences.

Duncan Agnew, *GJI* Deputy Editor-in-Chief

The N Plate Problem of Plate Tectonics
C. G. Chase
Geophysical Journal International, Volume 29, Issue 2, August 1972, Pages 117–122,
https://doi.org/10.1111/j.1365-246X.1972.tb02202.x

Numerical Modelling of Instantaneous Plate Tectonics
J. B. Minster, T. H. Jordan, P. Molnar, E. Haines
Geophysical Journal International, Volume 36, Issue 3, March 1974, Pages 541–576,
https://doi.org/10.1111/j.1365-246X.1974.tb00613.x

Current plate motions
C. DeMets, R. G. Gordon, D. F. Argus, S. Stein
Geophysical Journal International, Volume 101, Issue 2, May 1990, Pages 425–478,
https://doi.org/10.1111/j.1365-246X.1990.tb06579.x

Geologically current plate motions
Charles DeMets, Richard G. Gordon, Donald F. Argus
Geophysical Journal International, Volume 181, Issue 1, April 2010, Pages 1–80,
https://doi.org/10.1111/j.1365-246X.2009.04491.x

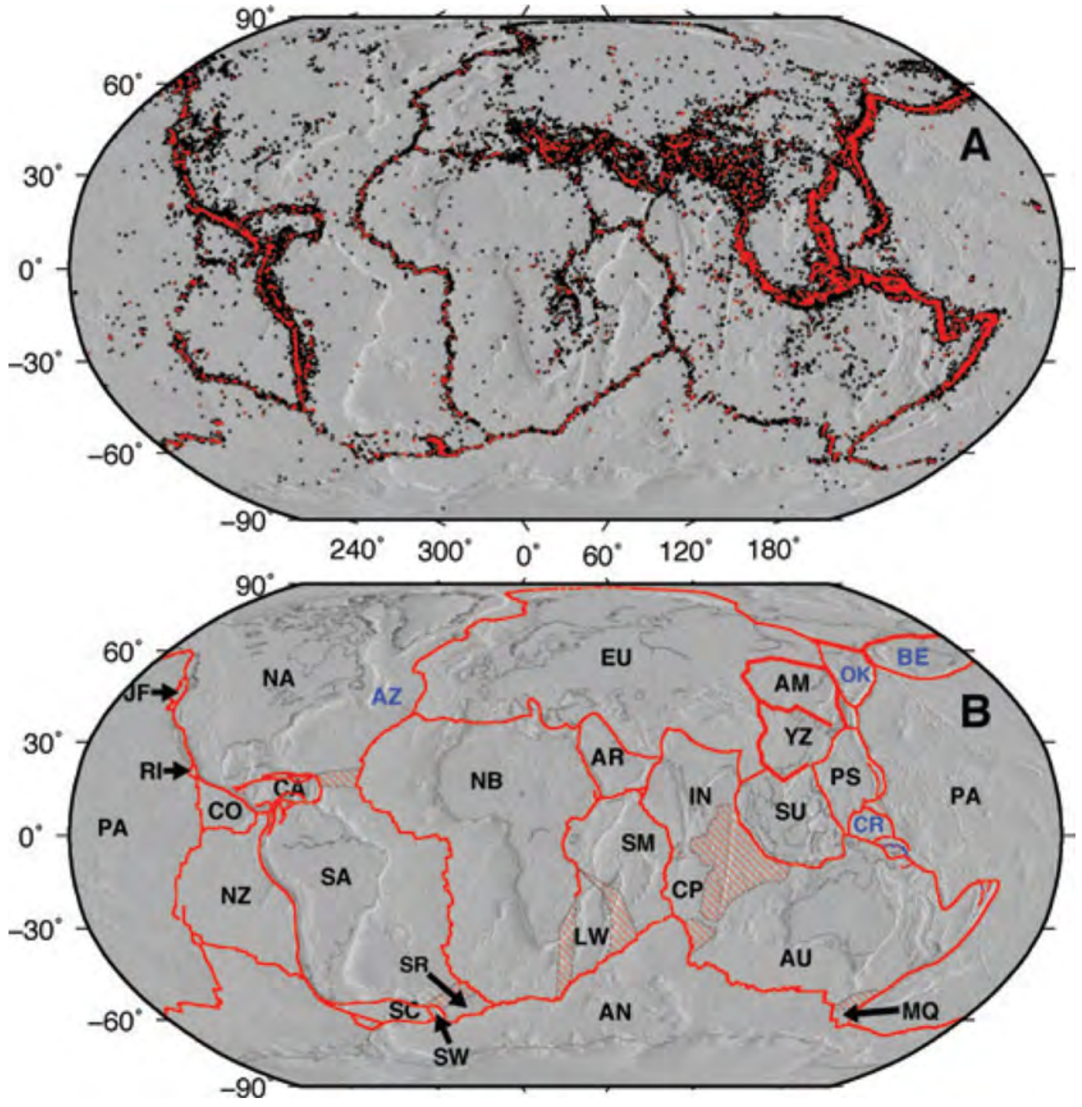

Fig. 1 from DeMets et al (2010). Please see the paper for the full caption.

Seismic Tomography

In this second set of our centennial collection of papers in *Geophysical Journal International*, we highlight the role that our journal has played in revolutionizing the science of seismic tomography in the first two decades of this century.

The speed of seismic waves depends on the properties of the materials in the medium through which they propagate: predominantly solid rock in the crust and mantle, liquid metal in the outer core. Three-dimensional, volumetric, maps of where wavespeeds depart from one-dimensional (only dependent on the radial coordinate, or depth) global reference models reveal the rich tapestry of compositional and thermal variations of our chemically differentiated, compositionally stratified, thermally inhomogeneous, dynamic planet.

With earthquakes as localized sources of mechanical energy, seismograms, time-series records of ground motion collected at seismic stations worldwide, are the surface data from which the three-dimensional makeup of the inner Earth can be reconstructed. From the 1970s on, seismic tomography focused on the inversion of travel times: discrete arrivals of specific seismic phases, mostly at the local and regional scales. Those waves are transmitted, refracted, and reflected, by sharp, e.g., compositional, material contrasts and diffuse, e.g., thermal, inhomogeneities. The 1980s witnessed the growth of the discipline and the genesis of whole-Earth wavespeed models that were constructed by incorporating surface-wave (e.g., Rayleigh and Love waves, dispersion measurements), and also normal-mode (spectra, splitting functions) constraints, into the rapidly exploding, increasingly digital, data sets. By the 1990s, seismic tomography had become a planetary-scale science. A plethora of global models provided detailed images of the interior of the Earth at a great variety of scales. Collectively they elucidated geological processes from crust formation to destruction, plate subduction, mantle plume upwellings, and everything in-between, much of it documented in our pages.

While approaches were markedly varied in the details, and data types phenomenally diverse, the paradigm that gave birth to the field had not fundamentally changed in its first thirty years. Seismic waves were primarily considered as propagating rays that carry travel-time information about the paths taken from source to receiver. The framework for understanding the tomographic inverse problem remained fundamentally geometric. The particularly insightful paper by **Lévêque et al. (1993)**, ostensibly a mere mathematical exercise, served as a mental model to comprehend how tomography worked — and where it did not, whether at the scale of a hand sample, in an exploration setting, or at the scale of the globe. The infinite-frequency approximation to seismic wave propagation and tomographic inversion was known to be incomplete, but thought to be eminently manageable for imaging and model building when supplemented by statistical and numerical regularization approaches.

That state of affairs was thoroughly upset at the turn of the century, when **Dahlen et al. (2000)** and Hung et al. (2000) derived and computed the first global 3-D "sensitivity kernels" for finite-frequency seismic travel times, measured not by picking time points along the seismogram, but by estimating time delays by cross-correlation of an observed waveform against a synthetically computed one, over a time interval. Their apt culinary metaphor, the banana-donut, which held for the kernels involved in the inversion of travel-time measurements, ushered in, and became the icon for, the era of global seismic tomography via full-waveform inversion in the twenty-first century.

No more mere rays along a one-dimensional wave path! Three-dimensional, frequency and path-dependent volumetric tubes linked earthquake sources to ground motion records. Early misunderstandings and manufactured controversy notwithstanding, the banana-donuts where not simply "fat-ray" regularizers. Partial derivatives of misfits with respect to earth parameters evaluated at particular model instantiations, they contained the very essence of the physics of seismic wave propagation, down to the practice of measurement making, while remaining mathematically reducible to the geometric optics approximation in the high-frequency regime that had reigned since the days of Willebrord Snel.

Paradoxically (and paraxially...), in its linearized treatment of the problem, **Dahlen et al. (2000)** used ray theory to kill ray theory, but their papers were rapidly followed by many other approaches (e.g., Dahlen & Baig 2002; Zhou et al. 2004; Dahlen & Zhou 2006; Zhao & Jordan 2006; Nissen-Meyer et al. 2007; Chen et al. 2007; Fichtner et al. 2008; Long et al. 2008; Bozdağ et al. 2011; Zhou 2009) to construct kernels for seismic tomography that were able to take into account a broader range of wave phenomena, different misfit definitions, and other target model parameters and material behaviours than those covered by their landmark paper, using a variety of algorithms and numerical methods.

A milestone case in point was the development of the spectral-element numerical method of wave propagation, tailored to global seismology by **Komatitsch & Tromp (2002a,**b). Marrying the flexibility of a finite-element method to the accuracy of a pseudo-spectral method, the spectral-element method combines the ability to simulate body and surface waves, reflected and diffracted phases, excited by complex earthquake sources. It allows for the incorporation of both sharp and smooth velocity and density heterogeneity within the medium, handling interfaces like surface and internal topography, including liquid-solid boundaries, and bathymetry covered by the load of the world's oceans. Wavespeeds can be an-isotropic as well as an-elastic, correctly capturing intrinsic attenuation. The model domain is all of the Earth, elliptic, rotating, self-gravitating, without intrinsic restrictions on the level of heterogeneity or the frequency range of the simulations.

The ability to compute synthetic seismograms, computationally demanding but essentially without any limitations or non-Earth-like compromises, could have been simply a tool to conduct model evaluations, to make measurements, or to construct 3-D kernels for seismic tomography within 1-D reference models (e.g., Kennett & Engdahl 1991), and indeed, the spectral-element method was thoroughly benchmarked in that sense. Yet, since the wavespeed models within which the kernels are being computed can be themselves fully 3-D (taking, for example, smooth global earth models as a point of departure, e.g., Ritsema et al. 2011), new kernels can be computed for every new measurement as part of an iterative tomographic inversion, in order to gradually reduce data residuals to the noise level.

Performing, in essence, that feat, is how the traditional inversion approaches have by now been almost universally supplanted by the adjoint method of global full-waveform inversion, thanks to the pioneering work by **Tromp et al. (2005)**. The 3-D kernels that embody the gradient of the data misfit functional, suitable for optimization constrained by the differential equations of global wave propagation in complex media (Liu & Tromp 2008), involve the elegant interaction between a forward-propagating regular and a time-reversed adjoint field. Seismic tomography with elastic, anelastic, isotropic, and anisotropic wave propagation in the global Earth had theoretically and practically caught up with the approaches implemented in other, more restrictive settings, where they had enjoyed a prior history, as reviewed by **Plessix (2006)**. Of note is also the parallel development of adjoint-state methods in global geodynamics, used to infer past mantle flow and earth structure from plate-motion histories and tomographic images (e.g., Bunge et al. 2003; Ghelichkhan et al. 2021).

Bozdağ et al. (2016) led the newest generation of global adjoint tomographic models that revealed an ever more complex and intriguing Earth, interpretable in all of its exquisite detail: the first in a sequence making history that continues to be written (e.g., Karaoğlu & Romanowicz 2018; Lei et al. 2020).

Geophysical Journal International looks back upon one hundred years of tradition in publishing papers that change the times — and stand the test of time. From short, probing contributions that remain indispensable reading for students to carefully wrought theoretical treatises, from pathbreaking numerical methods and novel techniques of data analysis to thought-provoking synthesis, from the construction of models to their detailed interpretation, we look forward to continuing our hundred-year streak into the next century.

Frederik Simons, *GJI* Editor

On the use of the checker-board test to assess the resolution of tomographic inversions
Jean-Jacques Lévěque, Luis Rivera, Gérard Wittlinger
Geophysical Journal International, Volume 115, Issue 1, October 1993, Pages 313–318,
https://doi.org/10.1111/j.1365-246X.1993.tb05605.x

Fréchet kernels for finite-frequency traveltimes — I. Theory
F. A. Dahlen, S.-H. Hung, Guust Nolet
Geophysical Journal International, Volume 141, Issue 1, April 2000, Pages 157–174,
https://doi.org/10.1046/j.1365-246X.2000.00070.x

Fréchet kernels for finite-frequency traveltimes — II. Examples
S.-H. Hung, F.A. Dahlen, Guust Nolet
Geophysical Journal International, Volume 141, Issue 1, April 2000, Pages 175–203
https://doi.org/10.1046/j.1365-246X.2000.00072.x

Fréchet kernels for body-wave amplitudes
F. A. Dahlen, Adam M. Baig
Geophysical Journal International, Volume 150, Issue 2, August 2002, Pages 440–466,
https://doi.org/10.1046/j.1365-246X.2002.01718.x

Three-dimensional sensitivity kernels for surface wave observables
Ying Zhou, F. A. Dahlen, Guust Nolet
Geophysical Journal International, Volume 158, Issue 1, July 2004, Pages 142–168,
https://doi.org/10.1111/j.1365-246X.2004.02324.x

Surface-wave group-delay and attenuation kernels
F. A. Dahlen, Ying Zhou
Geophysical Journal International, Volume 165, Issue 2, May 2006, Pages 545–554,
https://doi.org/10.1111/j.1365-246X.2006.02913.x

Structural sensitivities of finite-frequence seismic waves: a full-wave approach
Li Zhao, Thomas H. Jordan
Geophysical Journal International, Volume 165, Issue 3, June 2006, Pages 981–990,
https://doi.org/10.1111/j.1365-246X.2006.02993.x

Spherical-earth Fréchet sensitivity kernels
Tarje Nissen-Meyer, F. A. Dahlen, Alexandre Fournier
Geophysical Journal International, Volume 168, Issue 3, March 2007, Pages 1051–1066,
https://doi.org/10.1111/j.1365-246X.2006.03123.x

Full three-dimensional tomography: a comparison between the scattering-integral and adjoint-wavefield method
Po Chen, Thomas H. Jordan, Li Zhao
Geophysical Journal International, Volume 170, Issue 1, July 2007, Pages 175–181,
https://doi.org/10.1111/j.1365-246X.2007.03429.x

Theoretical background for continental-and global-scale full-waveform inversion in the time-frequency domain
Andreas Fichtner, Brian L. N. Kennett, Heiner Igel, Hans-Peter Bunge
Geophysical Journal International, Volume 175, Issue 2, November 2008, Pages 665–685,
https://doi.org/10.1111/j.1365-246X.2008.03923.x

Wave-equation shear wave splitting tomography
Maureen D. Long, Maarten V. De Hoop, Robert D. Van Der Hilst
Geophysical Journal International, Volume 172, Issue 1, January 2008, Pages 311–330,
https://doi.org/10.1111/j.1365-246X.2007.03632.x

Misfit functions for full waveform inversion based on instantaneous phase and envelope measurements
Ebru Bozdağ, Jeannot Trampert, Jeroen Tromp
Geophysical Journal International, Volume 185, Issue 2, May 2011, Pages 845–870,
https://doi.org/10.1111/j.1365-246X.2011.04970.x

Surface-wave sensitivity to 3-D anelasticity
Ying Zhou
Geophysical Journal International, Volume 178, Issue 3, September 2009, Pages 1403–1410,
https://doi.org/10.1111/j.1365-246X.2009.04230.x

Spectral-element simulations of global seismic wave propagation — I. Validation
Dimitri Komatitsch, Jeroen Tromp
Geophysical Journal International, Volume 149, Issue 2, May 2002, Pages 390–412,
https://doi.org/10.1046/j.1365-246X.2002.01653.x

Spectral-element simulations of global seismic wave propagation — II. Three-dimensional models, oceans, rotation and self-gravitation
Dimitri Komatitsch, Jeroen Tromp
Geophysical Journal International, Volume 150, Issue 1, July 2002, Pages 303–318,
https://doi.org/10.1046/j.1365-246X.2002.01716.x

Traveltimes for global earthquake location and phase identification
B. L. N. Kennett, E. R. Engdahl
Geophysical Journal International, Volume 105, Issue 2, May 1991, Pages 429–465,
https://doi.org/10.1111/j.1365-246X.1991.tb06724.x

S40RTS: a degree-40 shear-velocity model for the mantle from new Rayleigh wave dispersion, teleseismic traveltime and normal-mode splitting function measurements
J. Ritsema, A. Deuss, H. J. van Heijst, J. H. Woodhouse
Geophysical Journal International, Volume 184, Issue 3, March 2011, Pages 1223–1236,
https://doi.org/10.1111/j.1365-246X.2010.04884.x

Seismic tomography, adjoint methods, time reversal and banana-doughnut kernels
Jeroen Tromp, Carl Tape, Qinya Liu
Geophysical Journal International, Volume 160, Issue 1, January 2005, Pages 195–216,
https://doi.org/10.1111/j.1365-246X.2004.02453.x

Finite-frequency sensitivity kernels for global seismic wave propagation based upon adjoint methods
Qinya Liu and Jeroen Tromp
Geophysical Journal International, Volume 174, Issue 1, July 2008, Pages 265–286,
https://doi.org/10.1111/j.1365-246X.2008.03798.x

A review of the adjoint-state method for computing the gradient of a functional with geophysical applications
R.-E. Plessix
Geophysical Journal International, Volume 167, Issue 2, November 2006, Pages 495–503,
https://doi.org/10.1111/j.1365-246X.2006.02978.x

Mantle circulation models with variational data assimilation: Inferring past mantle flow and structure from plate motion histories and seismic tomography
Hans-Peter Bunge, C. R. Hagelberg, B. J. Travis
Geophysical Journal International, Volume 152, Issue 2, February 2003, Pages 280–301,
https://doi.org/10.1046/j.1365-246X.2003.01823.x

Global mantle flow retrodictions for the early Cenozoic using an adjoint method: evolving dynamic topographies, deep mantle structures, flow trajectories and sublithospheric stresses
S Ghelichkhan, H-P Bunge, J Oeser
Geophysical Journal International, Volume 226, Issue 2, August 2021, Pages 1432–1460
https://doi.org/10.1093/gji/ggab108

Global adjoint tomography: first-generation model
Ebru Bozdağ, Daniel Peter, Matthieu Lefebvre, et al.
Geophysical Journal International, Volume 207, Issue 3, December 2016, Pages 1739–1766,
https://doi.org/10.1093/gji/ggw356

Inferring global upper-mantle shear attenuation structure by waveform tomography using the spectral element method
Haydar Karaoğlu, Barbara Romanowicz
Geophysical Journal International, Volume 213, Issue 3, June 2018, Pages 1536–1558,
https://doi.org/10.1093/gji/ggy030

Global adjoint tomography — model GLAD-M25
Wenjie Lei, Youyi Ruan, Ebru Bozdağ, Daniel Peter, Matthieu Lefebvre, Dimitri Komatitsch, Jeroen Tromp, Judith Hill, Norbert Podhorszki, David Pugmire
Geophysical Journal International, Volume 223, Issue 1, October 2020, Pages 1–21,
https://doi.org/10.1093/gji/ggaa253

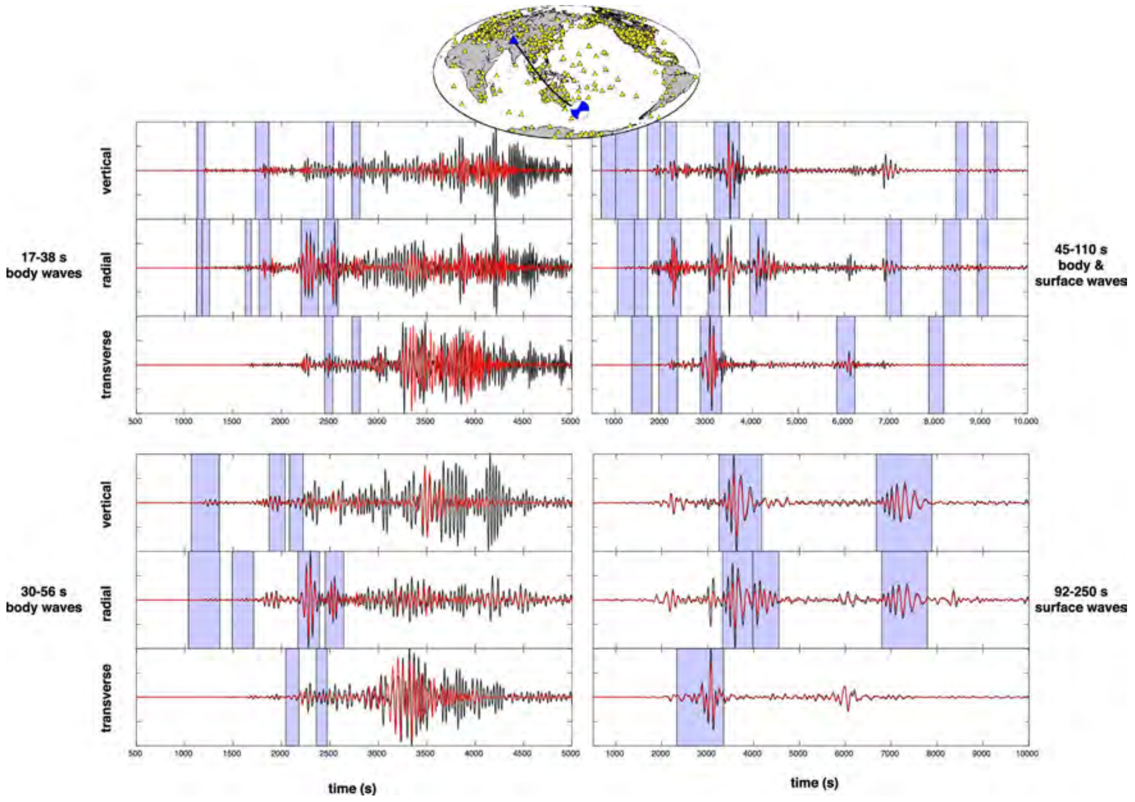

Fig. 4 from Bozdağ et al (2016). Please see the paper for the full caption.

Rheology of the Earth

Between dynamics and kinematics lives rheology: at least, that is how I try to introduce rheology to students. Material specifics determine to what extent forces lead to motion of entire bodies or in them. The rigid body comes in handy in some fields of geophysics, its underlying rheological assumption is not useful at all in others. Rocks are probably among the rheologically most complicated materials, because of their compositional variability including the absence of material, addressed by many terms, such as voids, pores, joints, cavities, fractures, faults etc. In addition, Earth's interior covers an incredible range in the state variables that affect rheological properties, e.g., pressure, stress, temperature, and fluid pressure. Unfortunately, rheological properties also strongly depend on the geometrical arrangement of components, the material's structure or fabric. Thus, internal variables, e.g., porosity, crack density, dislocation density, crystallographic preferred orientation, foliation etc., become central in irreversible thermodynamics. As if it were not complicated enough, we face the problem of scale, in geoscience twofold, with respect to time and space. Are deformational properties measured on length and time scales accessible to us representative for behaviour over geological length and time scales? The answer to this question has obviously significant implications for our (chances of) understanding of processes inside Earth.

Kümpel (1991) undertook an admirable effort to clarify the relation between the many poro-elastic parameters used in different fields. At the root of the "parameter zoo" lies the necessity to describe a porous solid with three bulk moduli rather than with a single one. The intimate relation between fluid flow and deformation of solids housing them is of relevance to geoscientists beyond the realm of elasticity. Porosity significantly affects brittle failure, and credit goes to **Ricard & Bercovici (2003)** for their successful normalization treatment for this difficult problem encountered in sedimentary rocks and in fault gauge. Treating plastic deformation of the solid instead, **Ribe's (1985)** seminal work on the scaling parameter "compaction length" in the problem of melt segregation below ocean ridges tackled an issue at the very heart of plate tectonics. Likewise, **Goetze & Evans (1978)** and **McNutt & Menard (1982)** aimed at advancing the idea of moving plates, perfectly unifying observations from diverse fields, by exploiting rheological concepts, but for convergent rather than divergent plate boundaries. Using the bathymetric profiles of deep-sea trenches, a prominent result of the international mid-20th century efforts regarding ocean surveying, they introduced the deductive chain related to the inseparable trio of temperature, strength as constrained by laboratory experiments, and in-situ stress, ever since practiced for large-scale lithospheric kinematic observations.

The advent of satellite technology allowed the move from interpreting the shape features resulting from the operation of geological processes over millions of years to "real-time" monitoring of phenomena related to Earth's deformation. The irregularities in Earth's rotation, e.g., those known as the Chandler wobble, reflect that it does not behave perfectly elastic as a whole either. **Smith & Dahlen (1981)** and later **Benjamin et al. (2006)** were able to pinpoint the cause of the wobble's damping to inelastic deformation in the lower mantle, the entire suite of geodetic observations constraining characteristics of dissipative mechanisms on time scales from decades down to below minutes. Observations on Earth's eigenmodes and seismic waves travelling through Earth relate to overlapping but also shorter time scales. The realization that seismic waves, despite the common habit to address them as elastic waves, actually cause irreversible deformation, as evidenced by attenuation, promises a whole new avenue for rheological investigations. However, such efforts need first an answer to "Are the measured apparent attenuations for short-period seismic waves caused by anelasticity of the media or by scattering of the heterogeneities in the media?", poignantly phrased by **Wu (1985**). Damping, dissipation, divergence, and dispersion are so intricately related leaving little chance for unique inversion results of either (local) intrinsic properties of homogeneous materials or the structures they form. As probably almost universally true in geoscience, progress in deciphering the rheology of the Earth requires combining the results of field observations and laboratory experiments with theoretical work, for the latter **Caputo's (1967)** exceptional work revealing the complexity of constitutive equations for the apparently simple class of visco-elastic material.

Joerg Renner, *GJI* Editor-in-Chief

Poroelasticity: parameters reviewed
H.-J. Kümpel
Geophysical Journal International, Volume 105, Issue 3, June 1991, Pages 783–799,
https://doi.org/10.1111/j.1365-246X.1991.tb00813.x

Two-phase damage theory and crustal rock failure: the theoretical 'void' limit, and the prediction of experimental data
Yanick Ricard, David Bercovici
Geophysical Journal International, Volume 155, Issue 3, December 2003, Pages 1057–1064,
https://doi.org/10.1111/j.1365-246X.2003.02112.x

The deformation and compaction of partial molten zones
Neil M. Ribe
Geophysical Journal International, Volume 83, Issue 2, November 1985, Pages 487–501,
https://doi.org/10.1111/j.1365-246X.1985.tb06499.x

Stress and temperature in the bending lithosphere as constrained by experimental rock mechanics
Christopher Goetze, Brian Evans
Geophysical Journal International, Volume 59, Issue 3, December 1979, Pages 463–478,
https://doi.org/10.1111/j.1365-246X.1979.tb02567.x

Constraints on yield strength in the oceanic lithosphere derived from observations of flexure
Marcia K. McNutt, H. W. Menard
Geophysical Journal International, Volume 71, Issue 2, November 1982, Pages 363–394,
https://doi.org/10.1111/j.1365-246X.1982.tb05994.x

The period and Q of the Chandler wobble
Martin L. Smith, F. A. Dahlen
Geophysical Journal International, Volume 64, Issue 1, January 1981, Pages 223–281,
https://doi.org/10.1111/j.1365-246X.1981.tb02667.x

Constraints on mantle anelasticity from geodetic observations, and implications for the J_2 anomaly
David Benjamin, John Wahr, Richard D. Ray, Gary D. Egbert, Shailen D. Desai
Geophysical Journal International, Volume 165, Issue 1, April 2006, Pages 3–16,
https://doi.org/10.1111/j.1365-246X.2006.02915.x

Multiple scattering and energy transfer of seismic waves — separation of scattering effect from intrinsic attenuation — I. Theoretical modelling
Ru-Shan Wu
Geophysical Journal International, Volume 82, Issue 1, July 1985, Pages 57–80,
https://doi.org/10.1111/j.1365-246X.1985.tb05128.x

Linear Models of Dissipation whose Q is almost Frequency Independent—II
Michele Caputo
Geophysical Journal International, Volume 13, Issue 5, November 1967, Pages 529–539,
https://doi.org/10.1111/j.1365-246X.1967.tb02303.x

Geodynamics

The fourth issue (May) of the centennial collection of papers in *Geophysical Journal International* focuses on geodynamics, yet another perspective on a century of geophysics, thanks to in-depth applications of classical dynamics to the Earth and other planetary objects. The main theme dealt with by the selected articles is mantle convection or global scale geodynamics, which includes the surface response to glaciation and deglaciation cycles. In the following, I have tried to systematically propose pairs of papers in order to highlight a collective endeavour.

The first two papers (**Pekeris, 1935; Hales, 1936**) are written by two scientists among the three who independently proposed the initial theory for mantle convection. The works of Arthur Holmes in the first years of the 1930s are justly considered to offer a physical basis to the then largely debated theory of continental drift: solid-state convection in the substratum (the term used by Holmes to refer to what is now Earth's mantle) was seen as a possibility owing to radiogenic heating in the deep interior. The threshold described by Lord Rayleigh for thermal convection (critical value of the Rayleigh number) on the basis of marginal stability of the fluid layer, subsequently refined by Harold Jeffreys with appropriate boundary conditions, was shown to likely be exceeded for the suitable viscosity of rocky materials in spite of the considerable uncertainty of available estimates. In his paper, Pekeris develops a significantly more sophisticated model with the derivation of equations in a spherical geometry and solutions for developed convection thus giving access to velocities and stresses. More progress came from a much-refined value for the viscosity derived by his colleague Norman Haskell through the analysis of the Fennoscandian uplift following deglaciation. The article also produces results on phenomena measured by subsequent fields: the deformation of the Earth's surface and the gravity signature of mantle convection. The paper by Hales also adds value to the seminal work by Holmes: again, velocities are evaluated based on equating heat transfer by radial convection currents within the bulk of the « fluid » to the heat delivered at the surface by conduction. Typical stresses are computed and gravity anomalies evaluated and compared to available estimates. In addition, Hales notes that the deep radioactivity postulated by Holmes is not required to fuel the convective process if Earth's core remains hot during the thermal evolution. Both Pekeris (1935) and Hales (1936), published a few months apart in the *Geophysical Supplements to the Monthly Notices of the Royal Astronomical Society (RAS)*, suggest convective velocities (1-10 cm/yr) that are compatible with those obtained decades later for tectonic plates, as described in Issue 1 of this collection.

It is interesting that both Pekeris and Hales use in their text the term « shell » for the mantle (Gutenberg and Richter already use « mantle » in their 1931 paper on discontinuities, albeit with a vague definition of the bottom boundary). This terminology might evidence their personal connection with Harold Jeffreys (Hales was one of his students) who always used « shell » and was always opposed to the idea of mantle flow, despite his important work on thermal convection at the beginning of his extraordinary career focused partly on fluid dynamics. Regardless of his opposition, Jeffreys communicated the results of Hales and Pekeris to the Royal Astronomical Society. Maybe because the topic was too speculative until observational evidence offered ground for the theory of plate tectonics, Pekeris and Hales then switched to other research fields in geophysics.

Harold Jeffreys was instrumental in supporting and developing geophysics in the RAS: he was serving as secretary of its Geophysical Committee at the time of the creation of the *Geophysical Supplement to the Monthly Notices* (1922) that the present collection commemorates. Jeffreys was an important contributor and editor of what became *GJI*. The paper we highlight here (**Jeffreys, 1943**), among many others, focuses on the state of stress in the Earth under surface loads, a long preoccupation of his. The idea is to minimize the maximum stress difference in the Earth's shell (i.e., mantle) that satisfies a mechanical equilibrium without invoking elasticity. The solution, derived by hand, is close to Airy isostasy. This paper's posterity belongs mostly to planetary applications to Mars, Venus and the Moon. Jeffreys is also an exception in this list: as he mostly worked alone, we do not associate his article with a companion paper!

The uplift of the crust formerly beneath ice sheets has already been mentioned as a key observation that helped constrain mantle viscosity. The next two papers in this collection (**Farrell and Clark, 1976; Peltier and Andrews, 1976**) belong to a series of works in the 1970s that proposed a theory for this process of glacial isostatic adjustment. Mathematically, the history of local sea-level change relative to the deforming surface of the solid viscoelastic Earth is computed as a solution to what is termed the Sea-Level Equation. Besides the rebound beneath ice sheets, important features described in these papers include the subsidence beneath the melt-water loaded ocean basins. To this day, *GJI* publishes articles proposing refinements of these initial efforts: later works have included, for instance, the time evolution of the so-called ocean function (1 at sea and 0 on land), while recent papers typically focus on improvements to the mantle rheology.

The next couple of papers in this collection relate to a central problem in geodynamics, i.e., the response of plates or the lithosphere to boundary forces and to the convecting mantle in addition to surface loads as studied by Jeffreys. An extremely insightful paper by **Forsyth and Uyeda (1975)** investigates the driving mechanisms for the motion of tectonic plates. This effort involves the careful inversion of a model with all body forces acting on the plate through torques (related to the downgoing slabs and ridges but also the mantle resistance). The outcome of this computation, the fact that « forces acting on the downgoing slab control the velocity of the oceanic plates and are an order of magnitude stronger than any other force » is already embedded in their (introductory) figure 8 showing that the velocity of a plate essentially correlates with the fraction of its circumference connected to a subducting slab. **England and McKenzie (1982)** also contributed to this general approach: a thin viscous sheet (the Stokes flow version with a power law rheology of the linear elasticity thin-shell problem) represents continents and the load results from variations in crustal thickness, which enables the analysis of tectonic stresses and an application to the India-Asia collision zone. As a clear heritage from the pioneering studies on mantle convection in this collection, such works emphasize how plate tectonics should not be separated from mantle convection, nor even considered as driven by mantle convection but belonging to mantle convection.

Two other articles published in approximately the same period are chosen to emphasize how mantle convection evolved as an independent discipline when compared to initial prospects directly related to the more generic fluid theory of thermal convection. Typical ingredients that make the mantle a rather odd fluid include multiphase flows and a complex, partly unknown, rheology. **Ribe (1985)** already cited in the Rheology issue of this collection (March, Issue 3) builds on the equations proposed by the same Dan McKenzie to describe the dynamics of partially molten rocks by two- phase flow. The focus is on the compaction length scale, shown to amount to a few tens of meters only, which thus demonstrates a minor effect on mantle dynamics at accreting mid-ocean ridges, contrary to what was considered by some. **Christensen (1984)** tackles yet another problem related to mantle rheology by considering, for the first time in a numerical model of mantle convection, a viscosity that is both temperature- and stress-dependent. Accounting for the strong temperature dependence of mantle viscosity led authors in the late 1970s to a paradoxical result: surface motion of the fluid (with reasonable velocities for Earth's plate tectonics) obtained with the simplistic hypothesis of uniform viscosity was replaced by a, possibly Venus-like, stagnant behavior of the coldest, most viscous part of the mantle when more ``reality" was included in the models. **Christensen (1984)** shows that convective dynamics for a fluid with both temperature- and stress-dependent rheology might offer a path to reconcile viscous flow with plate behaviour. More work has since then convincingly elaborated on the role of a « damage » parameter whose evolution must be considered in the line of two-phase flow (cf. a series of articles by Yanick Ricard and David Bercovici including one also cited in Issue 3 of this collection), which offers perspectives to address the diversity of terrestrial planets as should be the case for a scientific theory. Christensen (1984) is also emblematic of the rise of numerical modeling dedicated to geodynamics in this era.

The last couple of papers are more recent and build on the growth of computing power. They also correspond to what might be one of the last efforts for mantle convection work published in *GJI* to date. Since the 1990s, some numerical models have described forced mantle convection driven by tectonic plate velocities but these lacked the resolution of the energy conservation. For the first time, **Bunge et al. (2003)** proposed to solve the whole set of equations for thermal convection in an inverse problem aiming at reconstructing mantle convection back in time with constraints from seismic tomography in addition to the history of plate motion. This approach relies on variational data assimilation techniques developed by meteorologists. Subsequent efforts have since tried to overcome some limitations of this pioneering work: in an ambitious study, **Bocher et al. (2016)** consider mantle convection models with plate-like behaviour that emerged in the 2000s. This approach enables them to use surface velocities as data to be assimilated rather than as boundary conditions for the flow. Data at a given time is accounted for via a two-stage process: first a forecast then an analysis of the most probable mantle state. Such an approach opens a promising perspective for the next decades. This last paper is also the first paper in this geodynamics collection with a female (first) author… No doubt, the collection of papers celebrating the second century of geodynamics publications in *GJI* will reflect a better equilibrium for gender contributions.

Gaël Choblet, *GJI* Editor

Thermal Convection in the Interior of the Earth
Chaim L. Pekeris, D.Sc.
Geophysical Supplements to the Monthly Notices of the Royal Astronomical Society, Volume 3, Issue 8, December 1935, Pages 343–367,
https://doi.org/10.1111/j.1365-246X.1935.tb01742.x

Convection Currents in the Earth
A. L. Hales, B.A.
Geophysical Supplements to the Monthly Notices of the Royal Astronomical Society, Volume 3, Issue 9, April 1936, Pages 372–379,
https://doi.org/10.1111/j.1365-246X.1936.tb01744.x

The Stress-Differences in the Earth's Shell
Harold Jeffreys, F.R.S.
Geophysical Supplements to the Monthly Notices of the Royal Astronomical Society, Volume 5, Issue 3, May 1943, Pages 71–89,
https://doi.org/10.1111/j.1365-246X.1943.tb00344.x

On Postglacial Sea Level
W. E. Farrell, J. A. Clark
Geophysical Journal International, Volume 46, Issue 3, September 1976, Pages 647–667,
https://doi.org/10.1111/j.1365-246X.1976.tb01252.x

Glacial-Isostatic Adjustment — I. The Forward Problem
W. R. Peltier, J. T. Andrews
Geophysical Journal International, Volume 46, Issue 3, September 1976, Pages 605–646,
https://doi.org/10.1111/j.1365-246X.1976.tb01251.x

On the Relative Importance of the Driving Forces of Plate Motion
Donald Forsyth, Seiya Uyeda
Geophysical Journal International, Volume 43, Issue 1, October 1975, Pages 163–200,
https://doi.org/10.1111/j.1365-246X.1975.tb00631.x

A thin viscous sheet model for continental deformation
Philip England, Dan McKenzie
Geophysical Journal International, Volume 70, Issue 2, August 1982, Pages 295–321,
https://doi.org/10.1111/j.1365-246X.1982.tb04969.x

The deformation and compaction of partial molten zones
Neil M. Ribe
Geophysical Journal International, Volume 83, Issue 2, November 1985, Pages 487–501,
https://doi.org/10.1111/j.1365-246X.1985.tb06499.x

Convection with pressure- and temperature-dependent non-Newtonian rheology
U. Christensen
Geophysical Journal International, Volume 77, Issue 2, May 1984, Pages 343–384,
https://doi.org/10.1111/j.1365-246X.1984.tb01939.x

Mantle circulation models with variational data assimilation: inferring past mantle flow and structure from plate motion histories and seismic tomography
Hans-Peter Bunge, C. R. Hagelberg, B. J. Travis
Geophysical Journal International, Volume 152, Issue 2, February 2003, Pages 280–301,
https://doi.org/10.1046/j.1365-246X.2003.01823.x

A sequential data assimilation approach for the joint reconstruction of mantle convection and surface tectonics
M. Bocher, N. Coltice, A. Fournier, P.J. Tackley
Geophysical Journal International, Volume 204, Issue 1, January 2016, Pages 200–214,
https://doi.org/10.1093/gji/ggv427

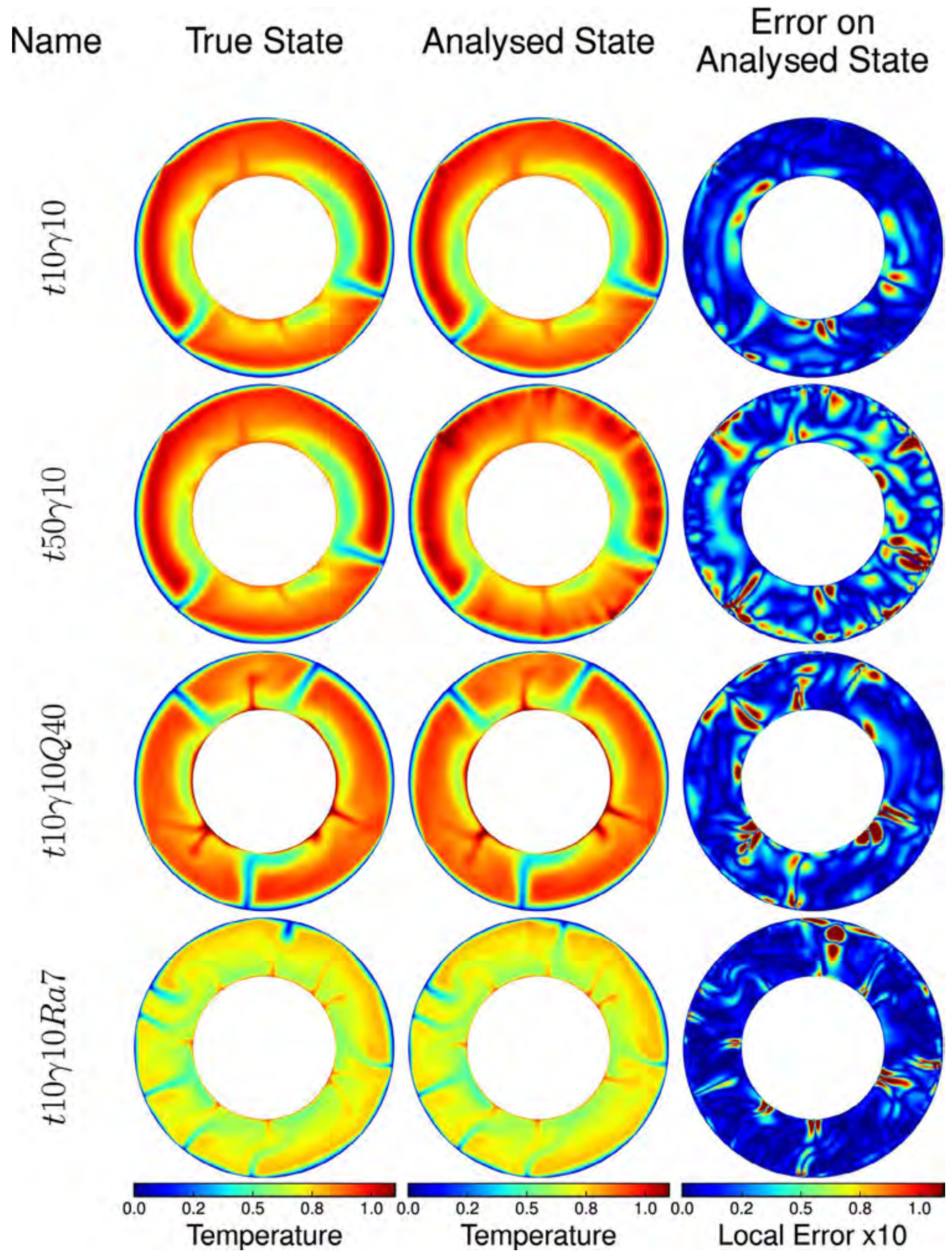

Fig. 6 from Bocher et al (2016). Please see the paper for the full caption.

Paleomagnetism and Environmental Magnetism

In this next set of our centennial collection of papers in *Geophysical Journal International*, we would like to emphasize the journal's publishing of major results about the geological records of the history of the geomagnetic field (palaeomagnetism), and the somewhat younger research topic of environmental magnetism. Magnetism was the first phenomenon to be attributed to the body of the Earth as a whole. Magnetic declination, the difference between magnetic and geographic north, was first recognized in China; in Europe, Pierre de Maricourt introduced the concept of magnetic poles in 1269. At the beginning of the 17th century, William Gilbert described the Earth itself as a great magnet. (For more on the history of geomagnetic research see Cliver and Petrovsky (2019) and Mandea and Petrovsky (2019).)

Resolving magnetic records stored in rocks millions of years ago, and exposed to many subsequent effects of physical and chemical character, requires consideration of many different constraints. Therefore, proper methods of rock sampling, laboratory measurements of the vector of remanent magnetization, and data processing were needed in addition to "benchmark" papers publishing observations and crucial findings in this field. *Geophysical Journal International* and its predecessor *Geophysical Journal of the Royal Astronomical Society* published several of these works, which are still valid and useful in contemporary paleomagnetic practice.

Natural remanent magnetization is stored in a rock during its formation. Later on, during the lifetime of the rock, several secondary components, reflecting local magnetic field at a given time, add vectorially to the original component. Thus, assessing the original record requires physical removal of the secondary components in reversed order (either using alternating magnetic fields or increased temperature) and relevant data processing, involving vector subtraction, remagnetization circles and difference vector paths. **Kirschvink (1980)** introduced a new method based on principal component analysis, which uses all data along a demagnetization path, not only two end-points of a line segment, and has become de rigeur in all subsequent palaeomagnetic studies.

One of the aims of paleomagnetism is to determine whether a magnetization was acquired before or after tectonic folding. For that purpose, a fold test was developed (Graham, 1949), subsequently used only sporadically due to insufficient reliability. **McElhinny (1964)** was the first to suggest a well-defined criterion to judge the reliability of the fold test. Since then, this test has been used routinely in many paleomagnetic works, although 17 years later it was found that the test does not apply to all cases. **McFadden (1990)** introduced a test, based on a correlation between the distribution of magnetic vector directions and tectonic information and argued to be sufficiently flexible to cover nearly all scenarios, even complicated ones.

Another type of test in paleomagnetism aims to determine whether directions deduced from rocks are stable, i.e., relate to a single component of magnetization. One of these is the reversal test, which examines whether two sets of observations, one with normal polarity and the other with reverse polarity, could have been obtained from distributions with mean directions opposite each other. This approach involves forming the null hypothesis that the two sets of observations are in fact drawn from distributions that share a common mean direction and then determining whether the observations are inconsistent with this hypothesis at some level of confidence. A positive reversal test is claimed on the basis of inability to reject this hypothesis. In fact, the positive reversal test is often based on a lack of information, which is unsatisfactory. **McFadden and McElhinny (1990)** suggested that positive reversal tests should be classified according to the amount of information that was available for the test.

Palaeomagnetic analyses can have strong palaeogeographical and tectonic implications but may also be applied to the study of the ancient magnetic field itself. The term palaeosecular variation is used to refer to the intrinsic variability of the palaeomagnetic field on timescales exceeding those for which humans have been making direct observations. Statistical and time-dependent field models attempt to capture these variations, and *GJI* has published significant examples of both. **McElhinny & McFadden (1997)** established a new database of more than 3,700 palaeomagnetic directions from rapidly cooled igneous rocks dating back to 5 Ma and calculated their virtual geomagnetic poles and the angular dispersion of these about the geographic pole. This work provided a landmark assessment of palaoesecular variation but also demonstrated the importance of data selection and further established the utility of the simple but effective "Model G" to summarise pole dispersion as a function of latitude.

Nilsson et al. (2014) represents an important contribution to documenting and understanding palaeosecular variation on the millennial timescale. Their family of models presented variations in the full-vector of the geomagnetic field globally over the last 9,000 years based on a combination of data from archaeological, igneous and sedimentary materials. A major difference in this study compared to previous ones was the careful resampling and modification of sedimentary datasets and their dating so as to reduce artefacts in the final model.

Sometimes, palaeosecular variation becomes so severe that the geomagnetic field loses its characteristic axial dipole dominated shape altogether. In such cases, the field may recover with the same or opposite polarity to that which it had prior to the collapse. Such geomagnetic reversals and excursions are important phenomena both for studying palaeomagnetic behaviour and for dating purposes, addressed in a key paper by **Langereis et al. (1997)**, who applied astronomical tuning to geochemical and rock magnetic measurements obtained from a sedimentary core drilled in the Ionian Sea. These results produced a high-quality age model spanning the last 1.1 Myr, which was then used to date excursion events observed from their magnetostratigraphic study of the same core. The outcome was a set of revised dates for Bruhnes-aged excursions that continue to constitute a benchmark today.

Measurements of the ancient intensity of Earth's magnetic field are notoriously more difficult to make than obtaining the palaeo-direction, and a wide variety of methodological innovations have aimed at addressing the difficulties. A major development in this respect was the approach outlined by **Shaw (1974)**, which, along with its derivative methods developed over subsequent decades, represents a major tool for those wishing to engage in palaeointensity measurements. Shaw-derived methods of palaeointensity measurement are attractive elements of many modern palaeointensity studies on account of (1) their ability to overcome lab-induced sample alteration in some instances, (2) their results being, theoretically at least, magnetic domain-state-independent, and (3) their capability to have experiments performed very quickly, efficiently and precisely using the latest generation of automated cryogenic magnetometers. Nearly 600 Dipole moment estimates, or 13% of the global palaeointensity database (www.pintdb.org), have been produced using the Shaw method or its direct descendants.

A primary goal of fundamental palaeomagnetism, and one of its most unique attributes, is to provide constraints on the evolution of Earth's interior over deep time. Using palaeomagnetism to gain detailed insight into core dynamics over geological timescales is a formidably complex problem, that will certainly entail the comparison of palaeomagnetic records to the outputs of numerical geodynamo simulations. The study of **Aubert et al. (2009)** stands out as a groundbreaking and ambitious attempt to exploit the combination of the state of the art of geodynamo simulation, scaling laws, and thermal evolution modelling to explain existing palaeomagnetic records as well as predicting what future observations of the ancient field may show. Amongst other things, their analysis ruled out that palaeomagnetic records require an early onset of inner core nucleation and also predicted that the Precambrian magnetic field was similarly dipole-dominated as the present but reversed polarity less frequently owing to lower convective forcing.

In the last decades of the 20th century, the field of environmental magnetism was developed. One of the very first papers showing the relevance of paleomagnetic measurements on samples of environmental significance was that of **Heller and Liu (1984)** who showed that natural remanent magnetization measured on about 500 samples from two sections of Chinese loess are consistent between the two sections and yield a clearly defined magnetic polarity zonation. Instead of vectorial measurements of remanent magnetization in solid rock specimens, composition, concentration, grain-size distribution (and grain alignment) of iron oxides (and/or sulphides) are investigated in different substances of environmental significance (ground, sea, lake, river and Aeolian sediments, soils, atmospheric dust and its biocarriers). The aim is to obtain information on climatic changes and environmental conditions, such as soil development and degradation, human activity (e.g., pollution), floods, wildfires, etc. This research was promoted by the ease and speed of basic measurements, usually of magnetic susceptibility. However, this positive feature is counter-balanced by the complexity of the measured substances and difficulties in interpreting the measured data. **Dearing et al. (1996)** provided one of the major achievements examining the theory, measurement, and interpretation of frequency-dependent magnetic susceptibility, reflecting the relative significance of nano-sized superparamagnetic (SP) magnetite, which is presumably of pedogenic origin. A model was proposed to explain it in terms of the behaviour of all SP grains with diameters below ≈0.03 µm. However, the work was based on measurements carried out by one specific instrument, which is now outdated and insufficiently sensitive. Later studies reported on more reliable and accurate measurements and procedures.

Andrew Biggin and **Eduard Petrovsky,** *GJI* Editors

The least-squares line and plane and the analysis of palaeomagnetic data
J. L. Kirschvink
Geophysical Journal International, Volume 62, Issue 3, September 1980, Pages 699–718,
https://doi.org/10.1111/j.1365-246X.1980.tb02601.x

Statistical Significance of the Fold Test in Palaeomagnetism
M. W. McElhinny
Geophysical Journal International, Volume 8, Issue 3, February 1964, Pages 338–340,
https://doi.org/10.1111/j.1365-246X.1964.tb06300.x

A new fold test for palaeomagnetic studies
P. L. McFadden
Geophysical Journal International, Volume 103, Issue 1, October 1990, Pages 163–169,
https://doi.org/10.1111/j.1365-246X.1990.tb01761.x

Classification of the reversal test in palaeomagnetism
P. L. McFadden, M. W. McElhinny
Geophysical Journal International, Volume 103, Issue 3, December 1990, Pages 725–729,
https://doi.org/10.1111/j.1365-246X.1990.tb05683.x

Palaeosecular variation over the past 5 Myr based on a new generalized database
Michael W. McElhinny, Phillip L. McFadden
Geophysical Journal International, Volume 131, Issue 2, November 1997, Pages 240–252,
https://doi.org/10.1111/j.1365-246X.1997.tb01219.x

Reconstructing Holocene geomagnetic field variation: new methods, models and implications
Andreas Nilsson, Richard Holme, Monika Korte, Neil Suttie, Mimi Hill
*Geophysical Journal Internationa*l, Volume 198, Issue 1, July, 2014, Pages 229–248,
https://doi.org/10.1093/gji/ggu120

Magnetostratigraphy and astronomical calibration of the last 1.1 Myr from an eastern Mediterranean piston core and dating of short events in the Brunhes
C. G. Langereis, M. J. Dekkers, G. J. de Lange, M. Paterne, P. J. M. van Santvoort
Geophysical Journal International, Volume 129, Issue 1, April 1997, Pages 75–94,
https://doi.org/10.1111/j.1365-246X.1997.tb00938.x

A new method of determining the magnitude of the palaeomagnetic field, application to five historic lavas and five archaeological samples
J. Shaw
Geophysical Journal International, Volume 39, Issue 1, October 1974, Pages 133–141,
https://doi.org/10.1111/j.1365-246X.1974.tb05443.x

Modelling the palaeo-evolution of the geodynamo
Julien Aubert, Stéphane Labrosse, Charles Poitou
Geophysical Journal International, Volume 179, Issue 3, December 2009, Pages 1414–1428,
https://doi.org/10.1111/j.1365-246X.2009.04361.x

Magnetism of Chinese loess deposits
Friedrich Heller, Liu Tungsheng
Geophysical Journal International, Volume 77, Issue 1, April 1984, Pages 125–141,
https://doi.org/10.1111/j.1365-246X.1984.tb01928.x

Frequency-dependent susceptibility measurements of environmental materials
J. A. Dearing, R. J. L. Dann, K. Hay, J. A. Lees, P. J. Loveland, B. A. Maher, K. O'Grady
Geophysical Journal International, Volume 124, Issue 1, January 1996, Pages 228–240,
https://doi.org/10.1111/j.1365-246X.1996.tb06366.x

Introduction in: Geomagnetism, Aeronomy and Space Weather: A Journey from the Earth's Core to the Sun
Cliver E. and Petrovsky E., 2019. , edited by: Mandea M., Korte M., Yau A., and Petrovsky E.,
Cambridge University Press, Cambridge, UK (available in print only)

IAGA: a major role in understanding our magnetic planet
Mioara Mandea and Eduard Petrovský
History of Geo- and Space Sciences, Volume 10, Issue 1, April 2019, Pages 163–172,
https://doi.org/10.5194/hgss-10-163-2019

The stability and significance of magnetism in sedimentary rocks
John W. Graham
Journal of Geophysical Research, Volume 54, Issue 2, June 1949, Pages 131–167,
https://doi.org/10.1029/JZ054i002p00131

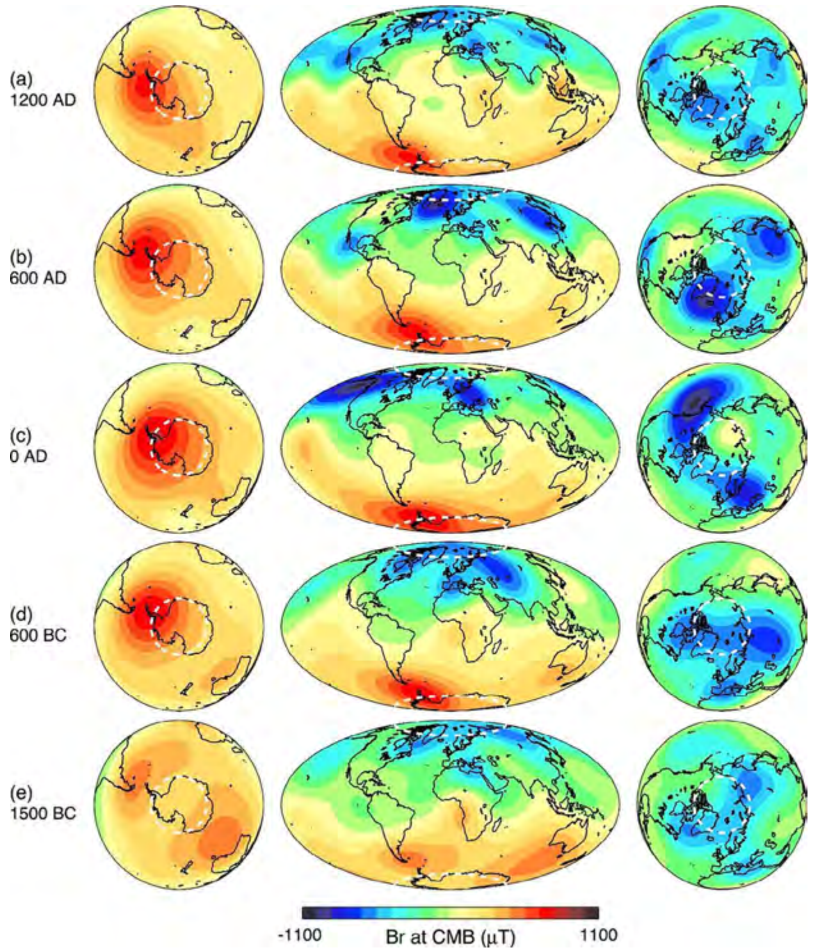

Fig. 9 from Nilsson et al (2014). Please see the paper for the full caption.

Seismic Traveltimes and their Uses

Issue 6 of our centennial collection of influential papers in *Geophysical Journal International* is dedicated to traveltime observations and measurements. Traveltimes have been the prime observable for solving the earthquake location problem and, up to the nineties of the previous century, the main source of information for deciphering the Earth's internal seismic velocity structure. The studies highlighted in this issue led to the early discoveries of Earth's interior, the determination of earthquake locations and their source parameters, and resulted in the first tomographic images showing lateral variations in Earth's interior. The latter is nicely described by Frederik J. Simons in his piece accompanying the second set of influential papers published in *Geophysical Journal International* (pp 6-10). Despite the increased availability of high-quality seismic data and the advent of high-performance computing, both promoting full-waveform inversion, traveltime measurements remain popular because of their robustness and the approximate linearity of the relations between phase and seismic model parameters. Thus, traveltime tomographic models commonly serve as starting models to mitigate issues associated with the non-linearity inherent in full-waveform inversions. In addition, discoveries regarding other deep planetary interiors and planetary quakes are still largely based on traveltime observations and measurements (i.e., Nakamura, 2005; Weber et al. 2011; Banerdt et al. 2020; Stähler et al. 2021).

The first paper we would like to highlight is by the hands of Herbert Hall Turner (**Turner 1922**), actually the first paper in the first volume of the *Monthly Notices of the Royal Astronomical Society, Geophysical Supplement*, which is the earliest predecessor of *Geophysical Journal International*. Because of this paper, Turner was accredited to be the first to have observed "deep" earthquakes. He reached this conclusion based on a careful analysis of antipodal P-wave travel-time residuals (i.e., travel time residuals at epicentral distances beyond 140°) for a set of large events recorded between 1913 and 1916. Turner found these travel-time residuals to vary significantly from one event to the other and could only explain this observation by large variations in depth of the individual events. Despite the questionable quality of his phase readings (Gutenberg & Richter, 1938), Turner's conclusion of the existence of "deep focus" events was later on confirmed by Wadati (1928), who, together with Hugo Benioff, is remembered as one of the two discoverers of the eponymous seismogenic zones accompanying the subduction of oceanic lithosphere.

Seismological exploration of the Earth's interior began a few decades before Turner's paper. This rise was not a coincidence: by 1901, the number of observatories capable of recording teleseismic phases reached 25, compared to only eight in 1894 (Ben-Menahem, 1995). The discovery of the first-order discontinuities within the Earth's interior relied on analyses of the systematic behavior of body-wave arrivals as a function of distance and time. Examples of such discoveries are the existence of the core (Oldham, 1906), the Moho discontinuity (Mohorovicić, 1910), the precise estimation of the depth of the core (Gutenberg 1914), and the existence of the inner core (Lehmann, 1936). Not much later, **Jeffreys (1939)** tabulated the mantle and the core phases, such as P, S, and SKS, and derived the relations to the P- and S-wave wavespeeds of the Earth's interior. This work led to the famous JB tables (Jeffreys & Bullen, 1940), a collection of arrival time tables larger and remarkably more accurate than its predecessors, which are still in use today.

Increased spatial sampling, more sophisticated instrumentation, and the arrival of digital computers heralded a new era in seismology. These developments also promoted advanced seismic measurement and processing techniques, many of which were demonstrated in regional studies. Three papers are particularly valuable in this context. **Gerver & Markushevich (1966)** proposed a technique to estimate the seismic velocities of the medium based on analyzing the characteristics of travel-time curves and fitting a theoretical travel-time curve to the observed one. **Landisman et al. (1969)** demonstrated the benefit of using a frequency-domain time-variable filter based on a moving window analysis of cross-correlated (surface wave) seismograms. Numerous studies, applying what is often referred to as the "two-station method", have hitherto made use of their technique. **Fuchs & Müller (1971)** augmented the reflectivity method, as formulated by Fuchs in 1968, by taking into account time shifts and (elastic) transmission losses resulting from the transmission through a stack of layers on top of the reflecting medium of interest. This addition was of great practical significance because, as such, the imprint of this stack of layers could be removed from the deeper reflections of interest (e.g., from the Moho discontinuity). Fuchs & Müller successfully demonstrated this by applying the proposed frequency-wavenumber method to interpreting observations of refracted waves along a profile in Central Europe. Their paper is one of the pioneering studies when it comes to the computation of "complete" synthetic seismograms.

Despite the advances in regional seismology, the necessity of a common reference Earth model in seismology remained. To that end, Dziewonski & Anderson (1981) constructed an average model, known as PREM (Preliminary Reference Earth Model), as a function of the Earth's radius, by modeling a large number of body wave traveltimes and surface-wave and free-oscillation data. The model IASP91 of **Kennett & Engdahl (1991)** is an updated version of the JB traveltime tables for addressing phase identification and earthquake location problems with a calculation scheme allowing for estimating consistent traveltimes for each phase based on event focal depths. This work is among the most cited articles in *Geophysical Journal International*. The model ak135 of **Kennett et al. (1995)**, the successor of IASP91, was then constructed using high-frequency body-wave traveltime measurements, which performed significantly better compared to its predecessors in fitting a broader range of phases. All these radially-symmetric models are still commonly used as reference models as well as background models for traveltime tomographic models constructed based on perturbation theory.

Recognizing the complexity of waveforms that could not be explained by just layered or radially symmetric models, the first tomographic models based on traveltime measurements came out in the 1970s. Since then, various traveltime tomographic models have depicted slab and plume features, which provided additional insight into the dynamics of the mantle. Combining multiple measurements of body wave traveltimes, surface wave dispersion, and free oscillations to improve data coverage, **Ritsema et al. (2011)** capitalized on the wealth of available data with the construction of the 3D global mantle model S40RTS, which is usually treated as a reference model by the seismology community. For a review of the evolution of seismic tomography and related papers published in *Geophysical Journal International,* we refer to Issue 2. Here, within the context of traveltime seismic tomography, we want to highlight **Liu & Tromp (2008)** who presented the first set of 3D numerical global finite-frequency body-wave kernels for mantle and core phases as well as those for surface waves based on cross-correlation traveltime measurements. Their study served as a basis for full-waveform inversion in earthquake seismology, where traveltime/phase measurements are still commonly used to linearize the inverse problem.

So far, we solely considered travel times of phases (i.e., arrivals) generated by earthquakes. At the beginning of this century, however, it was demonstrated that reliable travel times might also be retrieved between pairs of stations (Campillo & Paul, 2003; Shapiro & Campillo, 2004) by means of a technique often referred to as "seismic interferometry". Specifically, and under specific conditions, responses obtained through the application of seismic interferometry can be related to the Green's function of the medium (Snieder, 2004; Wapenaar, 2004). This was already proven as early as 1968 for vertically propagating wave fields recorded by a single receiver atop a simple horizontally stratified subsurface (Claerbout, 1968). **Wapenaar et al. (2004)**, however, extended this to wave fields in 3D inhomogeneous media recorded by separate receivers at the Earth's free surface. Their proof has been the basis for numerous studies in which body waves were retrieved by merely time averaging noise crosscorrelations. The study by **Boué et al. (2013)**, for example, revealed that time-averaged noise crosscorrelations contain teleseismic body waves, including triplications and core phases. Another *Geophysical Journal International* paper that certainly deserves mentioning in this context is the study by **Bensen et al. (2007)** who explain and exemplify (i) how surface waves can be retrieved from year-long records of ambient seismic noise, and (ii) how phase and group velocity can best be extracted from these surface waves. Since its publication, their study has been a valuable source of information for many researchers attempting to exploit the ambient seismic surface wave field (e.g., Lin et al., 2008; Shen et al., 2016).

Whether it concerns regional scale arrival times (e.g., Spetzler & Dost, 2017) or teleseismic travel times (e.g., Ritsema et al. 2011), the accuracy and consistency of arrival-time picks is of utmost importance: inaccurate arrival times result in erroneous subsurface/Earth models or mislocated hypocenters. For over half a century, seismologists have attempted to automate the picking process. Amplitude-based approaches have been proposed, such as the short-term average/long-term average method (Allen, 1978) and the envelope-based improvement of the latter (Baer & Kradolfer, 1987). Later, Sleeman & van Eck (1999) used the Akaike

Information Criterion to determine the onset of an arrival. The last and most recent influential paper in our set is by **Zhu & Beroza (2019)**. These authors introduced a deep-neural-network-based phase-picking method, which they dubbed “PhaseNet”, that exhibits a much higher picking accuracy as well as a higher recall rate than existing methods (in 2019) and demonstrated superior performance. With the contemporary rapid developments in machine learning and artificial intelligence in general, this study has shown to be a harbinger of things to come in the field of seismology.

Cornelis Weemstra and **Ebru Bozdağ**, *GJI* Editors

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Earth Rotation and Oscillations

This month's historic *GJI* papers examine some aspects of the Earth's modes of motion, either rotational or elastic-gravitational, and whether free or forced oscillations.

An unusual feature of this list is that four of the authors (Freeman Gilbert, Tony Dahlen, Martin Smith, and John Wahr) formed a lineage of theoretical geophysicists — a lineage that published not just these, but many other papers, in *GJI*. And, this essay will be slightly more personal than other *GJI* centennial reviews.

The first paper, by **Walter Munk and Roger Revelle (1952)**, dealt with the simplest mode, the rotation of the Earth on its axis; more specifically possible geophysical causes of changes in the Earth's spin rate over periods from years to decades. Such changes were needed for observations of the Moon and planets to agree with the theories of celestial mechanics. Walter first learned about all this from an article in Astounding Science Fiction (Richardson 1949). Munk and Revelle pointed out that possible mass redistributions (then the usual explanation) would also affect the direction of the Earth's spin axis and variations in sea level. Fifty years later Walter (Munk 2002) used observations of these same phenomena to argue that the global sea level rise of the twentieth century could not have been caused by melting of polar ice, leaving its cause an enigma (but see Mitrovica et al. 2015). In this earlier paper he and Roger showed that such melting could only explain a small part of the observed changes in spin rate; sadly, this is no longer true. They also ruled out vertical motions of continents, leaving variable core motion as the only possible source: still the accepted cause of decadal spin-rate changes.

The other well-observed rotational mode is the Chandler wobble, the theory for which was exhaustively discussed by **Smith and Dahlen (1981)**. This mathematically formidable paper applied two theoretical approaches to determining the period of the wobble. First was the angular-momentum equations for a deforming Earth: an analytical, and nineteenth-century, approach. The second, used for including the deformations for a realistic Earth, was the theory of elastic-gravitational modes of an elliptical and rotating body. Combining these results with corrections for the core and the pole tide on the ocean, gave a period of 432.5 days, consistent with observed values then and now. The mode theory allowed them to rigorously connect the Q of the wobble to that of the materials in the Earth, correcting many earlier estimates to get information on anelasticity in an otherwise unobservable frequency range.

To include the pole tide in their computation, Smith and Dahlen assumed it to be an equilibrium tide, in part using the results of **Proudman (1960)**. Because the ocean can support modes of motion down to very low frequency, the approach to equilibrium depends on the level of friction. Proudman demonstrated that a single friction parameter was relevant, and made a rough calculation that suggested that reasonable amounts of turbulent dissipation would cause any tides with periods of more than about a year to be close to equilibrium, a result supported by modern numerical models.

Smith and Dahlen also included, as a small but important correction, anelastic dispersion: making the stress-strain relationship dissipative means that the elastic parameters must vary with frequency. **Davies (1967)** pointed out that comparisons between surface-wave and body-wave estimates of Earth structure needed to take this into account. This paper, unlike the others in this list, was not much noticed; indeed, its interest is that it was actually an example of a scientific blind-spot. The discrepancy between Earth models fitting body-wave data and models fitting normal-mode data was widely remarked on as an unresolved problem (for example, by Gilbert et al 1973); it was left to Randall (1976) and others to rediscover this already-published explanation.

Turning to the actual elastic-gravitational normal modes of the Earth, we have chosen, out of many possible papers, those by **Dahlen (1968)** and **Woodhouse (1980)**. Both of these address aspects of how these modes behave in the actual Earth, as opposed to the idealized Spherical, Non-Rotating, Elastic, and Isotropic (SNREI) model that was the basis for early computations of mode frequencies and eigenfunctions. The first observations of free oscillations, after the 1960 Chilean earthquake, revealed that modes computed for a SNREI model, which usually have multiple mode shapes at the same frequency (multiplets made up of singlets), were observed to be split, something immediately explained as a consequence of Earth rotation. **Dahlen (1968)** produced a unified treatment of the splitting to be expected, not just from rotation, but also from the Earth's ellipticity, and lateral heterogeneity, including shifts of internal boundaries (this last being later corrected by Woodhouse and Dahlen (1978)).

If two different modes of a vibrating system have nearly identical frequencies, any perturbation can cause these to become coupled, altering the frequencies and attenuations from what would be found for each one in isolation. In the Earth, the splitting of multiplets complicates this even further, as individual singlets from different multiplets can be close in frequency. **Woodhouse (1980)** determined the coupling expressions for such cases given perturbations from rotation, ellipticity, and lateral heterogeneity, while including attenuation (complex-valued frequency) as a parameter for each mode.

The Earth's normal modes provided data for determining Earth structure; **Freeman Gilbert (1971)** showed how they are related to the source parameters of an earthquake, more specifically the moment tensor, which was here introduced to most seismologists. The expressions in this paper led to spatial stacking methods that were crucial in identifying particular modes; and also provide the forward calculation for the source-mechanism inversions of the global and regional Centroid Moment Tensor catalogs, which have by now been used in thousands of papers. This paper is itself quite brief, claiming only to be an application of results found by Rayleigh and Routh; the only reference given is to Rayleigh's 1877 The Theory of Sound, which does begin with a general treatment of vibrating systems. Freeman recommended this book to students taking his long-period seismology course; Rayleigh's discussion is indeed quite readable, and I still have my copy. One other oddity of this paper, its emphasis on using sums of modes to determine permanent offsets, can be explained as being a contribution to contemporary interest in ``zero-frequency" seismology (Press 1965, Agnew 2007).

The Earth has both free and forced modes of oscillation, the latter driven by tidal forcing, which both deforms the Earth and changes the direction of its angular momentum vector to create the nutations and precession long known to astronomers. The systematic treatment of these forced modes, in which the Earth's rotation is fundamental, was first done in a comprehensive way in the paper by **John Wahr (1981)**. Or perhaps it would be better to say, papers, since this was one of six by Wahr that took up over half of the March 1981 issue of *GJRAS*. I well remember the impact of first seeing its table of contents. The paper selected here is the most abstract, finding a way to express the motion of the rotating Earth in terms of orthogonal modes, partly by carefully defining the meaning of "orthogonal". This formal framework could then be applied to produce improved models for the Earth's tidal deformations and nutations; the results were almost immediately applied to upgrade descriptions of these used by astronomers.

The final paper for this month, **Tamura et al. (1991)** is also about tides, but about data analysis rather than theory, and produced by a collaboration between three geophysicists (Y. Tamura, T. Sato, and M. Ooe, all at the Mizusawa branch of the National Astronomical Observatory of Japan: as befits a station of the International Latitude Service, more of a geophysical facility than an astronomical one) and a statistician, M. Ishiguro. They produced a procedure which decomposed a time series into tides, changes correlated with other series, and a flexible representation of "drift" as a stochastic process. This decomposition depended on several hyperparameters, and used the Akaike Bayesian Information Criterion to find optimal values of these. In a move unusual for this time, the authors made available a program, BAYTAP-G, which implemented this procedure; it has continued to be widely used to the present by the earth-tide community.

Duncan Agnew, *GJI* Deputy Editor-in-Chief

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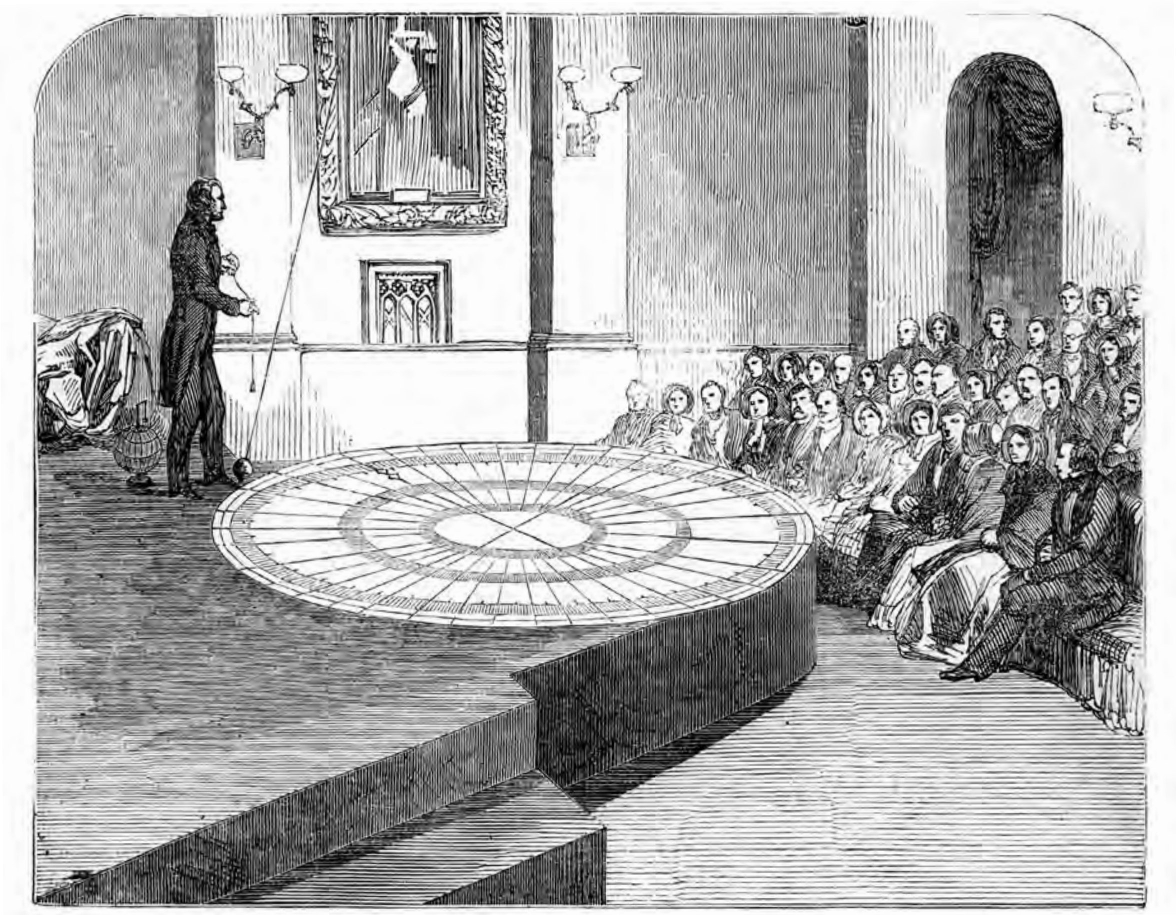


Foucault's Pendulum lecture. This lecture, 'The Rotation of the Earth Made Visible', was delivered at the Royal Polytechnic Institution, Regent Street, London, in May 1851 by one of its founders, the British inventor George Henry Bachhoffner (1810-1879). **Photo credit: Royal Astronomical Society/Science Photo Library.**

Marine Geophysics

In the next set of our centennial collection of papers in *Geophysical Journal International* we shine the light on the contribution of marine geophysics to the emergence of plate tectonic theory. We have selected seven papers from the pioneering 1958-1976 period that encompass all the key observational methods — echo sounding, magnetics, heat flow, gravity and seismics. Sneaking under the radar will be one paper on land (well Iceland almost counts as marine) and an over-representation of authors from my own host institution (Imperial College London) amongst the marine powerhouses of Cambridge, Scripps and Lamont. Reading any papers or personal reflections from this period reveals a strong community endeavour — there is much borrowing of equipment, scrounging of ship time, and in pre-plate tectonic times a general feeling that despite not knowing what the value of any given measurement was, having some measurements must be better than none. It was a truly pioneering age, with marine geophysics benefitting significantly from the Cold War political situation and growing interest in the sea.

Our initial paper, perhaps fittingly, was published in the inaugural volume of the *Geophysical Journal of the Royal Astronomical Society* which took over from the Society's *Geophysical Supplements to the Monthly Notices* established in 1922 (**Mason, 1958**). This paper was the first sight of the extraordinary magnetic lineations off the west coast of the US that were critical to confirming the 1963 Vine and Matthews seafloor spreading hypothesis. The surveys were conducted at a time when there was little understanding of what the endeavour of towing a magnetometer behind a ship might reveal. Instead, the magnetometer surveys were piggy-backed on a US Navy project to systematically map water depths in the Pacific out to 300 nm from the coastline. Mason developed methods to reduce the huge volume of shipboard data and produced a contoured map of the magnetic anomaly encompassing the Murray Fracture Zone. The paper correctly identifies the magnetic source as the upper crust (although it intriguingly describes this layer as "volcanics" that overlay "crust" reflecting the notion at the time that the oceans were simply sunken continents). At this time, a major focus for land geologists was the understanding of large transcurrent faults such as the Great Glen and San Andreas Fault, and the highlight of the paper is the recognition of the ~150 km lateral offset of anomalies at the Murray Fracture Zone. This was inconvenient as it seemed common to answer the difficult question of how transcurrent faults end by slipping them into the neighbouring ocean. Somewhat logically the US Navy survey started at the Mexican border and at this stage it was entirely on the Pacific plate. So, it was not until the work extended northwards over the following three years that the positive/negative "zebra stripes" symmetry about the topographic ridges did the seafloor spreading fabric become clear. Nonetheless, the 1958 paper is a remarkable contribution which paved the way to the unlocking of plate tectonics.

Next, we highlight a paper reporting some very early heat flow measurements (**Bullard and Day, 1961**). The equipment needed to take such measurements at sea had been under development since the early 1950s, and this 1961 paper is notable as it marks a time when there were sufficient values recorded globally to draw some conclusions that would help establish the relative simplicity of oceanic (compared to continental) lithosphere. Whilst only 15 measurements are presented here (which are spread over a large area of the western Atlantic from southern Britain to north Africa) the paper makes the key observation that the results are essentially the same as those made in the Pacific. The authors therefore conclude that both oceans have a similar origin and history. They show that both the Mid-Atlantic Ridge and East Pacific Rise have significantly higher heat flow (up to x6) than anywhere else and so the ridge axes are elevated because they were hotter. In fact, Bullard and Day only have a single measurement in the Mid-Atlantic rift valley and those from the East Pacific Rise have a wide distribution that overlaps with the background seafloor values, so this is quite a bold conclusion, which turned out to be right. Anyone interested in the history of science will find the sample map — with hand-drawn 2000 m bathymetry contours and no real indication of the ridge axis at all — very evocative of an era when going to sea was stepping into the relatively unknown.

Paper 3 is the interloper – an early proposal of "crustal drift" (later known as "subaerial seafloor spreading") for Iceland (**Bodvarsson and Walker, 1964**). The study is the result of 10 years of fieldwork and includes the correlation of lava units across the whole island — which anyone who has ever shredded a pair of walking boots in a single afternoon traversing fresh basalt can only admire. The lead author's affiliation is given as "State Electricity Authority, Reykjavik" and one can only assume that this association supported the huge logistics that would have been required at that time (the paper sadly has no acknowledgement section). The mapping of the lava sequences showed an upward decrease in dip (8° at sea level, 4° at mountain tops) that is related to an updip thinning of the sequence. The paper contains arguably the first cartoon for the development of seaward dipping reflectors later imaged along the continental margins of northern Europe and Greenland that lead to the recognition of Large Igneous Provinces and the likely involvement of mantle plumes in continental breakup. The paper correctly recognises the link between Iceland and the Mid Atlantic Ridge, with a central zone of dyke injection. Finally the paper combines the field observations with geophysical surveys to dismiss the hypothesis that Iceland was just a static syncline that had filled up vertically with lava since the Tertiary to conclude that the structure was instead due to lateral motions or "crustal drift". Without doubt work such as this would have significantly influenced those still sceptical of the marine magnetic results at this time and hanging on to the idea that the continents pushed through the ocean floor to achieve the paleomagnetically measured drift that had been established a decade earlier.

It is not possible to pin-point the birth of plate tectonic theory — and many scientists from different specialisms contributed to the many layers of the process (specifically the putting together of seafloor spreading, continental drift and the recognition of transform faults as the third type of plate boundary). However, most people would agree that it was completed in the 1960s, so as Neil Armstrong walked on the moon Earth Science gained its unifying theory that explains the (post-Archean at least) history of our planet. As an early example of the application of this new theory we have chosen **McKenzie and Sclater, 1971**, who used magnetic anomaly dating of the floor of the Indian Ocean to propose a model for its tectonic evolution. Unlike the better-studied and geometrically simple Atlantic Ocean, the Indian Ocean was a challenge as it involves the post-Pangea separation of a large number of plates, such as Antarctica, Australia and India which could be put back together in a number of configurations and oddities like the granitic Seychelles to explain. The paper uses the solution of Euler poles and vector stability diagrams for triple junctions to make the reconstruction. Given the complexity and modest data it was a convincing demonstration of the theory on a large scale.

The final three papers in this set are from the immediate post-plate tectonic era when the race was on within the marine geophysical community to provide further evidence for the theory's predictions. The first paper we highlight in this context is that of **Lister, 1972**, who returned to the western US seaboard of our first paper to conduct heat flow measurements. Unlike our second paper, where heat flow stations were distributed somewhat arbitrarily over a large part of the ocean floor, here they are organised into a transect. According to the new theory, plates were made by magmatism at mid-ocean ridges and cool by conduction as they age. Therefore, given you can date the ocean floor from the magnetic anomalies you should be able to confirm this pattern. Unfortunately, Lister found that across the Juan de Fuca ridge axis the heat flow showed huge scatter and even peak values fell far short of the predicted values. This was potentially a major hiccup for the new theory, but Lister correctly identified that hydrothermal circulation through the hot, porous young basalt could explain the discrepancy. The paper predicts the later discovery of the spectacular black smokers made seven years later. At the time, one suspects that the scatter of results may have been seen as due to experimental error, but today with significantly improved positioning capabilities and a much larger database it is clear that it is a genuine characteristic of hydrothermal circulation systems of the seafloor which show distinct recharge and discharge features.

Up to this point, we have mainly focussed on the places where oceanic plates are created – but of course according to plate tectonic theory they also need to be destroyed. Whilst earthquake locations supported the idea of the consumption of plates below island arcs, the forces required to bend the incoming plate seemed extreme and maybe the new oceanic lithosphere could be accommodated by an expanding Earth after all? Our sixth paper uses a particularly extensive compilation of gravity data from the "ring of fire" in the north-west Pacific to investigate this phenomenon (**Watts and Talwani, 1974**). The paper shows a number of transects across various island arcs and identifies the so-called outer rise some 400 km or so seaward of the trench itself as the expression of the flexural bending of the elastic oceanic plate as it starts its journey back into the asthenospheric mantle. The dataset used is particularly impressive bearing in mind that early gravity measurements in the oceans were made from pendulum instruments in submarines because methods to compensate for the huge horizontal and vertical accelerations experienced when measuring from a ship at the sea surface took a while to be developed. The Watts and Talwani paper first correlates the gravity and topographic high from several subduction zones and then elegantly lifts some engineering theory from the mechanical bending of beams to show that the amplitudes and wavelength of the two observables can be explained by the flexure of the elastic plate. The paper is also notable as it refers to early satellite-derived gravity measurements, although it dismisses them as being too low resolution for the study of the outer high.

In the final paper we highlight the application of active-source seismology to our understanding of the sub-seafloor. We have chosen a paper from 1976 which was the first to identify a low-velocity zone below a mid-ocean ridge (**Orcutt et al., 1976**). The result is significant as the velocity inversion could be interpreted as a magma chamber that would be expected to lie below the continuous volcanic chain at the ridge axis responsible for making the entire world's ocean floors. Its position in the mid-crust also elegantly explained the volcanic stratigraphy of erupted lavas and injected dykes above and cumulates below (the so-called "Penrose model" developed together with ophiolite observations). The work used data from just three ocean-bottom seismometers and about 40 explosive charges let off every 10 km or so along a stretch of the East Pacific Rise to generate 1D velocity-depth profiles at 0, 3 and 5 My ages. Despite this modest dataset the authors show that the mid-crustal velocity inversion was restricted to the zero-aged crust. By 3 Ma it had gone, although the underlying mantle still had a slightly suppressed velocity indicating it was still warm. However, by 5 Ma, the velocity structure was essentially that seen everywhere else in the oceans. These results supported those coming in from heat flow, in suggesting that significant (non-conductive) cooling was happening at the ridge axis.

Much can be learned from looking back into the archive. With the benefit of hindsight, these papers show some remarkable insights made with very little data, and also the slow shrugging off of incorrect paradigms that dog all subjects. We hope you enjoy dipping into one or two of them as much as we did. One can of course speculate what marine scientists working in the 20-year period we highlight here would be most surprised about in the discoveries that followed. In terms of seafloor mapping, the ocean-scale satellite-altimeter maps that emerged in the 1990s demonstrated plate tectonic theory geometries beyond doubt and the multi-beam echo sounder maps that emerged around the same time showed a level of detail of seafloor processes that would have been hard to foresee. Both demonstrate how going to sea before was effectively doing science with a blindfold. Major surprises in the last 20 years include the recognition that non-Penrose layered oceanic crust floors so much of the slow-spreading Atlantic Ocean and the discovery of a new class of mid-ocean ridge: ultra-slow spreading centres that have little magmatism. Timing and instrumentation collided to capture seabed motions during the Tohoku earthquake that served to demystify devastating tsunamis. Today the subject is moving towards environmental matters as we shift to the green economy with activities such as harvesting metals from the seafloor and sequestering CO_2 within it. There is also a new focus on better understanding offshore hazards and the need to protect the growing marine infrastructure in a climate changing world. None of our preparedness would have been possible without our pioneers and *GJI* as a society journal will no doubt reflect this shift in emphasis going forward.

Jenny Collier, *GJI* Editor

A magnetic survey off the west coast of the United States between latitudes 32° and 36° N, longitudes 121° and 128° W
R. G. Mason
Geophysical Journal International, Volume 1, Issue 4, 1958, Pages 320-329
https://doi.org/10.1111/j.1365-246X.1958.tb05341.x

The Flow of Heat through the Floor of the Atlantic Ocean
E. C. Bullard and A. Day
Geophysical Journal International, Volume 4, Issue Supplement_1, December 1961, Pages 282–292,
https://doi.org/10.1111/j.1365-246X.1961.tb06820.x

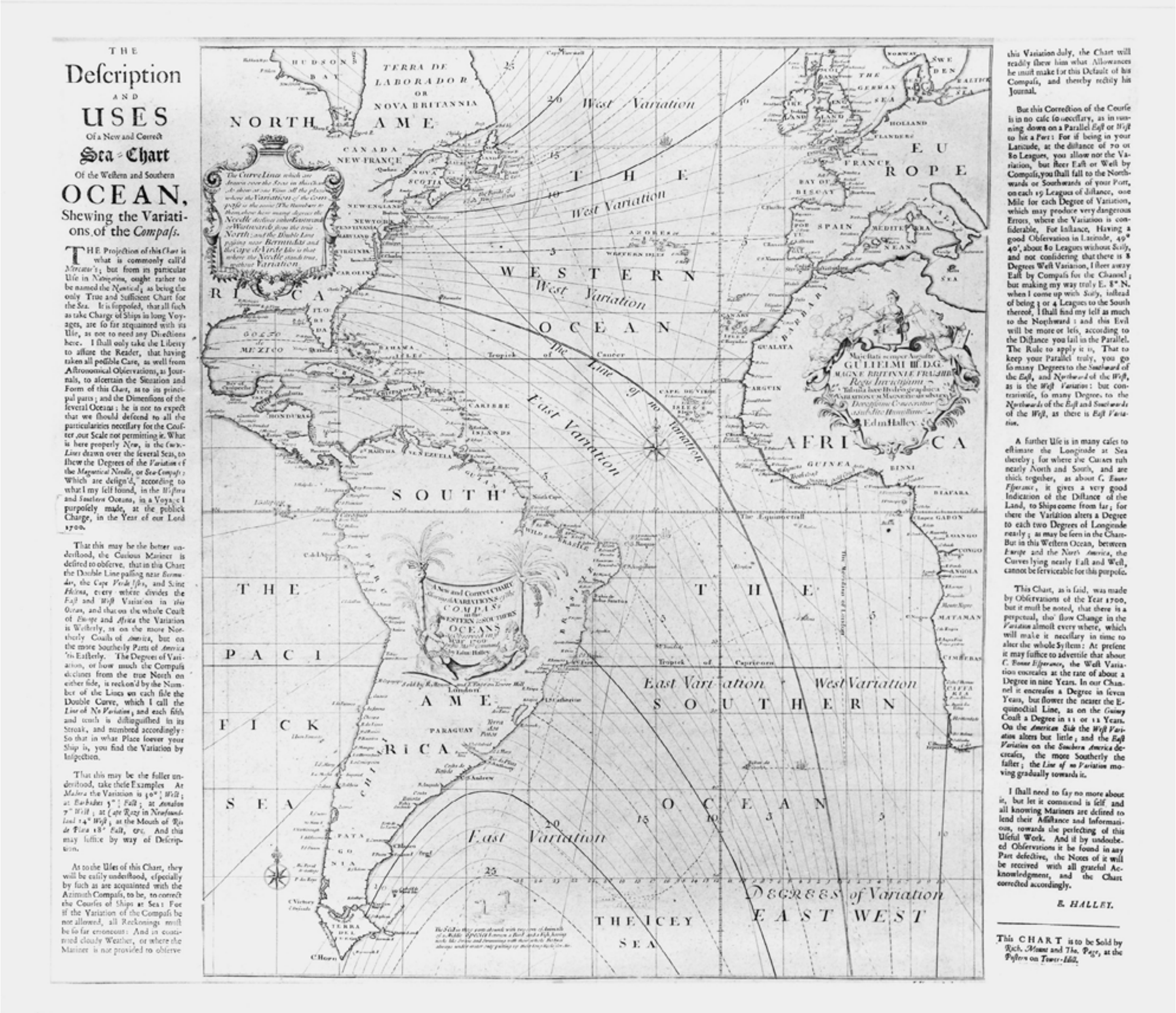
Crustal Drift in Iceland
G. Bodvarsson and G. P. L. Walker
Geophysical Journal International, Volume 8, Issue 3, February 1964, Pages 285–300,
https://doi.org/10.1111/j.1365-246X.1964.tb06295.x

The Evolution of the Indian Ocean since the Late Cretaceous
Dan McKenzie and John G. Sclater
Geophysical Journal International, Volume 24, Issue 5, December 1971, Pages 437–528,
https://doi.org/10.1111/j.1365-246X.1971.tb02190.x

On the Thermal Balance of a Mid-Ocean Ridge
C. R. B. Lister
Geophysical Journal International, Volume 26, Issue 5, April 1972, Pages 515–535,
https://doi.org/10.1111/j.1365-246X.1972.tb05766.x

Gravity Anomalies Seaward of Deep-Sea Trenches and their Tectonic Implications
A. B. Watts and M. Talwani
Geophysical Journal International, Volume 36, Issue 1, January 1974, Pages 57–90,
https://doi.org/10.1111/j.1365-246X.1974.tb03626.x

Structure of the East Pacific Rise from an Ocean Bottom Seismometer Survey
John A. Orcutt, Brian L. N. Kennett, LeRoy M. Dorman
Geophysical Journal International, Volume 45, Issue 2, May 1976, Pages 305–320,
https://doi.org/10.1111/j.1365-246X.1976.tb00328.x



Halley's magnetic Atlantic chart. Chart of the Atlantic Ocean showing variations in compass readings, published in 1700 by the English astronomer, meteorologist and physicist Edmond Halley (1656-1742). **Photo credit: Royal Astronomical Society/Science Photo Library.**

Electromagnetic Methods and their Applications

This month's issue of our centennial collection of papers in *Geophysical Journal International* is dedicated to groundbreaking developments of methods and applications in electromagnetics that were published in our journal over the last one hundred years. Electromagnetic methods form a discipline within geophysics applied to study the electrical conductivity structure within the Earth in a wide depth range. Electromagnetic methods thereby include both galvanic current conduction and induction processes. With respect to the sources, passive methods, which measure natural electromagnetic fields, and controlled-source methods, utilizing manmade sources, exist.

Electrical conductivity is vital for understanding properties of rocks as well as geological and tectonic settings as it serves as a powerful indicator of subsurface structures and processes. Different rock types exhibit varying conductivity levels due to e.g. their mineral composition and porosity. By exploring conductivity, we can infer geological structures, identify potential mineral deposits, and gain insights into groundwater flow and many more aspects of the undisclosed subsurface.

The history of electromagnetic methods in geophysics dates back to the late 19th century, when scientists began using electromagnetic principles to probe the Earth's subsurface. Pioneering experiments by Conrad Schlumberger in the early 20th century laid the foundation for modern exploration techniques. His development of electrical-resistivity surveys revolutionised the field, allowing researchers to map subsurface conductivity variations.

Induction methods depend on recordings of magnetic and electric field variations and allow for deeper sounding depths. Compared to other geophysical disciplines, EM methods based on induction processes are comparatively young. For instance, the foundation of the geophysical sounding method Magnetotellurics (MT) was formulated and published by L. Cagniard in 1953. Only later, it was revealed that even before in 1950, A.N. Tikhonov published an equivalent theory in Eastern Europe, in Russian. Both were henceforth appreciated as the discoverers of Magnetotellurics. However, only lately we realised that a Japanese author, M.H. Hiramaya, published an equivalent theory already in 1934. Our following collection, which deals mainly with induction processes, starts in 1967, but we will not present it in chronological order, but grouped thematically into data-related, computational and applied aspects of electromagnetic research.

Data play a paramount role in electromagnetic geophysics, as it serves as the basis for deciphering the Earth's subsurface properties and geological structures. Precise and extensive data collection through electromagnetic surveys and observatories has been technically and operationally challenging. Advances are made until this day. Against this background, Ulrich Schmucker and Roger Banks complemented and influenced each other on the subject of the electrical conductivity of the mantle. In the 1960s and 1970s, it was difficult or technically impossible to measure the electric fields with the stability required for a classical magnetotelluric approach. Even suitable recordings at observatories were rare, but could be used under certain assumptions to derive first 1D models of the Earth's mantle. Interestingly, the publication by **Banks (1969)** is still relevant, as can be seen from the citations, which are not only limited to geophysics or geosciences, but also come from the fields of engineering, mathematics, chemistry, and astrophysics. Based on measurements of magnetic variations, he derived a consistent relation of the electrical conductivity distribution with temperature and pressure for mantle mineralogy phase transitions at a depth of 400 km.

In a two-part paper (**Schmucker, 1999a, b**) on both methods and results, Ulrich Schmucker contributed to global induction studies, which aimed at revealing the conductivity structure of the deep Earth. To reach several hundreds of kilometres deep, very low frequency fields have to be analysed. Therefore, Schmucker investigated the solar daily variations during two years. His findings enhanced and validated those obtained through other approaches, contributing to a more comprehensive grasp of the global induction process. This understanding is crucial for unravelling Earth's deep conductivity structure. Furthermore, it also shows how closely research in the field of electromagnetic deep sounding is interwoven with the magnetic observatories, and how this potential can be well utilised in a joint effort.

An inherent challenge when working with magnetotelluric data is the derived complex 2 x 2 impedance tensor, representing the ratio of the magnetic and electric field variations. It carries the information about the spatial conductivity distribution in the subsurface. The tensor elements themselves are physically unimaginable. Therefore, they are represented in terms of magnitude (apparent resistance) and phase. Thus, they lose their tensor properties and important information such as dimensionality, directionality or even the influence of galvanic distortion remain hidden. **Weaver et al. (2000)** have derived other physical/mathematical quantities to better understand and graphically represent the properties of the tensor, supporting the analysis and interpretation of MT data. These ideas inspire even nowadays MT practitioners and theoreticians to derive new quantities and new, intuitive images of MT data.

A little later, **Caldwell et al. (2004)** published a very smart idea. The impedance tensor might be distorted by near surface heterogeneities, which can be mathematically described by a real 2 x 2 distortion tensor causing a static shift that is expressed by a parallel shift of apparent resistivity values. However, the phases, as a quotient of imaginary and real parts of the impedance tensor elements, are free of this distortion. Since the convenient and important tensor properties get lost, when calculating apparent resistivities and phases, the authors thought about a phase tensor. This idea was something like a revolution in dimensionality and directionality analysis, as the phase tensor together with its properties can be displayed graphically. It has developed to the state of the art approach, and the majority of papers with MT data uses this transformation to understand the physical background of the acquired data. Even in inversions, the phase tensor data is used to circumvent the described challenges and to obtain more robust and reliable models.

The availability of suitable numerical methods, such as simulation and inversion techniques, is and has been essential throughout the course of the development of electromagnetics. Without them the interpretation of measured electromagnetic data sets is very limited if not impossible. Simulation methods enable us to predict the behaviour of electromagnetic fields as they propagate through the Earth's subsurface. They also help mimicking realistic geophysical surveys, while inversion methods iteratively refine subsurface models by comparing observed data with simulated responses, effectively unravelling the electrical conductivity distribution of the Earth.

Finite differences was the first numerical technique that allowed for simulation of electromagnetic fields in variable geometry, which is approximated thereby by box-shaped structural elements. A significant contribution on the way to 3D electromagnetic modelling by means of finite differences was the work by **Brewitt-Taylor and Weaver (1976)**. They provided adapted formulations of 2D induction problems and developed the finite difference equations including already the possibility of an extension to 3D. The paper is considered a fundamental work in the evolution of 3D modelling techniques, shaping the state-of-the-art methods used today in geophysics and electromagnetic studies. Finite difference techniques are and have been widely used and also have been successfully transferred to non-inductive EM processes. An insightful example is the work by **Weller et al. (1996)** on the galvanic induced polarisation method. Thereby, an extended concept of the nature of electrical conductivity comes into focus. Owing to polarisation effects, conductivity is considered to be a complex-valued physical property even in the absence of inductive effects.

A different mathematical approach to solve electromagnetic field problems is the integral equation approach. It involves converting the differential equations governing electromagnetic phenomena into integral equations, which are then solved numerically. The foundation was established by **Weidelt (1975)** with his paper on electromagnetic induction in three-dimensional structures. Seminal for many in the EM community, this very important manuscript describes the basis for many numerical and modelling developments including source description. This paper was preceded by works of Gerald W. Hohmann, who introduced a theoretical solution in the form of an integral equation for the EM response of a two-dimensional inhomogeneity in the field of a line source of current. **Newman et al. (1987)** applied integral equation techniques for 3D modelling of transient electromagnetic fields. The active transient electromagnetic method (TEM) bears particular challenges posed by the high dynamic range of the time domain data. In this context, the authors focused on classic central-loop experiments and examine the errors that arise when interpreting measurements over 3D structures as if they were 1D layered half spaces. The study sheds light on critical considerations in data interpretation and is therefore relevant to all electromagnetic methods.

The increased flexibility and efficiency in handling complex geometries and advantageous mathematical properties of the numerical solution lead to the introduction of the finite element technique used by many codes today. Phil Wannamaker, who sadly passed away too early and unexpectedly last year, reported on the successful application of the finite element technique in 2D magnetotelluric modelling. **Wannamaker et al. (1987)** employed a secondary field approach and notably attained stable solutions even at low frequencies. Their work was an important step in the advancement and establishing of the finite element method in electromagnetic modelling, which today allows to computationally recreate arbitrary and realistic geometries, a crucial capability for 3D inversion.

The forward simulation methods are key components for any inversion, which is essential to recover electrical conductivity distributions from electromagnetic data sets. The paper by **Key & Ovall (2011)** is exemplary for the rapid development of numerical possibilities and approaches with respect to 2D and 3D inversion of magnetotelluric data. Typically, this type of manuscript tends to be published in industry-related or journals with a mathematical or numerical focus. Key's code and the associated publication have enabled countless interpretations of EM data, whether off-shore, as the name suggests and for which this code was primarily developed, or on-shore. This paper also shows that even a rather technical topic can be illustrated in a very comprehensible manner, even for those of the geophysical community who approach numerics and inversion for the first time.

Accompanied by the computational techniques and capabilities of the time, electromagnetic methods have been successfully applied to study the subsurface throughout the decades. Sitespecific insights were thereby often accompanied by methodological developments or the study of generalisable aspects of data acquisition and processing. **Vasseur & Weidelt (1977)** for instance addressed the challenging aspect of distortion, the influence of local conductivity anomalies on magnetotelluric data. They used a thin sheet approach to overcome computational limitations at that time. The method was applied to a northern Pyrenees MT survey, revealing deep conductive materials. This study contributed to the ongoing discussion on deep conductors in magnetotelluric research.

An alternative approach to circumvent measuring the electric field variations that might be subject to distortion is presented in **Schmucker et al. (2009)**, published even after Ulrich Schmucker passed away in October 2008 during the 19th 'Workshop on Electromagnetic Induction in the Earth' in Beijing. The manuscript was much advanced so that his co-authors with the help of some of his former students finished it in 2009. Besides spatial gradients, the authors introduced the vertical gradient method as a promising approach, for which the horizontal magnetic field is simultaneously measured in a borehole and at a surface reference station. Based on Maxwell's equations, the vertical magnetic field gradient can replace the electric field under certain assumptions regarding the intervening conductivity.

The *GJI* papers presented in this selection represent a very personal view and do not claim to cover the most important contributions in the field of EM. Many excellent papers were published in other journals. However, the MT-related publications in *GJI* constitute strong contributions and progress over time in terms of theoretical and numerical tackling of electromagnetic processes and techniques, data acquisition and application. Advancements in instrumentation and computational tools have further refined electromagnetic methods, making them indispensable tools for geophysicists and contributing significantly to our knowledge of the Earth's subsurface.

Jana H. Börner and **Ute Weckmann,** *GJI* Editors

Geomagnetic Variations and the Electrical Conductivity of the Upper Mantle
R. J. Banks
Geophysical Journal International, Volume 17, Issue 5, July 1969, Pages 457-487,
https://doi.org/10.1111/j.1365-246X.1969.tb00252.x

A spherical harmonic analysis of solar daily variations in the years 1964-1965: response estimates and source fields for global induction-I. Methods
Ulrich Schmucker
Geophysical Journal International, Volume 136, Issue 2, February 1999, Pages 439-454,
https://doi.org/10.1046/j.1365-246X.1999.00742.x

A spherical harmonic analysis of solar daily variations in the years 1964-1965: response estimates and source fields for global induction-II. Results
Ulrich Schmucker
Geophysical Journal International, Volume 136, Issue 2, February 1999, Pages 455-476,
https://doi.org/10.1046/j.1365-246X.1999.00743.x

Characterization of the magnetotelluric tensor in terms of its invariants
J. T. Weaver, A. K. Agarwal, F. E. M. Lilley
Geophysical Journal International, Volume 141, Issue 2, May 2000, Pages 321-336,
https://doi.org/10.1046/j.1365-246x.2000.00089.x

The magnetotelluric phase tensor
T. Grant Caldwell, Hugh M. Bibby, Colin Brown
Geophysical Journal International, Volume 158, Issue 2, August 2004, Pages 457-469,
https://doi.org/10.1111/j.1365-246X.2004.02281.x

On the finite difference solution of two-dimensional induction problems
C. R. Brewitt-Taylor, J. T. Weaver
Geophysical Journal International, Volume 47, Issue 2, November 1976, Pages 375–396,
https://doi.org/10.1111/j.1365-246X.1976.tb01280.x

Induced-polarization modelling using complex electrical conductivities
A. Weller, M. Seichter, A. Kampke
Geophysical Journal International, Volume 127, Issue 2, November 1996, Pages 387-398,
https://doi.org/10.1111/j.1365-246X.1996.tb04728.x

Electromagnetic induction in three dimensional structures
P. Weidelt
Journal of Geophysics (Zeitschrift für Geophysik), Issue 41, 1975, Pages 85-109.
http://www.mtnet.info/papers/PeterWeidelt/Weidelt_1975_JGeophys.pdf

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Gregory A. Newman, Walter L. Anderson, Gerald W. Hohmann
Geophysical Journal International, Volume 89, Issue 3, June 1987, Pages 889-914,
https://doi.org/10.1111/j.1365-246X.1987.tb05200.x

A stable finite element solution for two-dimensional magnetotelluric modelling
Philip E. Wannamaker, John A. Stodt, Luis Rijo
Geophysical Journal International, Volume 88, Issue 1, January 1987, Pages 277-296,
https://doi.org/10.1111/j.1365-246X.1987.tb01380.x

A parallel goal-oriented adaptive finite element method for 2.5-D electromagnetic modelling
Kerry Key and Jeffrey Ovall
Geophysical Journal International, Volume 186, Issue 1, July 2011, Pages 137-154,
https://doi.org/10.1111/j.1365-246X.2011.05025.x

Bimodal electromagnetic induction in non-uniform thin sheets with an application to the northern Pyrenean induction anomaly
G. Vasseur and P. Weidelt
Geophysical Journal International, Volume 51, Issue 3, December 1977, Pages 669-690,
https://doi.org/10.1111/j.1365-246X.1977.tb04213.x

An electromagnetic sounding experiment in Germany using the vertical gradient of geomagnetic variations observed in a deep borehole
Ulrich Schmucker, Klaus Spitzer, Erich Steveling
Geophysical Journal International, Volume 178, Issue 3, September 2009, Pages 1273-1288,
https://doi.org/10.1111/j.1365-246X.2009.04199.x

Earthquake Source Theory and Observations

In the next set of our centennial collection of papers in *Geophysical Journal International,* we focus on advances on earthquake source research. We have selected nine papers from 1976 to 2002 encompassing theoretical, numerical and observational advances, as well as breakthrough applications in active tectonics and seismic hazard studies.

The first paper, by **Backus and Mulcahy (1976)**, theoretically clarified the relation between different aspects of seismic source representations. They derived that the source descriptions by equivalent forces, the stress-free strain, and the stress glut are equivalent to that by a moment tensor density. This contribution marked a step change in earthquake source studies by enabling sources to be represented in a simple and elegant way by moment tensor densities, which greatly accelerated progress in the field. Further key developments on earthquake source theory include work by **Kagan (1991)** who introduced a minimum rotation angle between a pair of double-couple earthquake sources. This angle is a unique measure of the differences between two double couple focal mechanisms and has been applied to various kinds of research such as the qualification of focal mechanism catalogues as well as the application of stress tensor analysis. Another important contribution was by **Zhu & Rivera (2002)**, who showed the equivalence of the solutions between dynamic and static displacements caused by a point source in layered media. This feature had not been rigorously proved due to the existence of a singularity in stress at zero frequency. Through their contribution, geodetic and seismic analyses were unified to obtain a global picture of the earthquake source phenomena.

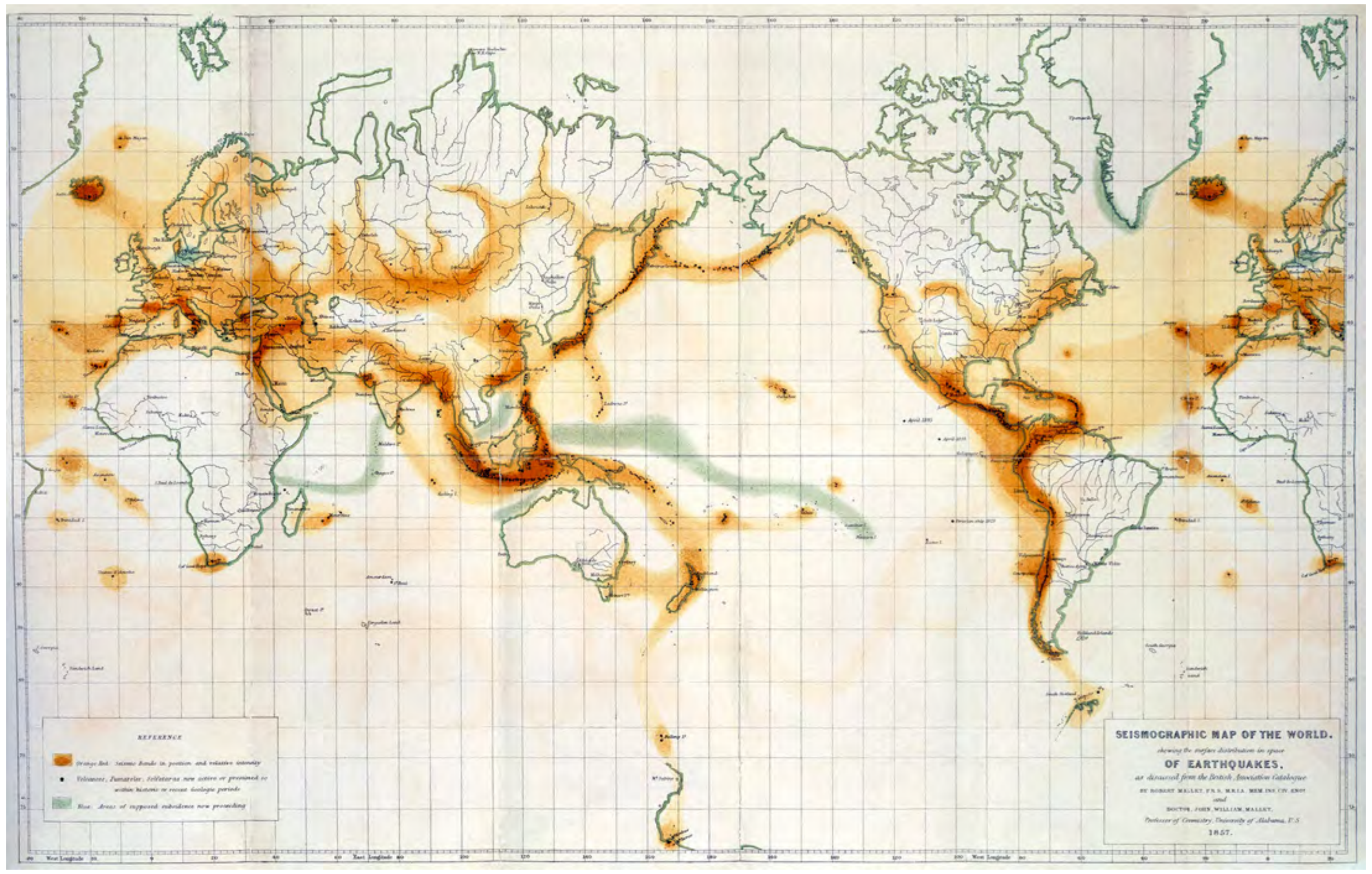
Developments in earthquake source theory paved the way for the systematic application of earthquake source analysis to active tectonics studies, leading to highly influential results. For instance, moment tensor analysis and its interpretation in terms of motion across zones of distributed deformation proved a powerful tool to quantify the style of crustal deformation worldwide. **Jackson & McKenzie (1988)** used such analyses to suggest that in the Zagros, Caucasus, Hellenic Trench and western Mediterranean only 10% or less of the upper-crust deformation is seismic, while in NE Iran, the North Anatolian Fault Zone and the Aegean Sea all or most of the deformation is perhaps taken up seismically. On the other hand, **Molnar & Lyon-Caen (1989)** used fault plane solutions from over 70 earthquakes within and on the edges of the Tibetan plateau to highlight a fascinating variety of deformation. While thrust faulting and crustal shortening was found perpendicular to the margins of the plateau, within the plateau strike-slip and normal faulting was observed to lead to east-west crustal extension. The main figure presented in their paper is now a classical picture used in classrooms, introductions of scientific presentations, outreach events, etc illustrating the links between beachball focal mechanisms and tectonic processes. With the advent of space geodesy (e.g., GPS, InSAR) in the 1990s many of these studies were revisited and refined, but nonetheless earthquake source analysis and notably moment tensor studies remain a crucial tool for active tectonics and earthquake geology studies.

Along with space geodesy, earthquake stress transfer calculations advanced substantially in the 1990s. These calculations require accurate earthquake source models (e.g., fault plane solutions) and led to significant breakthroughs on our understanding of earthquake triggering. In a seminal study, **Stein et al. (1997)** calculated Coulomb stress changes for 10 moderate-large magnitude earthquakes that ruptured along ~1,000 km of the North Anatolian fault (Turkey). They found that nine out of 10 ruptures were brought closer to failure by the previous earthquakes and estimated stress-based earthquake probabilities for the region. This new approach has strongly influenced many subsequent earthquake hazard studies, notably for aftershock hazard assessment.

On the fundamental science front, the 1970s saw exciting new developments in earthquake source physics, notably new numerical approaches in dynamic rupture models of earthquakes. These could reproduce spontaneous rupture propagation of shear cracks under specific stress and friction conditions. **Das and Aki (1977)** implemented a boundary element method to compute spontaneous slip development in two-dimensional infinite elastic medium without assuming the temporal evolution of slip on the fault. This was achieved by introducing a critical stress-jump fracture criterion which was easy to implement numerically; the method implemented is applicable to all three modes of 2-D crack extension: tensile crack, in-plane and anti-plane shear cracks. In the same year, **Madariaga (1977)** investigated the high-frequency radiation from the source based on spontaneously propagating crack models. He showed that abrupt changes in crack tip velocity strongly contribute to the production of high-frequency seismic waves. He explained that this high frequency fall-off comes from the change in rupture velocity, which is an intrinsic feature of the omega-squared (ω^{-2}) source spectral model that is commonly used at present. These developments were particularly important for seismic engineering purposes where high-frequency radiation from earthquakes is a major concern.

When discussing earthquake source research, one cannot shun the topic of earthquake prediction, an everlasting yet controversial one. In his critical review, **Geller (1997)** summarised a wide range of failed efforts over 120 years to find precursors to large earthquakes, including case studies from various countries and non-conventional methods. He elucidated this issue by designing strict criteria for successful predictions in terms of earthquake spatial and temporal location, and magnitude. From his evaluation using such strict criteria, he suggested that earthquakes may be inherently unpredictable due to highly sensitive non-linear dependence on the initial rupture conditions. It remains to be seen if new methodological and observational approaches (e.g., from geodesy, background ambient noise analyses, …) might change this picture.

Ana Ferreira and **Eiichi Fukuyama**, *GJI* Editors



Seismographic world map. This map, centred on the Pacific and produced in 1857, shows the world's earthquake zones (orange). Areas of subsidence are blue, and volcanoes are marked as black dots. **Photo credit: Royal Astronomical Society/Science Photo Library.**

Moment Tensors and other Phenomenological Descriptions of Seismic Sources-I. Continuous Displacements
George Backus and Marjorie Mulcahy
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Lupei Zhu and Luis A. Rivera
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Geophysical Journal International, Volume 128, Issue 3, March 1997, Pages 594-604,
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Raul Madariaga
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Robert J. Geller
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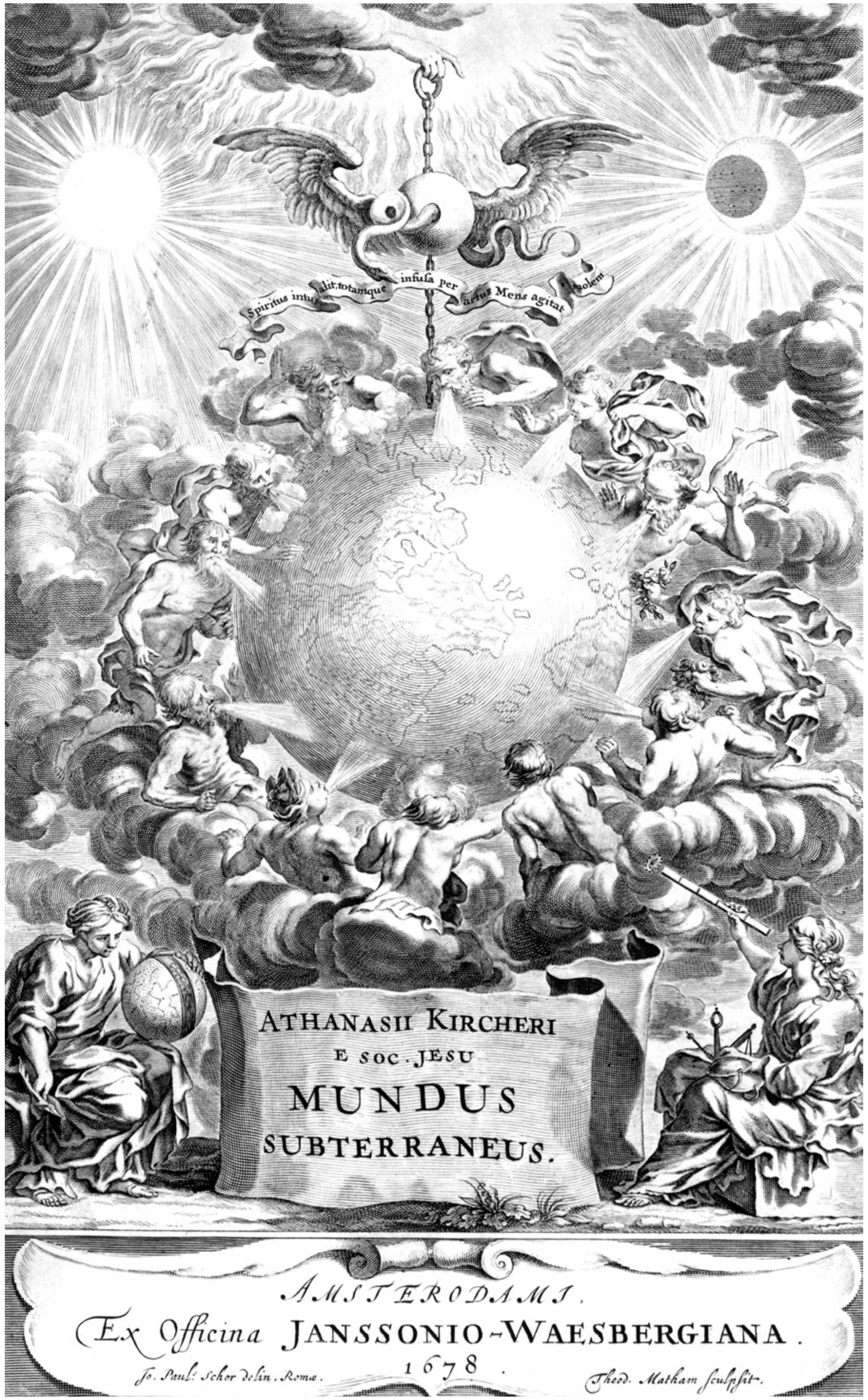

Kircher's book on geology. Title page of the 1678 treatise on geology *Mundus Subterraneus (Subterranean World)* by the German Jesuit scholar Athanasius Kircher (circa 1601-1680). **Photo credit: Royal Astronomical Society/ Science Photo Library.**

Inversion, Inverse Methods, and Inverse Theory

Solid-Earth geophysicists are often limited, in comparison to scientists in other fields, by not having the luxury of being able to design experiments that allow a parameter of interest to be isolated and measured. Like astronomy, our field is largely the study of unique (and often temporally-bounded) phenomena and objects, by monitoring. We have only one Earth; we are confined to its surface; and we cannot control — or, often, even predict— when or where our phenomena of interest will occur. We can only observe — and often, observe only the indirect effects of what we are trying to understand. Consequently, we find ourselves relying on the mathematical tools of inference and inversion to extract useful information from whatever data are available. Our field has many significant papers discussing the "inverse problem": both the challenge of finding models that fit the data (inverse methods); and the even harder problem of working out, given that many models may fit the data, what features of such models can and cannot be determined. A number of these have appeared in *GJI* — indeed, the very first paper published in the *Geophysical Supplement* concerned the inverse problem of determining earthquake locations from teleseismic data (**Turner, 1922**).

To find out what the observable effects of a particular model will be, we must first solve the "forward problem". Many inverse methods require us to solve the forward problem for a large number of models, so efficient solutions of any forward problem are valuable. Our first paper, **Parker (1973)**, is of this type, showing how to use Fourier methods to rapidly calculate the gravitational or magnetic field above an irregularly-shaped body. The rapidity came from the then-recent development of the Fast Fourier Transform, with the author pointing out that by using a sum of Fourier transforms of the topography "geophysicists could take advantage of the remarkable speed of this algorithm", reducing the computation time from over a minute to less than a second, for a model with 128 points.

Parker's 1973 paper also contains the remark that some other methods create "the illusion of uniqueness in the solutions". This comment is, unsurprisingly, in keeping with the spirit of the next paper, **Backus and Gilbert (1968)**: unsurprising because these two authors were in offices adjacent to Parker's. Our featured paper is the middle one of a trilogy that between them set out the basis of a very general treatment of inverse problems, where the model was described by a vector, not of parameters, but of functions that form an infinite-dimensional vector space: observations limit models to a portion of this space (still infinite-dimensional). The key concept of this paper is averaging kernels: these describe how, for a specific observation, the value of the function at a point depends on a weighted average of the actual function. These kernels are illustrated for the determination of the quality factor Q and density from normal-mode data, the appropriate use of which was of major interest at the time. The authors conclude the paper by saying that, with properly chosen data, "the conclusions are not only rigorous but geophysically interesting".

Jackson's 1972 paper was clearly stimulated by the work of Backus and Gilbert, but dealt with the much simpler, and to most geophysicists more familiar, situation in which the model was a set of parameters, which allowed the whole problem of inversion using "inaccurate, insufficient, and inconsistent" (that is, typical) data to be treated using linear algebra. Using a variety of matrix decompositions (notably the Singular Value Decomposition, though not named as such) the paper showed how to extend the standard least-squares methods to stabilize unstable inversions, form (discrete) averaging kernels, and examine the marginal utility of particular data. The work by Backus and Gilbert furthermore constituted a "benchmark" for subsequent works, i.e., authors of new formulations of inversion strategies felt the need to demonstrate the relation to (if not the inclusion as special cases of) the early formulations in theirs. **Tarantola & Nercessian (1984)** demonstrated, using the travel-time problem of seismic waves (see also Bozdag's and Weemstra's contribution to this series) that an integral formulation can avoid the necessity of separating the Earth's interior into blocks. The subdivision of real space for inversion, as crucial as it is for constraining "resolution", may systematically bias results.

If the assumption that the data-model relationship is linear, or at least that it can be approximated as such is not warranted, two challenges arise. First, one can no longer rely on the gradient of this relationship as a signpost towards a good model; second, there may be multiple, disjoint regions of model space that provide equally-plausible explanations for the observed data. These solution-landscape issues motivate the use of Monte Carlo methods: techniques based on testing many randomly-generated models — either in search of a single best-fitting solution, or with the aim of generating a statistically-representative 'ensemble' of possibilities.

Monte Carlo methods were introduced into geophysics by researchers working in the USSR — reported beyond the 'Iron Curtain' by **Keilis-Borok & Yanovskaja (1967)** — and employed by Press (1968) and **Anderssen et al (1970)** to produce models of Earth's structure. However, these early studies lacked any mechanism to target sampling towards promising regions of space, making the process computationally uneconomical. A major step forward came with the introduction of genetic algorithms by **Sen & Stoffa (1992)** and others, enabling samplers that adapt and evolve. A similar idea underpins the Neighbourhood Algorithm, developed by **Sambridge (1999a,b)**: if a sampler constructs a map as it explores, it can be used both as a guide, and as the basis for further calculations.

In particular, the Neighbourhood Algorithm can be used to accelerate Markov chain Monte Carlo (McMC) inversion, where the goal is to generate a set of models that are distributed according to the (Bayesian) posterior probability. The McMC techniques have been widely applied across geophysics, such as early applications to magnetotelluric (**Grandis et al., 1999**) and resistivity (**Schott et al. 1999**) imaging. More recently, attention has focussed particularly on trans-dimensional McMC, introduced into geophysics by **Sambridge et al. (2006)**, which avoids the need to impose a fixed parameterisation on models, alleviating another potentially-significant source of systematic error in results.

The last few years have seen massive growth in the fields of machine learning (ML) and artificial intelligence, and this development has been reflected in the work published in *GJI*. One attractive application of machine learning is as a route to solve inverse problems: given that we can readily simulate observations for a wide range of possible models, perhaps we can just train an ML system to 'go the other way'? In fact, this idea was proposed by **Raiche (1991)**, and demonstrated by Röth & Tarantola (1994) — but could not be fully exploited without recent advances in computational capacity. The work of **Dai & MacBeth (1995)** also deserves mention here, it illustrated how neural networks could automate data processing and selection tasks that were previously manual. This use of ML vastly expands the scale at which inversion can be deployed, and has improved the quality of life for countless graduate students.

As *GJI* moves into its second century, inverse theory will continue to feature heavily in our pages. The field of machine learning has also given us novel tools for representing and manipulating probability distributions, including variational methods and generative models, creating opportunities to combine the expressive power of ensemble methods with the efficiency of optimisation. Another avenue for potential development lies in the use of techniques such as surrogate modelling or reduced order methods for forward modelling, offering substantial computational speedups and enabling inversion at a scale that has previously been infeasible. And— as **Curtis (1999)** pointed out — even though we can't get inside the Earth, we can still optimise our experiments and surveys to ensure we get the best results possible.

Andrew Valentine, *GJI* Editor,
Duncan Agnew, *GJI* Deputy Editor-in-Chief,
and **Joerg Renner**, *GJI* Editor -in-Chief

On the Arrival of Earthquake Waves at the Antipodes, and on the Measurement of the Focal Depth of an Earthquake
H. H. Turner, D.Sc., F.R.S.
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Gunter Röth and Albert Tarantola
Journal of Geophysical Research, Volume 99, Issue B4, April 1994, Pages 6753-6768,
https://doi.org/10.1029/93JB01563

Peripheral Realms and a Backwards Look at Beginnings

Our next group of papers might be called "other kinds of waves", meaning, not waves in the solid Earth, though related to it. The two types we consider are low-frequency atmospheric waves (infrasound) and tsunami, neither of which has a set of journals clearly defined as appropriate. So *GJI* has tried to be open to these, though requiring, usually, some tie to the solid Earth. Infrasound from meteors (Belli et al 2021) is an especially borderline case, but *GJI* is, after all, published by an astronomical society.

Our first paper, by **Kanamori and Rivera (2008)**, is about a seismic wave, the W phase, but we include it here because of its relevance to tsunami studies. The W phase is a gradual displacement that starts with the P wave and grows until the arrival of the S wave, related to resurfacing body waves. While it could have been recognized on synthetic seismograms, it was not; the first recognition came with the combination of broadband seismic recordings and an earthquake (Nicaragua 1992) that had an unusually small amount of high-frequency energy, making the W phase visible even when plotted along with the later surface waves (Kanamori and Kikuchi 1993). The name "W phase" was adopted by Kanamori (1993) partly because of an analogy with the normal-mode interpretation of whispering-gallery effects, and because the ray path of PP, with two mantle legs enclosing a reflection from the Earth's surface, is shaped like a W (H. Kanamori, pers. commun.). The 2004 Sumatra-Andaman earthquake highlighted that existing procedures could not reliably determine the magnitudes of the largest earthquakes soon enough to be useful for tsunami warning. The 2008 paper solved this problem by estimating magnitude from the W phase after applying a causal lowpass filter; because the phase arrives before the largest motions, clipping of these has no effect, and because the W phase energy is largely in the upper mantle, it shows little of the spatial variability produced by crustal structure. The procedure was rapidly adopted by operational agencies, and proved its value in the response to the 2011 Tohoku earthquake.

The second and third papers, from the same volume of *GJI*, are both about wave interactions between the ocean and atmosphere, but in two different directions. The 1883 eruption of Krakatoa caused a tsunami that was catastrophic locally and observed globally. Since for the global observations the waves arrived sooner than expected given the velocities for water waves and the length of the ocean paths (some very circuitous), it was assumed that these waves were caused by another eruption somewhere else. Starting in 1950 Press and Ewing argued that the waves were caused by the global air-pressure pulse from the eruption. **Harkrider and Press (1967)** is one of several attempts by Press and others to show how this might happen. Increasing computer power made it possible to find the modes of a combined global ocean and atmosphere and to use these to compute synthetic tide-gauge records, which show a weak response to the air wave and a large variation at the time of the fundamental-mode water wave. The latter is explained as a resonant reaction to air-pressure changes too small to be observed. When published, and for the next 55 years, this paper could be viewed as a speculative explanation of a one-time oddity. This view changed in January 2022, when the Hunga (Tonga) eruption produced both a global air wave and similarly early tsunami arrivals. The connection between these is still being studied, but it seems likely that it depends much more on local circumstances than a global effect.

The first two papers are interesting illustrations of how, in an observational science, advances depend on events that bring something not thought of to the attention of geophysicists: observations precede improved theory or new ideas. Our third paper, by **Posmentier (1967)** is somewhat similar, in explaining a phenomenon, though in this case one observed for many years before: ongoing fluctuations of atmospheric pressure with periods of about six seconds, and called, by analogy with seismic microseisms, microbaroms. As with microseisms, the tie to ocean waves seemed clear, though the generation mechanism was not. The contribution of this paper was to point out that the same mechanism applied to the generation of both, namely that for standing waves there was a pressure fluctuation associated with the oscillation of the center of mass of the water (or the air) at twice the wave period. Such standing waves occur in the ocean whenever two wave trains are travelling in opposite directions, and a major part of this paper is devoted to showing that plausible models for ocean waves will produce the microbaroms of the amplitude observed. *GJI* has remained hospitable to papers on this subject, notably that of **De Carlo et al (2020)**, which introduces a much fuller model.

The "other kinds of waves" bundle concludes our journey through 100 years of publishing geophysical research by the Royal Astronomical Society and the German Geophysical Society, starting 1923 and 1924, respectively, and joining forces ultimately leading to continuous operation of the *Geophysical Journal International* since 1989. Geophysics is very much an observing discipline implicating exceptional responsibility regarding open science, long acknowledged and practiced by cataloging events in seismology and increasingly by exploiting the advent of open data repositories in other subdisciplines. An implication of "simply" observing and recording natural phenomena is the journal's lived mandate to look well beyond publication metrics when processing submissions. Our journal was and continues to be the place for research results in niches and off-mainstream of solid-Earth geophysics. A look at how it all started (the table of contents of the first *Geophysical Supplement* and the first *Zeitschrift für Geophysik* provided to the curious reader on the following pages), however, also evidences amazing continuity in the hunt for answers on how Earth works, including the development of theoretical tools and instruments.

Joerg Renner, *GJI* Editor -in-Chief
and **Duncan Agnew,** *GJI* Deputy Editor-in-Chief

Detection and source parametrization of small-energy fireball events in Western Alps with ground-based infrasonic arrays
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The Krakatoa Air-Sea Waves: An Example of Pulse Propagation in Coupled Systems
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The 1992 Nicaragua earthquake: a slow tsunami earthquake associated with subducted sediments
Hiroo Kanamori, Masayuki Kikuchi
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W phase
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Turner, H. H.
On the Arrival of Earthquake Waves at the Antipodes, and on the Measurement of the Focal Depth of an Earthquake.

Wrinch, Dorothy, Jeffreys, Harold
On the Seismic Waves from the Oppau Explosion of 1921 Sept. 21.

Jeffreys, Harold
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On Maxwell Hall's suggested Periodicities in Jamaica Earthquakes.

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Reception of Wireless Time-Signals at the Adelaide Observatory.

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Schmidt, Adolf
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Angenheister, G.
Appendix. Sound observations in Göttingen during the explosions in Jüterbog on July 24, 1924

Siebert, August
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Tammann, G.
Bemerkungen zur Geochemie / Comments to geochemistry

Meissner, O
Ermittlung der Tiefe von schwerestörenden Massen mittels Drehwaage / Determination oft he depth of gravity-disturbing masses using a torsion balance

Amsel, E. A.
Die Alpen im Lichte ihrer Schwerestörungen / The Alps in the light of their gravity anomalies

Prandtl, L., Tollmien, W.
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Linke, F.
Die Verwertung von Sonnenstrahlungsmessungen in Luftfahrzeugen / The exploitation of solar radiation measurements in aerial vehicles

Schuler, Max
Der Kreisel als Richtungsweiser / The gyroscope for direction determination

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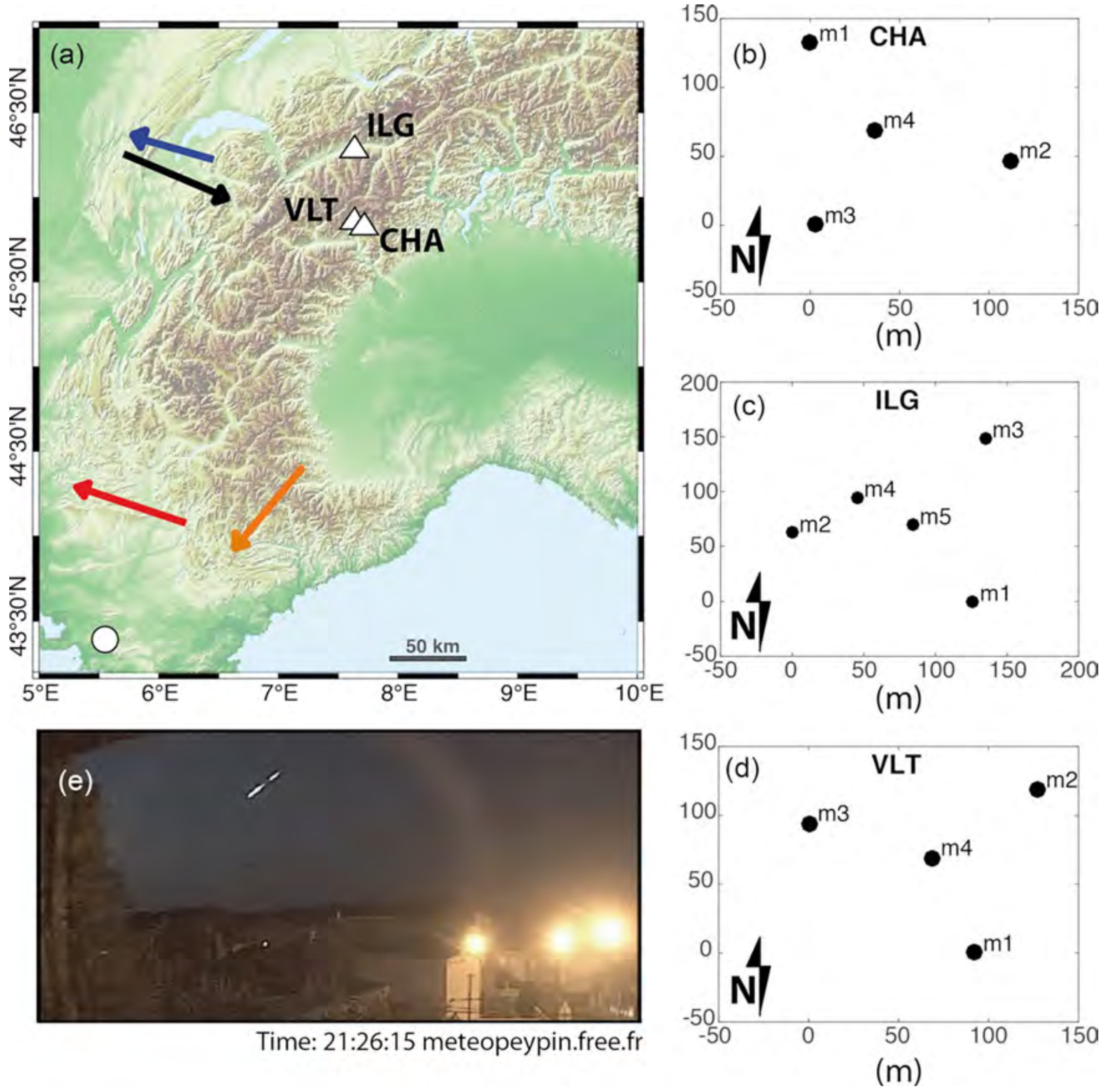
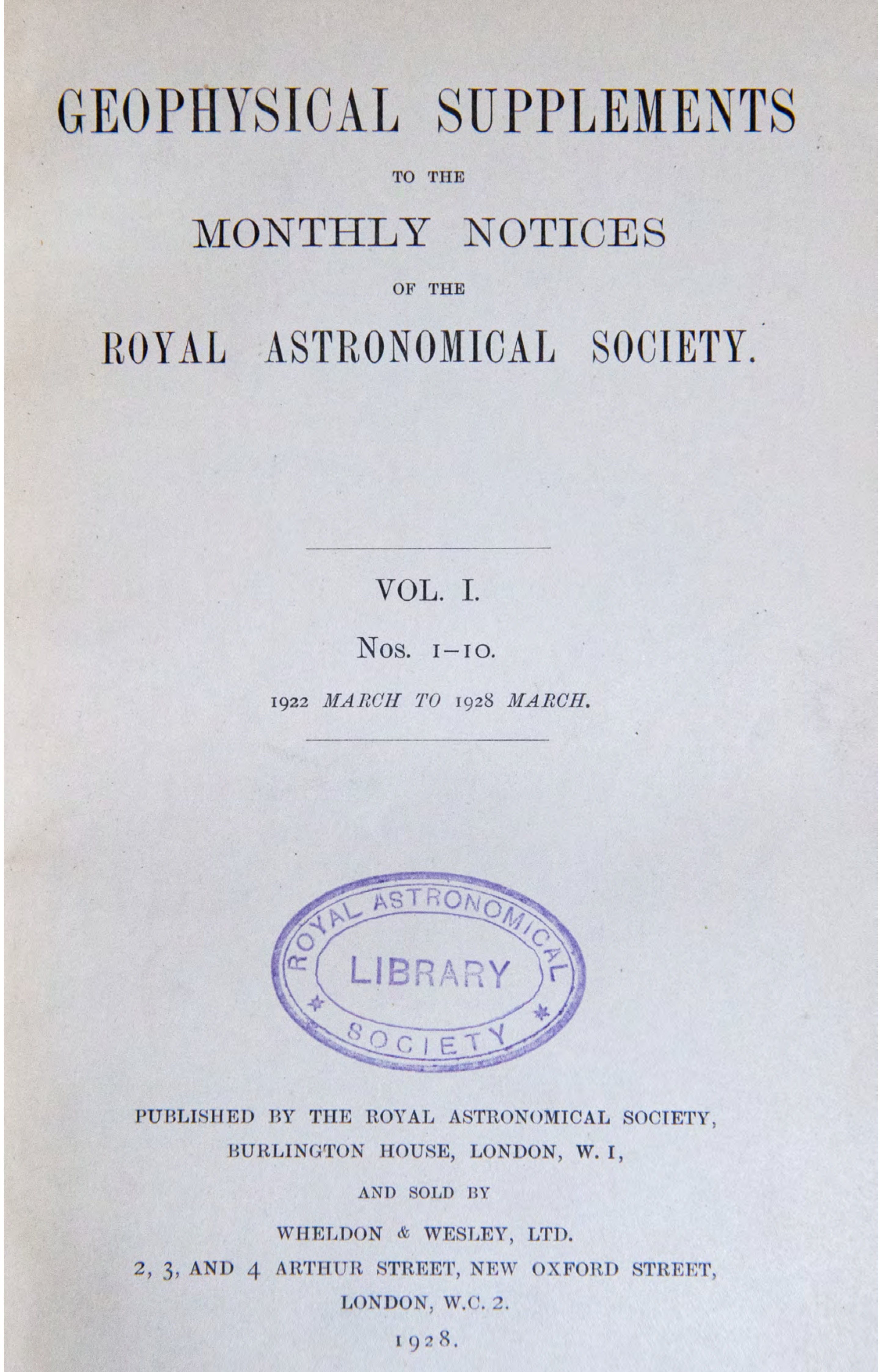


Fig. 1 from Belli et al (2021), showing a map of Western Alps showing the optical trajectories of the four analysed fireball events, reconstructed on http://prisma.imo.net, and the position of the three infrasonic arrays, VLT, CHA and ILG (white triangles). Please see the paper for the full caption (the link is on p 51).



GEOPHYSICAL SUPPLEMENTS
TO THE
MONTHLY NOTICES
OF THE
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Eruption of Krakatoa. Lithograph from a photograph, taken 27 May 1883, of Krakatoa, a volcanic island in the Sunda Strait between the Indonesian islands of Sumatra and Java. **Photo credit: Royal Astronomical Society/Science Photo Library.**

100 Influential Papers from *Geophysical Journal International*

Since 1922, when the first paper in the *Geophysical Supplement to the Monthly Notices of the Royal Astronomical Society* was published, the Royal Astronomical Society has been at the forefront of the promotion of geophysics as well as astronomy. Following a merger with three other publications, *Geophysical Journal International* in its present form has been published since 1989 on behalf of the Royal Astronomical Society and the Deutsche Geophysikalische Gesellschaft (DGG) (The German Geophysical Society).

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