ACADÉMIE
DES SCIENCES
INSTITUT DE FRANCE

Comptes Rendus

Géoscience

Sciences de la Planète

Michel Faure, Olivier Fabbri, Jacky Ferrière, Laurent Jolivet and Sylvie Leroy

Avant-propos

Published online: 14 May 2024

Part of Special Issue: Geodynamics of Continents and Oceans – A tribute to Jean Aubouin
Guest editors: Olivier Fabbri (Université de Franche-Comté, UMR CNRS 6249, Besançon), Michel Faure (Université d'Orléans-BRGM, UMR CNRS 7325, Institut des Sciences de la Terre, Orléans), Jacky Ferrière (Université de Lille, faculté des Sciences), Laurent Jolivet (Sorbonne Université, ISTeP, UMR 7193, Paris) and Sylvie Leroy (Sorbonne Université, CNRS-INSU, ISTeP, Paris)

https://doi.org/10.5802/crgeos.260

CENTRE MERSENNE

The Comptes Rendus. Géoscience — Sciences de la Planète *are a member of the Mersenne Center for open scientific publishing*
www.centre-mersenne.org — e-ISSN : 1778-7025

ACADÉMIE DES SCIENCES
INSTITUT DE FRANCE

Comptes Rendus. Géoscience — Sciences de la Planète
Published online: 14 May 2024
https://doi.org/10.5802/crgeos.260

Foreword

Geodynamics of Continents and Oceans – A tribute to Jean Aubouin

Avant-propos

Michel Faure *, Olivier Fabbri, Jacky Ferrière, Laurent Jolivet and Sylvie Leroy

E-mail: michel.faure@univ-orleans.fr

Manuscript received and accepted 15 April 2024.

Témoignage de René Blanchet

Jean Aubouin, 1928–2020
Académie des sciences : élu Correspondant en 1978, Membre en 1981
Président de l'Académie des sciences en 1989 et 1990
Président de l'Institut de France en 1989

Tous les élèves de Jean Aubouin, français et étrangers, trop nombreux pour être nommés ici, sont reconnaissants au comité éditorial des Comptes Rendus Géoscience de l'Académie des Sciences d'avoir promu un numéro thématique « Géodynamique des continents et des océans » en hommage à leur Maître et Professeur.

Un comité scientifique animé par Michel Faure a sollicité les auteurs en accueillant, dans la diversité, des approches nouvelles et stimulantes comme l'aurait souhaité J. Aubouin. L'article introductif de Jacky Ferrière et Michel Faure montre toute la richesse de l'œuvre scientifique de J. Aubouin.

Depuis son élection à l'Académie des sciences en 1978 et jusqu'en 2012, J. Aubouin a manifesté un engagement sans faille pour l'Institution. Provincial très assidu et actif aux séances et aux réunions des comités et commissions, il animait souvent les débats scientifiques par ses interventions claires et rigoureuses d'une grande courtoisie. Président de l'Académie (1989 et 1990), président de l'Institut (1989) il a notamment joué un rôle majeur dans la préparation et la mise en œuvre des nouveaux statuts et du règlement intérieur.

Jean Aubouin a eu le souci constant de l'évolution et de l'impact des Comptes Rendus Géoscience. Il a suivi depuis sa retraite l'installation d'une nouvelle équipe éditoriale, et a pu avec satisfaction, en connaitre les premiers succès. Le fait que ce numéro thématique soit publié dans la revue de l'Académie des Sciences est donc un hommage particulièrement justifié.

Jusqu'à son dernier souffle, Jean Aubouin a eu à cœur de suivre la carrière, et souvent les aléas de la vie, comme les résultats scientifiques nouveaux de ses élèves et, autour d'eux, des jeunes générations, en France et dans le Monde.

Au nom de cette « Ecole » je remercie chaleureusement le comité éditorial et tous les auteurs des publications de ce volume spécial, qui représente un vrai moment de synthèse et de projection, bien utile dans le cours foisonnant des publications scientifiques.

René Blanchet
Professeur émérite, Université Côte d'Azur, Nice
Membre de l'Académie des Sciences

* Corresponding author.

Jean Aubouin entouré de ses élèves lors de la mission du Charcot sur la zone de subduction des Tonga Kermadec en 1985. De gauche à droite : J. Ferrière, R. Louat, J. Aubouin, B. Pelletier, R. Blanchet.

Témoignage de Xavier Le Pichon

Le numéro thématique « Géodynamique des Continents et des Océans » en hommage à Jean Aubouin témoigne de la qualité exceptionnelle des chercheurs qui se réclament de lui. Quant à moi, j'avais lu son livre « Geosynclines » dans les années soixante et j'avais été fasciné par cet essai de synthèse auquel il ne manquait qu'une connaissance des espaces océaniques. Car Jean Aubouin est pour moi l'homme qui visualisait tout paysage tectonique comme un espace organisé avec ses racines.

Je ne l'ai rencontré pour la première fois qu'en 1968. Je venais d'arriver en France et mes présentations de la Tectonique des Plaques, sponsorisées par Jean Coulomb, se heurtaient au scepticisme des principaux géologues. Ce fut le cas pour Jean Aubouin qui me critiqua vivement. Je lui répondis qu'avant de critiquer, il ferait mieux de lire la littérature scientifique récente. Furieux, il se leva et quitta la salle. Mais un mois plus tard, il revint me voir en me disant qu'il avait maintenant lu ces articles et qu'on pouvait discuter. Ce fut le début d'une solide amitié qu'il me manifesta jusqu'à la fin de sa vie.

Une dizaine d'années plus tard, il m'emmena dans une traversée des Hellénides « à la recherche des océans perdus ». Je découvris là son talent pour faire parler les paysages en faisant apparaître ses origines. Cette excursion géologique donna naissance à une publication commune intitulée « Les Hellénides dans l'optique de la tectonique des plaques » [1]. Dès lors, Jean Aubouin comprit que, pour reconstruire ces océans perdus, il fallait étudier la tectonique des océans actuels. C'est ainsi qu'il devint l'élément moteur dans la marche à la mer des géologues. Je me souviens d'une présentation qu'il fit à la Scripps Institution à San Diego. Il se mit à une extrémité du grand tableau et commença à dessiner une très longue coupe tectonique en progressant vers l'autre extrémité, d'un tracé rapide et sûr sans une seule interruption. L'assemblée était bouche bée. Il se fit un grand silence.

Le reste de sa vie, Jean Aubouin n'eut de cesse que de partager avec joie la découverte de ces océans perdus qu'il avait soupçonnés mais ne pouvait décrire.

Xavier Le Pichon
Professeur au Collège de France
Membre de l'Académie des Sciences

[1] Aubouin, J. Le Pichon, X., Winterer, E., Bonneau, M. 1977. Les Hellénides dans l'optique de la tectonique des plaques, *6th Colloquium on the Geology of the Aegean region, Athènes, Proceedings*, Volume III, pages 1333–1354. IGME, Athens, 1979.

Introduction to the thematic volume

At the end of the sixties, the plate tectonics theory provided a new fruitful framework to explain all the geological aspects of the Earth evolution, at least since the Paleo-Proterozoic. This revolution in Earth Sciences was rapidly understood by Jean Aubouin who shifted from the geosyncline model to the new paradigm that was able to account for the sedimentological, petrological, and tectonic features he observed in the Hellenides. J. Aubouin also realized that the understanding of orogens was dependent on the improvement of our knowledge on the geology of the oceanic domains. This "walk to the sea" was one of the guidelines of the tectonic school led by J. Aubouin. Ferrière and Faure [2024] relate the scientific itinerary of this Master who deeply influenced the evolution of Earth Sciences.

During more than half a century, the principles of plate dynamics have been considerably improved. This thematic issue of the Comptes Rendus Géoscience presents some of the major advances in the understanding of tectonic and geodynamic aspects of oceans and continents. Tectonics is an integrative speciality of Earth Sciences that requires the contribution of several methods. Therefore, this Volume introduces also recent methodological progresses in several fields such as analogue and numerical modelling, low- and high-temperature geochronology, petrochronology, and crustal rheology.

Subduction zones are the places where pre-orogenic material is accreted to the upper plate, but in many convergent plate boundaries the ablation (or subductive erosion) is a major phenomenon. The physical causes such as fluid flux or sediment porosity controlling accretion or erosion in the trench are analyzed by Lallemand et al. [2024]. The Alaska-Aleutian subduction zone exhibits trench-parallel extension that accommodates slip partitioning. As shown by Kahrizi et al. [2024], trench oblique- and parallel-faults are often inherited structures that play a significant role in tsunamigenic rupture. The consequences of subduction of buoyant structures are explored by Scalabrino and Lagabrielle [2024] from the example of the Chili ridge. Ridge subduction induces lithospheric thermal erosion leading to crustal extension in the upper plate. This process has also important effects on surface geodynamics, allowing the opening of sea-ways and controlling climate changes. Moving to ancient orogens, the analysis of detrital zircon age distribution in the matrix of ophiolitic mélanges allows Lin et al. [2024] to decipher the source of the sedimentary rocks involved in the closure of the Paleo-Tethys ocean and the building of the Permian-Triassic Indosinian belt of SE Asia.

Extensional tectonics that develop in the upper plate of convergent active continental margins is well documented in the South China Block. The large data base is synthetized by Chu et al. [2024] who show that the formation of domes and basins resulted of two cycles of compression and extension during the Cretaceous.

Since the sixties, the considerable amount of investigations collected in the Hellenides allows Ferrière et al. [2024] to propose a synthetic geodynamic evolution model of this orogen. The model encompasses all the stages of the formation of a mountain belt from continental rifting, oceanic opening, oceanic subduction and obduction, continental collision, and late to post-orogenic extension. The Hellenides provide also an example of tectonic inversion. Chanier et al. [2024] document the reactivation of the Frontal Thrust of the Internal Zones as the Main Pelagonian Detachment. The reactivated Early Cenozoic (Eocene) compressional structures control the development of Oligo-Mio-Pliocene intramontane basins.

Although not fully understood yet, oroclines are major structures widespread in most of orogens. The arcuate shape of the Western Alps is investigated by Brunsmann et al. [2024] who show that bent structures, partly inherited from the Eocene Pyrenean orogeny, already existed before the Alpine collision. The oroclinal bending was enhanced by the Miocene NW-directed indentation of Adria. The Western Alps are also an ideal place to unravel the interplay between climatic and tectonic processes. The formation of the High Verdon Gorge is analyzed by Cardinal et al. [2024]. The timing of incision evidenced by ^{36}Cl dating supports the view that the High Verdon Gorge morphology was controlled by tectonics and isostatic uplift during the Quaternary, around ca 2–1.5 Ma, and is thus related to the Quaternary glaciation, even if a contribution of the Late Miocene, Messinian, salinity crisis cannot be definitely ruled out.

The Alpine and Variscan orogens are emblematic systems of Western Europe. Their geodynamic evolution is compared in the framework of the Wilson cycle by Faure [2024]. The main difference between the Alpine, Variscan and eo-Variscan belts lies in the contrasted geothermal gradients. This feature accounts for the variations in crustal melting, fluid circulation, and ore deposits. Crustal thickening was accommodated by nappe stacking in the lower plate for the Alps and the eo-Variscan belts whereas in the Carboniferous Variscan belt *stricto sensu* nappe stacking involved the upper plate (i.e. Gondwana) continent.

Along-strike segmentation of orogens is partly controlled by inherited pre-orogenic structures. Analogue modelling carried out by Dall'asta et al. [2024] document several types of rift linkage. The results are applied in the external zone of the Westen Alps to account for the formation of the Jurassic passive continental margin and its Cenozoic inversion.

Due to it transient character, continental rifting cannot be easily investigated in natural cases. The mechanisms of continental lithospheric thinning are reviewed by Tugend et al. [2024], using a two-layer numerical model. Extension rates and initial thermal conditions are two of the major conditions accounting for the different modes of rifting. This modelling is applied to the conjugate passive continental margins of Iberia and Newfoundland, and also to the N. part of the S. China sea. In this last case, the wide lithospheric thinning appears to be controlled by the high initial geothermal gradient. Thermomechanical modelling is also developed by Perron et al. [2024] who address the formation of complex real passive continental margins formed through multiphase continental rifting and break-up. The approach that uses a new kinematic calibration module and thermo-mechanical evolution enables the authors to define specific areas where deformation is localized in the continental crust. The method is benchmarked by calibrating a 2D cross-section extracted from a 3D model. The result provides a satisfactory prediction of the thermal history and helps to mitigate some uncertainties in the deformation path compared to the previous approaches. The model is also applied to the magma-poor Iberia-Newfoundland conjugate continental margins. Numerical models are also used by Guillou-Frottier et al. [2024] to reassess the potential of high-temperature geothermal systems. Permeability, topography, fault dip and tectonic regimes are investigated to propose possible targets for geothermal exploitation.

Fluids play a major role in the rheological behavior of the brittle crust. Fabbri et al. [2024] analyze the relationships between fluids, faulting and earthquakes in various geodynamic settings. Several lines of evidence suggest that supra-hydrostatic pore fluid pressures contribute to the reactivation of low-angle thrust faults or normal faults, rather than vertical or steeply-dipping plate boundary transform faults or intra-continental strike-slip faults. Supra-hydrostatically pressurized fluids also play a role in the nucleation and propagation of seismic ruptures in the continental or oceanic crust, and in subducting slabs at convergent plate margins, as reported from aftershocks, swarms, slow earthquakes, and to a lesser extent for major earthquakes. Lastly, variations of pore fluid pressure due to human activities such as hydrocarbon extraction, dam impoundment, gas storage or geothermal energy production result in many cases in the inception of seismic activity.

Dating faulting and folding developed in the brittle upper crust remains a challenge. After reviewing the sedimentological, stratigraphic, and geomorphic tools commonly used to get an estimate of fold formation, Lacombe and Beaudoin [2024] present the recent advances allowed by low-temperature geochronological methods such as K–Ar and U–Pb on illite and calcite, respectively. In spite of their limitations, these new methods are powerful approaches to quantify the duration and rate of deformation developed in fold-and-thrust belts. Among the numerous geochronological methods, the $^{40}Ar/^{39}Ar$ method is one of the most popular. The *in-situ* approach of dating synkinematic minerals is introduced by Monié et al. [2024] The dating of ductile shear zones documents the reworking of mica porphyroclasts involved in polyphase deformation. The dating of authigenic clay minerals in fault gouges is another way to access to the time of faulting. The interpretation of the $^{40}Ar/^{39}Ar$ results must be carefully conducted considering the effects of re- and neocrystallizations, grain inheritance, and mineral-fluid interactions.

Although investigated since decades, the relationships between metamorphism and deformation recognized at all geological observation scales still raise open questions. On the basis of several world-examples of recent and ancient subduction and collision zones, Lardeaux [2024] discusses how metamorphic rocks allow us to access lithospheric- and crustal-scale tectonics. At the rock- and mineral-scale, the contrasted metamorphic textures are related to the heterogenous distribution of finite strain. The interpretation of geochronological dates requires an accurate knowledge of the analyzed rocks from their mineral compositions, including REE profiles, metamorphic textures, up to km-scale tectonic structures. After giving an historical perspective on the progress of isotopic dating methods coupled with the understanding of metamorphic processes at the mineral lattice-scale, Labrousse et al. [2024] show how low-uncertainty dates and *in-situ* approaches represent major advances in deciphering the tectono-metamorphic units stacked in the root zones of orogens. Petrochronology and hygrochronology provide examples of how dates and rates must be combined to reach a more realistic view of orogeny.

The implementation of the most improving tools must not make us forget that to be useful, they have to be tested with natural objects, since following the Master, “les faits valent mieux que l'idée qu'on s'en fait” (facts are better than the idea we have of them). The reliability of the laboratory and modelling results must always be validated by field survey as expressed by “la vérité du terrain” cherished by Jean Aubouin.

The Editors of this Special Issue thank all authors for their relevant contributions. Their patience during the review rounds is also deeply acknowledged. Nothing would have been possible without the involvement of the reviewers who accepted to spend a significant part of their time and provided much effort to improve the quality of the articles of this thematic issue. They are warmly acknowledged.

Michel Faure
CRG Associate Editor
michel.faure@univ-orleans.fr

Olivier Fabbri
Guest Editor
olivier.fabbri@univ-fcomte.fr

Jacky Ferrière
Guest Editor
jacky.ferriere@univ-lille.fr

Laurent Jolivet
Guest Editor
laurent.jolivet@sorbonne-universite.fr

Sylvie Leroy
Guest Editor
sylvie.leroy@sorbonne-universite.fr

References

Brunsmann, Q., Rosenberg, C., and Bellahsen, N. (2024). The Western Alpine arc: a review and new kinematic model. *C. R. Géosci.*, 356. Online first.

Cardinal, T., Petit, C., Rolland, Y., Schwartz, S., Valla, P. G., Scalabrino, B., Audin, L., Bertauts, M., Zerathe, S., Thiéblemont, D., Braucher, D., and Aster Team (2024). The interplay of geology, climate and tectonics on river incision: the example of the High Verdon Gorges, Southwestern French Alps. *C. R. Géosci.*, 356. Online first.

Chanier, F., Ferrière, J., Averbuch, O., Graveleau, F., Caroir, F., Gaullier, V., and Watremez, L. (2024). Extensional reactivation of the Frontal Thrust of the Internal Zones in the Hellenides (Greece): the Main Pelagonian Detachment (MPD) and its contribution to rift basin development. *C. R. Géosci.*, 356. Online first.

Chu, Y., Liu, T., Lin, W., Meng, L., Feng, Z., Wei, W., Ji, W., and Xue, Z. (2024). Lithospheric reworking and thinning by cyclical continental extension: a synthesis of Cretaceous extensional domes in the South China Block. *C. R. Géosci.*, 356. Online first.

Dall'asta, N., Denèle, Y., Regard, V., Frayssignes, A., Hoareau, G., Leroy, S., and Pires, T. (2024). Analogue model of rift linkage and inversion with application to the Western Alps. *C. R. Géosci.*, 356. Online first.

Fabbri, O., Raimbourg, H., and Leclère, H. (2024). Fluids, faulting and earthquakes in the brittle crust: recent advances and new challenges. *C. R. Géosci.*, 356. forthcoming.

Faure, M. (2024). Alpine, Variscan, eo-Variscan belts: comparisons and differences from the French segments. *C. R. Géosci.*, 356, 1–19. Online first.

Ferrière, J. and Faure, M. (2024). Jean AUBOUIN et les chaînes de montagnes: des observations aux synthèses. L'itinéraire scientifique d'un géologue au rayonnement international. *C. R. Géosci.*, 356. Online first.

Ferrière, J., Jolivet, L., and Chanier, F. (2024). From subduction to collision and subduction again, the drivers of crustal-scale deformation in the Hellenides-Aegean region. *C. R. Géosci.*, 356. Online first.

Guillou-Frottier, L., Milesi, G., Roche, V., Duwiquet, H., and Taillefer, A. (2024). Heat flow, thermal anomalies, tectonic regimes and high-temperature geothermal systems in faulted zones. *C. R. Géosci.*, 356. Online first.

Kahrizi, A., Delescluse, M., Chamot-Rooke, N., Pubellier, M., Bécel, A., Shillington, D., Nedimović, M., and Bulois, C. (2024). Extensional forearc structures at the transition from Alaska to Aleutian Subduction Zone: slip partitioning, terranes and large earthquakes. *C. R. Géosci.*, 356. Online first.

Labrousse, L., Bonnet, G., François, C., Godet, A., and Gyomlai, T. (2024). Recent advances in petrochronology: from dates to ages and rates of deep orogenic processes. *C. R. Géosci.*, 356. Online first.

Lacombe, O. and Beaudoin, N. (2024). Timing, sequence, duration and rate of deformation in fold-and-thrust belts: a review of traditional approaches and recent advances from absolute dating of brittle structures. *C. R. Géosci.*, 356. Online first.

Lallemand, S., Peyret, M., Heuret, A., and Arcay, D. (2024). Accretion versus erosion and sediment transfer balance near the subduction interface. *C. R. Géosci.*, 356. Online first.

Lardeaux, J.-M. (2024). Metamorphism and linked deformation in understanding tectonic processes at varied scales. *C. R. Géosci.*, 356. Online first.

Lin, W., Liu, F., Wang, Y., Meng, L., Faure, M., Chu, Y., Nguyen, V. V., Wu, Q., Wei, W., Hoai, L. T. T., and Vu, V. T. (2024). Temporal and spatial heterogeneity of the Ailaoshan-Song Ma-Song Chay ophiolitic mélange, and its significance on the evolution of Paleo-Tethys. *C. R. Géosci.*, 356. Online first.

Monié, P., Münch, P., Milesi, G., Bonno, M., and Iemmolo, A. (2024). ^{40}Ar/^{39}Ar geochronology of crustal deformation. *C. R. Géosci.*, 356. Online first.

Perron, P., Le Pourhiet, L., Jourdon, A., Cornu, T., and Gout, C. (2024). Toward the calibration of 2D thermomechanical simulations of magma-poor passive continental margins. *C. R. Géosci.*, 356. forthcoming.

Scalabrino, B. and Lagabrielle, Y. (2024). Subduction of active spreading ridges and the disappearance of Andean-type cordilleras. *C. R. Géosci.*, 356. Online first.

Tugend, J., Mohn, G., Duretz, T., Petri, B., and Le Pourhiet, L. (2024). Extension of continental lithosphere in rifted margins: a review of thinning mechanisms. *C. R. Géosci.*, 356. forthcoming.