We are IntechOpen, the world's leading publisher of Open Access books Built by scientists, for scientists

6,300

Open access books available

172,000

International authors and editors

190M

Downloads

Our authors are among the

154

Countries delivered to

TOP 1%

most cited scientists

12.2%

Contributors from top 500 universities

WEB OF SCIENCE™

Selection of our books indexed in the Book Citation Index
in Web of Science™ Core Collection (BKCI)

Interested in publishing with us?
Contact book.department@intechopen.com

Numbers displayed above are based on latest data collected.
For more information visit www.intechopen.com

Chapter

A Globally Significant Potential Megascale Geopark: The Eastern Australian Mantle Hotspot Interacting with a North-Migrating Heterogeneous Continental Plate Creating a Variety of Volcano Types, Magmas, Xenoliths, and Xenocrysts

Vic Semeniuk and Margaret Brocx

Abstract

Australia commenced separating from Antarctica some 85 million years ago, finally separating about 33 million years ago, and has been migrating northwards towards the Eurasian plate during that time. In the process, Australia, on its eastern side, progressively passed over a mantle hotspot. A magma plume intersected a variable lithocrust with various lithologic packages such as Phanerozoic sedimentary basins, fold belts and metamorphic terranes, and Precambrian rocks. As such, there was scope for compositional evolution of magmas through melting and assimilation, as well as plucking of host rocks to include xenoliths, and xenocrysts. The volcanic chain, volcanoes, and lava fields that are spread latitudinally along 2000 km of eastern Australia present a globally-significant volcanic system that provides insights into magma and crust interactions, into the variability of xenoliths and xenocrysts, into magma evolution dependent on setting, and into the mantle story of the Earth. The Cosgrove Volcano Chain is an example of this, and stands as a globally-unique potential megascale geopark.

Keywords: Australia, mantle hotspot, volcanic chain, Cosgrove Volcano Chain, heterogeneous continental plate, potential megascale geopark

1. Introduction

Heritage is a legacy from the past. It includes architectural heritage, art heritage, cultural heritage, as well as geological heritage. Geological heritage (or geoheritage) is the legacy of the Earth that has preserved the story, at all scales, of its inception and history

in terms of rock types, major geological structures, history of Life (in fossils), and many other features. In detail, Geoheritage resolves down to the identification, categorisation, and preservation of significant Earth geological features, and is recognised as important globally, as reflected in various international and intra-national bodies set up for conservation, with agreements, conventions, and inter-governmental initiatives [1–4].

To date, however, Geoheritage has mostly focused on medium and large-scale features and cliff faces of significant geology and, in some cases, geological phenomena at the crystal scale [5]. Examples of recognised sites of geoheritage significance include columnar basalt, Isle of Staffa, Scotland [6], chevron folds, Millook Haven, England [7], the Silurian and Devonian unconformity at Siccar Point, Scotland [8], the Cretaceous/Tertiary boundary (K/T contact) at Gubbio, Italy [9], Cambrian fossils, Burgess Shale, Canada [10], the Precambrian Ediacara fauna, Rawnsley Quartzite, South Australia [11], and Uluru, a very large inselberg of geological (and cultural) importance in central Australia [12]. Generally, geological features at the sub-global scale, involving 1000s of kilometres, unless partly integrated into large-scale geoparks, are not included as geoheritage sites: examples include entire mountain chains such as The Himalayas and The Andes that formed by tectonic plate collisions, or extensive (subcontinental-scale) sand-dominated deserts (*e.g.*, the Great Sandy Desert of Western Australia), extensive plains/plateaux formed by lava outpourings (*e.g.*, the Deccan Traps [Deccan Plateau], India), island arcs, and extensive inland-located volcanic chains (such as the Cosgrove hotspot track [13] in eastern Australia or, in our terms, the Cosgrove Volcano Chain, the subject of this Chapter). Exceptions to this are the 2300-km-long Great Barrier Reef offshore from eastern Australia, and Shark Bay (150 km x 100 km), both World Heritage Sites and with geoheritage as a component of their nominated values [14–17].

Brocx & Semeniuk developed the Geoheritage Tool-kit [18], a classification system to categorise and assess sites of geoheritage significance (**Figure 1**), and a

Figure 1. Diagram showing the scope of geoheritage in terms of its conceptual categories, its scales of application, and potential levels of significance (modified from Brocx & Semeniuk 2007, with an emphasis on volcanology).

semi-quantitative evaluation method to determine their International, National, State-wide to Regional, or Local significance (**Figure 2**) [1]. This system has been adopted in other countries and in different geological contexts [18–20]. Brocx & Semeniuk also addressed spatial scale in categorising sites of geoheritage value and identified/defined the small, medium, and large scales of reference

Figure 2. Diagrammatic representation of the levels of significance applicable to volcanic geoheritage features (modified from Brocx & Semeniuk 2007, with an emphasis on vulcanology). A: International; B: National; C: State-wide to regional; and D: Local. Definitions (after Brocx & Semeniuk 2007) are embodied in the diagram. This method of evaluation is semi-quantitative.

Figure 3. Map of eastern Australia showing outcrops of Cainozoic volcanism and their ages, and the general trackway of the Cosgrove volcanic chain (modified from Davies et al. [21]).

assigning numerical limits to the scale of reference [1], but did not venture to the megascale involving mountain chains and other the sub-global geological phenomena noted above.

Sites of geoheritage significance, regardless of their scale, are important to Society in that they preserve a history of the Earth, can be used for research and teaching, provide reference localities, provide a record of the history of scientific enquiry, can function as sites for geotours, and may be linked to Indigenous cultural history and values (Row A, **Figure 1**). The sites of geoheritage significance listed above [6–12] accord with these principles.

In this context, the Cosgrove Volcano Chain (some 2000 km long) in eastern Australia (**Figure 3**) is an example of an extensive suite of volcanic rocks that have global geoheritage significance and qualify to be recognised as a globally-important mega-geopark. To convey this concept, this paper is structured as follows:

1. mantle plumes, and the significance of xenoliths, xenocrysts, and magma mixing
2. the eastern Australian volcanic framework
3. the eastern Australian continent geological framework
4. geoheritage significance of the eastern Australian Cosgrove Volcano Chain
5. Discussion and Conclusions: a globally-significant mega-geopark centred on the Cosgrove Volcano Chain.

While the innumerable papers on the eastern Australian volcanic corridor have focused on petrology, geochemistry, mechanisms of emplacement and extrusion, and origin of the magma [22–26], this Chapter definitively focuses on the geoheritage significance of one volcanic chain [13].

2. Mantle plumes, and the significance of xenoliths, xenocrysts, and magma mixing

Convection of hot rock within the Earth's mantle has been proposed as the mechanism for the formation of a magmatic plume or mantle plume (acting like a diapir) that results in volcanic hotspots such as those located at Hawaii or Iceland, and for large igneous provinces such as the Deccan Traps [27–29]. Mantle plumes are thought essentially to be areas of hot, upwelling magma, with a hotspot that develops above the plume (this is the Wilson-Morgan hypothesis of hotspots, typified by high heat flow, positive gravity anomaly and alkalic volcanism, resulting in surface expressions of mantle plumes rising by thermal convection [30]). Magma generated by hotspots rises through the more rigid overlying lithosphere and produces active volcanoes and lava flows at the Earth's surface [31–34]. Accompanying, and critical to this process is the fact that, on its ascent, a plume will entrain rock fragments from deep in the Earth's crust (evident as mafic and ultramafic xenoliths) or, when traversing the lithosphere such as sedimentary basins higher in the Earth's crust, entrain Phanerozoic and Proterozoic xenoliths such as sandstone, shale, coal, low-grade metamorphic rock, and granite [21, 30, 32–36]. Where there is melting or partial melting, xenocrysts can be released [30, 37–40]. Also, where there is melting or partial melting of the lithosphere there is geochemical contamination of magma [37, 38].

To account for geochemical heterogeneity in hotspot and flood basalt lavas, Farnetani & Richards [37] suggest either inherent plume-source heterogeneity or contamination from the lithosphere through which the primary magma ascended. We accord with the latter, *i.e.*, contamination from a heterogeneous lithosphere, particularly when the magma rises through a thick lithosphere [13] or through a complex sedimentary basin.

3. The eastern Australian volcanic framework

Australia commenced separating from Antarctica some 85 million years ago, finally separating some 33 million years ago, and has been migrating northwards towards the Eurasian plate [13, 23, 33, 40, 41]. In the process, it progressively passed over a mantle hotspot on its eastern side.

Globally, volcanic activity typically is located at the edge of a tectonic plate boundary (subduction zone), or a rift, or a crustal spreading zone [35–39]. However, along the length of eastern Australia in response to the continent passing over the mantle hotspot, there is a wide ‘corridor’ or trackway of volcanoes and eruptive activity that is quite distant from the edge of the Indo-Australian Plate, and here volcanism appears related to a mantle plume, or a cluster of mantle plumes, or at least a mantle plume that, over time, found several proximally related weaknesses in the lithosphere through which to intrude and erupt. Sutherland [41] first suggested plate migration over magmatic upwellings with the oldest Australian volcanoes in north Queensland, and the eruptive centres have moved southwards as the Australian plate has drifted northwards over a mantle plume, forming a ‘corridor’ of eruptive and magmatic activity.

The volcanoes in this corridor have been active along the eastern part of Australia for at least the last 33 million years [40], showing a *series of volcanic tracks* with some starting in the north some 33 Ma ago, and others starting mid-length along the Australian eastside some 27–21 Ma ago; these various trackways have been mapped by different authors and range in age from the oldest to the north and youngest to the south [25, 40–48]. These trackways, showing a younging to the south, implicate a northward drift of the continent over a mantle hotspot as the Indo-Australian plate (a major tectonic plate that includes the continent of Australia and surrounding ocean, and extends northwest to include the Indian subcontinent and adjacent waters [43–45, 49]) migrated over a relative stable (static) mantle plume [13, 36, 42]. It has been estimated that the eastern part of the Indo-Australian Plate (Australia) is moving northward at the rate of 5.6 cm per year while the western part (India) is moving only at the rate of 3.7 cm per year due to the impediment of the Himalayas [43–46].

Within this corridor, volcanism has been expressed as eruptions determined by the thickness of the lithosphere [13]. Of interest in this Chapter, the main trackway within the corridor is what Davies *et al.* [13] termed the ‘Cosgrove hotspot track’ which we term the ‘Cosgrove Volcano Chain’ (**Figure 3**). Davies *et al.* linked the volcanoes, eruptive centres, and magmatic activity along the ‘Cosgrove hotspot track’ (or ‘Cosgrove Volcano Chain’) based on a number of criteria: *viz.*, 1. standard basaltic compositions of magma in regions where lithospheric thickness is less than 110 km, 2. volcanic gaps in regions where lithospheric thickness exceeds 150 km, and 3. low volume, leucite eruptions in regions of intermediate lithospheric thickness. Davies *et al.* found that trace-element concentrations along this track support the notion that compositional variations result from different degrees of partial melting, controlled by the thickness of overlying lithosphere, and concluded that lithospheric thickness played a dominant role in determining the volume and chemical composition of plume-derived magmas [13].

From south to north, with increasing age, the volcanoes in the Cosgrove Volcano Chain have been increasingly eroded so that with the oldest volcanoes all that often remains of the volcanic morphology is the erosion-resistant plug and the array of dykes. Clearer and more evident volcanic landscapes are present in the younger terrain to south.

The principles we intend to develop for the Cosgrove Volcano Chain in terms of magma mixing, nature of xenoliths and xenocrysts, the influence of lithospheric lithologies on both xenolith types and magma contamination, and the relationship of volcanic expression to crust thickness are applicable to other volcanic trackways in the eastern Australia volcanic corridor and, as will be discussed later, have geoheritage relevance.

4. The eastern Australian continent geological framework

Eastern Australia contains a large number of Phanerozoic and Proterozoic sedimentary basins and fold belts that, depending on geological setting, (former) palaeoclimates, and on geologic period, have quite a variable sedimentary

Basin, or fold belts	Age, thickness of the basin or fold belt and its main lithologies
Drummond Basin [50]	Late Devonian to Early Carboniferous basin filled with >5000 m quartzose, felspathic and lithic sandstones, mudstone, chert, algal limestone, volcanoclastic and volcano-quartzose sandstone, and tuff overlying folded crystalline rocks of the Cambro-Ordovician Thompson Fold Belt (siltstone, fine-grained quartzose to feldspathic sandstone, phyllite, schist, cleaved mudstone, tonalite, limestone, volcanoclastic and primary volcanic deposits, felsic volcanic detritus and primary felsic volcanics, fossiliferous sedimentary rocks, rhyolitic and basaltic lavas, ignimbrite, gabbro/diorite to syenogranite, and granite
Bowen Basin [51]	Permian to Triassic basin filled with 10,000 m of fluvial and lacustrine sediments (quartzose sandstones, mudstone), limestones, volcanic rocks, tuffs, and thick succession of coals
Surat Basin [52, 53]	Early Jurassic to Early Cretaceous basin filled with 2500 m of sandstone, coal, siltstone, shale and limestone; during the Early Jurassic, deposition was mostly fluvio-lacustrine; by the Middle Jurassic coal swamp environments predominated
Murray Darling Basin [54]	Late Silurian to Early Carboniferous basin, largely Devonian in age with up to 8000 m of mostly continental red-bed facies and marginal marine facies in the latest Silurian and Early Devonian
Lachlan Fold Belt [55–58]	Ordovician to Carboniferous folded/faulted and weakly metamorphosed rocks of turbidites, trench sedimentary complexes, volcanic arcs with andesites, oceanic crust and micro continents; individual rocks are mostly sandstone and shale interbedded with chert, limestones, and metavolcanics (andesites), and intrusive granites; because of folding, crustal shortening, thrusting/faulting, estimates of basin-filling thickness are difficult to determine though Collins <i>et al.</i> [58] provide estimates that, depending on crustal history, varied from ~20,000 m to 40,000–50,000 m
Otway Basin [59]	Early Cretaceous to Tertiary basin filled with thick continental, fluvio-lacustrine, and marine sediments, followed by volcanoclastic, fluvio-lacustrine deposition, and then Late Cretaceous coastal-plain, deltaic and marine deposition and, later, Cretaceous to Middle Eocene deposition of coastal plain, deltaic and shallow marine sediments, and Middle Eocene to Early Oligocene near-shore to offshore, mixed clastic and carbonate sediments, and Late Oligocene to Late Miocene, open-marine carbonate deposition, capped by Plio-Pleistocene deposition of mixed siliciclastic-carbonate succession

Table 1.
Characteristics of basins/fold belts that the Cosgrove volcanic chain intersects.

Figure 4. Map of eastern Australia showing occurrence of the sedimentary basins and fold belts (modified from geoscience Australia https://www.ga.gov.au/__data/assets/image/0020/13943/GA14654.gif) that the trackway of the Cosgrove volcanic chain will have intersected. Dominant lithologies that will yield xenoliths/xenocrysts are listed in Table 1.

history, metamorphic history, and structural history, *viz.*, 1. mainly siliciclastic, 2. carbonate-dominated, 3. changing mega-stratigraphically between siliciclastic and carbonate-dominated, 4. basins with sedimentary sequences as 1–3 above but with insertion of coal measures and/or volcanic events (**Table 1**). This is the geological framework that mantle plumes, in ascending towards the surface, have intersected. Thus, along eastern Australia, the range of mantle plumes (or mantle hotspots) from northernmost Australia to Tasmania (the Cosgrove Volcanic Chain trackway is shown in **Figure 3**) needed to transgress these various heterogeneous lithological systems.

As mentioned earlier, we have opted to focus only on the Cosgrove Volcanic Chain (trackway) to illustrate what this volcanic plume needed to transgress lithologically, what it needed to cross in basin thickness, and what it encountered in stratigraphic/lithologic heterogeneity. The Cosgrove Volcano Chain crosses a number of sedimentary basins and a fold belt (**Figure 4**) that are of various ages, thicknesses, and lithologies (**Table 1**) and, as such, the trackway had the potential to interface with a variety of rocks that could be involved in melting/mixing and melt contamination, and yielding of discrete xenoliths and xenocrysts. Given that the volcanic trackway may not have been strictly linear, and may have deviated from the trackway that is shown in **Figures 3** and **4**, the most probable xenolith and xenocryst contributions to the evolution of the Cosgrove mantle plume are from lithologies from the following basins and tectonic zones (from north to south): Drummond Basin, Bowen Basin, Surat Basin, Murray Darling Basin, the Lachlan Fold Belt, and the Otway Basin (**Table 1**). **Table 1** list the, thickness of the basin or fold belt, its main lithologies, and its age. The deepest part of each basin often rests on metasediments or on crystalline rocks though the bulk of the sedimentary fill of the basins tend not to be metamorphosed.

5. Geoheritage significance of the eastern Australian Cosgrove volcanic chain

The Cosgrove Volcano Chain provides a globally-unique system to explore an intra-plate migratory volcanic system and, additionally, in this context, with its globally-distinct suite of sedimentary basins that it has over time intruded through, it has global geoheritage significance. From north to south, in its younging direction, the Cosgrove Volcano Chain has a rich history and expression of volcanic activity with a range of lava types and eruptive volcanic rocks (dominantly basaltic lava [alkali olivine basalts, hawaiites, mugearites], but with occurrences of leucitite, trachyte, rhyolite, andesite, andesitic basalt, trachyandesite, and, where explosive and where expressed pyroclastically, tuff, breccia and agglomerate). Geomorphically, these volcanic eruptions are expressed as a range of primary volcanic landforms as well as eroded-residual geometry types (shield volcanoes, stratovolcanoes, domes, plugs, spires, *etc.*), and stratiform ash deposits, dykes, plugs, and sills. There are also valley fills, conic accumulations of tephra (*e.g.*, accretionary pyroclastic cones), ash sheets, and lava tubes.

In a sub-global context, the Cosgrove Volcano Chain presents a range of magma types, volcanic expressions, a history of interactions with the variable but regionally diagnostic lithosphere (*i.e.*, regionally-specific and lithologically-diagnostic sedimentary basins). It also presents a landscape-*cum*-climate response as the various volcanic and eruptive centres passed progressively through a climate gradient as Australia migrated from arctic/boreal climates through to subtropical/tropical

climates with its attendant influence on erosion and weathering styles and transformation of volcanic rock and tephra to climate-specific landforms and climate specific soils. This variability in volcanic expression, in a north-to-south gradient influences content of xenoliths and xenocrysts and magma composition, as well as volcanic landscape types, and in climate-influenced weathering styles changing progressively over 33 million years – it thus provides a globally-unique natural laboratory as a window into Earth processes, and a teaching and research resource in perpetuity.

The key elements of the Cosgrove Volcano Chain of geoheritage significance are as follows:

1. first example of a long, continent-length volcanic chain [13];
2. volcanic activity linked to lithosphere thickness;
3. volcanic magma composition linked to lithosphere heterogeneity;
4. variability of magma along the volcanic chain;
5. magma evolution at a volcano, *e.g.*, from basalt lava to rhyolitic lava;
6. magma and volcanic evolution, *e.g.*, magma flows varying to ash beds and breccias;
7. volcanic eruption style linked to magma composition;
8. volcanic xenolith/xenocryst linked to lithosphere heterogeneity and sedimentary basins;
9. volcanic expression at different scales linked to magma composition;
10. northwards volcano drift passes through different climates and weathering regimes.

To further the disciplines of geoheritage and geoconservation, Brocx & Semeniuk provided a Geoheritage Tool-kit to systematically compile an inventory of the full diversity at various scales of geological and geomorphological features in a given area, assess their levels of significance, and address whether geoheritage features are treated in isolation or as inter-related suites that should be conserved as an ensemble. Utilising the Geoheritage Tool-kit, many of the features listed 1–10 above individually would be evaluated as internationally to nationally significant, but specifically (1), (2), (3), and (8) are globally significant features of this volcanic chain. However, the cross-continent assemblage of volcanic features of the Cosgrove Volcano Chain should not be viewed as isolated separate geological phenomena spread across the north-to-south length of Australia but, from a geoheritage perspective, should be viewed as a single, integrated ensemble recording 1. a gradient of magma types, 2. the effect of a variable thickness of lithosphere, 3. the variety of volcanic landform expression, 4. the rock types intersected by the ascending plume, and 5. the changes in styles of erosion and weathering as the volcanoes passed through the various climate zones. However, while the Cosgrove Volcanic Chain is suggested as a global-significant mega-park, there is much planning, valorisation, community involvement, and government support required to achieve this (matters that are beyond the scope of this Chapter).

6. Discussion and conclusions: a globally significant mega-geopark centred on the Cosgrove volcano chain

As reiterated above, Australia, having finally split from Antarctica some 33 million years ago, has been migrating northwards towards the Eurasian plate progressively passing on its eastern side over a mantle hotspot (magma plume) which intersected various, variable lithologic packages such as Phanerozoic sedimentary basins, fold belts and metamorphic terranes, and Precambrian rocks. With xenolith plucking, enclave plucking, and xenocryst incorporation, there had been compositional evolution of the magma plume. The volcanic chain, the individual volcanoes, and the lava fields that are spread latitudinally along 2000 km of eastern Australia present a globally-significant volcanic system that provides insights into Earth magma and crust interactions, into the variability of xenoliths and xenocrysts, into magma evolution dependent on setting, and into the story of the Earth. The Cosgrove Volcano Chain stands as an example of a globally-unique example of these processes and a potential megascale geopark.

In summary, this Chapter has described the significance of a magma plume pulsing through a heterogeneous continental crust, with lithospheric heterogeneity giving rise to a mix in magma composition and a mix of xenoliths/xenocrysts. The movement of the Australian plate to northward gives clues (as a window) to sub-continental lithology via the enclosed xenoliths and xenocrysts and the influence of the thickness of crust as to whether there is volcanic expression of the magma plume at the Earth's surface [13]. And while they have been noted in previous studies and their occurrence is important, xenoliths and xenocrysts have not been a detailed focus of many studies, yet they are important as they provide clues to the sub-crustal influences and processes at the base of a magma plume. The phenomena of magma mixing, nature of xenoliths and xenocrysts, the influence of lithospheric lithologies in generating xenolith/xenocryst types and on magma contamination, and the relationship of volcanic expression to crust thickness are applicable to other volcanic trackways here in eastern Australia and elsewhere globally.

Also, it is worth pointing out that a similarly large volcanic field has been recognised for its geoheritage values in Harrat Khaybar, Kingdom of Saudi Arabia [60, 61] which has local and global implications for geo-education, research, and reference site for global volcanism.

On a final note, we emphasise that we consider the Cosgrove Volcano Chain to be a megascale geological feature of global geoheritage significance and should be considered as a potential megascale geopark. In effect, it would be the volcanic equivalent of the latitudinally extensive Great Barrier Reef which is accepted as a World Heritage Site.

IntechOpen

Author details

Vic Semeniuk^{1,2,3} and Margaret Brocx^{3*}

1 V & C Semeniuk Research Group, Warwick, Western Australia

2 School of Arts and Sciences, Notre Dame University, Fremantle,
Western Australia

3 Environmental and Conservation Sciences, Murdoch University,
Western Australia

*Address all correspondence to: geoheritage@iinet.net.au

IntechOpen

© 2021 The Author(s). Licensee IntechOpen. This chapter is distributed under the terms of the Creative Commons Attribution License (<http://creativecommons.org/licenses/by/3.0>), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

References

- [1] Brocx M & Semeniuk V 2007. Geoheritage and geoconservation - history, definition, scope and scale. *Journal of the Royal Society of Western Australia* 90: 53-87.
- [2] Brocx M 2008. Geoheritage - from global perspectives to local principles for conservation and planning. Western Australian Museum, 175p. ISBN 978-1-920843-35-9.
- [3] Worboys G L, Lockwood M, Kothari A, Feary S & Pulsford I (eds). 2015. Protected area governance and management. ANU Press, Canberra (2015).
- [4] Casadevall T J, Tormey D & van Sistine D 2019. Protecting our global volcanic estate: Review of international conservation efforts. *International Journal of Geoheritage and Parks* 7(4): 182-191.
- [5] Brocx M & Semeniuk V 2010. The geoheritage significance of crystals. *Geology Today* 26: 216-225.
- [6] Phillips J C, Humphreys M C S, Daniels K A, Brown R J & Witham F 2013. The formation of columnar joints produced by cooling in basalt at Staffa, Scotland. *Bulletin of Volcanology* 75: 1-17. <https://doi.org/10.1007/s00445-013-0715-4>.
- [7] Bastida F, Aller J, Toimil N C, Lisle R J & Bobillo-Ares N C 2007. Some considerations on the kinematics of chevron folds. *Journal of Structural Geology*. 29 (7): 1185-1200.
- [8] Barclay W J, Browne M A E, McMillan A A, Pickett E A, Stone P & Wilby P R 2005. The Old Red Sandstone of Great Britain. *Geological Conservation Review Series*, No. 31, Joint Nature Conservation Committee, Peterborough, 393 p.
- [9] Alvarez W 2009. The historical record in the Scaglia limestone at Gubbio: magnetic reversals and the Cretaceous-Tertiary mass extinction. *Sedimentology* 56: 137-148. doi: 10.1111/j.1365-3091.2008.01010.x.
- [10] Whittington H B 1985. The Burgess Shale. Yale University Press, New Haven, USA.
- [11] Drexel J F, Preiss W V & Parker A J 1993. The geology of South Australia. Volume 1: The Precambrian. *Geological Survey of South Australia Bulletin* 54.
- [12] Twidale C R & Campbell E M 2005. Australian landforms. Rosenberg. ISBN 1-877058-32-7.
- [13] Davies D, Rawlinson N, Iaffaldano G & Campbell I H 2015. Lithospheric controls on magma composition along Earth's longest continental hotspot track. *Nature* 525: 511-514 (2015). <https://doi.org/10.1038/nature14903>
- [14] Hopley D, Smithers S G & Parnell K E 2007. The geomorphology of the Great Barrier Reef - development, diversity, and change. Cambridge University Press, Cambridge.
- [15] UNESCO 1981. Great Barrier Reef (World Heritage Site). <https://whc.unesco.org/en/list/154/>
- [16] Logan B W (ed) 1974. Evolution and Diagenesis of Quaternary Carbonate Sequences, Shark Bay, Western Australia. American Association of Petroleum Geologists Memoir 22. Tulsa, Oklahoma
- [17] UNESCO 1991. Shark Bay, Western Australia (World Heritage Site). <http://whc.unesco.org/en/list/578/>.
- [18] Brocx M & Semeniuk V 2015. Using the Geoheritage Tool-Kit to identify inter-related geological features at

- various scales for designating geoparks: case studies from Western Australia. In: E Errami, M Brocx & V Semeniuk (eds), *From Geoheritage to Geoparks -Case Studies from Africa and Beyond*. Springer, Amsterdam, 245-259.
- [19] Brocx M 2018. The Geoheritage Tool-kit for the Geological Society of Australia Inc. https://www.gsa.org.au/Public/Geoheritage/Geoheritage-Tool-Kit/Public/Geoheritage/Geoheritage_Tool-Kit.aspx?hkey=2f275860-e038-4bfa-8a59-f13fbe657c19.
- [20] Worboys G L, Lockwood M, Kothari A, Feary S & Pulsford I (eds). 2015. *Protected area governance and management*. ANU Press, Canberra (2015)
- [21] Ismail M, Delpech G, Moine B, Grégoire M, Guilbaud C & Cottin J-Y 2020. Sapphirine-bearing pyroxenite xenoliths in Cenozoic alkali basalt from Jabal El Arab (Syria): insights into the nature and composition of the lithosphere beneath the southern Syrian Rift, northern part of the Arabian Plate. *Journal of Asian Earth Sciences* 190: article 104146. doi: <https://doi.org/10.1016/j.jseas.2019.104146>.
- [22] Wilshire H G & Binns R A 1961. Basic and ultrabasic xenoliths from volcanic rocks of New South Wales. *Journal of Petrology* 2(2): 185-208.
- [23] Sutherland F L 1991. Cainozoic volcanism, Eastern Australian: a predictive model on migration over multiple 'hotspot' magma sources. In: P DeDeckker & A P Kershaw (eds), *The Cainozoic in Australia: a re-appraisal of the evidence*. Geological Society of Australia, Special Publications 18: 5-43.
- [24] Gibson D L 2007. Potassium-argon ages of late Mesozoic and Cainozoic igneous rocks of eastern Australia. CRC LEME open file report, Volume 193: Bentley, W.A., Cooperative Research Centre for Landscape Environments & Mineral Exploration and Geoscience Australia.
- [25] Whitehead P W 2010. The regional context of the McBride Basalt Province and the formation of the Undara lava flows, tubes, rises and depressions. *Proceedings 14th International Symposium on Vulcanospeleology, 2010 Undara Volcanic National Park, Queensland, Australia August 2010*.
- [26] Cohen B E 2012. The scenic rim of southeastern Queensland, Australia: A history of mid Cenozoic intraplate volcanism. *Episodes* 35(1): 103-109.
- [27] Atwater T. 1989. Plate tectonic history of the northeast Pacific and western North America. In: E L Winterer, D M Hussong & R W Decker (ed), *The Geology of North America*, Vol. N, The Eastern Pacific Ocean and Hawaii. Geological Society of America: 21-70.
- [28] Thordarson T & Höskuldsson A 2008. Postglacial volcanism in Iceland. *Jökull: The Icelandic Journal of Earth Sciences* 58: 197-228.
- [29] Dessai A G & Vaselli O 1999. Petrology and geochemistry of xenoliths in lamprophyres from the Deccan Traps: implications for the nature of the deep crust boundary in western India. *Mineralogical Magazine* 63(5): 703-722
- [30] Basu A R 1975. Hot-spots, mantle plumes and a model for the origin of ultramafic xenoliths in alkali basalts. *Earth and Planetary Science Letters* 28(2): 261-274.
- [31] Foulger G R 2010. *Plates vs. plumes: a geological controversy*. Wiley-Blackwell. ISBN 978-1-4051-6148-0
- [32] French S W & Romanowicz B 2015. Broad plumes rooted at the base of the Earth's mantle beneath major hotspots. *Nature* 525(7567): 95-99.

- [33] White W M 2010. Oceanic island basalts and mantle plumes: the geochemical perspective. *Annual Review of Earth and Planetary Sciences* 38(1): 133-160.
- [34] Wilshire H G 1961. Sedimentary xenoliths and dolerite patch pegmatites from an analcite basalt intrusion. *American Journal of Science* April 1961, 259 (4): 260-279; DOI: <https://doi.org/10.2475/ajs.259.4.260>.
- [35] Thompson R N & Gibson S A 2000. Transient high temperatures in mantle plume heads inferred from magnesian olivines in Phanerozoic picrites. *Nature* 407: 502-506.
- [36] Krienitz M-S, Haase K, Mezger K, van den Bogaard P, Thiemann P & Shaikh-Mashail A 2009. Tectonic events, continental intraplate volcanism, and mantle plume activity in northern Arabia: Constraints from geochemistry and Ar-Ar dating of Syrian lavas. *Geochemistry Geophysics Geosystems* 10(4) 1-26. Q04008, doi: 10.1029/2008GC002254.
- [37] Farnetani C G & Richards M A 1995. Thermal entrainment and melting in mantle plumes. *Earth & Planetary Science Letters* 136: 251-267.
- [38] Cinzia G, Farnetani C G, Legras B & Tackley P J 2002. Mixing and deformations in mantle plumes. *Earth and Planetary Science Letters* 196 (2002) 1-5.
- [39] Barry T L, Saunders A D, Kempton P D, Windley B F, Pringle MS, Dorjnamjaa D & Saandar S 2003. Petrogenesis of Cenozoic basalts from Mongolia: evidence for the role of asthenospheric versus metasomatized lithospheric mantle sources, *Journal of Petrology* 44 (1): 55-91. doi.org/10.1093/ petrology/44.1.55.
- [40] Johnson R W, Knutson J & Taylor S R (eds) 1989. Intraplate volcanism in Eastern Australia and New Zealand, Cambridge, England: Cambridge University Press, 408 p.
- [41] Sutherland L 1995. The volcanic Earth. University of New South Wales Press, Sydney. 248p.
- [42] Schmincke H-U 2003. Volcanism. Springer, Berlin.
- [43] Knesel K M, Cohen B E, Vasconcelos P M & Thiede D S 2008. Rapid change in drift of the Australian plate records collision with Ontong Java plateau. *Nature* 454: 754-757.
- [44] Sutherland F L, Graham I T, Meffre S, Zwingmann H & Pogson R E 2012. Passive-margin prolonged volcanism, East Australian Plate: outbursts, progressions, plate controls and suggested causes. *Australian Journal of Earth Sciences* 59(7): 983-1005.
- [45] Jones I & Verdel C 2015. Basalt distribution and volume estimates of Cenozoic volcanism in the Bowen Basin region of eastern Australia: Implications for a waning mantle plume. *Australian Journal of Earth Sciences* 62(2): 255-263.
- [46] Keep M & Schellart W P 2012. Introduction to the thematic issue on the evolution and dynamics of the Indo-Australian plate. *Australian Journal of Earth Sciences* 59(6): 807-808.
- [47] Wellman P & McDougall I 1974. Potassium-argon ages on the Cainozoic volcanic rocks of New South Wales. *Journal of the Geological Society of Australia*, 21:3, 247-272, DOI: 10.1080/00167617408728849
- [48] Vasconcelos P, Knesel K, Cohen B & Heim J 2008. Geochronology of the Australian Cenozoic: a history of tectonic and igneous activity, weathering, erosion, and sedimentation. *Australian Journal of Earth Sciences* 55, 865-914

- [49] Delescluse M, Chamot-Rooke N, Cattin R, Fleitout L, Trubienko O & Vigny C 2012. April 2012 intra-oceanic seismicity off Sumatra boosted by the Banda-Aceh megathrust. *Nature* 490: 240-244.
- [50] Purdy D J, Withnall I W & Bultitude R J 2016. Geology, geochronology and geochemistry of the northeast Drummond Basin Region. Geological Survey of Queensland, Record 2016/01 134pp.
- [51] Dickins J M & Malone E J 1973. Geology of the Bowen Basin, Queensland. Bureau of Mineral Resources, Australia, Bulletin 130.
- [52] Senior B R, Harrison P L & Mond A 1978. Geology of the Eromanga Basin, Queensland. *Bureau of Mineral Resources Bulletin* 167.
- [53] Exon N F 1976. Geology of the Surat Basin in Queensland. Bureau of Mineral Resources, Australia, Bulletin 166.
- [54] Kingham R 1998. Geology of the Murray-Darling Basin — simplified lithostratigraphic groupings. AGSO Record 1998/21. Australian Geological Survey Organisation - Department of Primary Industries & Energy. 33pp.
- [55] Packham G H (ed) 1969. The Geology of New South Wales, Geological Society of Australia Inc., Sydney. 654p.
- [56] Foster R A & Gray D R 2000. Evolution and Structure of the Lachlan Fold Belt (Orogen) of Eastern Australia. *Annual Review of Earth and Planetary Science* Vol. 28:47-80.
- [57] Gray D R & Foster R A 2004. Tectonic evolution of the Lachlan Orogen, southeast Australia: historical review, data synthesis and modern perspectives. *Australian Journal of Earth Sciences* 51: 773-817.
- [58] Collins W J, Mcnwain G & Mantle G 2004. Crustal thickness variations in the Lachlan Fold Belt - implications for tectonic and metallogenic models. *In*: Bierlein, F.P., Hough, M.A. (eds), *Tectonics to Minerals Discovery - Deconstructing the Lachlan Orogen. Proceedings Volume and Field Guide, MORE-SGEG Conference, Orange, NSW, July 6 - 8, 2004. Geological Society of Australia Abstracts No 74: 37 - 44.*
- [59] Morton J G 1995. Otway Basin (Chapter 9). *In*: J F Drexel & W V Preiss (eds), *The Geology of South Australia, Volume 2, The Phanerozoic. South Australia. Geological Survey, Bulletin* 54: 142-147.
- [60] Nemeth K & Moufti R 2013. Monogenetic volcanic fields and their geoheritage values of western Saudi Arabia and their implication to holistic geoeducation projects locally and globally (Invited). *In*: American Geophysical Union, Fall Meeting 2013, abstract id. ED13F-0813, pp ED13F-0813
- [61] Nemeth K & Moufti M R (2017) Geoheritage values of a mature monogenetic volcanic field in intra-continental settings: Harrat Khaybar, Kingdom of Saudi Arabia. *Geoheritage* 9(3):311-328.