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EDITORIAL

Rifts, arcs and orogens in space and time: a volume in honor of J. Duncan Keppie—an introduction

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Duncan keppie: an appreciation and a celebration

John Duncan Moorhouse Keppie is, quite simply, one of the most influential geologists of our time. He was received a B.Sc. (honors) degree in 1964 and a Ph.D. in 1967 both from the University of Glasgow (Scotland), and his career with geological surveys and universities in Zambia, Nova Scotia and Mexico spans 45 years. Trained as a structural geologist, Duncan was soon bitten by the plate tectonic bug and paleogeographic reconstructions, which he used to bring the geology of Atlantic Canada and Paleozoic Mexico to the world stage, became one of his most enduring scientific legacies. To fuel this passion, Duncan became an expert in petrology, geochronology, paleomagnetism, geochemistry, and stratigraphy. He was the first geoscientist to interpret the geology of Nova Scotia in terms of plate tectonics and one of the first to apply the principles of terrane analysis to the Appalachians, extrapolating this analysis to include the circum-Atlantic orogens and Mexico.

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This volume is an outcome of a symposium entitled "Amalgamation and Breakup of Pangea in the Americas" held in Duncan's honor in conjunction with the Cordilleran Section Meeting of the Geological Society of America on March 29–31, 2012 in Querétaro, Mexico. The symposium was co-sponsored by IGCP 597 (Origin and Evolution of Pangea) and IGCP 574 (Bending and Bent Orogens, and Continental Ribbons) and featured 16 contributions from friends, colleagues, current and former students, and one from his son, Fraser. Many of the papers presented at Querétaro are represented in this volume, supplemented by others from friends and colleagues who could not make that meeting but wished to contribute to this commemorative volume (Fig. 1).

Duncan Keppie's CV reveals a record of sustained excellence and productivity for nearly 40 years with the publication of more than 260 papers in refereed journals, over 40 book chapters, and a host of government publications, maps and memoirs, and the editorship of 7 books or journal special issues. But those of us who have known Duncan Keppie as a friend and scientific colleague know that these numbers only begin to tell the story. Duncan has been an excellent motivator and innovator and has an infectious enthusiasm for the earth sciences. His papers are not just a documentation of the evolution of various orogenic belts, although that in itself is a significant accomplishment. They also document fundamental processes, the principles, and practices of which have been applied to the structural evolution of orogenic belts throughout the world and continue to provide a theoretical framework for the understanding of the evolution and growth of continental crust.

One of his many gifts, and a major strength in his research, is an unparalleled ability to grasp the essence of concepts and synthesize geological data from a very wide range of fields and from seemingly disparate pieces

Fig. 1 Duncan Keppie preparing for field work, breakfast at Hotel Almazo in Tehuitzingo, Mexico, on April 8, 2002

of research. This has not only led to a host of innovative papers in the field of structural geology and tectonics, but has also been the inspiration behind groundbreaking papers in igneous and metamorphic petrology, geochronology, paleomagnetism, geochemistry, stratigraphy and paleontology. This is an extraordinary breadth of knowledge, and all the more so for its high level of expertise.

Duncan worked for more than 20 years at the Nova Scotia Department of Mines (now the Department of Natural Resources) as a senior geoscientist where his mandate was to provide structural and tectonic maps and models of the province to complement parallel studies in mineral deposits. To the international geoscience community, he was the catalyst that brought the geology of Nova Scotia to the world stage, mainly through his involvement with UNESCO's International Geoscience (formerly Geological Correlation) Program (IGCP).

Duncan recognized early on the potential of IGCP to foster the discussion and exchange of ideas from the local to global scale and has been one of its most effective and enthusiastic supporters. Indeed, he has probably initiated and organized more successful IGCP projects and conferences than any other geoscientist, starting with the highly influential circum-Atlantic terranes project in the 1980s, which brought together experts from almost every country that borders the Atlantic. In connecting geoscientists from a wide variety of ethnic and cultural backgrounds, he overcame language barriers and a host of technical issues to coordinate meetings, facilitate the publication of papers, field guides and books, and synthesize the many contributions that culminated in the terrane map for the circum-Atlantic orogenic belts. His leadership of IGCP projects went on to include Project 376 (Laurentia-Gondwana Connections Before Pangea) and Project 497 (Ancient Orogens and Modern Analog) and continues to this day with Project 597 (Origin of Pangea), which involves earth scientists from both the circum-Atlantic and circum-Pacific regions with a mandate to discuss global-scale structure and tectonics in the Paleozoic with the purpose of understanding the origin and evolution of Pangea.

Duncan's thought-provoking theories and hypotheses encourage and challenge us to participate in them. But while he has always been an articulate and passionate advocate of his own hypotheses, he has never been afraid to abandon them and admit that he was wrong when the weight of scientific evidence went against them. In the 1970s and 1980s, he had the vision to realize that by deducing the tectonic evolution of terranes and tracing their relative motions back through time, new mineral discoveries in places such as Iberia, West Africa, Arabia and Colombia could have immediate impact on exploration in Nova Scotia because of their proximity at the time of mineralization. He set out to understand the structural and accretionary history of terranes within the Nova Scotia segment of the Appalachian orogenic belt and rapidly became a world-renowned expert on the relationship between the structural evolution of the Appalachian orogen and its tectonic history. His 1985 paper on the Appalachian collage was one of the first to combine a rigorous application of the principles of terrane analysis with a detailed assessment of the commonality and distinctions between adjacent fault-bounded blocks. He also recognized the pivotal importance of precise geochronology and advanced geochemistry to terrane analysis, collaborating with researchers such as Tom Krogh and Dave Dallmeyer for then state-of-the-art U–Pb and Ar–Ar data, and Jarda Dostal for high quality geochemistry.

Duncan became a Professor at the Universidad Autonóma de Mexico (UNAM) in 1995, and immediately set about re-evaluating the geology of Mexico. His papers on the tectonostratigraphic evolution of Mexican terranes and those outlining tests on the "Baja-BC connection" directed his attention to the Pacific Rim. At the same time, he skilfully deduced the relationship between the Paleozoic evolution of terranes in Mexico and that of terranes in the Appalachians, and in so doing, provided another dimension to our understanding of Appalachian tectonics.

Since his early days at the Nova Scotia Department of Mines, Duncan has maintained active involvement in the mentorship of students, initiating, funding and co-supervising student theses from the undergraduate to the doctoral level. He was also the prime motivator in a successful inter-university international field school that involved students from universities in Mexico (UNAM), USA (Arizona and Ohio) and Canada (St. Francis Xavier, St. Marys and Windsor) and was funded in its entirety by NAFTA. More recently, at UNAM, he has demonstrated his excellence as a teacher—always captivating his audience, challenging the conventional wisdom, and showing an uncanny ability to trigger intellectual curiosity and convey difficult concepts in an understandable manner.

In summary, Duncan Keppie has an established world-class reputation in the field of tectonics that has been cemented by his involvement in UNESCO-IGCP projects since their inception. He has been truly inspirational scientific leader for a generation of graduate students and young faculty, many of whom have also been subjected to his infectious enthusiasm for accordion-playing and Scottish dancing! It has been a great pleasure for all of us to have worked with him on rocks from around the globe, and we are delighted that he has passed on his passion for geology to his son, so that we will be reading insightful Keppie papers for decades to come. We are honored to dedicate this volume to our great friend and colleague.

Foreword to the special issue

This special volume of the *International Journal of Earth Sciences* presents a collection of contributions volunteered by many friends, colleagues and former students of Duncan Keppie who wish to honor him and show their appreciation on the occasion of his retirement. Because Duncan's professional career was multidisciplinary, the volume includes papers dealing with a wide variety of disciplines, all aimed at understanding the varied geological processes contributing to the evolution of the globe through time. The selected papers cover processes that took place from the Precambrian to the present, and from Africa to Europe and the Americas, the very same continents on which Duncan developed his career. All of the contributions share an interest in understanding plate tectonics and paleogeography throughout Earth history, and we have arranged them accordingly into three main groups—*rifts*, *arcs* and *orogens*—corresponding to the most important elements of the plate tectonic cycle. In the following paragraphs, we provide a brief synopsis of each paper organized within each group from older to younger.

Rifts

Hofmann et al. (2014) present whole-rock geochemical and combined U/Pb, Th/U and Hf zircon isotopic analyses from basement and Cryogenian sedimentary rocks in the Namuskluft and Dreigratberg sections of the Gariep Belt in southern Namibia. They use these data to argue for a history of Neoproterozoic rifting along the southwestern margin of the Kalahari Craton associated with the breakup of Rodinia and the opening of the Adamastor Ocean. The basin fill records recycling of mainly Palaeoproterozoic crust of the Kalahari craton and felsic continental arc rocks of the Mesoproterozoic Namaqua Belt and does not allow for correlation with other cratons, such as the Rio de la Plata or Australia/Mawsonland.

Sánchez García et al. (2014) provide new lithogeochemical, Sm–Nd and U–Pb (zircon) data from two Cambrian magmatic pulses in the Ossa-Morena Zone (SW Iberia) that herald the Lower Ordovician opening of the Rheic Ocean. The first pulse produced granitoid rocks, mostly formed by crustal anatexis. However, some data reveal the influence of lower crustal or mantle sources suggesting advanced rifting occurred in some localities. The 524 Ma age for the granitoid rocks provides a maximum age for the age of the metamorphic basement it intrudes and constrains the timing of the transition from a convergent setting in the Ediacaran to intra-continental rifting in the Cambrian along this segment of the northern margin of Gondwana.

Murphy et al. (2014) address the question of why subduction in both the Iapetus and Rheic oceans occurred so soon after the oceans opened. The Sm–Nd isotopic compositions of remnants of these oceans preserved in ophiolites and related mafic complexes reveal a highly depleted mantle source, implying either the preservation of such mantle in a long-lived oceanic plateau within the Paleopacific, or the recycling of mantle previously depleted during an episode of magmatism that occurred prior to ocean opening. To account for this, they suggest that subduction in both oceans was initiated by the capture of buoyant Paleopacific lithosphere in a manner analogous to the incorporation of the Pacific-derived Caribbean plate into the Atlantic realm during the Mesozoic–Cenozoic.

Skála et al. (2014) describe the geochemistry of various rock types in the České středohoří Mts., the dominant volcanic center of the Ohře (Eger) rift zone, including the Roztoky Intrusive Complex, which is made up of a caldera vent and intrusions of 33- to 28-Ma-old hypabyssal bodies of essexite–monzodiorite–sodalite syenite and a radial 30- to 25-Ma-old dike swarm comprising about 1,000 dikes. The hypabyssal rocks are mildly alkaline, mostly feldspathoid-bearing rock types of mafic to intermediate compositions. The dike swarm consists of mildly alkaline and rare strongly alkaline rocks (tinguaites). The geochemical signatures of the mildly alkaline hypabyssal and associated dike rocks are consistent with HIMU mantle sources and contributions from lithospheric mantle. The compositional variations of essexite and monzodiorite are best explained by fractional crystallization of parent magma without significant contributions of crustal material, whereas the monzosyenite, leuco-monzodiorite and sodalite syenite compositions reflect fractional crystallization coupled with variable degrees of crustal assimilation. The authors suggest that the parent magmas in the Ohře rift were produced by adiabatic decompression melting of ambient upper mantle in response to lithospheric extension associated with the Alpine Orogeny.

Arcs

Sánchez Lorda et al. (2014) provide new geochemical data on late Ediacaran metabasalts of the Ossa-Morena Zone (OMZ, Iberian Massif). These rocks have N-MORB, E-MORB, as well as some volcanic arc characteristics. Although E-MORB metabasalts occur across the entire OMZ, N-MORB "Serie Negra" metabasalts occur in the southern and the central OMZ, and calc-alkalic metabasalts occur in the northern OMZ. These authors interpret the data to reflect an arc–forearc environment produced by a north-dipping subduction zone that underwent extension soon after subduction initiation.

Ortega-Obregón et al. (2014) describe Permian–Carboniferous arc magmatism in the Oaxacan and Acatlán complexes of southwestern Mexico, and use the varying Hf zircon isotopic signatures of granitoid plutons to suggest different degrees of crustal contamination of arc-related mafic magmas with the Oaxacan complex as the main contaminant. They consider the magmatism to be part of a Late Carboniferous–Permian magmatic arc that extended from southern North America to Central America and attribute it to the initial stages of eastward subduction of the Pacific plate beneath the western margin of Gondwana.

Orogens

Many of the papers in this group use U–Pb, Sm–Nd and geochemical data as tracers of the provenance of both sedimentary and igneous rocks, indicative of paleogeographic and paleotectonic environments. So Solari et al. (2014) provide zircon data from metasedimentary units that underwent granulite facies metamorphism at ca. 990 Ma in the Grenvillian-aged Oaxacan Complex in Mexico. They find that most zircons in most samples range from 975 to 995 Ma, 1,100 and 1,120–1,170 Ma. In order to constrain the Mesoproterozoic conjugate margins of Oaxaquia, they compare these data with the timing of similar events in other Grenville-aged orogens, including Sveconorwegian orogens, the Sunsas and Rondonia-San Ignacio belts of Amazonia, and some of the Precambrian massifs in the Andes.

Lubnina et al. (2014) present paleomagnetic data from Ediacaran strata in the Southern Urals. The high-temperature components are interpreted as primary and provide new paleomagnetic poles. The authors combine these new data with previously published data from Baltica and Laurentia to produce a series of paleogeographic reconstructions for the Late Ediacaran–Early Cambrian opening of the Iapetus Ocean.

Fernández-Suárez et al. (2014) compare detrital U–Pb zircon ages from Ediacaran and Early Cambrian metasedimentary rocks from the Cantabrian and Central Iberian zones in NW Iberia. Major and trace elements including REE and Sm–Nd isotopes were also analyzed on the same set of samples. The detrital zircon U–Pb age patterns are very similar in the Ediacaran samples from both zones, with major age groups at ca. 0.55–0.75 Ga and ca. 0.85–1.15 Ga, and minor Paleoproterozoic (ca. 1.9–2.1 Ga) and Archean (ca. 2.4–2.6 Ga) populations. The same is true of their Nd isotopes, REE patterns and trace element concentrations. The two Cambrian samples, however, show contrasting signatures. The sample from the Cantabrian zone lacks the ca. 0.85–1.15 Ga population and has a higher proportion of Paleoproterozoic and Archean zircons (>60 %) and a more negative ε_{Nd} and higher T_{DM} values than the Ediacaran samples. The Cambrian sample from the Central Iberian Zone has the same characteristics as the Ediacaran samples but has a significantly more negative ε_{Nd} value. These data suggest continuous sedimentation in the NW Iberian realm of northern Gondwana between ca. 600 and 550 Ma and changes in the detrital influx around the Ediacaran–Cambrian boundary. With respect to the paleoposition of NW Iberia in Ediacaran–Early Cambrian times, the authors conclude that it may have lain closer to present-day Egypt–Israel–Jordan and that a potential source of the hitherto enigmatic Tonian–Stenian zircons could be traced to exposed segments of arc terranes such as those described in the Sinai Peninsula.

Strachan et al. (2014) establish the provenance of the Devonian sedimentary rocks of the Meneage Formation within the footwall of the Lizard ophiolite complex in SW England by comparing detrital zircon suites derived from five samples analyzed from SW England (Avalonia) and NW France (Armorica). All the samples have a bimodal U–Pb zircon age distribution dominated by late Neoproterozoic to middle Cambrian (ca. 710–518 Ma) and Paleoproterozoic (ca. 1,800–2,200 Ma) populations. Both can be linked to lithologies exposed within the Cadomian belt, as well as the West African craton, which is characterized by major tectonothermal events at 2.0–2.4 Ga. Since the detrital zircon signature of Avalonia is distinct from that of Armorica in having a much larger proportion of Mesoproterozoic detritus, the authors conclude that the Meneage Formation mélange was derived from the Armorican plate during Rheic Ocean closure and obduction of the Lizard Complex and that previous correlation of quartzite blocks within the Meneage Formation with the Ordovician Grès Armoricain Formation of NW France is warranted.

Arenas et al. (2014) present a new U–Pb zircon age of 400 ± 3 Ma from a mylonitic greenschist from the Moeche Ophiolite, one of the mafic units involved in the Variscan suture in the Cabo Ortegal Complex (NW of the Iberian Massif). This unit is consequently a Devonian ophiolite, the most extensive group of oceanic units in the Variscan belt. The mafic rocks show transitional compositions between

N-MORB and island-arc tholeiites, although Lu–Hf isotope signatures in zircons clearly indicate contribution from an old continental source. εHf values in the analyzed zircons are negative (generally below $\varepsilon\text{Hf} = -5$), and not compatible with their generation from a juvenile mantle source. Instead, the igneous protoliths were generated in a setting where juvenile mafic magmas interacted with old continental crust. Devonian ophiolites from the Variscan suture have been repeatedly interpreted as remnants of the Rheic Ocean. However, the presence of a continental source in the mafic rocks of the Moeche Ophiolite makes an intra-oceanic setting for their generation very unlikely. Instead, the authors suggest an ephemeral oceanic basin opened within a continental realm and that the true Rheic suture is not represented in NW Iberia.

Three papers provide new insights into the evolution of the Pulo do Lobo suture zone, which is located between the South Portuguese Zone (Laurussia) and the Ossa-Morena Zone (Gondwana) in southwestern Iberia. Dahn et al. (2014) present a detailed geochemical and U–Pb geochronological study of the Peramora Mélange which is part of an accretionary complex within the suture zone and is characterized by fault-bounded units of meta-sedimentary rocks, mélanges and mafic complexes. A mafic block-in-matrix mélange has a juvenile, N-MORB composition, and a range of zircon ages that suggests incorporation of a sedimentary component. These data are interpreted to reflect erosion of a N-MORB source, mélange formation, and imbrication during Laurussia-Gondwana collision.

Gladney et al. (2014) provide U–Pb (zircon) geochronological constraints on a plutonic complex that intrudes the Pulo du Lobo suture zone. The Gil Márquez pluton is part of the composite Sierra Norte Batholith and consists of an older (ca. 355 Ma) gabbro, and younger syn- to late-kinematic (ca. 345 Ma) intermediate and felsic phases. Inherited ages indicate that Gil Márquez magmas traversed through South Portuguese Zone and Pulo do Lobo crust during emplacement. Post-kinematic granites are dated at ca. 335 Ma, which together with field relationships provide tight constraints for the latest stage of deformation in the suture zone.

Dupuis et al. (2014) provide geochemical and isotopic data on a suite of late stage mafic dykes that intrude the Pulo do Lobo suture zone. U–Pb zircon geochronology suggests a crystallization age of ca. 316 Ma and Sm–Nd isotopic data suggest a deep mantle source consistent with crustal delamination during the waning stages of Laurussia–Gondwana collision.

Pereira et al. (2014) use major and trace element geochemical and zircon U–Pb geochronological data to decipher the provenance of Carboniferous turbidites in the South Portuguese Zone (SW Iberia). The results indicate that sedimentation was marked by variability in sources, involving the denudation of different crustal blocks and a break in synorogenic volcanism. The Visean is characterized by the accumulation of immature turbidites (Mértola Formation and base of Mira Formation) derived from a terrane with intermediate to mafic source rocks and an almost total absence of pre-Devonian zircons typical of the Gondwana and/or Laurussia basements. The presence of Carboniferous grains in Visean turbidites indicates volcanism was active at this time. Serpukhovian to Moscovian turbiditic sedimentation (Mira and Brejeira Formations) includes sedimentary detritus derived from mature felsic source rocks situated far from active magmatism. The abundance of Precambrian and Paleozoic zircons reveals strong recycling of Gondwana and/or Laurussia basements. A peri-Gondwanan provenance is indicated by zircon populations with Neoproterozoic (Cadomian–Avalonian and Pan-African), Paleoproterozoic, and Archean ages. The presence of late Ordovician and Silurian detrital zircons in Brejeira turbidites, which have no corresponding sources in the Gondwana basement of SW Iberia, suggests Laurussia as the likely provenance.

Franke (2014) focuses on the tectonic significance of the widespread Devonian to early Carboniferous marine strata within the Variscan orogen of Europe. These strata occur in a variety of settings including foreland fold and thrust belts, in post-tectonic basins within these foreland belts, and within Cadomian basement. He interprets their distribution to preclude high elevations where they occur, implying that comparisons with Cenozoic evolution of the Himalayan/Tibetan plateau are unfounded. He proposes several mechanisms to account for the low elevations, with lithospheric thinning accompanied by high heat flow and magmatism caused by the Tethys rift being the favored mechanism accounting for the abundance of granitoids and HT/LP metamorphic belts.

Keppie and Keppie (2014; son and father) propose that Yucatán block was oriented NE–SW within the Ouachita embayment, instead of the E-W orientation indicated in most reconstructions. A NE–SW orientation minimizes overlap, simplifies magnetic anomaly distributions, and provides features that fit better with known features in the Grenvillian rocks and Appalachian rocks in that region. The implications of this reconstruction are that (1) much of the Yucatán has a Laurentian origin, (2) the Laurentia–Gondwana suture transects the Yucatán west of the Maya Mountains, and (3) the Ouachita embayment results from the formation of the Gulf of Mexico during the breakup of Pangea, instead of the Cambrian removal of the Argentine Cuyania terrane.

Lefort and Danukalova (2014) examine the elevation of the lowest part of the Upper Cretaceous–Eocene and Aktschagylian–Quaternary stratigraphic assemblages on the western slope of the Southern Urals, documenting the existence of an east–west elongated dome which follows the N53° latitude. At depth, the ridge is superimposed on remnants of the Sernovodsk–Abdulino Aulacogen and the Belaya tear fault, supporting recent rejuvenation of these old structures. North of these disruptions, the Southern Urals display a clear bend to the east. Detailed microstructural studies show that this curvature is associated with a typical stress pattern, suggesting the existence of an indentation of the fold belt by the East European craton. To the north, there is no evidence of an equivalent east–west deep-seated fault. However, a long N100° magnetic anomaly, interpreted as a shear zone, may represent the northern boundary of this Ufa indenter. Quaternary uplift and crustal thickening at the front, as well as seismological data, suggest the curvature of the Urals observed at 53° latitude represents rejuvenation of a preexisting structure in the East European craton and that some of the structures described on the URSEIS deep seismic profile may be much younger than previously thought.

Due to editorial problems, an additional paper that was intended to be included in this special issue was published earlier in a regular volume of the *International Journal of Earth Sciences*. In it, Gärtner et al. (2014, Volume 103, Issue 2, pp 579–595) reconstruct the tectonothermal evolution of the southern Congo Craton from the U–Pb ages of detrital zircons in recent fluvial sediments along the craton's southern margin. The results suggest that sources in the East Lufilian and Kibaran belts dominate, although input from the South Damara Belt increases to the west. Peaks in the age distribution indicate destabilisation of the craton's southern margin at ca. 2.7, 1.9, 1.0 and 0.6 Ga in accordance with major events within the supercontinent cycle.

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