The evolving continents: understanding processes of continental growth – introduction

TIMOTHY M. KUSKY[1], MINGGUO ZHAI[2] & WENJIAO XIAO[2]

[1]*Ministry of Education, Three Gorges Geohazards Research Center and State Key Lab for Geological Processes and Mineral Resources, China University of Geosciences, Wuhan, Wuhan, China*

[2]*Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing, China*

**Corresponding author (e-mail: tkusky@gmail.com)*

We have organized and edited this Special Publication of the Geological Society of London to honour the career of Brian F. Windley, who has been hugely influential in helping to achieve our current understanding of the evolution of the continental crust, and who has inspired many students and scientists to pursue studies on the evolution of the continents. Brian has studied processes of continental formation and evolution on most continents and of all ages, and has educated and inspired two generations of geologists to undertake careers in studies of continental evolution. The contributions in this volume represent only a small percentage of studies that Brian has influenced, yet the scope and significance of these papers are clear, and stand as a testimony to Brian's contributions to understanding processes of continental evolution, growth, and stabilization.

The volume is organized into six sections: oceanic and island arc systems and continental growth; tectonics of accretionary orogens and continental growth; growth and stabilization of continental crust: collisions and intraplate processes; Precambrian tectonics and the birth of continents; active tectonics and geomorphology of continental collision and growth zones.

The first section, oceanic and island arc systems and continental growth, begins with a paper by **Stern**, who summarizes the current state of knowledge about intra-oceanic arc systems from petrological, geophysical, and tectonic viewpoints and emphasizes that these systems have been the most important sites of juvenile continental crust formation for as long as plate tectonics has operated (the time of the start of plate tectonics is a matter of debate between some geologists). **Stern** describes the main components and zonation of intra-oceanic arc systems, including the trench, forearc, volcanic–magmatic arc, and back-arc, typically forming a system about 200 km wide, and strongly influenced by hydrous melting process in the underlying mantle. He then describes differences between the various stages of intra-oceanic arc systems, including juvenile arc lithosphere preserved in many forearcs, to mature arc systems where magmatism is concentrated along the magmatic–volcanic front. Mature intra-oceanic arc systems are typically extensional with volcanism and sea-floor spreading developing in the back-arc, and also show a transition in mantle types from serpentinized harzburgite beneath forearc sections, pyroxene-rich low-V_p mantle beneath the magmatic front, and lherzolite–harzburgite mantle beneath back-arc basins.

In the second paper in this section, **Xiao *et al.*** describe the major differences between the types of arc systems found in the circum-Pacific region, including Mariana-, Japan-, Cordillera-, and Alaska-type arcs, and compare these systems with accreted terranes in accretionary orogens. They show how arcs are complex systems that can be different along strike (such as in the Alaska-type systems), and change with time. They suggest that some unresolved issues in accretionary and collisional orogens may be related to geologists not appreciating some of the complexities in modern arc systems, and use examples from the Altaids and other systems to demonstrate their points.

Part 2 of the book, tectonics of accretionary orogens and continental growth, highlights a common thread of Brian Windley's multi-year efforts of trying to work out the framework and evolution of accretionary orogens. His studies followed through early studies on the Tien Shan, Altai, and Central Asian Orogenic Belt in Mongolia, the Solonker suture in China, the Qilian Shan, the western Kun Lun Mountains and the Bei Shan in China. His most recent work in Asia has all been done in collaboration with Xiao Wenjiao, and in the Mona Complex in Anglesey and Lleyn in Wales with Shigenori Maruyama. Appropriately, the first paper in this section is by **Maruyama *et al.*** They recognize three types of strongly imbricated oceanic plate stratigraphy in the Neoproterozoic accretionary orogen on the island of Anglesey and the Lleyn Peninsula.

From: Kusky, T. M., Zhai, M.-G. & Xiao, W. (eds) *The Evolving Continents: Understanding Processes of Continental Growth*. Geological Society, London, Special Publications, **338**, 1–6.
DOI: 10.1144/SP338.1 0305-8719/10/$15.00

These include an old section (at the structural top of the accretionary complex), a central section that was subjected to deep subduction and exhumed as blueschists, and the youngest section at the bottom of the structural sequence, which is an olistostrome-type deposit that formed by gravitational collapse of previously accreted material. **Maruyama *et al.*** use their structural observations to reconstruct the accretionary history of this orogen, providing a lesson to workers in other orogens world-wide about the use of recognizing and using ocean plate stratigraphy for deciphering the tectonics of accretionary orogens.

The second paper in this section is by **Santosh *et al.*** In this paper, the authors propose a new, untraditional classification of orogens that includes continental crustal material that is deeply subducted through tectonic erosion at trenches, subduction of young arc sequences, and continental collisions. Their classification includes: (1) deeply subducted material that is taken down to mantle depths and that never returns to the surface, termed ghost orogens; (2) orogens that are subducted to deep crustal levels, undergo melting and are recycled back to the surface, temporarily, called arrested orogens; (3) extant orogens, which are partly returned back to the surface after deep subduction; (4) concealed orogens, which have been deeply subducted and only the traces of which are represented on the surface by mantle xenoliths carried by younger magmas. **Santosh *et al.*** use this new classification to postulate material circulation within the Earth, throughout geological time, and note that this type of analysis leads to insight into understanding radiogenic heat generation in the mantle, and to models for the growth of continents through time.

The third paper in this section is by **Wilde *et al.*** In this paper the authors describe the geology and U–Pb geochronology of the Khanka Block, a poorly known part of the Central Asian Orogenic Belt. Granitic magmatism at 518 ± 7 Ma was followed by high-grade metamorphism at 500 Ma, suggesting a correlation with the Jiamusi block to the west. Younger magmatism at 112 ± 1 Ma in the Khanka Block is related to Pacific plate subduction and post-collisional extension. **Wilde *et al.*** suggest that the Khanka Block is a product of circum-Pacific accretion, and not a microcontinental block that was trapped by the northward collision of the North China craton with Siberia as part of the assembly of the main Central Asian Orogenic Belt.

Part 3 of the book, growth and stabilization of continental crust: collisions and intraplate processes, includes work related to Brian Windley's fascination with the $MgO–Al_2O_3–SiO_2–H_2O$ (MASH) system. In 1980, Brian organized a metamorphic group (with Dietrich Ackermand, Kiel and Richard Herd, Ottawa), whose aim was to calibrate natural mineral assemblages against equivalent, experimentally determined, assemblages in petrogenetic $P–T$ grids in the MASH system together with $P–T$ conditions calculated with standard geothermobarometric methods. For over 10 years they studied key assemblages, chemographic relationships, and specific mineralogical problems in rocks from the Limpopo belt in Zimbabwe; the Grenville belt in eastern Canada; Bahia, Brazil; Fiskenaesset, West Greenland; Madagascar; and Scotland. Their studies showed that it is possible to work out the complicated array of minerals, assemblages and reactions that are frozen into these refractory rock systems. In Limpopo rocks they defined 29 mineral reactions with 25 assemblages and used them to calculate an isothermal $P–T$ path without recourse to geothermobarometric methods. Appropriately, this section begins with a paper by **Razakamanana *et al.*,** on the petrology, chemistry, and phase relations of borosilicate phases in phlogopite diopsidites and granitic pegmatites from the Tranomaro belt, SE Madagascar, with special attention to the boron-fluid evolution. **Razakamanana *et al.*** discuss the role of boron-rich fluids in the evolution of Gondwana, including how the presence of sinhalite and serendibite associated with phlogopite lenses in metasedimentary diopsidites indicates an evaporitic origin from calc-silicate sediments. Other borosilicates are associated with shear zones that acted as conduits for the boron-rich fluids, derived from calc-silicate sedimentary protoliths. **Razakamanana *et al.*** use geothermometry and geobarometry of minerals from associated rocks to calculate that ambient pressures and temperatures changed in time from 7.5 to 4.0 kbar and from *c.* 800 °C to 700 °C. Their results confirm the important role of shear zones in channelling the fluid flow of boron-bearing fluids that were derived from crustal melt granites in the same shear zones, but that ultimately derived their boron from early metasediments.

The second paper in this section is by **Peng**, who uses the Taihang–Lvliang dyke swarm in the central North China craton as an example to show how these short-lived events are keys to the interpretation of continental evolution and tectonics, reconstruction of continental palaeogeographical regimes, and petrogenesis of the associated volcanism. **Peng *et al.*** relate this dyke swarm to the coeval Xiong'er volcanic province on the southern margin of the North China craton, and suggest that the dykes radiated from a triple junction rift centred on the Xiong'er volcanic province. The triple junction volcanism and radiating dyke swarms are related to the break-up of the North China craton at 1.78 Ga, which probably was influenced by the impact of a mantle plume at the base of the lithosphere. Similar volcanism and dyke swarms are located on other cratons, including the Uruguayan dykes on the Rio de Plata craton, the Avanavero dykes on the Guyana shield, the Crepori gabbro–dolerite sills and dykes in Australia (e.g. Harts Range volcanic rocks and sills and Eastern Creek volcanic rocks; Tewinga volcanic rocks; Mount Isa dykes; Hart doleritic sills) and possibly others (e.g. India: Dharwar dykes), and may relate to the break-up of the Columbia supercontinent.

Part 4 of the book is concerned with Precambrian tectonics and the birth of continents. This section highlights Brian's drive to apply the principles of uniformitarianism to help understand the evolution of ancient, complex high-grade terranes. Many of the secular research themes culminate in Brian's interest in the way the continents have evolved in the last 4 Ga. One of his main contributions has been in the form of innovative syntheses, using techniques such as U–Pb geochronology coupled with field mapping, to assess tectonic and crustal development of the Precambrian, and the wider issues of the growth and differentiation of the continental crust. This was initially done in collaboration with John Dewey, and all was brought together in his acclaimed book *The Evolving Continents* (Windley 1995). In his 1993 Hutton–Lyell commemoration paper to the Geological Society of London, Brian pointed out what uniformitarianism means today in terms of the operation of plate-tectonic processes since the start of the geological record.

Brian made the first proposal (with David Bridgwater) in 1971 that there are two main types of Archaean terrane representing different erosional levels, the greenstone–granite, and the then little known granulite–gneiss terranes. They also predicted that the oldest rocks were most likely to be found in deeply buried lower crustal rocks; later proved correct.

His work on the Archaean of West Greenland in the 1960s led to a detailed study with Joe Smith (1974) in Chicago of the silicate, oxide and sulphide chemistry of the anorthositic Fiskenaesset complex. They suggested that these rocks were tectonically intercalated with subduction-derived, tonalite-dominated continental rocks. Complementary geochemical studies were made by Barry Weaver and co-workers (1978) of Archaean complexes in the Limpopo belt of South Africa and the Scourian of Scotland. Joe and Brian first pointed out that Archaean tonalitic orthogneiss belts in the world most probably formed in Cordilleran–Andean-type continental margins later inter-thrust with oceanic crust. In 1980, Bob Newton, Joe Smith and Brian produced a new model to explain CO_2 vapour flux giving rise to carbonic metamorphism and formation of granulites. In a landmark paper, Norman Sleep and Brian proposed in 1982 that higher temperatures beneath Archaean mid-oceanic ridges resulted in more partial melting and at a greater depth than now, in turn resulting in an oceanic crust more than 20 km thick that was composed at least in part of tholeiitic lavas and anorthositic complexes. This model was widely supported by the geological community, and was used by Tim Kusky and co-workers to explain the thick sections of tectonically emplaced tholeiitic lavas in the Zimbabwean greenstone belts (Kusky & Kidd 1992; Kusky & Winsky 1995; Kusky 1998; Hoffman & Kusky 2004). With John Tarney *et al.* (1982), Brian suggested that tectonic underthrusting of Archaean oceanic crust into Archaean continental crust at Cordilleran-type margins led to crustal thickening and formation of granulites (followed by more thrust-controlled thickening in collisional environments.

Throughout much of Brian's career the mode of origin of many Precambrian orogens was poorly understood. For example, the role and implications of oceanic plateaux and Tibetan-type plateaux and their eroded and/or extended, collapsed equivalents were underestimated. Brian (Windley 1983) produced new ideas to explain the formation of four major Proterozoic orogens in terms of modern plate-tectonic processes: the Ketilidian in South Greenland, the Grenville in eastern North America, the Aravalli–Delhi in Rajasthan in NW India, and the Kola and Svecofennian orogens in the Baltic Shield. These studies showed that tectonic processes during the Proterozoic were not significantly different from those that operate today. With Japanese colleagues and Kevin Pickering, Brian produced a detailed comparative analysis of the similarities and differences between late Archaean island arcs and accretionary prisms and their close modern analogues in Japan (Taira *et al.* 1992).

The section begins with a review paper by **Kröner** about the role of geochronology in understanding continental evolution. **Kröner** highlights the importance of U–Pb dating for understanding processes of crustal growth and evolution, and discusses the merits of different techniques and how recent advancements such as the ability to perform *in situ* dating and to apply high-resolution ion microprobe and laser ablation inductively coupled plasma mass spectrometry to complex, multiple-deformed high-grade terranes has revolutionized models for crustal evolution that were previously based on just field and traditional geochronological and geochemical techniques. He shows how the combination of mineral ages with Sm–Nd, Lu–Hf and O isotopic systematics constrains magma sources and their evolution, and a picture is emerging that supports the beginning of modern-style plate tectonics in the Early Archaean.

Rollinson *et al.* contribute a paper on chromitites from the Fiskenaesset anorthositic complex, West

Greenland. The authors note that the chromitites in the Fiskenaesset complex have an unusual mineral assemblage, including highly calcic plagioclase, iron-rich aluminous chromites, and primary amphibole, and they relate its formation to partial melting of aluminous harzburgite in a mantle wedge above a subduction zone rather than in a continental layered intrusion. They propose that the aluminous mantle source of the parent magma was produced by the melting of a harzburgitic mantle refertilized by small-volume, aluminous slab melts. **Rollinson *et al.*** propose that this process ceased at the end of the Archaean because the dominant mechanism of crust generation changed such that the melt production shifted from the slab into the mantle wedge, thus explaining why highly calcic anorthosites are almost totally restricted to the Archaean.

Garde & Hollis describe an ophiolitic complex consisting of amphibolite-facies tholeiitic pillow lavas, chloritic shale, manganiferous banded iron formation (BIF), podded chert, jasper, andalusite–staurolite schist cut by numerous sills, and terrigineous sandstones in the northern Nagssugtoqidian orogen, West Greenland. By comparison with modern environments with similar rock associations such as the Resurrection ophiolite in southern Alaska, **Garde & Hollis** suggest that the ophiolite formed in a spreading centre undergoing burial in a forearc trench.

Zhai *et al.* follow with a paper on the Precambrian tectonic evolution of the North China craton. They outline the main crustal formation periods for the Precambrian evolution of the craton, beginning with the oldest crustal remnants forming at *c.* 3.8 Ga, and the main crustal formation events occurring between 2.9 and 2.7 Ga. They suggest that by 2.5 Ga these microblocks amalgamated to form a coherent craton, which was cut by a major dyke swarm at 2.5 Ga. Volcanic and plutonic belts formed between 2.3 and 1.95 Ga, and Palaeoproterozoic mobile belts formed as intracontinental orogens between 1.9 and 1.85 Ga. **Zhai *et al.*** note that the strong metamorphism at *c.* 1.8 Ga is not restricted to a central orogenic zone (termed the Trans-North China orogen) but instead is found nearly everywhere in the North China craton, so they argue that models calling for a simple collision between the western and eastern blocks of the craton at that time are not compatible with the data, including patterns of high-pressure and high-temperature or ultrahigh-temperature (UHT) metamorphism and uplift rates. **Zhai *et al.*** thus conclude that previous tectonic models for the North China craton need to be re-evaluated.

The final paper in this section is by **Oliveira *et al.*** on the the Itabuna–Salvador–Curaçá orogen, in the São Francisco craton, Brazil. They review the geology and present new U–Pb and Nd isotopic ages, along with major and trace element data to support a new tectonic model for the northern segment of the Itabuna–Salvador–Curaçá orogen in which oceanic and island arc sequences were accreted at 3.3 Ga to form the Mundo Novo greenstone belt, and then a second generation of accretion at 2.15–2.12 Ga formed the Rio Itapicuru and Rio Capim greenstone belts. Between 3.08 and 2.98 Ga, mafic crust experienced partial melting and formed the Retirolândia and Jacurici tonalite–trondhjemite–granodiorite belts of the Serrinha block. From 2.69 to 2.58 Ga an Andean-type arc with ocean crust remnants formed the Caraiba complex possibly at the Gavião block margin. Between 2110 and 2105 Ma, the Rio Itapicuru arc collided with the Retirolândia–Jacurici microcontinent, possibly involving slab breakoff. Oblique convergence between 2.09 and 2.07 Ga led to the collision of the Serrinha microcontinent with the Caraíba–Gavião superblock and reworked the Caraíba arc to granulite facies, locally at UHT conditions. At the same time, arc dacites spread over the Rio Itapicuru greenstone belt, and the 3.12–3.0 Ga Uauá terrane, crosscut by 2.58 Ga mafic dykes, extruded from south to north possibly together with the 2.15 Ga Rio Capim greenstone belt.

Part 5 of the book is on active tectonics and geomorphology of continental collision and growth zones. In 1979, Brian started British research in the Himalayas and Karakorum, partly because of the opening of the Karakorum Highway, and partly because at that time these classic orogenic belts were known only in reconnaissance outline. He also felt that a better understanding of Precambrian tectonics depends on a better knowledge of modern collisional orogenic belts. His NERC grant lasted for 10 years and brought to that region more than 20 students and staff, most notably Mike Coward, Mike Searle, and Qasim Jan. They produced new data on the lithology and structure, mineralogy, geochemistry, and isotopic history of the Pakistan Himalayas, and produced a comprehensive model for the igneous and tectonic development of the Kohistan arc–batholith in terms of a three-stage plutonic development (island arc, Andean-type batholith, post-collisional leucogranites), and for the mineral chemistry and tectonic environment of the Chilas complex that formed in the magma chamber of the island arc. In 1986, they produced a comprehensive synthesis of the tectonic evolution of the Himalayas (Coward *et al.* 1986; Searle & Windley 1986; Hoffman & Kusky 2004). With two mountaineering post-doctoral research fellows, Mike Searle and Tony Rex, Brian organized the remapping and study of structural and magmatic development of the Karakorum mountain range, which contains a mid-crustal gneissic block intruded by a mid-Cretaceous Andean-type granitic batholith, uplifted by thrusting and intruded by a crustal melt leucogranitic batholith in the Miocene.

The 7000 m Tien Shan and 4000 m Altai mountain ranges of Central Asia formed 2000 km and 2500 km respectively from the main deformation front in the Himalayas as a result of the post-collisional indentation of India into Asia. Brian's work in the Tien Shan with Mark Allen (Windley *et al.* 1990) led to new data and ideas on the Palaeozoic collision tectonics, the Mesozoic basin development, redeformation in the Late Cenozoic, and active tectonics of the region. They demonstrated for the first time that there are two Palaeozoic sutures in the Tien Shan, and that the Turfan basin has been downloaded by Cenozoic thrusts. The Altai is the northernmost mountain belt to be thrust and uplifted as a result of the India–Asia collision. Later, Dickson Cunningham and Brian carried on these ideas into the Altai in Mongolia, where transpressional restraining bends have controlled the uplift of flat-topped mountains in the Cenozoic (Cunningham *et al.* 1996).

In the first paper in this section, by **Petterson**, reviews more than 100 years of geological observations in Kohistan, including work he and Brian Windley were involved with during the past 30 years. The great bulk of the 30 000 km^2 Kohistan terrane represents growth and crustal accretion during the Cretaceous in an intra-oceanic island arc dating from *c.* 134 Ma to *c.* 90 Ma. This early period saw the extrusion and deposition of a *c.* 15–20 km thick arc sequence as well as the intrusion of the oldest parts of the Kohistan batholith, lower crustal plutons, crustal melting and the accretion of an ultramafic mantle–lower crust sequence. The crust had thickened sufficiently by *c.* 95 Ma to allow widespread granulite-facies metamorphism to take place within the lower arc. At around 90 Ma, Kohistan underwent a *c.* 5 Ma long high-intensity deformation caused by collision with Eurasia. Kohistan, now an Andean margin, was extended and further volcanic and plutonic series were emplaced. Collision with India at *c.* 55–45 Ma saw the rotation, upturning, underplating and wholesale preservation of the terrane. The Kohistan terrane represents a complete section through juvenile crust extracted from the mantle in a subduction-zone setting. The differences in composition between Kohistan and average continental crust indicate the substantial fractionation undergone by primitive arc crust to form mature continental crust.

The second paper in this section, by **Allen**, covers the roles of strike-slip faulting during continental deformation, with examples from the active Arabia–Eurasia collision. **Allen** notes that the active strike-slip faults in the Arabia–Eurasia collision zone play several roles, including acting as collision zone boundaries, accommodating tectonic escape, as strain partitioning structures, as shortening arrays, and as transfer zones. **Allen** notes how complex the roles of these strike-slip fault systems are in this active collision zone, and suggests that understanding their complexity can be used as a lesson for interpreting ancient orogens.

The third paper is by **Searle & Treloar**, and poses the question 'Was Late Cretaceous–Paleocene obduction of ophiolite complexes the primary cause of crustal thickening and regional metamorphism in the Pakistan Himalaya?' They note that the Pakistan Himalaya includes both ultrahigh-pressure coesite eclogite rocks and medium-pressure and -temperature kyanite–sillimanite-grade Barrovian metamorphic rocks that show that peak conditions were reached at about 47 Ma. ^{40}Ar–^{39}Ar hornblende cooling ages date post-peak metamorphism of both units through 500 °C by 40 Ma, some 20 Ma earlier than for metamorphic rocks in the central and eastern Himalaya. **Searle & Treloar** propose a new idea in which the earlier metamorphic and cooling ages of the Pakistan Barrovian metamorphic sequence are partially explained by Late Cretaceous to Early Paleocene crustal thickening linked to obduction of an ophiolite thrust sheet onto the leading edge of the Indian plate. Heating following on from this Paleocene crustal thickening explains peak Barrovian metamorphism within 5–10 Ma of subsequent obduction of Kohistan. Remnants of the ophiolite sheet, and underlying Tethyan sediments, are preserved in NW India and in western Pakistan but not in north Pakistan, suggesting that tectonic erosion has removed the ophiolites and other cover sequences from the Indian plate basement.

This section continues with a paper by **Cunningham** on the tectonic setting and structural evolution of the Late Cenozoic Gobi Altai orogen. This orogen is an intraplate, intracontinental transpressional orogen in southern Mongolia that formed in the Late Cenozoic as a distant response to the Indo-Eurasia collision. The basement consists of a series of Palaeozoic accreted terranes intruded by granitic rocks. The Quaternary faulting largely follows, and is controlled by Palaeozoic basement structural trends, Precambrian basement blocks, and stresses from the India–Asia collision. Some modifications of the fault pattern may have been induced from thermal weakening of the lower crust.

The final paper in this section is a review by **Owen** on the landscape development of the Himalayan–Tibetan orogen, focused on the dynamics of landscape development within the orogen. **Owen** describes many tectonic–climate–landform development links, including the influence of climate on surface uplift by denudational unloading; the limiting of topography by glaciation; localized uplift at syntaxes by enhanced fluvial and glacial erosion that, in turn, weaken the lithosphere, enhancing surface uplift and exhumation. He also documents climate-driven out-of-sequence thrusting and crustal channel flow; glacial damming leading to differential erosion and uplift; paraglaciation; and the influence of extreme events such as earthquakes, landslides, and floods as major formative processes. This contribution demonstrates how new technologies such as satellite remote sensing, global positioning system, and numerical modelling have led to recent advances in understanding landform development in active collision zones.

In summary, the papers in this volume attest to the remarkable and highly influential career of Brian Windley, and highlight some of the fundamental contributions he has made to understanding the evolution of the continental crust. Brian's career began with some of the oldest rocks on Earth in Greenland, and slowly evolved into neotectonics in central Asia, but his feet never left the foundation of the Precambrian. Brian has consistently applied principles of uniformitarianism to the analysis of old terranes, and his interdisciplinary approach to understanding continental tectonics and evolution from the oldest to the youngest terranes on Earth has shown how the same physical processes have operated throughout geological time. *Salut* to you Brian!

We would like to acknowledge the many reviewers of papers in this volume, including D. Cunningham, P. Mann, A. Polat, L. Ashwal, J. Connelly, T. Raharimahefa, M. Santosh, S. Liu, R. van Schmus, H. Halls, M. Sun, N. Pinter, L. Wang, L. Webb, R. Stern, O. Jagoutz, S. Wilde, B. Windley, H. Rollinson, and several anonymous reviewers.

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