

# Fifty years of the Wilson Cycle concept in plate tectonics: an overview



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**Abstract:** It is now more than 50 years since Tuzo Wilson published his paper asking ‘Did the Atlantic close and then re-open?’. This led to the ‘Wilson Cycle’ concept in which the repeated opening and closing of ocean basins along old orogenic belts is a key process in the assembly and breakup of supercontinents. This implied that the processes of rifting and mountain building somehow pre-conditioned and weakened the lithosphere in these regions, making them susceptible to strain localization during future deformation episodes. Here we provide a retrospective look at the development of the concept, how it has evolved over the past five decades, current thinking and future focus areas. The Wilson Cycle has proved enormously important to the theory and practice of geology and underlies much of what we know about the geological evolution of the Earth and its lithosphere. The concept will no doubt continue to be developed as we gain more understanding of the physical processes that control mantle convection and plate tectonics, and as more data become available from currently less accessible regions.

Over five decades have passed since Tuzo Wilson published his paper asking ‘Did the Atlantic close and then re-open?’ (Wilson 1966). This paper emerged at a key time in the development of the theory of plate tectonics (Oreskes 2013), and was one of a number of seminal papers Tuzo Wilson wrote that shaped our understanding of plate tectonics. This was not the first time that a reconstructed fit of the North Atlantic had been presented, with various researchers including Wegener (1929), Argand (1924), Choubert (1935), Du Toit (1937) and Bullard *et al.* (1965), all having published reconstructed maps previously. It was, however, the observation that the present day North Atlantic margin (which opened in the Mesozoic) lay in very close proximity to a much older faunal divide (Fig. 1) which led Tuzo

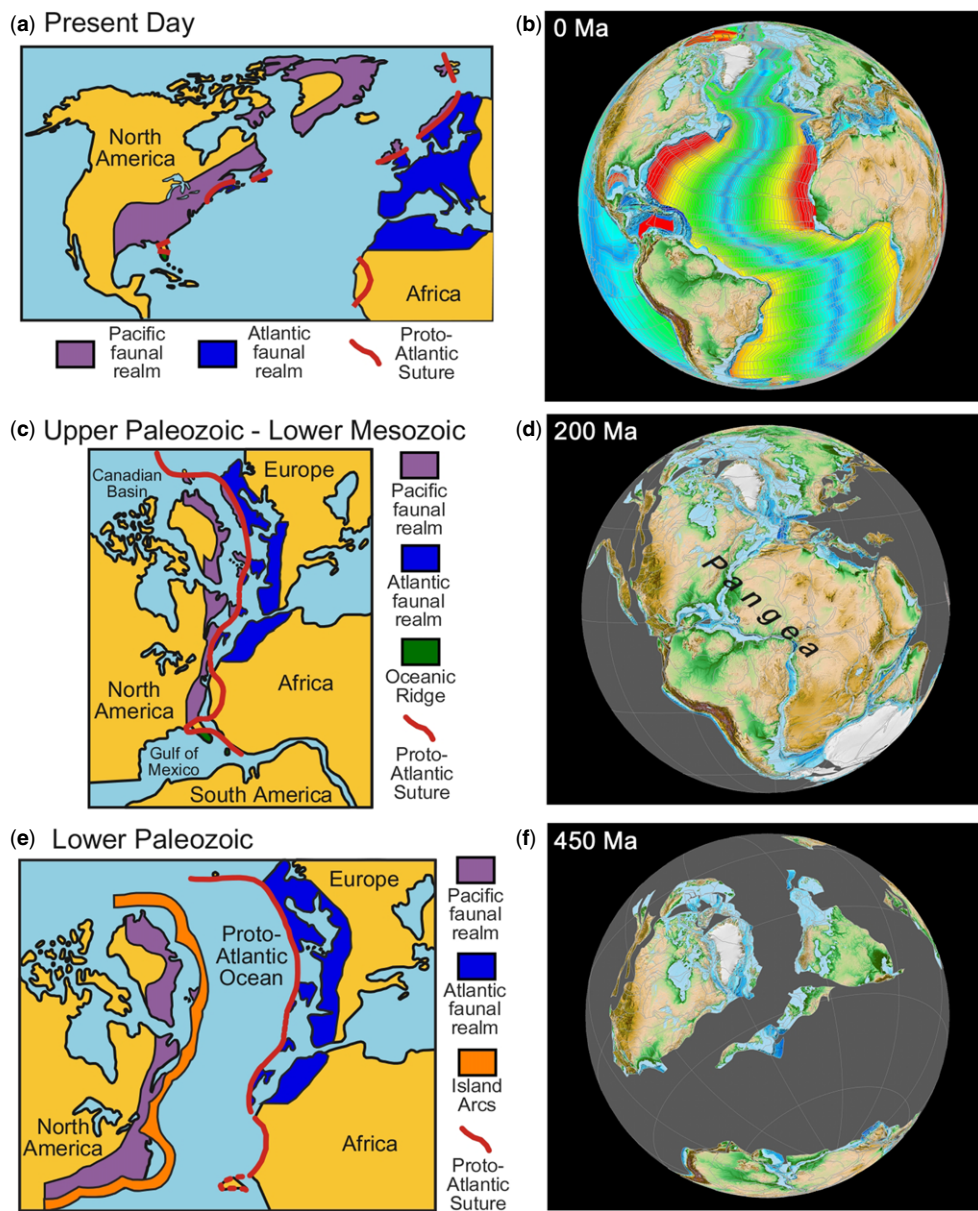
Wilson to propose that the present-day ocean must have formed along the remnant suture of an older Lower Paleozoic ocean, which he named the proto-Atlantic Ocean (Fig. 1; an ocean we now know as the Iapetus Ocean; Harland & Gayer 1972). By making this observation, Tuzo Wilson fundamentally changed the newly emerging concept of plate tectonics from what some argued to be a relatively young (Mesozoic and younger) geological phenomenon, to the key control on almost all crustal architectures we see today. These observations were also the foundation of the concept that later came to be known as the Wilson Cycle (Burke & Dewey 1975), whereby successive ocean basins are opened by extensional and spreading processes then closed by subduction and collisional orogenesis.

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**Fig. 1.** Comparison of Tuzo Wilson's 1966 reconstructed maps for the North Atlantic (panels a, c, e redrawn by Buiter & Torsvik 2014 and reproduced with permission by Elsevier) with modern day examples using GPlates (b, d, f; Müller *et al.* 2018). Plate reconstruction models (e.g. plates ant rotation files) shown in (b), (d), (f) are from CGG Plate Kinematics. Oceanic crust in (b) coloured by isochron ages from Müller *et al.* (2018). Topography in (b), (d), (f) from ETOPO global grid (Amante & Eakins 2009).

## The Wilson Cycle

The Wilson Cycle, also termed the Plate Tectonic Cycle, and coupled by some with the Supercontinent Cycle (Nance *et al.* 1988), is fundamental to the

theory of plate tectonics. It outlines the concept in which the repeated opening and closing of ocean basins along the same plate boundaries is a key process in the assembly and breakup of continents and supercontinents. This implies that the processes of

rifting and mountain building somehow pre-conditioned and weakened the lithosphere in these regions, making them susceptible to strain localization during future deformation episodes (Audet & Bürgmann 2011; Buiter & Torsvik 2014).

As outlined in Table 1 and Figure 2, the six-stage cycle for opening and closing of ocean basins (only later termed the Wilson Cycle) comprises: (1) the dispersal (or rifting) of a continent (Embryonic Ocean); (2) the formation of a young new ocean by seafloor spreading (Young/Juvenile Ocean); (3) the formation of large oceanic basins by continental drift (Mature Ocean); (4) new subduction initiation (Declining Ocean); (5) the subsequent closure of oceanic basins through oceanic lithosphere subduction (Terminal Ocean); and (6) continent–continent collision and closure of the oceanic basin (Relic Suture Zone). This cycle was developed in Wilson's paper of 1968 and further adapted by Dietz (1972), Jacobs *et al.* (1973) and Burke & Dewey (1975). In recent years there has been increased recognition for tectonic deformation phases that were not originally accounted for in these early works, such as intracontinental/epicontinental sag basins (e.g. Paranaíba Basin in Brazil and West Siberia Basin in Russia; Middleton 1989; Allen *et al.* 2015; Daly *et al.* 2018).

A number of retrospective papers have been published in recent times, highlighting the work and notable contributions by Tuzo Wilson to plate tectonics (Garland 1995; Polat 2014; Dewey 2016) and the Wilson Cycle concept more generally (Burke 2011; Buiter & Torsvik 2014). Between 1961 and 1968, Tuzo Wilson made several seminal contributions to our understanding of Earth Sciences, identifying a number of key elements of global geodynamics that dominated the evolution of our planet, namely plate tectonics, mantle plumes of deep origin and the 'Wilson Cycle' of ocean opening and closing (Burke 2011). The Wilson Cycle concept was then further developed and applied on a more global scale during the following decades. The following sections form a brief review of the development of the Wilson Cycle concept, starting with early notable works prior to those of Tuzo Wilson; the key seminal works during the plate tectonic revolution of the 1960s; early adaptors and the evolution of the concept over the following decades; and a brief look at more recent trends.

### Early drifters (pre-1960)

As with the development of most concepts, there are a number of precursor works that are worthy of note. Alfred Wegener's (1912) paper 'On the origin of continents' is widely acknowledged as the seminal paper on the concept of continental drift, by recognizing that Europe and Africa were once connected to

North and South America as a supercontinent (Pangaea; Fig. 1d). As the observations could not be explained by a physical theory that allows the continents to drift, Wegener's concept met fierce debate (Waterschoot van der Gracht *et al.* 1928). Émile Argand, an early proponent of Alfred Wegener's theory of continental drift, went on to propose that the Appalachian–Caledonian, Alpine and Himalayan mountains chains formed by the collision of continental terranes (Argand 1924). It was in this 1924 paper that Argand first described a proto-Atlantic Ocean (the name later used by Wilson (1966) for what we now know as the Iapetus and Rheic Oceans, Harland & Gayer 1972; McKerrow & Ziegler 1972) in relation to the origin of the North American Caledonides.

Another less well-known work was by Russian–French geologist Boris Choubert. In 1935 Choubert published a reconstructed map of the pre-breakup ('Hercynian') circum-Atlantic continents, highlighting the distribution and correlation of Paleozoic and Precambrian orogenic basement terranes. Building on the concepts proposed by Argand (1924), Choubert (1935) proposed that these Paleozoic orogenic belts formed as the result of the collision of ancient cratons. Though not able to define the driving forces (attributing variations to 'slowdowns or accelerations in the Earth's rotation'), Choubert suggested that the formation of coastal mountains is unlikely during the divergent 'drift' of continents, and thereby formulated cycles of convergence and divergence akin to those of the modern-day Wilson Cycle. Perhaps because Choubert's paper was published in French, it was overlooked by various researchers, including Bullard *et al.* (1965), Wilson (1966) and others, in the early 1960s. Furthermore, the title of Choubert's paper ('Research on the genesis of Paleozoic and Precambrian belts') did not reveal its full scientific content, and thus probably contributed to its lack of wider acknowledgement (Kornprobst 2017). Thankfully, in recent years this early work of Choubert has started to receive the recognition it deserves (Kornprobst 2017; Letsch 2017). Other notable contributions that pre-date the Plate Tectonic paradigm of the 1960s include Alexander Du Toit (1937) and Arthur Holmes (1931, 1944). Du Toit (1937) proposed the first supercontinents, Laurasia and Gondwana, of Paleozoic age. The work of Holmes (1944) overcame one of the important obstacles to the theory of plate tectonics, the lack of a mechanism that explained continental movements. Holmes proposed that Earth's mantle flows over geological time in convection cells and that this flow moves the crust at the surface. These developments enabled the emergence of the concepts of seafloor spreading and the formation of mid-ocean ridges (Heezen & Tharp 1965; Vine 1966). It should be stressed, however, that teaching on global tectonics

**Table 1.** The six-stage Wilson Cycle of opening and closing of basins as proposed by Wilson (1968)

Tectonic cycle	Stage	Examples	Dominant crustal motions (and drivers)	Geological and geomorphic characteristics	Igneous rock types	Sedimentary systems	Metamorphism (grade)
Ocean opening	(1) Embryonic rift	East African Rift; Gulf of Suez, Egypt	Rapid basin Subsidence (crustal thinning) and localized uplift (thermal)	Rift valleys	Tholeiitic basalts, alkali basalt centres (hot spots)	Minor sedimentation, terrestrial (fluvial, alluvial, lacustrine) to shallow marine setting	Negligible
	(2) Young ocean	Red Sea, Gulf of Aden; Baja California	Basin subsidence (thermal) divergence/spreading (ridge push?)	Narrow seaways with central depression and young active spreading ridge	Tholeiitic basalts (inc. MORB), alkali basalt centres (hot spots)	Shelf and basin deposits; evaporites common	Minor (local low grade/thermal)
	(3) Mature ocean	Atlantic Ocean; Indian Ocean	Basin subsidence (thermal) divergence/spreading (ridge push?)	Large ocean basins with active spreading ridge	Tholeiitic basalts (inc. MORB), alkali basalt centres (hot spots)	Abundant shelf to deep marine deposits	Minor (local low grade/thermal)
Ocean closing	(4) Declining ocean	Pacific Ocean	Shrinking/subduction local subsidence (flexure and slab pull?)	Island arcs and deep ocean trenches round ocean margins	Andesites, granodiorites at margins	Abundant deposits derived from island arcs	Locally extensive (moderate)
	(5) Terminal ocean	Mediterranean Sea; Black Sea; Caspian Sea	Shrinking/subduction Local uplift (compression) and subsidence (flexure)	Young mountains and restricted seaways	Volcanics, granodiorite at margins	Abundant deposits derived from island arcs; evaporites possible	Locally extensive (moderate-high)
	(6) Continental orogen	Indus Line in Himalayas; Iapetus Suture in the Caledonides	Regional uplift (crustal shortening)	Young, extensive, high mountains, foreland basins	Minor	Extensive terrestrial (aeolian red beds) and marine clastic systems	Extensive (high)
Cratonic	(7/0) Relic scar/geosuture	Onshore North America, Australia, Africa	Stable onshore continental settings	Extensive plains and low relief topography	Minor	Terrestrial (aeolian red beds)	Minor
	(8) Intracratonic sag basin	West Siberia, Russia; Paranaiba, Brazil	Slow/gradual basin Subsidence (thermal?)	Wide, shallow basins in terrestrial to shallow marine setting	Limited	Regionally extensive sedimentary systems in a Paralic setting	Negligible

The table presented is modified after the original in Jacobs *et al.* (1973) and later re-published in Burke (2011). Modifications to the original include the addition of Intra-cratonic Sag Basins (incorporating learnings from Daly *et al.*, this volume), plus some minor re-wording/revised terminologies. MORB – Mid Ocean Ridge Basalts.

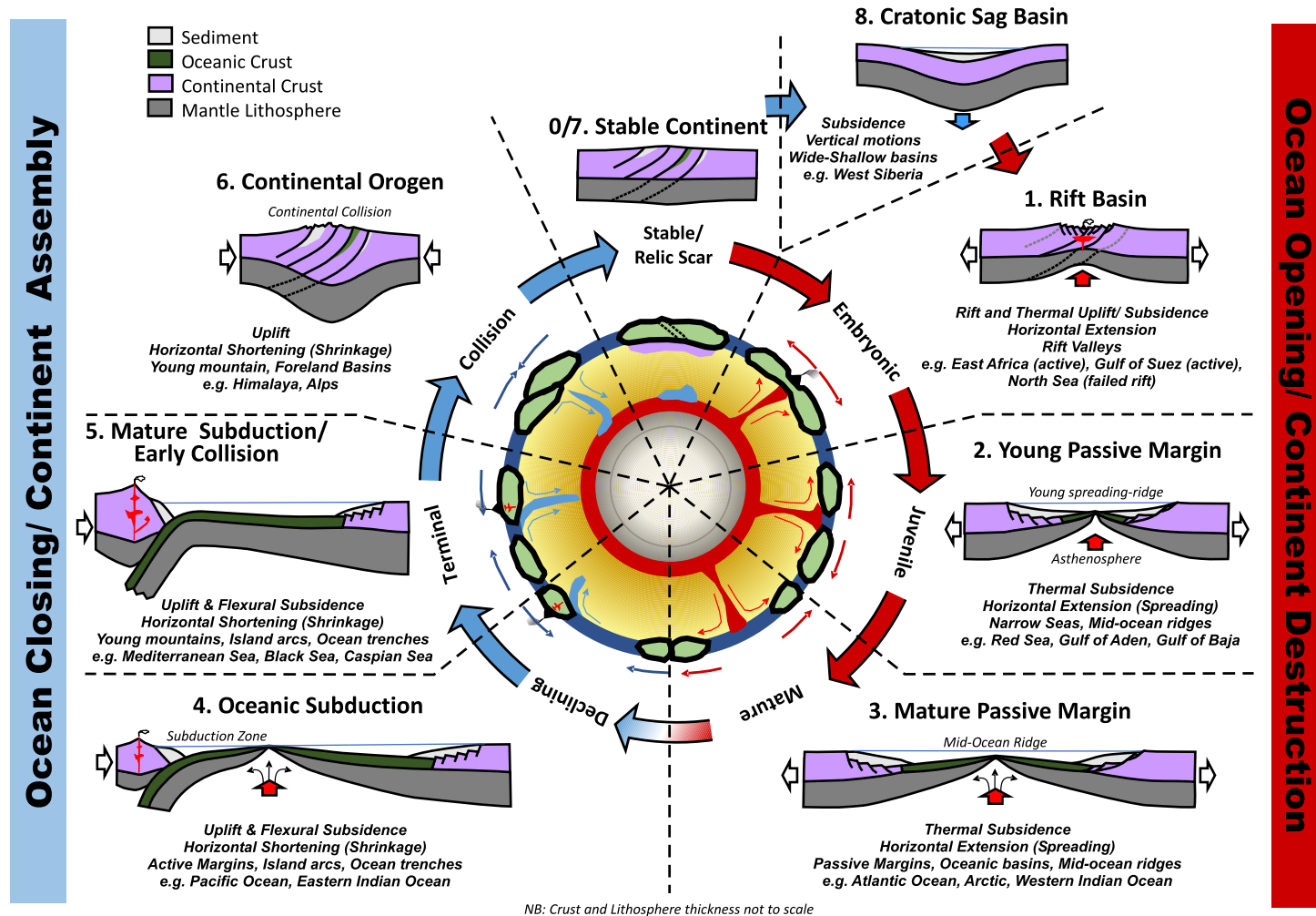


Fig. 2. Stages of the Wilson Cycle as defined in Table 1.



prior to the mid-1960s was still overwhelmingly dominated by geosynclinal theory. Geosynclines were defined as continental-scale superbasins encompassing what we now recognize as passive margins, forelands, trenches and back-arcs, which were subject to deformation and mountain-building while remaining fixed on the globe (e.g. Kay 1951; Aubouin 1965). The subsequent complete obliteration of geosynclinal theory in just a few years, and its replacement by plate tectonics, was undoubtedly the most significant paradigm shift in geology since the mid-19th century.

### **Tuzo Wilson and the plate tectonic revolution of the 1960s**

*Tuzo Wilson* was one of the key contributors to the so-called ‘Plate Tectonic Revolution’ of the 1960s (Dietz 1977; Mareschal 1987). Prior to the 1960s, however, Tuzo Wilson is well known to have been in opposition to models for continental drift and mantle convection (Hoffman 2014; Dewey 2016), preferring a ‘fixed model’ of progressive continental accretion around fixed Archean nuclei (Wilson 1959). However, by late 1961 Tuzo’s opinions towards continental drift began to change rapidly, apparently on reading the papers by Dietz (1961) and Hess (1962) on seafloor spreading and its role in continental drift (Wilson 1961; Hoffman 2014). It is perhaps due to the fact that prior to 1961 Tuzo Wilson was such a staunch ‘anti-drifter’ that he was not aware of the earlier works that supported the new ideas that he formulated himself in the mid-late 1960s.

On rescinding his scepticism of continental drift theory, he quickly moved on to produce a number of seminal contributions to our understanding of seafloor spreading, mantle plumes, plate tectonics and the life cycles of ocean basins (Wilson 1962a, b, 1963a, b, 1965, 1966, 1968; Vine & Wilson 1965; Frankel 2012). To change ones’ opinions so dramatically commands respect, let alone the fact that he then went on to be one of the key influencers in developing these new models through the 1960s. At the time of this reversal in thinking, from fixism to drifter, Tuzo Wilson was already 53 years old and a leading international figure in Earth science. This renunciation of one model for another would not only have taken courage, but it also emphasizes the vision that he must have had, and clearly his dramatic actions inspired others at the time too (see the accounts of Burke 2011; Dewey 2016; and Dalziel & Dewey 2018; on the influence of Tuzo Wilson in their early careers).

In 1965, Tuzo Wilson was on sabbatical in Cambridge (Dewey 2016), working with *Harry Hess* and *Teddy Bullard*. At this time Tuzo Wilson was also

recognizing the role of transform faults at ocean ridges (Wilson 1965), while Bullard was publishing his quantitative fit of circum-Atlantic continents (Bullard *et al.* 1965). It is likely that this close interaction led Tuzo to utilize Bullard’s reconstruction as the basis for his 1966 paper. In the following years several other seminal papers were published (e.g. McKenzie & Parker 1967; Isacks *et al.* 1968; Le Pichon 1968; Morgan 1968), establishing the concept of plate tectonics as the basis for our subsequent understanding of geology.

Soon after, Tuzo Wilson (1968) went on to describe the three key elements of geodynamics: plate tectonics, mantle plumes and the opening and closing of oceans (Burke 2011). It was in this 1968 paper that an early version of Table 1 was first published (later published in Jacobs *et al.* 1973 and Burke 2011). The original table clearly describes the six key stages of the tectonic cycle (later to become known as the Wilson Cycle) of opening and closing of oceans, and their wider geological impact. Figure 2 highlights these various stages of ocean opening and closing, and also includes new thinking with regards continental sag basins and mantle dynamics.

### **Maturing of the Wilson Cycle concept**

Over the following decade, the concept of repeated opening and closing of oceans was actively adopted by a number of authors, notably by *Kevin Burke*, *John Bird*, *John Dewey* and *Robert Dietz* (Dewey 1969; Bird & Dewey 1970; Dewey & Bird 1970; Dietz 1972; Burke & Dewey 1975; Burke *et al.* 1977). Dewey (2016) records how Tuzo Wilson personally influenced his early development as a research student, recalling the moment Tuzo Wilson first presented to him his new research on a new class of fault: ‘ridge transform faults’ (later published; Wilson 1965). It was not, however, until the early 1970s that the term ‘Wilson Cycle’ came in to practice, with Burke & Dewey (1973, 1974, 1975). Burke and Dewey went on to discuss the role of hot spots/mantle plumes in the context of the Wilson Cycle (Burke & Dewey 1974; Thiessen *et al.* 1979) and also to map former ocean sutures globally (Burke *et al.* 1977). Dietz (1972) published one of the earliest visual depictions of the Wilson Cycle (i.e. precursor versions to the cross sections presented in Fig. 2) and provided an explanation of these new tectonic concepts in the context of geosynclinal models; many of these terminologies have since gone, but the images still bear strong similarity to those we use today.

Although initially described in the context of the opening and closing of oceans, the Wilson Cycle is also now widely recognized in terms of the tectonic

amalgamation and breakup of continents (Fig. 2; Table 1). Nance & Murphy (2013) highlight that although Tuzo Wilson was the first to identify tectonic episodicity in the context of oceanic plate tectonics, others were identifying similar patterns within the continents during this period (e.g. Holmes 1944; Sutton 1963). However, as much of the new data and learnings that helped formulate plate tectonic theory were collected in the 1960s, these learnings from the continental realm were not integrated until later.

By the 1980s correlations were being made between plate tectonics (in particular the formation of supercontinents such as Pangaea), and Earth's geologic, climatic and biological records. The concept that much of Earth history has been punctuated by the episodic amalgamation and breakup of supercontinents, which then influenced the wider geological record, is commonly termed the *Supercontinent Cycle* (Nance *et al.* 1988; Nance & Murphy 2013). Supercontinent assembly and breakup was first proposed by Thomas Worsley, Damian Nance and Judith Moody (Worsley *et al.* 1984). Although the existence of the supercontinent Pangea was first proposed by Wegener (1912), the proposition that other supercontinents have existed through Earth history is still debated (Nance *et al.* 2013; Nance & Murphy 2018), although this in part may be linked to discrepancies in how a 'supercontinent' is actually defined. Fundamentally the terms Wilson and Supercontinent Cycles may be interchangeable as both refer to the assembly and breakup of continents; however, others prefer to keep them separate as they may operate on significantly different time, and perhaps also spatial, scales (see Heron 2018).

As the concept of the Supercontinent Cycle took shape, large-scale episodicity was recognized in many other Earth processes beyond simply tectonic motions (e.g. ore genesis; Meyer 1981; magmatism, Engel & Engel 1964; global sea-level; Vail *et al.* 1977; climate, Fischer 1981 and 1984; and evolutionary biogenesis, Hallam 1974). Links and commonalities in these cycles suggest that these are part of a wider integrated system with interdependencies and feedback loops (Whitmeyer *et al.* 2007). Whether it is termed the Wilson Cycle, or the more encompassing Supercontinent Cycle, the tectonic episodicity identified by Tuzo Wilson in his 1966 paper defines a fundamental aspect of Earth's tectonic, climatic and biogeochemical evolution over much of its history.

## Deepening our understanding

Ideas of continental drift were originally inspired by geological observations, but general acceptance by the earth-science community of plate tectonics and the Wilson Cycle followed two major developments.

Firstly, the global seismograph network (Oliver & Murphy 1971) allowed accurate determination of earthquake locations and mechanisms, delineating the subducted slabs in the Earth's mantle that accommodate ocean closure. Secondly, the mapping of magnetic anomalies in the oceans allowed the age of the ocean floor to be determined almost everywhere once the idea of geomagnetic field reversal was established (Vine & Matthews 1963). The concept of seafloor spreading was greatly helped by the recognition of the Mid-Atlantic Ridge through the early seafloor maps of Tharp and Heezen in the 1950s (Barton 2002). The theoretical understanding of why plate tectonics occurs developed more slowly. A key step in this development was the recognition by Holmes (1915) that radioactive decay was an important source of heat in the Earth. Equally important was the realization by Haskell (1937) that the post-glacial uplift of previously glaciated lands in Fennoscandia could be attributed to the viscous flow of the Earth's mantle, and thereby permitted an estimate of the viscosity of the Earth's mantle. With this knowledge of the physical properties, those who understood the theory of thermal convection (e.g. Holmes 1931, 1944) developed by Rayleigh (1916) appreciated that convection in the Earth's mantle had a firm physical basis and might explain features of surface geology such as mobile continents, rifting and convergent mountain belts, even before the data-driven advances of the 1950s.

Turcotte & Oxburgh (1967) provided one of the first quantitative analyses of how the oceanic lithosphere could be understood as the upper boundary layer of a convecting mantle. However, a deeper understanding of mantle convection and how it relates to plate tectonics and the Wilson Cycle awaited the development of fast electronic computers. A landmark contribution by McKenzie *et al.* (1974) developed the idea of using numerical solutions to the equations governing convection to explain the effects of mantle convection on surface observables like plate velocity, topography, gravity and heat flow. With the subsequent explosion in computational power available for such investigations, computer-based simulations of convection have become an essential tool in exploring how mantle convection governs plate tectonics. Schubert *et al.* (2001) provide a comprehensive review of the many contributions made in this area in the last quarter of the twentieth century, but the topic continues to attract many researchers and increasingly sophisticated computational methods now allow plate tectonic models to be meshed with mantle convection models in a dynamically self-consistent way (e.g. Conrad & Gurnis 2003; Zahirovic *et al.* 2012; Yoshida & Santosh 2014). Allowing for the variability of physical properties like viscosity, the possibility of phase changes and the intrinsic time-dependence

of 3D convection solutions, there is a huge scope for complexity in the numerical solutions – and apparently in the Earth. Convection cells that can spontaneously re-organize, or even reverse direction, are observed in numerical models and are probably fundamental in explaining the Plate Tectonic Cycle. *Zhong et al. (2007)* demonstrate degree-1 convection planforms which would lead to super-continent amalgamation, and degree-2 planforms where dispersal is more likely, and speculate that the alternation of these two modes of mantle convection through geological time could cause the Super-continent Cycle.

The computer revolution and rapid expansion of seismograph networks also enabled another major development in global geophysics, which is central to our understanding of the global plate tectonic cycle. Prior to the 1980s the structure of the Earth at large scale was essentially understood to be radially stratified, but almost nothing was known of lateral variation within the Earth apart from the existence of Wadati–Benioff earthquake zones (*Wadati 1935; Benioff 1949*). The concept of global seismic tomography introduced by *Dziewonski (1984)* and *Woodhouse & Dziewonski (1984)* enabled earth scientists to map lateral variations in seismic velocity, which gave new insights into the forces driving convection and plate tectonics. One of the first results to emerge from global seismic tomography was the unsuspected existence of a large-scale degree-2 density anomaly which is now understood to be explained by two massive structures that rise hundreds of kilometres above the core–mantle boundary and are called Large Low Shear Velocity Zones situated beneath Africa and beneath the Pacific. The relocation of hot-spot activity through geological time suggests that the Low Shear Velocity Zones are relatively immobile, and may provide long-term stability to the mantle convection system (*Burke & Torsvik 2004*), even though the lithospheric plate motions may change unpredictably in the course of the Wilson Cycle. Seismically fast regions are generally identified as relatively lower temperature, implying that they comprise material that has sunk from shallower cooler depths. The lower temperature is associated with greater density, providing a local downward force that contributes to driving convective flows. Thus, mantle convection models have sought to incorporate seismic velocity structure as well as the complexities of tectonic plate motion, with cold subducted slabs providing an important driver of downward flow in the mantle (*van der Hilst et al. 1997*) and, hot plume-type structures driving upward flow (*Romanowicz & Gung 2002*). Seismic tomography has also proved essential in interpreting sublithospheric intraplate processes at the regional scale (e.g. *Ren et al. 2012*).

The oceanic plates generally have a much simpler history than the plates that include continental regions. They are returned to the mantle via subduction, leaving only the evidence of ophiolites: small slices of previously oceanic crust preserved in collisional domains (*Moore 1982*), and anomalous isotopic signatures apparently preserved in different sublithospheric mantle domains (*Hofmann 1997*). Ophiolites are important indicators of ocean closure but further evidence for the Wilson Cycle is provided in the long-lived but multiply deformed continents that have undergone cycles of rifting, shear and orogeny. Impressive advances in geochronology (e.g. *de Laeter 1998*) and deep seismic reflection imaging using controlled-source methods (*Oliver 1982; Klemperer & Hobbs 1991*) have provided essential support to the structural mapping that has been the basis for interpretation of plate tectonic cycles. The development of computer-based environments like GPlates (*Müller et al. 2018*) has facilitated reconstruction of past plate configurations and testing of hypotheses. The development of extensive GPS networks has enabled us to accurately measure displacement rates across plate boundaries, and to map those regions of the continents that now undergo distributed deformation (*Kreemer et al. 2014*). Advances in understanding of mineral rheological laws (*Karato 2012; Hirth & Kohlstedt 2004*) and lithospheric deformation mechanisms controlled by faulting in the upper layers and viscous or plastic creep below the brittle–ductile transition can now be used in quantitative models of the strength of lithosphere (*Brace & Kohlstedt 1980; Burov & Watts 2006; Bürgmann & Dresen 2008*). Global crust and lithospheric thickness and structure estimates, derived from earthquake, gravity and seismic tomography data, are now readily available (*Laske et al. 2000, 2013; Priestley et al. 2008; Priestley & McKenzie 2013*). Variations in thermal regime and pore fluid pressures can explain the stability of cratons on the one hand, and the activation of mobile belts in extension or orogeny on the other. These lithospheric deformation models in general are able to provide an accurate representation of the strain-rate field of lithosphere that undergoes distributed deformation today (e.g. *England et al. 2016*) and have thus provided important insights into past phases of extension and orogeny that have affected the continents. The interpretation of past deformations, however, is naturally more complex, as continental lithosphere locally may have been subject to multiple phases of reactivation in which deformation, metamorphism and magmatism occurred at different times (*Holdsworth et al. 2001*). Better understanding of crustal rheology (*Bürgmann & Dresen 2008*), reactivation and reworking (*Holdsworth et al. 2001*), and weakening processes (*Holdsworth*



2004) all help to explain the inheritance that underpins the Wilson Cycle.

### This volume

The following 20 papers in this Special Publication have been arranged into six themes. (recognizing that a number of papers straddle multiple themes). These themes begin with a selection of papers on *the Classic Wilson v. Supercontinent Cycles*, followed by sections on *Mantle Dynamics in the Wilson Cycle*, *Tectonic Inheritance in the Lithosphere*, *Revisiting Tuzo's question on the Atlantic*, *Opening and Closing of Oceans*, and ending with *Cratonic Basins and their place in the Wilson Cycle*.

#### *The Classic Wilson v. Supercontinent Cycles*

The opening section begins with a paper reviewing the classic Wilson Cycle (Dalziel & Dewey 2018), including some personal accounts as geologists actively working during those early years when the concepts were being defined. Dalziel & Dewey (2018) re-evaluate the Early Paleozoic evolution of Laurentia and its ultimate collision with Gondwana, proposing a more convoluted dextral oblique collision model than the original model proposed by Wilson (1966). This highlights the logical deduction that plate motions on a sphere will intrinsically have an oblique component, thus extending the orthogonal view of the original Wilson Cycle. The term 'Supercontinent Cycle' has been proposed as a more descriptive alternative to the 'Wilson Cycle' (Worsley *et al.* 1984; Nance *et al.* 1988); however, challenges to this terminology arise owing to differing opinions of what defines a 'supercontinent', and therefore the use of the term 'Supercontinent Cycle' ('If Pangea is the only Supercontinent in Earth's history, then how can there be a cycle?' being an argument used e.g. by Burke 2007, 2011). Pastor-Galán *et al.* (2018) provide a detailed synopsis of what might define a supercontinent and the wider connections between the amalgamation and breakup of these landmasses and other cyclic variations of the planet. Nance & Murphy (2018) put forward a case for Pannotia as a Neoproterozoic supercontinent, and highlight the global characteristics and signatures that are similar to those observed during the amalgamation and subsequent breakup of Pangea in the late Paleozoic and early Mesozoic.

Heron (2018) also discusses the similarities and differences between the Wilson and Supercontinent cycles, highlighting that while Wilson Cycles may be linked to the opening and closing of individual oceans and basins, Supercontinent formation will probably require the involvement of more than one lifecycle of an ocean (i.e. a Wilson Cycle).

Furthermore, Heron (2018) also suggests that Supercontinent Cycles are likely to impact and influence the thermal dynamics of the mantle. However, these distinctions are defined mainly by the period and wavelength of the cycles, and in reality, Supercontinent Cycles may be synonymous with larger-scale, i.e. longer-wavelength, Wilson Cycles.

#### *Mantle Dynamics in the Wilson Cycle*

It was recognized from very early in the development of the concept that mantle dynamics probably had a significant role to play within the Wilson Cycle. In recent decades, and thanks to the global network of broadband seismometers and tomographic studies, our understanding of the structure of the deep mantle has advanced significantly. Heron (2018) gives a detailed review of current thinking on the thermal evolution of the mantle following large-scale tectonic events (such as formation of Pangea). In his review paper, Heron (2018) investigates the role of mantle plumes and mantle dynamics in the Wilson and Supercontinent cycles. The paper highlights some of the recent advances in our understanding of deep mantle dynamics as well as emerging concepts regarding thermal variability within the mantle (e.g. heating of the mantle beneath thickened crust, deep mantle reservoirs, thermal upwelling/downwelling and mantle flow), and the role of subducting slabs and mantle plumes as drivers (i.e. top down v. bottom up) in mantle dynamics.

#### *Tectonic Inheritance in the Lithosphere*

Fundamental to the Wilson Cycle is the concept of tectonic inheritance, which forms a re-occurring theme across multiple papers in this volume. It is generally agreed that the generation and evolution of most geological architectures are primarily controlled by interactions between plate motions, the thermally induced mechanical stratification of the continental lithosphere and pre-existing structures locked into the buoyant continental crust. However, our detailed understanding of the processes leading to structural and thermal inheritance at different scales and their influence over the kinematic and dynamic evolution of geological architectures is still very limited. The spatial association between continental breakup and pre-existing orogens is often described within the context of a Wilson Cycle, wherein orogenic belts formed by continental collision during closure of ancient ocean basins are reactivated during subsequent rifting episodes (Wilson 1966; Vauchez *et al.* 1997). This association between the locations of continental breakup and older orogenic belts is usually attributed to weakening of the lithosphere owing to faulting in the brittle upper crust and the presence of a crustal root

(Dunbar & Sawyer 1989; Audet & Bürgmann 2011; Huerta & Harry 2012).

In the first paper of this section [Şengör \*et al.\* \(2018\)](#) discuss the different styles of tectonic inheritance and reactivation, recognizing three distinct structural classes (when describing younger structures with respect to their older pre-cursors): resurrected (i.e. reactivated), replacement (i.e. inversion) and revolutionary (i.e. new) structures. [Şengör \*et al.\* \(2018\)](#) illustrate these distinct structural types using case studies from Europe and the USA.

Access to seismic and field outcrop data has allowed many studies of orogens and continental margins to focus on crustal architectures, terranes and weaknesses (e.g. [Manatschal 2004](#); [Péron-Pinvidic & Manatschal 2009](#)). Deformation phases can create structural and thermal inheritance in the continental crust, the mantle part of the lithosphere or even the sublithospheric mantle ([Manatschal \*et al.\* 2015](#)). *A priori* it is not always clear which level of inheritance controls the localization of subsequent deformation. The next two papers address the role played by mantle lithosphere during continental rifting and breakup. [Heron \*et al.\* \(2018\)](#) review the role played by pre-existing weaknesses ('mantle scars'), while [Chenin \*et al.\* \(2018\)](#) consider the implications for compositional variability within the mantle lithosphere. [Heron \*et al.\* \(2018\)](#) discuss the growing evidence (e.g. deep seismic imaging, etc.) for widespread scarring in the continental mantle lithosphere and go on to argue that the role of crustal inheritance in controlling continental breakup may need a reassessment. Building on this mantle lithosphere theme, [Chenin \*et al.\* \(2018\)](#) discuss the potential influence of the variability of the physical properties in the mantle (i.e. composition, density, rheology) and consider three types of mantle: inherited, fertilized and depleted oceanic mantle. These varying mantle types are inherited from the precursor collisional terranes of the earlier orogen and influence the magma-generation potential during subsequent breakup processes.

In contrast, [Lima \*et al.\* \(2018\)](#) and [Scisciani \*et al.\* \(2019\)](#) look at the role played by crustal structures, fabrics and lithologies in subsequent deformation events. Pre-existing structures (from tectonic belts, discrete faults and shear zones, or even micro scale fabrics) play an important role in later deformation styles and structural geometries. [Lima \*et al.\* \(2018\)](#) take a closer look at rheological inheritance within the upper and lower crust using field examples from the Basin and Range. [Lima \*et al.\* \(2018\)](#) use outcrop and microstructural observations, and associated thermodynamic modelling, to illustrate how the history of past collision, involving, e.g. partial melts, compositional domains and retrograde fabrics, influences crustal strength and fabric evolution during later extensional systems. Focusing on the

upper crust, [Scisciani \*et al.\* \(2019\)](#) use seismic and field examples, from the North Sea and Italian Apennines respectively, to look at the role of pre-existing crustal structures in repeated tectonic events. In both examples, they show that during repeated episodes of inversion (a common characteristic of the Wilson Cycle), inherited basement structures tend to control strain localization.

### *Revisiting Tuzo's question on the Atlantic*

In this group of papers, we return to the North Atlantic where Tuzo Wilson's 1966 paper was focused. The first paper, by [Ady & Whittaker \(2018\)](#) presents a new kinematic plate model for the North Atlantic and Labrador Sea region. The NW Atlantic margin is the classic example often used in explaining the Wilson Cycle concept and [Ady & Whittaker \(2018\)](#) test the most suitable restoration methods (rigid v. deformable plate models) to investigate tectonic inheritance models in the region. Their findings support the use of deformable plate kinematic models in areas influenced by tectonic inheritance as well as regions of hyper-extended crust in distal passive margins.

Then follows a selection of papers looking at the evolution of Eastern Laurentia: [Murphy \*et al.\* \(2018\)](#) provide an interesting retrospective view of insights that have come from studies of the Avalonia continental block, and their importance in shaping our understanding of the Wilson Cycle and other tectonic paradigms. Avalonia is one of several peri-Gondwanan terranes which were distributed along the periphery of northern Gondwana in the Late Neoproterozoic–Early Cambrian. The Avalonia block records multiple tectonostratigraphic events throughout the Neoproterozoic–Early Paleozoic, which ultimately led to the closure of the proto-Atlantic (Iapetus) Ocean as Avalonia docked with Laurentia. [Waldron \*et al.\* \(2018\)](#) provide a detailed analysis of the collision and docking of various microplates (including Ganderia and Avalonia) with Laurentia that now outcrop in Eastern Canada and Newfoundland. They describe the diachronous nature of individual microplate and arc-terrace convergence and ultimate collision. [White & Waldron \(2018\)](#) then present a detailed case study from Western Newfoundland looking at the inversion of pre-existing Paleozoic rift structures during the Taconic arc-continent collision in the Ordovician. They note that these structures show similar basement-cored inversion geometries to those of the Cenozoic Laramide Orogen in SW USA (e.g. [Bump 2003](#)), and suggest that these Taconic structures may be more widespread across the Eastern US region.

[Thomas \(2018\)](#) provides an extensive review of the onshore field evidence for two full Wilson Cycles within Eastern Laurentia. [Thomas \(2018\)](#)

highlights the large-scale superposition of transform fault domains, which supports the model for crustal and lithospheric inheritance in the region. In contrast, the rift domains do not appear to show this same level of superposition, and thus inheritance. These observations may indicate that steeply dipping crust (and lithosphere) structures whose strike is close to regional extension vectors may be more susceptible to reactivation during the rift and breakup process.

The final paper in this section looks to the conjugate margin, off SW England, where [Alexander \*et al.\* \(2019\)](#) describe the Permian extensional reactivation of the Rheic–Rhenohercynian Ocean suture zone formed during the Devonian–Carboniferous Variscan Orogen. They integrate regional potential-field data, offshore seismic and field outcrop data. Both onshore outcrop and offshore seismic data show low-angle extensional shear structures (ductile), which appear to be superimposed on older thrust fabrics, and associated steeper brittle structures. These structures record a failed breakup attempt between the British Isles and Eurasia in the Permian.

### *Opening and Closing of Oceans*

If asked to define the Wilson Cycle in simple terms, a geoscientist might reply that it describes the opening and closing of ocean basins, and fundamentally that is exactly how it was first portrayed ([Wilson 1968](#); [Jacobs \*et al.\* 1973](#); [Burke 2011](#); Table 1; Fig. 2). In this fifth group of papers we have a selection of case studies that document the process and show how complexity emerges in real examples.

Although the Wilson Cycle concept is often represented as two-dimensional, the deformation of plates with pre-existing zones of weakness in a variety of orientations upon a spherical Earth leads inevitably to three-dimensional motions. Thus, continents may rift and re-collide but those motions and the deformations that result are typically oblique and change markedly over time. [Lundin & Doré \(2018\)](#) emphasize the importance of oblique and transform segments in the early development of rifted margins, highlighting that it is easier to break plates via strike-slip shear than it is by orthogonally rifting the crust ([Withjack & Jamison 1986](#); [Brune \*et al.\* 2012](#)). They use a number of examples from the opening of the North Atlantic and Arctic to argue that rifted continental margins are often weakened by a preceding phase of strike-slip motion. As these strike-slip domains predominantly reactivate pre-existing crustal weaknesses, this model, while still consistent with the general concepts outlined in the Wilson Cycle, emphasizes that breakup processes are inherently three-dimensional, and more complex than the two-dimensional models that are often depicted in

vertical section (e.g. Fig. 2). [Schiffer \*et al.\* \(2018\)](#) also reassess the opening of the North Atlantic, with particular focus on the development of the Jan Mayen microplate. They present a model where pre-existing Caledonian structures (a fossil subduction zone) influence the location of major transform fault zones offsetting the early spreading centre. Following a cessation of seafloor spreading in West Greenland (Labrador Sea and Baffin Bay), a major regional stress reorganization results in a ridge jump north of the transform, thus forming the Jan Mayen microplate. The model nicely depicts the structural complexity that can develop from pre-existing structures and regional stress variations within a Wilson Cycle.

[Hall \(2018\)](#) looks at subduction initiation using a number of examples from South East Asia. The transition from opening to closing of an ocean is a key point in any Wilson Cycle; however the controls and drivers of subduction initiation are poorly constrained. [Hall \(2018\)](#) presents a number of modern-day basin examples from Southeast Asia which exhibit early stage subduction. Subduction initiation appears to occur predominantly at the edges of ocean basins and not at former spreading centres or transforms. [Hall's \(2018\)](#) observations also suggest that the age of the ocean crust appears to be unimportant; however, the relative elevation between the ocean floor and the adjacent hot, weak and thickened arc/continental crust appears important. [Hall \(2018\)](#) also highlights that SE Asia has an abundance of subducting slabs which, when combined with the identification of anomalous tectonic subsidence in the region, may reflect a deeper mantle influence (i.e. negative dynamic topography; [Wheeler & White 2002](#); [Heine \*et al.\* 2008](#); [Yang \*et al.\* 2016](#)), or may simply be due to the presence of weak mobile continental fragments situated between two major converging plates (i.e. similar to the Mediterranean). [Beaussier \*et al.\* \(2018\)](#) apply 3D numerical modelling techniques to understand the mechanisms that lead to alternating subduction polarity along suture zones. Their results highlight that the size and spacing of these slab segments are intrinsically linked to the inherited rift/transform structure established during the opening phase.

### *Cratonic Basins and their place in the Wilson Cycle*

We end with a look at Cratonic basins and where these fit in the Wilson Cycle. [Daly \*et al.\* \(2018\)](#) present a review of Cratonic basins, highlighting their present-day global distribution, apparent lack of plate deformation characteristic of the Wilson Cycle, and long-lived episodic subsidence histories. [Daly \*et al.\* \(2018\)](#) provide a case study example from

the Paranaíba Basin, Brazil, using newly acquired deep seismic reflection data to highlight the apparent variability of crustal structure across the basin. Based on their observations they propose that Cratonic Basins, such as Paranaíba, occupy a specific place in the Wilson Cycle, initiating after continental collision, but before rifting (as depicted in Fig. 2), and they discuss various processes that could drive basin subsidence during this phase.

## Open questions in Wilson Cycle research

The plate tectonic and Wilson Cycle theories have come a long way since their formulation in the 1950s and 1960s. However, as with most fields of science, when some observations are explained and questions answered, new questions arise. While we cannot know the future development of Wilson Cycle research, we conclude by highlighting some directions of current research and open questions:

- (1) How do we recognize older Wilson Cycles? What diagnostic criteria can we use? Which was the first supercontinent and the first Wilson Cycle? Indeed, when was plate tectonics established on early Earth with its greater mantle temperatures?
- (2) What triggers supercontinent dispersal? Are the driving forces located in the Earth's mantle and/or provided by subduction zones? If the latter, how does subduction initiate?
- (3) How frequent are switches in subduction zone polarity? How do new subduction zones form near their predecessor?
- (4) What controls localization of deformation along the same plate boundaries over geological time? How can we recognize when inheritance is controlled by crust or mantle?
- (5) Is continental lithosphere constructed from coherent domains that are rheologically anisotropic and, if so, how is that anisotropy developed? And how does it determine the geometry of rifted margins?

The Wilson Cycle concept in the last 50 years has proved enormously important to the theory and practice of geology, and underlies almost everything we know about the geological evolution of the Earth and its lithosphere. The concept will no doubt continue to be developed as we gain more understanding of the physical processes that control mantle convection and plate tectonics, and as more and better data become available from regions that are currently less accessible.

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