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Introduction

Two giants of geology: Kevin Charles Anthony Burke and John Frederic Dewey

A. M. Celal Şengör and Ali Polat

This special issue of the *Canadian Journal of the Earth Sciences* celebrates the career of two of the greatest geologists of our times, who, during the last three decades of the twentieth and the first decade of the twenty-first century, have put their stamp on the tectonic interpretation of the Earth’s behaviour (Burke also extended his efforts into extra-terrestrial space). How fortunate it is for geology that they are both still active and, by all appearances, are likely to remain so for some time to come. It is an immense honour for us as their students and fellow geologists to introduce this special issue with a few lines about them whom we have had the great privilege of knowing closely both as colleagues and as friends.

In the late sixties, few geologists grasped the significance of plate tectonics because a broad view of the geological behaviour of our planet was the first necessity to be able to do so. In the sixties, there were a number of such geologists with an encyclopaedic knowledge of global geology, yet not one of them became a Kevin Burke or John Dewey, because they lacked the other, in our view the more critical, component of a broad world-view of geology: A critical rational approach, i.e., the courage to ask the question: *what ought it to be like*? Such a question had long been anathema in the twentieth century geology because of the prevalent Baconianism. As Tuzo Wilson wrote in his own autobiography 'more geological mapping was both the method and the aim of geology' in those days.

Most geologists in the twentieth century were instructed to learn 'the basic principles' first and then be ready to question the data. However, those very 'principles' that they were advised to learn (implicitly, without questioning) were the mistakes of tomorrow. Burke and Dewey have always actively questioned even the most basic 'principles.' Their incredibly quick and inquisitive minds, their genuine love for and determination to seek the truth, their vast knowledge in all branches of geology and their generosity towards their colleagues have been the hallmarks their professional activity.

When the kinematic theory of plate tectonics was almost complete in 1969, very few geologists dared to reinterpret geological data from an entire mountain belt in terms of it. We know of five papers that came out in 1969 on this topic: Dewey's on the Appalachian/Caledonian

System and on the conversion of Atlantic-type continental margins to Pacific-type continental margins (see Dewey 1969a, b), Warren Hamilton's on Mesozoic California, Hans Laubscher's on mountain-building (but essentially confined to the Alps) and Mitchell and Reading's on geosynclines in terms of plate tectonics. Of these only Dewey's and Hamilton's papers dealt with the motion of the plates not only to explain why the mountains were where they were, but also got into the bowels of the orogens to show us what the single lines geophysicists were drawing along convergent boundaries in reality were and how they worked to create the real geological record. At about the same time Burke and Dewey conceived together that the Pan-African orogeny to be an ancient analogue of the Himalayan/Tibetan area of wide orogeny and thermal basement reactivation. This was their response to Kennedy's problem of having wide areas of thermal basement reactivation—much wider than could be accommodated in classical models of orogeny in pre-plate tectonics days and those inherited by plate tectonics. This is a nice example illustrating their originality, broad knowledge of world geology, and quickness of mind. Both the Burke continental rifting model and the Himalayan/Tibetan model of wide orogeny were applied to problems elsewhere in now-classical papers he wrote with Dewey in 1973 (see Dewey and Burke, 1973) and 1974 (see Burke and Dewey, 1974). While working on the Pan-African problem, in 1970 we see Burke outlining what later came to be known as the Burke hypothesis (so named by the late Marshall Kay) of continental separation caused by plume-generated uplifts and the rift-rift-rift junctions forming atop them. His type examples were the Red Sea-Gulf of Aden and the Ethiopian Rift and the Benue Trough-Central Atlantic-South Atlantic. The Benue Trough could play such a significant place in the formulation of the Burke hypothesis owing to the data collected largely because of Kevin's initiatives in Ibadan, Nigeria, where he was head of department of geology in the University of Ibadan. Both the continental rifting model and the Himalayan/Tibetan model of wide orogeny were applied to problems elsewhere in now-classical papers Burke and Dewey wrote together 1973 and 1974.

Burke's scientific work during his Nigerian years shows his amazing breadth and versatility. For example, his demonstration of the role of the earth worms (over that of termites) in the formation of laterites, field data on rare catastrophic erosion processes (rain heaving of boulders and the damage they do as they are rolled down slopes where they normally stand in a metastable condition), and the publication of a Bouger gravity map of Nigeria are only a few examples from this wide spectrum.

After his initial papers on plate tectonics, Dewey's research forked: he continued to explore the theoretical implications of plate tectonics alone and also with his friend Burke. By that time he had been united with Burke in the legendary Albany Department of Geological Sciences of the State University of New York, which they turned into one of the most powerful research institutions in the world, and he got into the field to test his and others' models. Therein we see how his critical rationlism was working. Dewey not only falsified many models by others, but also some of his own (including those dating from pre-plate tectonics days from the British Isles). Initially, for example, he thought ophiolites could glide down as gravity nappes. After work in Newfoundland with his students and visits to many ophiolites in the world, he changed his mind. In fact, his team's ophiolite research created such a sturdy edifice, that much of what is going on now on ophiolites is icing on its cake (see Dewey, 1976).

Dewey spent the early seventies exploring plate tectonics in many mountain belts and, together with his colleague and life-long friend Kevin Burke, in rift valleys, along continental margins and on continental plateaux. Through these studies, Dewey reached a conclusion that horrified both him and those who read it and tried to come to grips with it. He documented, in an ingenious paper in the John Rodgers volume of the *American Journal of Science* in 1975 (see Dewey, 1975), that plate tectonics must destroy geological evidence on such a scale as to render unique reconstructions of the past impossible! Anybody who understood the reality of subduction should have guessed that, but Dewey showed, on hypothetical worlds masterfully draughted on Wulff-nets, how a continuously-evolving network of plate boundaries must behave and which kind of evidence would get destroyed in what sequence and at what stage of plate bundary evolution. This kind of rigorous analysis, while forcefully driving home to geologists that they cannot hope at the end of the day to be all-knowing, rescued them from despondency by showing them what systematic clues they can hope to find to fill the gaps, albeit hypothetically, that open up during plate boudaray evolution. Dewey has repeatedly emphasised the chance aspect in geological evolution. Anybody who has not read his 1975 *American Journal of Science* paper and its offspring his 1976 *Tectonophysics* paper is at a serious disadvantage in interpreting geological history in terms of plate tectonics. Dewey showed that, while much evidence is lost, history may still be testable as much as physics is, and that geologists must strive to erect testable hypotheses to reconstruct the past. Both Dewey and Burke never tired of emphasising this in papers, communications in meetings, class-room lectures and in conversations with their colleagues.

In the middle and the later part of the 1970’s we see Burke and Dewey getting into the Precambrian. They showed that the naive interpretation of the greenstone belts as little deformed synclines was hopelessly wrong and resulted from not appreciating how the structures of the Phanerozoic orogenic belts had been unravelled by a judicious combination of detailed biostratigraphy and structural geology (see Burke et al., 1976). In the Pre-Cambrian, the lack of biostratigraphy had crippled structural interpretations much more than most Precambrian geologists seemed to have recognised. They took a position akin to that adopted by Eduard Suess a centuary earlier; they were willing to be actualistic but without losing sight of the fact that the terrestrial globe had an irreversible history. Today, Precambrian, especially Archaean, tectonic research rises on the pillars that Burke and Dewey erected.

In the 1980’s, Dewey returned to the more detailed structural evolution of the orogenic belts and considered arcs, collapsing orogens, and "terranes." About terranes he initially had a most tolerant approach, adopting graciously the terminology of those who reinvented what already Tuzo Wilson and he had clearly said in the late sixties and the seventies. Our friends from Albany days will recognise that those papers fundamentally say nothing that we had not been hearing in the mid-seventies in Dewey's lectures and conversations with us. When terranology became an end in itself, however, both Burke and Dewey revolted.

In the beginning of the 1980’s Burke turned his attention to the Caribbean, where he had worked earlier. With P. Jeffrey Fox and A. M. C. Şengör he had shown already in 1978 that the Caribbean floor was a trapped oceanic plateau (see Burke et al. 1978; Burke 1988). Together with his students he then undertook detailed field studies of the northern, southern and southwestern parts of the plate and its active frame. The plateau hypothesis was corroborated but brought with it numerous implications for the tectonics of the Caribbean region. Among numerous ones, an offshoot was his study of the nature and timing of the closure of the Panama isthmus and the influence of that closure to the world climate.

Dewey joined in the Caribbean research and with James Pindell presented a detailed tectonic history of the entire Caribbean, Central American and Central Atlantic regions, a research topic that Pindell continues to this day.

Later, Dewey's interests became concentrated around complex strain histories and they culminated, in 2002, in his masterly analysis of transtension (see Dewey, 2002). Here we see one of the best examples of Dewey's method of approach to geological problems. He first lays out all the theoretically possible aspects of a problem, then takes individual geological objects, such as hand samples, outcrops, entire orogens, and tests the models using observations. Observations inspire further generalisations, correct errors, and lead to further questions. Then, he returns to the drawing board and tries to answer the questions first theoretically, laying out the basis for the next field-checks by modifying the original model, the iterative, networking, approach.

Most recently, Dewey's research has centred on 3-5 Ma transtension along the eastern side of the Sierra Nevada and the pre-Carboniferous history of the US Cordillera west of the '706' line, where he takes the superexotic view that all 'terranes' with pre-end Devonian deformation originated in the Appalachians. He has also been mapping and describing mega-boulder deposits generated by freak waves and tsunamis, especially in New Zealand and western Ireland.

In the 1990's, Burke returned to rift problems and began taking Africa apart in some detail and his Du Toit lecture in 1996 is the first fruit of this concentrated effort. The African work also had two amazing offshoots. Burke showed in collaboration with Trond Torsvik in Norway that the major mantle plumes of the Earth rise from the edges of the two large low shear wave velocity regions (LLSVP) which he termed Tuzo and Jason. He and his colleagues showed that these regions had a very long-term stability, perhaps since the moon-forming event! He also showed, together with his colleagues in South Africa that deformed alkaline and carbonatite complexes (DARCS) may be used in mapping old sutures where all other evidence fails.

Burke and Dewey have never been seduced by the numerical pseudo-precision of simplistic physical models derived from the application of elementary engineering concepts to geology. They have long warned against the bogus air of precision that one may obtain by ignorant application of ideal models, developed on unreal objects and for unreal circumstances, to real geological objects and processes evolving in inscrutable complexity in the abyss of deep time. They have been rightly intolerant of those producing numbers from either computers not tied to field reality or samples collected in the absence of a carefully-constructed geological map. While we were their students, they allowed none of us obtain a degree without making a detailed geological map. Later, they allowed those with physical handicaps or of a more geophysical bent to do so but, even then, they made sure that they studied and understood geological maps und used them in their work.

Burke and Dewey are not only superb gelogists and researchers, but they also inspire the people around them with their infectious enthusiasm. As we write these lines Burke is 87 and Dewey is 79. They still publish papers, go to meetings and engage in a lively correspondance with their students and colleagues around the world over about problems that interest them. They have lost not an iota of their love and passion for geology. This volume is only a small tribute to their immesley rich lives by which they also enriched the collective knowledge of mankind and contributed to its civilisation. May they continue to do so for many more years to come.

This special issue contains eighteen research aricles and one commentary article written by the students and/or colleages of Burke and Dewey, and by Burke and Dewey. These papers discuss various aspects of plate tectonic processes recognized in the Archean to the Cenozoic geologic record. The topics of the papers include extensional, compressional and strike-slip tectonic regimes documented in Eurasia, Africa, Australia, Greenland and the Americas.

It gives us a great pleasure to thank all of the authors for their contributions to the special issue. We greatly acknowledge the reviewers; without their significant input this special issue could have not been produced.

This introduction summarizes the major conclusions of the papers published in this special issue of the *Canadian Journal of Earth Sciences*. A short statement on each paper is as follows:

(1) Torsvik and co-workers review the contributions of Kevin Burke to our understanding of Earth's evolution and geodynamics. They state that over the past sixty years Kevin Burke continuously made outstanding contributions to plate tectonic and mantle plumes, and their interactions in space and time. Torsvik et al. call Kevin Burke's model explaining the plate tectonics and mantle plume interaction process as "the Burkian Earth". In this model, plate tectonics makes an essential contribution to the mantle through subduction, and slabs restored in the lowermost mantle trigger mechanism for plumes that rise from the margins of the two large-scale low shear-wave velocity structures in the lowermost mantle, which are named as TUZO and JASON by Kevin Burke.

(2) Burke and Wilkinson discuss the landscape evolution in Africa during the Cenozoic and Quaternary. The authors propose that African landscape evolution since 66 Ma reflects interactions among parts of the Earth system from the core to the biosphere. They argue that the following three events have dominated landscape development in Africa: (i) a climatic revolution when the circumpolar current and the East Antarctic Ice Sheet first formed ca. 37 Ma; (ii) a tectonic revolution at ca. 32 Ma dominated by elevation of ca. 30 topographic structural swells continent wide; and (iii) a second climatic revolution in a Northern Hemisphere cooling event (at ca. 2.7 Ma) that triggered Sahara desert initiation and the beginning of glacial cycles in the Northern Hemisphere (at 2.15 Ma).

(3) Ernst et al. summarize the plate-tectonic evolution of the Earth. They suggest that oceans were present, surface temperatures had fallen below the low-P solidi of dry peridotite, basalt, and granite by 4.3 or 4.2 Ga, allowing rigid lithosphere to form. They present the following four evolutionary stages in plate tectonics: (i) 4.5-4.4 Ga, magma ocean overturn involved ephemeral, surficial rocky platelets; (ii) 4.4-2.7 Ga, formation of oceanic and small continental plates were obliterated by return mantle flow prior to ca. 4.0 Ga; continental material gradually accumulated as largely sub-sea, sialic crust-capped lithospheric collages; (iii) 2.7-1.0 Ga, progressive suturing of old shields + younger orogenic belts led to cratonal plates typified by emerging continental freeboard, increasing sedimentary differentiation, and episodic glaciation during transpolar drift; and (iv) 1.0 Ga-present, laminar-flowing asthenospheric cells are now capped by giant, stately moving plates.

(4) Wang and co-workers compare the tectonic history of the North China craton, which has lost parts of its lithospheric root, with the Yilgarn and Superior cratons, which still preserve their lithosphere. The authors suggest that lithospheric thinning beneath craton margins is a common phenomenon, which may be caused by plate convergence, but craton destruction is not always accompanied by lithospheric thinning, except for cratons that suffered subduction and collision from multiple sides. The western block of the North China craton, Yilgarn and Superior cratons have not experienced craton destruction because they are surrounded by weak zones, sheltering them from deformation. They argue that water released by the

subducting oceanic crust beneath cratons may weaken the overlying lithospheric mantle and lead its delamination or erosion.

(5) Paper by Brun et al. focuses on extensional tectonics in the Aegean region since 45 Ma. The authors attribute the extension in the region to slab rollback and divide it into two main stages. Stage 1 represents localized back-arc extension that lasted between the Middle Eocene and Middle Miocene, leading to the exhumation of high-pressure metamorphic rocks to crustal depths, the exhumation of high-temperature metamorphic rocks in core complexes, and the deposition of sedimentary basins. Stage 2 extension started in the Middle Miocene and distributed over the whole Aegean domain and controlled the deposition in onshore and offshore Neogene sedimentary basins.

(6) Contribution by Bosworth and Stockli deals with the timing and tectonic significance of early magmatism in the greater Red Sea rift, showing that the initial late Cenozoic syn-rift strata and extensional faulting are closely associated with alkali basaltic volcanism. Continental rifting at 31-30 Ma was coeval with the onset of continental flood volcanism in many parts of the region. A new phase of volcanism began at 24-23 Ma with the intrusion of a dike field reaching over 2000 km into northern Egypt. It appears that each episodic enlargement of the greater Red Sea rift system was triggered and facilitated by breakthrough of mantle plumes.

(7) Hoffman and co-authors describe the occurrence of extensional, brittle detachments formed as submarine slides on the outer slope of an Ediacaran collisional foredeep, eastern Kaoko belt, Namibia. The authors argue that the existence of coherent, large, scale, submarine landslides on modern continental margins implies that their apparent rarity in ancient orogenic belts is due to non-recognition. Hoffman et al. suggest that failure to recognize similar detachments existing in other orogenic belts can lead to misinterpretations of stratigraphy, sedimentary facies and paleogeography.

(8) In their contribution Jolivet et al. focus on geodynamics in the Neo-Tethys, mantle convection, ophiolite obduction, and extensional and compressional geological events in Africa. The late Cretaceous (ca.100 to 75 Ma) in the Neo-Tethys was characterized by the emplacement of several giant ophiolite nappes (e.g., Cyprus, Turkey, Oman etc.) on

continental margins ranging from the Mediterranean region to the Himalayas, resulting from large scale convergence between Africa and Eurasia. Joliet and co-workers attribute this event to a large part of the convecting mantle and propose that that alternating extension and compression in Africa could be explained by switching convection regimes. They think that the extension may have corresponded to steady-state whole-mantle convection, Africa being carried northward by a large-scale conveyor belt, while compression and obduction might have occurred when the African slab penetrated the mantle transition zone at 660 km during a 25 million years-long period.

(9) In his contribution, Karson focuses on crustal accretion of thick, mafic crust in Iceland and discusses its implications for volcanic rifted margins. Seismic studies, crustal drilling, and exhumed margins show that the upper crust in volcanic rifted margins is composed of basalts erupted in subaerial to submarine environments and intruded by downward increasing proportions of dikes and sparse gabbros. The lower crust of these regions is not exposed but is inferred from seismic velocities and petrological constraints to be gabbroic to ultramafic in composition. Active processes in Iceland provide a glimpse of subaerial spreading with the creation of a thick (40-25 km) mafic igneous crust that may be analogous to the transitional crust of rifted volcanic margins

(10) In their contribution, Ashwal et al. propose a lithospheric mantle origin for alkaline rocks and carbonatites in southern Africa, using the examples of the 1134 Ma Bull’s Run alkaline complex (nepheline syenite) in South Africa, and the 726 Ma Tambani alkaline complex (nepheline syenite) and the 130 Ma Chilwa Alkaline Province (alkaline and carbonatitic intrusive and extrusive rocks) in Malawi. They suggest that alkaline magmas and carbonatites in southern Africa originally formed during continental rifting, became deformed and subducted into the mantle lithosphere during later orogenic events, and constituted part of a source component for later rift-related alkaline and carbonatite magmatism. The authors use Sr, Nd and Hf isotopic data from deformed and undeformed nepheline syenites and carbonatites to argue that alkaline and carbonatite rocks over hundreds of millions of years in spatially restricted areas like southern Africa can be explained by melting processes in the lithosphere, rather than in the asthenosphere.

(11) Lamb's paper deals with Cenozoic uplift of the Central Andes in northern Chile and Bolivia using paleo-altimetry data. The study concludes that prior to ca. 25 Ma, during a phase of amagmatic flat slab subduction, thick skinned crustal shortening and thickening was focused in the Eastern and Western Cordilleras, separated by a broad basin up to 300 km wide and close to sea level, which today comprises the high Altiplano. Oligocene steepening of the subducted slab is indicated by the initiation of the volcanic arc at about 27 - 25 Ma, and widespread mafic volcanism in the Altiplano between 25 and 20 Ma. Lamb proposes that the steepening of the subducted slab may have resulted in detachment of mantle lithosphere and possibly dense lower crust, triggering 1 – 1.5 km of rapid uplift (<< 5 million years) of the Altiplano and western margin of the Eastern Cordillera, establishing the present day lithospheric structure beneath the high Andes. He argues that since ca. 25 Ma, surface uplift has been the direct result of crustal shortening and thickening, locally modified by the effects of erosion, sedimentation and magmatic addition from the mantle.

(12) In their contribution, Dewey and Ryan discuss the significance of the Connemara terrain of Ireland in the early Ordovician Grampian orogeny and suggest that Connemara contains the key information for understanding the evolution of the Grampian Orogen in the Irish and British Caledonides. The paper presents a new interpretation of the evolution of Connemara and the Grampian Orogeny. The authors propose that the Grampian Orogeny was the result of collision between the Laurentian rifted margin and an Ordovician oceanic island arc. They show that Connemara is not a terrane, displaced with respect to the remainder of the Grampian Orogen, rather it was overridden, northwards, by the arc and its fore-arc basin, frontal ophiolite complex and accretionary complex.

(13) Friedrich and Hodge presents the spatial distribution of ^{40}Ar/^{39}Ar mica ages across the Connemara belt of the Irish Caledonides that is interpreted as remnant of an Ordovician continental arc, recording regional scale high-temperature metamorphism. On the basis of U-Pb, Rb-Sr, and K-Ar mineral ages, the tectonothermal evolution of the Connemara belt was previously interpreted as lasting more than 75 Ma. The authors show that the tectonothermal evolution lasted about 32 Ma (ca. 475 to 443 Ma). New results imply that the large (≥ 50 Ma) spread in thermochronometers commonly observed in orogens does not automatically

translate into a protracted cooling history, but that only a small number of thermochronometers supply permissible cooling ages.

(14) Şengör's paper discusses the structural evolution of the Albula Pass region in eastern Switzerland. The study shows that the region records a complex history of sedimentation and deformation in the Late Paleozoic and Mesozoic. The initial structures appear to have formed before the deposition of the Jurassic sedimentary rocks. He suggests that shortening resulted in the formation of the south vergent Elalbula Nappe that was later dismembered into the Ela and the Albula Nappes in the Albula region. The southerly vergence was later reversed resulting in the generation of closely spaced new thrust faults.

(15) Natal'in et al. report new zircon U-Pb ages from the Strandja Massif, Western Turkey. The authors describe five fault-bounded tectonic units in the massif ranging in age from Neoproterozoic to Jurassic. They interpret the Strandja Massif as a fragment of the long-lived, Cambrian to Triassic magmatic arc evolving on the northern side of Paleo-Tethys, rather than being a passive margin as previously assumed.

(16) Paper by Polat et al. compares the lithological, structural, and geochemical characteristics of the Mesoarchean Târtoq greenstone belt, South-West Greenland, and the Mesozoic to Cenozoic Chugach-Prince William accretionary complex, southern Alaska. They interpret the Târtoq greenstone belt as a remnant of a supra-subduction zone ophiolite that originated as back-arc basin oceanic crust and later became part of an accretionary complex. On the basis of similarities between Archean granitoid-greenstone terrains and Phanerozoic subduction-accretion complexes, such as the Alaskan and Altaid subduction accretion complexes, they conclude that Archean continental crust was built by uniformitarian geological processes taking place at convergent plate margins.

(17) Paper by Glen et al. discusses crustal growth processes in modern and ancient orogenic belts, using a Gondwana-Land perspective. In their discussion, the authors focus on the orogenic belts in northern Australia, New Guinea, Southwest Pacific, Tasmania, and New Zealand. They classify the orogenic belts in these regions as non-collisional (accretionary) orogens. Glen and co-authors claim that all non-collisional orogens involve continental

growth, but only the New England orogen and to a lesser extent the New Guinea Orogen involve significant crustal growth.

(18) Le Pichon and co-workers discuss the tectonic processes in the Aegean-Anatolian-Eurasian plate boundary resulting from the westward propagation of the North Anatolian Fault, Turkey. They demonstrate that the Sea of Marmara marks a key point in the propagation of the North Anatolian Fault toward the northern Aegean region, and argue that no localized plate boundary existed in the north of the Aegean portion of the Anatolia plate prior to 2 Ma. The absence of the localized plate boundary is attributed to the distribution of shear over the whole width of the Aegean-West Anatolian western portion, resulting from the southward migration of the Aegean-West Anatolian subduction. Le Pichon et al. attribute the formation of the Aegean-Anatolia/Eurasia plate boundary in Pliocene-Pleistocene time due to the geodynamic interplay between the subduction of the oceanic Ionian lithosphere and the westward motion of the Anatolia plate.

(19) In his commentary, article Burke discusses theorems in Pure Mathematics and models used in Applied Mathematics, Natural and Social Sciences, and Engineering. He suggests that the most significant difference between Pure Mathematics and models constructed in Applied Mathematics, Engineering and the Sciences is that while theorems in Pure Mathematics can be proved right, whereas models in Applied Mathematics, Engineering and the Sciences can only either be proved wrong or not yet proved wrong. Scientific models are falsifiable. Those working in Applied Mathematics, Engineering and the Sciences have the task of building models and of testing those models.

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