PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Concluding Remarks

J. F. Dewey

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Concluding remarks

By J. F. Dewey, F.R.S.
Department of Earth Sciences, Parks Road, Oxford OX1 3PR, U.K.

During the course of this Discussion Meeting, a very large amount of regional tectonic geology was displayed, and debated critically in a terrane framework, on scales ranging from the whole of the North American Precambrian or the Mesozoic–Cenozoic Tethys down to particular segments of the Caledonides and Alpides. A wide spectrum of opinion was expressed from those who believe that the terrane methodology is a critical and essential objective stage in data handling before any rational palaeogeographic and palaeotectonic synthesis can be attempted in plate boundary zones to those who believe that the terrane philosophy is fundamentally flawed, dangerous, and pernicious, in that it leads to random data collection and the obscuring of fundamental plate tectonic processes. Another view was that terranology has been useful in drawing our attention to the importance of large pre-collisional strike–slip or transform motions in orogenic belts and the juxtaposition of disparate elements and zones. Yet another position was that there is nothing new in terranology that is not implicitly and explicitly inherent in plate boundary processes and that terrane analysis is simply another harmless word for what most careful regional geological synthesizers have been doing since the early 1970s. Naturally, no coherent consensus view emerged from the discussion, but an important result was that a huge amount of excellent regional and global geology and tectonic ideas were discussed in the context of the problems and complexities of plate boundary zone evolution and the mechanisms by which objects from the size of 'knockers' to continents, detach, move and weld to form collages at all scales.

Davy Jones, one of the originators of terranology in the North American Cordillera, elegantly expounded the terrane methodology with many detailed examples and emphasized that terrane analysis is not an end in itself but merely a 'holding operation' for a particular terrane until its provenance can be established. Jones argued that the 'home port' of any major Cordilleran terrane has not been identified unequivocally, even those that have a North American cratonic margin provenance. Faunal studies suggest that some terranes, previously thought to have originated near the Cordilleran margin were situated thousands of kilometres to the west and were separated from the continent by broad ocean basins. Jones elaborated his view that only fragments of plate tectonic environments can be recognized in the Cordilleran terrane collage and that all attempts to draw cohesive plate tectonic cross sections across the Cordillera, even on a limited scale is impossible. This position was supported broadly, in the northern Cordillera by Irving and Wynne from palaeomagnetic data, although they argued that the various elements of the western Cordillera in Canada were always close to North America, moving first south, then north. This view of the Cordillera was challenged by Gary Ernst and Warren Hamilton, who, while admitting the clear evidence of great mobility, believe that sensible palaeotectonic coherence exists between some Cordilleran elements on a fairly large scale. They cited, particularly, the Franciscan Assemblage, the Great Valley and the Sierra Nevada as an originally laterally and genetically related subduction-accretion complex, forearc basin and calc-alkaline arc, a view supported in discussion by Alastair Robertson. Ernst argued against a haphazard accretion of Cordilleran terranes because a gradual sectorial enlargement towards the modern continental margin is indicated by coherent broadly continuous isotopic–geochemical provinces from scales of entire physiographic province to that of quadrangle. Ernst suggested further that, metamorphic and structural discontinuities reflect movements among closely associated, co-evolving lithotectonic units and do not imply the juxtaposition of exotic genetically unrelated terranes. Hamilton supported this view and also took the more aggressive stance that few of those who attempt terrane analysis have sufficient expertise in and knowledge of the characteristics of modern convergent margins, of the petrology of modern magmatic provinces, of global patterns of sedimentation and palaeobiogeography with the result that the literature is cluttered with simplistic assumptions and ill-constrained speculations.

Plate boundary evolution, within which framework terranes must be understood, is immensely complicated for several reasons. First, plate kinematics is inherently complicated; slip vectors must continuously change and triple junctions evolve and migrate along plate boundaries. Thus plate boundaries cannot be simple single narrow fault zones across which motions remain constant. Secondly, the vertical rheological structure of plate boundary zones is a response to thermo-mechanical structure. Brittle layers that fragment rotate and displace may alternate with ductile layers in which continuum mechanics is more important. The rock response to plate displacement is also dominated by lithospheric zones in which the vertically integrated strength is lowest such as the axes of volcanic arcs and the zones just inboard of rifted continental margins analysed by Steckler. Thirdly, plate slip vectors in the continental lithosphere are, generally, converted and partitioned into strain and displacement in extremely complicated ways, such that principal displacement zones change with time. Fourthly, direct and simple relationships between plate slip vector and plate boundary zone structure, may be modified and obscured by local body force mechanisms. Orogenic collapse and subduction roll-back are driven by topographic gradients, variations in crustal and lithospheric thickness, and the sink rate of subducting slabs and may generate local slip directions and rates that are at azimuthal variance and much faster than plate relative slip vectors. This may allow very fast, but localized slip and strain rates that allow very rapid terrane motion for short distances and short periods.

A particular difficulty lies in a semantic problem of terranology. If we define a terrane as a geographic unit with a distinctive tectono-stratigraphic assembly, what are the minimum and maximum size limits? Discarding the motion of boulders and sand grains, is there a scale at which terrane becomes a useful word from the upper extreme of a continent like peninsular India to the lower limit of a knocker in a mélange via units such as microplates, microcontinents, blocks slivers and flakes? I believe that, although rigorous size definitions are not useful, the term terrane does not become useful above the scale of a few hundred kilometres or below a few kilometres. Its particularly useful function is in denoting palaeogeographic uncertainty; continents, even pre-Mesozoic ones, can be palaeogeographically manipulated successfully and the prevalence of knockers in mélanges and shear zones is bound to remain an obviously difficult problem. Least of all, the term terrane is not useful in denoting degree of allochthoneity, as a supposed novel methodology, or as a process that somehow replaces and goes beyond plate tectonics. Terranology, if it is useful at all, is only relevant as an obvious consequential subset of plate boundary kinematics as a concept involving the rearrangement of crustal and lithospheric fragments. There is a particular danger in the confused usage of the word terrane, which of course is scarcely the fault of those who would use the term in a 'rigorous' way. During the meeting, the dangers of the term emerged in such phrases and statements as 'Himalayan Terrane', 'an unknown terrane to the west', and 'we really don't need to use the word terrane'. In this context, the real value, or perhaps lack of value, of the terrane concept was impressed upon me by listening to Davy Jones's excellent exposition of the way in which the Cordilleran belt might have evolved. Jones spoke, not of the mindless definition of terranes, but about the genetic significance of tectono-stratigraphic assemblages and how they might have been related; his lecture was almost a denial of so-called 'objective' terranology and a lesson to the sycophantic followers of the terrane concept.

Terranology occupies a wholly different role and significance in different orogenic belts depending on the size and history of the oceanic complex whose subduction and/or demise led to the belt's development and on the plate slip rates and duration along its margins. The North American Cordillera has lain along the margin of a plate tectonic 'shredding machine' throughout at least the Mesozoic and Cenozoic and probably throughout the Palaeozoic since the late Precambrian extensional event that generated the western North American rifted margin. During the late Mesozoic and Cenozoic, the shredding has been principally dextral just as the shredding was mainly sinistral along the northwest Iapetus margin of the Caledonides from middle Ordovician to middle Devonian times. A large ocean, and lots of space and time is likely to lead to substantial terrane motions along its margin. In contrast, short-lived smaller oceans are less likely to generate large terrane motions caught up in the final collisional collage. Thus, in the western region of the European Tethysides, terrane motion was severely constrained in a concertina mode as argued by Sengör and Yilmaz in Turkey. To the east, as the Tethyan oceanic complex widened, large terrane motions are indicated by palaeomagnetic (Lin and Fuller) and geological (Metcalfe, Audley Charles and Harris) data.

If terrane mapping is followed as a mindless procedure that portrays an orogenic zone as an undecipherable, model-independent collage of disparate elements, little progress can be made. If, on the other hand, we look for 'non-terraned' segments of the orogen that may be used as a template to decipher terrane assemblages with excision and repetition elsewhere along strike, substantial progress can be made. The Appalachian–Caledonian system illustrates this extremely well. The British Caledonides are an exceedingly complex assemblage of elongate disparate terranes, whose individual history can be related sensibly to plate boundary histories but whose present spatial distribution makes no plate boundary 'template' sense. This, perhaps, is the basis of David Howells complaint that plate tectonic templates, or 'Dewey-grams', have infected the regional tectonic literature so that geologists analysing and synthesizing a particular region have attempted to force disparate elements into 'Dewey-gram' cross sections. If regional geologists have used this methodology, this is indeed a disaster but 'Dewey-grams' are essentially plate boundary cross-sectional snapshots that apply strictly to actualistic present scenarios. Enforcing 'Dewey-grams' upon every orogenic cross section is doomed to failure, is not a practice that informed tectonicians follow, and is not a methodology ever used or encouraged by the writer in regional tectonic synthesis. However, there can be no question, as Alastair Robertson, Wes Gibbons, Donny Hutton and I emphasized during the meeting, that terrane thinking has changed the way in which we think about the Appalachian–Caledonian belt. The terrane complexity of the British Caledonides scarcely

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could be understood without reference to the Newfoundland segment of the Appalachians in which strike–slip terrane motion along the critical western margin has been small. In Newfoundland, Ordovician arc collision and ophiolitic forearc obduction can be used, as shown by Dewey and Shackleton, to restore and explain the complex terranes of the British Caledonides.

In the Pan-African complex of the Afro-Arabian Shield, Harris, Gass and Hawkesworth argued that accretion of island arc terranes at a continental margin can result in rapid rates of crustal growth and that, in such cases, geochemical constraints provide strong evidence for allochthonous terranes in Precambrian belts. The Afro-Arabian Shield was produced by calc-alkaline magmatism between 900 and 600 Ma ago, where field evidence and trace element geochemistry suggest that Pan-African tectonics began as a series of intra-oceanic island arcs that were accreted together to form continental lithosphere over a period of 300 Ma. The great majority of Nd and Pb isotope ratios obtained for igneous rocks from the shield are indicative of a mantle magma source and estimated crustal growth rates are similar to those calculated from Phanerozoic oceanic terranes in the Canadian Cordillera. Such high rates in the Afro-Arabian Shield are consistent with the accretion of island arc terranes along a continental margin. Paul Hoffman warned, however, that rates of crust formation estimated from Nd model ages tend to be too fast because they give only the mean age of crust formation and, thereby, underestimate the duration of crust-forming episodes.

Paul Hoffman showed that cratonic North America is composed of a cluster of Archaean microcontinents, centred on the Canadian shield, and that juvenile early Proterozoic crust underlies the western and southern interior platforms. Formation of both the Archaean and Proterozoic crust is explicable by forearc accretion and magmatic arc progradation. Late Archaean and early Proterozoic accretionary systems differed through the involvement of older continental terranes that were narrower and wider, respectively, than the operative zones of collisional tectonism. The Archaean crust also differs from younger crust in having roots of buoyant refractory mantle tectosphere, possibly resulting from more prevalent physical underplating by depleted oceanic lithosphere. Hoffman believes that the buoyant tectosphere accounts for the biased exposure of Archaean crust in the shield and, conversely, the burial of Proterozoic crust beneath platform cover. Consequently, the isotopic ratios of detritus eroded from the craton overestimates the mean age of the continental crust, and sampling limited to the shield gives a false impression of predominant Archaean crust formation and Proterozoic epicontinental deposition.

Clearly, the terrane concept has been useful in emphasizing the role of large orogen-parallel strike–slip motions and the uselessness of the balanced-cross-section approach to orogens that evolve on the margins of large oceans. Most orogens consist of a collage of terranes of oceanic and continental origins that are assembled by the great natural complexities of plate boundary zone evolution. Terrane definition is only useful at the intermediate tectonic scale, otherwise their size ranges from the sand grain to the continent. Terrane boundaries are commonly intraorogenic transforms that excise and repeat earlier-assembled tectonic elements so that ocean margins orogens commonly assume a complicated braided pattern in which terrane boundaries with large motions commonly contain a wide range of exotic slivers, substantial mylonite zones with abundant constant shear sense indicators and palaeomagnetic evidence of large systematic rotations of upper crustal flakes and lack the characteristics of smaller displacements such as pull-apart basins with subjacent granite plutons, and transpressional

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zones. The margins of large oceans are characterized by regions such as the Andes from which terranes have been stripped and regions such as the U.S. Cordillera and Alaska to which terranes have been added. Smaller oceans lack this tectonic style and are typified by small-scale 'concertina' tectonics and/or windscreen-wiper tectonics whereby arc slivers leave one margin to collide with the other.

Perhaps the most energizing and illuminating aspect of the meeting, apart from the opportunity for a group of geologists to present and synthesize regional tectonic data from a wide variety of areas, was a heated and substantial wide-ranging epistomological discussion on the methodological relationship between hypothesis, model building and the collection of geological field data. Opinions varied from the view, expressed by John Sutton, that one should go into the field to collect data and to make geological maps untainted by hypothesis, to the other extreme, expounded by Celal Sengör, that one goes into the field strictly and only to test a hypothesis and that so-called objective data gathering is valueless. While leaning to the popperian end of the spectrum avowed by Sengör, I believe that much valuable, though limited, work has been done by 'objective' mapping untrammelled by hypothesis. However, as argued by Jack Soper, it must be true, surely, that the mindless acquisition of field data never leads to conclusions. Science advances by the complex iterative testing of ideas by data collection that shows these ideas to be wrong and by the injection of ideas that give us new ways of looking at the data and new kinds of data to collect. Lastly, the title of the Royal Society Discussion Meeting following this one may well have been used for this. Many geologists would regard terranes as Migrant Pests!

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