A Matter of Scale

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Abstract Plate tectonics, one of the greatest scientific discoveries of the twentieth century, works particularly well in oceanic regions but has considerable difficulty to account for widespread, diffuse deformation of the continents. There has been an enduring discourse on whether continuous deformation of the crust or slip along discrete faults is a better approximation of continental tectonics. A key difficulty in resolving this issue is that the distinction between flow and slip is scale dependent. Moreover, even at scales of tens of millimeters or less, both mechanisms of deformation can coexist. Over times much longer than about 100 years, the limit of reliable geophysical data, the scale in time further complicates the problem of spatial scales. However, solutions to some problems in continental tectonics do not rely on end-member models, and advances in understanding the role of the lithospheric mantle beneath the continental crust point the need to extend our focus below the crust.

Plain Language Summary In the aftermath of plate tectonics, one of the greatest scientific discoveries of the twentieth century, the nature of widespread, diffuse deformation of the continents has been on the leading edge of research for over 50 years. This issue is also of great societal impact as many of the most devastating continental earthquakes occur away from boundaries of tectonic plates. I trace how two contrasting concepts on this subject developed and conclude that scales in space and in time are keys to understanding deformation of the continental crust.

By the late 1960s plate tectonics has been firmly established. Conceptually, this new paradigm of global tectonics portended the end of the age-old belief of terra firma and ushered in the mobile view of the solid Earth. While the basic idea of mobile continents has been raised before, including in the works of Wegener (1924) and Holmes (1945), a key in establishing plate tectonics is new information concerning the nature of ocean basins (e.g., Molnar, 2015; Uyeda, 1978). In basic terms, the outermost layer of the solid Earth, the lithosphere, is composed of both the crust and the uppermost mantle immediately below, with an overall thickness on the order of 100 km or so. The lithosphere is an assembly of about a dozen major pieces. These pieces of tectonic “plates,” or more precisely irregular spherical shells, are in constant motion relative to each other.

A point that caused considerable confusion before the mid-1960s is that the ocean-continent boundary may or may not be a plate boundary. To put it differently, a plate may comprise entirely of oceanic lithosphere, or continental lithosphere, or both. Therefore, it is no surprise that without access to data from the oceans, land-bound studies of traditional geology missed one of the most significant scientific discoveries of the twentieth century. Equally important is that the inaccessibility of oceans also means that much new evidence comes from geophysics, unfamiliar to traditional geologists who almost worked exclusively with the geologic record preserved in rocks on land. For instance, the study of deep earthquakes near Japan by Wadati (1931) laid a solid, early foundation for understanding how oceanic lithosphere is recycled back into the mantle, a process now known as subduction.

As the new paradigm of global tectonics, plate tectonics works particularly well in oceanic regions, evident from the collection of key articles by Cox (1973). In the aftermath of its initial triumph, the crucial question is whether plate tectonics can achieve the same success in explaining the deformation of continents. Chase (1978) illustrated the inadequacy of plate tectonics to describe continental tectonics by adding a boundary between the Nubian and Somalian plates in eastern Africa. The fact that this boundary exists is obvious, with numerous earthquakes, recent volcanism, and topographic expressions of rifting along the East African rift system. However, the rate of slip there is too low, only millimeters per year, to be resolved in global models whose uncertainties on the rate of plate motions are of the same order of magnitude (e.g.,
Minster & Jordan, 1978). This is an early example of increasing the resolution of global plate tectonics by growing the number of plates.

A cornerstone of plate tectonics is that relative plate motion can be approximately by the rotation of rigid spherical shells—the Euler’s theorem of rotation (e.g., McKenzie & Parker, 1967). Implicit in this concept is that the amount of deformation within a plate is negligible, with significant deformation occurring only in narrow zones along plate boundaries. But even before the plate tectonic era, it is already known that seismic activity is diffuse in many continental regions (Gutenberg & Richter, 1954), in obvious violation of the approximation of rigid plates. So continental tectonics became the next frontier of global tectonics and the quest continues to this day.

To this end, a significant advance came in 1975 when Peter Molnar and Paul Tapponnier attributed the active deformation of central Asia to the ongoing continental collision between India and Eurasia. A key point of their work is that the collision apparently has far-reaching consequences, affecting or even controlling active deformation for several thousand kilometers from the collision front.

In the following years, two end-member models were proposed to account for widespread, diffuse deformation in continental regions. One took the view of continuum mechanics and treated continents like a viscous fluid. An early example of this perspective is the thin, viscous sheet models advanced by England and McKenzie (1982) in which the continental lithosphere takes the approximation of a uniform, thin, viscous sheet. In this approach, there is no distinction between the rheology of the continental crust and the lithospheric mantle below. This is perhaps hard to accept for most geologists, for whom the lithological contrast between the crust and the mantle is too striking to ignore. In any event, a key factor here is the accumulation and release of gravitational potential, in the form of elevation changes, resulting from continental collision. In a simplified view, the collision causes the uplift of the Himalayas and the vast, high Tibetan Plateau. Meanwhile, potential energy of the elevated regions drives deformation in low-lying areas for thousands of kilometers.

The other view emphasized the role of large-scale strike-slip faults (also called transcurrent fault where the slip is predominantly horizontal and parallel to the trend of the fault). In essence, large blocks or geologic terranes slide past each other along major fault systems to “escape” or make space for the continuing convergence between India and Eurasia. This concept is perhaps more in line with views of traditional geology. In 1982, Tapponnier et al. used plasticine (modeling clay), sandwiched between Plexiglas plates, to simulate continental collision. Large-scale strike-slip faults developed in the analog model and the concept of continental escape took root. Although there is strong field evidence supporting this idea, the phenomenon observed by Tapponnier et al. (1982) in the laboratory is hardly surprising.

The Tapponnier et al. (1982) setup is for plane strain, so the plasticine has nowhere to go except to escape laterally when pushed by the “indenter,” representing India. Obviously, Earth is not under plane strain, as the pressure at the free surface is very small and the tallest mountain chain and the largest high plateau both exist immediately in front of the Eurasia-India collision zone. Because we do not have details of this experiment under finite strain, it is perhaps heuristic, as a first step, to examine the simplest case of infinitesimal, elastic strain on Earth’s surface. After all, in numerical simulations, each time step involves only infinitesimal strain and finite strain results over many time steps. Here, the vertical strain is about the same size as the two components of horizontal strain, $\varepsilon_{11}$ and $\varepsilon_{22}$. For a Poisson solid where the two Lamé constants are equal, the vertical strain at the surface is $-(\varepsilon_{11} + \varepsilon_{22})/3$, or one third of the areal strain. Therefore, the strong visual effect of the experiment is impressive, but the relevance of its physics may be debatable. Nonetheless, this report has been widely cited, including by many textbooks.

Complications in adequately describing continental deformation arise from two key factors. First is the buoyancy of the thick, light continental crust. The buoyancy prevents wholesale recycling of the continental crust into the mantle below, resulting in longevity of the continental crust, in which the oldest mineral preserved goes back to about 4 Ga, only about 0.5 Gyr after the formation of our planet (e.g., Windley, 1995). So the continental crust has been constantly reworked, and previous features, such as old suture zones and major fault systems between continental blocks, tend to influence the behavior of later tectonic processes. This is the all-important concept of inheritance in classic geology.
The second factor is the rheological contrast between the continental crust and the underlying lithospheric mantle. Except when the crust is very old (and therefore very cold) or as warm as the mid-ocean ridges, the lower continental crust generally has a much lower effective viscosity than the uppermost mantle (e.g., Chen et al., 2013). Overall, the level of shear stress that can be sustained over geologic timescales, when integrated over the entire thickness of the lithosphere or tectonic plates, is much higher in the oceanic than in the continental lithosphere (e.g., Molnar, 2015). As such, the approximation of a rigid plate works well only for the oceanic lithosphere.

Some astute structural geologists have noted the importance of spatial scale in distinguishing discrete slips from continuous flow (e.g., Price & Mountjoy, 1970; Turner & Weiss, 1963). In a voluminous textbook, Davis et al. (2012, p. 52) stated, “The distinction between slip and flow is scale dependent.” The difficulty here is that for a given problem, one does not know what the right scale is, especially because of the limited time window of reliable data, typically much less than 100 years. In other words, the role of the temporal scale further complicates issues caused by the spatial scale.

Over timescales of years to decades, the Earth is approximately elastic. In this case, Kostrov (1974) showed from theoretical considerations that strain caused by earthquakes can be calculated by the summation of seismic moment tensors. This tensor contains information on the true size of an earthquake, the (scalar) seismic moment or the product of the fault area, the amount of fault slip, and the rigidity of the faulted region. Additionally, it includes information about the orientation of the earthquake fault and the sense of slip across it (see Chen & Molnar, 1977, for the first applications to real data). In this snapshot, the strain in the volume, a concept of a deforming continuum, and discrete slips on faults neatly tie together.

At longer timescales, deformation associated with viscous relaxation of the lithosphere and farther below becomes important, even for seismogenic faulting (e.g., Wang et al., 2012). In the late 1980s, the widespread availability of geodetic-grade GPS receivers and other space-based techniques, such as interferometric synthetic aperture radar, to carry out geodetic work was a major boon to the study of the solid Earth. Together with seismic observations over a very wide frequency range (broadband seismology), one should be able to detect both discrete and continuous deformation simultaneously, provided that dense enough geodetic observations are available.

At one point, over half of the funding for structural geology and tectonics at the U.S. National Science Foundation was devoted to studies using GPS, but we are still far from having dense enough data to solve the conundrum of discrete versus continuous deformation (e.g., Wang et al., 2001). Take, for example, the quest for microplates on a global scale. In 2003, Peter Bird included 52 plates and microplates in his model, and this number has been increasing over time (e.g., Argus et al., 2011). Just compare this number with about a dozen major plates in the global models of DeMets et al. (1990). If one continues with this route, eventually, the distinction between discrete and continuous deformation will diminish, at least theoretically.

It is interesting to hear directly from Peter Bird, often considered a leading figure in the quest for microplates. He recently wrote to me that he is not a “believer” of microplates (P. Bird, personal communication, 12 March 2019): “I needed to finalize a global plate model for just one purpose: To study the rates of earthquake produced by different kinds of plate boundaries (Bird & Kagan, 2004, BSSA). This does not mean that I am a “believer” in continental microplates. In fact, my study of the western U.S. neotectonics (Bird, 2009, JGR) showed me that probably one third of Pacific-North America relative motion is absorbed by distributed deformation, and only two thirds are absorbed by slip on famous major faults. The same thing may be occurring in other orogens (like Persia-Tibet-Burma).”

Figure 1. Fractures in a drill core from the base of the Three Gorges Dam in China. A conjugate fracture set (pointed out by the right hand of a doctoral student, Ms. Qing Chen, in the image) and the lack of any plumose textures on the fracture surfaces indicate that these fractures are not joints but microfaults (of shear slip). Scratches and furrows produced by frictional abrasion (called slickensides, not visible in this photograph) on the fracture surface suggest that the sense of slip is topdown (a normal fault). The sample is located in front of the library on the main campus of China University of Geosciences (Wuhan).

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Every earthquake, no matter how small, is a manifestation of sudden slip. Figure 1 shows a photograph of microfaults of shear slip sampled by a drill core from the base of the massive Three Gorges Dam along the Yangtze River in China. The amount of shear slip is small, on the order of about 10 mm. Even at this scale, discrete and distributed shear can coexist.

Figure 2 shows an example of the S-C fabric, a well-known feature of deformation in metamorphic rocks (Davis et al., 2012). C surfaces are discrete zones of high shear strain (“cisailllement” in French) that distort and cut across the sigmoidal-shaped S surfaces (i.e., foliation or “schistosity” in French) of distributed plastic flow. Note that even for true plastic deformation, such as the deformation associated with the S surfaces, ever so slowly but surely, slip occurred at the atomic scale such as dislocation glide and dislocation climb (Figure 2). This view does not make me a believer or nonbeliever of microplates, simply an agnostic researcher still working on this vexing problem.

The lack of a suitable tectonic framework is a serious problem. No one relishes the days before plate tectonics. For certain problems, however, I do believe that the debate of continuous versus discrete deformation is unnecessary, even counterproductive, because many problems can be addressed without resorting to a particular end-member model. For instance, a number of detailed studies of instrumentally recorded earthquakes and the long record of historical seismicity are sufficient to provide a solid background for understanding the seismic hazard of the densely populated North China basin.

In particular, Chen and Nábelek (1988) pointed out that this is an active, large-scale pull-apart basin controlled by north-northeast trending strike-slip faults. To my knowledge, this tectonic model has not been superseded by recent work. Here numerous active faults, on the scale of 100 to 200 km in lengths, are known to have produced devastating earthquakes, including the Tangshan earthquake sequence of 1976 that caused at least a quarter million deaths (e.g., Chen et al., 1988). Since this earthquake sequence occurred near the end of the infamous, long political unrest known as the Culture Revolution when China was entirely closed to the outside world, the death toll may have reached three quarters of a million people (Chen & Nábelek, 1988).

Furthermore, new perspectives have risen from advances in continental tectonics at depth. Now it is clear that the longevity of the most stable continental terranes, the cratons, lies in the strong, buoyant, and melt-depleted (relative to the average mantle of the Earth) uppermost mantle beneath the cratonic crust that remained stable for over two billion years (e.g., Jordan, 1978; Lee & Chin, 2014). The buoyant, strong uppermost mantle and the crust together constitute a stable cratonic lithosphere. In the active zone of continental collision between Asia and India, the most iconic case of active mountain building, the stable mantle keel of the Indian craton, marked by its characteristic high speed of seismic shear waves, is easily recognized beneath the Tibetan Plateau, some 600 km farther north of the collisional front along the Himalayas (Chen et al., 2012; Hung et al., 2011, 2010). As such, tectonic models that focused mainly on the crust or oversimplified the lithosphere are likely to have missed the critical role of the lithospheric mantle in continental deformation.

Finally, it is heuristic to bear in mind that whenever continents are involved in deformation, the original plate tectonic concept of a narrow boundary separating tectonic plates is an oversimplification. Even in the supposedly simple situation of a long strike-slip fault boundary with an oceanic lithosphere on one side, such as the San Andreas fault system in California, the zone of deformation on the continental side is wide and complex. Dense geodetic and seismic observations, including those from the Plate Boundary
Observatory, showed that about 20% of dextral slip between the oceanic Pacific plate and the North America continent is accommodated along the Walker Lane near the Nevada-California border, at least 200 km eastward of the San Andreas fault system along the California coast (Bormann et al., 2016; https://www.unavco.org/education/resources/modules-and-activities/exploring-tectonic-motions/exploring-tectonic-motions-1-large.jpg).

Recently, I met a new colleague who asked me: “What scale of problems are you working on; thousands of kilometers?” It is clear that he was referring to the spatial scale, a good way of gauging the interest of a geophysicist, as we, by default, are dealing with the present. However, because the equivalence between spatial variations of geologic features and time progression of the underlying process often exists (diachronism), an even more insightful question would be “On what scales of problems, in space and in time, are you working?”

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