LLS2024 Part 2 — Lithospheric kinematics viewed 6 decades after the plate tectonics revolution

2-Revolution1-Script-20241005.docx to accompany 2-Revolution1-Tectonics-20241005.key

By Vincent S. Cronin, revised October 5, 2024

SLIDE 01 Lecture Series Title Slide

SLIDE 02 A current view of plate tectonics (lithospheric kinematics) six decades after the revolution

https://CroninProjects.org/Oct2024/Instantaneous-Tectonics/

SLIDE 03 This talk is **not** a history of the development of plate tectonics. If you would like a good summary of the development of plate tectonics, read "Continents in Motion" by the great science journalist Walter Sullivan. The details about this book and my other references for this talk are included in the webpages for this lecture series.

SLIDE 04 These two books by my friend Naomi Oreskes are also great reads if you are interested in understanding that history. The chapters in the book on the right were written by the people who were primarily responsible for the Plate Tectonics revolution in 1965-1969.

SLIDE 05 I will refer to ***rigidity*** and ***deformation*** during this talk, so let's define these terms. Points in a **rigid body** maintain their initial angular and distance relationships with one another over time. Points in a **deforming body** do not... Their angular and distance relationships to one another change over time.

SLIDE 06 When I was born in early 1957, there were several prominent hypotheses concerning the Earth's surface. Folks who were considered Fixists thought Earth's crust was essentially rigid and the ocean basins were as old as the continents (although of different basement composition). The only exceptions involved vertical motions related to isostasy. Many geoscientists in the US and the oil business held this view.

SLIDE 07 Many geoscientists thought that because the confining stress increases with increasing depth below the Earth's surface, and the rock materials that had been tested become stronger with increasing confining pressure in experiments with big rock-squeezing rigs, it follows that Earth's solid crust and mantle must be strong and rigid. They would argue that continents can't have moved to their current positions.

SLIDE 08 It is true enough that rock strength increases with increasing confining pressure during experiments conducted at room temperature. This is true for most rock materials, as Jim Byerlee showed in a series of classic experiments with this and other rigs. But that's not the end of this story...

SLIDE 09 Other geoscientists, particularly in Europe and the southern hemisphere, were persuaded by work done by Wegener, duToit, and others who focused on how the ancient cores of continents seemed to fit together -- physically like puzzle pieces, geochemically, petrologically, and paleontologically. They could not explain ***how*** this might happen, but the geological evidence they had strongly suggested it ***did*** happen.

SLIDE 10 Still, other geoscientists, prominently led by S. Warren Carey of the University of Tasmania, thought that the continents could fit together on an Earth of smaller radius and that Earth had expanded to its current dimensions. To them, the ocean basins were young features separating ancient continents.

SLIDE 11 The first convincing computer-assisted fit of Africa and South America was done in service of the expanding Earth hypothesis. In this slide, the current Earth is shown on the right side, and a smaller Earth with just the same area of continental crust (colored black) is depicted inside the current sphere of Earth's surface for comparison.

SLIDE 12 Finally, some geoscientists thought that Earth is contracting. Harold Jeffries of Cambridge University and Perry Byerly of Caltech thought that, well, let's repeat Byerly's own words from his textbook at Caltech on seismology:

SLIDE 13 "Most theories of the origin of the earth assume that it has cooled from a molten mass. It is now solid, that is, possesses rigidity, at least as deep as its core at a depth of 2,900 kilometers, as is shown by the free transmission of shear waves to this depth. (The radius of the earth is about 6730 kilometers.) Cooling of a mass as large as the earth is a slow process.

...it is apparent that the temperature is considerably higher below the crust than in it, and a failure of strength in rocks below the crust would not be surprising, although it is not known as yet how far the effect of higher temperature toward lowering the strength is counteracted by the effect of the high pressures toward increasing the strength."

The default position was to presume that Earth's materials strengthened with depth.

SLIDE 14 When Byerly wrote his seismology textbook in 1942, he did not have access to a map of global epicenters. The first global map of earthquake epicenters was published in 1953 for a Royal Society conference about earthquakes. There was no World Wide Seismograph Network when I was born in early 1957. There was no published map of the global seafloor. (The US Office of Naval Research embargoed that information.) Notably, Rothé's epicenter map of 1953 shows earthquakes along what we now know as the mid-ocean ridge system.

SLIDE 15 So that was the world I was born into. A decade later, things had changed profoundly.

SLIDE 16 Work continued on the experimental deformation of rock material ***at room temperatures***, and this generated an understanding of the brittle-ductile transition going from the ground surface to nearly 80 km depth. But it is **not** room temperature below Earth's surface where the pressure is 20 kilobars — at nearly 80 km depth.

SLIDE 17 Clever experimentalists at the Shell Research Lab, UCLA, and the USGS developed heated deformation rigs that could deform rocks up to 800°C. They found that, holding other parameters like grain size, rock type, strain rate, and confining pressure constant, rock weakens as the temperature rises. Pyroxenite -- an analog for lower oceanic crust -- drops to less than half its lab-temperature strength at 800°C. Dunite -- an analog for the upper mantle -- drops to about one-third of its initial strength when heated to 800°C.

SLIDE 18 Similar results were obtained for basalt and granite, typical rock types in the oceanic and continental crust, respectively. A basalt that takes just over 16 kilobars of differential stress to break at room temperature takes between 2 and 3 kilobars at 800°C. Its melting temperature is somewhere in the 1100-1200°C neighborhood, so it is still solid but will flow due to high-temperature crystal plasticity under differential stress.

SLIDE 19 And thanks to Defense Department support of a modern standardized seismograph network in the early 1960s that could detect nuclear detonations, and the proliferation of research networks after that, we now have an excellent ability to detect, locate, and characterize the focal mechanism of earthquakes worldwide. This is a recent map of epicenters of earthquakes with magnitudes greater than 4.5 from 1904 to 2018.

SLIDE 20 The experimental demonstration that rock weakens and flows at higher temperatures below its melting point was a significant blow to the Fixist worldview. That and mapping earthquakes, volcanoes, the seafloor, and marine magnetic anomalies were major influences on the development of plate tectonics.

SLIDE 21 Plate tectonics was a significant paradigm shift in the solid-Earth geosciences. This profound revolution led to remarkable progress in our understanding of Earth.

SLIDE 22 It was a revolution in the same sense as the development and mass production of the horseless carriage. I note that my great-grandfather Dawson drove Irish jaunting cars for his clients in Dublin in the late 1800s and early 1900s. When they became available, he became a chauffeur in a motor car.

SLIDE 23 When I took my first courses in geology at Pomona College circa 1976, plenty of geoscientists were still skeptical of this shiny new object called "plate tectonics." Many of my textbooks had no Tectonics content.

As Nobel laureate physicist Max Planck observed, "A new scientific truth does not triumph by convincing its opponents and making them see the light, but rather because its opponents eventually die, and a new generation grows up that is familiar with it."

SLIDE 24 Economist and philosopher John Maynard Keynes wrote, "The difficulty lies not so much in developing new ideas as in escaping from old ones."

SLIDE 25 Let's fill in some basic ideas using this film, produced by the IRIS Consortium of research seismologists for a general audience. <show video>

SLIDE 26 Just over three decades after he played a significant role in the development of plate tectonics, Dan McKenzie wrote, "Plate tectonics was clearly defined as a **kinematic** theory, one that is concerned with geometry. It is not a **dynamic** theory: one that is concerned with the driving forces."

SLIDE 27 As soon as maps of the South Atlantic Ocean Basin were available in the mid-1500s, people noticed the similar shape of the east coast of South America and the west coast of Africa. This is one of the earliest images suggesting that these two continents might have fit together at some earlier time. But this is just a work of art, not science.

SLIDE 28 The most famous of several scientific attempts at fitting the two continental edges was published by Bullard, Everett, and Smith in 1965. Gil Smith says that Jim Everett did most of the work, Smith added some geological knowledge, and Sir Edward Bullard (known to all as Teddy) made a one-sentence contribution. As he was passing through his research lab, he mentioned to Jim Everett that he should look into Euler's fixed-point theorem as he tried to write computer code to fit the continents together. For that (and the fact that it was, after all, Bullard's lab), Bullard became the paper's first author, and the result is called the "Bullard fit." Life is unfair sometimes.

SLIDE 29 The idea that plates move around Euler poles was very influential in the early history of plate tectonics. It has also been misunderstood and enthusiastically misused by many folks to this day. We'll talk more about them later.

SLIDE 30 The hot core of the plate tectonic revolution occurred from about 1963 to 1969. In 1973, Professor Allan Cox of Stanford University compiled the most important papers of this new field (that he could get permission to reproduce) and published them with his own comments in introductions to each related group of papers. Cox had made fundamental contributions (along with Brent Dalrymple and Richard Doell) to the study of terrestrial magnetism and created the first magnetic polarity time scale. His book "Plate Tectonics and geomagnetic reversals" became the most influential coursebook of the early plate tectonic era, with another textbook by Xavier LePichon (published the same year) a close second.

SLIDE 31 Cox defined two hypothetical postulates that are fundamental to plate tectonics. Postulate 1: "[Lithospheric] plates are internally rigid but are uncoupled from each other. At their boundaries, two plates may pull apart or slip one beneath the other, but within the plates there is no deformation."

SLIDE 32 Dan McKenzie wrote, "For me, the central idea is the rigidity of plate interiors. It is this property that allows the surface motions of the Earth to be described by so few parameters."

SLIDE 33 And so, in current geology textbooks, students learn about plate tectonics by studying simple plate maps and by hearing that plates are rigid and that virtually all of the deformation occurs along (or immediately adjacent to) plate boundaries. They learn that there are three types of plate boundaries. In other words, they learn first-order tectonics, vintage 1968.

SLIDE 34 Here's our first-gen Motorwagen and a current-gen electric vehicle. Let's leave first-gen ideas to science historians if they have been superseded by new data and better hypotheses.

SLIDE 35 New data like the instantaneous velocity vectors of GPS stations worldwide, expressed relative to well-defined reference frames. This map shows velocities relative to the essentially rigid cratonic interior of the North American plate.

Notice that the arrows on this map's right or east side are very short -- barely visible. That area is essentially rigid. To the west on the left side of the map, the vectors are typically longer than 15 mm/yr. If the North American plate were rigid to the San Andreas fault, these velocities would be 0 mm/yr or darn close.

SLIDE 36 Thanks to these new data, we now know that there are places on Earth where the crust of the plate interior is deforming. In other areas, the crust of plate interiors is essentially rigid. Postulate 1 is not universally valid.

SLIDE 37 Cox's Postulate 2: The pole of relative motion between a pair of plates remains fixed relative to the two plates for long periods of time.

SLIDE 38 Bullard's use of Euler's fixed-point theorem was perfectly fine for the limited purpose of rotating the South American continental edge to a best-fit position along the African continental edge. This is sometimes called a "total-opening" axis and is associated with a "total opening" angle. There is no implication that South America ***actually*** rotated around that axis over tens of millions of years — that the axis defined South America's ***actual*** trajectory. In fact, it didn't.

SLIDE 39 Just over three decades after the revolution, Dan McKenzie wrote, "It seems to me unlikely that plate tectonics will require changes. It is a precisely formulated theory that provides an accurate description of the large-scale tectonics of the earth."

I have encountered this sentiment many times in discussing my work in plate kinematics as if the initial hypotheses of plate tectonics are immutable laws of nature. New data is acquired, and sometimes, those new data render old hypotheses obsolete.

SLIDE 40 We have known since ~1969 that the pole of relative motion between a pair of plates cannot remain fixed relative to the two plates.

Allan Cox called this **the three-plate problem**. (More about this later.)

SLIDE 41 Postulate 1 is not universally valid. Postulate 2 is not valid for any system involving more than two plates. (As you know, Earth has more than two plates.)

SLIDE 42 So, let's take a moment to hit the reset button. Admiring this fine young pup is a charming way of giving our brain a bit of a cleansing. Let's leave the postulates of the late 1960s and early 1970s behind. They were formulated in good faith by well-meaning intelligent geoscientists, who did not have access to the data that we now have.

SLIDE 43 As Rory the cat would tell you if he was here with us today, we need to observe the world as it is. We must attempt to explain our observations humbly and dispense with hypotheses that do not lead us toward more reliable information about the Earth. Let's move forward.

SLIDE 44 When I was born, there were no publicly accessible bathymetric maps of the world's ocean floors. The first was published that year, 1957 — the first of a set of hand-drawn physiographic maps made using data classified by the US Navy because of its potential use in submarine warfare. It was a complete revelation.

SLIDE 45 Now our topographic and bathymetric maps are compiled from satellite altimetry and gravity data, shipborne sonar, lidar, and other land surveys. Upon this publicly accessible base...

SLIDE 46 ...we can map the two basic types of crust comprising the surface of the solid Earth. The tan areas are continental crust with an average composition similar to the rock granodiorite and ages ranging from 0 to more than 4 billion years. The blue areas are oceanic crust, with an average composition similar to basalt, mostly created during sea-floor spreading along mid-ocean rift zones, and ages ranging from 0 to about 200 million years.

SLIDE 47 The map of seafloor ages is derived from marine magnetic anomaly mapping with ground-truthing supplied by isotopic dating of samples collected at the bottom of exploratory wells drilled during the Ocean Drilling Program and the Deep Sea Drilling Program. The deep red zero-age crust is along the rift axis of mid-ocean ridges, and marks zones of high heat flow and thin lithosphere. Here, the lithosphere consists only of the oceanic crust — typically 5 to 8 km thick.

SLIDE 48 Here is a map of heat flow, with shorelines superimposed. The red to pink to white areas showing the highest heat flow are mostly along mid-ocean ridges, where the lithosphere is thinnest.

SLIDE 49 The rate of heat flow, in Watts per square meter, varies with age of the oceanic crust away from the axial rift. This graph is a composite representing data from all mid-ocean ridge systems.

SLIDE 50 The seafloor's depth increases with age — it increases with distance from the axial rift. The spread of the data is primarily related to different spreading rates along other parts of the global rift system.

SLIDE 51 From base to top, this idealized block diagram includes the upper-mantle asthenosphere, the upper-mantle lithosphere, the oceanic crust, and ocean water.

- The ocean's depth increases with increasing distance from the axis of the mid-ocean ridge.

- The crystalline part of the oceanic crust reaches its final thickness at the ridge axis and remains essentially the same thickness as it ages. (Of course, the older it is, the more sediment accumulates on top of it.)

- The upper-mantle lithosphere thickens by cooling away from the ridge axis. It thickens by accreting mantle material from the cooling asthenosphere. As the lithosphere cools and thickens, it sinks into the asthenosphere like a boat displacing water along its hull.

SLIDE 52 The fact that the thickness of the oceanic crust varies only a little bit across all of the ocean basins explains why, in this map of crustal thickness, the oceanic crust is a rather uniform shade of blue. The thickness averages about 5 to 8 km.

SLIDE 53 Back to the block diagram.

- The upper-mantle lithosphere thickens by cooling away from the ridge axis. It thickens by accreting mantle material from the cooling asthenosphere. As the lithosphere cools and thickens, it sinks into the asthenosphere like a boat displacing water along its hull.

SLIDE 54 Returning to this crustal thickness map, we see that the continental lithosphere varies in thickness from around 20 to more than 70 km. The thickest is beneath the Himalaya Mountains and Tibetan Plateau, and the crest of the Andes. Otherwise, the average continental crust is around 40 km thick.

The thickness of most of the crust is less than 1% of Earth's radius.

SLIDE 55 The lithosphere includes the crust and the rigid-elastic uppermost part of the upper mantle. The oceanic lithosphere is as expected: thin along the axial rifts and thickening away from them. The continental lithosphere ranges from quite thin in continental rifts to more than 200 km thick under old stable cratons and the Himalaya-Pamir area. Most of this thickness is upper mantle lithosphere, so these thick areas also reflect low thermal gradients — smaller change in temperature with depth.

SLIDE 56 This graph of isotherms in the solid Earth is capped by oceanic crust, with a mid-ocean ridge to the left and around 165-million-year-old crust to the right. The parallel vertical lines indicate a lower-seismic-velocity zone in which the upper mantle is hotter than 1000°C and weaker than the surrounding mantle. This is a seismologist's view of the active asthenosphere below the oceanic lithosphere.

SLIDE 57 We will take the information in the red box, adjacent to the ridge axis...

SLIDE 58 ...and use it to update a figure published by Bohannon and Parsons in 1995, on the right. Thanks to the experimental rock deformation studies published by Steve Kirby and others, we can plot the strength of several characteristic rock types as a function of temperature, shown on the left. Quartzite is an analog for the upper continental crust, quartz diorite represents the lower continental crust, diabase represents the upper oceanic crust, and dunite represents the uppermost mantle. Dunite is mostly olivine.

All of these weaken as the temperature rises to more than half of their melting temperature, which increases from quartzite to dunite.

Quartzite is as weak as a kitten at 400°C, which is still cooler than its melting point, while dunite is quite strong at that temperature. But even dunite weakens significantly above 700°C.

SLIDE 59 Using this information, Bohannon and Parsons constructed strength-depth curves for a few different ages of oceanic lithosphere. From left to right, we have 3-million-year-old oceanic lithosphere (from quite near the ridge axis), 4 million years, and 20 million years. The oceanic crust is 6 km thick in all cases.

- At 3 million years, the geothermal gradient is quite high, and the strong part of the crust extends to about 3 km depth. Below that, it weakens considerably (as the temperature increases considerably) to the Moho, where the upper mantle lithosphere is quite weak.

- At 4 million years, the strong part of the crust thickens a bit, and the upper mantle just below the Moho has strengthened significantly due to the cooler temperatures.

- At 20 million years, the crust and upper mantle lithosphere have no significant weak zones, and the strength of the lithosphere increases to around 25 km depth.

SLIDE 60 Changing the vertical scales by a factor of two, we are now looking at the strength-depth curves to a depth of just over 50 km in lithosphere capped by continental crust on the left and 20 million-year-old oceanic crust on the right.

• We've already seen that the oceanic lithosphere strengthens to a depth of about 25 km after 20 million years of cooling.

• The continental lithosphere on the left is represented by quartzite in the upper crust and quartz diorite in the lower crust.

•• The upper continental crust strengthens to about 10-12 km depth in general accordance with "Byerlee's Law." Then it weakens as the temperature increases beyond about half of its melting point.

•• The top of the lower crust is strong, but it too weakens with increasing temperature and depth

• The lithospheric mantle below the Moho is strong in this model because it reflects an average geothermal gradient.

SLIDE 61 In this simplified continental crust profile, there are a couple of depth/compositional zones in the continental crust that are hot enough to be weak, but not hot enough to melt. Some have called this sort of feature a crustal asthenosphere. Deep-seated listric normal faults and the flats of large thrust sheets might be associated with this weak layer in the continental crust.

The ***presence*** of these potential zones of weakness in the continental crust where the geothermal gradient is high helps to explain why these areas deform if they are subject to differential stress.

The ***absence*** of potential zones of weakness in the oceanic crust explains why older oceanic lithosphere tends to be essentially rigid with a mostly-elastic rheology.

SLIDE 62 Reprise: Using site velocities from 3 GPS stations to measure crustal strain.

SLIDE 63 We are going to use actual data from 3 GPS stations just northwest of Salem, Oregon, to determine the present state of crustal stress in that area. the GPS sites are located on North American continental crust above the subducted Juan de Fuca Plate

SLIDE 64 GPS Stations P395, P396, and P406 are shown on this map.

SLIDE 65 They form the apices of a triangle bounding the area where we will measure average horizontal strain.

SLIDE 66 For each station, we collect the average East and North velocities from their location time series, which are available from the Nevada Geodetic Lab, the GAGE facility of the EarthScope Consortium, and NASA-JPL.

SLIDE 67 I know that I have shown you cartoons of straining circles and triangles while I was introducing this method to you earlier, but what I ***actually*** do is compile a spreadsheet of relevant data and feed it into a Mathematica program or Excel-based calculator that I have written. You have access to these resources through the lecture webpage.

The necessary input data for each station are the longitude and latitude of the site, the east velocity and uncertainty, and the north velocity and uncertainty. Velocities are expressed in millimeters per year.

SLIDE 68 The rest of the data file is metadata that reminds me where the data are from and which GPS station generated them. This is the Mathematica version of the strain calculator, and we direct it toward the dataset file and let'er rip. <notice the steps>

SLIDE 69 That process gives me what I need to create a map symbol that characterizes the strain ellipse, and a second-invariant value so I can produce a regional strain map with color. This area is shortening from the east-northeast to the south-southwest, and stretching perpendicular to that.

SLIDE 70 I drop that map symbol on the map and step back to consider the context

SLIDE 71 ... and step back to consider the context

SLIDE 72 So the continental crust of the upper plate is deforming due to the subduction of the oceanic Juan de Fuca Plate. Above the subducting slab, the geothermal gradient is higher than average and the water from the slab contributes hydrothermal weakening of the overlying lithosphere.

SLIDE 73 We computed the second invariant of the strain-rate tensor to be 59.12 nano-strain per year, which corresponds to a yellow-orange color. That is the color used in Zheng's published map in the area of our three GPS stations. So we've walked through a simplified version of how a map like this is compiled. The reason this whole map area is not dark blue (which would indicate little to no horizontal strain) is that this broad area is actively deforming, from the front range of the Rockies west to the ocean.

SLIDE 74 Using GPS data and methods like these we can find the parts of Earth that are not behaving like rigid plates. The colored areas are deforming, and the white areas are either not deforming or we do not have enough data to tell.

SLIDE 75 Here's a map of the GPS sites used to define the plate and non-plate areas. We have good coverage on continents, but are limited to islands in the ocean basins.

SLIDE 76 To summarize, Earth's surface includes areas that behave as rigid plates, and other areas away from plate boundaries that actively deform. These are "non-plate areas."

SLIDE 77 Hasterok and other coauthors recently gave us an up-to-date map of Earth's lithosphere, differentiating it plates and microplates from areas that are actively deforming.

SLIDE 78 The explanation of the colors is a bit wonky, but the gist of it is that the pale colors indicate essentially rigid plate areas, medium density colors are for microplates, and more intense colors indicate the non-rigid non-plate deformation zones.

SLIDE 79 So this is the map of Earth's lithosphere that students should start with. We should leave the first-generation ideas to the science historians.