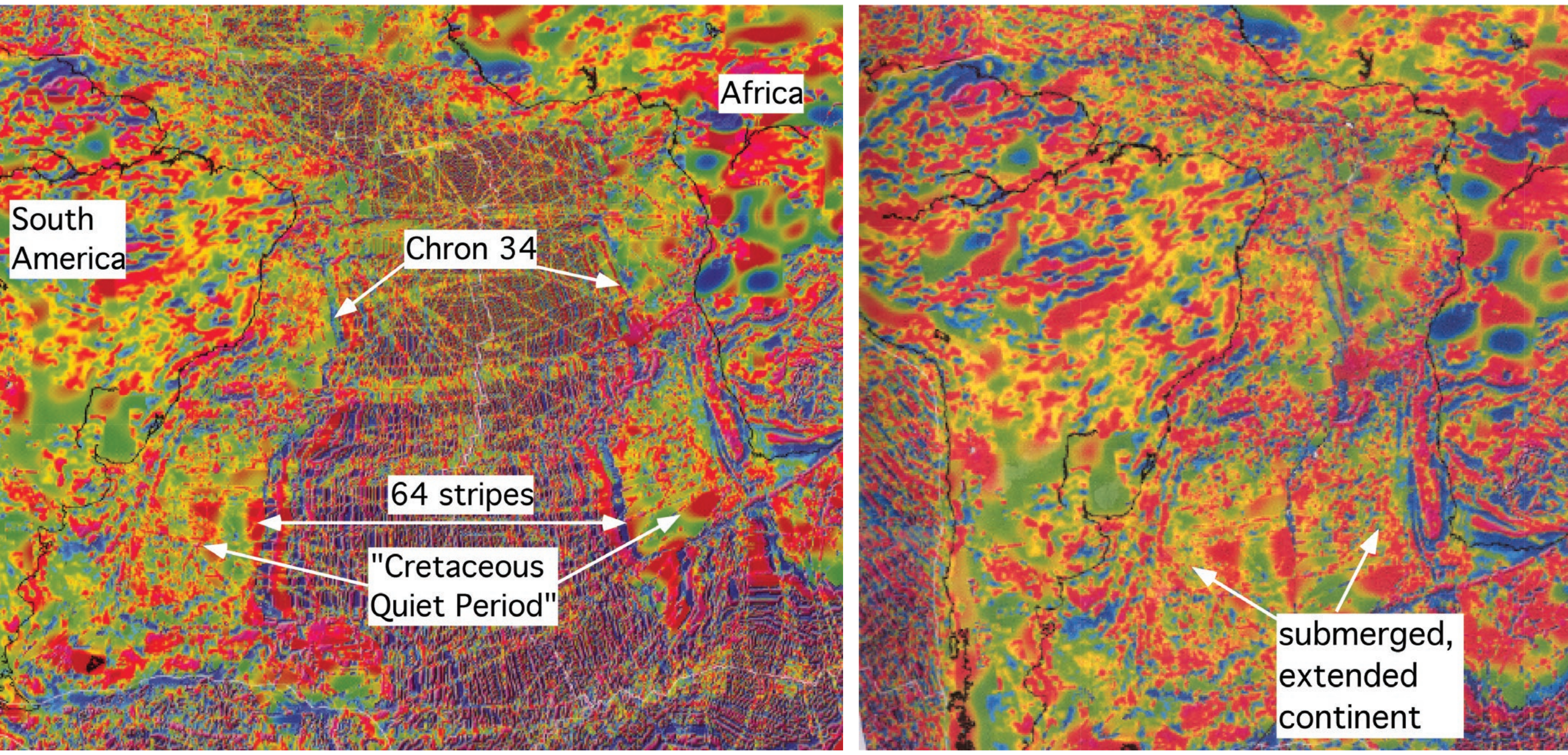

Not Written in Stone

Plate tectonics at 50

The Plate tectonic paradigm – "the unifying theory of geology" – has just turned 50.

In 2017, the Geological Society of London's William Smith Meeting celebrated this historical occasion, perhaps with a touch of self-congratulation, but with little discussion of alternative ideas.

Plate tectonics (PT) is an enormous topic with a convoluted history. This article highlights some problems, some old ideas, emerging data and some different possibilities.

Supercontinent Pangaea began to fragment in the Triassic. PT holds that from the Jurassic onward, mid-ocean ridges (MORs) generated new seafloor that separated continents. Here, magnetic stripes record reversals of Earth's magnetic field and spreading progress.

This crust is consumed by subduction, which creates blueschists and new continental crust below volcanic arcs. Collision raises mountains.

PT's predecessor theory, continental drift, used the fit of South Atlantic coastlines and fossil distributions as basic arguments for the former connection of South America and Africa (see figure 1). Mantle convection distributed continents.

Continental Reconstruction

Magnetic data (see figure 2) suggest an intriguing alternative to coastlines/bathymetric contours for Pangaean reconstruction. Large areas without magnetic stripes below the South Atlantic adjacent to South America and Africa supposedly record the Cretaceous Quiet Period, when magnetic field reversals paused for 40 million years. Alternatively, a similar signature suggests they are foundered parts of adjacent continents. They reconstruct well (see figure 2). A similar signature appears off eastern North America where seafloor fractures that continue onshore to Palaeozoic/older Appalachian offsets indicate ancient, continental origins.

In today's PT, paleontology takes a back seat. A new book published by the Geological Society of London, "Crustal Evolution of India and Antarctica: The Supercontinent Connection," edited by N.C. Pant and S. Dasgupta, relates India to Antarctica using geochronological data/petrology. Fossil data relate India to neighboring Eurasia. Dinosaurs, freshwater snails, catfish, cichlid fish, angiosperms, flightless birds and manatees evidence communication between supposedly long-separated areas. Monkeys and rodents travelled 2,600 kilometers from Africa to South America (early Cretaceous separation) in the Oligocene. Mammals migrated between Africa and Madagascar (Jurassic separation) as recently as the Eocene-Miocene. Explanations offered include swimming, rafting or island hopping.

> "Published PT teaching is complacent. It should adapt to emerging data, include multiple working hypotheses and enable students to think and choose."

Foundered continental areas are an interesting alternative.

Convection and Sea Floor Magnetic Stripes

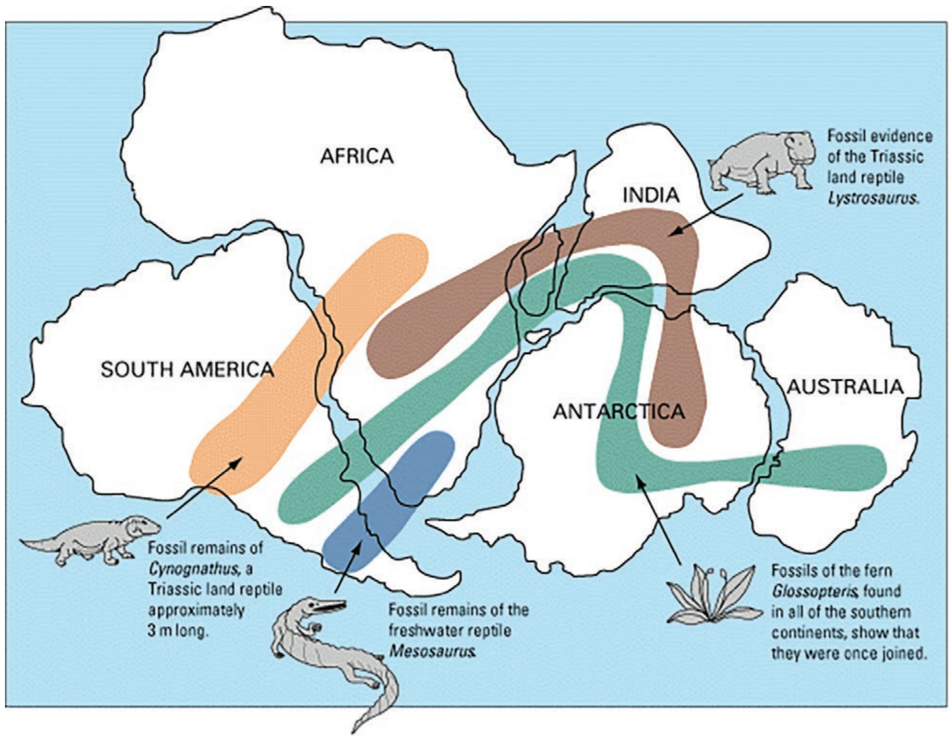

Figure 1. As noted by Snider-Pellegrini and Wegener, the locations of certain fossil plants and animals on present-day, widely separated continents would form definite patterns (shown by the bands of colors), if the continents are rejoined. Image courtesy of the United States Geological Survey.

Today's PT maintains that subduction slab pull is the major driver of spreading. This seems to be a non-starter – no spreading, no pull, and vice-versa. 2-D models of mantle convection cells rising at MORs, diving below subduction zones and carrying continents apart are still alive but could they be segmented in the third dimension? MOR offsets up to several hundreds of kilometers along fractures surely rule them out.

A major pillar of PT is that sea floor magnetic stripes, sometimes attributed to magnetic field reversal, others to high versus low intensity, record spreading. They also occur in continental rifts.

Moving ever further offshore, seismic surveys reveal lightly stretched continental crust followed by thinning from 30 kilometers to less than 10 kilometers, and thence to highly extended crust, presumed continent-ocean boundaries and "oceanic" crust. The crust is being stretched. That seems to rule out ridge push as a spreading driver.

Extended crust carries asymmetric basins, between 60 and 200 kilometers wide and up to 25 kilometers deep, where reflections, some with sedimentary architecture (truncation, onlap), dip toward bounding faults (seaward-dipping reflections, or SDRs). Here, magma rises to intrude sills and extrude basalt. Stretching also results in serpentinization (with magnetite) of exhumed peridotite, generating magnetic anomalies unrelated to MOR spreading.

Could they explain seafloor magnetic stripes?

Deep sea drilling aimed at calibrating increasing age of oceanic crust away from MORs encountered basalts assumed to be "basement," but some contained sediment clasts and some deeper basalts were interbedded with sediments. Perhaps "oceanic" crust includes extended continent basins far offshore. Is there any evidence?

Continent Below Oceans

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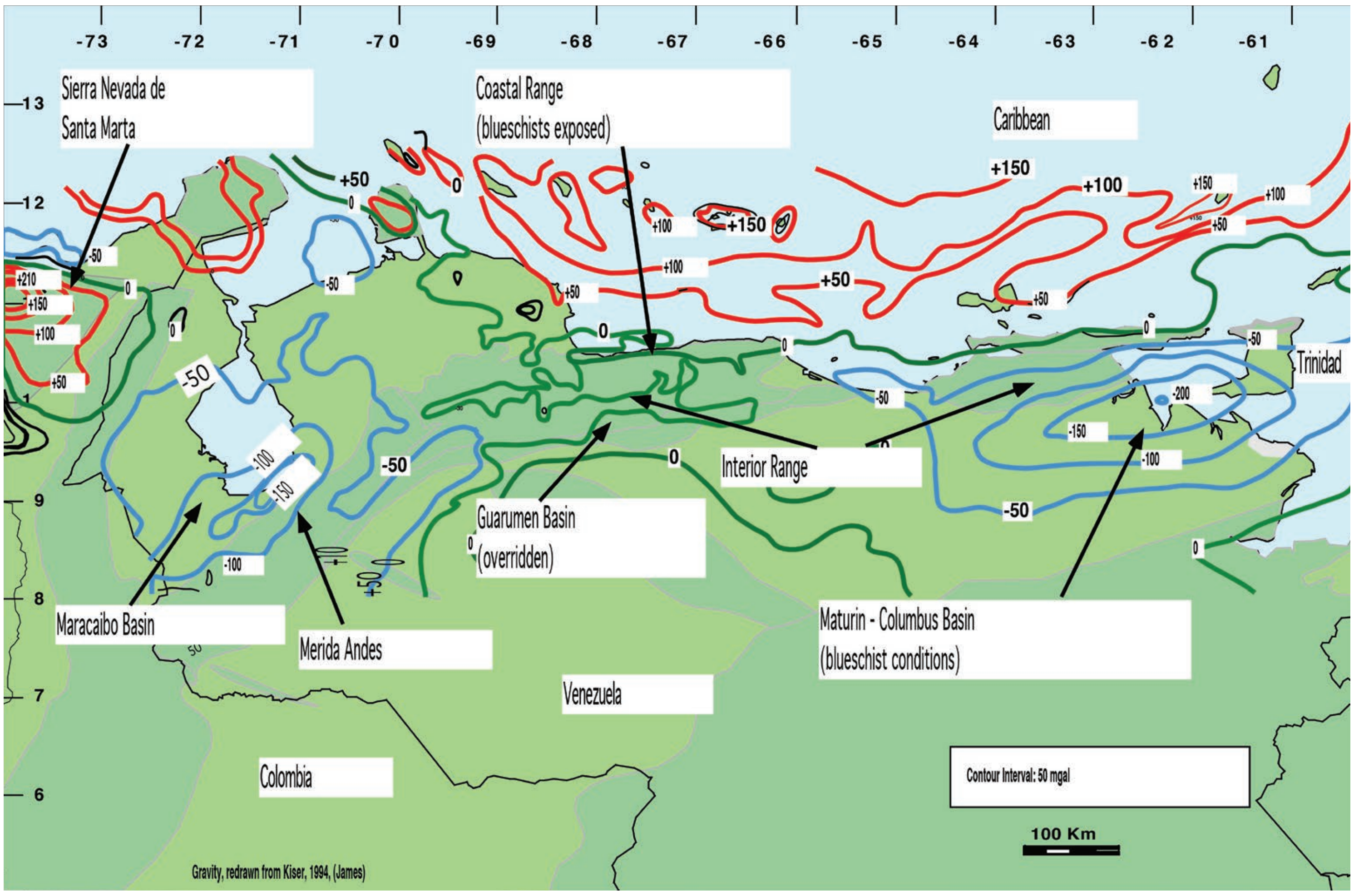

Figure 2 (far left). This signature of non-striped submarine crust similar to adjacent Africa and South America suggests subsided, extended continent. Image extracted from the Magnetic Anomaly Map of the World by J.V. Korhonen of the Commission for the Geological Map of the World in Paris.

Figure 3 (middle). Removal of striped crust (fig. 2) indicates reconstruction of much larger Pangaean Africa and South America, with significant implications for occurrence of continental material on the ocean floor, fossil distributions and exploration possibilities.

Figure 4 (right). This gravity map of northern South America indicates dynamic, eastward-migrating, deep (blueschist conditions) foreland basins pursued by inverted, overriding uplifts exposing metamorphic rocks.

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PT overlooks numerous samples of continental material dredged from ocean floors, some with trilobites and graptolites, (e.g., Bald Mountain, 80 kilometers-cubed of Proterozoic granite, and King´s Trough in the North Atlantic).

Rocks as old as 2 billion years occur on the Mid-Atlantic Ridge Peter and Paul's islands. Proterozoic-Paleozoic zircons occur in gabbros on the Mid-Atlantic Ridge.

Continental isotopes are widespread in Indian Ocean basalts. Proterozoic zircons in lavas on Mauritius suggest ancient basement, newly christened "Mauritia" in 2013, below the island and adjacent Mascarene Plateau. Magnetic data indicate a large submerged continental area to the east. It carries some of the features of the previous paragraph.

In the South Atlantic, granite was in 2013 discovered on the northwest-to-southeast Rio Grande Ridge (outer edge of South America's magnetic extension). Basalts on the "conjugate" Walvis Ridge show continental signature. Both are seen as migration tracks over the same Tristan da Cunha hot spot but they are oblique to seafloor fractures (flowlines). Both ridges are associated with those large extensions of neighboring continents and SDRs are present.

Precambrian-Devonian zircons have just been reported in lavas of the Galapagos Islands, a 20 million-year-old supposed hotspot 1,000 kilometers west of South America. Mesozoic zircons occur on Iceland, 13-15 million years old, on the Mid-Atlantic Ridge.

In 2017, Zealandia was nominated as a newly recognized continent. This fragmented, largely submerged area between Australia and New Zealand is the size of India. It explains plant and animal distributions in the

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South Pacific. There is much more, however. Magnetic data indicate very large extensions to the north and east. Permian-lower Cretaceous sandstones in New Zealand's eastern Torlesse Terrane, 3,500 kilometers long, 300 kilometers wide and 30 kilometers thick, came from here.

Pangaean Reconstructions and Earth Size

Proliferating models of Pangaea, its breakup and dispersal show Increasing complexity, recognizing ever more small terranes and their migrations, but they overlook important data.

One objective, to model paleoclimate and thence source rock presence, requires knowledge of ocean currents. Mid-Jurassic/Miocene shallow-water deposits and subaerially weathered rocks, now 1 – 7 kilometers deep, in Deep Sea Drilling Project sites in the Atlantic, Indian and Pacific Oceans must have been influenced by these, but reconstructions do not show them. Those large subsided continental masses need to be taken into account as well.

Reconstructions show oceanic crust east of Japan and New Zealand, and west of South America. But Japan received sediments from the east in the Palaeozoic-Paleogene and a million cubic kilometers of Devonian micaceous sediments in Bolivia and Argentina came from the west. Geological, geophysical and dredge data evidence Precambrian, younger continental crust under northwest Pacific abyssal plains. It subsided below deep sea at the end of the Jurassic, but you can still see it on the magnetic map.

The reconstructions use constant size Earth. There are 75,000 kilometers of "spreading" ridges and only 30,500 kilometers of trenches and 9,000 kilometers of collision zones. Production of more crust than consumption implies that the Earth is expanding.

Space-geodetic data show that the solid Earth expanded about 0.24 millimeters annually in recent decades. Growth increments on fossil corals and brachiopods show that days per year declined from 424 in the Middle Cambrian to 365 today – like a pirouetting ballerina extending her arms, Earth grows and slows.

How?

Serpentinization of shallow mantle peridotite results in up to 40-percent volume increase and release of heat. Is this responsible for elevation of MORs, with their black smokers? Does radial growth contribute to continental separation, extension and subsidence?

Origin of Continental Crust

Intra-oceanic volcanic arcs are characterized by high silica andesite (named from the Andes of South America). This cannot derive from subducting slab low-silica basalt so we have an "andesite problem." For PT, the rock reflects "new" continental crust formed by complex partial melting of sediments, the slab, the mantle or the mantle wedge (or combinations of these) in "subduction factories." This is where continental crust forms.

Recently discovered Precambrian and Palaeozoic zircons produced by the volcanoes of and continental seismic velocities below island arcs Izu-Bonin, Luzon, Vanuatu, Solomon Islands, East Java and the Lesser Antilles show they are underpinned by original continent. There is no andesite problem and subduction factories are not required.

Blueschists (high-pressure/low-temperature metamorphism) are seen as classic indicators of fossil subduction zones, involving descent of material to 40–80 kilometers over millions of years, metamorphism, and then unexplained resurrection. However, some radiometric data suggest metamorphism only slightly younger than predecessor rocks. There are no blueschists in the Central American or Lesser Antilles subduction arcs. Along the north and south Caribbean margins, metamorphism increases and high-pressure/low-temperature rocks occur close to strike-slip faults. Some are even interbedded with sedimentary equivalents.

How Do Mountains Form?

While normal faults might involve tens of kilometers of displacement and thrusts up to several hundreds, strike-slip displacements can be many hundreds. These latter, primordial faults form a conjugate northwest and northeast global pattern. Transtention/transpression within this generates secondary north-trending extension and east-trending compression. The polygonal blocks these define are repeatedly shuffled within this global fabric.

Africa supposedly converged 2,000 kilometers with Eurasia, pushing up the Alps. Yet there is no uplift along the same boundary to the west in the Atlantic. The Alps and Carpathians carry European brachiopods. There is nothing African present. India is supposed to have migrated 7,500 kilometers north across the Indian Ocean to push up the Himalayas, but fossils relate India to Eurasia. Head-on collision of far travelled continents is not indicated. Perhaps strike-slip plays a role.

There is an interesting, dynamic, natural strike-slip laboratory along northern South America (see figure 4). Right-lateral offset generates eastward-younging foreland basins followed by inversion into overriding uplifts. The 200 milligal negative gravity anomaly, the world's largest at sea level, over the eastern, Maturín Basin suggests a root without a mountain. Major hydrocarbon reserves occur here. Industry data (sediment thickness, overpressures, low heat flow) point to blueschist conditions at depth.

The 210 milligal positive anomaly over Colombia's 5,800 meter Sierra Nevada de Santa Marta, the world's highest ocean-side mountain, indicates a mountain without a root, overriding the Caribbean.

The Mérida Andes, also strike-slip related, lie halfway over the 150 milligal negative gravity anomaly in the southern Maracaibo Basin – the mountain is arriving over its root. It has already covered the Guarumen Basin and inversion further north exposes blueschists in the Coastal Range. Graphitic rocks record former hydrocarbon systems.

Unlike the Atlantic, the Pacific is markedly

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Heloise Lynn started her career with Texaco in 1975. Thereafter, she completed her doctorate in geophysics from Stanford University in 1980. Then she worked for Amoco-BP and has been consulting in anisotropy, multi-component, and multi-azimuth seismic data. In 2015, she was presented with the Fessenden Award of the Society of Exploration Geophysics for her contributions to the industry on the use of azimuthal anisotropy contained in field data to extract geologic information.

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horizontal stress and/or vertical aligned fractures), then our images are clear and crisp.

ORT is the current standard symmetry for the industry … plus we have as "attribute" volumes the quantification of the velocity fields – and these we use in interpretation. Velocity is affected by lithology, porosity, pore fluids, horizontal stress (in the direction of source to receiver) and fracture sets. From laboratory studies, we know that stress in the direction of S-R has a proportional effect upon the P-wave velocity. The standard explanation for the laboratory observations is that increasing the stress in one direction will close the micro-cracks that are normal or near normal to the increased stress; this closure of the cracks normal to the increased stress will increase the P-wave velocity. Interval velocities (V_{INT}) average large volumes of rock, bounded by reflectors, and tend to change slowly spatially. The reflection amplitudes, however, are a spatially high-resolution dataset: they record the local contrast in impedance. The macro-fractures that flow fluids usually govern the azimuthal amplitude signatures: at least, this can be an initial hypothesis, to be tested against your own seismic data and calibration data. Since azimuthal V_{INT} and azimuthal amplitudes are arising from different volumes of rock, they need not agree. If they do agree, that's fine. When they don't agree, we note the heterogeneity between the two different rock volumes.

Evidence of azimuthal P-P travel times is visible in figure 3 (a) where the farther offsets show the travel time variation by source-receiver azimuth (a wobble, red arrow). The data are sorted first by offset group, then by azimuth within each offset group. The corrected travel times for orthorhombic processing are shown in Figure 2(b). The red arrow indicates where the azimuthal travel time variation is greatly reduced.

To be continued in next month's Explorer. E

Acknowledgements: My thanks to Mike Perz of TGS-Calgary for his kindness to supply figure 1 in this article. I thank Satinder Chopra for requesting this article after he soldiered through my Geophysical Society of Houston webinar, "Azimuthal P-P for Better Imaging, Fractures, and Stress Analysis" in December 2017.

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asymmetric – the East Pacific Rise (EPR) approaches South America and converges with North America. Magnetic data indicate large areas of extended, subsided continent west of the Rise but none to the east. Yet large amounts of conglomerates/sandstones in the Andes came from the Pacific. Crustal thicknesses here up to 70 kilometer speak of merger.

Since the EPR hit the trench Pacific/North America strike-slip motion has occurred along the San Andreas Fault. From Alaska to Mexico the North American Cordillera carries far travelled (hundreds of kilometers) distal/oceanic thrust sheets, detached from subducted Pacific crust to overly Precambrian-Mesozoic shelf sequences.

Extended/thinned continental crust is perhaps easily thrust onto continental margins. Paleozoic and Mesozoic troughs in Peru, with steep western boundaries and gentle eastern slopes, contain 10-12 kilometer thick prisms of shallow deepwater deposits (upward concave SDR reflections possibly indicate basinward velocity decline). Bounding growth faults acted as volcanic conduits. They resonate with those asymmetric basins seen on deepwater seismic.

These "vanished continents" once linked North America, southeast Asia, Australia and South America. They explain plant and animal fossil distributions.

Obviously, many will disagree. That's fine, discussion is good. But don't overlook those large areas of subsided continent remaining to be recognized. They could carry huge reserves. Someone will eventually lay claim to them. Meanwhile, published PT teaching is complacent. It should adapt to emerging data, include multiple working hypotheses and enable students to think and choose. If not, the writing in stone might eventually read "RIP." E