Plate Motion

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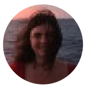

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Plate Motion

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Synonyms

Plate tectonics

Definition

Plate motion can be relative or absolute. Relative plate motion describes the motion of one tectonic plate relative to another. Absolute plate motion describes the motion of one plate relative to a fixed reference system. Plate motion can be described by a pole of rotation and an angular velocity about this pole.

Introduction

A tectonic plate is defined as a portion of the outer shell of the Earth that moves coherently as a rigid body without any significant internal deformation over geological timescales. The Earth's surface is composed of a mosaic of rigid plates that move relative to one another over hotter, more mobile mantle material. Plates interact at plate boundaries, which are dynamically evolving and continuous features.

History

Alfred Wegner's idea of "continental drift" (Wegener, 1915) to explain the geometrical, geological, environmental, and paleontological similarities between now distant continents lacked a physically plausible mechanism to explain the vast distances travelled by the continents. The interpretation of ocean floor data during a rapid increase in seafloor mapping after World War II led Hess (1962) and Dietz (1961) to propose the concept for seafloor spreading. They suggested that new seafloor is created at mid-ocean ridges, where a cold, strong surface boundary layer diverges, dividing tectonic plates. The new seafloor then spreads away from the mid-ocean ridge as it ages and is eventually subducted at deep-sea trenches, where it detaches from the surface and is recycled back into the Earth's convecting mantle. Wilson (1965) developed the concept of plates and transform faults, suggesting that the active mobile belts on the surface of the Earth are not isolated but continuous and that these mobile belts, marked by active seismicity, separate the Earth into a rigid set of plates. These active mobile belts consist of ridges where plates are created, trenches where plates are destroyed, and transform faults, which connect the other two belts to each other.

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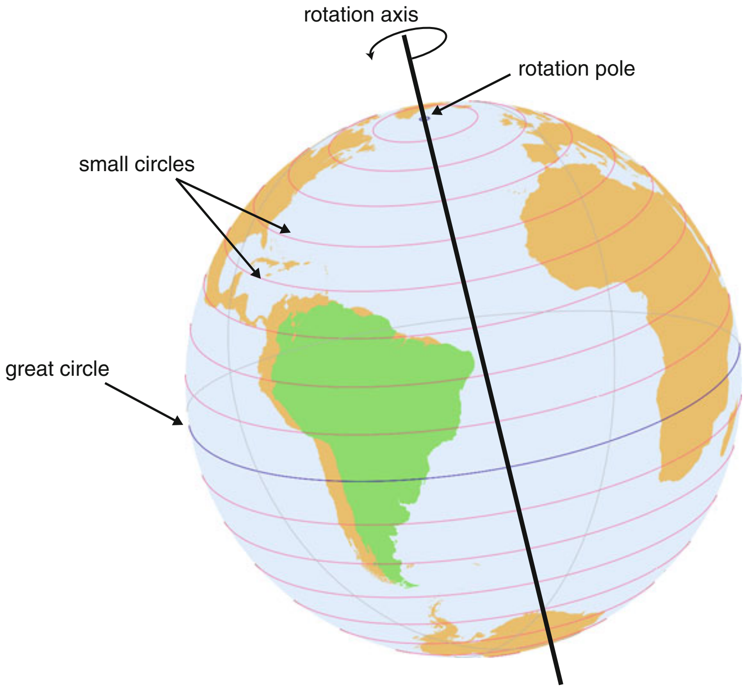

Fig. 1 Euler's theorem describes the motion of a tectonic plate by a rotation about a virtual axis that passes through the center of the sphere. The Euler poles are the intersections between the rotation axis and the surface of the sphere. *Small circles* describe the angular motion of a given plate. The set of *small* and *great circles* describing the rotation pole coordinate system is equivalent to a tilted (rotated) version of the familiar geographic coordinate system of the Earth represented by parallels and meridians

Euler's Theorem

All tectonic plates can be viewed as rigid caps on the surface of a sphere. The motion of a plate can be described by a rotation about a virtual axis that passes through the center of the sphere (Euler's theorem). In terms of the Earth, this implies that a single angular velocity vector originating at the center of the globe can describe the motion of a plate. The most widespread parametrization of such a vector is using latitude and longitude to describe the location where the rotation axis intersects the surface of the Earth and a rotation rate that corresponds to the magnitude of the angular velocity (in degrees per million years or microradians per year). The latitude and longitude of the angular velocity vector constitute the so-called Euler pole (Fig. 1).

Plate Tectonic Hypothesis

The formal hypothesis of plate tectonics states that the Earth is composed of an interlocking internally rigid set of plates in constant motion. These plates are rigid except at plate boundaries, which are lines between adjoining plates. The relative motion between plates gives rise to earthquakes; these earthquakes in turn define the plate boundaries. There are three types of plate boundaries: (1) divergent boundaries, where new crust is generated as the plates diverge; (2) convergent boundaries, where crust is destroyed as one plate dives beneath another; and (3) transform boundaries, where crust is neither produced nor destroyed as the plates slide horizontally past each other. Not all plate boundaries are as simple as the main types discussed above.

In some regions, the boundaries are not well defined because the deformation there extends over a broad belt, a plate-boundary zone (Gordon, 2000). These plate-boundary zones tend to have complicated geological structures and earthquake patterns as they involve at least two large plates and one or more microplates caught up between them.

Relative Plate Motions

Present-Day Plate Motions

Relative plate motions at the present are represented by so-called instantaneous rotations described by angular velocity vectors and follow standard vector algebra, i.e., the angular velocity vectors ${}_{\mathrm{A}}\mathbf{w}_{\mathrm{B}}$ and ${}_{\mathrm{B}}\mathbf{w}_{\mathrm{C}}$ describing the rotations of plate B relative to plate A and plate C relative to plate B can simply be added vectorially to obtain ${}_{\mathrm{A}}\mathbf{w}_{\mathrm{C}}$, the rotation of plate C relative to plate A. Models of present-day plate motions are often called “geologically current” plate models and can be measured using satellite technology (e.g., GPS measurements (Argus and Heflin, 1995) or space geodesy (Argus et al., 2010)) and/or a number of other observations:

1. The orientation of active transform faults between two plates can be used to compute their direction of relative motion. The relative motion of two plates sharing a mid-ocean ridge is assumed to be parallel to the transform faults and in turn assumed to follow small circles. Based on two or more transform faults between a plate pair, the intersection of the great circles, which are perpendicular to the small circles paralleling transform faults, approximates the position of the rotation pole (e.g., Morgan, 1968).
2. The spreading rates along a mid-ocean ridge as determined from magnetic anomaly patterns (e.g., Müller et al. (2008)) can be used to compute a rotation pole, since the spreading rate varies as the sine of the colatitude (i.e., angular distance) from the rotation pole.
3. Fault plane solutions (focal mechanisms) of earthquakes at plate boundaries can be utilized to compute the direction of relative motion between plates. Only the location of the pole, but not the spreading rate, can be determined this way. A global model for current plate motions based on data of types (1), (2), and (3) has been constructed and reviewed by DeMets et al. (2010), utilizing data which cover 3.2 million years of plate motion.
4. Geological markers are used along plate boundaries on land, in particular along strike-slip faults, to determine geologically recent local relative motion. Markers used include streambed channels, roads, and field boundaries that have been offset by strike-slip motion.
5. A satellite method called very-long-baseline interferometry (VLBI) uses quasars as signal source and terrestrial radio telescopes as receivers. The difference in distance between two telescopes is measured over a period of years.
6. Satellites have made it possible to measure present-day plate motions in real time at many more stations than possible using the VLBI technique, which depends on permanent radio telescopes as the receivers. Satellite laser ranging techniques using the Global Positioning System (GPS) have been used very successfully recently to measure plate motions all over the world, especially in areas that are subject to earthquake hazards. A current plate motion model based on a few decades of GPS data was constructed by Kogan and Steblov (2008).
7. Coupled geodynamic plate models, which model plate boundary locations and mantle density heterogeneity, have been used to predict present plate motions (e.g., (Stadler et al., 2010)). These predicted motions are entirely model driven and sensitive to the mantle properties used but can be compared to present-day observations.

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Plate Motions Through Geological Time

The reconstruction of plate motions through geological "deep" time requires the use of finite rotations whose manipulation is considerably more complex than those used for current plate motion (Cox and Hart, 1986). Relative plate motions for plate pairs which have preserved ocean floor generated by seafloor spreading at a common mid-ocean ridge can be reconstructed by fitting marine magnetic anomalies and fracture zones from conjugate ridge flanks. The Earth's magnetic field experiences reversals over geological time, leading to linear bands of ocean crust magnetized during a normal or reversed state of the Earth's magnetic field as seafloor spreading progresses. Thus, the ocean floor acts like a giant tape recorder and the magnetic anomalies caused by the alternating bands of normal and reversely polarized crust on the ocean floor can be fitted back together with the additional aid of fracture zones (Matthews et al., 2011), which are passive traces left on the seafloor by the transform fault offsets at mid-ocean ridges. A qualitative method for fitting such data visually ("visual fitting method") is provided by the community GPlates software (Boyden et al., 2011), and a quantitative method including the computation of uncertainties ("Hellinger method") has been developed by Hellinger (1981) and Chang (1988).

When only one flank of a spreading system is preserved due to partial subduction of an ocean basin, the computation of rotations describing plate motion is more complicated and relies on a "half-stage rotation" methodology described by Stock and Molnar (1988). This method involves computing a stage rotation between adjacent seafloor spreading isochrons on one flank and doubling the angle (assuming spreading symmetry) to obtain a "full-stage rotation." In instances where crust from both ridge flanks has been subducted, we rely on the onshore geological record (e.g., mapping of major sutures, terrane boundaries, and active and ancient magmatic arcs) to help define the locations of paleo-plate boundaries and use inferences from younger, preserved crust to estimate earlier spreading directions and rates. Where continental terranes have crossed ocean basins, a combination of paleomagnetic and geological data can be used to reconstruct terrane migration (Stampfli and Borel, 2002) and the now subducted ocean basins (Seton et al., 2012).

Absolute Plate Motions

Absolute plate motions represent the motion of individual plates relative to a reference system regarded as fixed, such as the Earth's mesosphere or the center of the Earth, in accordance with the forces that drive the plates. Relative plate motions are merely consequences of absolute plate motions, yet absolute plate motions are much more difficult to reconstruct. The main methodologies to constrain absolute plate motions are based on paleomagnetic data and volcanic hot spot tracks (Torsvik et al., 2008). Paleomagnetic data can be used to determine the orientation and latitude of a plate through time. However, since the Earth's magnetic dipole field is radially symmetric, paleo-longitudinal information cannot be deduced from paleomagnetic data alone. Seamount chains with a linear age progression (i.e., hot spot tracks) can be used to restore plates to their paleopositions with the assumption that hot spots are either fixed or nearly fixed relative to each other ("fixed hot spot hypothesis" (Morgan, 1971)). In considering seamounts and island chains as markers of past plate motion over stationary hot spots, Morgan (1971, 1972) suggested that such trails should form sets of co-polar small circles on the Earth's surface as a consequence of Euler's theorem for plate motions on a sphere. Wessel and Kroenke (1997) refined this method by introducing the "hot-spotting" technique which constructs seafloor flow lines backward in time using a combination of seamounts with and without age constraints. Another class of models combining plate motion and mantle convection (Steinberger and O'Connell, 1998) is designed to move away from the fixed hot spot hypothesis and consider the deflection of plumes through time in a convecting mantle. Absolute plate motion models in which seamount chains with age progression are assumed to be due to the interaction of plates relative to non-stationary hot spots are termed moving hot spot models (Doubrovine et al., 2012; O'Neill et al., 2005). Moving hot spot models only work well for the last 70–100 million years at most and thus require a changeover to an alternative reference frame (e.g., paleomagnetic-based) for earlier times. These models, which combine reference frames using two techniques, are termed "hybrid models." Another complication for constructing absolute plate models is the process of true polar wander, the wholesale rotation of the Earth relative to its spin axis (Torsvik et al., 2002). True polar wander is believed to occur mainly in response to the changing mass distribution in the Earth's convecting mantle due to the time dependence of subduction (Steinberger and Torsvik, 2010). When true polar wander is much faster than the average speed of the tectonic plates, it is expressed in all plates on the same hemisphere exhibiting the same sense of rotation. This method can be used to construct a true polar wander corrected absolute plate motion model (Steinberger and Torsvik, 2008).

Global Plate Motion Models Through Time

The most up-to-date global plate motion model is that by Seton et al. (2012). It combines relative and absolute plate motions in a global plate model, including the reconstruction of the global network of plate boundaries and the plates themselves through time. It uses a hybrid reference frame, which merges a moving Indian/Atlantic hot spot reference frame (O'Neill et al., 2003) back to 100 Ma (from "Megannum," meaning millions of years before present) with a paleomagnetically derived true polar wander corrected reference frame (Steinberger and Torsvik, 2008) back to 200 Ma. This reference frame links to the global plate circuit through Africa, as Africa has been surrounded by mid-ocean ridges for at least the last 170 million years and has moved relatively little since the breakup of the Pangaea supercontinent. The model (Fig. 2) is freely available on the internet in a GPlates-compatible (Williams et al., 2012) format.

Pre-200 Ma plate motions are based entirely on continental paleomagnetic data due to the absence of preserved seafloor spreading histories. Although paleomagnetic data on continents do not provide paleo-longitudes, the relative plate motions and tectonic unity of two continental blocks can be inferred from commonalities in the apparent polar wander (APW) paths (Van der Voo, 1990). If two or more continents share a similar APW path for a time period, then it can be inferred that these continents were joined for these times. Similarly, tectonic affinities can be deduced from the continuity of orogenic belts, sedimentary basins, volcanic provinces, biofacies, and other large-scale features across presently isolated continents (Wegener, 1915). A community plate motion model covering most of the Phanerozoic Eon, i.e., the last 550 million years, has been published by Wright et al. (2013). It builds on the models of Golonka (2007) and Scotese (2004) and provides examples for the use of paleobiology data as additional constraints for absolute and relative plate motions.

Summary and Conclusions

The main outstanding challenge for understanding plate motion through time is to further develop models that treat the tectonic plates and the convecting mantle as a coupled system, as well as extending plate models further in time that include plate boundary geometries and locations as well

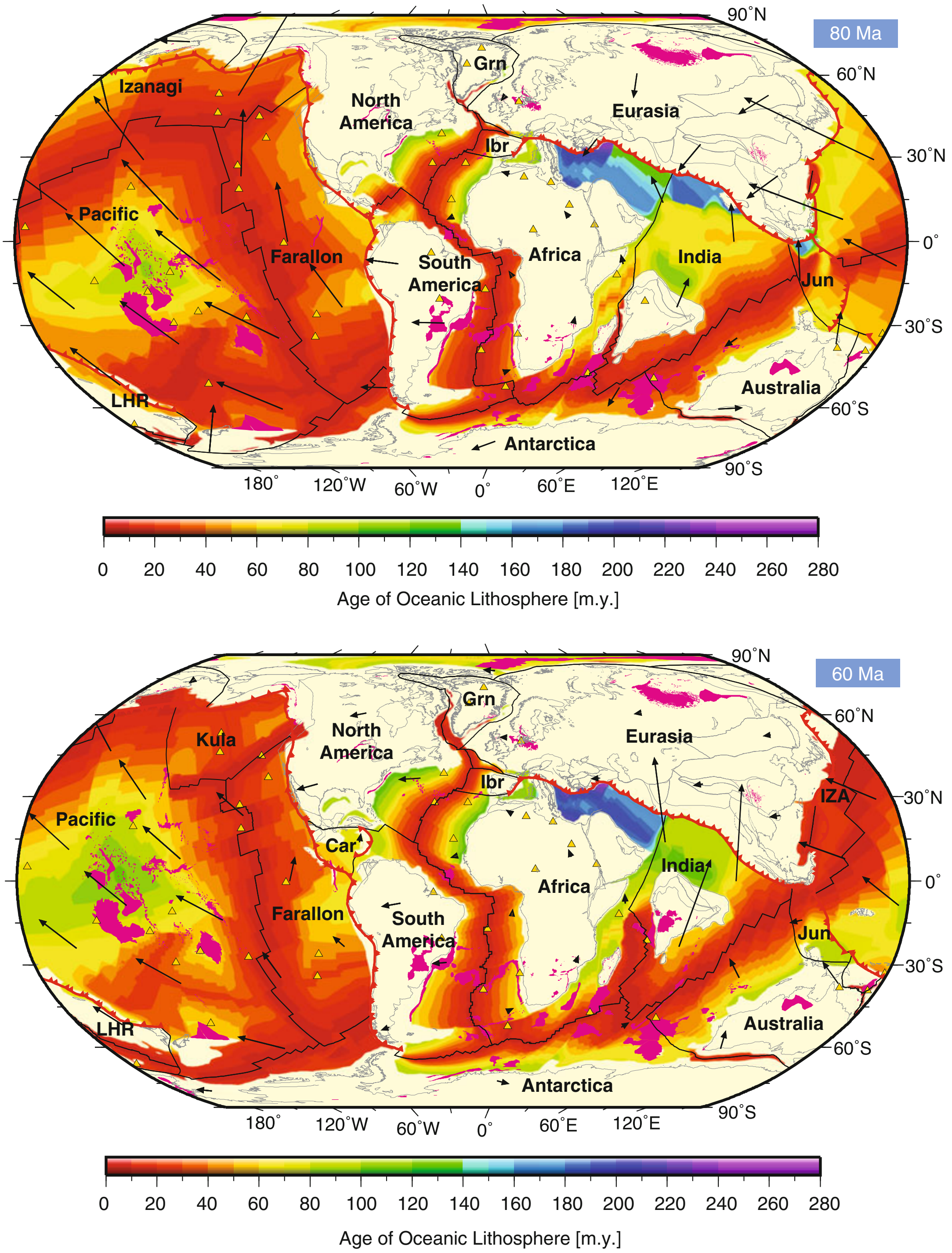

Fig. 2 (continued)

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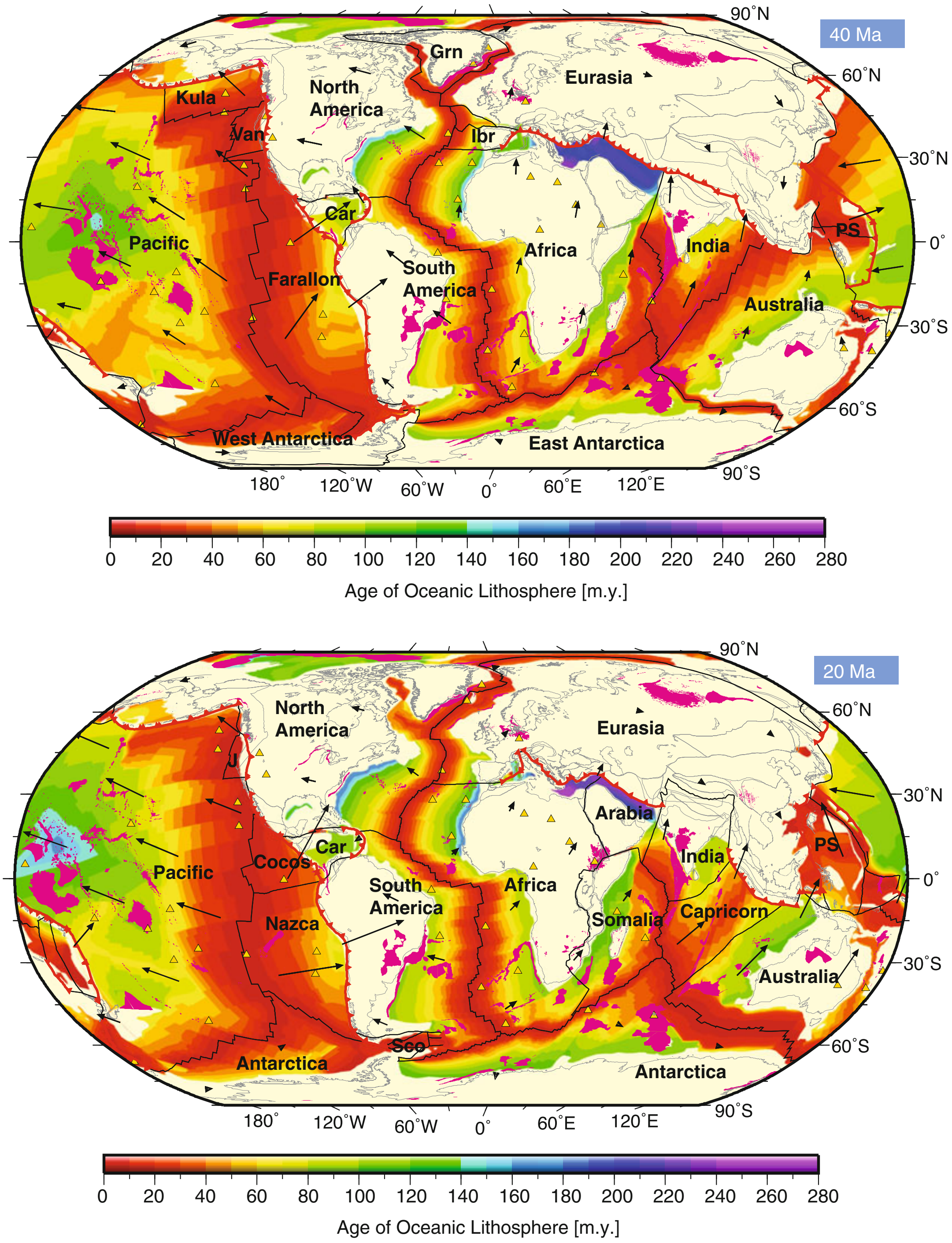

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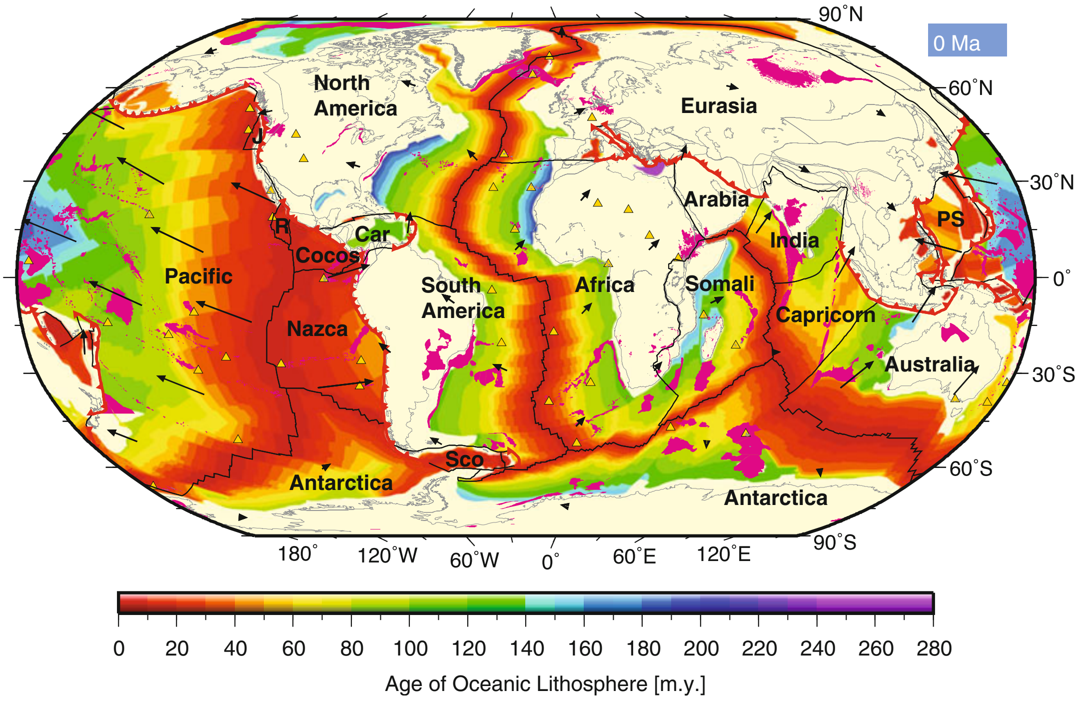

Fig. 2 Global plate reconstructions from 200 Ma to the present day in 20 million year time intervals. Base map shows the age-area distribution of oceanic lithosphere. *Red lines* denote subduction zones and *black lines* denote mid-ocean ridges and transform faults. *Pink polygons* indicate products of plume-related excessive volcanism (e.g., LIPs and volcanic plateaus). *Yellow triangles* indicate present-day hot spot locations. Absolute plate velocity vectors are denoted as *black arrows*. Major plates are labeled. Abbreviations include *Car* caribbean, *Col* colorado, *Flk* falkland, *Grn* greenland, *Ibr* iberia, *J* juan de fuca, *Jun* junction, *LHR* lord howe rise, *Man* manihiki, *Pat* patagonia, *PS* philippine sea, *R* rivera, *Sco* scotia sea, *Van* vancouver

as reconstructed ocean basins. This is essential for understanding absolute plate motions in terms of plate driving forces through time and to evaluate to what extent mantle plumes and the surface hot spots they cause may have been moving relative to each other. In order to advance our understanding of the coupling and feedbacks between deep earth processes and plate kinematics, new software tools and workflows need to be established in which observations, plate kinematics through time, geodynamic modeling, and model/data visualization are seamlessly linked, based on open standards and open-source tools. The burgeoning fields of simulation and modeling and "big data" analysis are likely to enable key advances in this area.

Cross-References

▶ Hot Spots and Mantle Plumes
▶ Lithosphere – Composition and Formation
▶ Sea-floor Spreading
▶ Subduction
▶ Transform Fault

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