PLATE TECTONICS: THE SCIENTIFIC REVOLUTION THAT REVEALED HOW OUR PLANET WORKS

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In the first part we will talk about our present-day knowledge of Plate Tectonics and of subduction margins and how we acquired this knowledge;

In the second part we will discuss the history of Plate Tectonics on the Earth and how scientists investigated this main issue of Earth Science
WHAT IS MODERN PLATE TECTONICS?

• New oceanic crust is produced along linear oceanic ridges;
• Oceanic lithosphere is consumed along convergent margins, subducting into the deep mantle;
EARTHQUAKES

https://www.youtube.com/watch?v=ph7Eczs-nTI
EARTHQUAKES WITH MAGNITUDES $\geq 6.5$
EARTHQUAKES WITH MAGNITUDES ≥ 8.0
WEGENER AND THE CONTINENTAL DRIFT HYPOTHESES (1912-1920)
WEGENER AND THE CONTINENTAL DRIFT HYPOTHESIS (1912-1920)

200 Ma emerged lands formed a uninc supercontinent called **Pangea**
WEGENER AND THE CONTINENTAL DRIFT HYPOTHESIS (1912-1920)

Evidences of continental drift: the shape of coastal lines

https://www.e-education.psu.edu/earth520/content/l2_p20.html
WEGENER AND THE CONTINENTAL DRIFT HYPOTHESES (1912-1920)

Evidences of continental drift: fossil distribution

http://www2.sunysuffolk.edu/vorwalb/Plate%20Tectonics%20&%20Cont%20Drift%20revised.ppt
Evidences of continental drift: continuity of geological structures

WEGENER AND THE CONTINENTAL DRIFT HYPOTHESES (1912-1920)

Earth: Portrait of a Planet 5/e, @2015 W.W Norton & Company Inc.
WEGENER AND THE CONTINENTAL DRIFT HYPOTHESES (1912-1920)

Evidences of continental drift: glacial deposits

Earth: Portrait of a Planet 5/e, @2015 W.W Norton & Company Inc.
SEISMOLOGY IN THE WEGENER’S TIME

Earthquake distribution map (1900)
SEISMOLOGY BETWEEN THE TWO WORLD WARS

Earthquake distribution map (1913-1930)
MODERN SEISMOLOGY AND PLATE TECTONICS

THE WORLDWIDE STANDARDIZED SEISMOGRAPH NETWORK (WWSSN)

123 STANDARD SEISMOGRAPH INSTALLED (1962–1971)

- Well established earthquakes location
- Focal mechanisms
- Earthquakes magnitude
The real nature of the active margins between continental and oceanic lithosphere represented one of the main issues in Plate Tectonics.
THE HERITAGE OF THE 1906 SAN FRANCISCO EARTHQUAKE

Horizontal displacement
THE HERITAGE OF THE 1906 SAN FRANCISCO EARTHQUAKE

Faults are sub-vertical

San Andreas Fault
CONVERGENT PLATE BOUNDARIES

HUGO BENIOFF (1899-1968)

https://www.e-education.psu.edu/earth520/content/l2_p13.html
CONVERGENT PLATE BOUNDARIES

BENIOFF (1954)

KURILI-KAMCHATKA ARC
Marginal Basin
Trench

1500
Km
0
10
Km

1500
Km
0
10
Km

W
E
68°
34°
Trench
KURILI-KAMCHATKA ARC
Marginal Basin

1140° 150° 160° 170°

150° 160° 170°

150° 160° 170°

150° 160° 170°

Magnitude

0
6
7
8

Modified from Benioff, 1954
Definition of the geometry and mechanism of subduction processes

CONVERGENT PLATE BOUNDARIES

BENIOFF (1954)

Modified from Benioff, 1954
THE BIG 1964 ALASKA EARTHQUAKE

- $M_w=9.2$
- $Depth= 23$ km
- 139 human losses
- $Run-up= 67$ m at Shoup Bay (Alaska)
“...The length of the primary fault is approximately 800 km as estimated from the extent of the belt of aftershocks. The distribution of polarity of first motion is consistent with a nearly vertical fault plane....”
“....We conclude that the primary fault came to within 15 to 20 km of the surface and extend to depths of 100 to 200 km.....”
THE INTERPRETATION OF GEORGE PLAFKER
COSEISMIC DEFORMATION
(PLAFKER, 1965)
The deformation field with uplifted area up to 11 m and subsiding area down to 2 m was interpreted as related to a low angle thrust fault, as suggested by Benioff.
For the first time a big earthquake was explained using the new Plate Tectonics theory. The convergent margin are related to subducting plates into the mantle.
The 1964 Great Alaska Earthquake demonstrated that the dense Pacific Plate is moving north, pushed into and under the more buoyant North American Plate.
THE GLOBAL TECTONIC MODEL BASED ON SEISMOLOGICAL DATA

Isacks, Oliver & Sykes (1968)
MODERN-STYLE PLATE TECTONICS:
THE ROLE OF SUBDUCTING SLABS

Trench rollback draws overriding plate towards trench

Bending resistance = 15%-40% resistive force
Ridge Push = ~10% driving force

~1.5% greater density of lithosphere than asthenosphere drives the plates

Slab Pull + Slab Suction = ~90% driving force

*Mantle viscous resistance & interplate friction = ~60%-85% resistive force

Stern, 2007
Lithospheric slabs on Earth reach great depths, typically 1100–1300 km, and possibly down to the core-mantle boundary (CMB).
B. Whole mantle convection

Oceanic ridge

Cool descending oceanic plate

Hot spot

Upper mantle

Hot rising mantle plume

Hot rising mega-plume

Core

680 km

Cool descending oceanic plate
MODERN-STYLE PLATE TECTONICS HAVE PETROTECTONIC ASSEMBLAGES THAT ORIGINATE IN SPECIFIC TECTONIC SETTINGS AND THAT ARE CHARACTERISTIC OF THOSE SETTINGS

1) **Ophiolites**: indicate the formation and consumption of oceanic lithosphere

2) **High Pressure/Low Temperature (HP/LT) and Ultra High Pressure (UHP) metamorphic units**: indicate deep subduction along convergent margins
SPREADING CENTERS TO CREATE NEW OCEANIC LITHOSPHERE
DEPOSITIONAL SYSTEMS GENERATING “OCEAN-PLATE STRATIGRAPHY”

- Fault scarp
- Mid-ocean ridge axis
- Sediment
  - Pillow basalt
- Dikes
- Gabbro
- Lithospheric mantle
- Crystal mush
- Magma
- Zone of partial melting
- Asthenosphere

Figure 4-8 Earth: Portrait of a Planet 3/e © 2008 W.W. Norton & Company, Inc.
Represent vestiges of oceanic basins now closed and entrapped in mountain belts.
OPHIOLITES

Present-day pillow lavas

Mesozoic pillow lavas
SUBDUCTION ZONES WHERE OCEANIC LITHOSPHERE IS RETURNED TO THE MANTLE
DISTINCT GEOTHERMAL GRADIENTS

SUBDUCTION ZONES

Subducting sediments are metamorphosed due to increase in pressure and temperature.

Shallow crustal rocks are metamorphosed by heat emanating from a nearby magma body.

Rocks buried in a large sedimentary basin may encounter low-grade metamorphic conditions near the bottom of the pile.

Low geothermal gradients are observed in subduction zones because cold oceanic crust and overlying sediments are descending into the mantle.

Rising magma transports heat to Earth’s upper crust causing an increase in the geothermal gradient.
PAIRED METAMORPHIC BELTS
SUBDUCTION ZONES

PAIRED METAMORPHISM
Barrovian ←-→ Blueschist

- Lithosphere (Ophiolite Suite)
- Asthenosphere
- Barrovian
- greenschist
- amphibolite
- granulite
- blueschist
- Eclogite
- Subducting Lithosphere

Blueschist
Eclogite
UHP TERRAINS: ECLOGITES
SUBDUCTION OF CONTINENTAL CRUST: UHP TERRAINS

Coesite
SUBDUCTION OF CONTINENTAL CRUST:
UHP TERRAINS

Diamonds
WHEN DID PLATE TECTONICS START?

There are several hypotheses about the starting of plate tectonics.

The main issues are:

1) What do we consider as Plate Tectonics?

1) What do we consider as beginning of Plate Tectonics (episodic vs. steady state and local vs. global)?
CONDITIONS REQUIRED FOR PLATE TECTONICS TO OCCUR

1) Plate tectonics could not have started until a significant fraction of the lithosphere became gravitationally unstable;

1) The lithosphere must be strong enough to remain coherent during subduction and plate motion, but weak enough to be broken into multiple plates.
PLATE TECTONICS CAN ONLY OCCUR WHEN APPROPRIATE MANTLE THERMAL CONDITIONS EXIST

• If the mantle is too cold, it is not possible to break the lithosphere and to form oceanic crust;

• If the mantle is too hot the oceanic crust is too thick and light to allow the oceanic lithosphere to subduct;
PLATE TECTONICS IS AN UNUSUAL WAY FOR A SILICATE PLANET TO COOL

Of the 5 largest silicate bodies of the Solar System (Mercury, Venus, Earth, Moon, and Mars), only Earth has subduction zones and plate tectonics.
SILICATE PLANETS

Key:
- Rocky crust
- Rocky mantle
- Metallic core
- Inner core
CONTINENTAL CRUST

Continents contain the oldest rocks and minerals in our planet, and give information on the thermal and tectonic regimes in the past.
Komatiites are ultramafic extrusive volcanic rocks.

During the Archean and Paleoproterozoic, komatiite melting temperatures ranged from 1600–1900°C probably at depth of 150 to 200 km. Their massive presence suggests a very hot mantle during Archean and Paleoproterozoic.
The predominance of komatiites in the Archean, their decreasing occurrence in the Proterozoic, and extreme rarity in the Phanerozoic have been interpreted to reflect secular cooling of the mantle.
AGE HISTOGRAMS FOR DISTINCTIVE PLATE TECTONIC AND SUBDUCTION INDICATORS FOR THE PAST 3 GA OF EARTH HISTORY

A. Kimberlites
   - Archean
   - Paleoproterozoic
   - Mesoproterozoic
   - Neoproterozoic
   - Phanerozoic

B. Ophiolites

C. Blueschists (*sensu lato*) and glaucophane-bearing eclogites
   - UHP metamorphic rocks
   - Lawsonite-bearing metamorphic rocks
   - Jadeitites

Stern et al., 2018
BEFORE MODERN-STYLE PLATE TECTONICS

Magma Ocean
4.5-4.4 Ga

Platelets
4.4-2.7 Ga

Proto Plate Tectonics
2.7-1.0 Ga

Ernst, 2017
MODERN-STYLE PLATE TECTONICS

1.0-0.0 Ga

Deep subduction, HP/LT and UHP Metamorphism

Ernst, 2017
PLATE TECTONICS IN THE EARTH

• Small-scale convection and differentiation of continental crust started soon after the end of the Magma Ocean stage;

• Proto Plate Tectonics and paired metamorphic belts started $\approx 2.7 \text{ Ga}$;

• Modern-style Plate Tectonics started $\approx 1.0 \text{ Ga}$;

• Subduction is the main driving mechanism of modern-style Plate Tectonics;
THANKS FOR YOUR ATTENTION!

...no vestige of a beginning...

...no prospect of an end....

James Hutton (1726-1796)