A broad introduction to geophysical studies of subduction zones

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A brief (and ancient) history of mantle convection

Examples of geophysical studies of:
  Incoming plate
  Seismogenic zone
  Deep (80-250 km) slab processes
  Mantle wedge and overriding plate

photo by Juli Morgan
Alfred Wegener (1880-1930)

Theory of continental drift (1915)

- Coastline shape
- Similar geology across continents
  - rock types
  - glacial features
  - fossils

[Map showing continental drift]
Continental drift rejection

Seismology: the earth is solid (1920s-60s)

“I believe that the final resolution of the problem can only come from geophysics since only that branch of science provides sufficiently precise methods. Were geophysics come to the conclusion that the drift theory is wrong, the theory would have to be abandoned by the systematic earth science as well, in spite of all corroboration, and another explanation for the facts would have to be sought”

Wegener (1929)
Mantle convection fueled by radiogenic heating (1930s)
Trenches and active downwellings (1930s)

Felix Vening Meinesz (1887-1966)
very low gravity indicates missing mass

Fig. 2. Gravity Anomalies in the East Indies, Showing Belt of Gravity Deficiency Peripheral to the East Indian Archipelago, Flanked by Bands of Positive Anomalies.
very low gravity indicates missing mass

Fig. 2. Gravity Anomalies in the East Indies, Showing Belt of Gravity Deficiency Peripheral to the East Indian Archipelago, Flanked by Bands of Positive Anomalies.

missing rock = missing mass

requires active dynamics
David Griggs:
The silicates in the Earth’s mantle can deform very slowly.
The earth’s mantle acts like a liquid over geological time.

American Journal of Science
SEPTEMBER 1939
A THEORY OF MOUNTAIN-BUILDING.
DAVID GRIGGS.

David T. Griggs
(1911-1974)
Distribution of Earthquake Focus in the Japanese Islands and their Neighbourhood.

Kiyoo Wadati (1935)
Marie Tharp (1920-2006)

From ship soundings:
North Atlantic (1957)
Entire Earth (1977)
Paleomagnetism:
Continents drift (late 1950s)
Keith Runcorn (1922-1995)
Paleomagnetic evidence for sea floor spreading (early 1960s)

Fig. 2 (left). The location of Reykjanes Ridge, southwest of Iceland, and the area of Fig. 3. The 1000-fathom submarine contour is shown, together with the 500-fathom contours for Rockall Bank. Fig. 3 (right). Summary diagram of the magnetic anomalies observed over Reykjanes Ridge (see Fig. 2). Straight lines indicate the axis of the ridge and the central positive anomaly (17).
Seismology

**EQ distribution** and source mechanisms
Earth structure
Geodetic studies (gravity, geoid, GPS, INSAR)

**Dynamics of subduction zones**
Paleomagnetism and electromagnetic method

**Continental drift**; paleogeographic reconstructions
Structure of subduction zones
Deformation studies

**Experiments** and field studies
Heat flow

Modeling
Subduction Cycles and Deformation

I. Incoming Plate
II. Megathrust
III. Slab Processes
IV. Mantle wedge and arc crust
ultramafic *peridotite* xenoliths brought up from 30 km depth in basalt
Bend faulting in Nicaragua provides fluid pathways to mantle below crust

Ranero et al., Nature, 2003

Grevemeyer et al., EPSL, 2007
Estimated water distribution in incoming slab

- Compacted sediments: 0.4-5 wt% (variable composition)
- Volcanics and sheeted dikes: 2 wt%
- Gabbro: 0.7 wt%
- Serpentinite in upper mantle: X wt% in Y km thick layer

Slab structure outboard of trench at Nicaragua (Ivandic et al., 2008)
Shillington et al., Nature GS, 2015
Seafloor EM studies show high conductivity regions

Naif et al., G3, 2015, 2016
Shallow slip in the forearc

Bilek & Lay, 2002
Episodic tremor and slip in Cascadia

Rodgers and Dragert, Science, 2003
Estimated Plate Coupling

from GPS data 1995-2000

slide from Jeff Freymueller
(SCD TEI student symposium 2015)

Meade and Loveless (2010)
Estimated Plate Coupling
from GPS data 1995-2000

Slow Slip Events

c. Coupling fraction

slide from Jeff Freymueller
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Slow Slip Events

Afterslip from 1994 quake

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Meade and Loveless (2010)
Comparison of Locked Zone to Slip

Colors: Loveless and Meade (2010) interseismic model
Contours: Jack Loveless’ slip model contours

To first order, the rupture area of the earthquake is the same as the interseismic locked zone

Loveless and Meade, 3/14/11
Loveless and Meade (2011)

slide from Jeff Freymueller
(SCD TEI student symposium 2015)
Stachnik et al., 2004

High quality

Low quality

EQs

NNA

\[ \Delta = 176 \text{ km} \]

PVW

\[ \Delta = 68 \text{ km} \]

(a)

(b) #40, 6/20/2000 20:23:38.4

low quality

high quality
Stachnik et al., 2004

Central Alaska

1/Qs

Low Q
High Q

Stachnik et al., 2004
Q (1/attenuation)

FIGURE 3.5  Q model for the Japan region. The hatched region has an anomalously high Q for the asthenosphere, $Q_p = 500$; normal oceanic asthenosphere has $Q_p = 200$.

Sacks, 1984

Figure 4.  Map showing the spatial distribution of S-coda-wave energy at a lapse time of 180 sec. The epicenter of the earthquake analyzed is denoted by a filled diamond. The open circles are normalized and scaled in proportion to the S-coda-wave energy calculated at each borehole station. The filled triangles show locations of the Quaternary volcanoes. The thick solid line indicates the volcanic front.

Yoshimoto, BSSA, 2006
heatflow

Figure for Cascadia subduction zone (young + slow = warm subduction)
Hyndman & Peacock EPSL 2003
van Keken, Kita, Nakajima, Solid Earth, 2012

Heatflow data from Tanaka et al., 2004.

Fast subduction of old lithosphere below Tōhoku and Hokkaido: example of cold subduction
Cascadia

Bostock et al., 2002
Olivine + water → serpentinite + magnetite

Subduction zone forearc serpentinites as incubators for deep microbial life

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Central Alaska (Rondenay, Abers and van Keken, Geology, 2008)

predicted blueschist-eclogite transition

• EQs
Blueschist

Photo by Sarah Penniston-Dorland

H₂O

increasing p,T

Eclogite

Photo by Brad Hacker
predicted from thermal-petrological modeling

Van Keken, Kita, Nakajima, Solid Earth, 2012
Very low P-wave velocity in upper crust below Tohoku
(Shiina et al., GRL, 2013)

A schematic figure of a PS wave
P-wave velocity $< 7.2$ km/s suggest presence of free fluids

Shiina et al., 2013
Further slides were not discussed since the lecture time was reduced
The mantle wedge

After van Keken, EPSL, 2003

Cold corner

Sediment melting, slab melting

Accretionary wedge formation

Continental Moho

Dehydration reactions in crust and mantle

Basalt-eclogite

Induced wedge flow

Transport of $\text{H}_2\text{O}$ into deep mantle?

Causes of intermediate-depth earthquakes
Liu and Zhao,
PEPI, 2016
Moho
Δ
Vs ~+6%

Kawakatsu and Watada, 2007
(interpretation by Brad Hacker, SCD TEI, 2015)

slow crust to 80–90 km

ΔVs ~+6% serpentine?

Moho
Tamura et al., EPSL, 2002

low seismic velocity (=‘hot’) fingers below volcano clusters in Tohoku.
Tamura et al., EPSL, 2002
Gao and Shen, 2014
Figure 5 | Spatial variations in the Moho reflectivity. Moho amplitudes derived from common midpoint stacking of the PmP phase are shown in (a). Grey dots denote station locations and stars are the shot locations. The locations of deep long period earthquakes from the Pacific Northwest Seismic Network catalogue are plotted as white dots whose size scales with magnitude. Reported hypocenter uncertainties are all less than 6 km, however, mislocations and/or misidentifications are possible due to the emergent low frequency arrivals\textsuperscript{34}. S-wave velocity models\textsuperscript{16} for the two Transportable Array stations northeast (E05A) and southwest (F05A) of the image region are shown on in (b) (see Fig. 2 for their locations).
Figure 2 | Primary seismic (a) and magnetotelluric (b) models. Panel b includes both a thermal profile (contours, labelled in degrees Celsius) and earthquake hypocentre locations (red circles) within 20 km of our profile line. Fluid released from the subducting slab enters the mantle wedge at A. Melt initiated at or very near the interface is transported upward by buoyancy and dragged down. The fluid/melt phase rises through the mantle wedge (B) until it reaches the crust, joining fluids released from shallower reactions (D). The combined fluid/melt continues to rise until reaching a reservoir (C) in the crust. Mount Rainier is shown as a red triangle.

McGary et al., 2014
Geophysical imaging of volcano activity and structure

Pritchard and Simons, 2002
Akutan:
most recent eruption: 1992
magma chamber depth:
  13 km (InSAR; Lu et al., 2000)
  4 km (GPS; Ji and Herring, 2011)
  4.5 km (petrologic; Zimmer, 2009)

Makushin:
most recent eruption: 1995
magma chamber depth:
  7 km (InSAR; Lu et al., 2002)
  5-6 km (petrologic; Zimmer, 2009)