EARTH 352 PLATE TECTONICS:
What is it
Why it matters
How it works

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Earth & Planetary Sciences 352 - Plate tectonics: On-line version syllabus

https://sites.northwestern.edu/sethstein/earth-352-global-tectonics/

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This online version is being used because of the COVID-19 pandemic. It’s an experiment, so things won’t be perfect and will evolve. We’ll all have to be flexible in this tough time. Still, we can have a good time and learn a lot.

Grade: 60% Homework problems, 20% Lab problems, 20%: Class questions

This course explores plate tectonics, the primary process driving Earth’s evolution and functioning, which makes Earth different from neighboring planets. Topics include how plates move, how their boundaries operate, how these have changed over time, and the resulting natural hazards. Lab will involve learning to use software to describe present and past plate motions.

Lectures are prerecorded, so you can download them and watch them at your own convenience and pace. You can also download a pdf to print. Contact us if you have difficulties.

We’ll have Zoom meetings at the scheduled time (1100 central) Tuesday and Thursdays for discussion of class questions and homework due that day, aspects of the material, and homework help.

You may work (presumably remotely) with other students on the homework problems and class questions, as long as at the beginning of each assignment you list whom you worked with and on which parts. Computer problems can be done by writing programs or using Matlab, Excel or equivalent. Please turn in problems and questions on Canvas.

Texts:

Stein & Wysession, mostly chapter 5

GPLATES software to be loaded on your computer
Much material from

Also used in Earth 323, 324, 327
EARTH 352 Problem set #1  Due April 16

Reading: Stein & Wysession 5.1, Appendix A.3, A.4, A.8

Because plate motions are described by vectors, let's review these.

1-2) Problems: Appendix: 1-2. Problem 2 can be done either using index notation or by elements for vectors in three dimensions, i.e. \(a_1, a_2, a_3\)

3-5) Computer problems: Appendix: C-3 - C-5. These can be done via computer programs or spreadsheets

6) Vector angles are tricky because of multiple definitions. Mathematically, we use angles clockwise from north, as shown below. Geologically, we often describe them using terms like N36°W, i.e. 36° west of north. Find the angle \(\alpha\) corresponding to N36°W.

![Diagram showing a vector V with angle \(\alpha\) from north]

7) Write a program or spreadsheet to plot a vector, as shown above, given its magnitude and direction. Use this to plot a vector with magnitude 46 mm/yr and azimuth N36°W. This vector describes the motion of the Pacific plate with respect to the North American plate in central California.

8) Watch the video

https://www.youtube.com/watch?v=pW1lkMqMa0M

about earthquake hazards in Bangladesh. Compare the plate tectonic setting and the scientific and sociopolitical earthquake hazard issues of Bangladesh to those of Nepal.
INTEGRATE COMPLEMENTARY TECHNIQUES TO STUDY TECTONIC PROCESSES

Each have strengths & weaknesses

Important to understand what can & can’t do

Jointly give valuable insight
No clear dividing lines between subfields

“When we try to pick out anything by itself, we find it hitched to everything else in the universe.”

John Muir
1: PLATE TECTONICS: BASIC CONCEPTS

San Andreas Transform Fault
Carrizo Plain
Central California

Pacific plate
North American plate

35 mm/yr
1: PLATE TECTONICS: BASIC CONCEPTS

Iceland Spreading Center, Thingvellir

North American plate

Eurasian plate

20 mm/yr

Class

Question 1:

Plate motions from space geodesy

How fast is Atlantic opening?

1) About how much longer (in mm) do your fingernails grow in a week? If this went on for a year, what would be their growth rate in mm/yr?

2) The graph shows the changing distance across over 12 years between Germany and Massachusetts. The data are from the difference in arrival times of signals from distant quasars at two radio telescopes. What is the rate of change in mm/yr?

b) Convert this rate to km/million year (km/Myr)

c) If this rate of motion continued for 200 million years, how far would the two sides of the Atlantic have moved apart?
Alfred Wegener (1880-1930) proposed that continents had been together as supercontinent of Pangea and then drifted apart.

“It is only by combing the information furnished by all the earth sciences that we can hope to determine 'truth' here, that is to say, to find the picture that sets out all the known facts in the best arrangement and that therefore has the highest degree of probability. Further, we have to be prepared always for the possibility that each new discovery, no matter what science furnishes it, may modify the conclusions we draw.”

Fig 6.1-1: Top: Areas glaciated 300 million years fit back together implying that they were joined and near the south pole. Arrows show the direction of ice movement. Bottom: The areas where similar fossils are found on different continents fit together (USGS).
Continental drift – all continents were joined into supercontinent Pangea 300 million years ago & drifted apart - explained the fit of the continents, the glacial data, and the fossils.

Fig. 6.1-2: Reconstruction of the supercontinent of Pangaea and the motions of the continents since its breakup (USGS).
Continental drift theory was controversial: R. Chamberlin of University of Chicago said "Wegener's hypothesis in general is of the footloose type, in that it takes considerable liberty with our globe, and is less bound by restrictions or tied down by awkward, ugly facts than most of its rival theories."

By the 1930’s it was largely abandoned because no one could explain how it could work. What forces could “push” continents through the earth’s solid mantle?

Fig. 6.1-2: Reconstruction of the supercontinent of Pangaea and the motions of the continents since its breakup (USGS).
By the 1960s, new data proved that continental drift had occurred. Much of the data came from the geology of the sea floor.
EARTHQUAKE LOCATIONS INDICATE PLATE BOUNDARIES
Seafloor heat flow is higher at midocean ridges than in the ocean basins.

Fig. 4 A 1°×1° global heat flow grid used for this paper. (a) Gaussian filter with a 500 km radius was applied to smooth unexplained small-scale variations. Grid is available in the online supplementary material to Goutorbe et al. (2011). (b) A color contour chart of global heat flow that uses a “similarity method” to fill in gaps in coverage (From Goutorbe et al. 2011).
Global Magnetic Map

Seafloor shows linear anomalies due to magnetized seafloor

https://www.ngdc.noaa.gov/geomag/emag2.html
Earth's outer shell – lithosphere - made up of ~15 major rigid plates ~ 100 km thick

Plates move relative to each other at speeds of a few cm/yr

Plates are rigid in the sense that little (ideally no) deformation occurs within them.

Most (ideally all) deformation occurs at their boundaries, giving rise to earthquakes, mountain building, volcanism, and other spectacular phenomena.

Type of boundary depends on direction & rate of motion
Strong plates of lithosphere move over weaker asthenosphere

Lithosphere and asthenosphere are mechanical units defined by their strength

Lithosphere includes both crust and part of upper mantle (defined by seismic velocity & thus presumably composition)
Warm mantle material upwells at spreading centers and then cools.

Because rock strength decreases with temperature, cooling material forms strong plates of lithosphere.

Cooling oceanic lithosphere moves away from the ridges, eventually reaches subduction zones and descends in downgoing slabs back into the mantle, reheating as it goes.

Lithosphere is cold outer boundary layer of thermal convection system involving mantle and core that removes heat from Earth's interior, controlling its evolution.
Heat transfer modes

https://learnmechanical.com/
Thermal Convection

Warmer water rises

Cooler water descends

Convection currents
Class question #2

Convection in certain crystal fabrication processes, such as some of those that produce optical fibers, gives rise to impurities. These could be avoided by manufacturing in a space station. Why?
Thermal convection is crucial in the solid earth, atmosphere, and oceans.
Plate tectonics & Earth’s heat engine

Stein & Wysession

Figure 5.1-2: Diagram showing ideas about mantle convection.
Thermal boundary layers
Lithosphere
Core/mantle boundary

Asthenosphere / LVZ
Geotherm close to solidus

Geotherm
SOLIDUS

MANTLE CONVECTION GEOTHERM

Stein & Wysession
Lithosphere is very thin layer compared to rest of the mantle (100 km is 1/29 of mantle radius)

Greatest temperature change occurs (from > 1400º at 100 km to about 0º at surface) making lithosphere a thermal boundary layer.

As a result, lithosphere is much stronger than the underlying rock, and so is also a mechanical boundary layer.

Lithosphere, which contains the crust, is also a chemical boundary layer distinct from the remainder of the mantle.

Continental lithosphere is especially distinct
PLATE KINEMATICS, directions and rates of plate motions  
Can observe directly  
Primary constraint on lithospheric processes

PLATE DYNAMICS, forces causing plate motions  
Harder to observe directly  
Observe indirect effects (seismic velocity, gravity, etc)  
Studied via models  
Closely tied to mantle dynamics  
Kinematics primary constraint on models
Direction of relative motion between plates at a point on their boundary determines the nature of the boundary.

At spreading centers, both plates move away from boundary.

At subduction zones, subducting plate moves toward boundary.

At transforms, relative plate motion parallel to boundary.

Real boundaries often combine aspects (transpression, transtension).

Arabia 4 mm/yr Sinai Transtension - Dead Sea transform
Characteristic features of plate boundaries

CONVERGENCE DIRECTION AT SUBDUCTION ZONES

- Ocean trench (convergence)
- Continent
- Ocean
- Lithosphere
- Asthenosphere
- Rising magma
- Shallow earthquakes
- Deep earthquakes (mainly thrust faulting)
Most (but not all) boundaries have topographic signature
Boundaries are described either as

- midocean-ridges and trenches, emphasizing morphology

- or as divergent (spreading centers) and convergent (subduction zones), emphasizing kinematics

Latter nomenclature is more precise because there are

- elevated features in ocean basins that are not spreading ridges

- spreading centers like the East African rift within continents

- continental convergent zones may not have active subduction
Need to know plate names (most are easy), boundaries, & approximate (cm/yr) rates
The cross-section above shows different types of plate geometries.

--Note that a plate can contain both continent and ocean.

--The continent-ocean boundary (continental margin) can be active or passive.
Class Question #3

Sketch the boundaries of the North American, Pacific, and Eurasian plates on the map.
WESTERN NORTH AMERICA

Three Plates:
- Juan de Fuca
- North America
- Pacific

Three Boundaries:
- Cascadia subduction zone
- San Andreas transform
- Gulf of California spreading center

Click for audio
Coachella Valley, California
Joshua Tree National Park
Plate motion causes earthquakes

How can we assess the danger of future earthquakes?
CHIMP - California Historical Intensity Mapping Project: Build database for comparison with hazard maps

Reinterpreted intensities for 1952 Kern County earthquake are ~0.6 units lower than originally inferred, yielding magnitude estimate $M = 7.2 \pm 0.2$

The 1952 Kern County, California earthquake: A case study of issues in the analysis of historical intensity data for estimation of source parameters

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Things look simple, but…
Evolution of western US plate geometry

Click to run animation
Class question #4: Watch the movie and explain:

a) What happens to the Farallon plate?

b) When does the Gulf of California spreading center form?

c) What plates are involved at the Gulf of California spreading center and what is their relative motion?

d) When does the San Andreas fault form?

a) What plates are involved at the San Andreas fault and what is their relative motion?
WHERE IS THE AFRICA/EURASIA BOUNDARY?

Oldow et al., 2002
Plate geometry important for understanding earthquake hazard & recurrence

Which plates are involved and what are their relative motions?
Plate geometry important for understanding earthquake hazard & recurrence

1964 Niigata M 7.5 ?
NW ASIA

Not clear where North America boundary is

May be Okhotsk plate distinct from North America

May be Amuria plate east of Baikal rift distinct from Eurasia

May be North China plate

Wei and Seno, 1988
In most places we know general plate boundary geometry from geology, topography, and earthquakes.

Ideal plate boundaries are very narrow.

Many real plate boundaries - especially continental - are deformation zones up to 1000 km wide, with motion spread beyond nominal boundary.

In some places: Indian Ocean, Mediterranean, NW Asia, etc. we’re still trying to figure out plate geometry.
The Wilson cycle: boundaries change over time

Oceans are born, grow, shrink, & die

Continental stretching & rifting

Young ocean

Mature ocean

Subduction starts

Closing ocean

Continental collision

East African Rift

Gulf of Aden, Gulf of California

Atlantic

Andes

Southern Europe

Himalaya Zagros

Stein & Wysession, 2003

Topic 1d 48
190 Ma
Pliensbachian (Early Jurassic)

PLATES/UTIG
July 1999
Class question #5: Identify and label at least 10 of the various continents and continental blocks in the reconstruction below.
150 Ma - SOUTHERN CONTINENTS RIFT APART

Indian plate moved north closing ocean basin

40 Ma collision with Eurasia

Himalayas rise, complex plate boundary zone develops
Class question #6

How fast did the Indian plate move north?

a) Given that earth’s radius is 6371 km, how many km are in a degree?

b) How fast (mm/yr) did India move northward between 55 and 40 million years ago?

c) How fast (mm/yr) did India move northward between 10 million years ago and now?

d) Compare the speeds in b) and c) and explain what’s happening
COMPLEX PLATE BOUNDARY ZONE IN SOUTHEAST ASIA

Northward motion of India deforms all of the region

Eastward motion in China & SE Asia

Many small plates (microplates) and blocks

Molnar & Tapponnier, 1977
Nepal earthquake hazard and policy

Hazard shown by Mw 7.8 2015 Ghorka earthquake

Developing nation – per capita GDP ~ $1000
> 8000 deaths

2015 Ghorka earthquake Mw 7.8

700,000 buildings damaged (96% brick)

Damage ~ 1/3 GDP

Economy already weak (40% unemployment)

Economy mostly tourism, agricultural, remittances

Many buildings were and remain unsafe.
Kathmandu Valley, 2.5 M people, growing ~4% per year
Cultural & political hub, UNESCO World Heritage Site
Need to better understand tectonics & hazard

Much larger earthquakes expected
Plate tectonics provides benefits as well as hazards to society

Plate tectonics is crucial for the origin of life, its survival, our climate, and resources
Why is Earth habitable, but not Venus and Mars?

Venus is too hot, Mars is too cold, Earth is just right

Plate tectonics is a key factor
PLATE TECTONICS: PRIMARY SURFACE MANIFESTATION OF THE HEAT ENGINE WHOSE NATURE AND HISTORY GOVERN EARTH’S THERMAL, MECHANICAL, AND CHEMICAL EVOLUTION ("heat is the geological lifeblood of planets")

Heat engine characterized by balance between three modes of heat transfer from the interior: plate tectonic cycle involving the cooling of oceanic lithosphere, mantle plumes, a secondary feature of mantle convection (?), and conduction through continents that do not subduct and so do not participate in oceanic plate tectonic cycle.

From sea floor topography and heat flow, Earth’s heat loss seems to occur primarily (~70%) by plate tectonics, with ~25% by conduction.

In contrast, grossly similar sister planets, Mars and Venus, seem conduction-dominated because large-scale plate tectonics appears absent, at least at present.

Conduction

Plate tectonics

Mars

Venus

Moon, Mercury

Solomon & Head, 1991

Earth

Plumes
Terrestrial (inner) planets may follow similar life cycle with stages including formation, early convection and core formation, plate tectonics, terminal volcanism, and quiescence.

Evolution driven by available energy sources as planets cool with time. Planets formed at about the same time but are at different stages in their life cycles. (Consider human and dog born on the same date).

Earth in middle age with active plate tectonics

Moon & Mars old, dead, inactive
Seismological and other data suggest the moon now has a thick lithosphere and is tectonically inactive.

Seems to have lost much of its heat, presumably because of its small size, which favors rapid heat loss.

In general, expect the heat available from gravitational energy of accretion and radioactivity to increase as the planet`s volume, whereas the rate of heat loss should depend on its surface area.

\[
\text{remaining heat} = \frac{\text{available}}{\text{loss}} \sim \frac{4/3 \pi r^3}{4 \pi r^2} = r/3
\]

so larger planets would retain more heat and be more active.

Hence Mercury and Mars, larger than the moon but smaller than earth, should have also reached their old age with little further active tectonics.
MARS - TOO COLD

In past Mars had liquid water, as shown by sediment deposits

Now, however, it doesn’t

Somehow Mars climate changed, perhaps several times between hot/wet periods when "greenhouse" gases in atmosphere kept planet warm to cold/dry times without a greenhouse when the surface got too cold for liquid water and most life (if there ever was any)
VENUS - RUNAWAY GREENHOUSE

Dense atmosphere (90 times Earth's) composed mostly of \( \text{CO}_2 \) (carbon dioxide).

Thick clouds of sulfuric acid obscure the surface.

Atmosphere produces run-away greenhouse effect that raises Venus' surface temperature to over 450 deg C (hot enough to melt lead).

Venus' surface hotter than Mercury's despite being nearly twice as far from the Sun.

Venus probably once had lots of water like Earth that boiled away, leaving it quite dry.

Earth might be like this if it were a little closer to the Sun.

Not yet clear why Venus turned out so differently from Earth.
There’s lot’s we don’t know and needs figuring out

“When a scientist does not know the answer to a problem, he is ignorant. When he has a hunch as to what the result is, he is uncertain. And when he is pretty damn sure of what the result is going to be, he is still in some doubt. We have found it of paramount importance that in order to progress, we must recognize our ignorance and leave room for doubt.”

Richard Feynman

“Half of what we will teach you in the next few years is wrong. The problem is we don’t know which half”

Medical school dean to incoming students