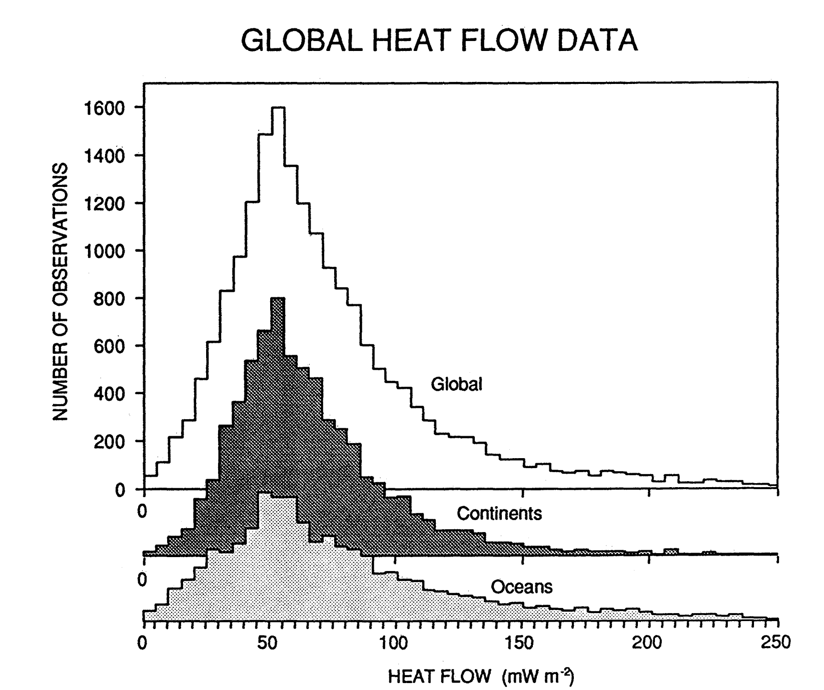
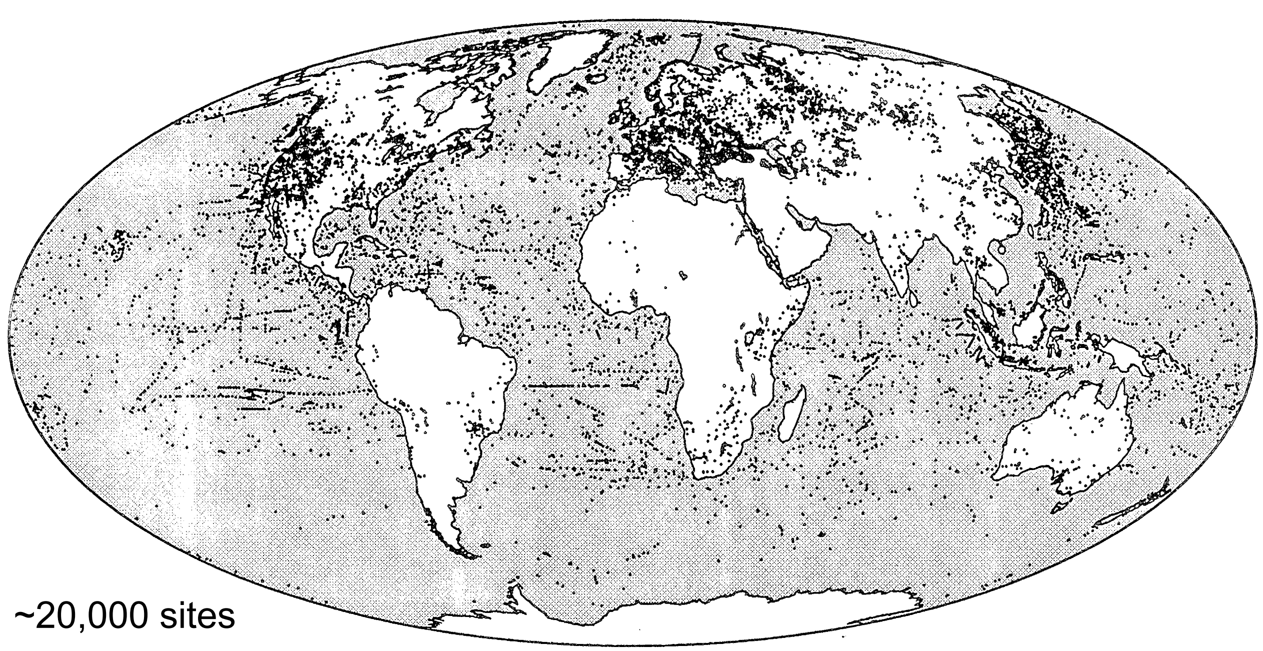
TERRESTRIAL HEAT FLOW:



Why do we care?

What do we (think we) know?

What don't we know (and welcome help with)?

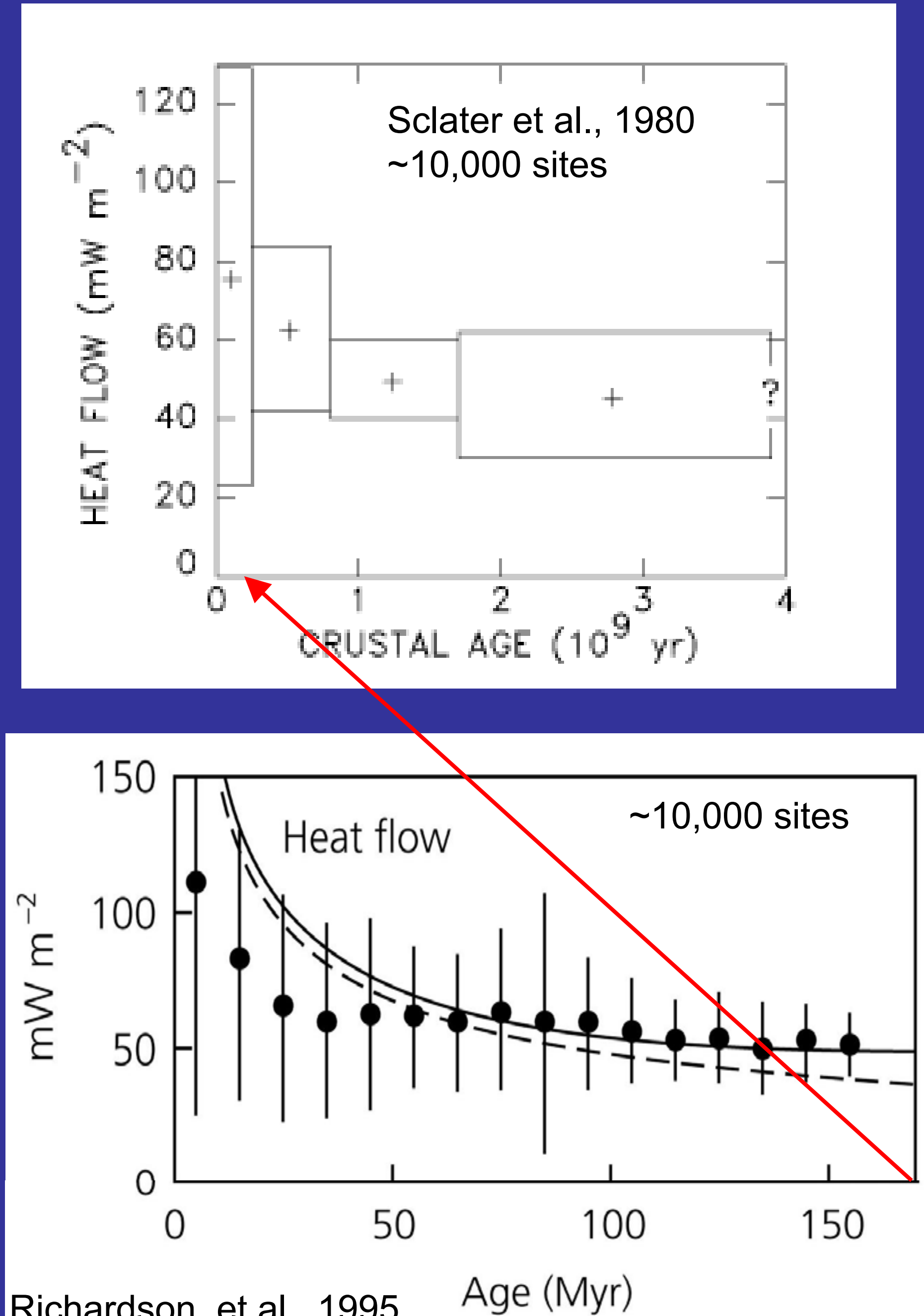


~20,000 sites

Carol Stein
University of Illinois at Chicago

Seth Stein
Northwestern University

Pollack et al. (1993)



CURRENT ESTIMATES

(Pollack et al., 1993)

Heat flow, mW/m^2

Continental 65 ± 1.6

Oceanic 101 ± 2.2

Global 87 ± 2.0

Global heat loss, TW

44.2 ± 1.0

70% oceanic (32 TW), 30% continents (12 TW)

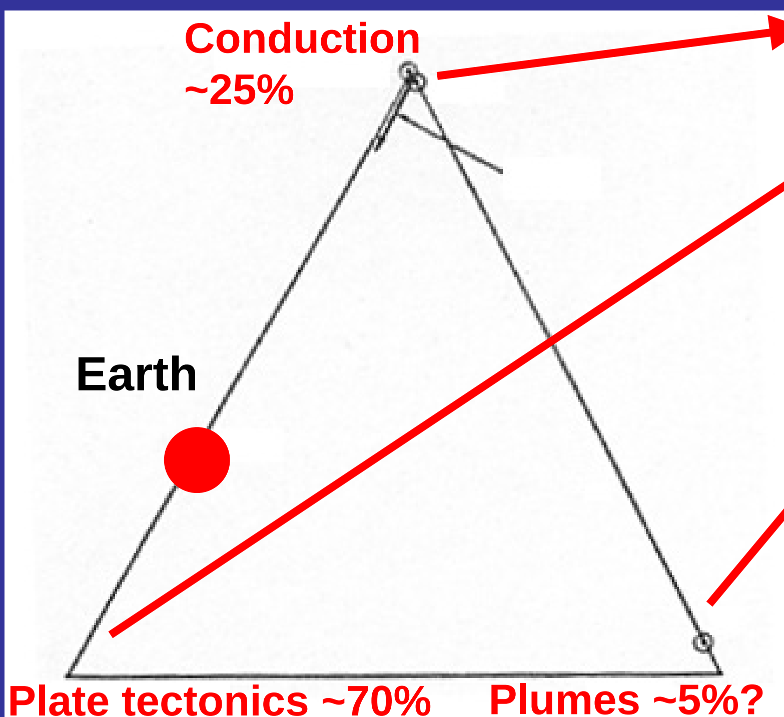
Errors quoted are formal, systematic errors larger

Largest possible sources of error in oceans

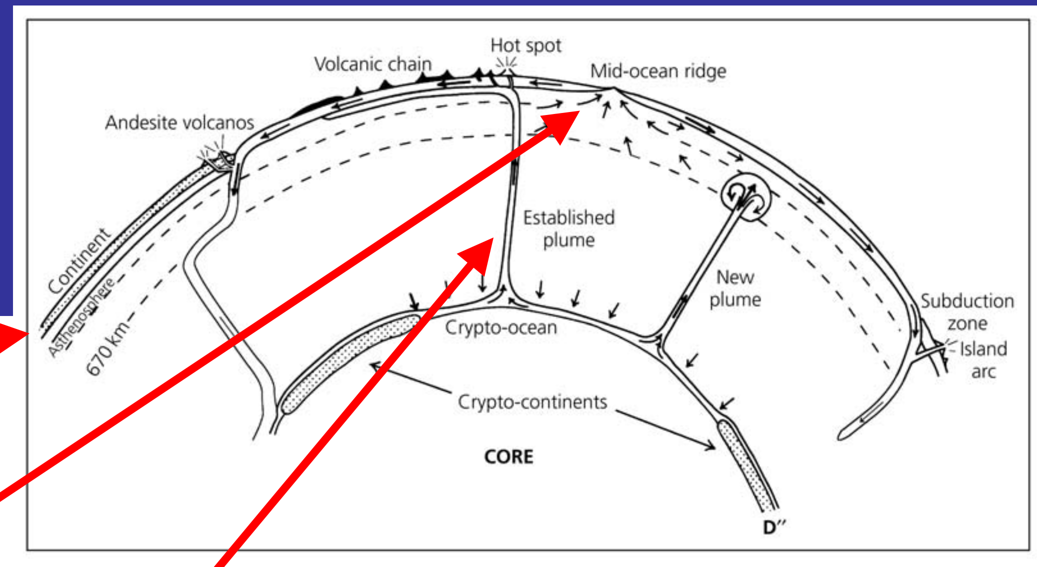
HEAT FLOW IS A PRIMARY CONSTRAINT ON EARTH'S HEAT ENGINE, WHOSE NATURE AND HISTORY GOVERN THE PLANET'S THERMAL, MECHANICAL, & CHEMICAL EVOLUTION

"Heat is the geological lifeblood of planets"

Earth is the plate tectonic planet

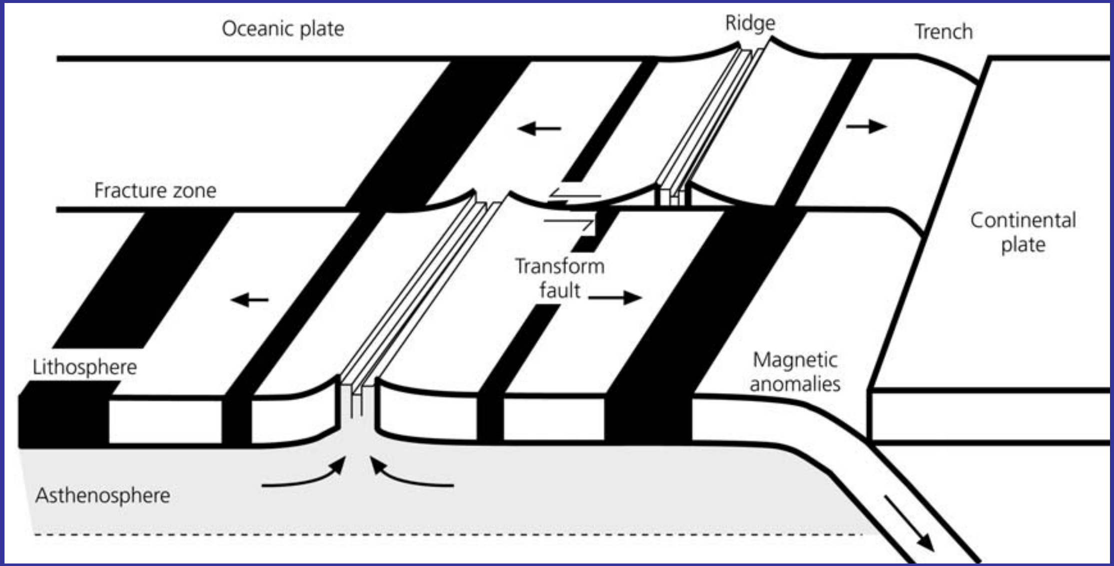


Solomon & Head, 1991



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

PLATE TECTONICS RESULTS FROM THERMAL EVOLUTION OF OCEANIC LITHOSPHERE



Warm mantle material upwells at spreading centers and then cools

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

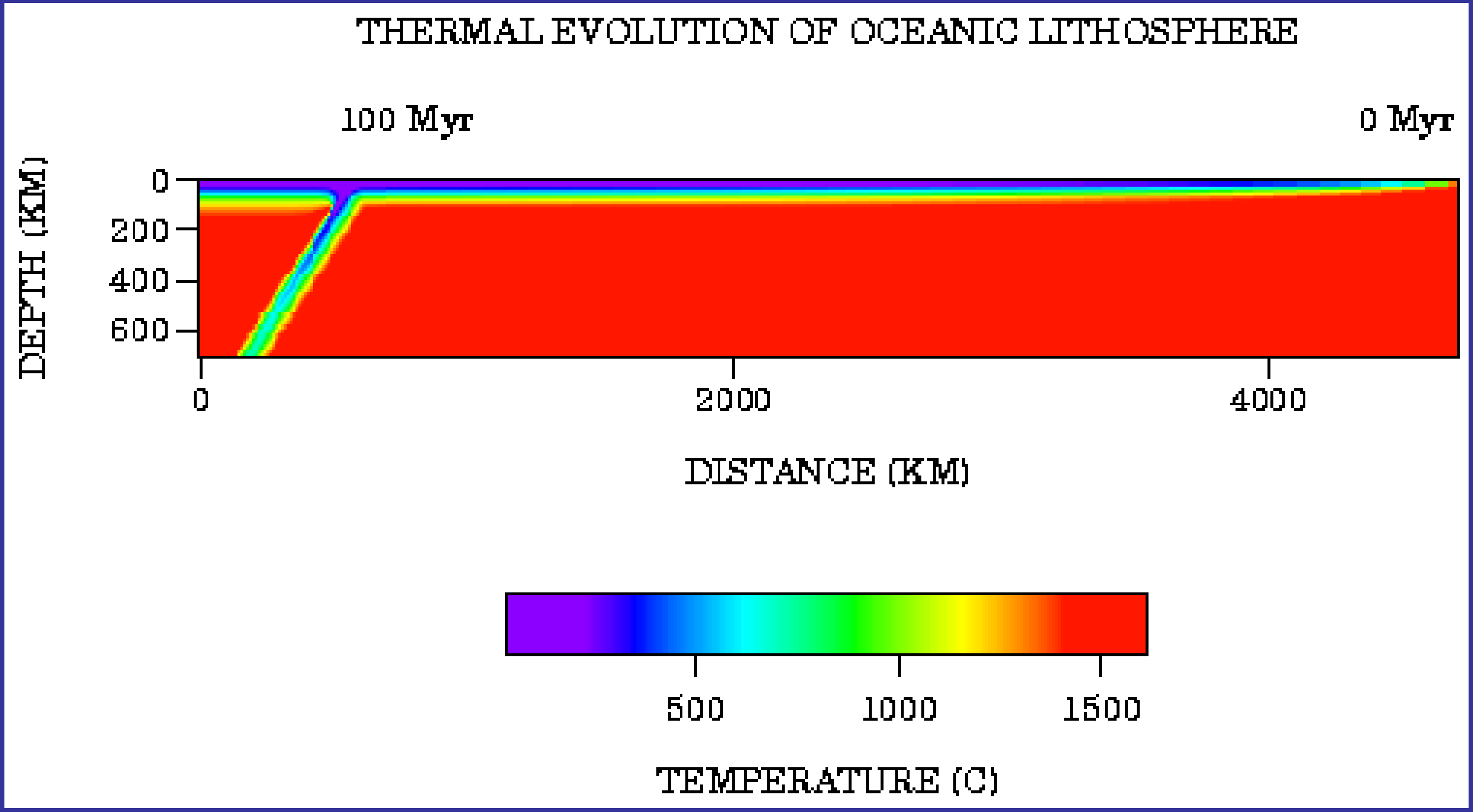
Cooling oceanic lithosphere moves away from the ridges (1-20 cm/yr), eventually reaches subduction zones and subducts in downgoing slabs back into the mantle, reheating as it goes

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

PLATE MOTIONS DRIVEN BY THERMAL BUOYANCY FORCES DUE TO DENSITY CONTRAST RESULTING FROM THE TEMPERATURE DIFFERENCE BETWEEN PLATES AND SURROUNDINGS

"Ridge push" is due to oceanic lithosphere cooling after it forms; "slab pull" is due to the cooled lithosphere heating up again as it subducts.

Locally it is useful to think of the forces separately: both are parts of the net buoyancy force due to mantle convection.

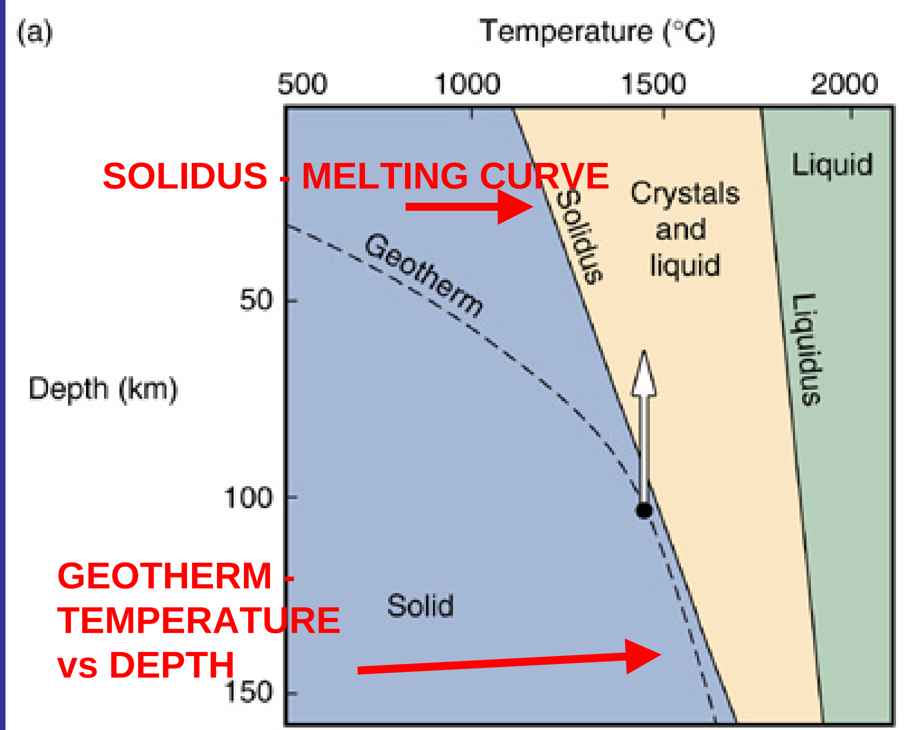


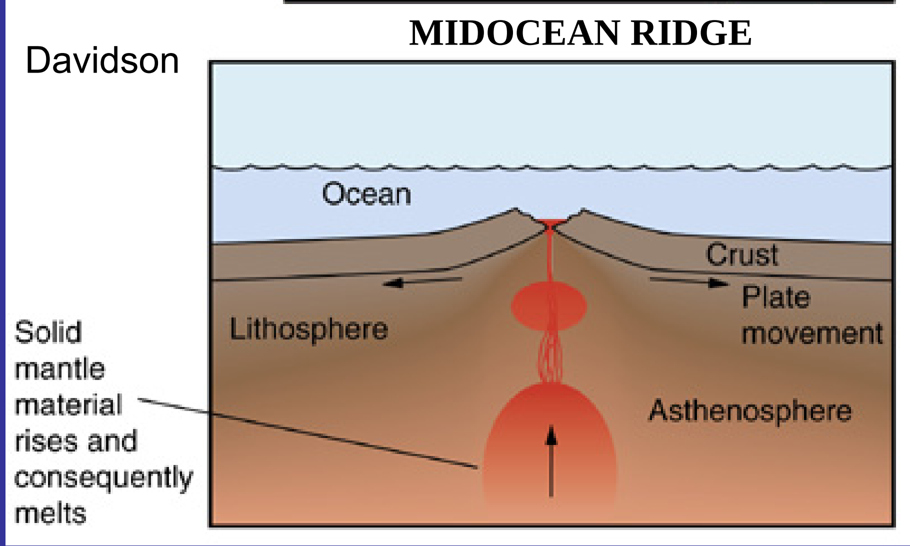
How plate tectonics works depends on thermal structure

Scientific issues with major societal impacts: hazards & resources

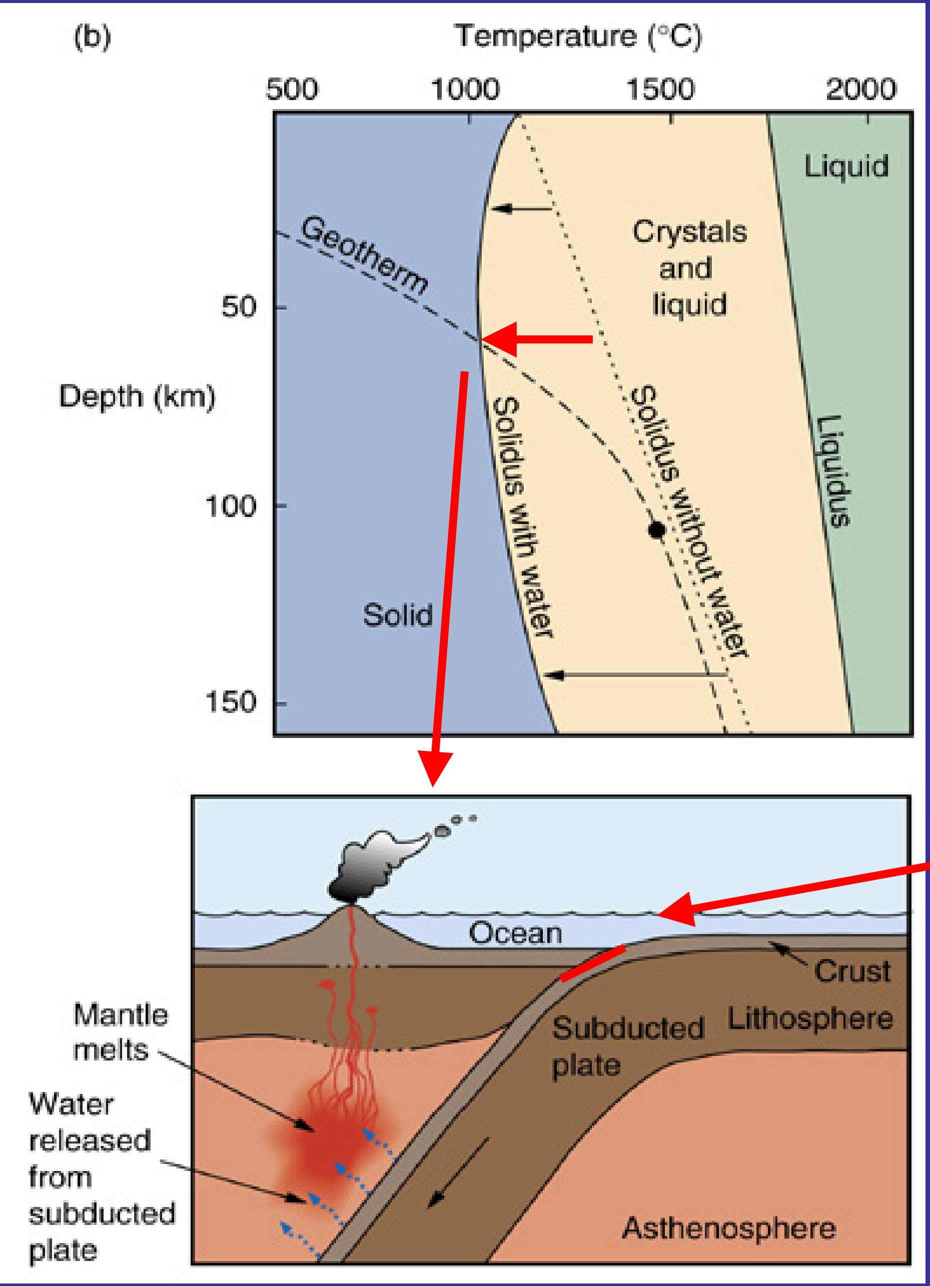
ICELAND

Decompression melting & fractional crystalization at midocean ridges





SUBDUCTION ZONE



Cold oceanic plate subducts & heats up

Volcanism: water lowers melting temperature

Earthquakes: locked slip released at interplate interface, whose mechanics are temperature controlled

December 2004 Indian Ocean tsunami generated by giant earthquake at interface where Indian plate subducts beneath Burma plate

WILSON CYCLE DESCRIBES OPENING & CLOSING OF OCEANS

CONTINENTS RIFT

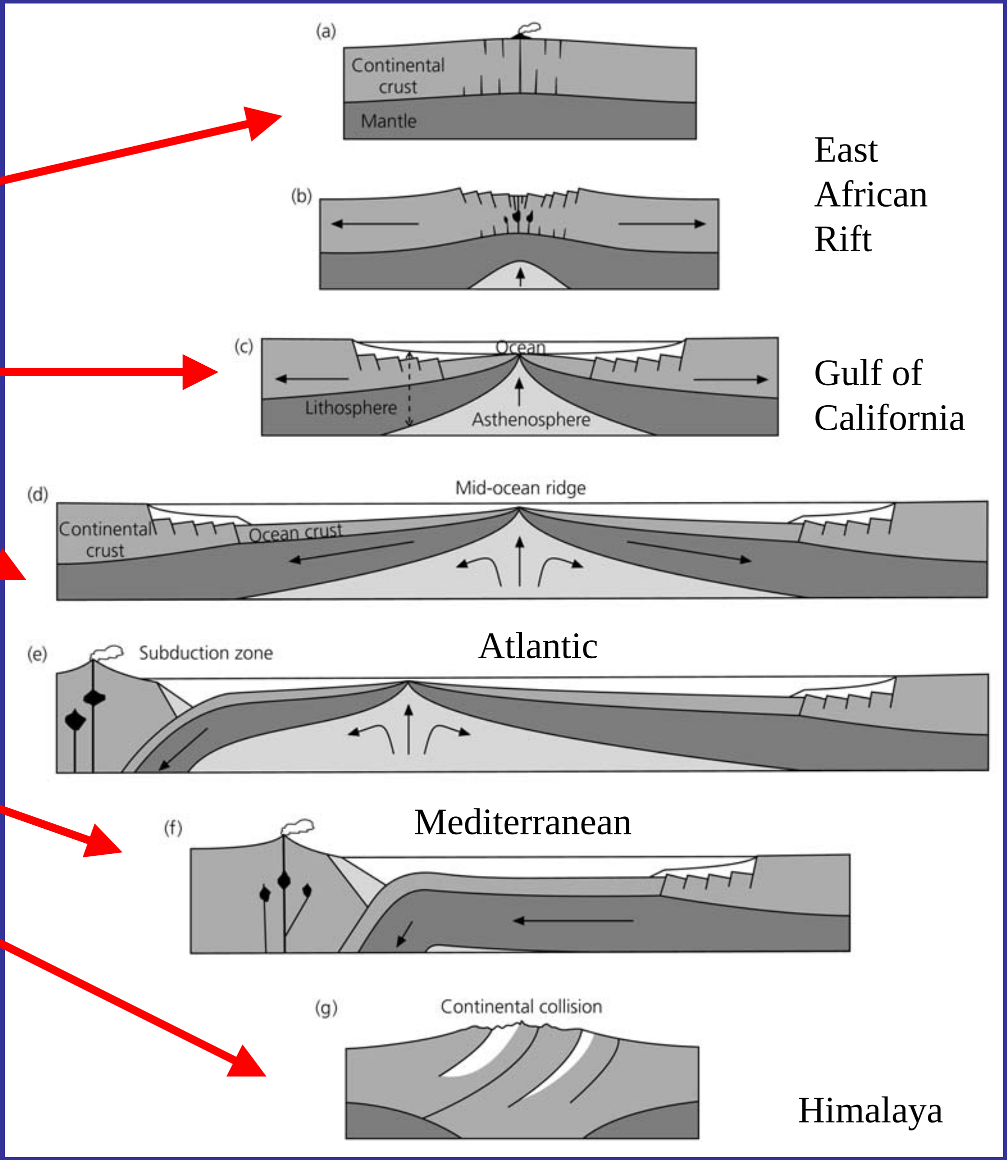
FORM NEW OCEAN BASINS

OCEAN BASINS OPEN & WIDEN

EVENTUALLY THEY CLOSE BY SUBDUCTION, CONTINENTAL COLLISION & MOUNTAIN BUILDING

CONTINENTS LATER RIFT APART AGAIN

OCEANS BORN, LIVE, & DIE WHEREAS CONTINENTS NEVER SUBDUCT BUT ARE REARRANGED



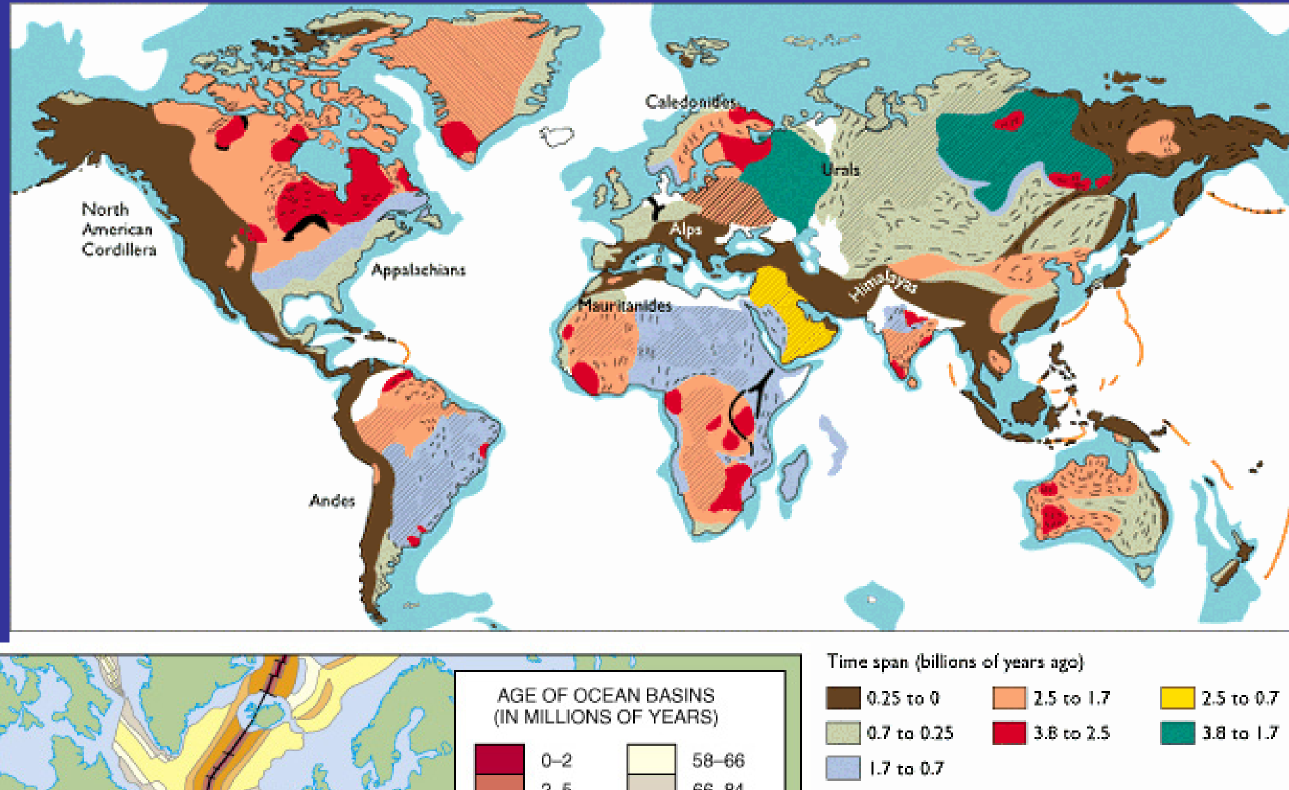
Like astronomy - infer history from different stages

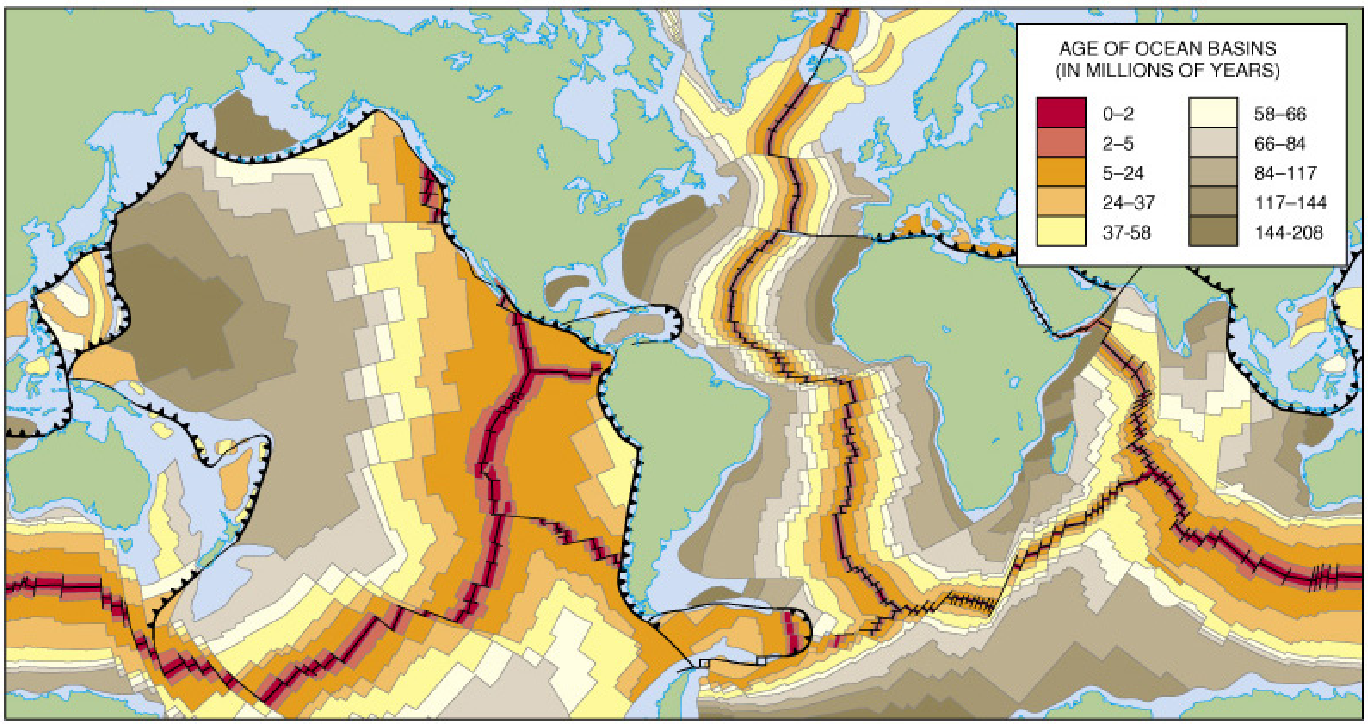
All seafloor younger than 200 Ma, continents up to 4 Ga

All seafloor younger than 200 Ma

Continents up to 4 Ga

Earth 4.6 Ga





4 Ga Acasta Gneiss

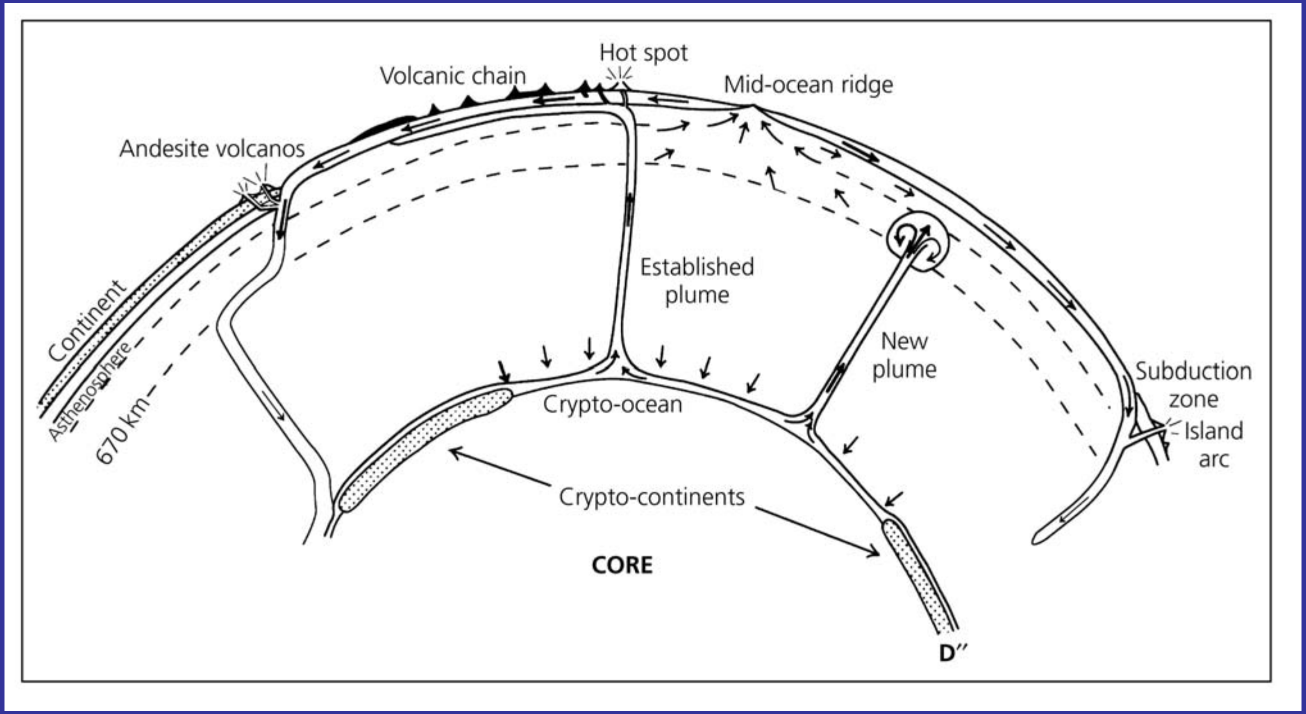
HOTSPOT / PLUME HYPOTHESIS

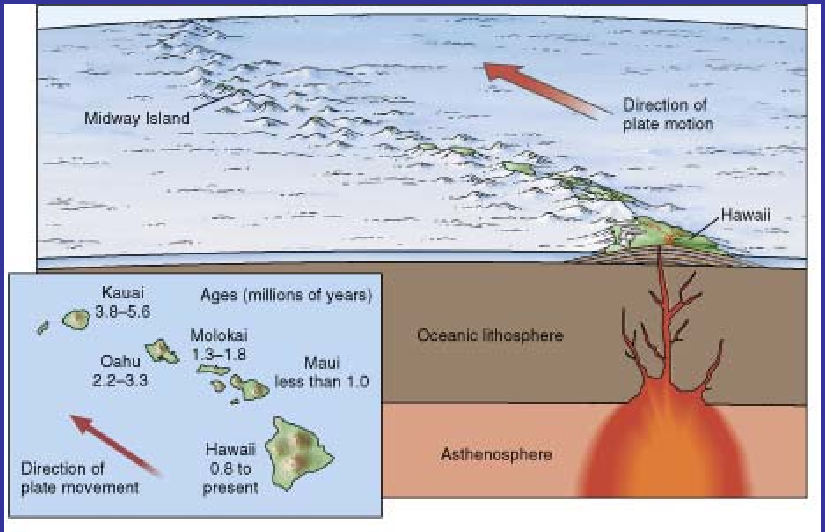
Assume hotspots result from plumes of hot material rising from great depth, perhaps core-mantle boundary

Plumes would be secondary convection mode, ~ 5% of heat transfer

Hawaiian Islands thought to result from motion over fixed hotspot

Nature & extent of plumes controversial





QuickTime™ and a GIF decompressor are needed to see this picture.

Earth topography reflects plate tectonics & thus thermal evolution:

Long shallow midocean ridges
Ocean depth increases away from ridges as plates cool
Deep trenches indicate subduction zones
High continents no longer subduct
Mountain chains produced by continental collisions
Rift valleys & young (narrow) oceans
Hotspot (plume?) tracks

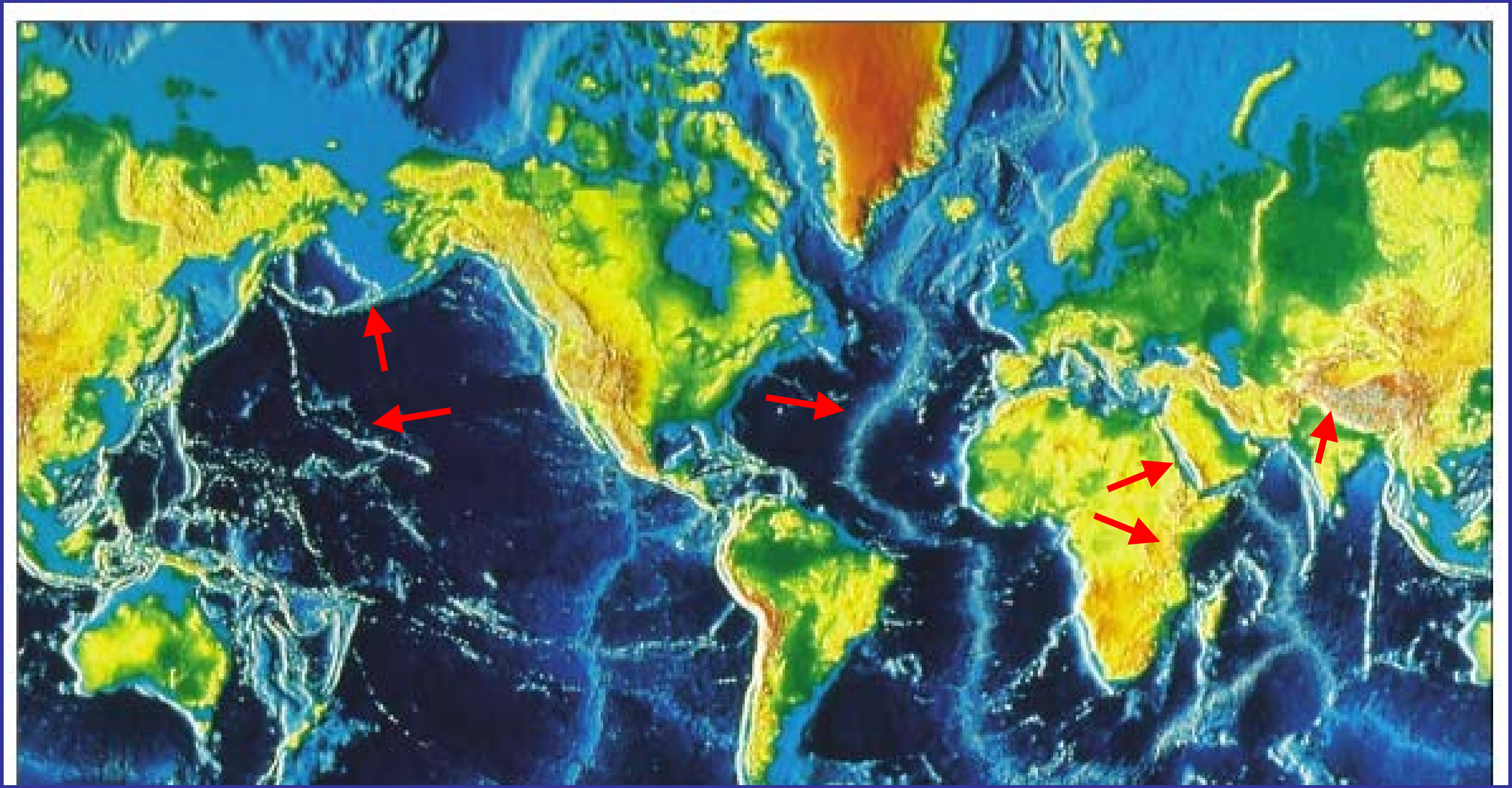
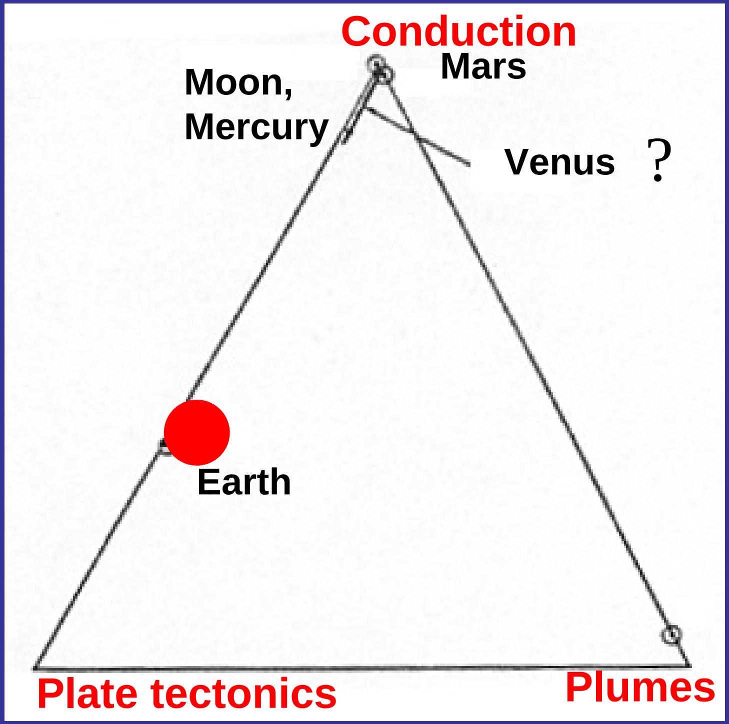


Plate tectonics makes Earth different



Solomon & Head, 1991

Seafloor topography and heat flow indicate Earth's heat loss primarily (~70%) by plate tectonics, with ~25% by conduction

Grossly similar sister planets, Mars and Venus, seem conduction-dominated: large-scale plate tectonics appears absent, at least at present

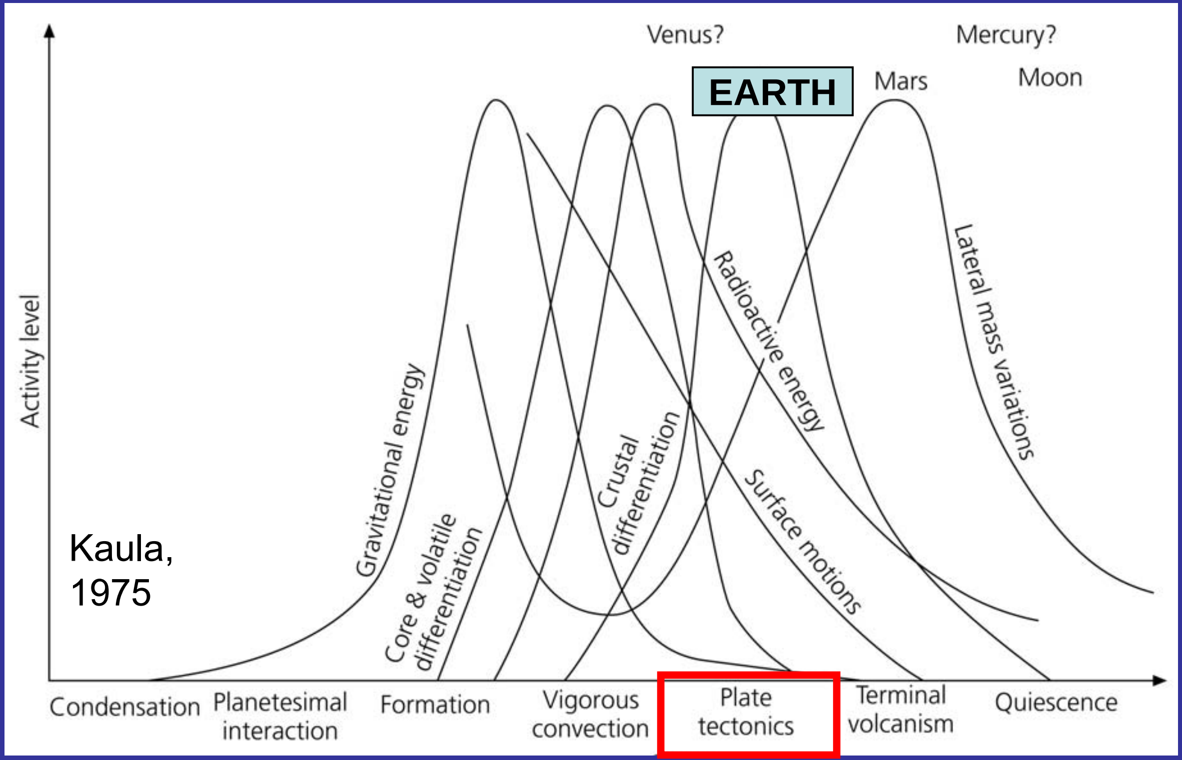
QuickTime™ and a
Photo decompressor
are needed to see this picture.

Mars may have had plate tectonics, now stopped, perhaps due to both cooling & loss of water (which reduces rock strength & thus may be needed for plate tectonics)

Venus may still be hot with episodic overturns rather than steady-state plate tectonics

QuickTime™ and a
YUV420 codec decompressor
are needed to see this picture.

PLATE TECTONICS CHARACTERIZES EARTH RELATIVE TO OTHER PLANETS



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 - “one plate planets”

DEAD MOON & MARS

Seismological & other data suggest 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 rate of heat loss should depend on surface area

$$\text{remaining heat} = \text{available / loss} \sim (4/3)\pi r^3 / 4\pi r^2 = r/3$$

Larger planets would retain more heat and be more active

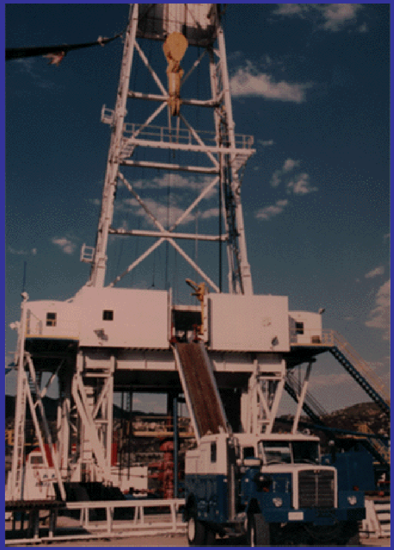
Mercury and Mars, larger than the moon but smaller than earth, should have also reached their old age with little further active tectonics.

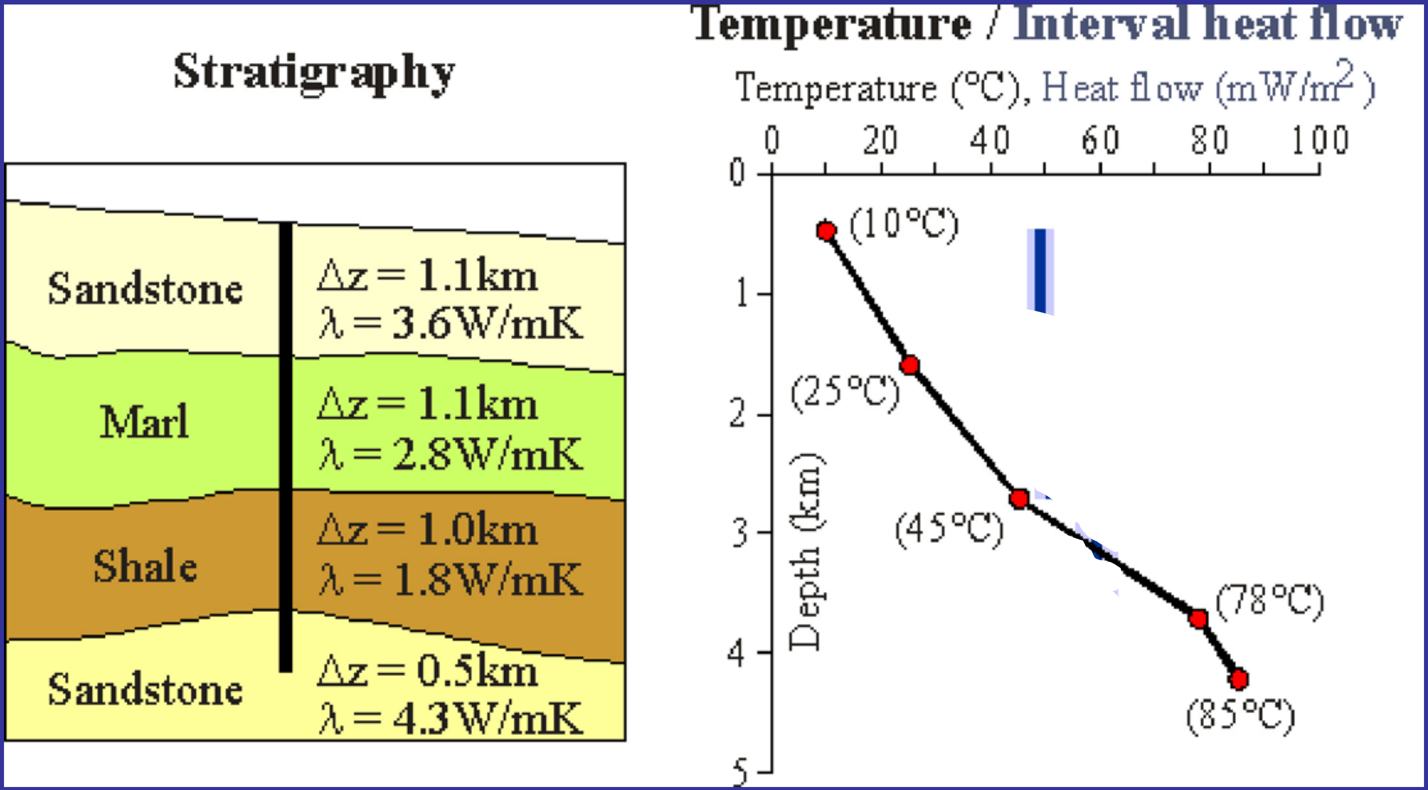
CONTINENTAL HEAT FLOW

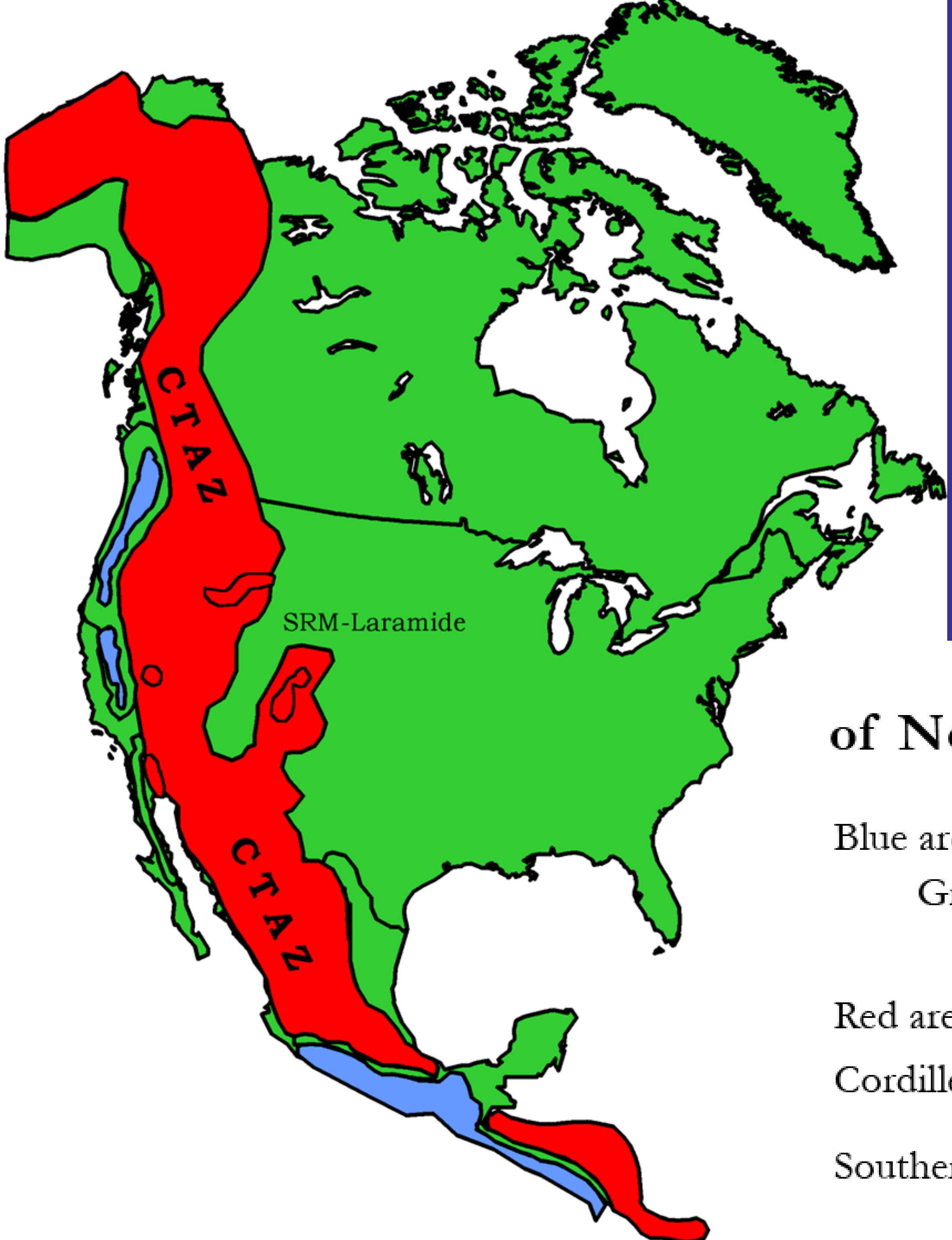
Measure temperature values from depths > 300 m to avoid climatic effects

Measure conductivity from samples

Correct for lithologic changes with depth







Continental heat flow values depend on:

Amount of radioactivity in crust

Amount of heat from mantle

Age of the crust & tectonic history

Areas of Cenozoic (< 65 Ma) extension/volcanism have higher heat flow

Generalized Map of North American Heat Flow

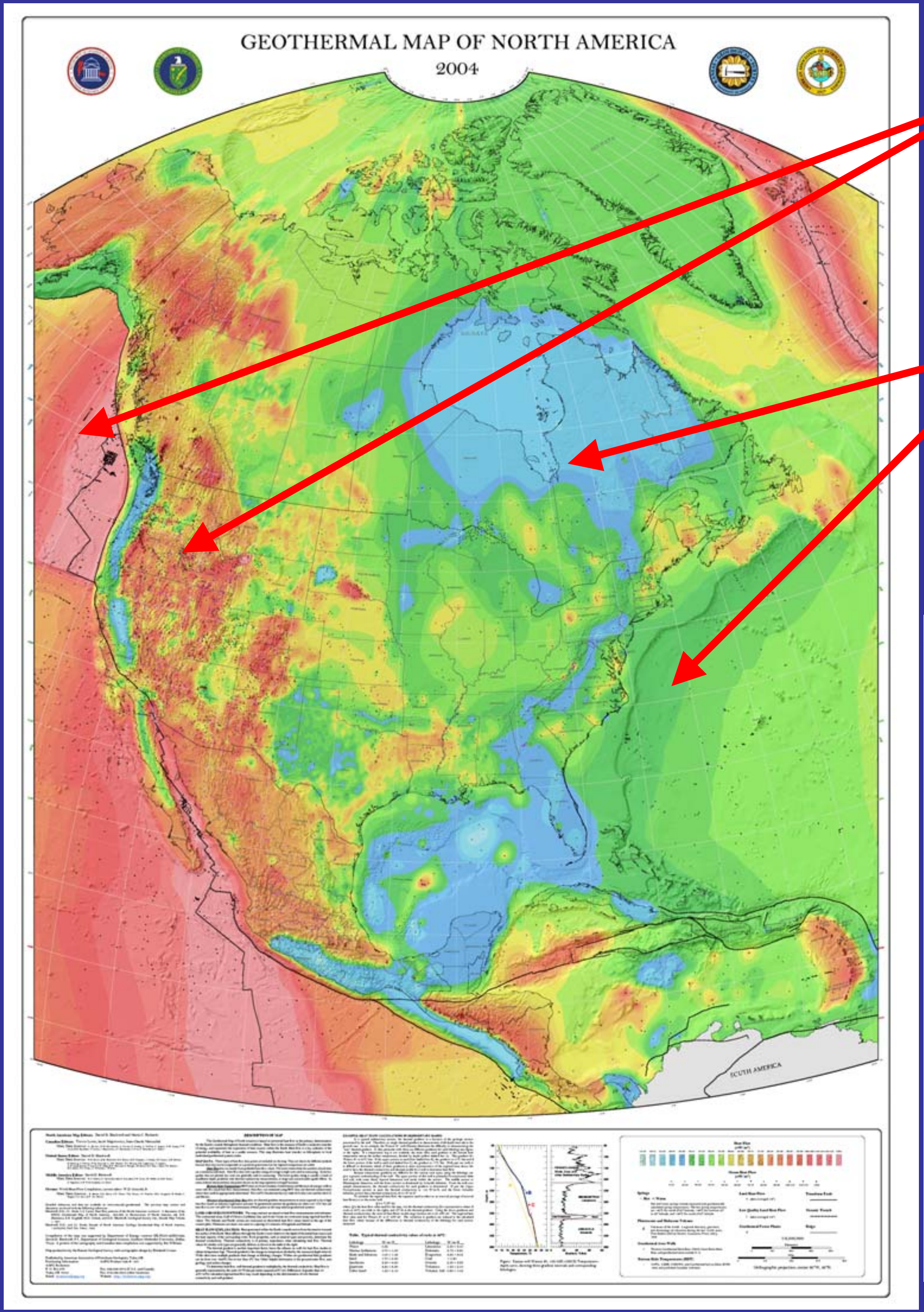
Blue areas are considered cool (< 30 mWm^2)

Green areas are considered moderate (30 - 80 mWm^2)

Red areas are hot (>80 mWm^2)

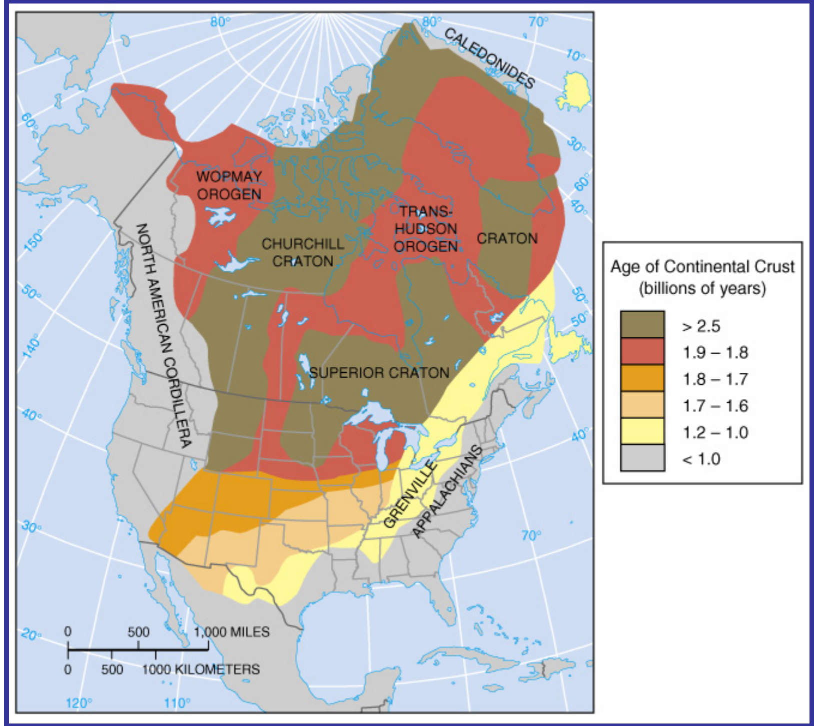
Cordillera Thermal Anomaly Zone (CTAZ)

Southern Rocky Mountains (SRM)

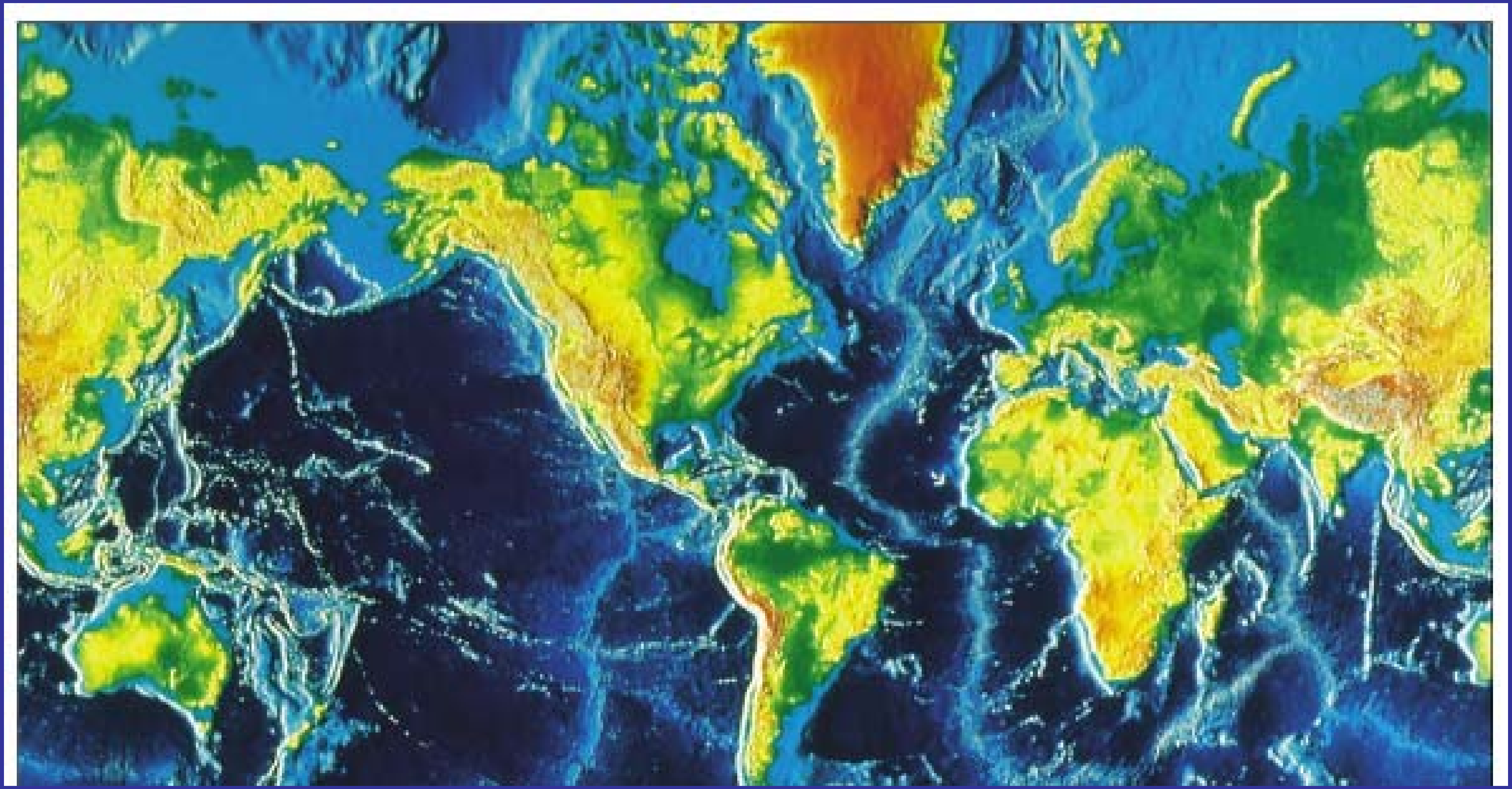


Continental areas of active tectonics comparable heat flow to young ocean

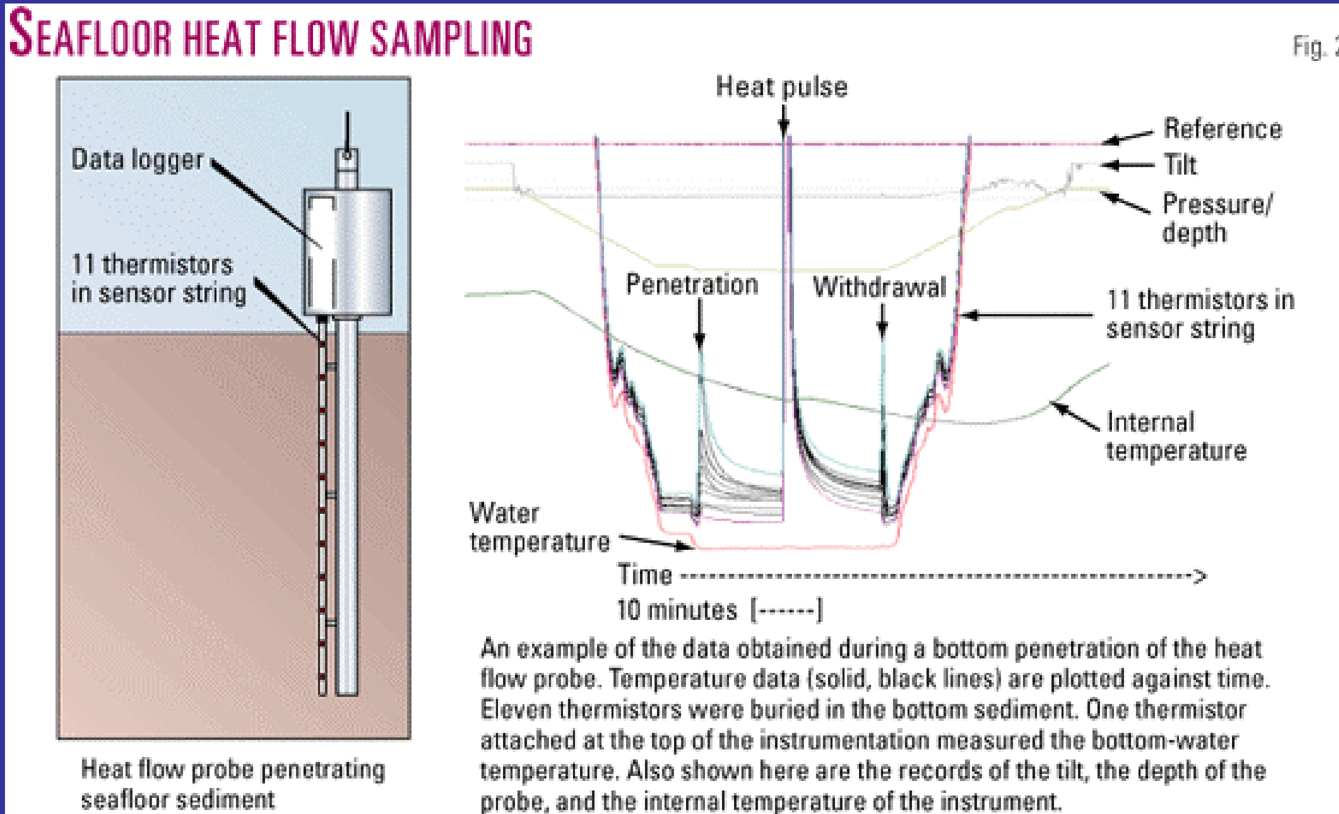
Oldest continental areas lower heat flow than oldest ocean



Increase of ocean depth away from ridges shows thermal evolution



Oceanic heat flow crucial to constrain process



Heat flow probe penetrating seafloor sediment

An example of the data obtained during a bottom penetration of the heat flow probe. Temperature data (solid, black lines) are plotted against time. Eleven thermistors were buried in the bottom sediment. One thermistor attached at the top of the instrumentation measured the bottom-water temperature. Also shown here are the records of the tilt, the depth of the probe, and the internal temperature of the instrument.

Measure:

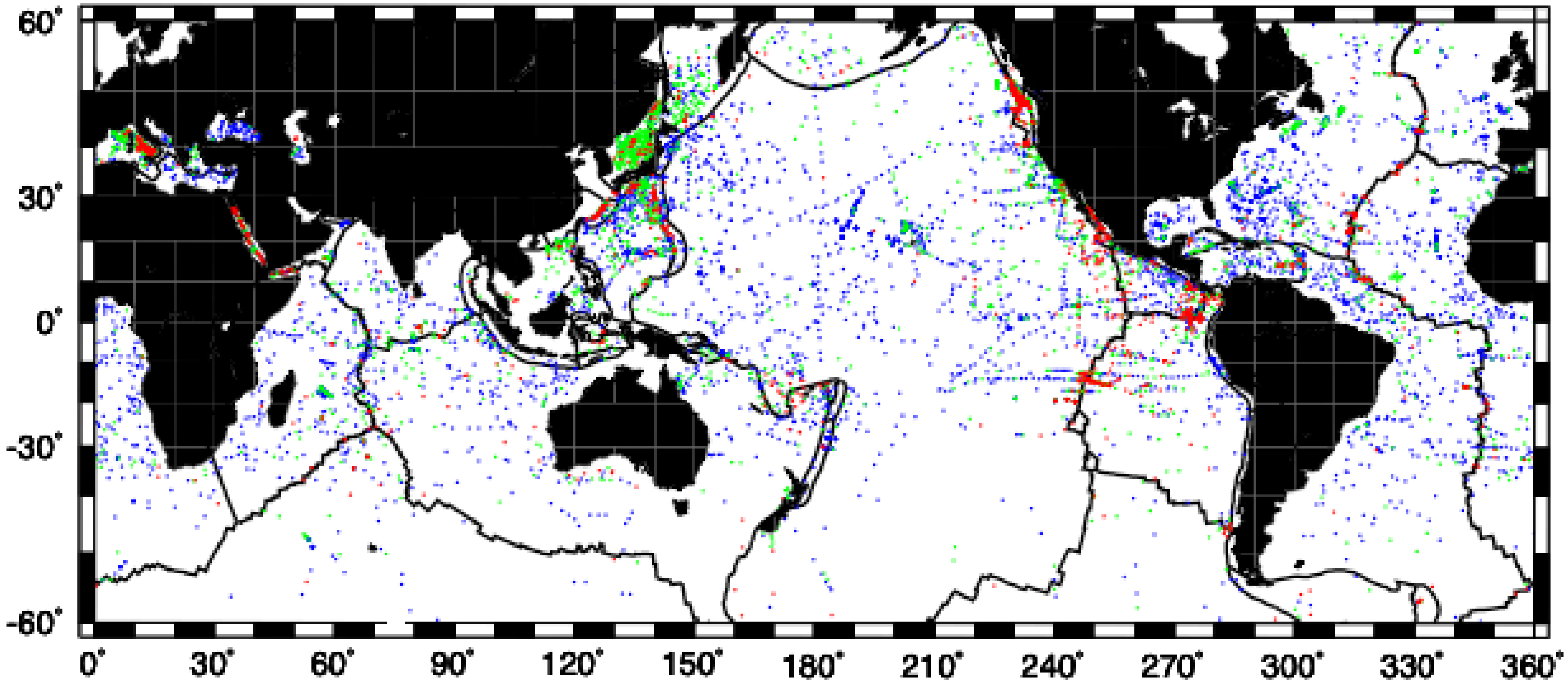
Thermal gradient

Conductivity from response to heat pulse

Good

Bad (probe requires 5 m of soft sediment)

Marine Heat Flow



About 10,000 measurements

Most data isolated - few detailed surveys

Less than one measurement per 1º x 1º square

Unevenly distributed geographically and with crustal age.

Heat flow decreases with increasing crustal age

>125 mW/m^2

70-125 mW/m^2

<70 mW/m^2

C. A. Stein 12/2004

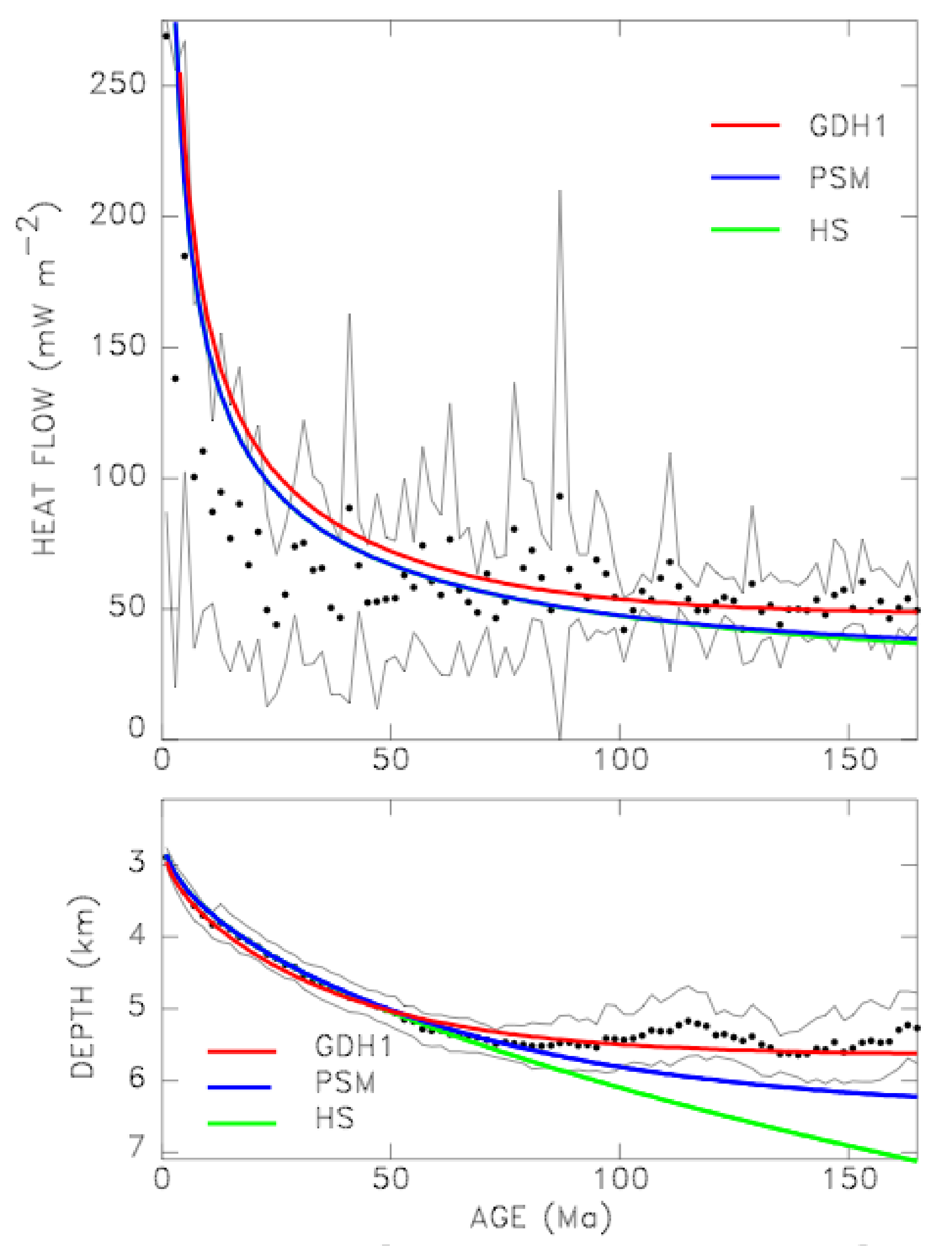
As expected for cooling lithosphere,

Average depth increases and heat flow decreases as plate moves away from ridge, ages, & cools

Scatter primarily reflects spatial variability

Indicates multiple secondary processes that are not well understood

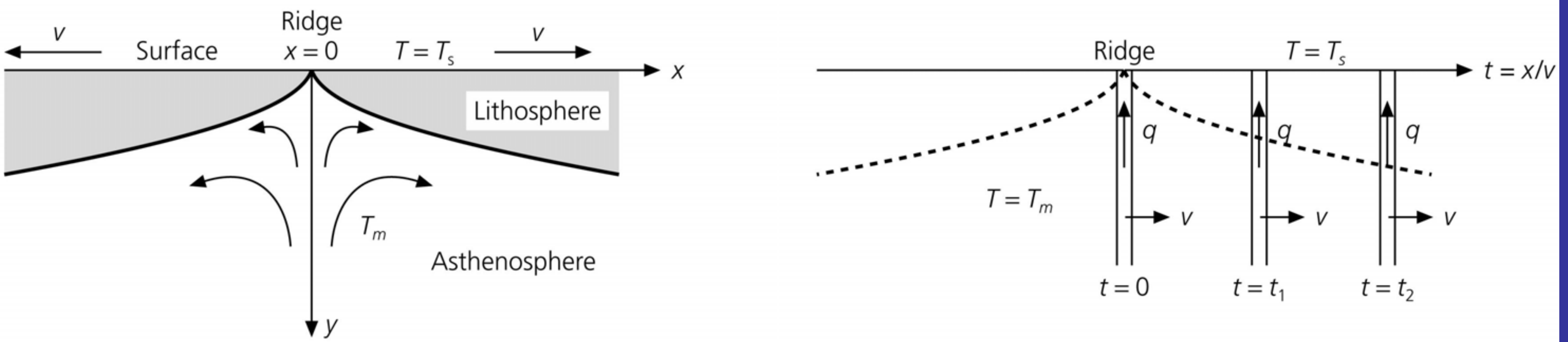
Stein and Stein, 1992



SIMPLE THERMAL MODEL - zeroth order behavior

Vertical heat conduction as cooling plate moves horizontally

Figure 5.3-4: Model for the cooling of the oceanic plate.



One-dimensional heat flow equation:
(how temperatures changes in a material as a function of the rate at which heat is conducted out of it)

$$\frac{\partial T(z,t)}{\partial t} = \frac{k}{\rho C_p} \frac{\partial^2 T(z,t)}{\partial z^2} = \kappa \frac{\partial^2 T(z,t)}{\partial z^2}$$

κ = thermal diffusivity, k = thermal conductivity, ρ = density, C_p = specific heat at constant pressure

It's solution has the form $T(z,t) = T_s + (T_m - T_s)erf(\frac{z}{2\sqrt{\kappa t}})$

with T_s = surface temperature, T_m = mantle temperature, and $erf(s) = \frac{2}{\sqrt{\pi}} \int_0^s e^{-\sigma^2} d\sigma$

If $T_s = 0°C$, then

$$T(z, t) = T_m erf\left(\frac{z}{2\sqrt{\kappa t}}\right)$$

or, as a function of distance from the ridge:

$$T(x, z) = T_m erf\left(\frac{z}{2\sqrt{\kappa x/\mathrm{v}}}\right)$$

Isotherms are defined by

$$\frac{z_c}{2\sqrt{\kappa t}} = c \quad \text{or} \quad z_c = 2c\sqrt{\kappa t}$$

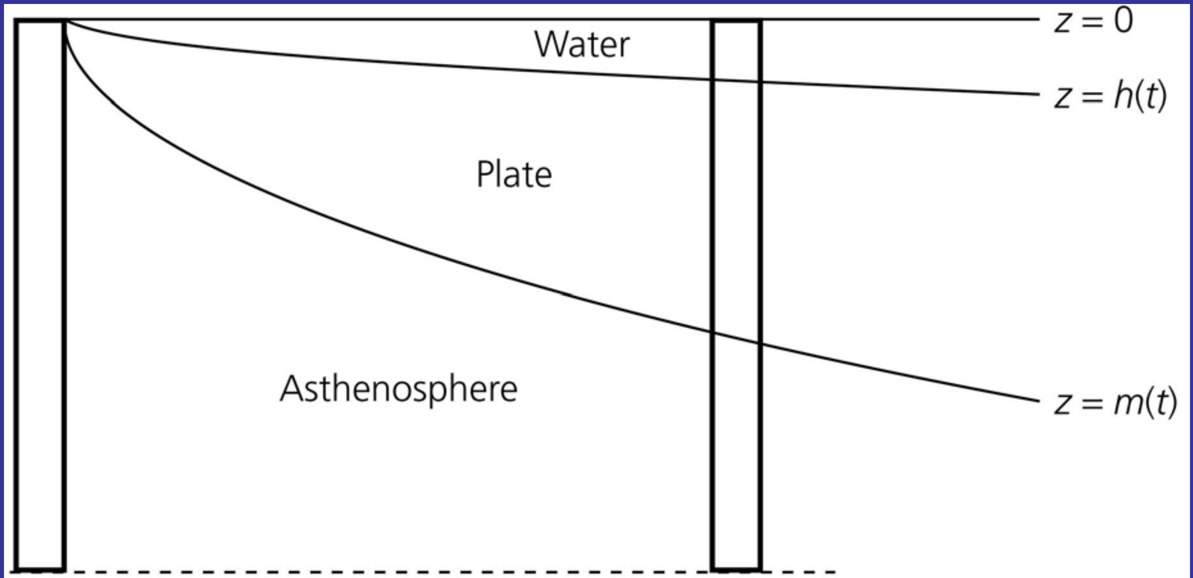
--> The depth to a given temperature increases as the square root of lithospheric age.

LITHOSPHERE COOLS WITH TIME, SUCH THAT ISOTHERMS DEEPEN WITH THE SQUARE ROOT OF AGE

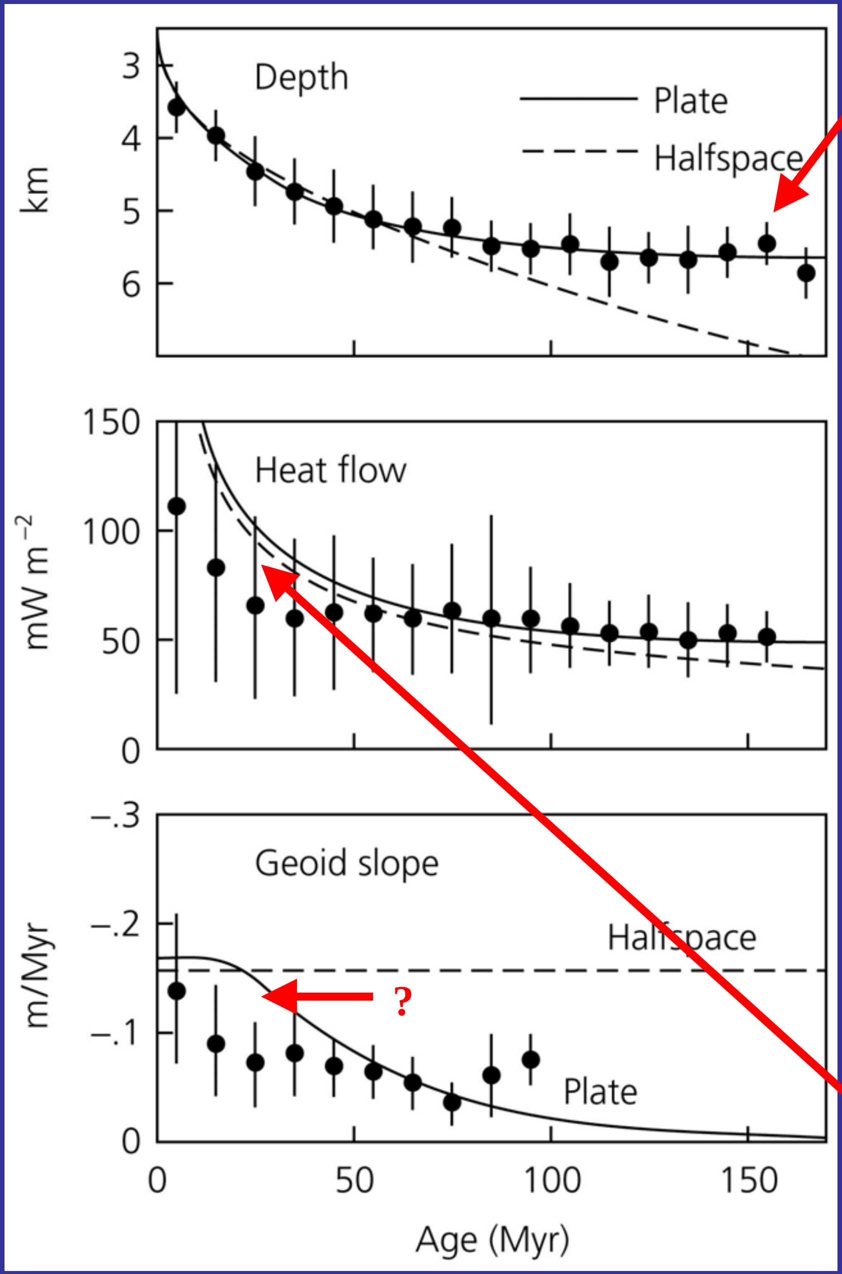
Consequences:

By isostasy, ocean depth increases as square root of age (ridge is shallow)

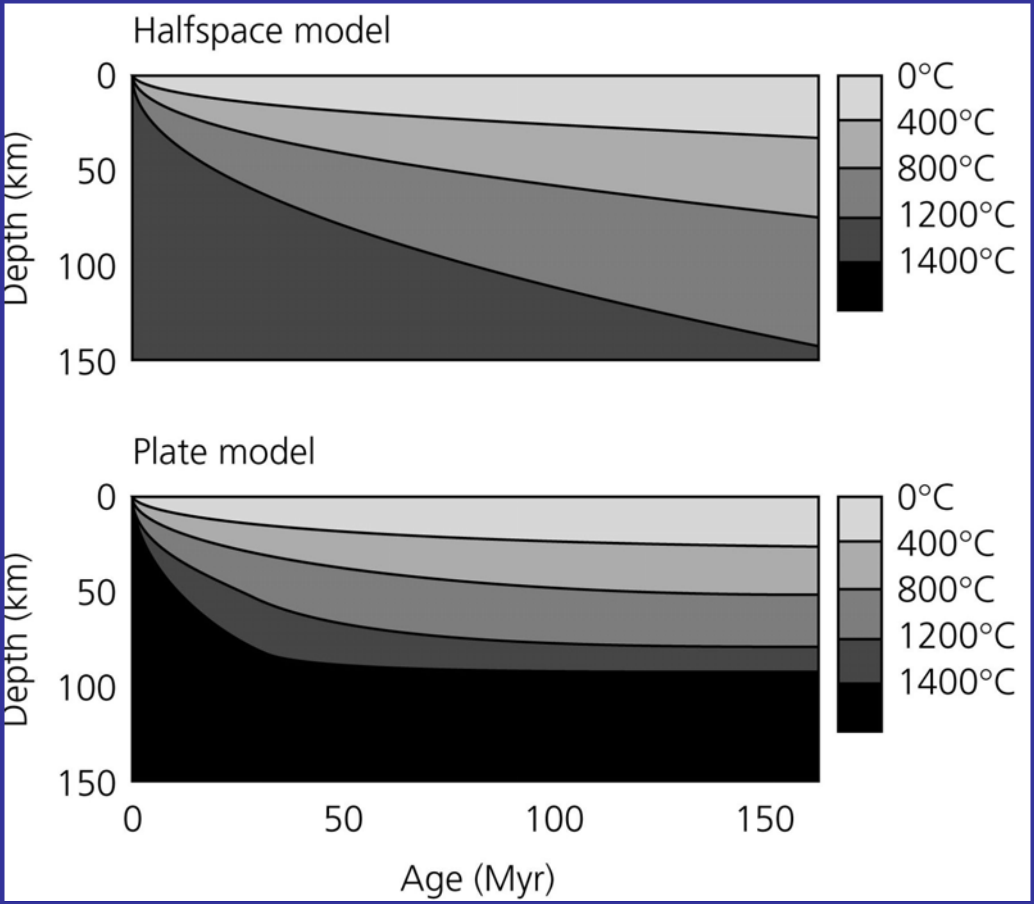
Seafloor heat flow decreases as square root of age (highest at ridge)



SIMPLE MODEL WORKS WELL, WITH INTERESTING MISFITS



Depth flattens at ~70 Myr: use plate model in which lithosphere evolves toward finite thermal thickness as heat added from below



For ages <~ 50 Ma, observed heat flow lower than predictions, because water flow in crust transports some of the heat

Ocean depth, heat flow, and other observables measures reflect temperature in the cooling lithosphere

Because observables depend on different combinations of parameters, can be used together to constrain model parameters that best fit data

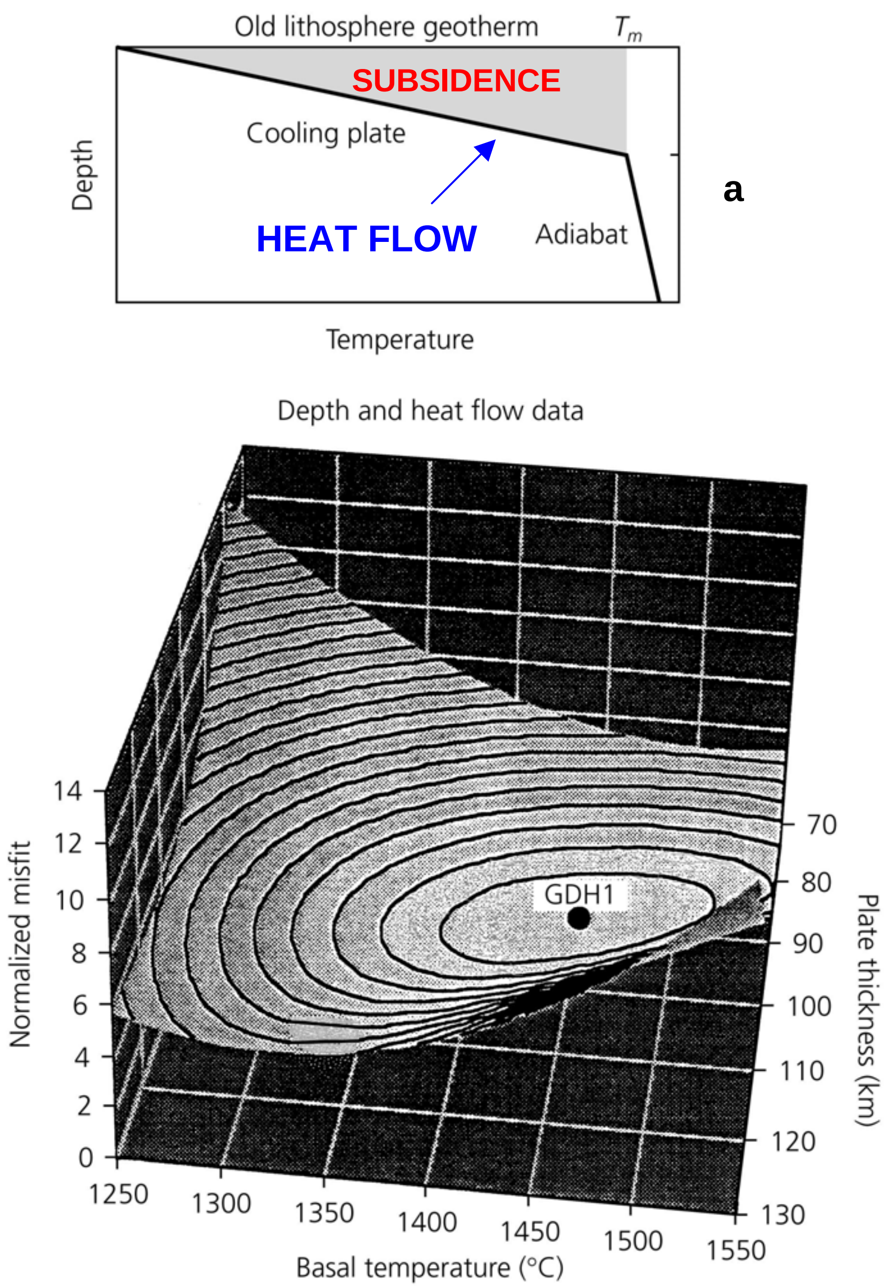
TABLE 1. CONSTRAINTS ON THERMAL MODELS FOR TEMPERATURE AS A FUNCTION OF DEPTH AND AGE $T(z,t)$

OBSERVABLE	PROPORTIONAL TO	REFLECTS
Young Ocean Depth	$\int T(z,t)\,dz$	αT_m
Old Ocean Depth	$\int T(z,t)\,dz$	$\alpha T_m a$
Old Ocean Heat Flow	$\frac{\partial T(z,t)}{\partial z}\Big\|_{z=0}$	T_m / a
Geoid Slope	$\frac{\partial}{\partial t}\int zT(z,t)\,dz$	$\alpha T_m \exp(-t/a^2)$

Plate thickness (a), basal temperature (T_m), coefficient of thermal expansion (α)

Halfspace model corresponds to $a \to \infty$

Figure 5.3-8: Best fit model of plate thickness and basal temperature.



Cooling of oceanic lithosphere also increases rock strength and seismic velocity. Thus

elastic thickness of the lithosphere inferred from the deflection caused by loads such as seamounts,

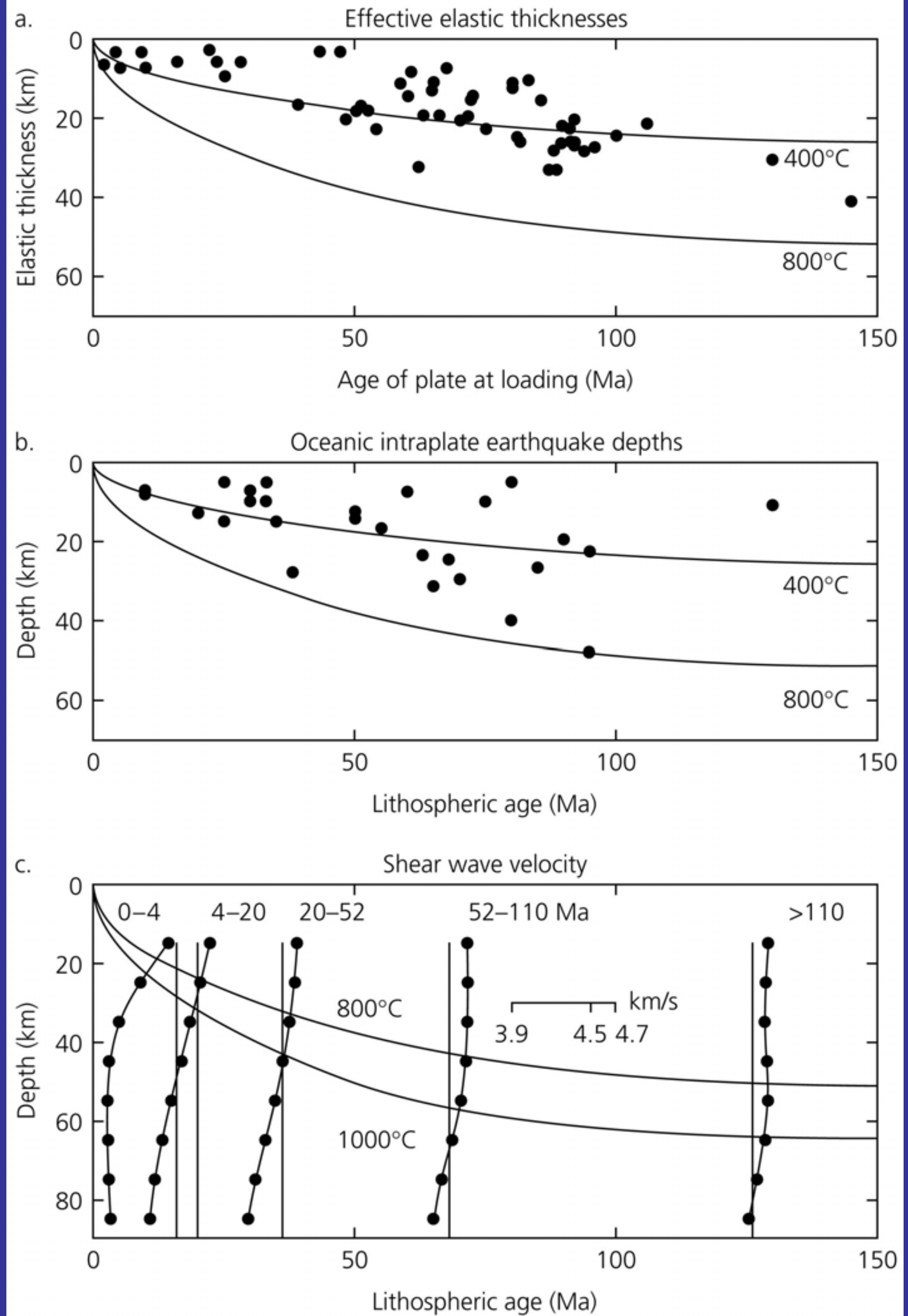
maximum depth of intraplate earthquakes within the oceanic lithosphere,

& depth to the low velocity zone determined from surface wave dispersion

all increase with age.

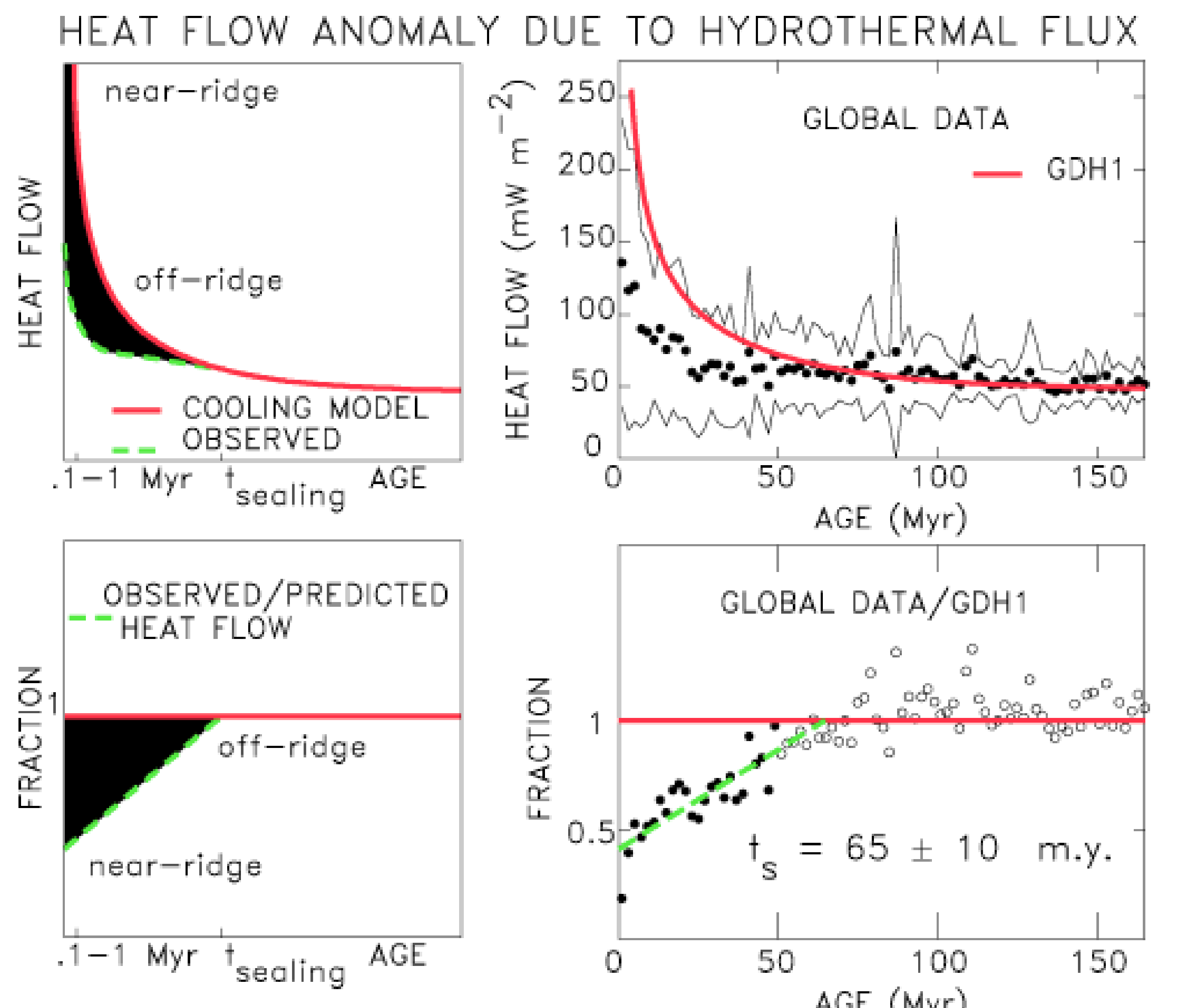
Stein and Stein, 1992

Figure 5.3-9: Elastic thickness, extent of seismicity, and seismic structure with age.



Assume difference due to heat moved by water convection near surface, which conductive measurements don't capture

Average measured heat flow in young crust is less than expected from the conductive cooling models



Stein and Stein, 1994

Discrepancy small for crust > 65 Ma, presumably because:

-Less flow due to increased sediment cover & reduced permeability from hydrothermal deposition of minerals

- flow of cool water transports little heat

Approximately 1/3 of total oceanic heat loss inferred to occur via hydrothermal circulation

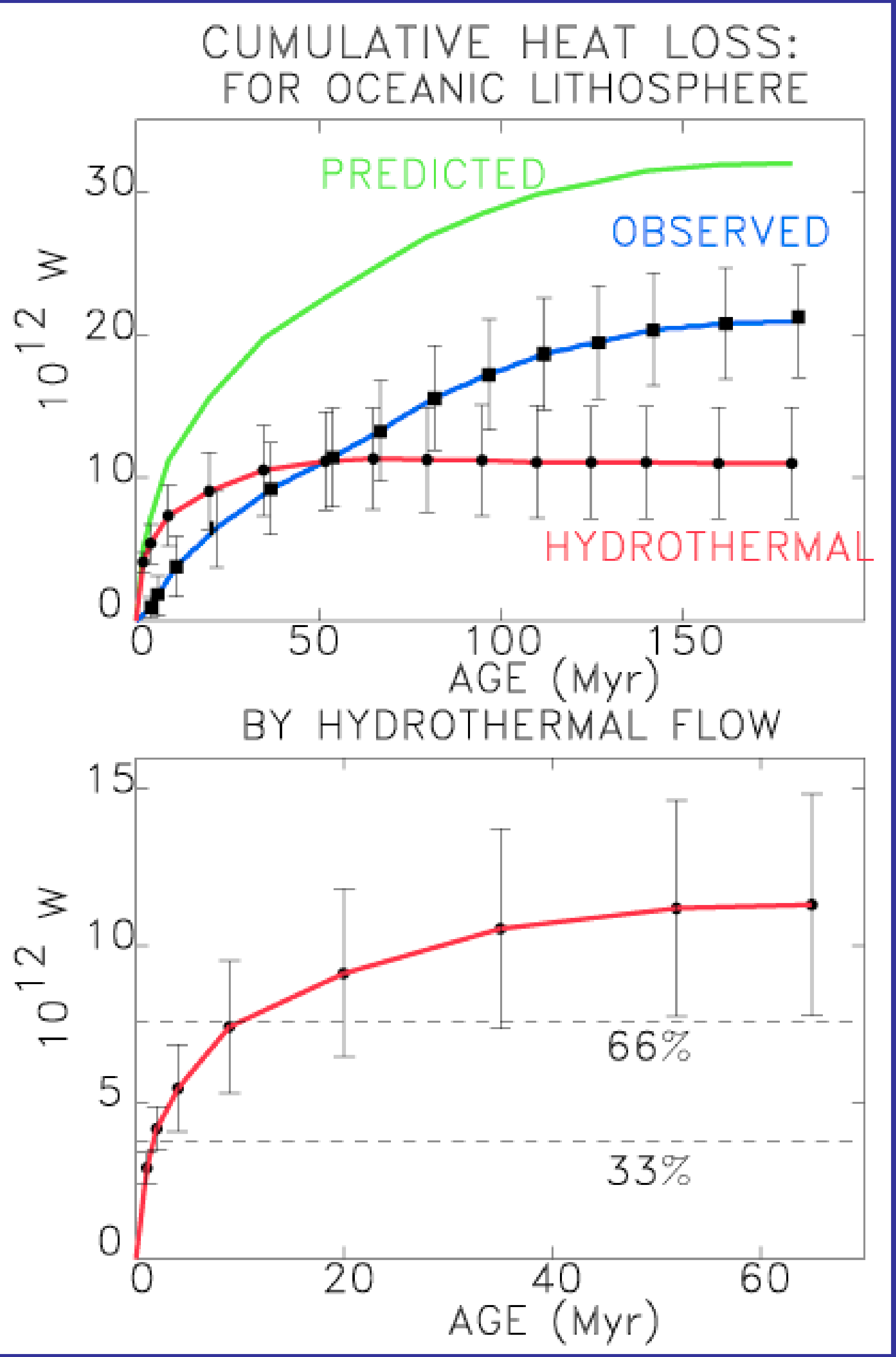
Primarily within first 65 Myr

30% of hydrothermal loss within 1 Myr (hot -warm water)

Hence most hydrothermal heat loss occurs away from ridge axis (cooler water)

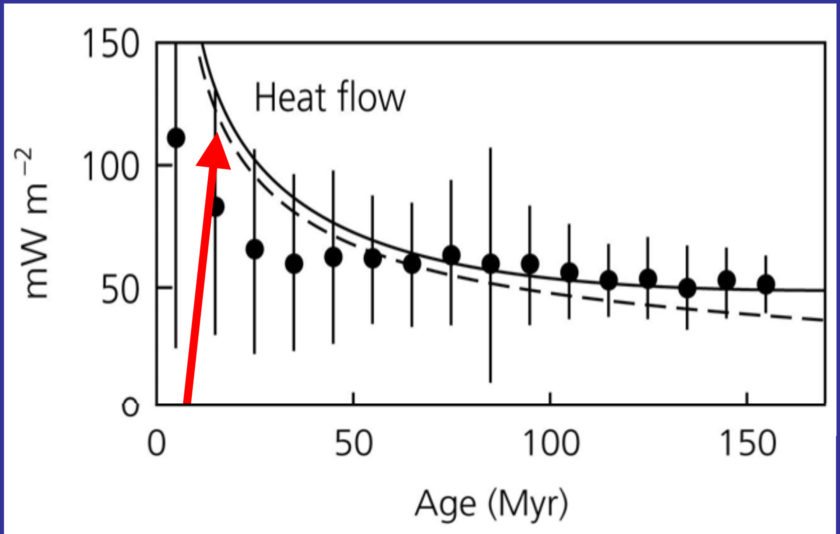
Even more of the water flow away from ridge

Does this make sense?



Stein and Stein, 1994

IS ATTRIBUTING HEAT FLOW DISCREPANCY IN YOUNG CRUST TO HYDROTHERMAL FLOW REASONABLE?



ARGUMENTS FOR:

Consistancy with thermal model derived from depths

Direct observations at ridge crest

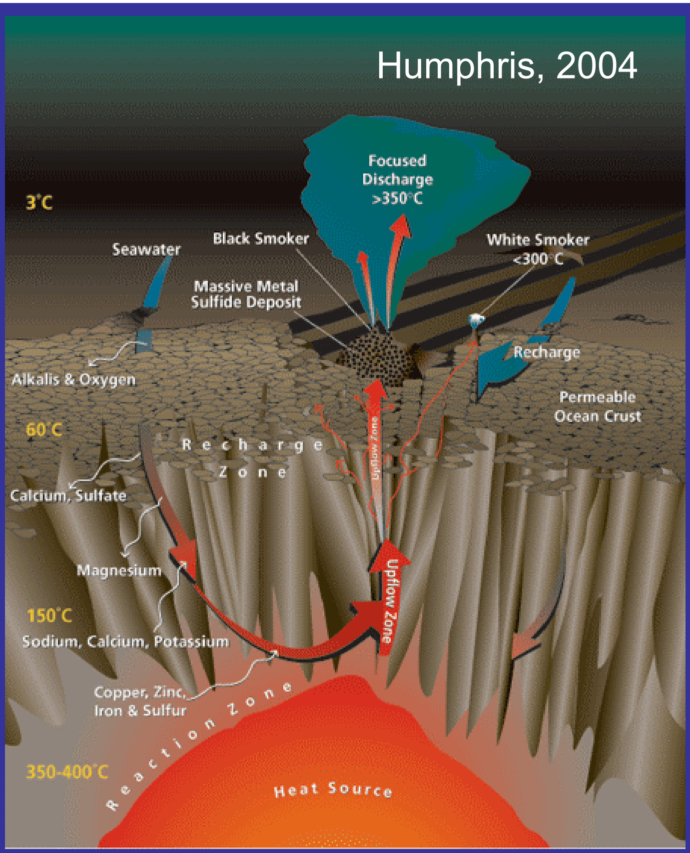
Magma chamber depth requires hydrothermal cooling

Heat flow patterns off ridge axis consistent with hydrothermal flow

Sampling biases favor low values

Geochemical data indicate water flow

Exhumed seafloor now on land (ophiolites) shows effects of water flow



PROBLEMS:

Total flow can't be measured directly, so model seems plausible but not proven

HYDROTHERMAL SYSTEMS AT RIDGES

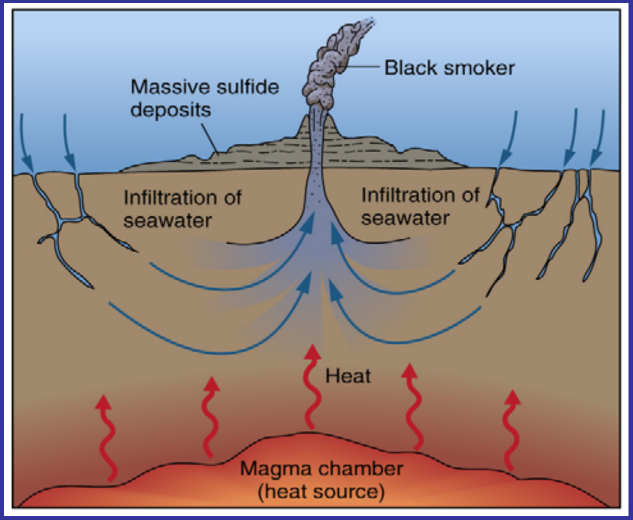
QuickTime™ and a
YUV420 codec decompressor
are needed to see this picture.

Water flowing into hot fractured basaltic crust reacts to form minerals and changes chemistry of sea water

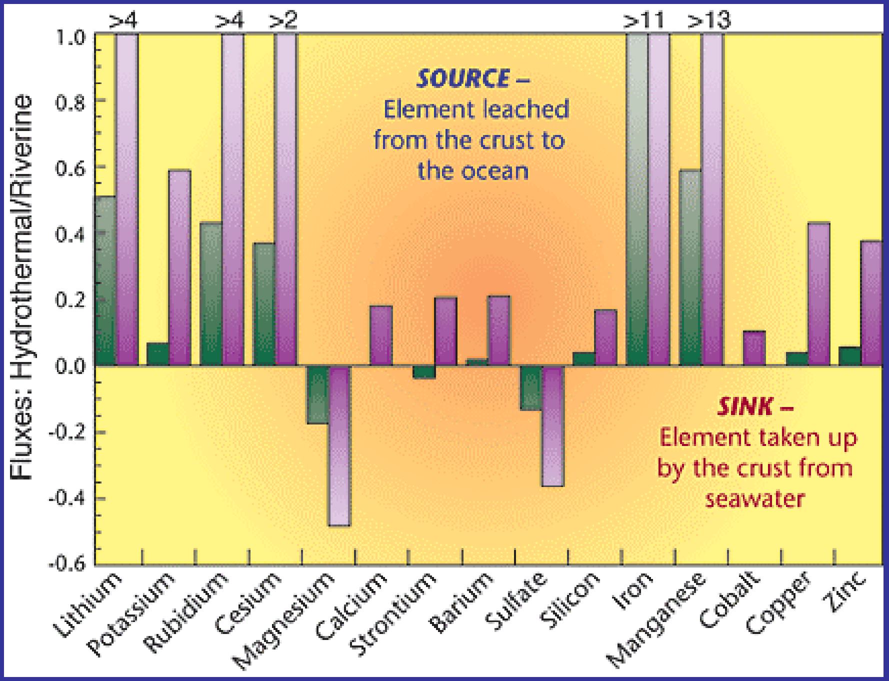
Hot (350°C) mineral-rich water discharges at vents called black smokers and forms mineral deposits rich in zinc, copper, and iron

Even more (10x?) heat transferred by cooler diffuse flow that's harder to observe

NOAA



Away from ridge axes, flow occurs by less spectacular seepage of low temperature water, but probably carries more heat



Humphris, 2004

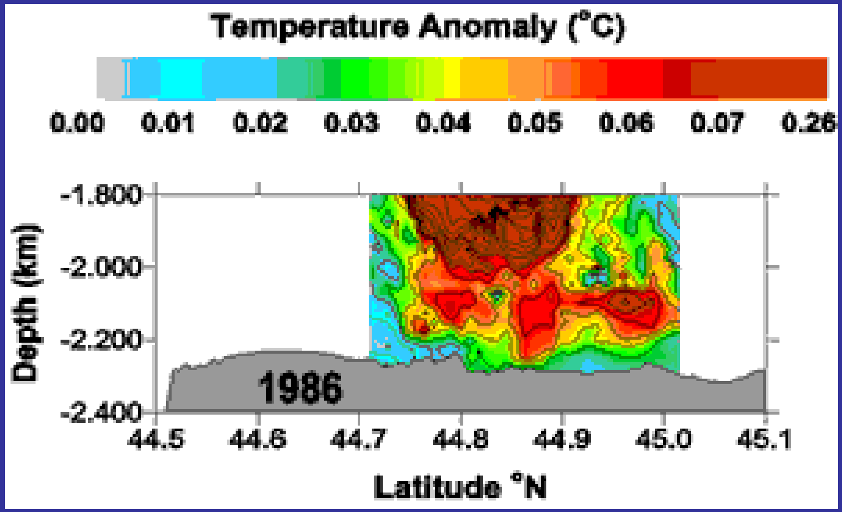
DIRECT MEASUREMENT OF HEAT IN FLUID FLOW: TRICKY

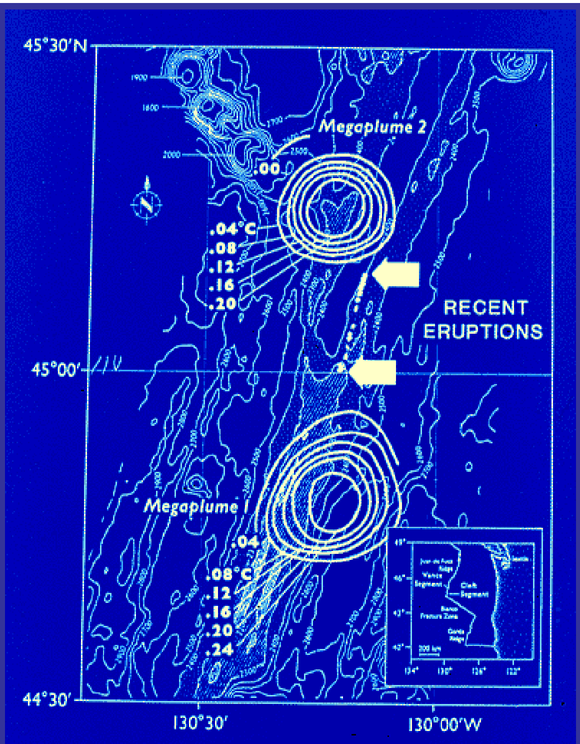
Thermal model predicts ~10 MW / km $^{-1}$ for average spreading rates

Estimates by sampling vents 1 MW / km^{-1} lower, implying sampling misses some vents and pervasive diffuse lower temperature flow.

Water temperature anomalies above large hydrothermal plumes estimate heat content ~ 1000 MW. If plumes represent ~ 10 km of ridge length, estimated flux per unit ridge length is an order of magnitude higher than our estimate. Thus plumes appear to be transporting more heat than the total steady state surface flux for the cooling lithosphere.

If both thermal and plume calculations are appropriate, plumes may be intermittent and only some of the ridge has plumes at any time



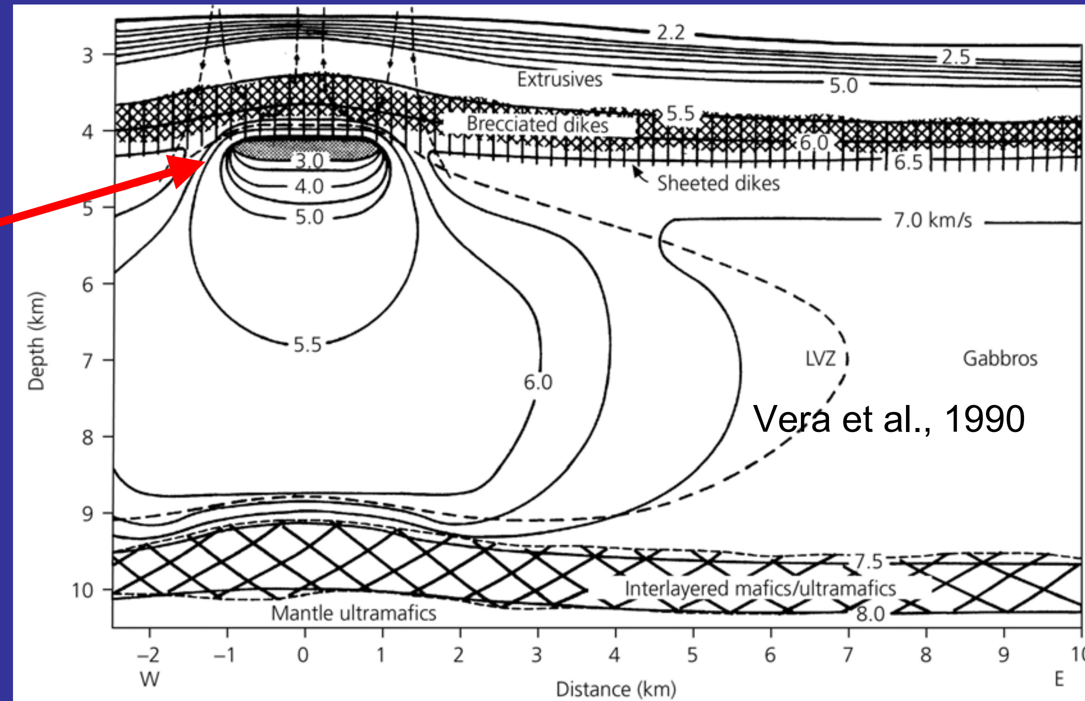


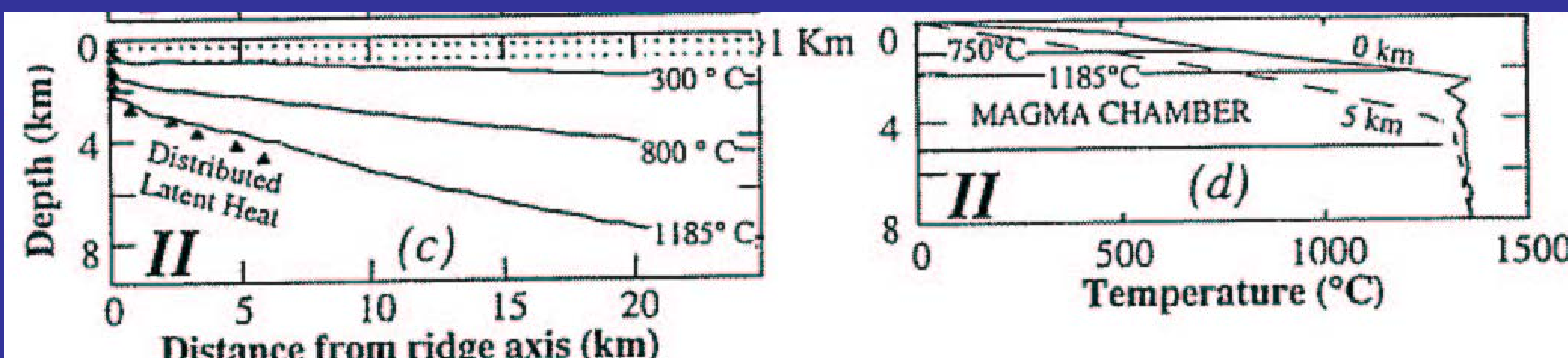
NOAA

INDIRECT ESTIMATES

Seismically observed depth of ridge axis magma chamber shallower than predicted by models without hydrothermal cooling.

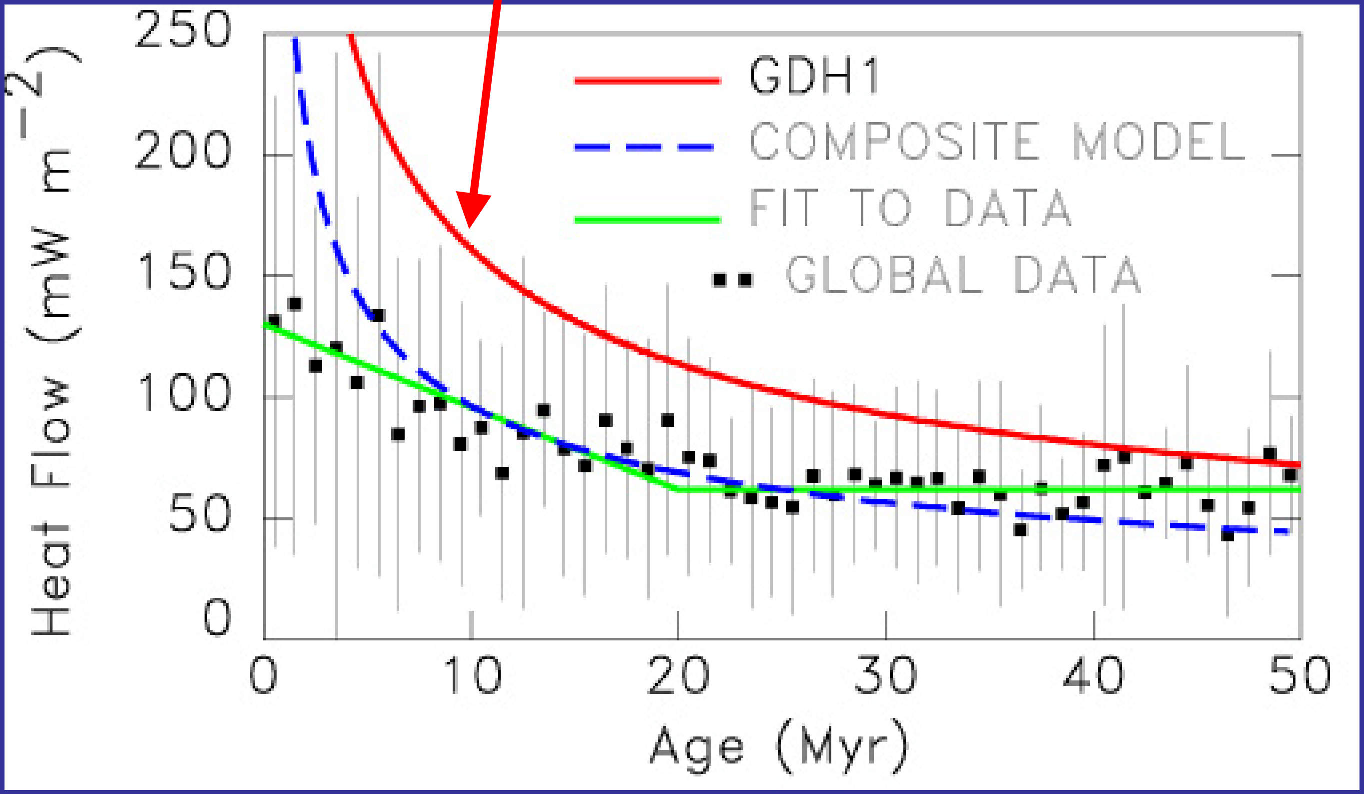
Model with hydrothermal cooling explains both shallow magma chamber and observed heat flow < 10 Ma not used in model





Stein et al., 1995

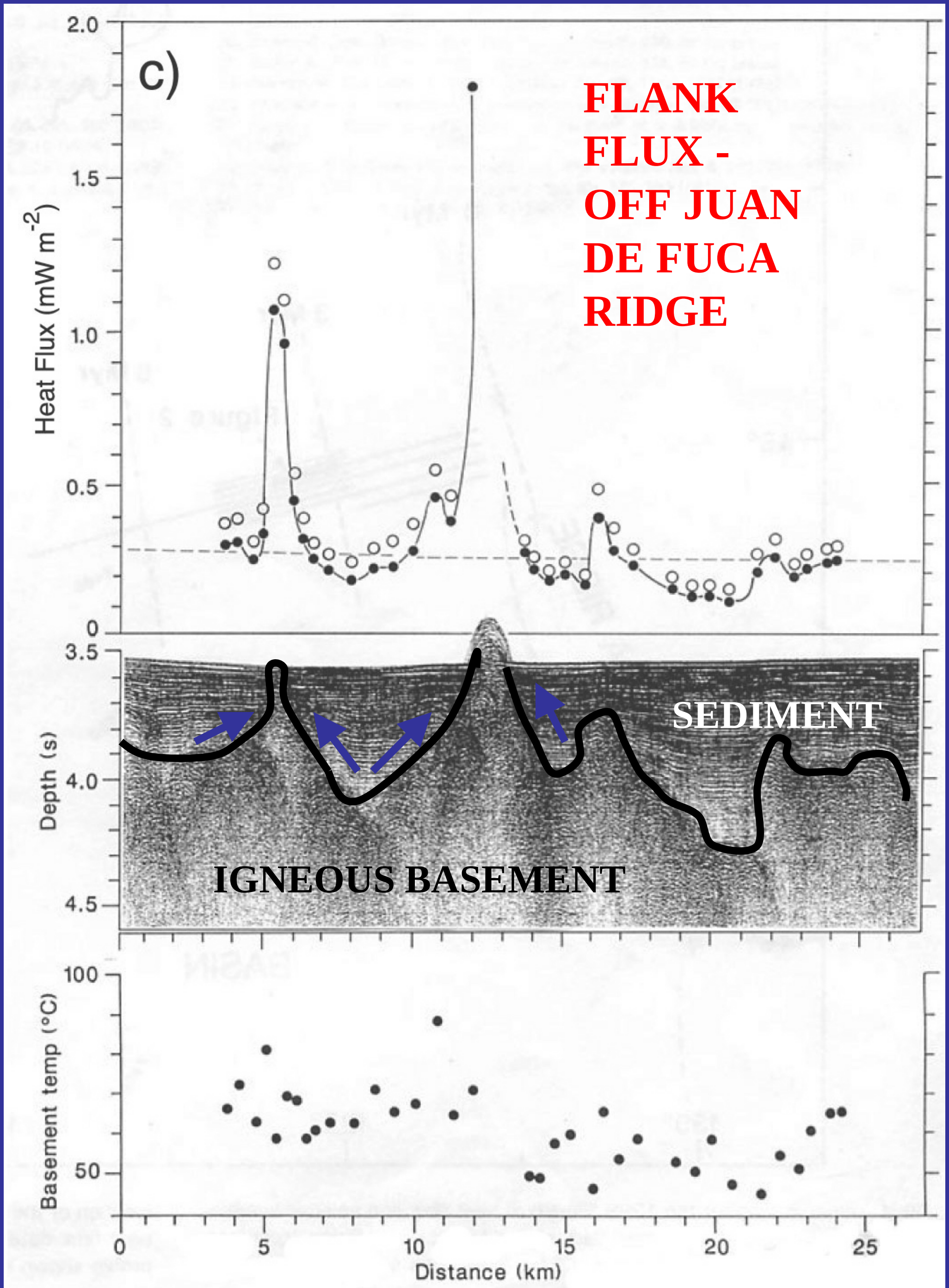
Composite model including hydrothermal cooling needed to explain both shallow magma chamber and observed heat flow lower than expected from global model without hydrothermal cooling (GDH1)



Stein et al, 1995

Composite model does better than GDH1 but still overpredicts observed heat flow means <10 Ma, presumably due to bias favoring sampling low values

Scatter appears to reflect geometry of hydrothermal flow & sampling biases

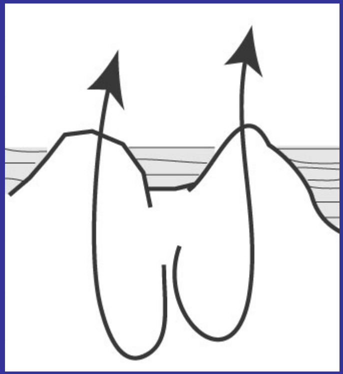


DETAILED SURVEYS OF WELL SEDIMENTED AREAS SHOW HEAT FLOW VARIES DEPENDING ON BASEMENT ROCK

High heat flow over basement highs that seem to function as chimneys for upwelling water

Thick layered sediment seems to block upward flow, so water flows along basement top, making it approximately isothermal

Basement highs allow water to reach sea floor



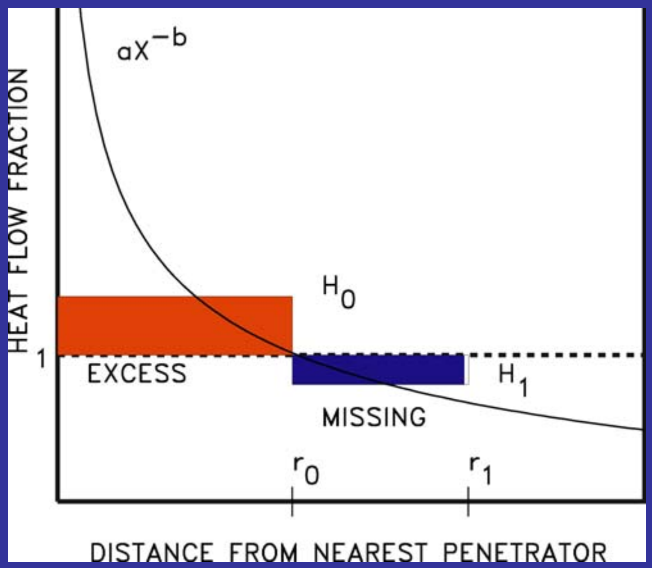
Harris & Chapman, 2004

Heat flow exceeds conductive prediction (heat flow fraction > 1) near isolated basement highs

Most of region has low heat flow

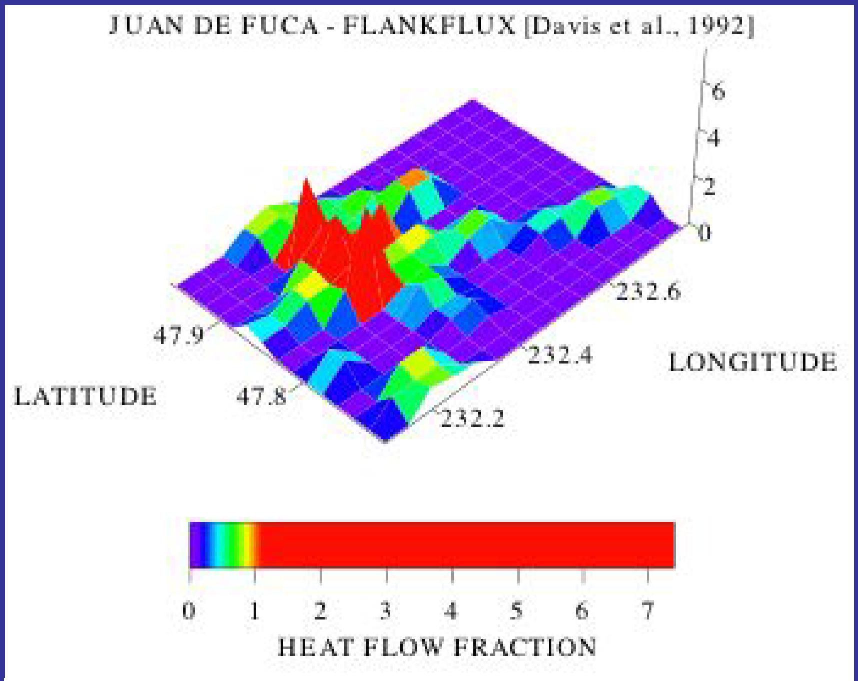
Water flows to highs, transporting heat

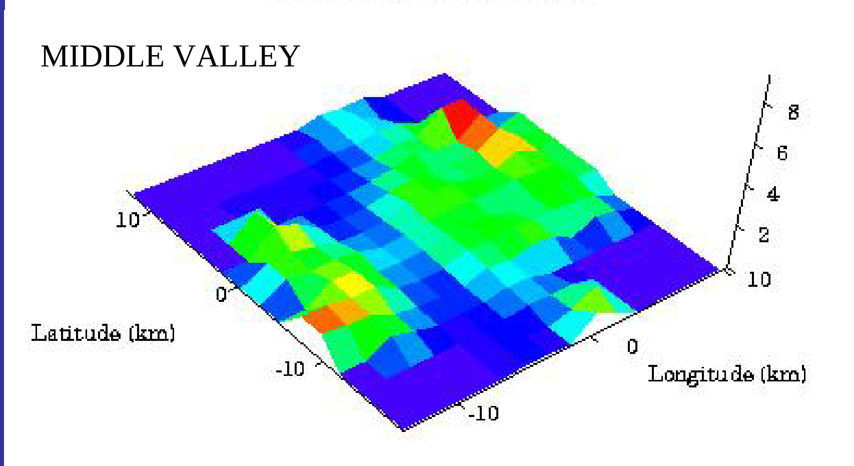
Simple energy balance implies 2-8 km radial flow distances here



Randomly selected site likely to have low heat flow

AREAL VIEW: DETAILED SURVEYS





Stein and Stein, 1997

Heat flow at highs exceeds predicted conductive model values (GDH1), since heat brought in from surroundings

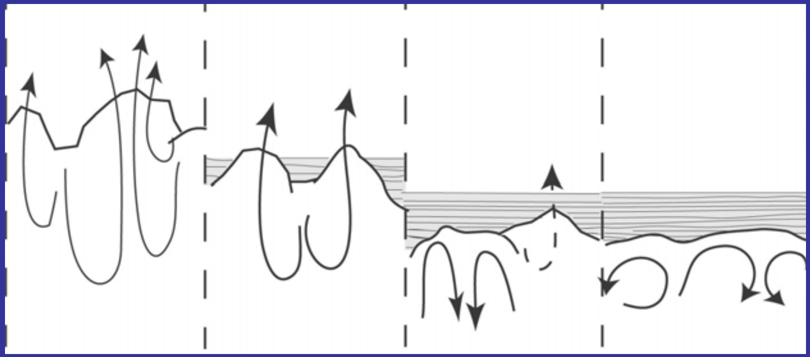
Regional average values described by composite model (CYH1) with hydrothermal flow

In this well sedimented area, both high & low values are observed

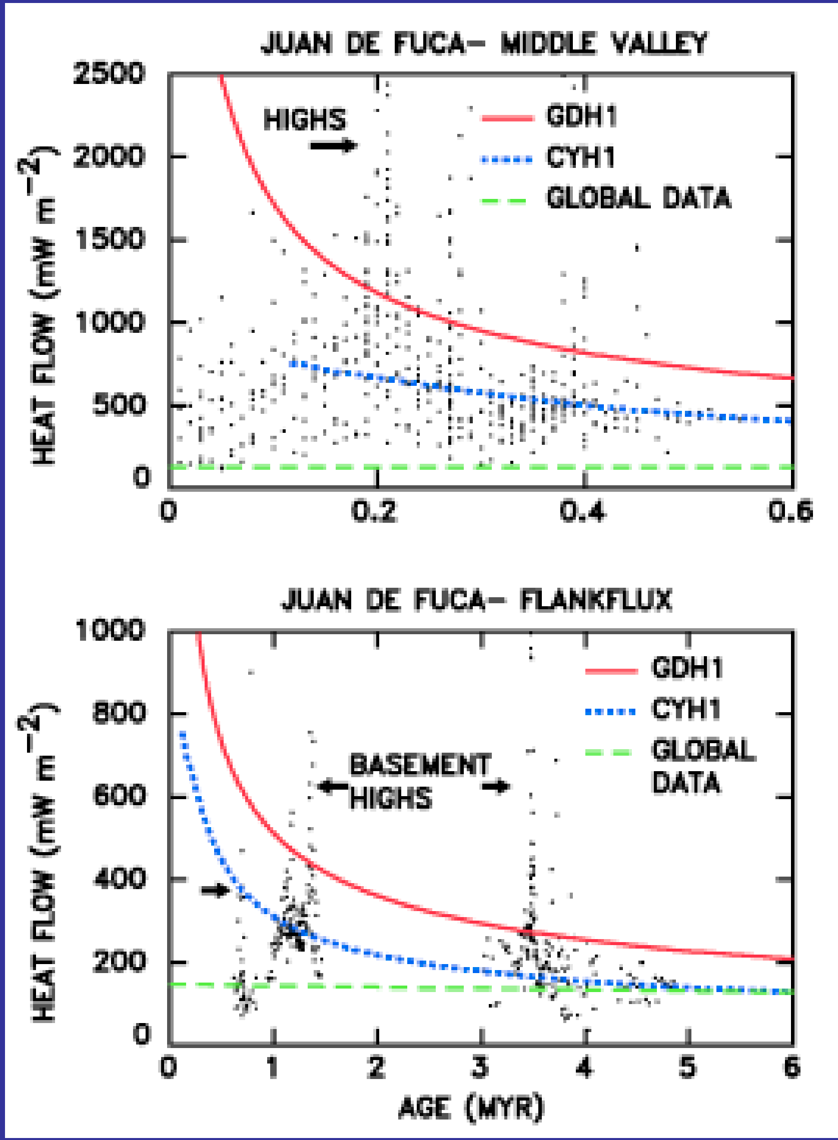
Global average is lower because:

-randomly selected sites more likely to have low heat flow where water goes down

- most young crust is less well sedimented, so measurements can be made only in lows where water is going down



Harris & Chapman, 2004



Stein et al, 1995

WHY NOT MEASURE EVERYWHERE TO GET TOTAL OCEANIC HEAT FLOW?

Time - While measurement in sediment takes ~ 10 minutes, getting up/down means about 2 hours per measurement

Spatial - variation pattern is 2 dimensional, not just one short profile

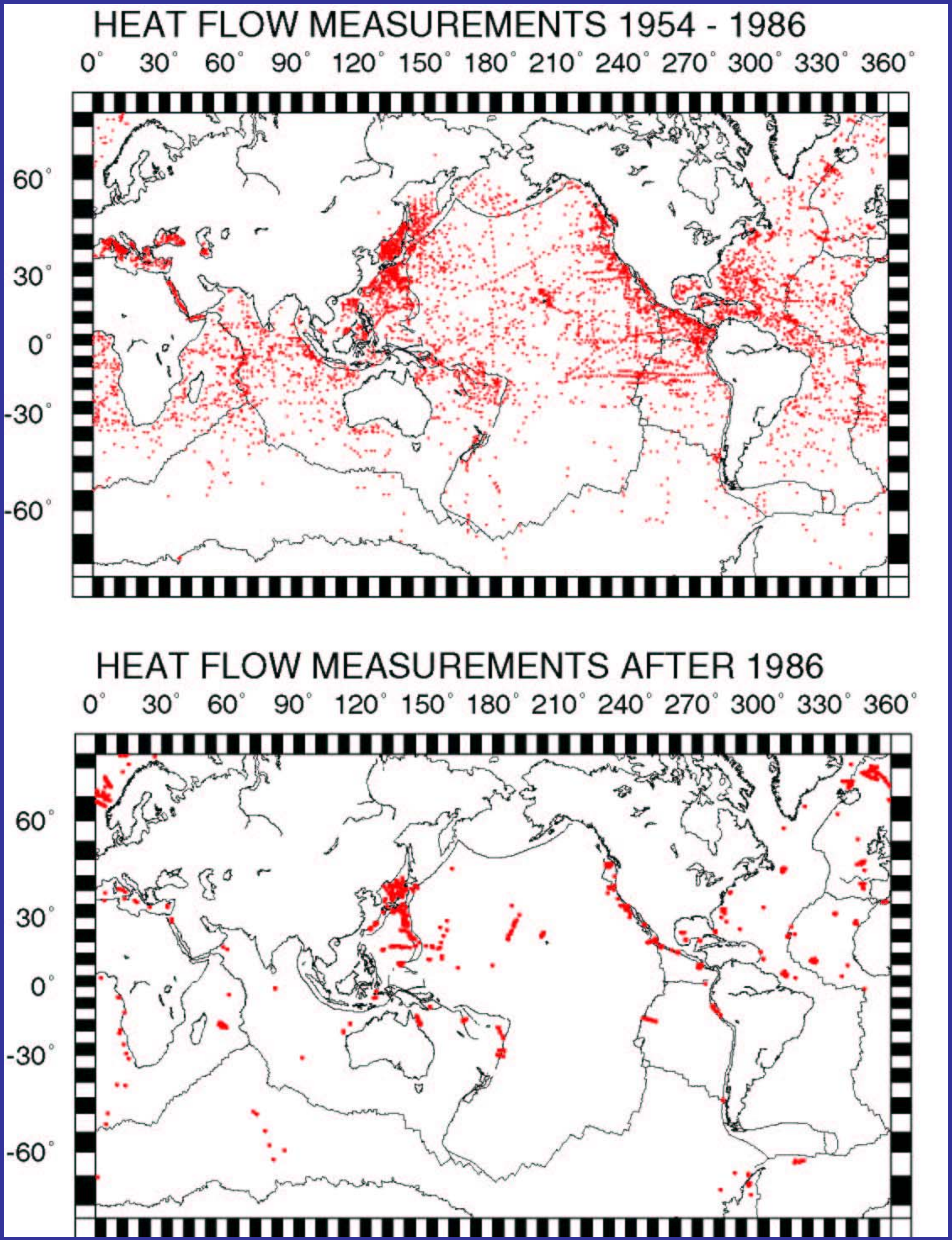
Ocean is a big place (1 km spacing requires 3.6 x 10^{8} measurements)

Bare rock - hard to measure heat flow in many places

Escaping water - either very local ,or diffuse and hard to locate, often not that hot

QuickTime™ and a
GIF decompressor
are needed to see this picture.

NOAA



Little recent advance in measuring global marine heat flow (focus on detailed local surveys)

No NSF interest yet in advanced robotic system

HEAT FLOW CONSTRAINT ON THE THERMAL EVOLUTION OF THE EARTH

Change in the average temperature *T* as a function of time *t* is given by the balance between heat produced and that lost at the surface

$$MC\frac{\partial T}{\partial t} = MH - Aq$$

***M* is the mass of the earth, *A* is its surface area, *C* is specific heat, *q* is the average heat flow, and *H* is the average rate of radioactive heat production.**

Heat flow used is an average of that coming from the mantle, about 72 mW m^{-2} , estimated by removing the approximately 17% thought to be produced by radioactivity in the continental crust.

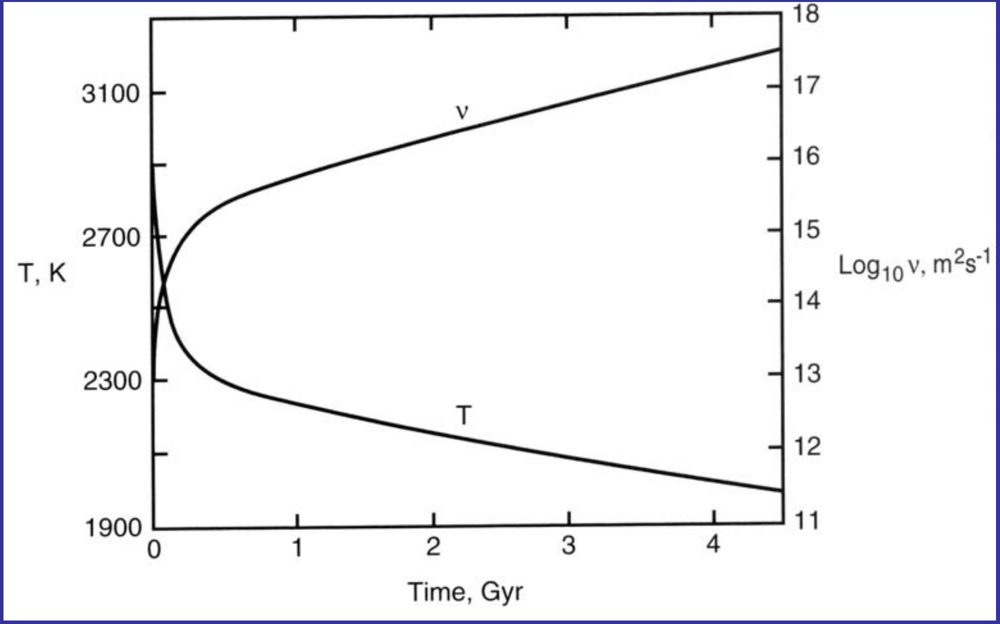
The balance between surface heat flow and heat production is given by the Urey ratio

$$Ur = MH/Aq$$

so the temperature evolves with time according to

$$\frac{\partial T}{\partial t} = \frac{Aq}{MC}(Ur - 1).$$

The Urey ratio is thought to be between 0.5 and 0.8, so heat is lost faster than it is produced, and the earth has been cooling with time.



Schubert et al., 1980

SUMMARY

Continental heat flow considered well known

Attributing heat flow discrepancy in young crust to hydrothermal flow seems reasonable, given what we know about hydrothermal circulation

If so, oceanic heat loss of 32 TW and global loss of 44 TW seem reasonable

However, since net oceanic flow can't be measured directly - if hydrothermal ideas correct - model seems plausible but not proven

Much thinking in tectonics & geochemistry uses hydrothermal model

Estimates of global heat loss from heat flow data seem unlikely to improve dramatically

Neutrino estimates potentially very valuable for understanding both global thermal evolution and variety of plate tectonic & geochemical processes

SHALLOW HYDROTHERMAL COOLING LOWERS HEAT FLOW BUT DOESN'T CHANGE TEMPERATURE & THUS DEPTH MUCH