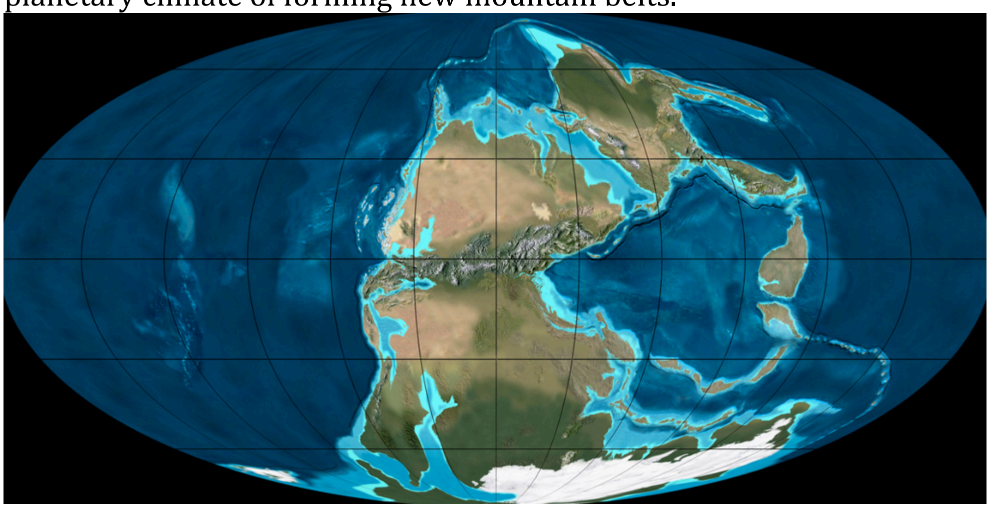
GEOS 22060/32060 – Spring 2019 – Homework 4

Due in Kite mailbox (which is in the mailroom on the 1st floor of the Hinds building) 4pm Friday 17th May. To get to the mailroom on the 1st floor of the Hinds building, turn left on entering Hinds through the main (East) entrance, walk past the sofas, and just after entering a windowless corridor, the mailroom will be the first room on your left. No credit will be given for answers without working. It is OK to use e.g. Mathematica, but if you do, please print out the work.

Q1. Effect of Supercontinent Formation. Mountains are important to the global weathering budget. This is because mountain uplift increases the amount of material available for weathering per year (the sediment mass flux). Because the total planet-integrated weathering must be constant (averaged over >10^7 yr timescales) in order to avoid a climate runaway, the increase in material available for weathering must be compensated by a decrease in the amount of weathering per unit sediment. The easiest way to decrease the amount of weathering per unit sediment is to lower the planet temperature. (The lowering of temperature is accommodated by a transient pulse of increased weathering. This transient increase in weathering lowers the CO_2 concentration, which lowers temperature. The planet is now less efficient at weathering each sediment parcel, and so the climate re-equilibrates at a new, lower temperature).

The purpose of this question is to work through the order-of-magnitude effect on planetary climate of forming new mountain belts.



Earth 280 Ma. Credit: Ron Blakey (NAU).

The most recent global supercontinent, Pangea, was completed ~280 Ma by collision of North America with Africa. The collision (the Alleghenian orogeny) created a mountain chain, the Central Pangean Mountains. The Appalachian Mountains approximately correspond to a remnant of this mountain belt. In this question, use the paleogeographic reconstruction above (grid spacing 30 degrees) and Earth radius = $6\text{x}10^6$ m.

Assume weathering efficiency (cations/yr/km^3 of sediment flux) scales as

$$\varpi \propto e^{-E/RT}$$

where E is activation energy and R is the gas constant, 8.314 J/mol/K, and surface temperature T is in K. Assume an effective activation energy for weathering ("effective" including the effect of temperature on rainfall) of E = 74 kJ/mol (West et al., Earth & Planetary Science Letters, 2005).

(a) Suppose paleomagnetic data[1] indicate Africa travelled N at 5 cm/yr and collided with a stationary North America. Assume continental crust is 35 km thick. Because continents are buoyant relative to the mantle, neither continent subducts. At steady state, continental crust is moving up to the surface at mountain belts, undergoing weathering and erosion, and the mass is being redistributed away from the mountain-belt, all at equal rates. What is the mass flux? Suppose the pre-collision eroded flux was equal to Earth's modern sediment flux of 8 km^3/yr; what is the fractional change in eroded flux (i.e., mass/volume available for weathering)?

(b) Assume an activation energy for the temperature effect on weathering of 74 kJ/mol (West et al., Earth & Planetary Science Letters 2005). What is the sign and magnitude of planetary temperature change?

(c) Suppose that the ice sheet in the S Hemisphere grows. Is this a positive or negative feedback on the change you calculated in part (b)? Why?

(d) It is often said of warming climates that "wet areas get wetter, dry areas get drier." [2] Given that weathering rate depends on both temperature and rainfall, explain qualitatively how changes in rainfall on the Central Pangean Mountains due to the warming you calculated in part (b) would feed back on (and thus modify) your answer to part (b).

(e) Suppose that collision had occurred in the desert belt at 25° N instead of at the humid equator. Explain how you answer to part (d) would differ.

The formation of the Himalayas and Tibet is one leading hypothesis for the cooling of Earth that led to the onset of ice sheets on Antarctica ~35 Myr ago.

Q2. Tidally Locked Exoplanet. Many, perhaps most, of the rocky habitable-zone planets in the Universe orbit M-dwarf stars; these are also the easiest habitable-zone rocky planets to detect and characterize. However, because M-dwarfs are faint,

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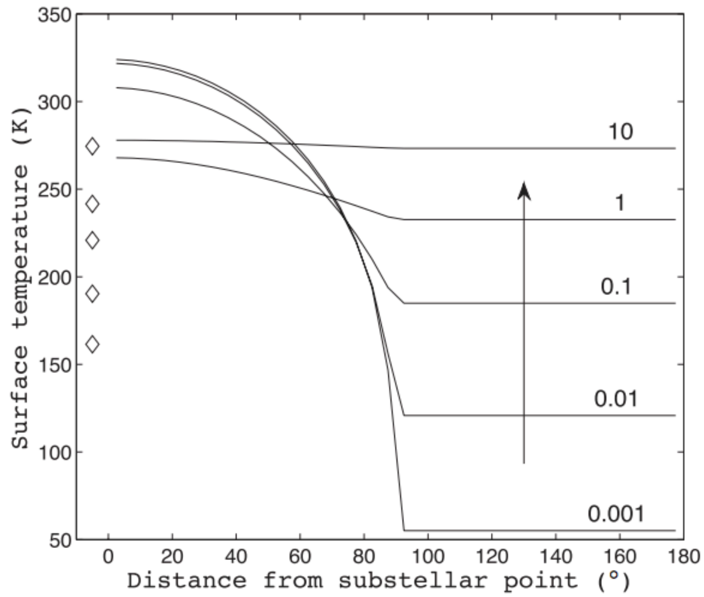
[1] Paleomagnetic data provide great constraints on latitudinal drift rates, but constraining paleo-longitudinal drift requires less direct methods such as matching up geologic provinces on either side of a rift zone, or looking for evidence of hotspot volcanism (hotspots are underlain by mantle plumes, which move slowly relative to plates and so define a "hotspot reference frame").

[2] This is not always exactly true. For example, an expanding Hadley cell under warming (the Hadley cells are currently expanding due to anthropogenic global warming) can turn the low-latitude edge of the desert belt into a wet zone.

the habitable zone is located close to the star (i.e. the ratio of planet radius r to orbital radius a is much smaller than on Earth). Because tidal locking timescales scale as a^{-5} for constant r, such planets are very vulnerable to tidal locking.



Surface temperature on a tidally locked planet, calculated using an idealized 1D climate model. The numbers 0.001→10 correspond to atmospheric pressure in bars. Local temperature is controlled by the greenhouse effect, but also by the tendency of thicker atmospheres to redistribute energy from the lightside to the darkside. (From Kite et al. ApJ 2011)

Consider the tidally locked planet from the figure.

(a) As in previous question, assume weathering rate scales as

$$\varpi \propto e^{-E/RT}$$

where E is activation energy and R is the gas constant. Assume an effective activation energy for weathering ("effective" including the effect of temperature on rainfall) of 74 kJ/mol, as for the previous homework. For the 0.01 bar tidally locked planet case, what is the ratio of weathering rate at the substellar point to weathering rate at 60° from the substellar point?

(b) Assuming mountain belts / tectonic uplift zones are randomly distributed with distance from the substellar point, comment on where on the planet most weathering occurs. Consider the likely effect of ice cover.

(c) Now assume that the gas that is the principal constituent of the atmosphere is also the principal greenhouse gas. (This assumption was used to calculate the temperatures shown in the plot. This assumption is not true for the Earth, but is true for Mars, Venus, Triton, and arguably also Titan). Explain how the planet-integrated weathering rate changes as we increase pressure from 0.001 → 10 bars.

(d) Is this hypothetical planet stable to a sudden two-fold step increase in the volcanic outgassing rate? Why?

(e) Now assume that everything is the same as in (e), but the effective activation energy is now 1000 kJ/mol. Is this hypothetical planet stable to a sudden two-fold step increase in the volcanic outgassing rate? Why? ***Hint:*** Recall that the threshold surface temperature for runaway greenhouse on a planet with water oceans is ~330K.