

EARTH AND SPACE SCIENCES 431

Principles of Glaciology

FINAL EXAM: December 14, 2007

Instructions:

- The actual 5 questions on the final exam will be selected from the questions below, or some variations on these questions.
 - Each question has equal value of 10 points.
 - The numbers in [square braces] with each sub-question indicate the points available for that sub-question. (The relative value assigned to each sub-question usually indicates the relative amount of detail that the instructor expects in your responses, e.g. a one-sentence response to a 5-point question is unlikely to cover all the expected points. ☺)
 - This is a closed-book test; however, you are free to use a calculator, and a dictionary.
 - Different instructors may grade the different questions. To facilitate grading, please **start each question on a new piece of paper, and write your name on each page.**
 - You have 1 hour and 20 minutes (2:30-3:50 p.m. Friday, Dec. 14, 2007).
 - Location, our regular classroom JHN 026.
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1. Terminology

Give short definitions of the following 10 terms.

[There may be different terms on the actual test.]

- Close-off depth
- GISP2
- Glacial polish
- Grounding line
- Milankovitch
- Pancake ice
- Péclet number
- Shear margin
- SMOW
- Stokes force

2. Glacier erosion

(a) [6] **Local scale:** describe 3 ways in which a glacier can erode its bed.

Be sure to address:

- the role of water
- the role of debris-rich ice
- the role of bedrock chemical composition
- which mechanism(s) tend to make the bed smoother, and which make(s) it rougher.

(b) [4] **Global scale:** Explain how topography of the Earth controls glacierization (existence of glaciers in a region), and conversely, how glaciers may also exert some control on the regional topography, particularly in areas of tectonic uplift.

3. Glacier erosion

The volume of sediments that accumulates in a fiord in front of a retreating glacier reflects the amount of erosion by that glacier.

- (a) [2] What are the factors likely to control the erosion rate?
- (b) [3] Assume that the drainage area is 1000 km^2 , and that the thickness of sediments in the fiord increases on average by 5 m in 50 years. The fiord is 50 km long and 2 km in width.
- Calculate the erosion rate for this glacier.
- (c) [2] What assumptions are implicit in this calculation?
- (d) [3] Most studies of erosion rates of tide-water glaciers yield estimates of these rates for the period since the Little Ice Age, during which glaciers have retreated substantially all over the globe.
- Explain why these studies are likely to yield erosion rates that are significantly higher than the long-term mean erosion rate.

4. Periglacial processes

(a) [5] Please plot a typical temperature profile for the upper 20 m of permafrost in the middle of the summer.

- Label your depth (m) and temperature (deg C) axes carefully.
- Label the active layer, which is the near-surface layer that thaws seasonally.
- Describe the salient features in your diagram.
- Why does the temperature gradient change at the base of the active layer?

(b) Consider a 1-meter-thick saturated soil layer, as it freezes. Assume that pore space makes up 30% of the soil by volume, and that it is full of water (saturated soil).

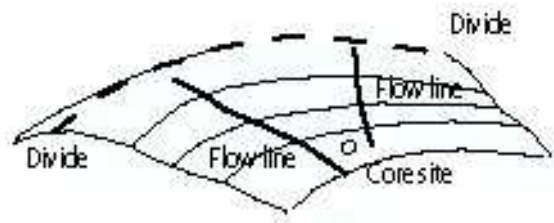
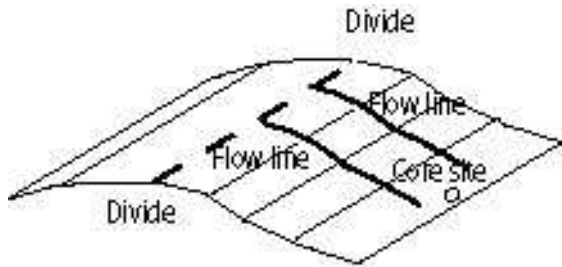
- (i) [2] Estimate the frost-induced heave of the ground surface, if the soil neither loses nor gains water as it freezes.
- (ii) [3] How is your answer to (i) likely to compare with observations of frost heave in sandy soils, in silty soils, and in clays, in cold regions where soil moisture is abundant? Explain why you see these differences.

5. Ice sheets of the solar system

(a) *Ice-core site selection*

UW glaciologists recently ran a field project to select the next site for a deep ice core in West Antarctica. As part of the planning process prior to going into the field, they needed to estimate the (horizontal) ice-flow velocity at the surface at one potential ice-core site. That site is ~29 km downstream from the flow divide, and the ice there is ~3350 m thick. The accumulation rate in this portion of the ice sheet is approximately 0.33 m a^{-1} .

- (i) [3] Assuming that this part of the ice sheet is in steady state (i.e. not thinning or thickening), estimate the velocity at the potential core site. ***Explain in prose the steps that you are taking and the assumptions that you are making.***
- (ii) [2] Would your answer be the same if the divide were curved, i.e. the ice flow from the divide was converging near the core site? Why do you think so?



(b) *Martian Ice Caps*

Geomorphological features near the polar ice caps on Mars are suggestive of past water flow. An obvious question is whether that water may have originated beneath an ice cap, due to subglacial melting. Based on current estimates for relevant physical parameters, assess the likelihood that basal melting is taking place beneath the current north polar ice cap.

The central portion of the north polar ice cap on Mars is ~3000 m thick, similar to the central parts of the Greenland and Antarctic ice sheets. The surface temperature is much lower, ~130°C below zero, as are accumulation rates, at $\sim 5 \times 10^{-4} \text{ m a}^{-1}$. Because the Martian ice is much colder, the thermal properties also differ from those for ice sheets on Earth. For water ice at -100°C,

$$k \text{ (thermal conductivity)} \sim 3.5 \text{ W m}^{-1} \text{ K}^{-1}$$

$$A(T) \text{ softness parameter} = 3.06 \times 10^{-22} \text{ Pa}^{-3} \text{ s}^{-1} \text{ (Glen flow law for ice)}$$

$$C_p \text{ (specific heat capacity)} \sim 1390 \text{ J kg}^{-1} \text{ K}^{-1}$$

$$R \text{ (universal gas constant)} = 8.314 \text{ J K}^{-1} \text{ mol}^{-1}$$

Areothermal flux (the Martian analog of geothermal flux on Earth) is estimated as $\sim 0.030 \text{ W m}^{-2}$.

- (i) [3] Does vertical heat transfer within the ice cap occur predominantly through advection or diffusion? Support your answer quantitatively using a Péclet number.
- (ii) [2] Based on your answer to (i), estimate the basal temperature for the ice cap. Is melting likely at present, assuming that the pressure melting point is approx. -1°C at the base of 3 km of ice, in Martian gravity?

6. Ice-core geochemistry

- (a) [2] Define $\delta^{18}\text{O}$, explaining the meaning of all terms.
- (b) [3] What climatic variables affect $\delta^{18}\text{O}$ of H_2O in ice cores, and why?
- (c) [3] What environmental changes affect $\delta^{18}\text{O}$ in foraminifera in ocean sediments, and why?
- (d) [2] $\delta^{18}\text{O}$ can be measured not only for O in H_2O in the ice, but also for O in O_2 in the air bubbles in the ice.
 - How might this measurement be useful for paleoclimate research?

7. Ice-core geochemistry

- (a) [4] The ice-age/gas-age difference is the age of the ice when it traps bubbles of (younger) air. We know that this age depends on climate at the site. How would this age difference in Antarctica change during an ice age, relative to today, and why? Consider changes in snow temperature and accumulation rate.
- (b) [3] Explain the importance of nitrogen isotopes in determining the ice-age/gas-age difference at times when the climate warmed rapidly.

(c) [3] Some geochemical tracers found in ice cores exhibit seasonal variations in transport onto the ice sheets. Counting such detectable annual layers allows researchers to absolutely date ice cores in calendar years.

- Might you be able to detect annual layers by measuring dust concentrations in the ice? Give your reasons for why or why not.

8. Former glaciers

What *physical evidence* can an earth scientist use to:

- (a) [2] determine the *extent* of a former glacier along a longitudinal profile?
- (b) [3] determine the *thickness* of a former alpine glacier along a longitudinal profile?
- (c) [3] estimate the *ELA* of a former glacier?
- (d) [2] infer the *thermal regime* (*i.e.* warm-based or cold-based) of a former glacier?

Be sure to explain how the physical evidence relates to the question in each case.

9. Ice sheet – climate interactions

Explain why:

- (a) [3] climate warming has different effects on an ice sheet, depending on the season in which the warming occurs (give 3 reasons)
- (b) [2] as a large ice sheet grows, accumulation changes tend to act as a negative feedback on further growth.
- (c) [2] the ablation on an ice sheet increases roughly as the third power of the summertime temperature (in °C) at the terminus.
- (d) [3] Using your answers above, why might you expect that the ice-volume curve during ice ages would look like saw-tooth cycles?

10. Brine in sea ice

Sea ice is distinguished from freshwater ice by its inclusions of liquid brine. The salinity of the liquid in an individual brine pocket (S_b) varies between 35 parts per thousand (‰) and about 250 ‰. The salinity of a bulk sample of natural sea ice (S_i) typically varies between 0 ‰ and approximately 12 ‰, depending on ice thickness and age (multiyear v. first year).

- (a) [5] You have just sampled a core from young first-year ice, of thickness 0.5 m, in the middle of winter. The air temperature (T_a) is -25 C. You measure the temperature of the ice (T_i) at 5cm intervals along the core. Sketch a vertical profile of the approximate values of T_i you expect to record as a function of depth, between the ice surface and the ice-ocean interface. Also sketch the approximate profiles of S_i and S_b that you expect to measure over the length of the core. Indicate the approximate magnitudes of maximum and minimum temperatures and salinities.
- (b) [3] Indicate on your sketch where you would expect to find maximum and minimum values of brine volume (v_b). An approximation for brine volume from Frankenstein and Garner (1967) may be useful:

$$v_b = S_i \left(0.0532 - \frac{4.919}{T_i} \right),$$

where S_i is in ‰, T_i is in °C, and v_b is a percentage.

- (c) [2] What will likely happen to the profiles of T_i , S_i , and S_b once the summer sun begins to shine on the ice?

11. Ice albedo feedback

- a) [2] Qualitatively describe the ice-albedo feedback (IAF) mechanism.
 b) [1] Is it a positive or a negative feedback?
 c) [2] Would changes in ice thickness or ice extent be more likely to impact the IAF? Why?
 d) One approach to quantifying the IAF is through a “gain ratio” defined by

$$R_T = (T_2 - T_1) / (T_3 - T_1),$$

where T represents surface temperatures predicted with a climate model. T_1 is the temperature resulting from a model run representing current climate conditions. T_2 is the temperature resulting from a model run with some external perturbation (like a $+5 \text{ W/m}^2$ increase in surface longwave flux) where all feedbacks are operative. T_3 is the temperature resulting from a simulation where the climate is subject to the same external perturbation and the IAF mechanism is switched off by keeping the surface albedo fixed in the perturbed run to the same values used in the baseline simulation. The following table gives annual averaged surface temperatures (T) and ice thicknesses (h) for three such model runs.

Type of simulation	Temperature	Ice Thickness
baseline simulation	$T_1 = -16.31 \text{ }^\circ\text{C}$	$h_1 = 3.18 \text{ m}$
$+5 \text{ W/m}^2$ flux with IAF	$T_2 = -15.76 \text{ }^\circ\text{C}$	$h_2 = 2.50 \text{ m}$
$+5 \text{ W/m}^2$ flux with no IAF	$T_3 = -15.90 \text{ }^\circ\text{C}$	$h_3 = 2.96 \text{ m}$

- (1) [1] Calculate the gain ratio R_T .
 (2) [1] A gain ratio R_h can also be defined for ice thickness (h) in an analogous manner. Evaluate R_h from the thickness data in the table.
 (3) [3] If the ice surface is typically melting during the summer, would you estimate R_T or R_h to be more sensitive to summer ice conditions? Why? Which gain ratio should be more sensitive to winter ice conditions? Why?

12. Glacial Geology

You are walking around near the front of a small mountain glacier, below the snout of the modern glacier, but just uphill of a prominent end moraine. You happen to walk into a stream gully which has eroded into the present surface, and you see a peat bog exposed in the gully wall, which is buried beneath a couple of meters of bouldery glacial till.

- a) You radiocarbon date some of the peat and find out that it has an age of 4,000 years before present (calendar years, after correcting for ^{14}C calibration). What was happening to the glacier 4,000 years ago, and what does that tell you about the local climate then?
 b) You then get an exposure age from a boulder on the surface of the moraine of 3,000 years B.P. What must have been happening to the local climate 3,000 years ago?
 c) Can you say anything about the mean annual air temperature either 3,000 or 4,000 years ago from this information? Why or why not?