Subglacial Heatflow Measurements in Greenland and Antarctica

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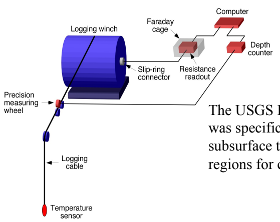
1. OUTLINE:

Heat flux into the basal ice is readily estimated from the basal temperature gradient in an ice sheet. However, basal melting (e.g. at NGRIP, Greenland) or basal freezing (e.g. at BYRD Station, Antarctica) introduces a local energy sink or source, so that basal gradients in the ice at those ice-core sites provide poor proxies for tectonic geothermal flux. Large glacial-interglacial temperature swings can also cause the heat flux into the basal ice today to differ substantially from its long-term average.

Estimates of long-term or tectonic geothermal flux can be derived from temperature profiles $T(z)$ in boreholes in polar ice sheets by solving a geophysical inverse problem to simultaneously obtain estimates of surface temperature history $T_s(t)$ and geothermal flux q_{geo}. The forward algorithm is a transient thermal model that uses $T_s(t)$ and q_{geo} to produce estimates of the modern temperature-depth profile. The associated inverse algorithm selects the $T_s(t)$ and q_{geo} with which the forward model results most appropriately match the observed profile $T(z)$.

Because Taylor Dome and Siple Dome are close to ice divides, and are thought to have undergone little thickness change in the Holocene, we used a 1-D ice-flow/heat flow model with constant ice thickness for the forward algorithm. Uncertainties in vertical advection contribute the largest source of uncertainty in geothermal flux.

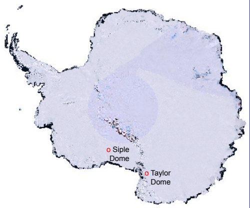
2. USGS POLAR TEMPERATURE LOGGING SYSTEM



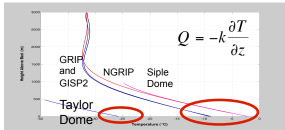
The USGS Polar Temperature Logging System (PTLS) was specifically designed to acquire high-quality subsurface temperature measurements in the polar regions for climate-change detection. (See Ref [1].)

Using a custom parallel-series network of hermetically sealed NTC thermistors for the sensor, the PTLS can measure temperatures as low as -60°C with a sensitivity ranging from 0.02 to 0.19 mK. A modular design allows the PTLS to reach depths as great as 4.5 km with a skid-mounted winch unit or 650 m with a small helicopter-transportable winch unit. Considerable attention has been devoted to electrically isolating the measuring circuit from various sources of noise. In addition, the resistance-measuring circuitry is held at 23±0.5°C during a temperature log to help maintain its calibration. As a result, the standard uncertainty of the ITS-90 temperature measurements obtained with the current PTLS ranges 3.0-3.3 mK for temperatures below 0°C. Under favorable logging conditions, the standard uncertainty of the sensor location (depth) measurements is on the order of 200-250 ppm.

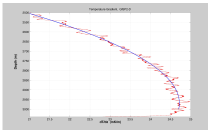
3. HEAT FLOW SITES IN GREENLAND AND ANTARCTICA



4. CURRENT FLUX INTO BASAL ICE FROM TEMPERATURE GRADIENTS



Care is needed to infer gradient
- Convection cells in large-radius core holes
- Heat refraction at bottom of hole



Results

	Site	dT/dz	q
		mK m-1	mW m-2
Greenland	GISP2-D	24.7	54.0
	GRIP-D	27.0	58.7
	NGRIP-2	31.5	67.3 *
Antarctica	TD-D	32.3	77.5
	SDM-A	31.2	65.5

* Hole stopped 91 m above bed when logged

5. INVERSE PROBLEM: Steady heat flow deep in the Earth

Good news:
- Ice has more uniform thermal properties than other rocks

Bad news:
- Ice flow adds advection term to heat equation.
- Ice-age climate transients can influence heat flow at great depths.

$$\rho c\left(\frac{\partial T}{\partial t} + v\frac{\partial T}{\partial z}\right) = \frac{\partial}{\partial z}\left(k(z)\frac{\partial T}{\partial z}\right)$$

Forward algorithm

Domain: 1D, from surface $S(t)$ to deep in bed.
For $\tau = 10^5$ years, $\kappa = k/\rho c$,
$H_{char} = (\kappa\tau)^{1/2} \approx 2$ km
Initial Condition: $T(z, t_0)$
Boundary conditions: $T_s(t)$, q_{geo}

Inverse algorithm

Adjust $T_s(t)$ and q_{geo} and accept combination that produces acceptable fit to measurements $T(z)$.

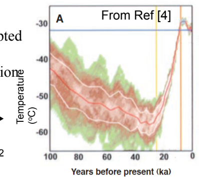
Approaches

(1) Monte Carlo

e.g. Ref [4]
- Statistics of accepted models define temperature solution

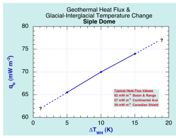
$T_s(t)$ ⟶

q_{geo} = 51.2 mW m-2

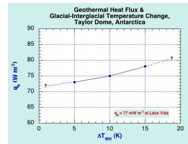


(2) Spectral Decomposition

- $T_s(t)$ inferred for range of assumed q_{geo}
- We accept only q_{geo} values that produce deglaciation temperature change in range 5°C to 15°C.



Siple Dome



Taylor Dome

Results

	Site	q_{geo}	Notes
		mW m-2	
Greenland	GISP2-D	--	
	GRIP-D	51.3	Ref [4]
	NGRIP	--	Basal melt
Antarctica	TD-D	75±5	
	SDM-A	70±4	

6. FUTURE HOLES AND MEASUREMENTS

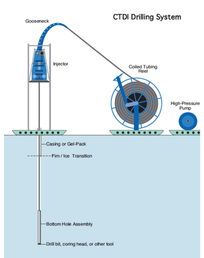
Not enough ice-core holes to sample wide variability in q_{geo} over short spatial scales.
- Rift zones (e.g. West Antarctica)
- Subglacial volcanoes
- Geological boundaries

Proposed Solution

CTDI (Coiled Tubing Drill for Ice)
- Cutters driven hydraulically by antifreeze
- Chips floated up outer annulus
- Deep holes in days, not years
- No core recovered
- Lower cost than ice coring.

- Minimal thermal disturbance.
- Holes remain open for logging
- Holes remain open for instrument recovery.
- Uniform diameter is good for tilt and sonic-velocity measurements

- Beyond heatflow measurements, tool would be community resource for subglacial sampling of rocks, sediments, biology.



From Ref [2].

References:

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