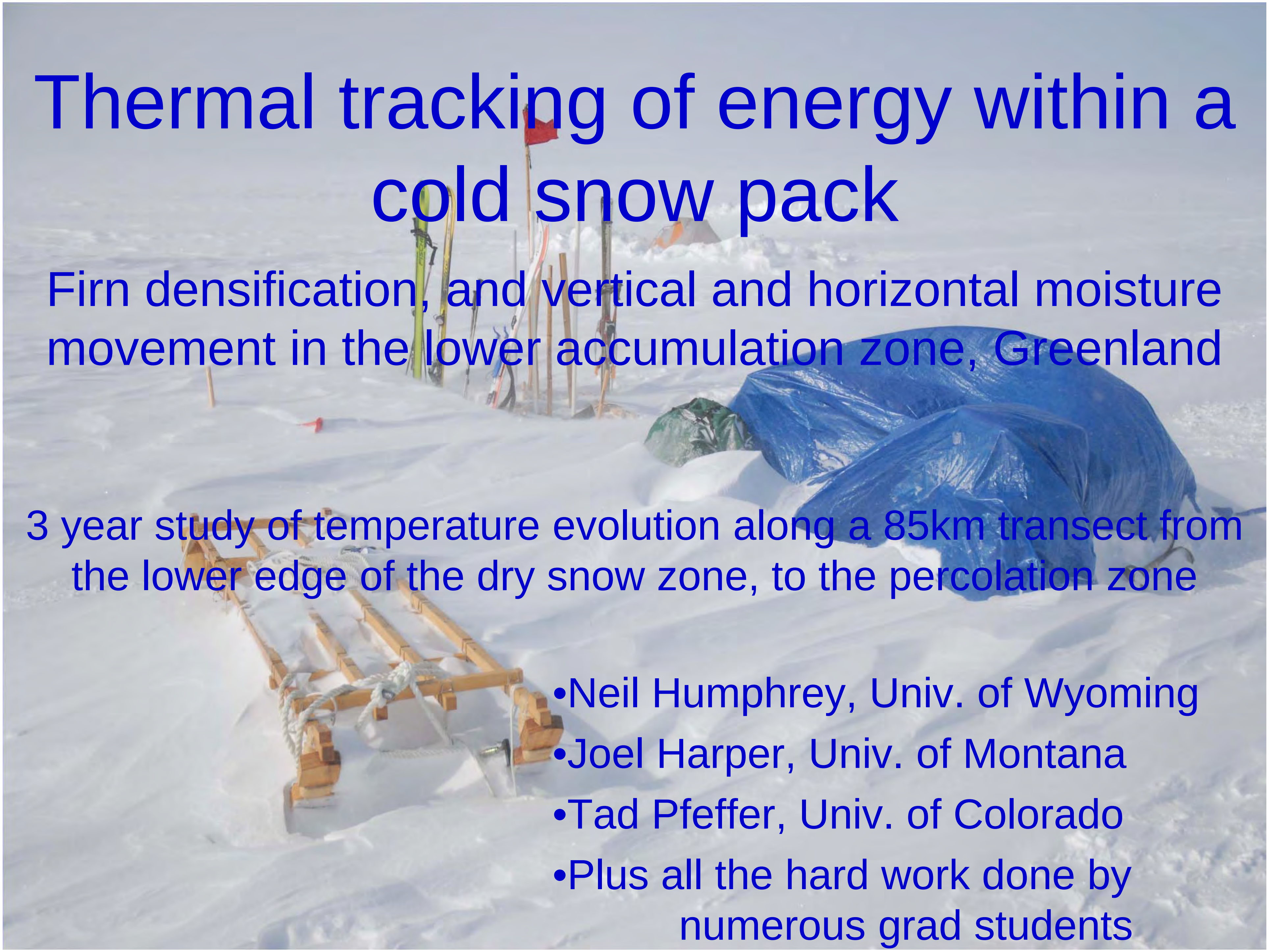


Thermal tracking of energy within a cold snow pack

Firn densification, and vertical and horizontal moisture movement in the lower accumulation zone, Greenland

3 year study of temperature evolution along a 85km transect from the lower edge of the dry snow zone, to the percolation zone

- Neil Humphrey, Univ. of Wyoming
- Joel Harper, Univ. of Montana
- Tad Pfeffer, Univ. of Colorado
- Plus all the hard work done by numerous grad students

A fundamental problem with estimating the response of an ice mass to a change in climate is to understand the energy transfer and the storage of phase-change energy in the percolation zone

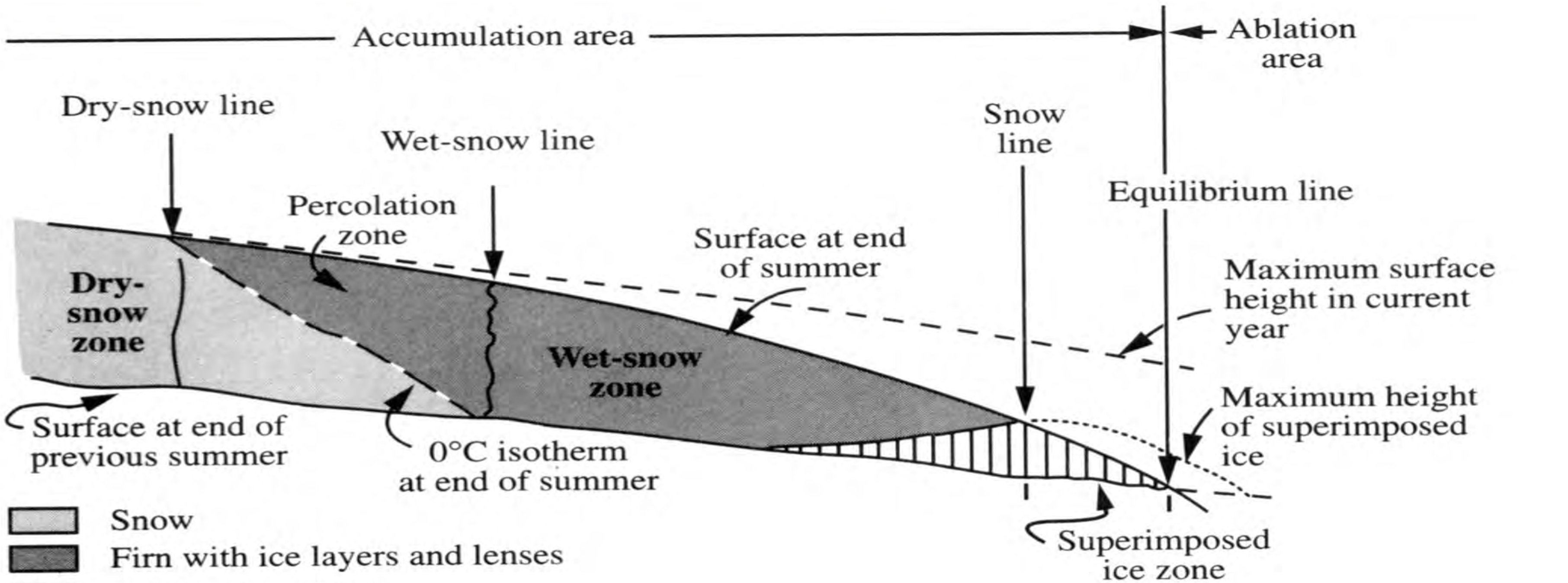
- This zone spans the colder region where all melt refreezes by percolating downwards, and lower (warmer) zones where melt water is able to run-off horizontally (the runoff-limit).
- It is only below the run-off limit that water is available to modify ice dynamics and sliding.
- The initial response of a warming climate tends to be a densification of the snow pack, not a marked increase in runoff area.

Purpose of study:

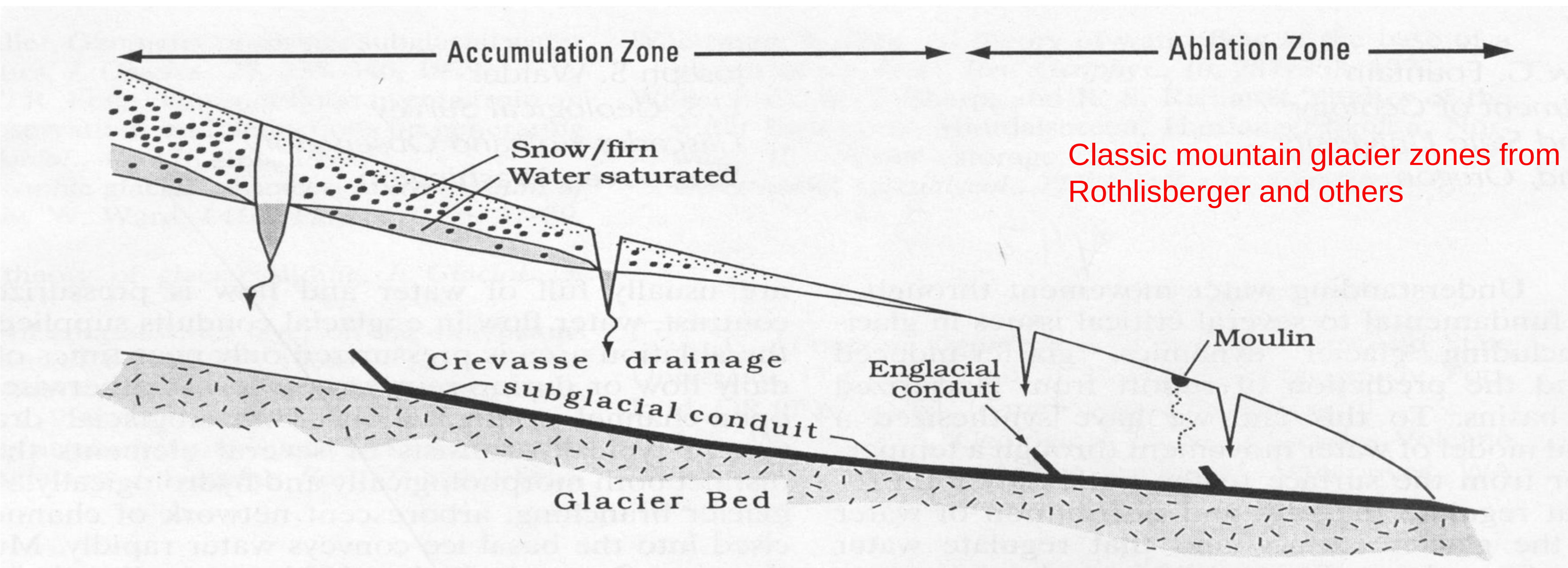
Meta-question, predict the evolution of a cold snow pack under a warming climate

Practical question, find out what happens to the melt generated at the surface, where does it lead to densification, where to runoff?

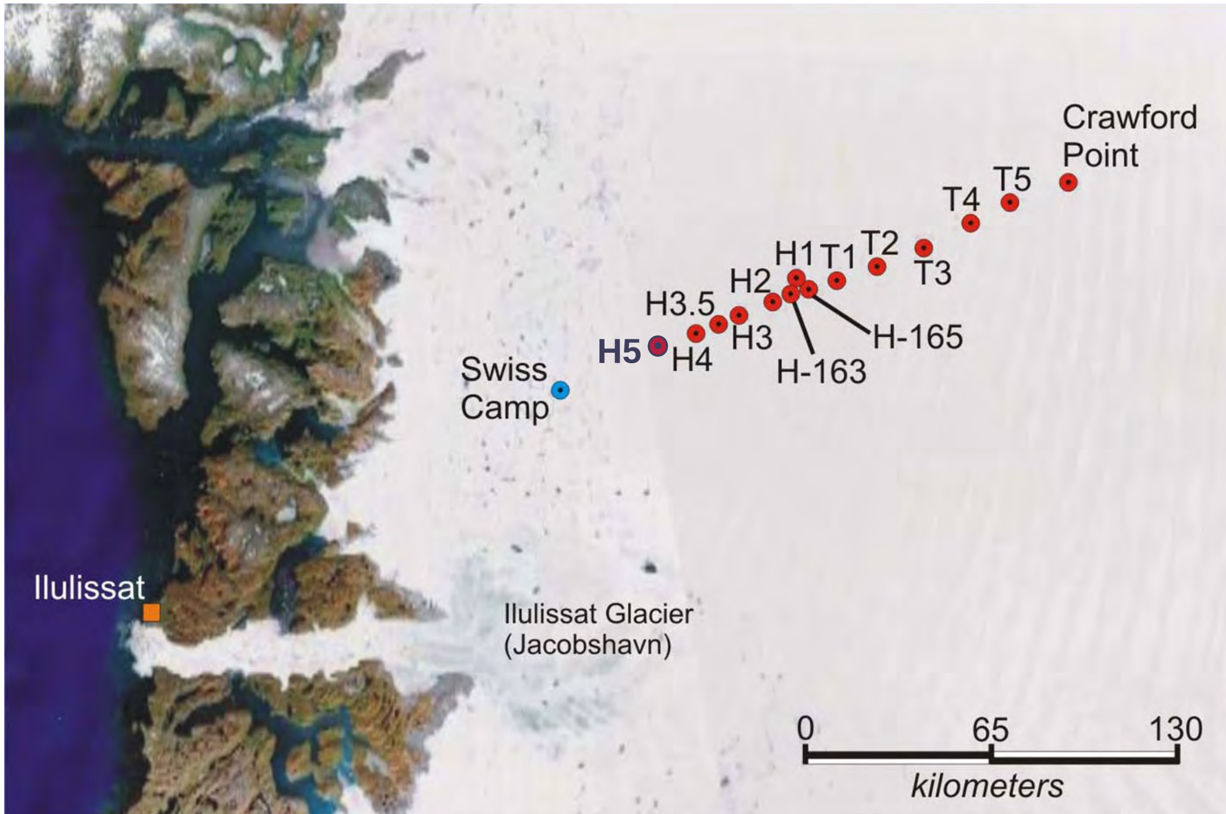
Basic science question, increase our understanding of the advection of energy by moisture and water motion within a cold snowpack

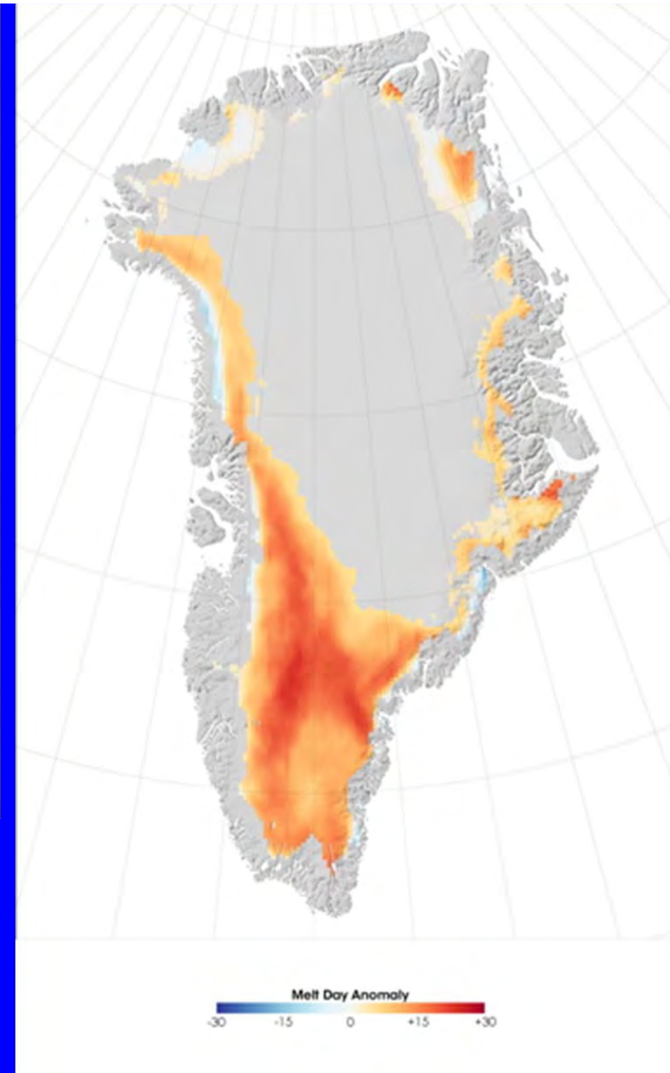


Classic icesheet zones from Benson



Classic mountain glacier zones from Rothlisberger and others

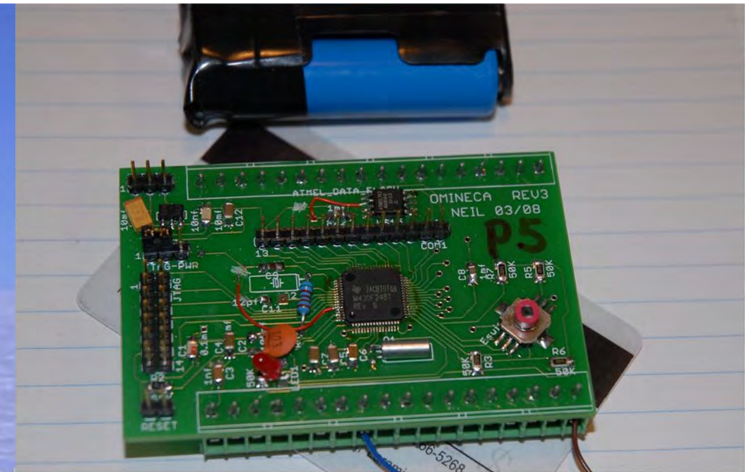


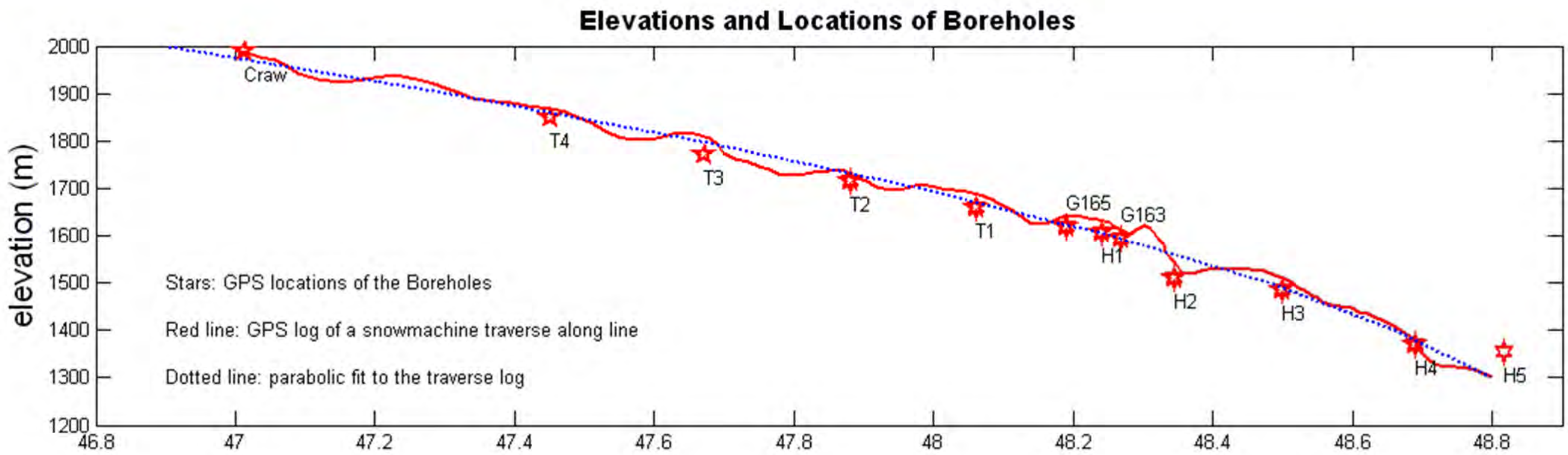


Three traverses, 2007-09

15 sites, some with multiple boreholes.
Each site has as a minimum:
- 10m temperature profile (32 thermistors)
  continuous monitoring/recording.
- Density/stratigraphy profiles.
- GPR survey, coupled to GPR traverse

This talk will focus on the temperature string data

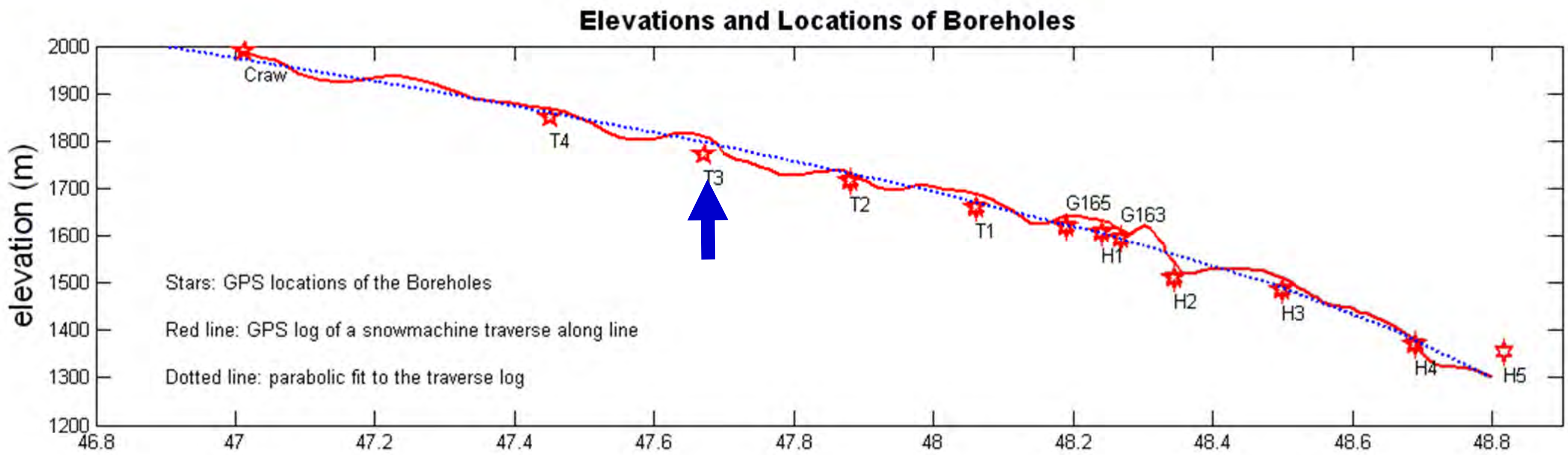

OMINECA REV3
NEIL 03/08
P5
RESET



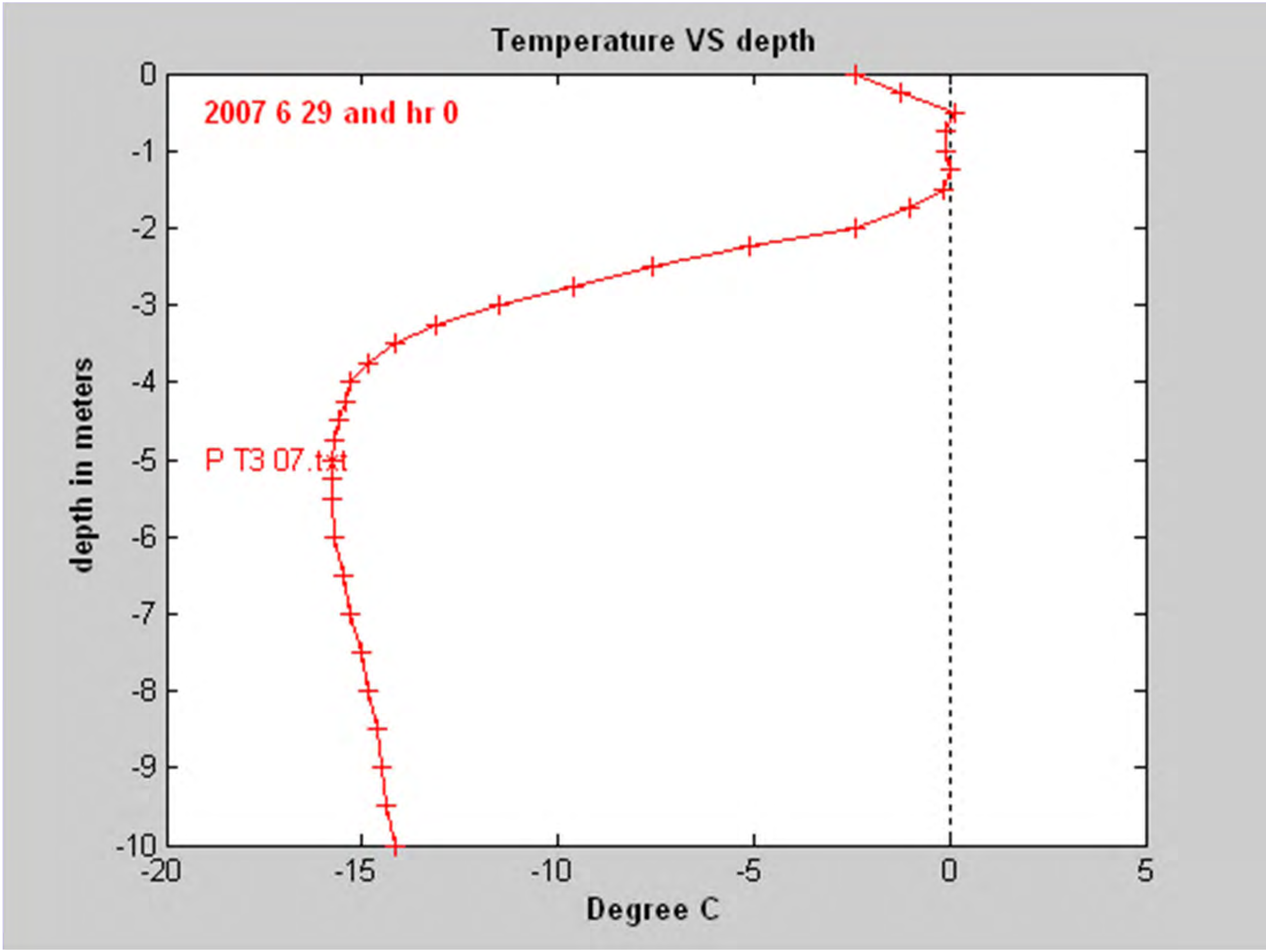
Profile of traverse, showing sites of 10m thermal data

4 main points:

- Thermal monitoring yields a detailed and quantitative view of moisture movement in this zone
- Piping carries melt water to great depths, leaving the bulk of the snow pack cold
- Water pools and flows in the snow pack, beneath cold snow, and persists from year to year
- The thermal structure of the snow can quantify net melt

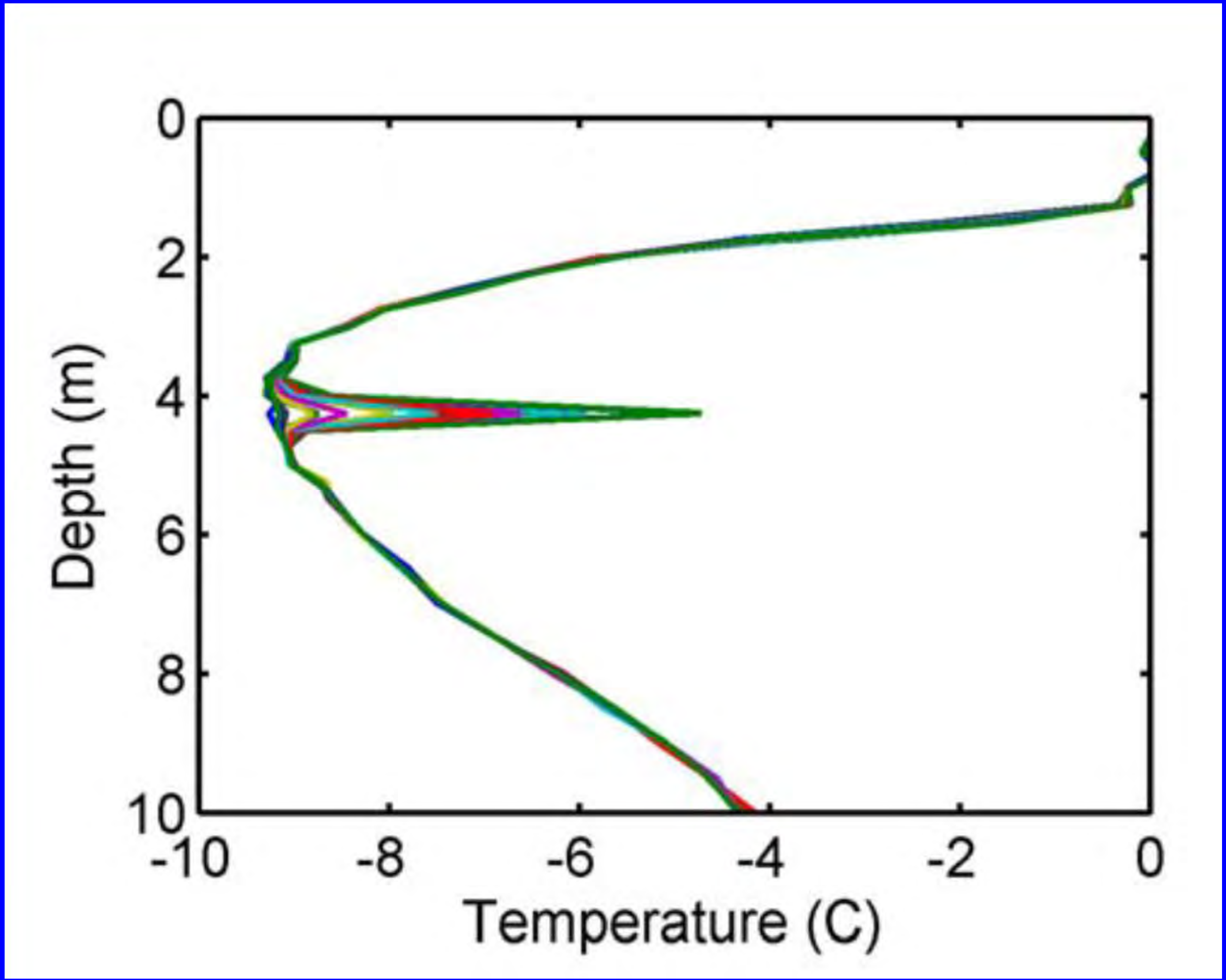


Profile of traverse, showing sites of 10m thermal data

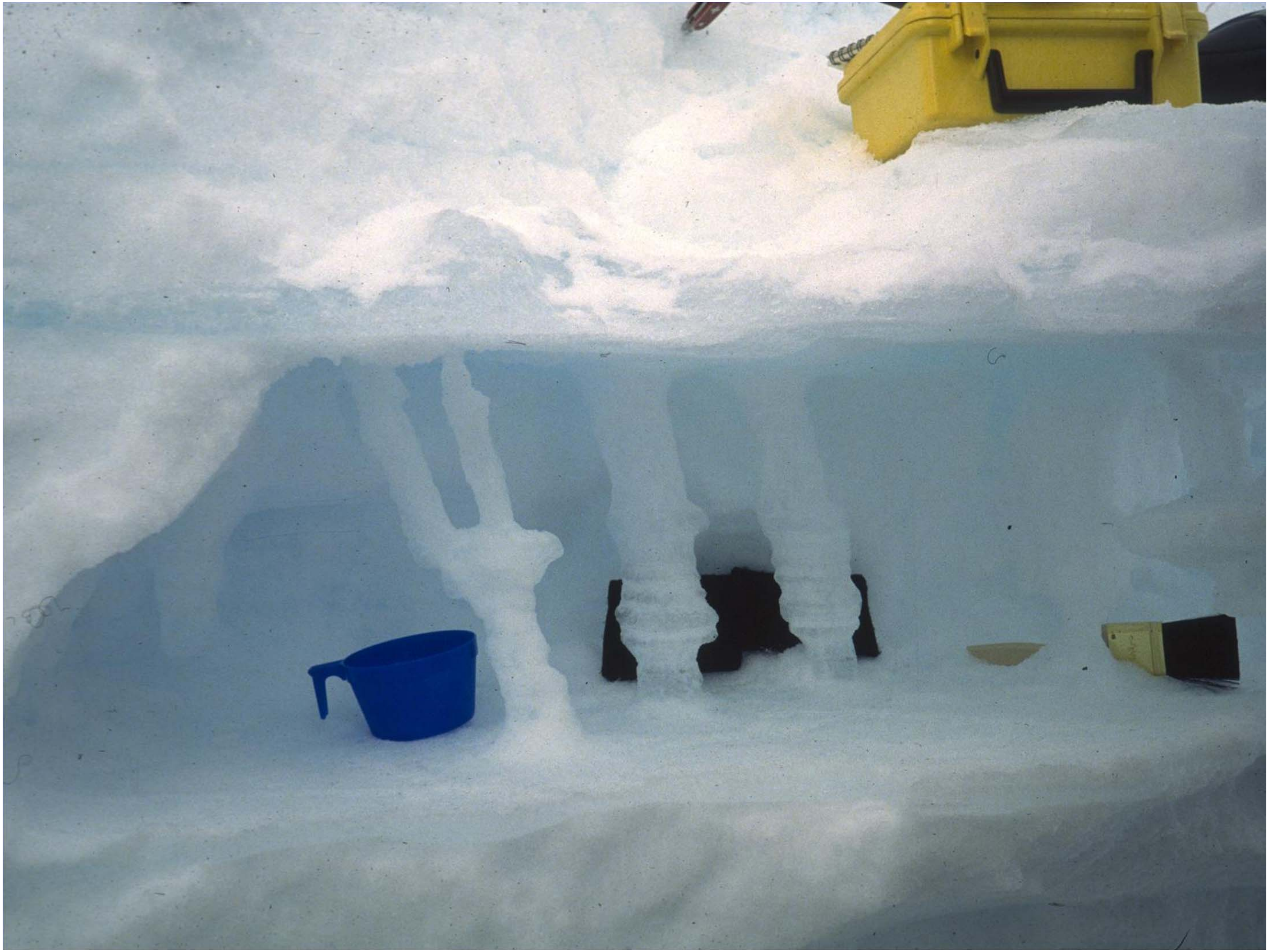

Temperature VS depth
2007 6 29 and hr 0
P T3 07.txt
depth in meters
Degree C
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
-10
-20
-15
-10
-5
0
5

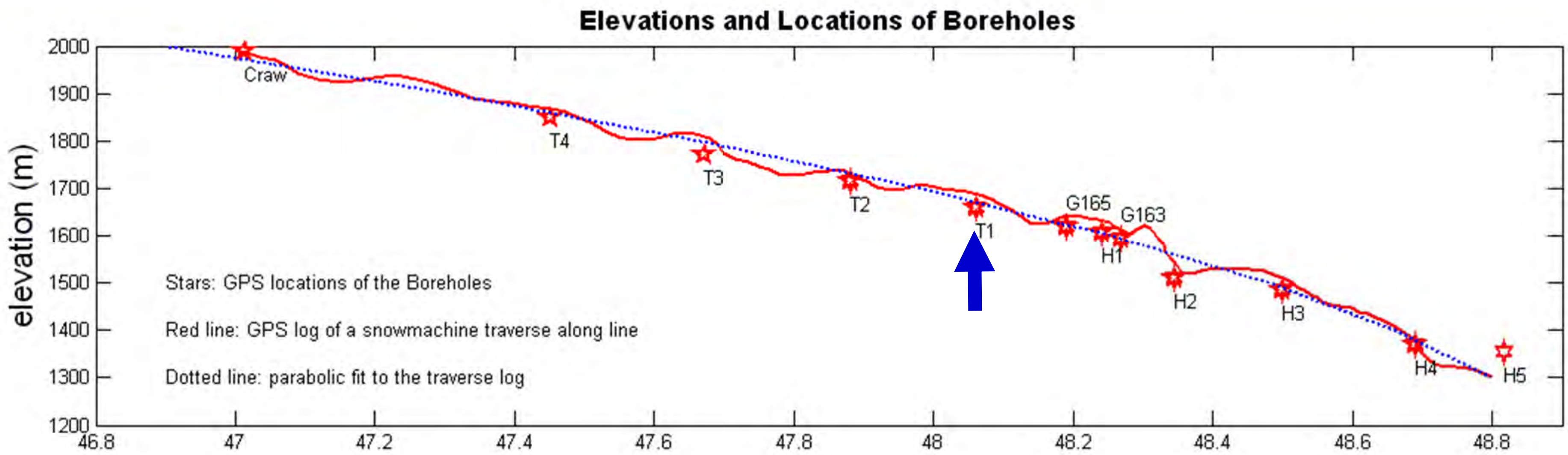
Detail of a piping event at H1

A 3 hour event



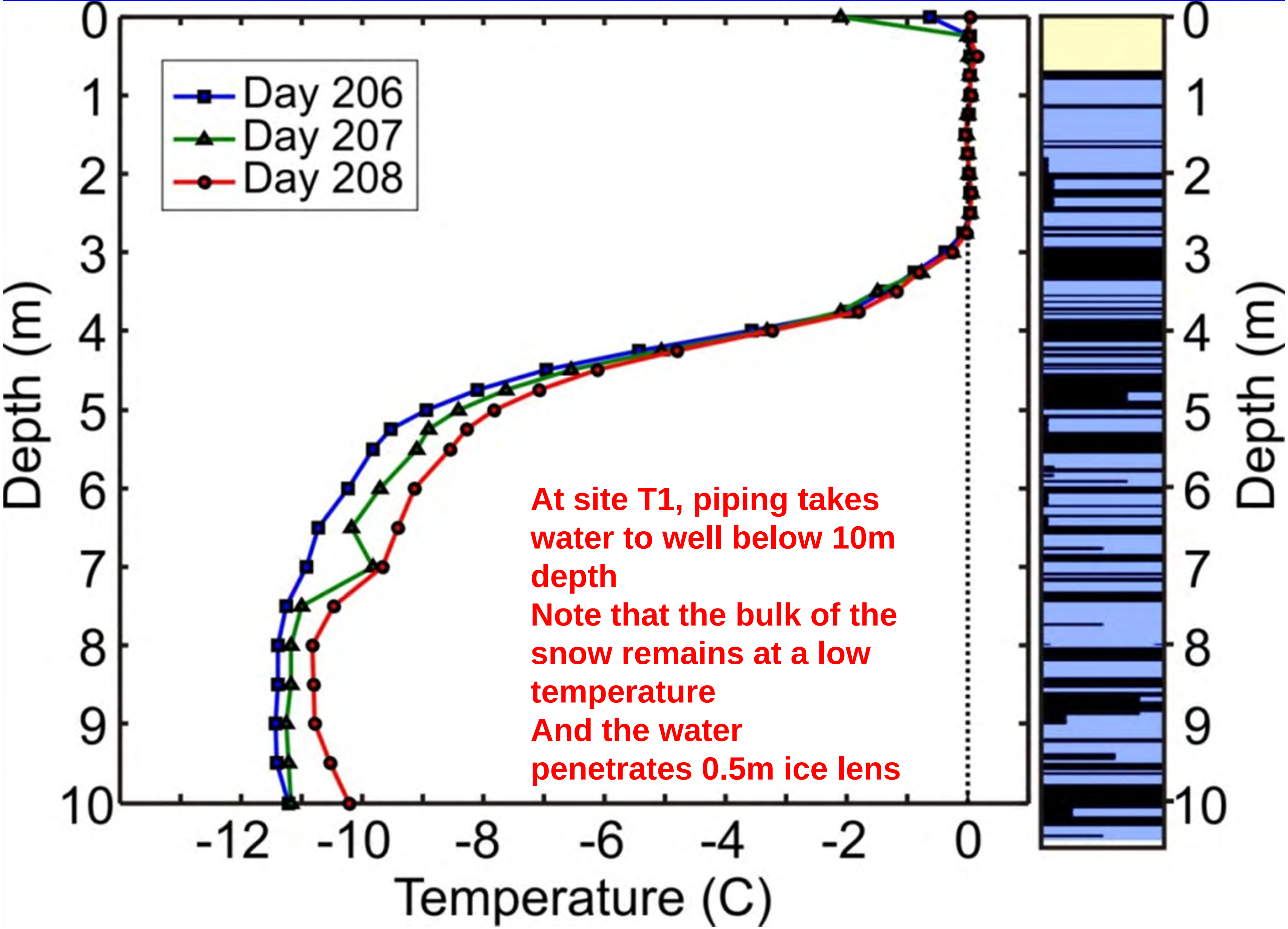

• Piping in the snow pack causes fingering of the heat advection downward into discontinuous annular disks
Deep lens of refreezing water



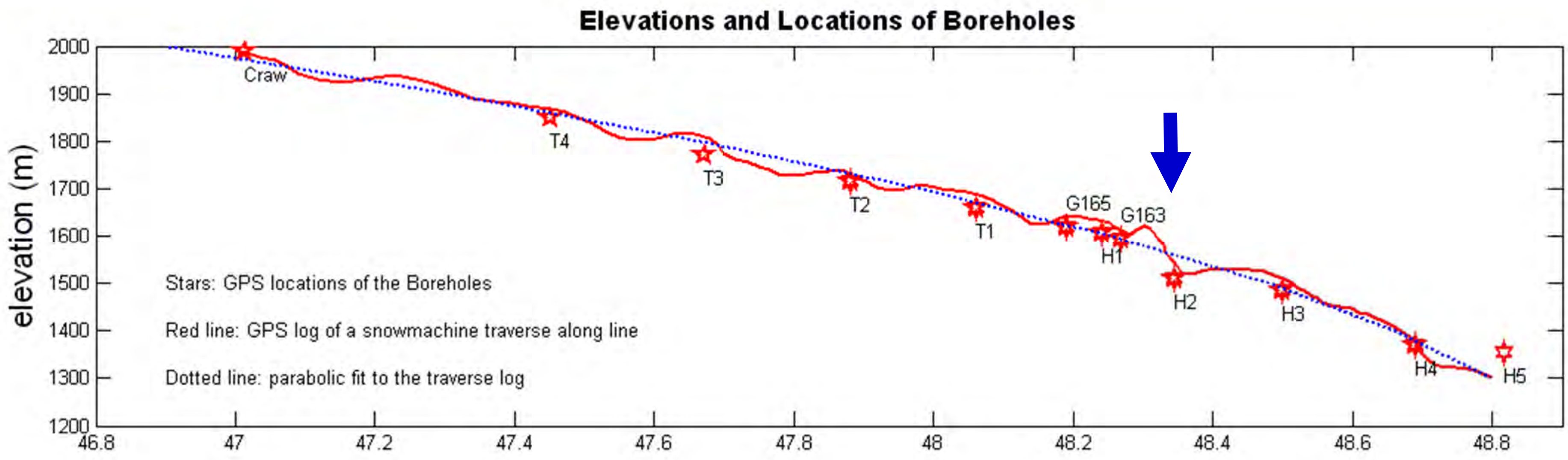


Profile of traverse, showing sites of 10m thermal data

Further down the traverse, piping occurs to large depths

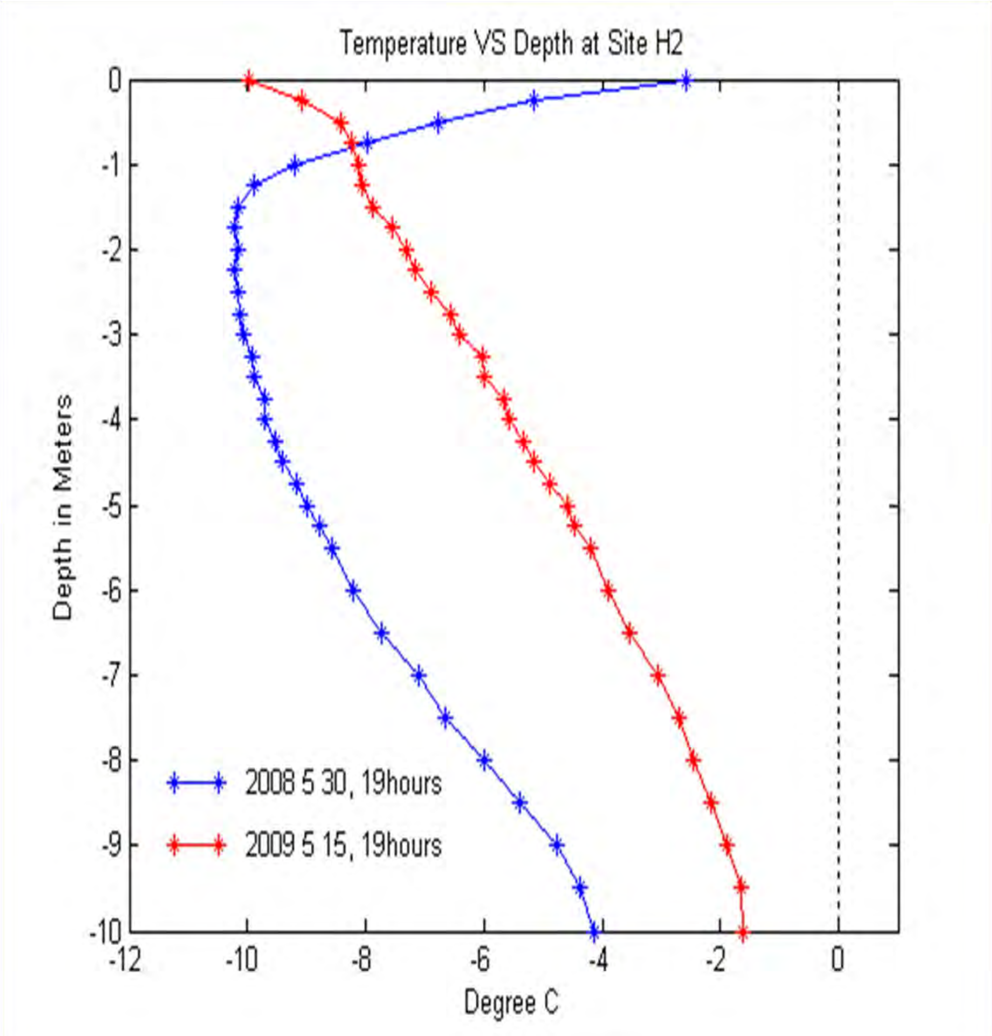


At site T1, piping takes water to well below 10m depth
Note that the bulk of the snow remains at a low temperature
And the water penetrates 0.5m ice lens

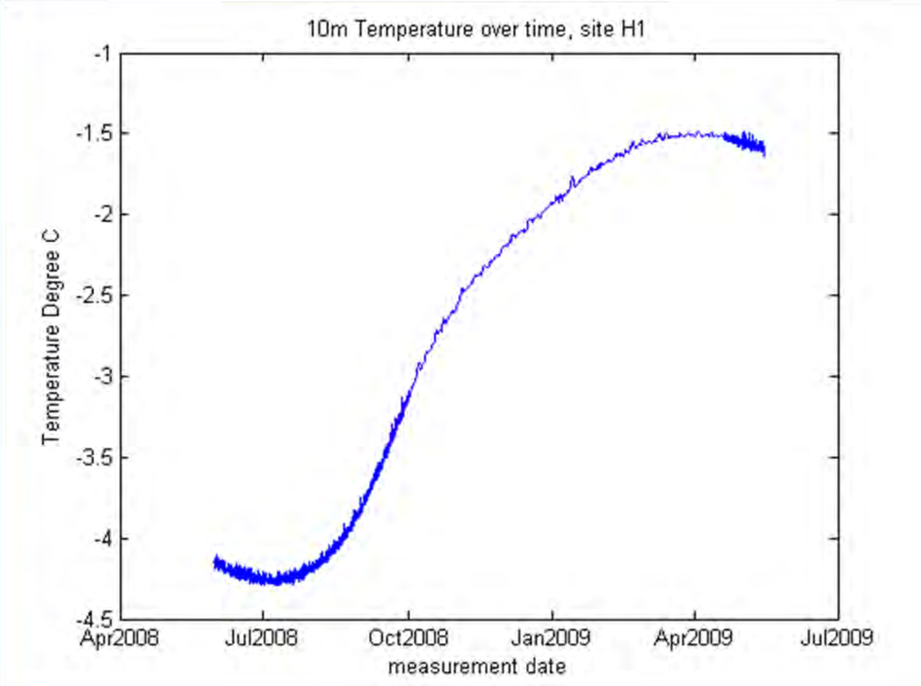


Profile of traverse, showing sites of 10m thermal data

At H2, massive ice layers 1-2m thick, inhibit vertical flow; water begins to flow horizontally, and pool at depth.



Temperature profile at H2, one year apart. Note the continuous heating from below

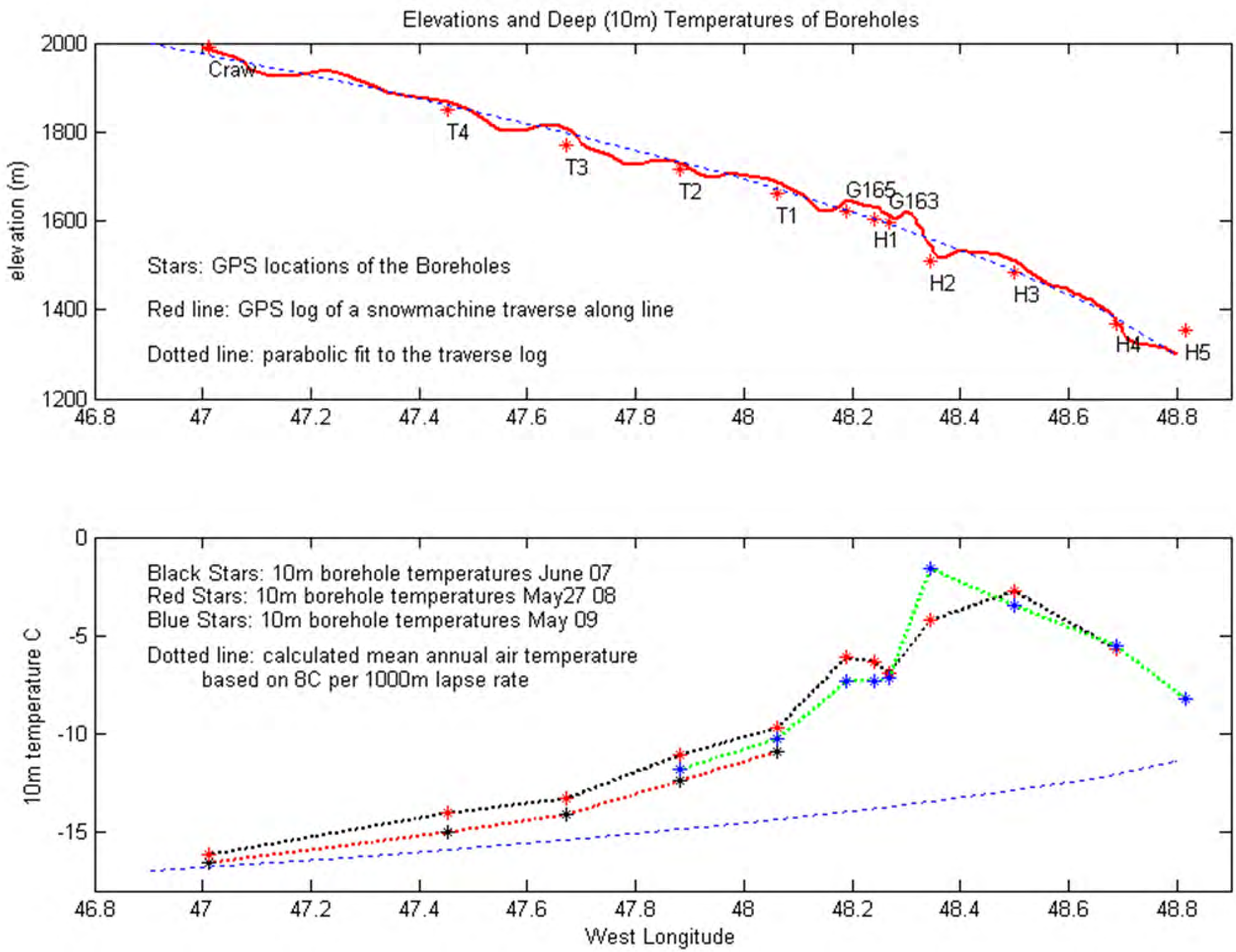


One year record of 10m temperature at H2

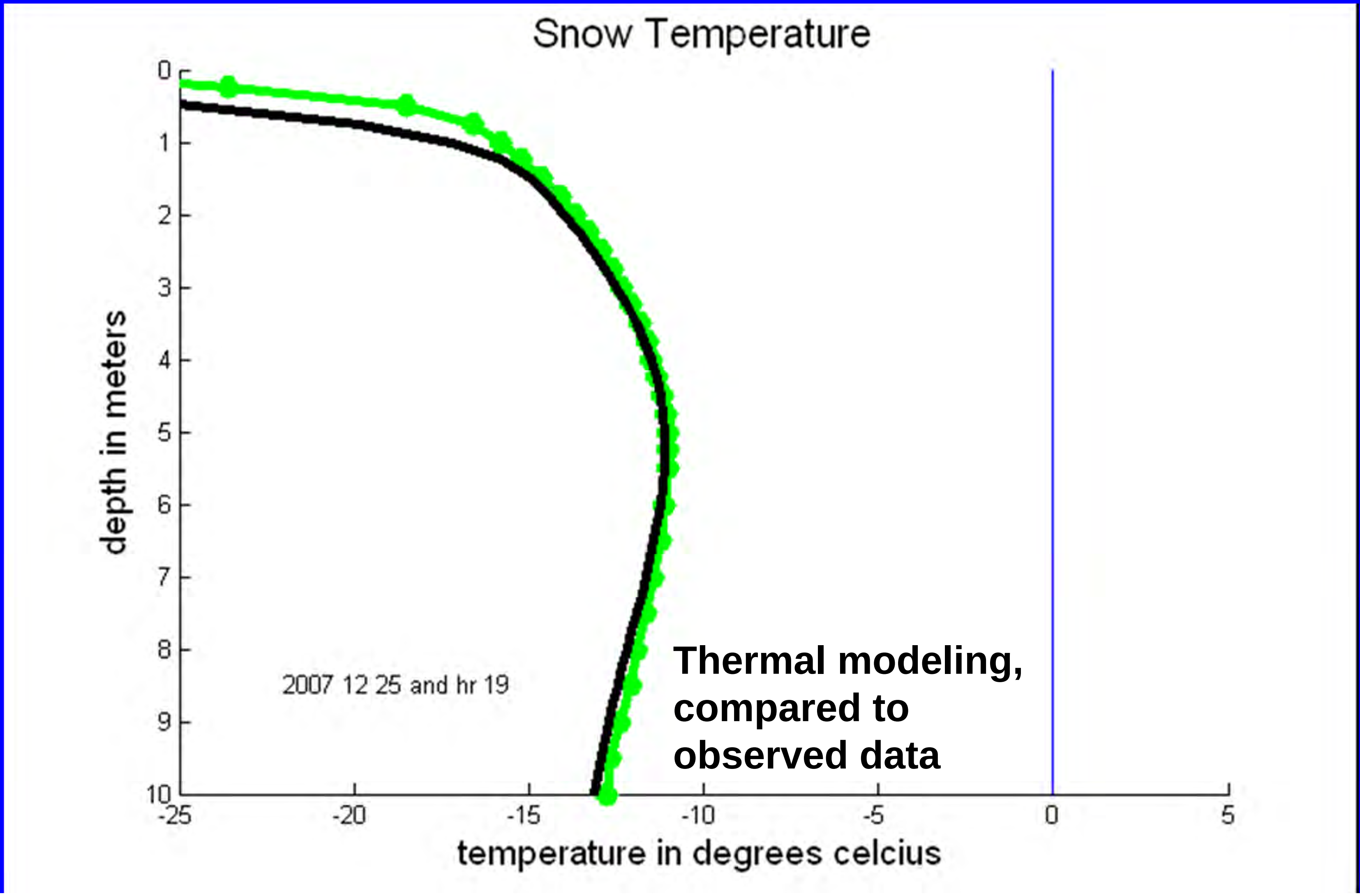

At this location (H2), there is free water moving downslope at depths of approximately 15m
The mean annual temperature is about -14C

Water/melt flow characteristics of lower accumulation region

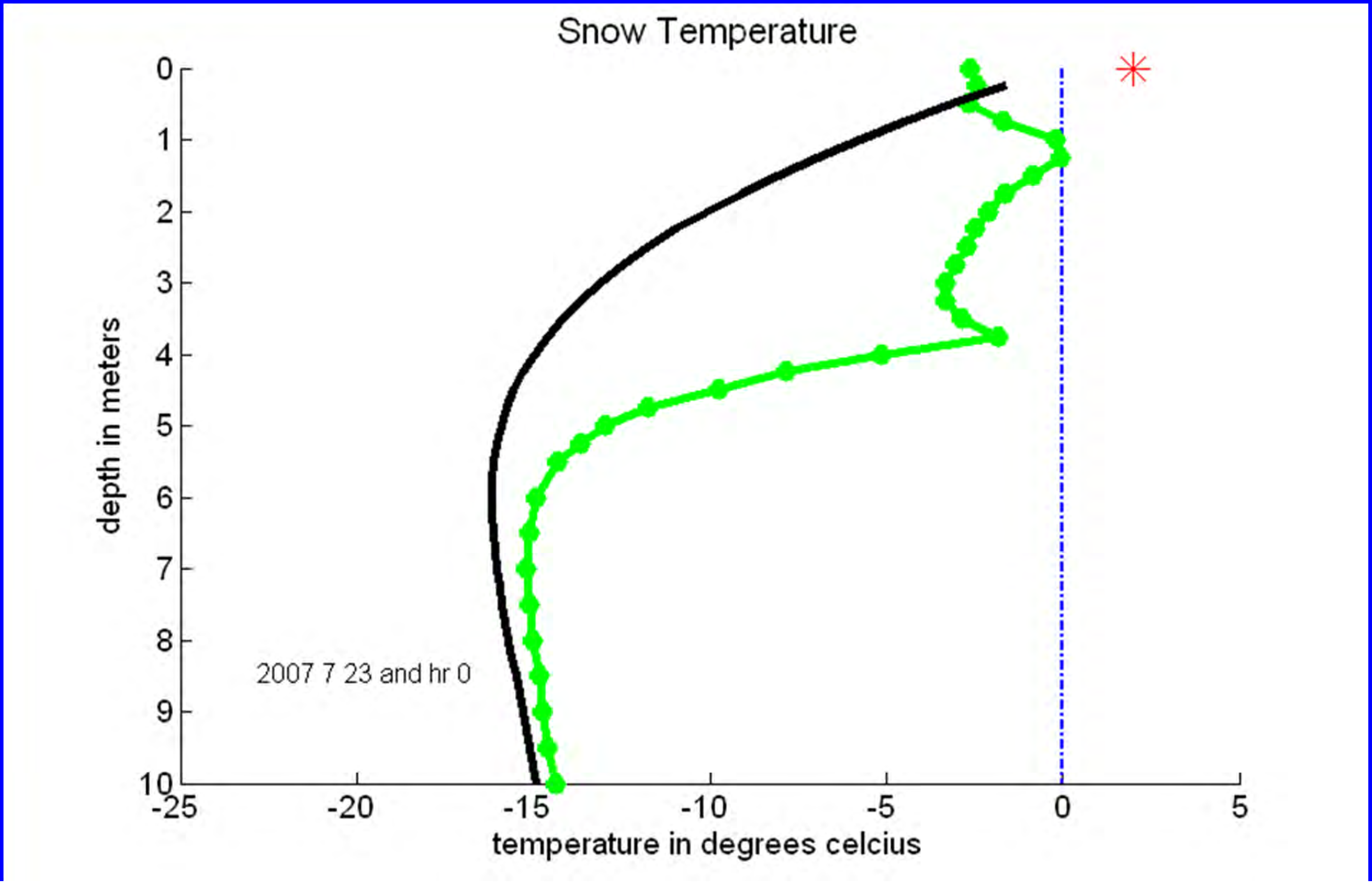
- The lower accumulation region is characterized by great heterogeneity generated by variability in the local weather, subtle topography and by the amplification of inherent variability in the snowpack by non-linear piping processes. The heterogeneity allows vertical water flow paths even in regions of intense ice layering.
- Piping carries water to great depths, through multiple years of snow accumulation, leaving the bulk of the snow cold above. Piping depths considerably deeper than 10m have been observed.
- The wet snow layer also descends through 1 or more years snow pack, but much shallower than the piping.
- Low in the zone sufficient water pools at depth to flow horizontally in-between ice layers, further densifying the snow. This water can remain unfrozen for much of the year.
- Even lower on the profile, water is pooling at shallower depths and eventually forms pingo structures that break to the surface.
- Below the pingo region, the snow uniformly approaches ice densities. Probably the snow pack behaves similarly to a mountain snowpack, including a shallow saturated snow layer that conducts water.


Elevations and Deep (10m) Temperatures of Boreholes
elevation (m)
2000
1800
1600
1400
1200
Craw
T4
T3
T2
T1
G165
G163
H1
H2
H3
H4
H5
Stars: GPS locations of the Boreholes
Red line: GPS log of a snowmachine traverse along line
Dotted line: parabolic fit to the traverse log
46.8
47
47.2
47.4
47.6
47.8
48
48.2
48.4
48.6
48.8
10m temperature C
0
-5
-10
-15
Black Stars: 10m borehole temperatures June 07
Red Stars: 10m borehole temperatures May27 08
Blue Stars: 10m borehole temperatures May 09
Dotted line: calculated mean annual air temperature
based on 8C per 1000m lapse rate
West Longitude

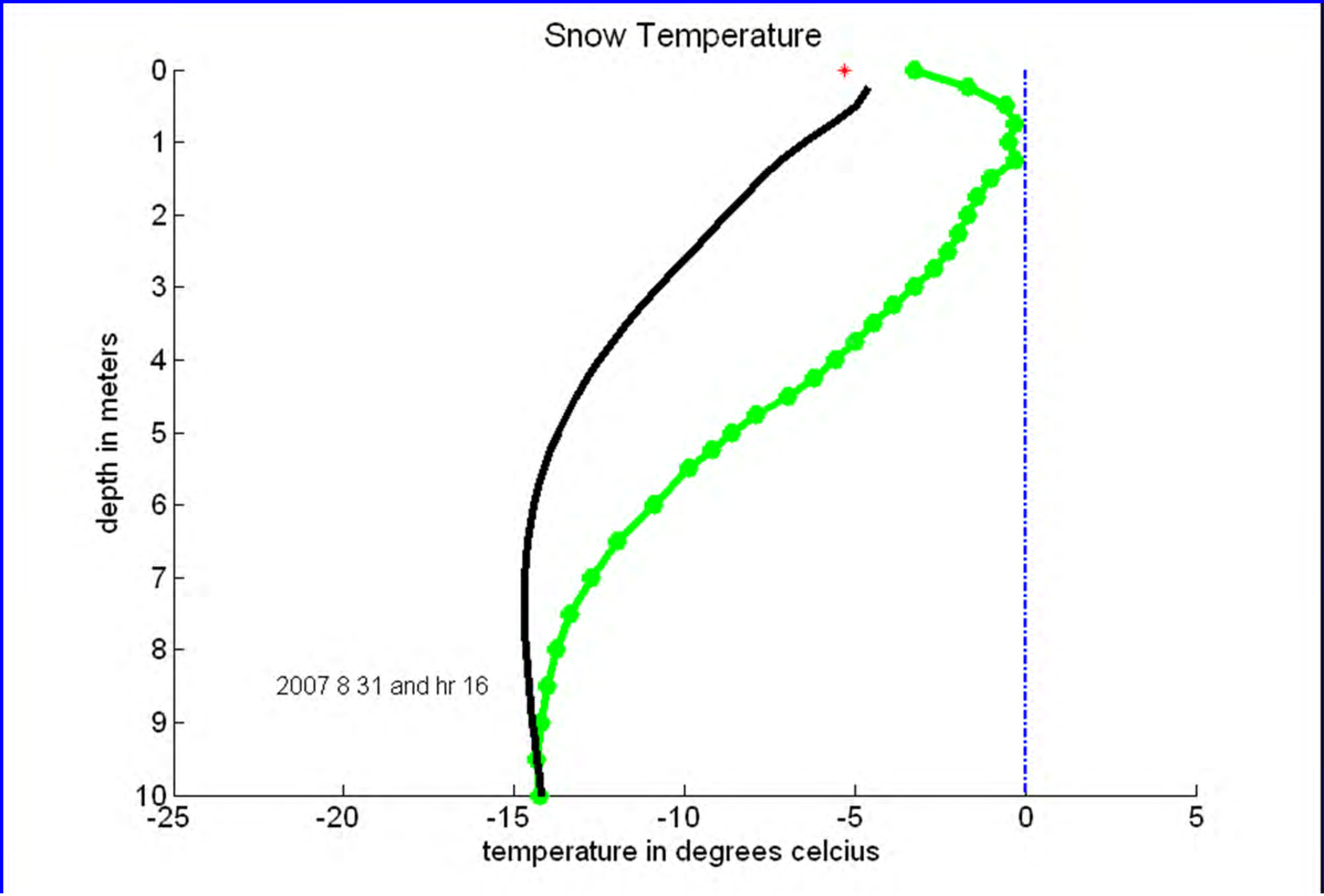
- When fingering and melt water infiltration is not occurring, and when the temperature field has settled, a conduction model reproduces the data reasonably well
- Black line is temperature field after 2 years of modeling



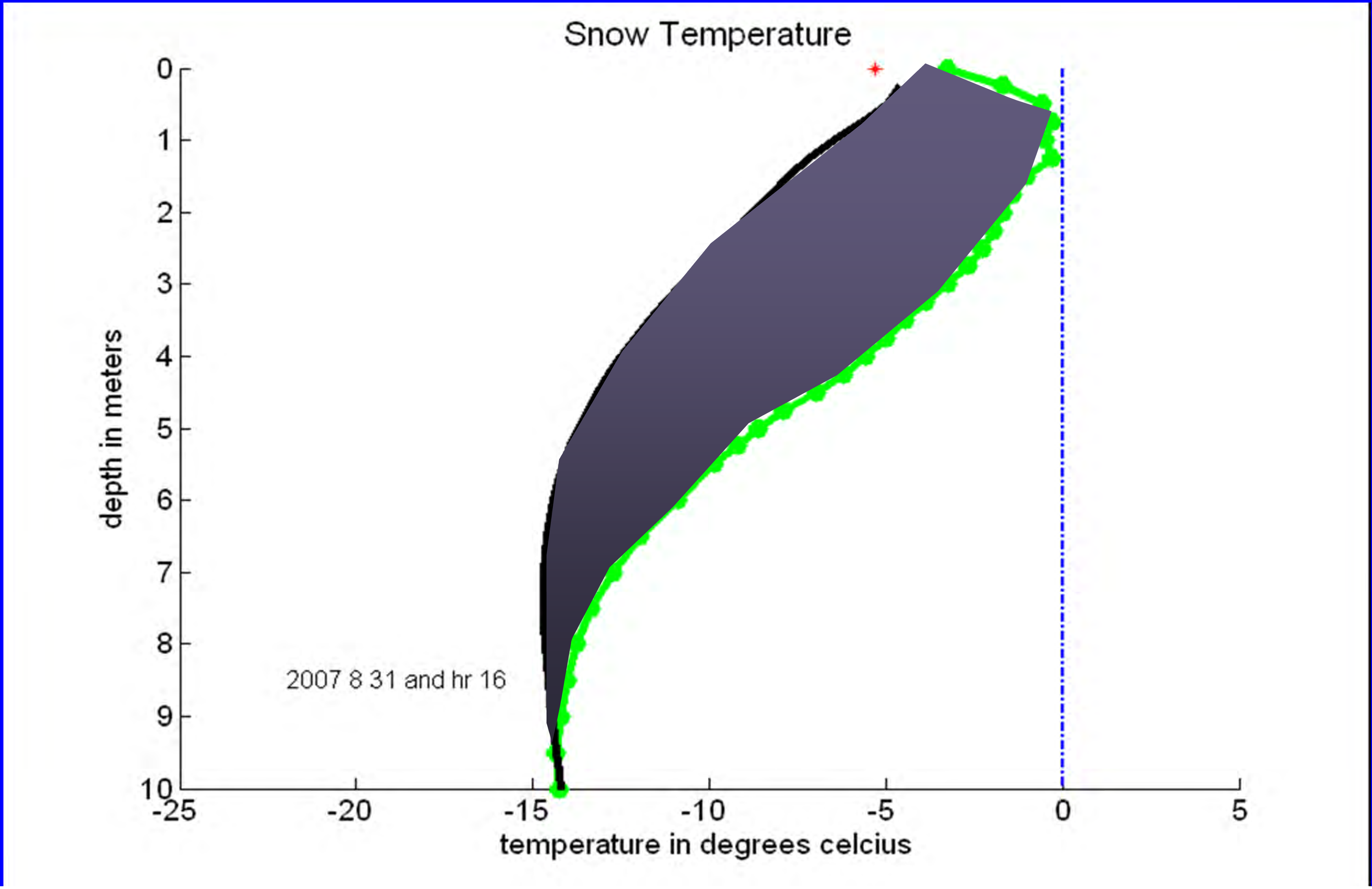
- Green: temperature data during a piping event
- Black: model results for pure conduction, with surface snow capped at 0 degrees
- Model surface heating uses recorded air temperature (red dot)

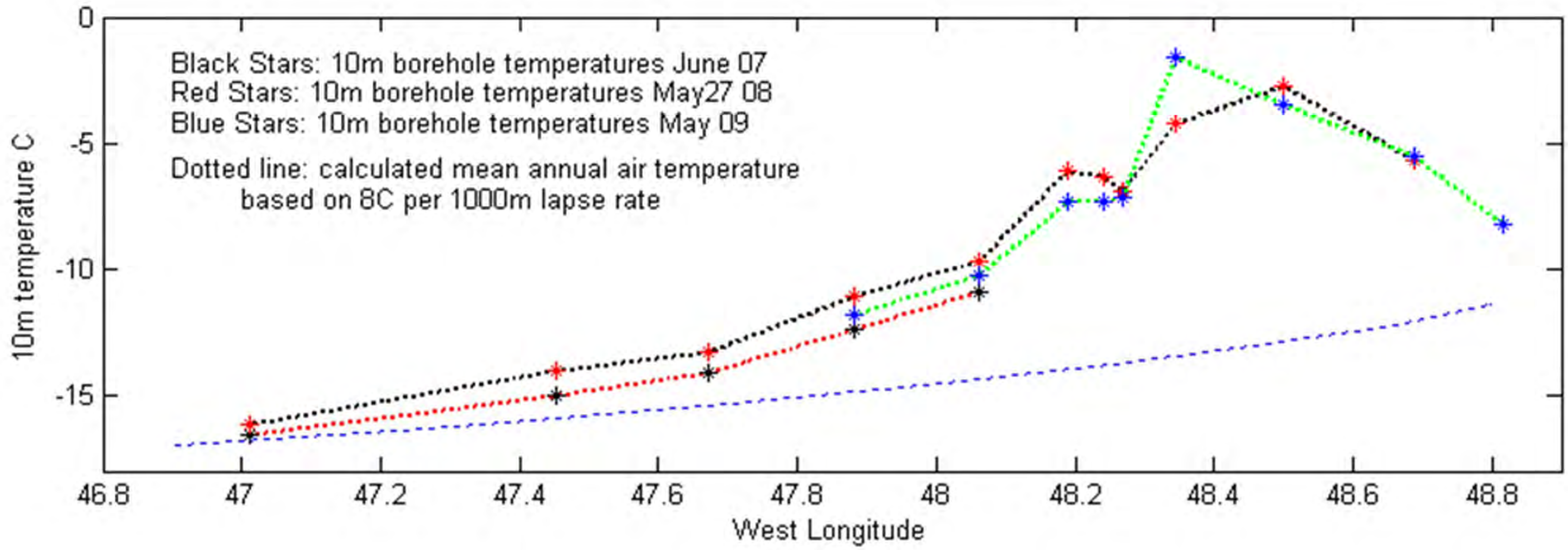


- Details of the melt water infiltration are complex
- However; it is possible to find the net melt (or more precisely, the net phase change energy added to the snow) by integrating between the curve of the data, and the model (no melt) curve



- **The shaded area represents a total of 0.2m of net melt water equivalent over the entire summer season descends into the snow column**
- **Considerable melt/refreezing occurs in the upper 0.5 meters from sensible heat losses and radiation cooling. However, this occurs on a much shorter time scale than the annual melt cycle.**





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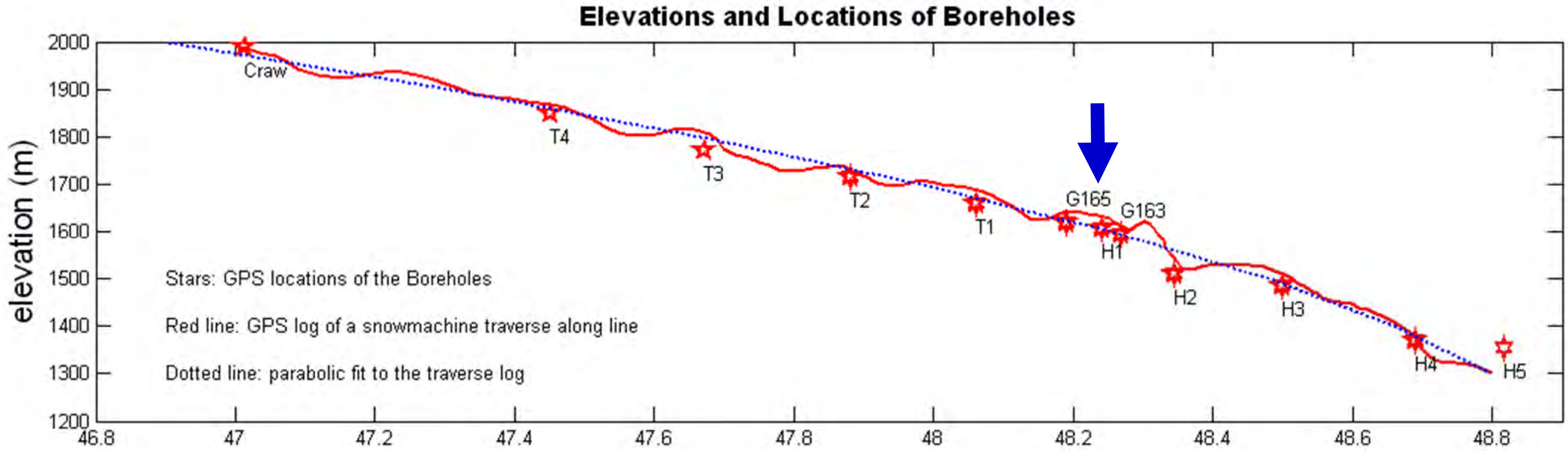
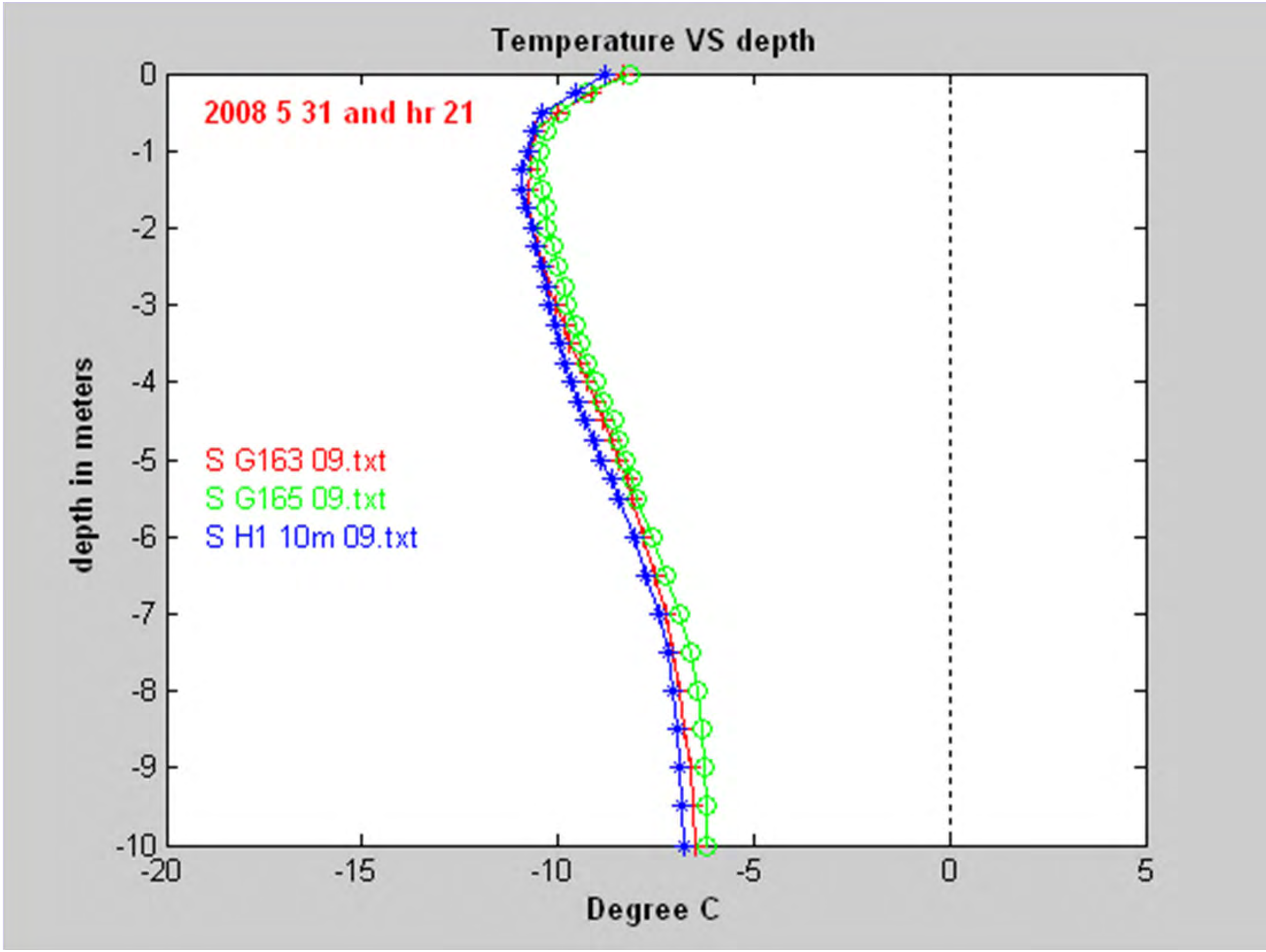
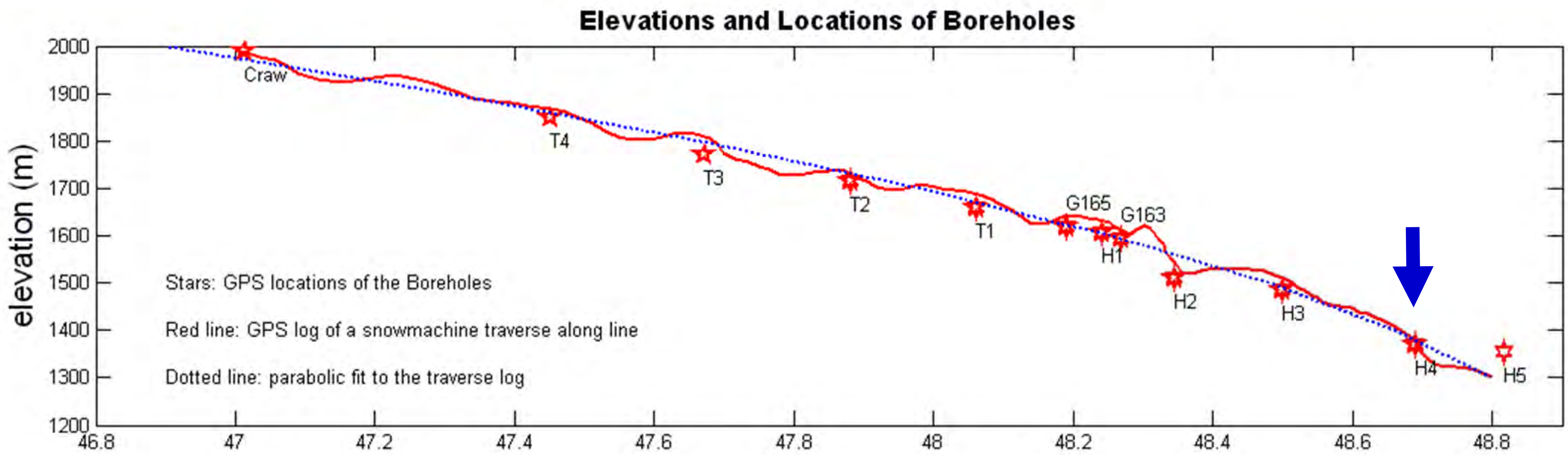
Thank you



Profile of traverse, showing sites of 10m thermal data

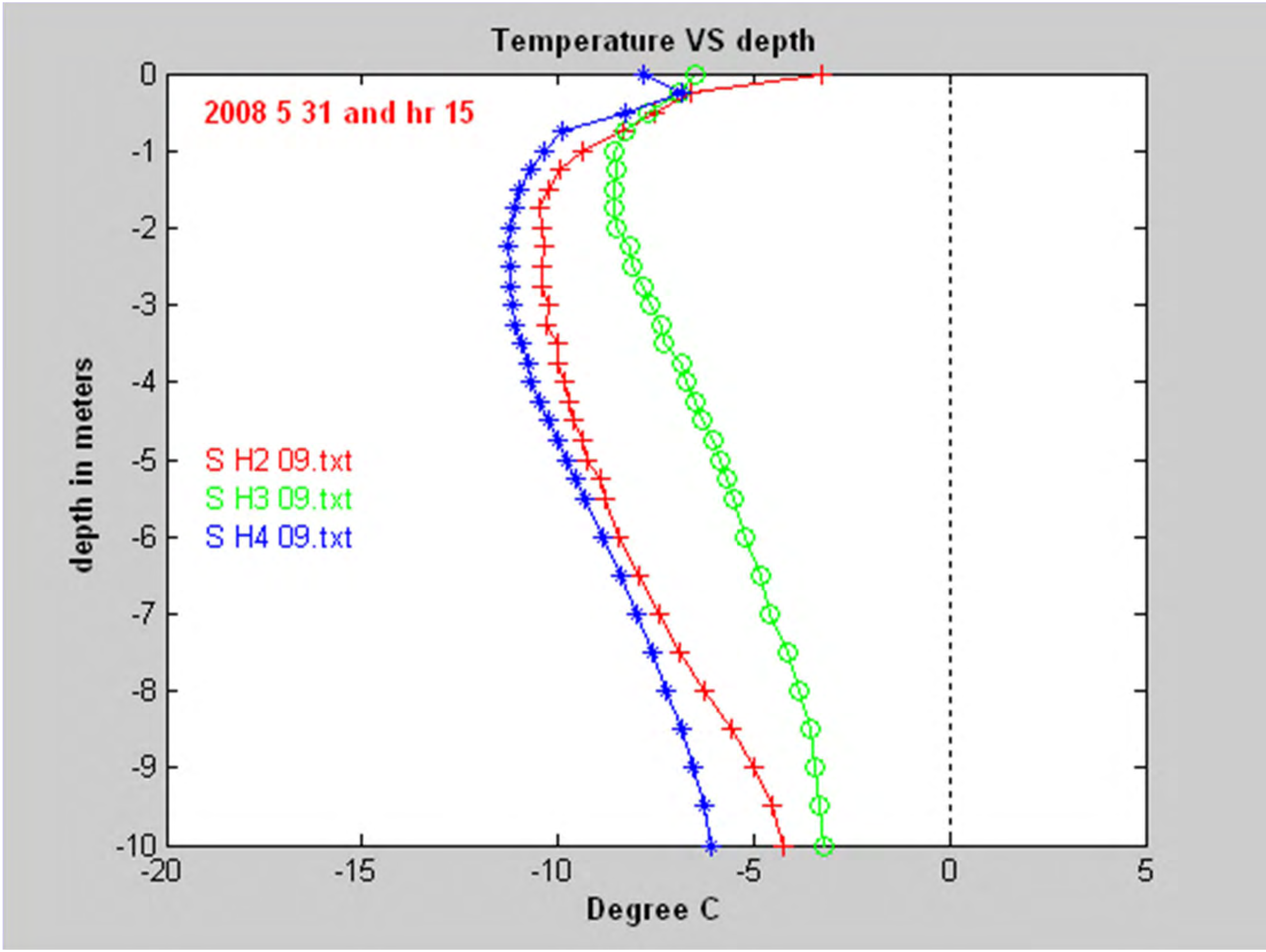
At even lower elevations, significant amounts of water are stored heterogeneously throughout the snow pack


Temperature VS depth
2008 5 31 and hr 21
S G163 09.txt
S G165 09.txt
S H1 10m 09.txt
depth in meters
Degree C
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
-10
-20
-15
-10
-5
0
5

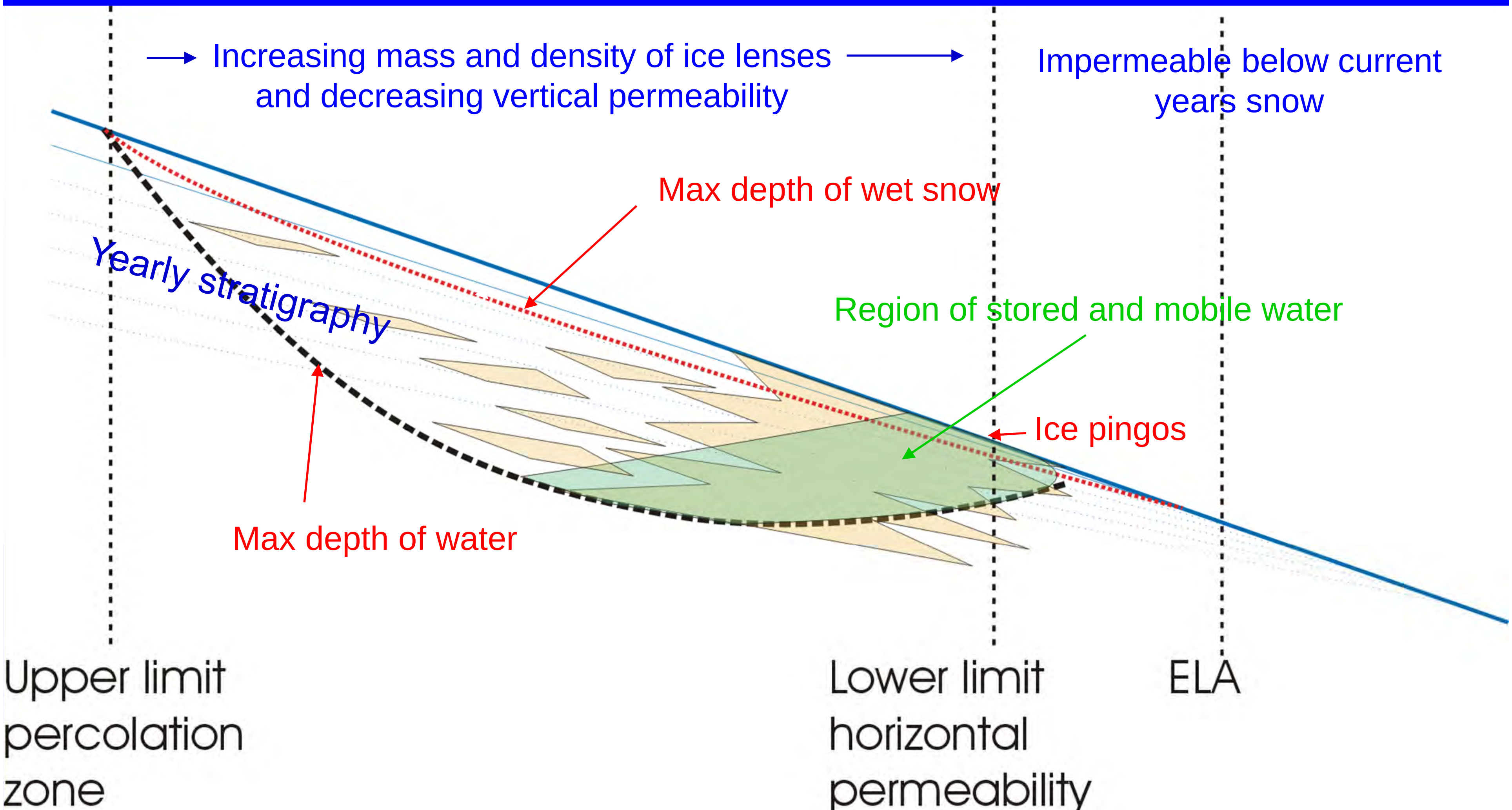


Profile of traverse, showing sites of 10m thermal data

At H4, the snow pack, all years, approaches ice density and becomes impermeable to both vertical and horizontal flow. Deep water is forced to upwell to near surface creating shallow ice structures. Pingos and naleds.

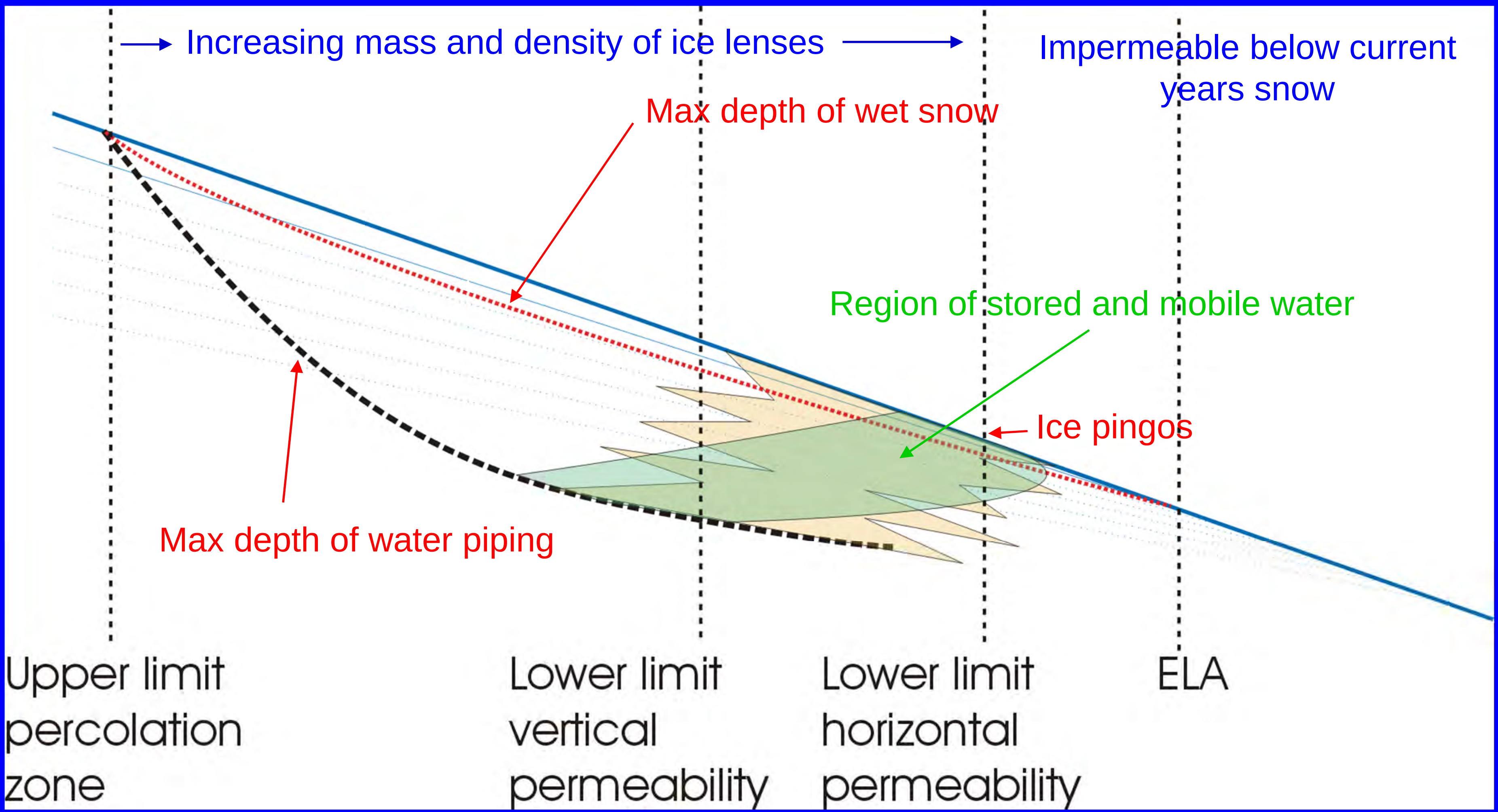


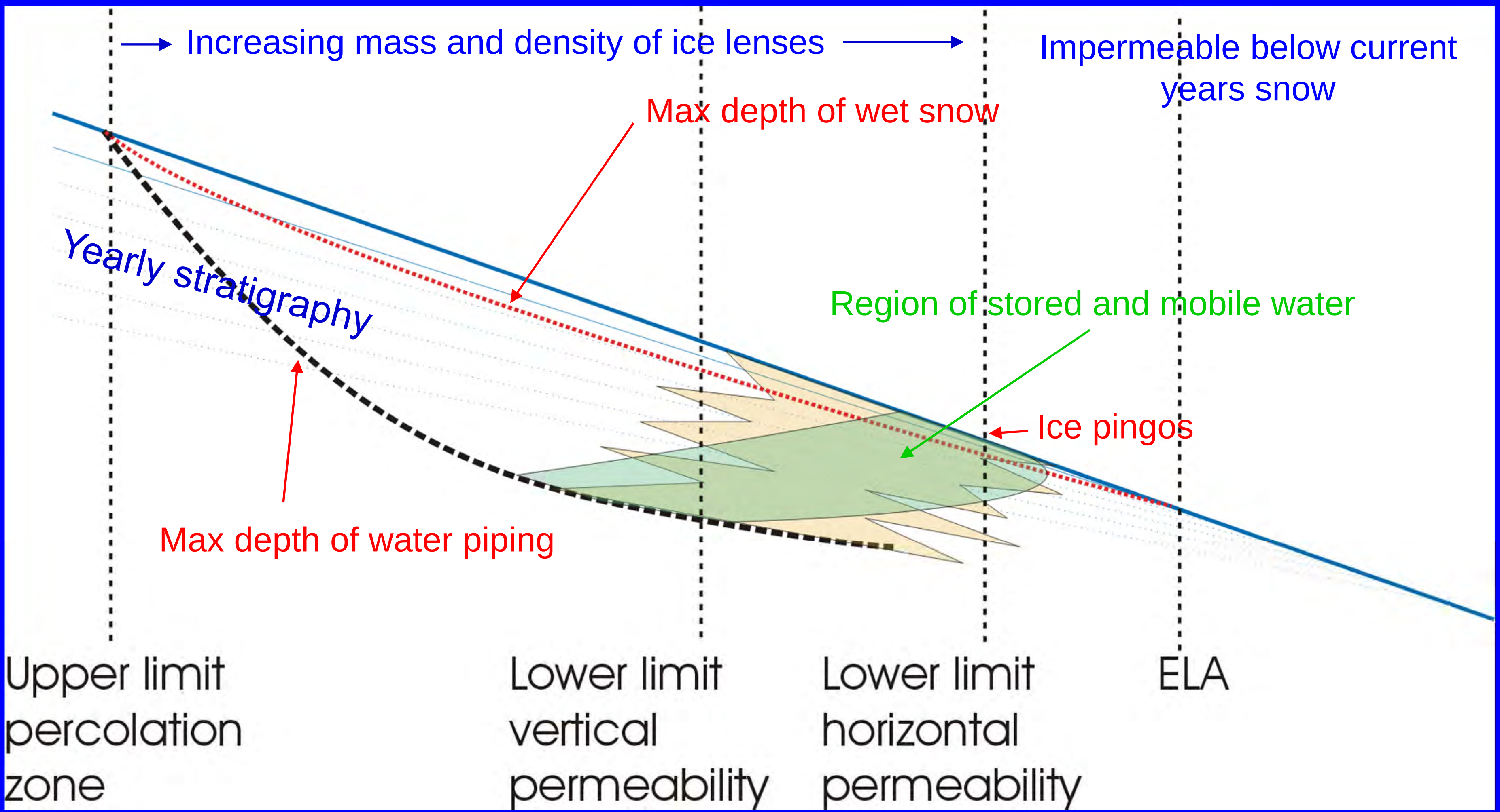
Temperature VS depth
2008 5 31 and hr 15
S H2 09.txt
S H3 09.txt
S H4 09.txt
depth in meters
Degree C
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
-10
-20
-15
-10
-5
0
5



Classic icesheet description

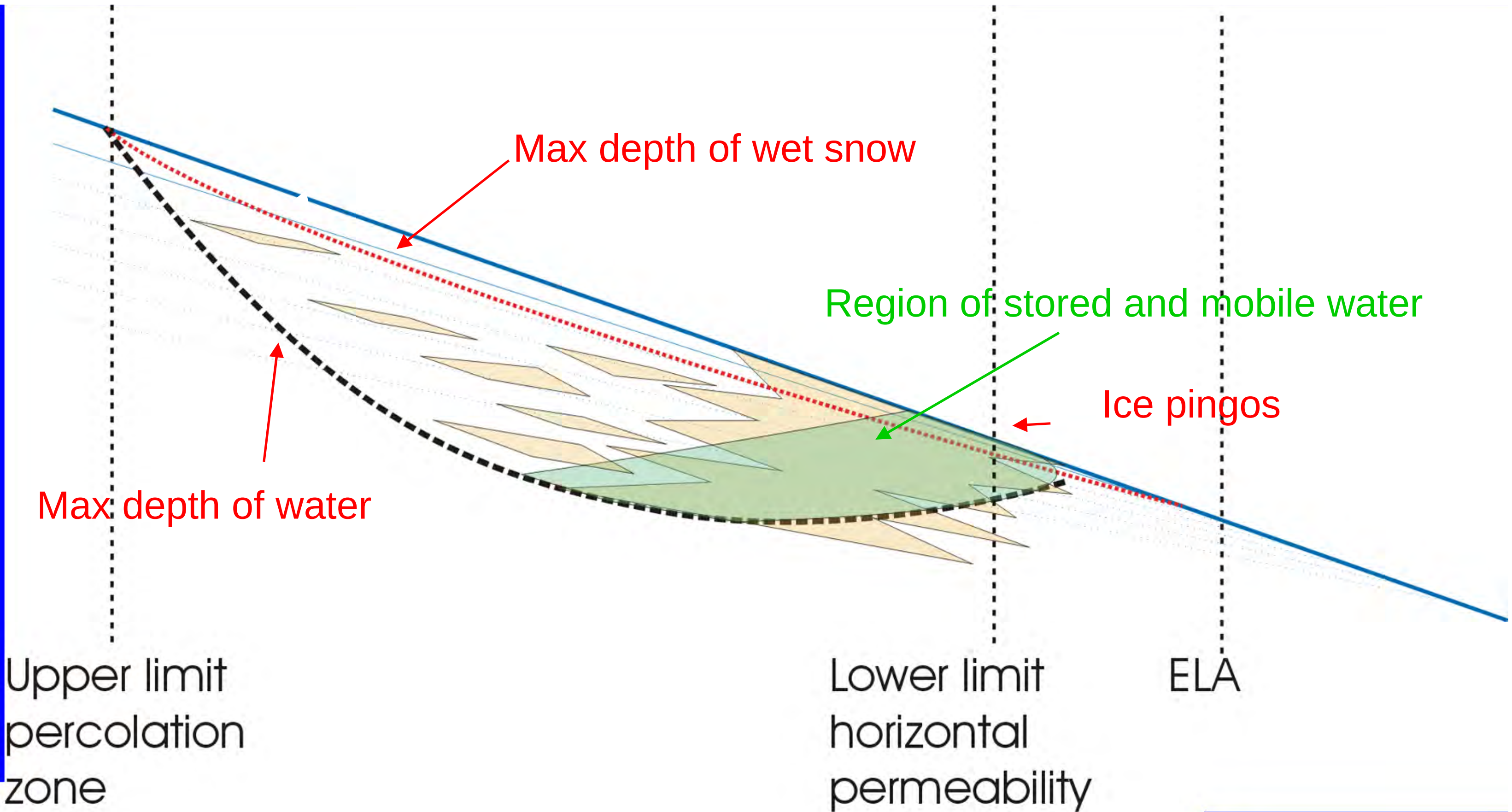
Mountain glacier description

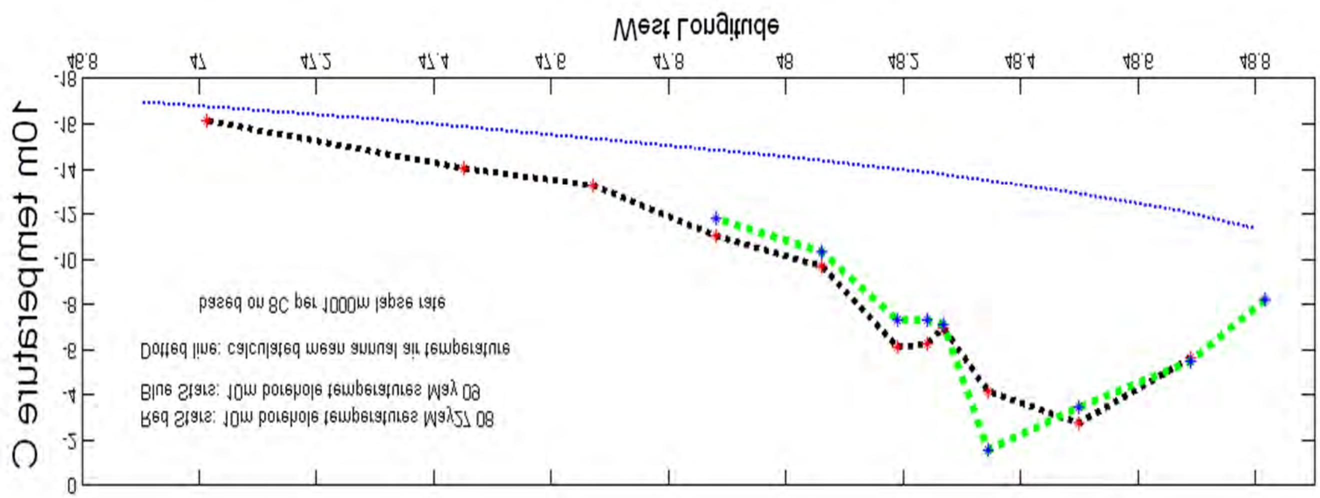

→ Increasing mass and density of ice lenses →
Impermeable below current years snow
Max depth of wet snow
Region of stored and mobile water
Ice pingos
Max depth of water piping
Upper limit percolation zone
Lower limit vertical permeability
Lower limit horizontal permeability
ELA

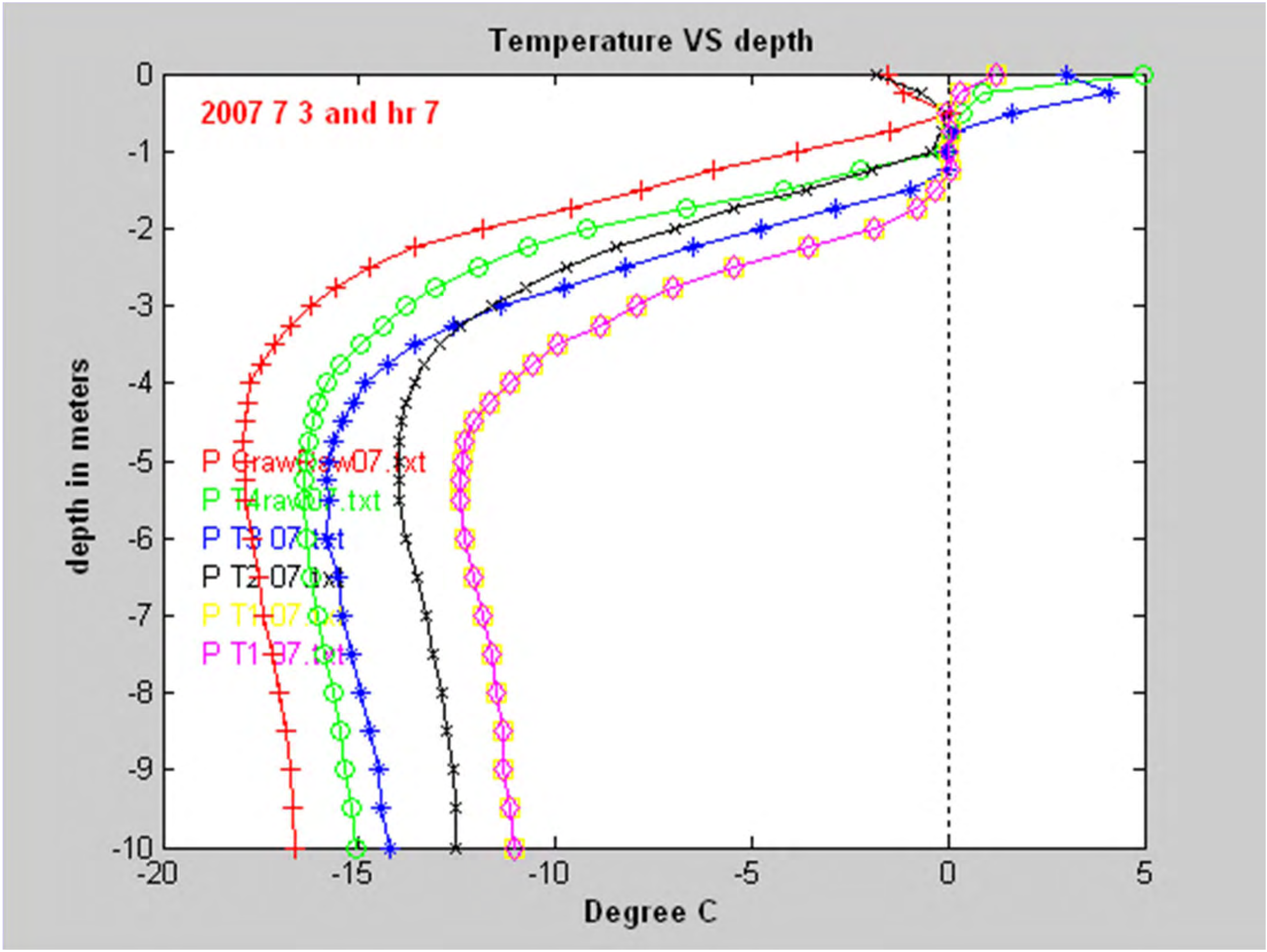


Classic icesheet description

Mountain glacier description

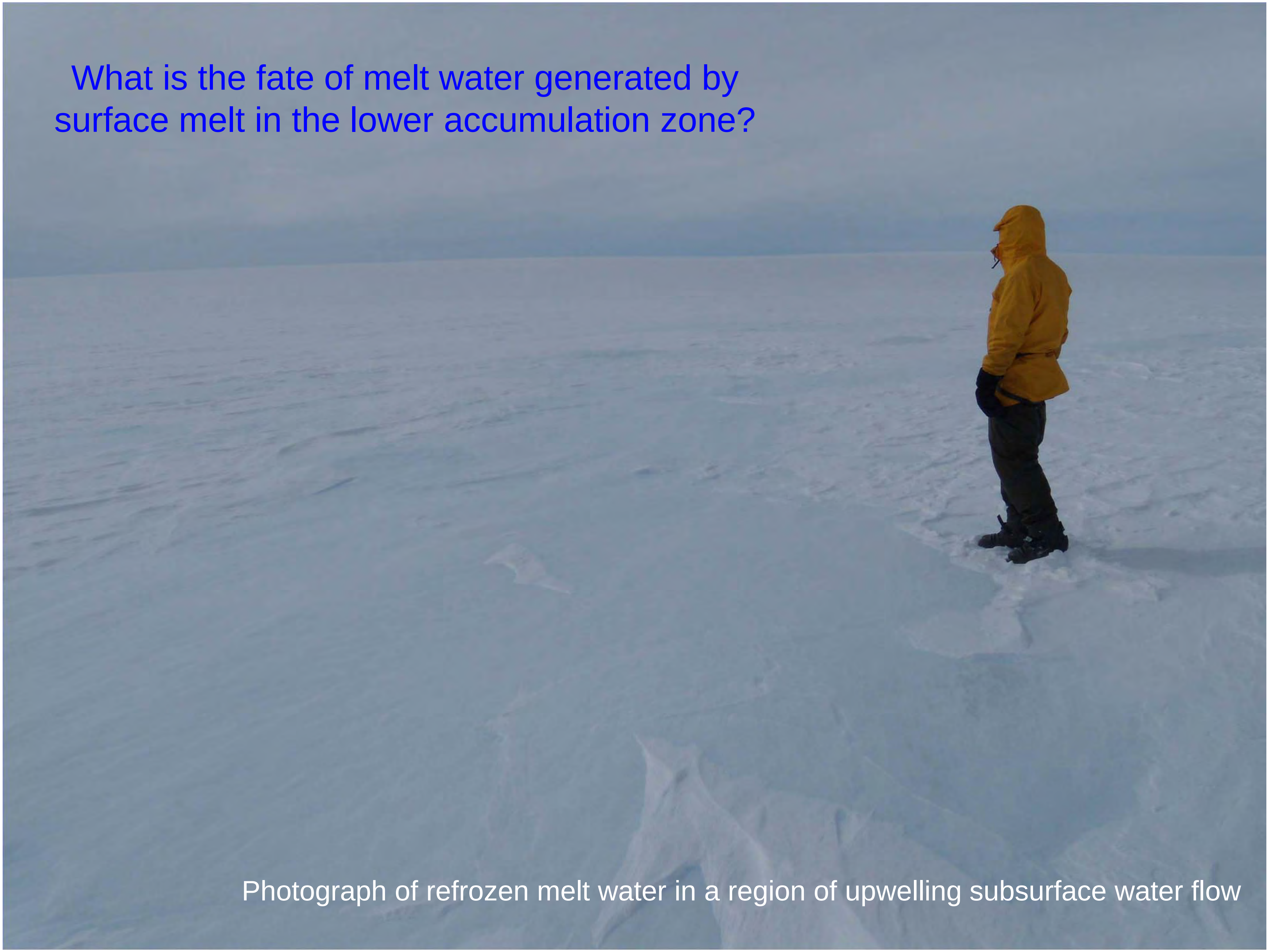

Max depth of wet snow
Region of stored and mobile water
Ice pingos
Max depth of water
Upper limit percolation zone
Lower limit horizontal permeability
ELA


West Longitude
10m temperature C
based on 8C per 1000m lapse rate
Dotted line: calculated mean annual air temperature
Blue Stars: 10m borehole temperatures May 09
Red Stars: 10m borehole temperatures May27 08

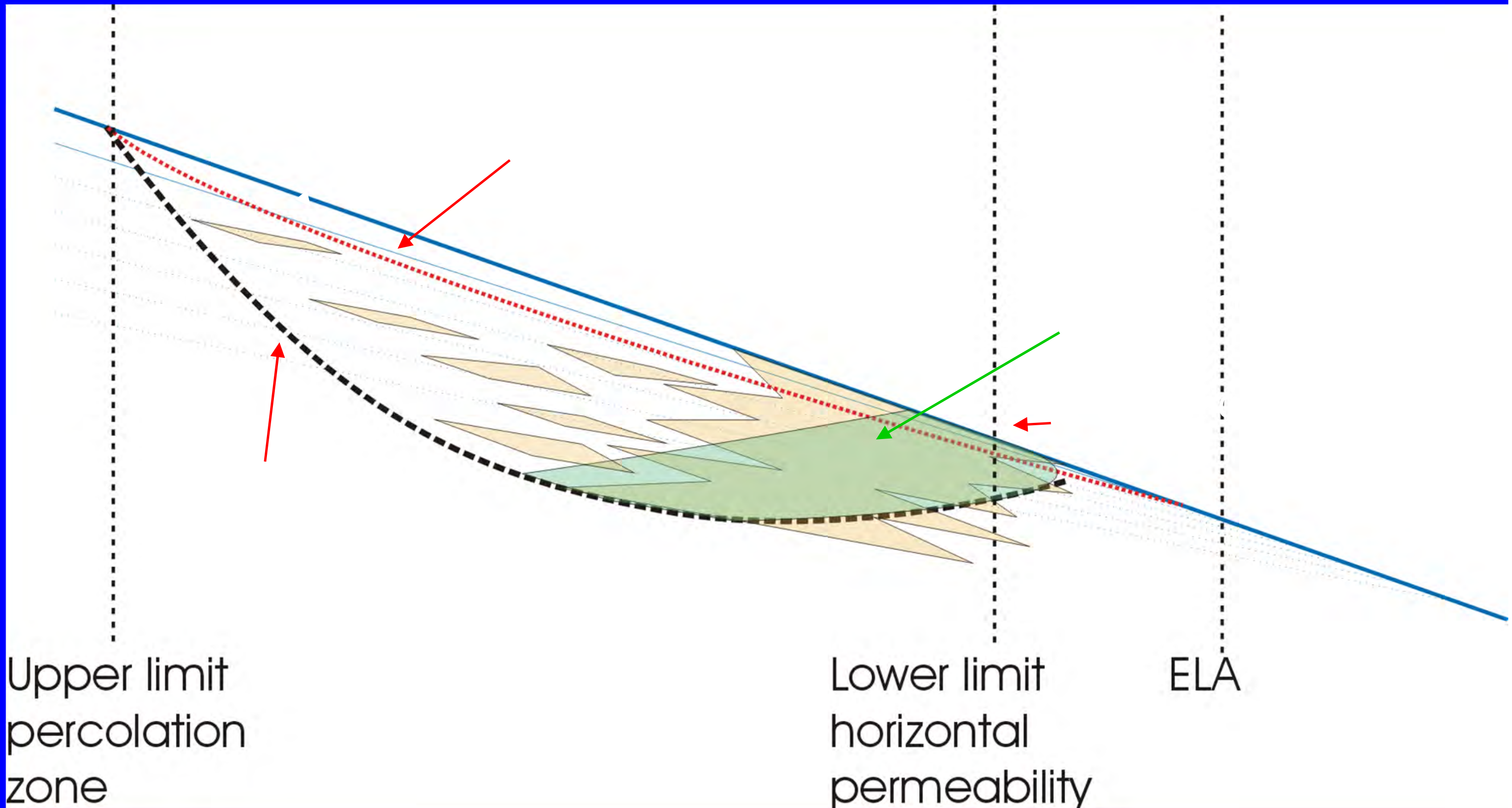


Temperature VS depth
2007 7 3 and hr 7
P T3 07.txt
P T2 07.txt
P T1 07.txt
P T1 07.txt
depth in meters
Degree C
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
-10
-20
-15
-10
-5
0
5

What is the fate of melt water generated by surface melt in the lower accumulation zone?



Photograph of refrozen melt water in a region of upwelling subsurface water flow



The vertical scale is order 20m, while the horizontal scale is order 100km. Or the vertical scale is 10s of years and the horizontal is order 1000yrs. As a result of this scale, the whole zone with water, freezes and is buried, at average temperatures throughout well below freezing. Only locally do pools of free water form, but these are potential sources of water to inject down to the basal system. This zone is the highest region that could supply basal water.