CAVES IN THE GLACIERS OF TERRA NOVA BAY (VICTORIA LAND, ANTARCTICA)

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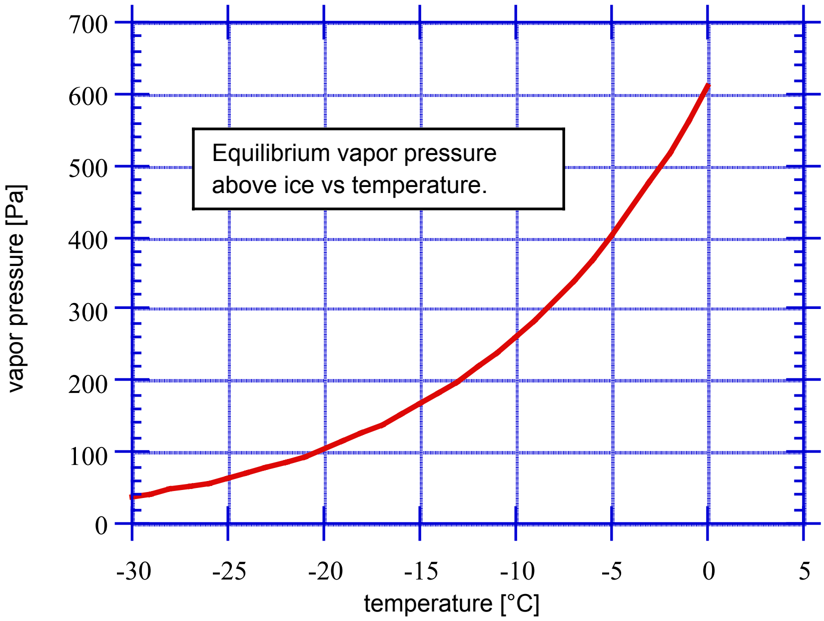
Abstract
In the 2000/2001 expedition of the Italian Programme of Research in Antarctica (PNRA) some investigations on karst phenomena in ice have been carried out around the Italian Station of Terra Nova Bay, on the western coast of the Ross Sea.
Some caves have been explored in the glacial terminus of glaciers reaching the sea and an other one has been found on the summit of Mt Melbourne, a volcanic cone 2700 m high. The caves on the coast have been generated by a dry process of speleogenesis due to sublimation of ice. The process is driven by temperature difference between the core of the glacier ice and the quite warmer sea water under the fast ice at the bottom of the caves.
The Mt Melbourne subglacial cave is generated by the heat of the volcanic rocks; also in that cave the water vapour state is of fundamental importance because in such a state the water is carried out from the cave.

INTRODUCTION
The glacial karst (thermokarst, due to melting of ice) is likely limited to the mountain regions or the high latitudes zones were the annual mean temperature reaches 0 °C. Under this value, the core of the ice bulk is under the freezing point and all the water that percolates is transformed in ice, seals all the meatuses and stops any further percolation. That is what happens on the Svalbard Islands, where a mean temperature just a little below 0°C is enough to reduce the thermokarst to an occasional phenomenon. So we deduced that around Terra Nova Bay, where the mean annual temperature is -14 °C, not even the ghost of karst in ice could exist.

GEOGRAPHIC OVERVIEW
We could explore the territory from the Italian Base of Terra Nova, placed on a granitic peninsula in a broad inlet of the western coast of the Ross Sea, at 74° 41’ 42” S lat. and 164° 07’ 23” E long.
The Base is open only during the warm season (from October to February) for about 80 people. Beside the Base rise the Transantarctic Mts, whose relief is often higher than 3000 m. South of the Base outlet glaciers cross the mountains and drains the ice of the inlandsis. The bigger of them, the David Gl., forms the Drygalski Ice Tongue, several dozens kilometres long. On the north huge valley glaciers flow from the mountains to the sea. The Italian Base is placed between the region of the Dry Valleys to the south, where a belt near the coast shows deglaciated areas and a northern region with a more extended ice cover and deglaciated zones are quite rare.
The mean annual temperature is -14 °C, the warmer month is January (mean temperature -2 °C), the colder ones are May and August (-23 °C). The vertical rate of the air temperature is 0.52 °C/100 m; in summer is 0.7 °C/100 m. The permafrost is everywhere, few decimetres under the ground. Of course the water (in the liquid state) is present by chance. Only in the warmest month some small creeks have been observed, fed by zones where ice and firn are exposed to the sun or to the radiation of rocks warmed up by the sun. Small lakes are present in the deglaciated zones of Tarn Flat and of the Northern Foothills; on the Hell's Gate Ice Shelf a meandering stream (with a discharge of few dozens litres / second) drains the water formed by irradiation on the surface of the blue ice. Some other small creeks flow on the eastern side of Mt Melbourne, where dark volcanic rocks outcrop from the ice.
There are also indirect evidences of water: a doline in ice has been mapped (and seen by one of us) on the surface of the Priestley Gl., but at the time of our scouting we find just a circular frozen lake, perhaps the filled doline. In other points there is a morphology due to flowing water: a gully near the Base, downstream of Carezza Lake; on the northern side of Edmonson Point an alluvial fan is present. Besides these evidences, the presence of thermokarst has to be forgotten (but thermokarst and speleogenesis in ice are not the same).

The first target of our scouting has been the snout of the Campbell Glacier, where we had seen that in the ice cliff of the glacier ice tongue some large caves were open. Their initial stage is tectonic, in fact they are crevasses closed in the upper part. When that caves are large, the effect of the load of the roof is evidenced by a parabolic profile of the ceiling, similar to the profile of the broad caves inside carbonatic mountains. It seemed to us to too easy to explain the processes of spelogenesis that produced so large caves at a temperature far below 0 °C.
The ice at the terminus is stable enough to ensure a rather safe exploration in the caves with the exception of the entrance where ice falls are often visible.
Inside the cave two opposite facts are present: temperature is 15-20 °C below 0° and the ice walls show evident solution forms. The synoptic vision is that of a clear karstic cave.
Some of them are swept by strong flow of cold air, sometimes colder than the mean local temperature. The floor is flat and smooth, and is a little bit lower than the fast ice outside the cave. On the walls there are scallops and rills elongated along the dip. From the ceiling stalactites hang, sometimes covered by sublimation crystals. All this morphology denotes both sublimation and melting/freezing processes.

The main process that govern the genesis of all that unexpected morphology is obviously that of the heat exchange: the caves are exactly at the contact between the glacier ice coming from the Transantarctic Mts, that has a temperature approaching the mean annual temperature of the air, about -18° C, and the sea that under the fast ice has a temperature of -1,9 °C.
In the perspective of Thermodynamics that is the place of thermic contact between two "heat sources", that is two systems able to yield heat and maintain the same temperature, because of their heat capacity that can be considered infinite. As a first approach to analyse the process we decided to measure the temperatures inside the ice to understand if, how much and in which direction the heat flows.
An other question is linked to the sea salt. We came out from the caves dotted by white salt spots, due likely to the fall of sublimation crystals. So not only there is a difference in temperature, but also a contrast between salty and fresh ice.
The measurements have been carried out in three caves, chosen among the others because nearby the Italian Base, enough safe, nice shaped and presence of air flow. Two of them are on the Campbell Gl. Ice Tongue, the third is in an unnamed glacier flowing from the slope of Mt Melbourne, near Baker Rocks.
Despite the impression of a slow evolution of the morphology of the caves, we noted that a small niche we excavated in the wall to sample ice, in few days was smoothed and striated by karstic processes working at -20 °C.
We found that the floors are quite warmer than the walls and that is the key to understand the process of that dry speleogenesis. The water vapour pressure of the floor ice is higher than that of the ice of the ceiling. So the floor warms up and moistens the air in contact; the air rises and, if it is not driven outside the cave, reaches the dew point and forms sublimation crystals releasing the latent heat at the same time. Probably it is this latent heat of sublimation that warms some air up whose flow besides the ice crystals moulds the rills.



In future we will have to investigate the factors controlling the processes in those peculiar environments, that is the heat exchange, the air flow inside the glacier (that is colder than expected), the role of the salt.

A more simple to understand but more astonishing cave we visited in the Terra Nova Bay zone, during a short survey at the end of our expedition, has been that formed at the contact of the ice with the warm surface of the Mt Melbourne volcano. The heat from the rocks surface flows into the ice, here at a temperature around -30 °C, and affects it by melting, sublimation and air circulation. Broad caves are here developed, whose main interest is to be a relatively warm place in a severely cold environment. There are peculiar biological associations that caused the place to be declared a reserve to be visited only after a permission of the SCAR and cautiously to avoid contamination. The cave was explored three times by Italian glaciologists and biologists few years ago before it were declared as reserve. Similar caves were found on the Mt Erebus (a volcano near the Mc Murdo and Scott Bases), by a party of the expedition of Tazieff in the Fifties.
The entrance of the cave is visible from far because the air rich in humidity coming from the ice melt by the volcano's heat flows outside and at the contact with the cold atmosphere deposits by sublimation a vertical "pipe" around the entrance, that stands up like a chimney. The ice is here thick just few dozens metres, but the cave is well developed, we walked inside for more than a hundred metres in a broad warm tunnel, without finding the provenance of the air. We didn't smell any volcanic gas.
The process is analogous to the one of other sub-glacial caves found in far regions, mainly in Iceland, but here is dominated much more by the water vapour state, than the liquid one, like the caves observed in the coast. Inside the cave there are the three states of the water: solid, liquid and gaseous, but is only the last that leaves the cave, in form of plumes of vapour, carrying 4.8 g of water every cubic metre. The cave is eventually a structure that represents the equilibrium between erosion, related to the air flux and the volcano's heat, and the collapse of the vault, due to the ice plasticity and flow. At the entrance of the cave we observed an air flux of about two cubic metres at second, with a related transport of 10 g/s of water vapour, equivalent to an erosion of about a ton of ice every day.

The only continent that was considered without ice caves is so revealing peculiar and enigmatic karst processes.

ANALYSIS OF THE INVESTIGATIONS CARRIED OUT IN THE FIELD

In the XVI Expedition of the PNRA we started to study three caves open in the ice cliff at the contact with the fast ice. Inside the caves we measured the vertical temperature rate of the floor and the horizontal rate of the walls at about one metre from the floor. We repeated the measurements after ten days. In that time interval the thermal wave has a displacement of 0.75 cm.

Fig.

Campbell Gl. 1. Cave without sensible air circulation. The heat subtracted by the ice walls is 8 W/m^2. The heat coming from the floor is 4 W/m^2. In the ten days lapse both walls and floor have been warmed up probably by air entered from the broad entrance.

Campbell Gl. 2. Is a large cave with a strong air flow that force the surfaces to a lower than expected temperature (here the mean annual air temperature is around -14 °C). One possible explanation (but we are not sure) is that the crevasses act as cold air traps so that the glacier could maintain its temperature below the mean annual temperature. Here too the floor is warmer than the ceiling, but it absorbs heat rather than supplying it, probably because the measurement was made far inside (70-80 m) from the glacier terminus, at a great distance from the zone of heat balance between sea water and glacier ice. The heat absorbed by the glacier is 1.8 W/m^2 on the floor and 2.2 W/m^2 in the walls.

Baker Rocks 1. The cave is somewhat different from the two previous ones, is rather narrow and elongated. There is an opening in the ceiling, through which the snow accumulates on the floor. The cave is not far from the grounding line of the glacier. The heat flow is 3.7 W/m^2 coming from the floor (the measures have been made at a dozen metres from the fast ice), and 1.7 W/m^2 going inside the walls in our first visit and 4 W/m^2 in the second one. The warming up of the walls is quite strong and, because of the position of the measurement point deep inside the glacier, cannot be explained by a process lasting only ten days. The heat balance is influenced by the strong air flow and mainly by the insulation of the snow covering the floor, responsible of the stability of the thermal profile in the two measurements.

As a comparison we display the thermal profile of the fast ice 30 m outside the cave of Baker Rocks. Here the ice is really warmer, but the heat (2.8 W/m^2) flow is comparable to the one inside the cave.

Mt Melbourne 1. This is a cave originated by the fumarolic activity at the summit of the Mt Melbourne volcano. The cave opens at the contact between the rocky surface of the volcano and the ice cover, here some dozens metres thick. The gallery is rather regular, 5 metres large and 2-3 metres high; we went inside for about two hundred metres without finding an end. The graphic shows that the wall absorbs 4.5 W/m^2 and the process is regular at all.