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THE CALDERONE GLACIER (GRAN SASSO D'ITALIA). DETERMINATION OF ICE THICKNESS AND BEDROCK MORPHOLOGY BY MEANS OF RADIO-ECHO SOUNDING

ABSTRACT: FIUCCI A., GIGANTE B., ROSSI C., SMIRAGLIA C. & VEGGETTI O., *The Calderone Glacier (Gran Sasso d'Italia). Determination of ice thickness and bedrock morphology by means of radio-echo sounding.* (IT ISSN 0391-9838, 1997).

The Calderone Glacier is situated on Corno Grande, Gran Sasso d'Italia. It is the only glacier in the Apennine mountain chain and is now rapidly reducing and thinning. Geophysical surveys were conducted there in 1992 for the purposes of measuring the ice thickness and determining the bedrock morphology. Six cross and one longitudinal radio-echo sounding (R.E.S.) profiles were carried out on the lower sector of the glacier. G.S.S. radar equipment, including an 80-Mhz antenna, was used. The glacier showed ice thickness of 26 m at most, with evident over-deepening. The debris cover showed a maximum thickness of 2 m.

KEY WORDS: Glacier, Radioglaciology, Calderone, Gran Sasso, Apennines.

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Il Ghiacciaio del Calderone, situato sul Corno Grande del Gran Sasso d'Italia, è l'unico apparato glaciale appenninico, attualmente in accentuata riduzione. Nel 1992 vi sono stati compiuti dei rilievi geofisici per determinare lo spessore del ghiaccio e la morfologia del substrato roccioso. Nel settore inferiore del ghiacciaio, mediante radio-echo sounding, sono stati effettuati sei profili trasvesali e uno longitudinale che hanno mostrato uno spessore massimo di ghiaccio di 26 m con una evidente sovraescavazione. Lo spessore massimo del detrito epiglaciale è risultato di 2 m. Si è utilizzata una strumentazione G.S.S., con un'antenna di 80 Mhz.

TERMINI CHIAVE: Ghiacciaio, Radioglaciologia, Calderone, Gran Sasso, Appennino.

INTRODUCTION

The Calderone Glacier, the only glacier in the Apennines, is situated inside a cirque on the NNE slope of Corno Grande (2 912 m), the highest peak on the Gran Sasso and in the Apennines.

Studied since the start of this century by Marinelli & Ricci (1916), its evolution was evaluated by Tonini (1961) up to the early nineteen sixties. In recent years, survey work has been resumed, with the aim of revealing recent areal variations (Gellatly & *alii*, 1994) and accumulation-ablation ratios (D'Orefice & *alii*, 1995).

Ice thickness is most definitely one of the most important factors in the determination of the geometry of a glacier and its «survival time». Therefore, besides direct measurements in crevasses and moulins, geoelectric surveys have also been conducted, revealing an ice thickness of at least ten m in the lower sector (Smiraglia & Veggetti, 1992). To confirm the results of the preliminary surveys and to extend the survey network, measurements of the thicknesses were made in July of 1992 using radio-echo sounding. The objective of this report is to illustrate the results of these surveys.

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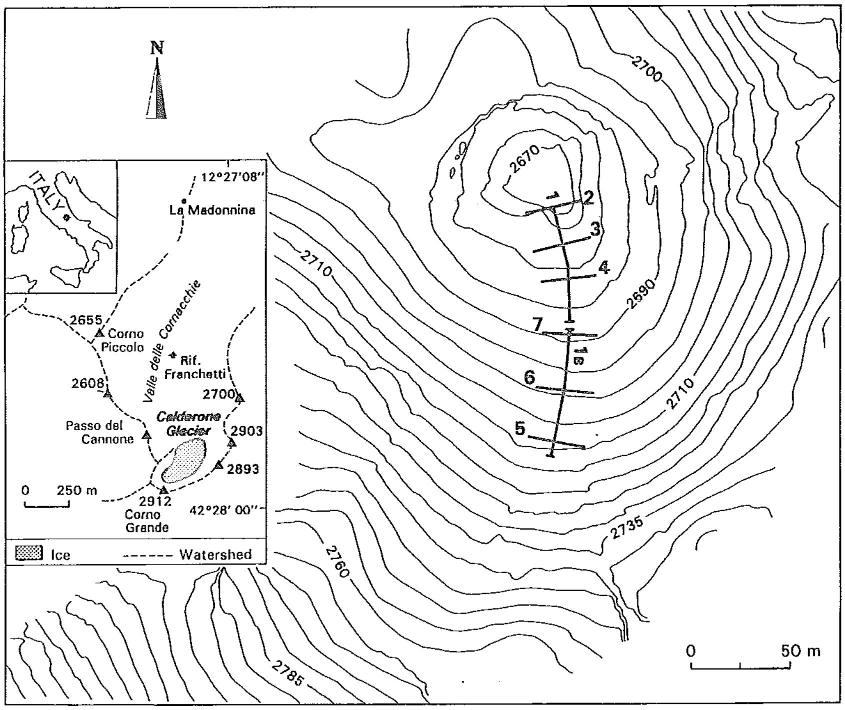


FIG. 1 - Topographic map of the Calderone Glacier with general location of the area, drawn by L. Le Donne and R. Palka, Faculty of Architecture, Università «D'Annunzio», Pescara. Contour interval: 5 m. The cross and longitudinal profiles nos. 1-7 are indicated.

RADIO-ECHO SOUNDING: METHODOLOGIES AND RESULTS

Radio-echo sounding[1] was carried out on the lower middle sector of the glacier, from about 2660 m to 2710 m, which at the time, was almost completely covered with firn. A longitudinal sounding profile was done in two sections over a total length of 118 m, intercalated with 6 cross-sounding profiles, each one of about 25 m in length (fig. 1). The pronounced steepness of the upper sector of the glacier prevented further sounding work from being conducted up-glacier. Profiles no. 6 and no. 7 are shown in figure 2.

It should be kept in mind that the glacier surface in the graphic representations shown in figure 2, and including the snow cover, is represented horizontally. The altitude variations are actually quite marked in reality, as may be observed in the topographic map (fig. 1), compiled by L. Le Donne and G. Palka of the University of Pescara. The individual profiles yielded the following results:

– Profile no. 1-1B: This profile has a total length of 118 m and it was conducted longitudinally with respect to the glacier, starting from the lower depression situated slightly up-glacier from the end moraine which blocks the cirque, where lake Sofia forms in some years. The distinction between ice and bedrock is not very clear in the lower part of the sounding, probably due to the presence of plentiful debris in contact with it. Further up the glacier beyond 50 m in length, the sounding becomes clearer. The reflection depth ranged from a few meters to about 26 m.

– Profile no. 2: Approximately 25 m in length, this profile was conducted transversally to the initial section of profile no. 1 and presented the same interpretation problems. Maximum reflection depth: about 3 m.

[1] The radio-echo sounding (R.E.S.) survey work on the Calderone Glacier, was conducted using equipment manufactured by *Geophysical Survey System* (USA), and called Sir-8 (*Subsurface Interface Radar*). The equipment consisted of the following units:

Control Units, Graphic Recorder, Distribution Unit, Vdu 38 Signal Transformer Unit, Calibrator, Magnetic Tape, Color Monitor, 80-Mhz Antenna (transducer transmit/receive electronics), Connection Cables.

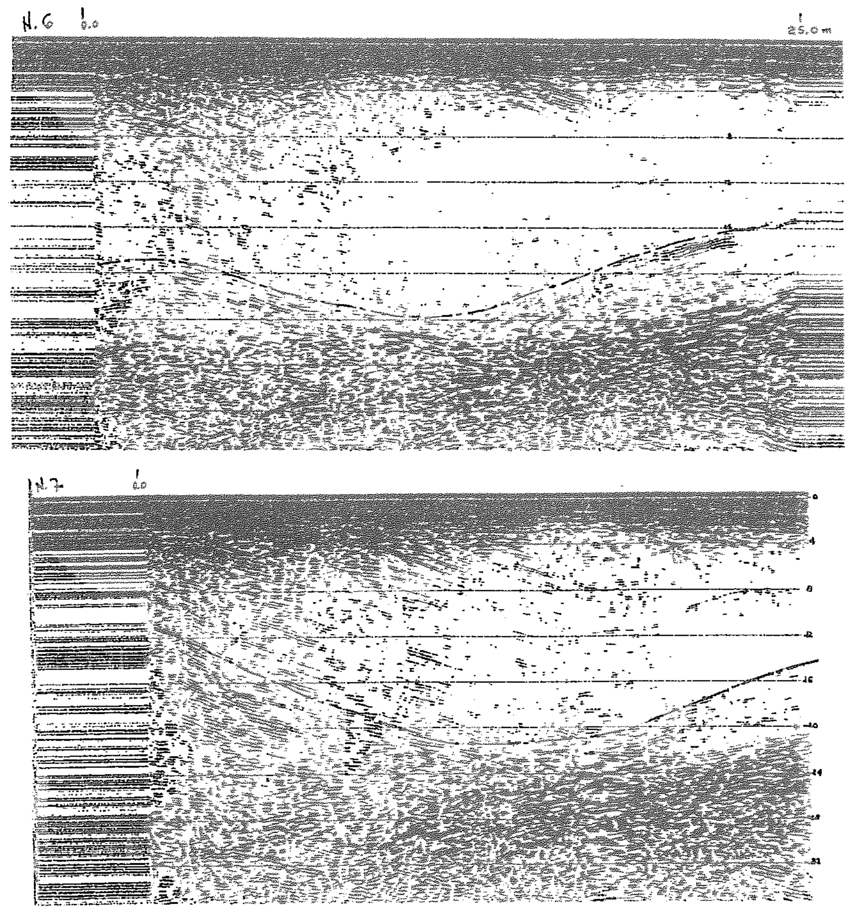
The Control Unit sends electrical energy and synchronized signals to the transmitter, which, in turn, sends electromagnetic pulses into the substratum by means of an antenna. These pulses, the speed of which approaches the speed of light, are partly reflected by the structures present in the substratum. The reflected pulse, with a duration of a few nanoseconds, is captured by the receiver antenna, transformed into an analog signal lasting for about 50-70 milliseconds and then again sent to the Control Unit. The signal is then processed and transmitted to the Graphic Recorder.

The intensity modulation recording of a two-way vertical path of the electromagnetic waves per centimeter of antenna shifting, supplies a continuous section of the material through which the waves themselves have passed. Radio-echo sounding, conducted along certain directions, permitted recordings (fig. 2) to be obtained which represent sections in which the x-axis corresponds to distances (antenna path) and the y-axis, the depth in meters from the ground level, calculated on the basis of the time (expressed in nanoseconds) required by the radar pulses to complete the two-way path.

Moreover, the pulses are recorded on a special magnetic tape through the Vdu 38 system, and then, computerized for all possible data-processing, with management and Radan (Radar Data Analyzer) interpretation software. The recordings thus obtained were also analyzed through the Range Gain variation application and special filters (scanners), which afforded improved definition of the ice-rock interface.

On the basis of data available in studies cited in the bibliography (Haeberli & *alii*, 1983; Bogorodskiy & *alii*, 1985; Funk & *alii*, 1993), it has been estimated that with a dielectric constant of 4, the propagation speed in the ice is equal to 0.154 m/ns. The time needed by the electromagnetic wave to pass through one linear meter one-way (outward) is therefore 6.5 ns, which added to the return time, yields 13 ns (C. Rossi).

FIG. 2 - Recordings of profiles 6 and 7. The discontinuities probably attributable to the ice-bedrock interface are underlined.



– Profile no. 3: Approximately 25 m in length, this profile was conducted transversally to the middle section of profile no. 1 and presented the same interpretation problems. Maximum reflection depth: about 12 m.

– Profile no. 4: Approximately 25 m in length and located transversally to the upper middle section of profile no. 1. It presented the same interpretation problems. Maximum reflection depth: about 17 m.

– Profile no. 5: Approximately 25 m in length and conducted transversally to the upper section of profile no. 1B. This profile is much clearer than the preceding ones. Maximum reflection depth: about 23 m.

– Profile no. 6: Approximately 25 m in length and transversal to the middle section of profile no. 1B. The sounding is very clear. It presents a discontinuous irregularity (englacial debris?) at a depth ranging between 8 and 12 m. Maximum reflection depth: about 24 m.

– Profile no. 7: Approximately 25 m in length and conducted transversally to the initial section of profile no. 1B. The diagram is sufficiently clear. Maximum reflection depth: about 22 m.

To sum up, in the longitudinal profile (no. 1 - 1B), a fairly sharp irregularity was revealed and it is attributable to the bedrock, which becomes increasingly evident moving upglacier away from the end moraine. The lower transversal profiles, located in the lower section of the longitudinal profile were not very clear, at least until no. 4. Further upglacier (profiles nos. 1B and 5, 6 and 7), the reflecting horizon was clearly evident, although another irregularity, albeit discontinuous, appeared in profile no. 6, at a lesser depth than that of the bedrock.

It could therefore be stated that the material subjected to the R.E.S. investigation presented substantial thicknesses, in some cases exceeding 20 m, with an increase in thickness upglacier, the maximum level was observable in the upper middle section of the area considered. The direct measurements made in moulins in 1990 showed that upglacier from the terminus depression, the depth was not less than 15 m and that the thicknesses increased from the end moraine moving upglacier. This depth is thus in keeping with the depth resulting from the vertical electrical soundings (about 10-11 m, in the area further down the glacier) and with that obtained in the same area using R.E.S. (about 15 m). As already mentioned, another increase in thickness was detected using this latter type of survey, further up the glacier, indicating a maximum of 26 m, approximately.

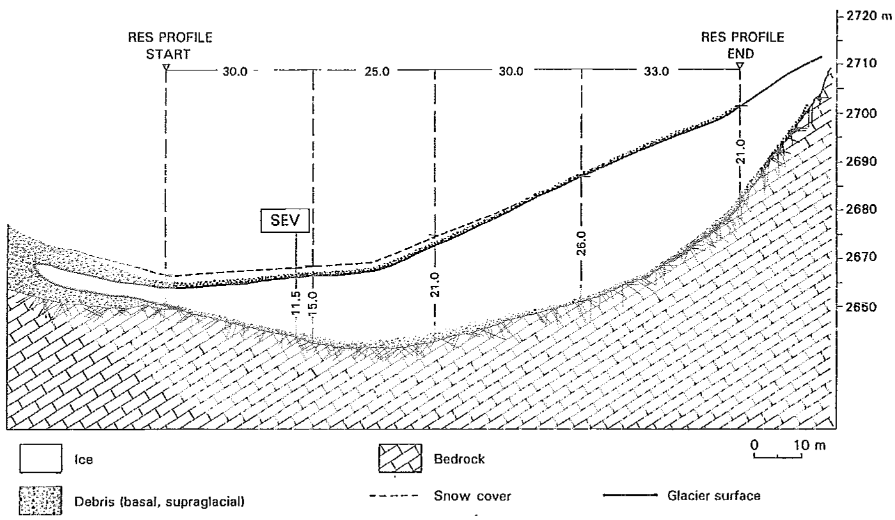


FIG. 3 - Calderone Glacier. Schematic longitudinal section of the lower sector including bedrock morphology and ice thickness as obtained by radio-echo soundings and vertical electrical soundings.

CONCLUSIONS

From the geomorphological and glaciological standpoint, the most interesting findings obtained from the R.E.S. may be summarized as follows (see also fig. 3, in which the longitudinal section has been reconstructed, taking into account the actual steepness of the glacier surface):

– The Calderone Glacier still exists. It presents an ice thickness and a volume that are relatively substantial, even if it is undergoing constant reduction and thinning. For the time being, re-classification of the glacier as a glacieret is still premature, also taking into account other signs of dynamics such as the crevasses in the right basin. The reduced activity and constantly negative balance in recent years (although 1995 and 1996 were definitely less negative), together with the intensive congelifraction of the walls forming the cirque, are rapidly transforming it into a minuscule black glacier, on which the active area is becoming smaller and smaller.

– The bedrock shows the standard morphology typical of over-deepening, with a counterslope downglacier that is made more prominent by the presence of an end moraine. It was not possible to survey the latter, which was already outcropping from the firn as of the survey date. However, direct observation confirmed that the moraine presents a substantial ice core and that it is likely that there is continuity between the ice detected by R.E.S. and the ice inside the moraine.

– The thickness of the supraglacial debris ranges from a few dm in the highest sector to about 2 m in the lower sector, presenting an undulate contact with the underlying ice. The englacial moraine appeared to be somewhat limited. Only in cross profile no. 6 is it possible to observe, as mentioned above, an irregularity that could be attributed to the presence of a layer of englacial debris. As regards the basal debris, the lack of clarity regarding detection of the ice-rock interface in the lower part of the longitudinal profile and the cross-profiles for the lowest sectors, may be due to chaotic debris horizons, or to rock structures that are highly fractured and subject to the passage of meltwater. The clearly evident separation between the cover and the substratum in the upper part of profile no. 1B and in cross-profiles 5-7 can be linked to the presence of a thick layer consisting almost exclusively of ice.

These latter considerations naturally require further confirmation in the field, by means of accurate morphostructure surveys and a radio-echo sounding campaign covering a denser network of sounding points.

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