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NEW RADAR SURVEYS IN MONITORING THE EVOLUTION OF THE CALDERONE GLACIER (CENTRAL APENNINES, ITALY)

ABSTRACT: PECCI M., DE SISTI G., MARINO A. & SMIRAGLIA C., *New radar surveys in monitoring the evolution of the Calderone Glacier (Central Apennines, Italy).* (IT ISSN 0391-9838, 2001).

The Calderone Glacier on the Gran Sasso d'Italia massif (Central Apennines) is a small *debris-covered glacier* of less than 5 ha. Located in the center of Mediterranean area the little apparatus well shows the generalized retreat phase of mid-latitudes European glaciers. The current thickness of the residual ice (27 m maximum) was evaluated by ground-probing radar surveying and in addition the morphology of the bedrock was determined. The comparison with previous surveys revealed a clear-cut reduction in the thickness of the ice near the terminal moraine and in the central part of the glacier. The overall results lend support to the possibility of developments in the use of ground-penetrating radar for detailed site investigations. In this regard, indirect mass balance evaluations carried out on the basis of the annual evaluation of ice thickness variations at control points seem to present interesting prospects.

KEY WORDS: Glacier retreat, GPR (Ground-Penetrating Radar), Calderone Glacier, Central Apennines, Italy.

RIASSUNTO: PECCI M., DE SISTI G., MARINO A. & SMIRAGLIA C., *Un nuovo rilievo radar per valutare l'evoluzione del Ghiacciaio del Calderone (Appennino Centrale, Italia).* (IT ISSN 0391-9838, 2001).

Il Ghiacciaio del Calderone, situato nel massiccio del Gran Sasso d'Italia (Appennino Centrale) è attualmente un piccolo *debris-covered glacier* con una superficie inferiore a 5 ha. Questo piccolo apparato, ubicato al centro dell'area mediterranea, ben evidenzia la fase di ritiro generalizzato che caratterizza i ghiacciai europei delle medie latitudini. L'attuale spessore del ghiaccio residuo è stato valutato con GPR (*Ground Penetrating Radar*) (spessore massimo di circa 27 m) ed è stata anche ricostruita la morfologia del fondo roccioso. Il confronto con altri rilievi radar mette in evidenza una netta riduzione di spessore nei pressi della morena frontale e nel settore centrale del ghiacciaio. I risultati ottenuti fanno ipotizzare un possibile sviluppo dell'uso del georadar per indagini glaciologiche di dettaglio. A questo proposito sembra presentare interessanti prospettive la misura del bilancio di massa mediante la valutazione annuale delle variazioni di spessore in determinati punti di controllo.

TERMINI CHIAVE: Ritiro glaciale, Indagini radar (GPR), Ghiacciaio del Calderone, Appennino Centrale.

INTRODUZIONE

The only glacier in the Apennines and Europe's southernmost glacier, the Calderone Glacier (fig. 1), is located within a cirque that is cut deeply on the side of Corno Grande of the Gran Sasso d'Italia, the highest peak in the Apennines (2912 m). At present, the glacier appears as a small debris-covered glacier, completely covered by a debris cover that is highly variable in thickness. This debris acts as a protective shield for the underlying ice. The contact between the glacier and rock are masked by the debris almost everywhere; yet, a surface area of less than 5 ha is a reasonable estimate. The glacier has been undergoing a phase of strong reduction since the mid-eighties and has managed to survive because of the considerable accumulation of snow transported by the wind and avalanches, its NNE aspect, the protection offered by the tall cirque walls, and its exposure to the wet NE winds from the Adriatic Sea. Together with the relatively easy access to the glacier, its location and features make it an ideal study area for environmental research. The main objective of this paper is to present the results of surveys carried out recently using the ground-penetrating radar (GPR) method. In addition, the present thickness of the residual ice was assessed and the relative interpretative profiles were prepared. The latter reveal the usefulness of these methods in glaciological investigations. In fact, the comparison with

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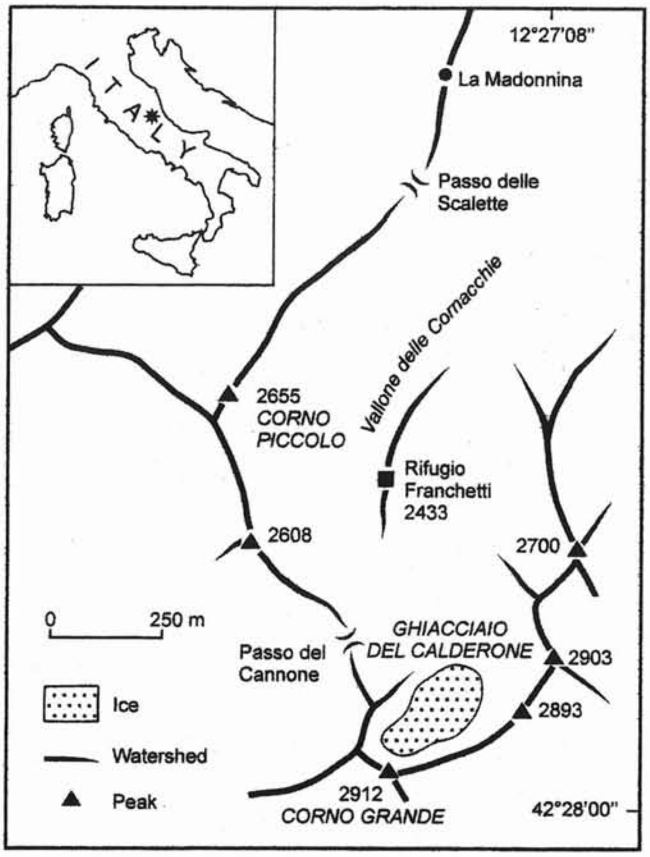


FIG. 1 - Location of the Calderone Glacier.

profiles obtained previously (Fiucci & *alii*, 1997; De Sisti & *alii*, 2000) provided a check as to the limits and advantages of the ground-probing radar method in evaluations of thickness variations over time, also with the prospect of its possible use in computing mass balances.

The investigation was carried out as part of the monitoring work that has been performed systematically since 1994 (D'Orefice & *alii*, 1996; Pecci & *alii*, 1997), and it followed similar GPR surveys conducted in the summer of 1992 (Fiucci & *alii*, 1997). The ground-probing radar investigations described in this paper were carried out on July 19th-21st 1999, with specific reference also to those carried out in July 1998 (De Sisti & *alii*, 2000).

GPR PROFILING ON THE CALDERONE GLACIER

The equipment included a GPR SIR 2 (Subsurface Interface Radar) manufactured by GSSI with a 200-MHz antenna (for the 1998 investigations) and a 40-MHz antenna (for the 1999 investigations), resulting in an overall weight of 60 and 40 kg, respectively. All of the equipment was transported in backpacks.

According to previous estimates, (Haeberli & *alii*, 1983; Bogorodskiy & *alii*, 1985; Funk & *alii*, 1993; Fiucci & *alii*, 1997), with a dielectric constant of 4, the rate of the electromagnetic waves in ice is equal to 0.154 m/ns, corresponding to a reflection interval of about 13 ns per meter in depth. Generally, antennas of lower frequencies, but with lower resolution, are used for depth investiga-

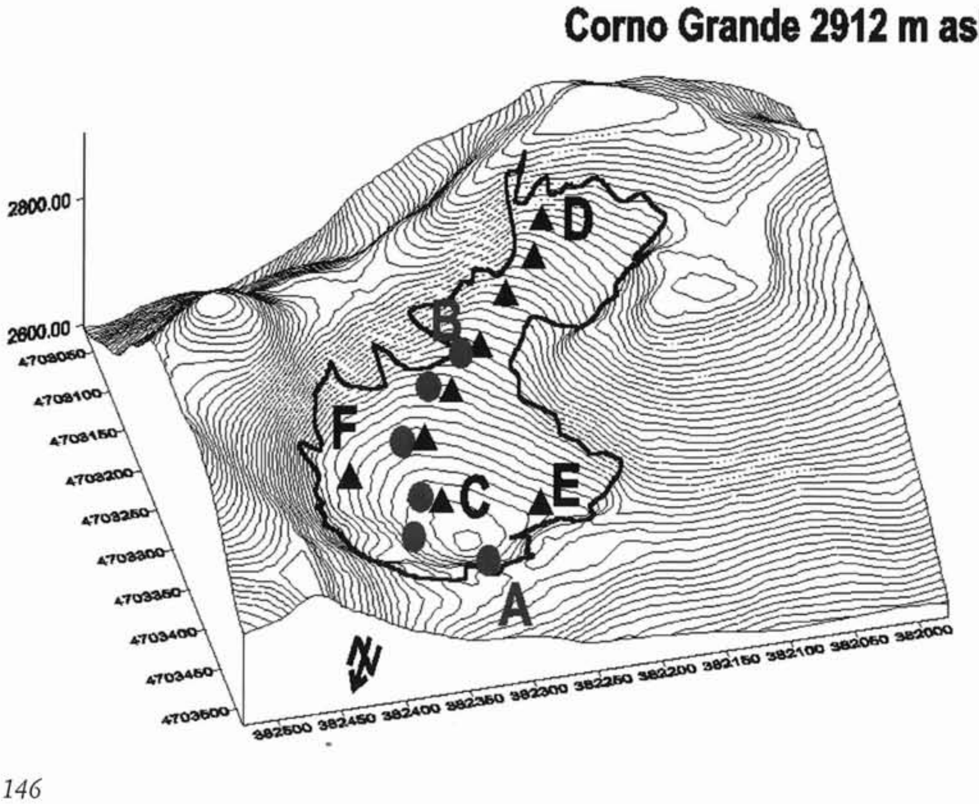


FIG. 2 - The Calderone glacier (solid line), where the 1998 (line A-B: gray circles) and 1999 (lines C-D and E-F: black triangles) GPR profiles are shown.

tions. All of the procedures are carried out automatically by the instrument after the software set-up phase with the data pre-set on the basis of the survey range, the antenna being used and the hypothetical features of the bedrock (dielectric constant).

The investigation was carried out along two alignments, one of which was a cross profile and the other, longitudinal (for both the 1998 and the 1999 investigations) (fig. 2). The antennas were shifted during the surveys at the most constant rate possible- the 200-MHz antenna being in direct contact with the snow cover and the 40-MHz antenna strapped over an operator's shoulder. A manual control signaled the passage of the antenna over the reference points, which were placed at 5-meter intervals. The survey depth was 24 m, corresponding to a reflection interval of 300 ns for the 200-MHz antenna and 500ns for the 40-MHz antenna.

Longitudinal profiles: The surveys were initially begun at an altitude of about 2660 m in the depression above the end moraine, at a distance of about 50 m from the inner ridge of the moraine itself. They were completed at an altitude of about 2715 m asl during the 1998 investigation (fig. 3) and at about 2820 m asl during the 1999 study (fig. 4). The profiles, which were approximately mid-range on the glacier surface, were equal to about 210 m and 320 m in length, respectively. In both longitudinal profiles, it is possible to note a first reflection that is very clear and continuous. It corresponds to the contact between the thickness of the winter snow accumulation, which is generally scanty and ranging between 0 to 5 m, and the glacier surface. In any case, the highly variable thickness of the surface debris, which covers the underlying ice and which in the middle sector of the profile varies between 0.1 and 1 m, is on the order of the resolution of the antennas. Therefore, the boundaries between the debris cover and the ice are not clearly visible. Another significant reflection is visible in both profiles for the middle sector, below the morphological narrow, at an estimated depth of 4 to 6 m. It could be correlated with the presence of ice layers containing higher concentrations of debris. The reflection corresponding to the glacier-bedrock interface is not clearly defined, nor it is characterized by signal continuity. It is difficult to interpret in the lower sector. The lack of clear definition could be due to the probable coexistence of subglacial debris and bedrock with many fractures, which, in turn, are probably filled with ice.

The presence of a structural pattern such as this is also observable in many places on the cirque walls on both sides of the lower sector.

The following distribution can be noted for the thickness and the comparison of both sections along the glacier:

- Lower sector: the thickness of the glacier can be estimated as between 3 and 27 m, with a mean thickness of about 15 m. This is the area with the greatest accumulation of ice. In addition, in some sectors, it appears to have a clearly vertical stratification. This sector shows inclinations starting at 15° and reaching 30° at the narrow.
- Middle sector: the thickness of the ice gradually tapers down as the narrow is approached and where the roches moutonnées of the bedrock outcrop and where the thickness of the ice thus seems to thin down to nothing. This actually determines a separation of the ice into two distinct patches. The signal was not distinct everywhere, but an outcropping of the bedrock on the surface was clearly appreciable at least in one segment along the course being investigated. This sector has virtually constant inclinations of 30°.
- Upper sector: the glacier shows an increase in thickness, which reaches a maximum of 15 m, and then a joining with the outcrops of massive limestone on the edge between Vetta Orientale and Vetta Centrale, with a sharper inclination of the ice-rock interface. The signal revealed the presence of irregular bedrock probably characterized by at least one step and by numerous fractures, probably filled with ice. This sector presents inclinations starting at 30° and reaching 35° and 40° in the last steep section covered with snow.

Cross profiles: the surveys were carried out along a section that was almost perpendicular to the longitudinal profile, at an altitude of about 2680 m, in the lower sector of the glacier. The results provided sections with a lot of disturbance, probably due to the large amount of debris, especially in the 1998 profile. Therefore, latter was not included in the graph (fig. 5).

The cross profile of 1998 had a length of about 60 m, whereas the 1999 cross profile had a length of about 120 m. The surveys were carried out along two consecutive segments. At a depth lower than the reflection of the contact with the snow cover, the ice-bedrock contact proved to be very distinct, with a sharp signal at the sides of the profile, and less clarity in the middle sector, probably due to greater amounts of debris there. The area in discussion represents the cirque floor, where the debris breaking away from the walls converges mainly due to gravity, but also due to glacial transport. The ice showed thickness ranging between 1 and 25 m, approximately. Figure 6 includes the field section FE in the *line scan* mode for the surveys conducted in the summer of 1999 and corresponding to the interpretative profile shown in figure 6.

The longitudinal sections and the transversal section shown in figures 3, 4 and 5 should be considered as indicative, owing to the approximation of the ground-level profile, which was obtained using rapid topographic methods, and to the overall irregularity of the bedrock, which could determine great variability of the offset. The strong irregularity of the cirque surface, which is evident in the areas without snow or debris cover, is strictly related to the particular structural conditions of the area.

CONCLUSIONS AND PERSPECTIVES

From a glaciological point of view, the comparison between present and previous ground-penetrating radar studies revealed a clear-cut decrease in the thickness of the

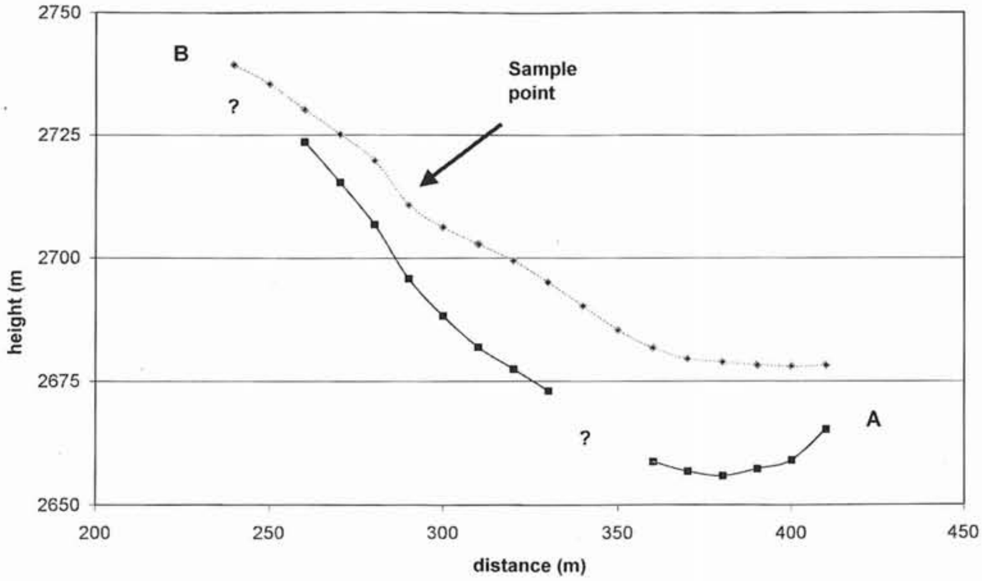


FIG. 3 - Interpretative longitudinal profile of the thickness of the ice, reconstructed on the basis of the GPR investigations of 1998 (extremes A and B are the same of fig. 2): the survey has been finished below the subdivision into the two distinct bodies well reconstructed by GPR surveys of 1999 (see fig. 4). In the diagram the marked line is used for the ice topography, the continuous line is used for the bedrock surface.

glacier, especially compared to the 1992 surveys (Fiucci & *alii*, 1997). Therefore, the evolution of this small Apennine glacier also falls within the picture of the general reduction in glaciation that involved the Alps since the end of the Little Ice Age and which had a particularly intensive impact on Mediterranean glaciers such as those found in the southern Maritime Alps, (Gellatly & *alii*, 1994; Pappalardo, 1999), the Pyrenees (Arenillas & *alii*, 1991) and Sierra Nevada (Messerli, 1980). The greatest reductions were found in the lower part of the profile, along the cirque edge, up glacier from the end moraine where there is now an evident depression, and in the middle sector. Roches moutonnées have outcropped in recent years in the middle sector where the above-mentioned narrow is found and which is now occupied by a strip about 4 m wide of blocks of sizes within the decimeter range. The resulting decrease in the thickness confirms the generally negative trend for the glacier, although the fact that it was not possible to

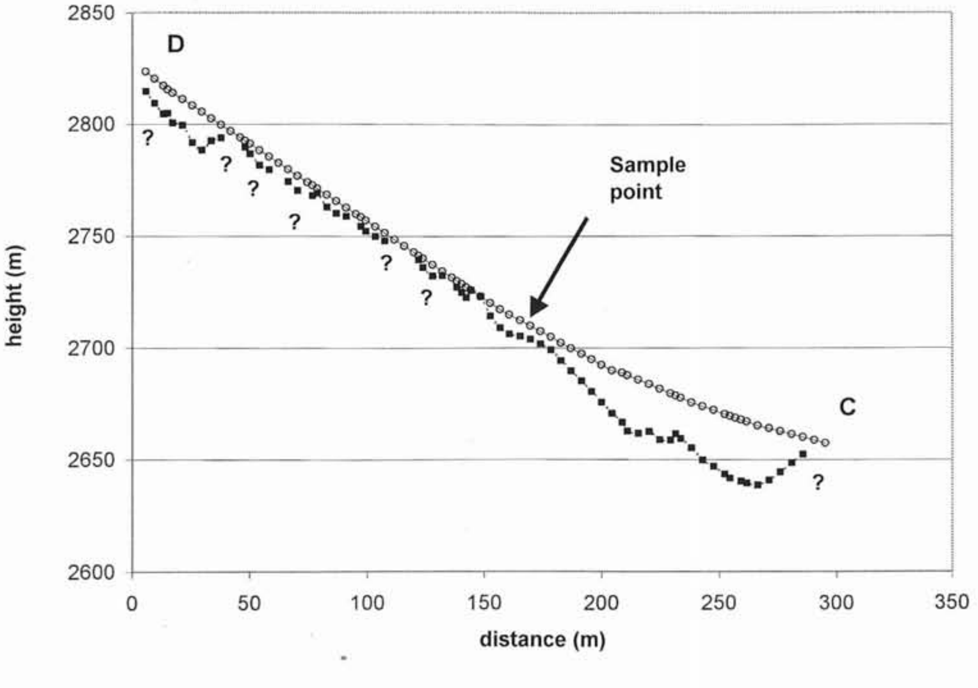
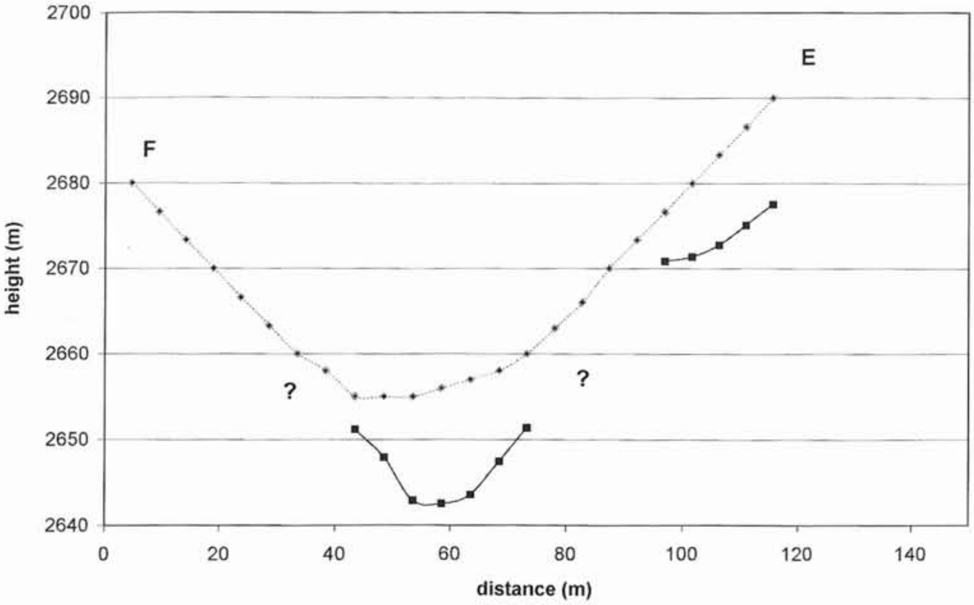


FIG. 4 - Interpretative longitudinal profile of the thickness of the ice, reconstructed on the basis of the GPR investigations of 1999 (extremes C and D are the same of fig. 2): the subdivision into two distinct bodies is well evident upword the sample point with at least two outcropping of bed-rock as roches mountonnees. In the diagram the marked line is used for the ice topography, the continuous line is used for the bedrock surface.

FIG. 5 - Interpretative F-E cross profile of the thickness of the ice, reconstructed on the basis of the GPR investigations of 1999 (the extremes are the same of fig. 2).



identify the bedrock in the middle sector of the longitudinal profile has prevented us from formulating a precise estimate of the extent of the reduction.

An example of this strong reduction emerged from the checks on the ice thickness performed on the profiles for the two years (1998 and 1999) at a sample point, represented by a stake located at the altitude of 2710 m asl. The reconstructed ice thickness in this position can be observed on the profiles for the 1999 and 1998 investigations shown in figures 3 and 4. The thickness amounted to about 14 m in 1998 and about 9 m in 1999. From field observations and from GPR survey it is possible to estimate a total reduction of about 5 m (3 m of ice and 2 m of firn) taking place between July of 1998 and July of 1999. This figure could be partly due to errors of various types (for example, the use of different antennas) but in any case, it does provide an estimate of the very high amount of ablation in the final part of the summer of 1998 and of the early ablation at the beginning of the summer of 1999.

In any case, the use of the ice thickness data collected during the 1998 surveys, supplemented with the more complete data obtained during the surveys carried out in the summer of 1999, did make it possible to define the previous reconstruction of the bedrock (D'Alessandro & *alii*, in press) more accurately. This was made possible especially through the data collected in the upper sector of the glacier, which were not collected during the 1998 surveys. It was thus possible to define the morphology of the bedrock and the respective reconstruction of the glacier thickness as shown in figure 7.

The overall results support the hypothesis of greater developments in the use of ground-probing radar for detailed surveys of glacier sites. The use of various antennas with different frequencies depending on the specific objectives of the research, seems to be indicated, even if the antenna that appears to have shown the best resolution and definition of the elements studied, the 200-MHz antenna, is, however, more difficult to use, due to its dimensions and weight, especially on steep glacier slopes cov-

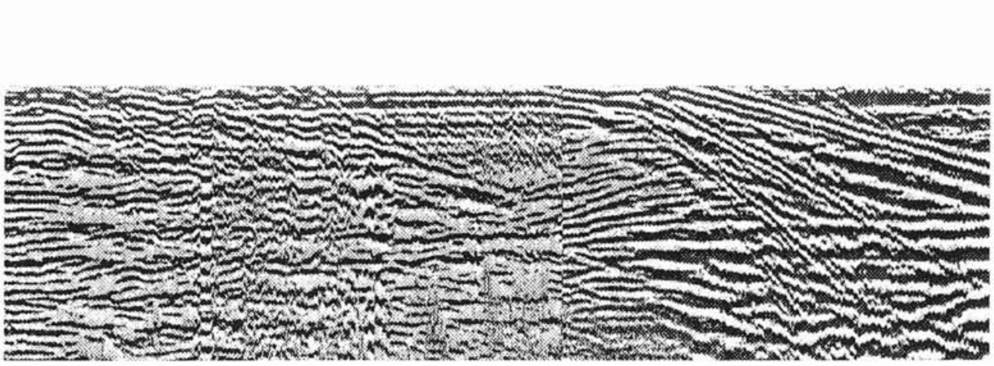


FIG. 6 - F-E cross section in the *line scan* mode, corresponding to the interpretative cross profile shown in figure 4.

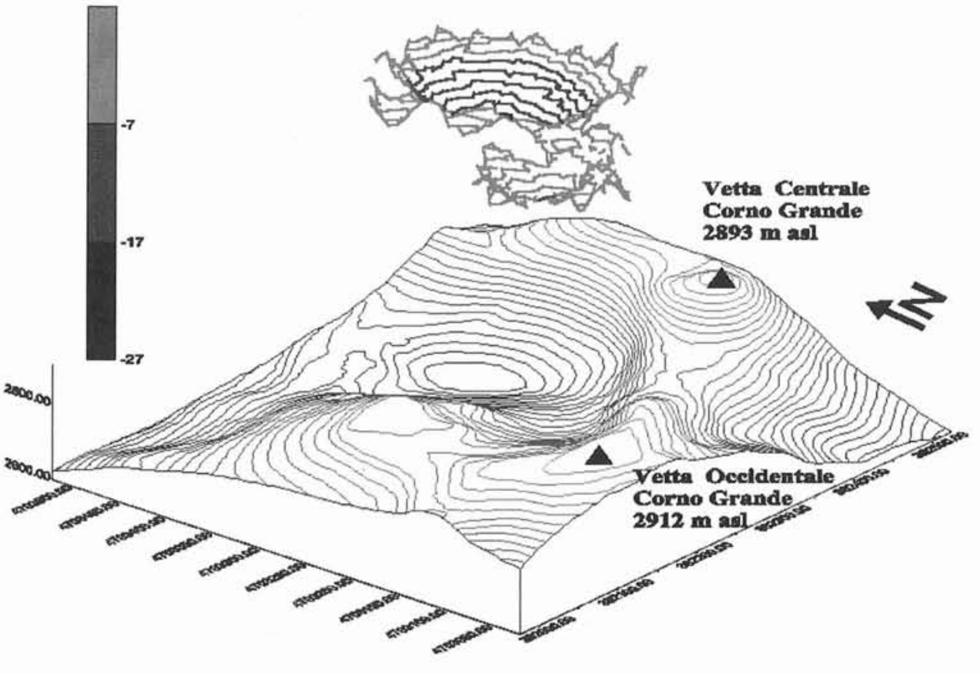


FIG. 7 - Reconstruction of the bedrock morphology and thickness of the residual ice. The graduated scale in gray tones refers to the latter. It was obtained on the basis of the 1998 reconstruction (D'Alessandro & *alii*, 1999), and supplemented with the data from the GPR campaign of July 1999.

ered with debris and snow. On the other hand, obviously, as was to be expected, the 40-MHz antenna proved to be easier to handle and use, however, to the detriment of definition.

Once the bedrock morphology has been reconstructed, and the surfaces (of bedrock and glacier), another interesting prospect seems to be represented by the evaluation of the mass balance by indirect means, through the annual measurement of the variations in the entire thickness of ice at the control points (network of poles/stakes).

In cases in which the poles have been geo-referenced in advance using traditional topographic methods, or better, using GPS, the measurement of ice ablation, measured directly on the pole, represents a means for checking the variation in the thickness of the glacier, as determined through timely GPR surveys. The continuation of the investigations on the Calderone Glacier thus could include the installation of network of 5 or 6 poles in the near future, which will serve for crosschecks.

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