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RESPONSES OF THE VAL D'ARCIA SMALL DOLOMITIC GLACIER (MOUNT PELMO, EASTERN ALPS) TO RECENT CLIMATIC CHANGES. GEOMORPHOLOGICAL AND GEOPHYSICAL STUDY

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On September 14, 1994, due to rapidly changing meteorological conditions an important debris flow on the northern slope of Mt. Pelmo (Dolomites, Eastern Alps), originating in Val d'Arcia, reached the underlying main road (S.S. 251), covering a part of it. In the detachment zone this event caused the outcropping of a small plate of ice, which extended to about a hundred metres in length, which had remained hidden by the slope debris.

Following this event a program of geomorphological, meteorological and geophysical research was carried out in the summers of 1996-99 in the Val d'Arcia. The aim was to ascertain the existence, the extension and the thickness of the mass of ice buried under the detritic cover; to locate the presence of permafrost and to find out the correlations with the debris flow, with respect to the geomorphological and meteorological local context.

The geomorphological research was based on a detailed mapping, on a 1:10,000 scale, in the area including the whole Dolomitic group of Mt. Pelmo, with a particular interest to the northern slope, where clear evidence of glacial, periglacial and gravitational processes and deposits still active have been recognised. From the study of this deposits it has been possible to reconstruct the würmian glaciation phases from the Late Glacial to nowadays. In particular, the most recent evolutional history of the glacier has been reconstructed by analysing the terminal moraines of the Little Ice Age present along the eastern sector of the Val d'Arcia.

This research has brought to light the areas involved by the debris flow of September 1994, the active landslides on the slopes of Mt. Pelmo and the gullies periodically interested by avalanches.

The geomorphological research has been complemented by a detailed meteorological analysis of the September 1994 event, carried out by ARPAV, the Avalanche Centre of Arabba (BL).

The geophysical prospection carried out in Val d'Arcia, based on a series of GPR profiles and vertical electrical soundings (VES), pointed out the structures underlying the debris cover. The GPR survey was done using a GSSI SIR-2 device, equipped with 100, 400 and 500 MHz monostatic antennas. Three longitudinal and four perpendicular to the valley axis profiles were made, for a total length of more than 2 200 metres, including the parts of profile repeated with different antennas.

The results obtained by the GPR survey along the main 1 km long profile, from West to East for the whole width of the glacier, agree with those obtained by VES which also allowed the calibration of the radargrams time scale. The very high resolution given by this technique allowed the recognition of an interface being interpreted as separation surface between the glacier ant the sub-glacial till or the bedrock and the calculation of the debris cover thickness along the GPR profiles directions.

KEY WORDS: Glacial Geomorphology, Debris flow, Georadar, Climatic changes, Eastern Alps (Italy).

RIASSUNTO: DEL LONGO M., FINZI E., GALGARO A., GODIO A., LUCHETTA A., PELLEGRINI G.B. & ZAMBRANO R., *Risposte del piccolo ghiacciaio dolomitico della Val d'Arcia (Monte Pelmo, Alpi Orientali) ai cambiamenti climatici recenti. Studio geomorfologico, meteorologico e geofisico.* (IT ISSN 0391-9838, 2001).

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This multidisciplinary research, carried out in the frame of the MURST National Project «Risposta dei processi geomorfologici alle variazioni ambientali», Research Unit of the University of Padua (Responsible for MURST funding Prof. G.B. Pellegrini) has been performed by researchers of the Dipartimento di Geologia, Paleontologia e Geofisica (Università di Padova) (E. Finzi, A. Galgaro, G.B. Pellegrini e R. Zambrano), of the Dipartimento di Georisorse e Territorio, Politecnico di Torino (A. Godio) and of the Arabba Experimental Avalanches and Hydrogeological Defence Centre, nowadays Research Centre of Veneto Region Environment Precautions Agency (ARPAV), under the direction of A. Luchetta (A. Luchetta, T. Robert Luciani and W. Cagnati, G. Fenti, R. Gnec, L. Roncat, W. Testor, M. Toldo, A. Viel). Dr. M. Del Longo took part in the research and some graduates of the Dipartimento di Geologia, Paleontologia e Geofisica (Università di Padova) have co-operated (R. Artioli, G. Muffato, A. Stella) during stages on the use of geophysical methods in the subsoil investigation.

A special acknowledgement is adressed to Dr. A.Luchetta, for his support by the ARPAV staff to the fieldwork logistics and for the meteorological informations on the September 14 1994 event.

Il 14 Settembre 1994, in concomitanza con particolari condizioni meteorologiche a rapida evoluzione, si originò nella Val d'Arcia, sul versante settentrionale del Monte Pelmo (Dolomiti, Alpi Orientali), un importante trasporto in massa di detriti (*debris flow*), che raggiunse la sottostante S.S. n° 251 della Val di Zoldo, invadendone la sede stradale. Nella zona di distacco questo evento portò all'affioramento di una placca di ghiaccio, estesa in lunghezza un centinaio di metri, la cui esistenza era rimasta fino ad allora nascosta dai detriti di versante.

Alla luce di questi eventi è stato condotto nelle estati del 1996-1999, un programma di ricerche geomorfologiche, meteorologiche e geofisiche nella Val d'Arcia. Lo scopo era di accertare l'esistenza, l'estensione e lo spessore della massa di ghiaccio sepolta sotto la copertura detritica, di individuare la presenza di *permafrost* e di inquadrarne le correlazioni, nell'ambito di un contesto geomorfologico e meteorologico locale, con il *debris flow*.

La ricerca geomorfologica si è basata su di un rilievo di dettaglio, in scala 1:10.000, dell'area comprendente l'intero gruppo dolomitico del M. Pelmo, con particolare riguardo al versante settentrionale, dove sono stati riconosciuti evidenti testimonianze di processi e depositi glaciali, periglaciali e gravitativi tuttora in atto. Dallo studio di tali depositi è stato possibile ricostruire le fasi della glaciazione würmiana dal Tardiglaciale ad oggi. In particolare, dall'analisi dei depositi morenici frontali presenti lungo il settore orientale della Val d'Arcia, riferibili alla Piccola Età Glaciale, si è potuto ricostruire la più recente storia evolutiva del ghiacciaio.

Questa indagine ha messo in evidenza le aree interessate dal *debris flow* del Settembre 1994, le frane attive nei diversi versanti del M. Pelmo e i canaloni percorsi periodicamente da valanghe.

La ricerca geomorfologica è corredata da un'analisi meteorologica di dettaglio dell'evento del Settembre 1994, curata dall'ARPAV, Centro Valanghe di Arabba (BL).

L'indagine geofisica condotta in Val d'Arcia, basata su una serie di prospezioni GPR (georadar) e di misure elettriche di resistività (SEV), ha consentito l'individuazione delle strutture sepolte sotto la copertura detritica. Il rilievo GPR è stato condotto con un'apparecchiatura GSSI SIR-2, equipaggiata con antenne monostatiche da 100, 400 e 500 MHz. Sono stati eseguiti 3 profili longitudinali e 4 trasversali all'asse vallivo, per una lunghezza complessiva, considerando anche i tratti di profilo ripetuti con le diverse antenne, di oltre 2 200 metri.

I risultati ottenuti con il metodo georadar, lungo il profilo principale di circa 1 km, esteso da Ovest verso Est per l'intera larghezza del ghiacciaio, concordano con quelli ottenuti dai Sondaggi Elettrici Verticali, che inoltre hanno reso possibile la taratura della scala dei tempi dei radargrammi. L'altissima risoluzione consentita da questa tecnica ha permesso di riconoscere un'interfaccia interpretabile come superficie di separazione tra il ghiaccio e la morena di fondo o il *bedrock* e di quantificare lo spessore della copertura detritica lungo le direzioni dei profili georadar.

TERMINI CHIAVE: Geomorfologia glaciale, Debris flow, Georadar, Variazioni climatiche, Dolomiti (Alpi Orientali).

FOREWORD

The debris flow which took place on September 1994 on the northern slopes of Mt. Pelmo, owing to particular meteorological conditions, has been the reason for a multidisciplinary analysis of the geomorphological processes which characterise this Dolomitic area. This event led us to begin an intense geomorphological, meteorological and geophysical study of Val d'Arcia, to achieve a palaeogeographic reconstruction of the effects of climatic changes which took place in this area since Late Glacial.

With this in mind a detailed geomorphological map was carried out at the scale of 1:10,000 of the whole Mt. Pelmo Dolomitic Group and a series of geophysical surveys, GPR and VES, in order to identify the presence of ice below the detritic cover and to value its thickness. The study of Val d'Arcia and the surrounding areas till lets us recognise the würmian deglaciation since the Late Glacial, with specific regard to the northern slope of Mt. Pelmo, where glacial, periglacial and gravitational processes and till of Little Ice Age have been recognised. A synthetic analysis of the geological-tectonic structure and an accurate meteorological study complete the geomorphological research in Val d'Arcia and provide not only the factors which produced the present face of this valley, but also the causes which generated a mass movement i.e. the debris flow which even now is found on the northern slope of Mt. Pelmo.

This phenomenon causes high risk conditions in the eastern Alps area (and not only); in the Mt. Pelmo zone the debris flow can most likely be connected both with the Val d'Arcia glacier, buried below a detritic slope cover, and to specific meteorological conditions which are the main triggering factor.

The geophysical survey was aimed to check the effective resolution capacity and the penetration of GPR and VES in this particular type of detritic and glacial deposits and to recognise buried ice, evaluating the thickness variations in order to estimate its volume. The geophysical data acquisition was obstructed by the morphological features, due to steep slopes and an irregular topography. The strongly varying texture with huge detritic cover blocks caused a number of difficulties, both during the GPR survey in the antenna towing along the transects and in the coupling with the ground, and during the electrical soundings, due to the high electrical resistivity values in the electrode/ground contact.

The ice thickness values obtained by the GPR interpretation were highly variable, between a few metres and more than 20 metres; the detritic cover reaches and even exceeds a couple of metres and this data are in accordance with the VES data, carried out with the aim to check the GPR.

The meteorological event of 14 September 1994 has been studied by the ARPAV, the Avalanche Centre of Arabba (BL). Only its most important data are presented in this article: a more detailed study will be published in the future concerning that phenomenon in its space-temporal evolution and the effects produced by the Mt. Pelmo debris flow.

GEOMORPHOLOGICAL SETTING

The northern slope of Mt. Pelmo is characterised by a large morphological step with an overlying transversal valley, Val d'Arcia, hanging at an altitude of about 2200 metres. This valley is superimposed on a tectonic line due to a south-vergent backthrust which reaches the great fissure which separates Mt. Pelmo (3168 m) and Mt. Pelmetto (2983 m) from the Val d'Arcia Fork. In this zone there is morphological evidence of a dextral movement towards North of Mt. Pelmetto with respect to Mt. Pelmo. Val d'Arcia thus results closed westwards by the Mt. Pelmetto steep cliffs.

The tectonic line is almost completely in Dolomia Principale (fig. 1); the Dachstein Limestones Formation is involved only in the area of Val d'Arcia Fork. The presence of backthrust well explains the structural origins of this valley: it can be said that the glacial and periglacial phenomena, which occurred and are still active in this area, characterising its landforms, developed in the area of main erodibility due to the mentioned tectonic movement.

Val d'Arcia shows a topographic decrease from East to West (from 2476 to 2260 m); the more western area is intensely affected by gravity and avalanches processes. The great amount of detritic deposits is due to the erosion of the cliffs of the overlying relieves and flows into the deep fracture of La Fessura, also known as La Fissura (Angelini, 1987). This fracture is interrupted in its central part by a saddle situated at 2758 m of altitude. During particularly strong meteorological events large amounts of detritus move from La Fessura and, as debris flow, cross the glacial deposits existing in the central-west sector of Val d'Arcia reaching the Val Fiorentina valley floor.

THE VAL D'ARCIA GLACIER

During the various phases of Pleistocene Val d'Arcia was affected by notable thickness of ice, not only produced by direct supplying but mainly by avalanches along La Fessura and along gullies cutting the steep northern cliffs of Mt. Pelmo (Zanon, 1990). La Fessura was also filled by ice supplying the Val d'Arcia glacier.

During the last maximum glaciation the glaciers of the Boite, Maè and Fiorentina Valleys bordering the northern sector of Mt. Pelmo, reached the maximum level of 2100 metres. It is probable that in that time a glacial mass connected uninterruptedly also the Fessura area to the valley floor glaciers.

The climatic changes of Late Glacial gave origin in these valleys to important variations of glacial tongues; during the initial phases of retreat they divided from each other, assuming their own form. During strong climatic changes, near the front of the local glaciers of Mt. Pelmo, heterogeneous detritus accumulated as elongated ridges delimitating the areas already filled by the glaciers. Their peculiar distribution allowed us to reconstruct their geometry.

Using the position of the morainic ridges and the equilibrium line altitude (ELA) of the local underlying glaciers it has been possible to reconstruct the shape of the surface, both in the Val d'Arcia glacier and in the whole Pelmo Group during the lower Dryas, and also recognise at least two expansion phases: the Bühl stage and the Gschnitz stage (fig. 2) (Del Longo, 1998).

The more recent Late Glacial stages have not been recognised as the rough morphology and the holocenic gravitational processes have not allowed it. Inside Val d'Arcia only two small completely grass-covered morainic ridges belonging to Late Glacial times can be found, the inner of which is attributed to Gschnitz stage (Del Longo, 1998). Almost all the detritic deposits present on the Val d'Arcia valley floor are linked to more recent events such as the Little Ice Age and to criogenic and gravitational processes. While the gravitational processes in the eastern part of the valley are well visible, with the typical detritic fans and talus, to the West the morphology is more complex and it is sometime difficult to understand which mechanism produced the different forms. In general the criogenic processes in this Alpine sector can be considered active at altimetric level higher than 2500 metres, where a frequent variation in temperatures around zero with maximum in the spring and autumn periods occurs (fig. 3). Using the thermal gradient of 0.53 °C/100 m, obtained by the comparison of the average monthly temperatures of the Selva di Cadore station (1470 m) with that of Punta Giatei (2183 m), the height of an average annual temperature of zero has been evaluated as being 2550 m. It has been found that Val d'Arcia, situated between 2476 and 2260 m, is strongly influenced by the effects produced on the rocks by freezing and thawing.

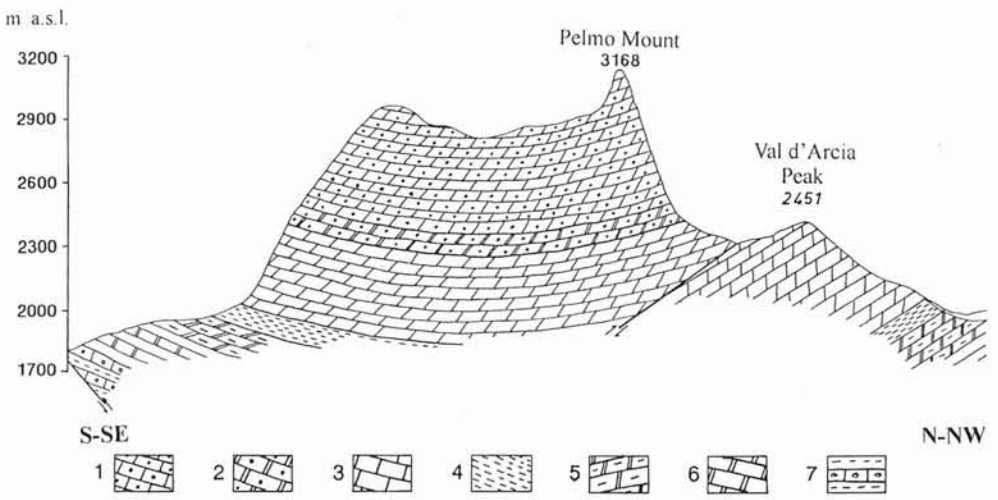

FIG. 1 - Geological section of Mt Pelmo (stratigraphic succession: 1 - Calcari Grigi; 2 - Dachstein Limestones; 3 - Dolomia Principale; 4 - Raibl Formation; 5 - Dürrenstein Formation; 6 - San Cassiano Formation; 7 - La Valle Formation.

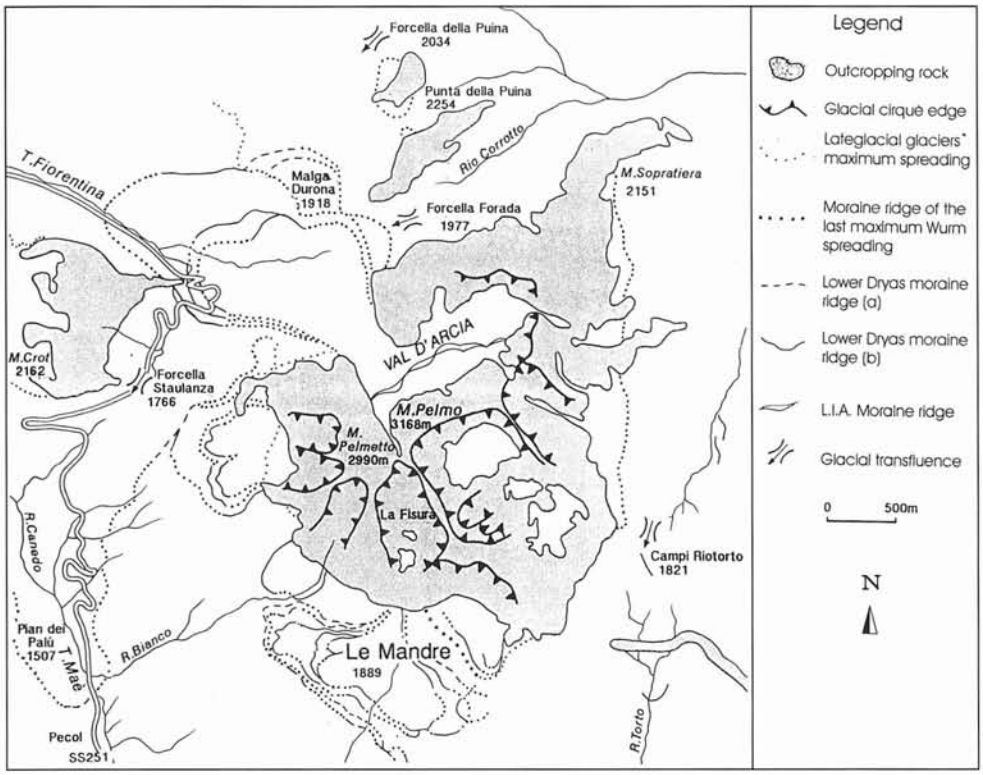

FIG. 2 - The Mount Pelmo glaciers during the maximum Würmian expansion and in Late Glacial (Bühl (a) and Gschnitz (b)).

The morphological situation of Val d'Arcia is anyway sufficient to explain the great amount of detritus which covers its valley floor. Moreover, the minimum activating level of the crionival processes could be sensibly reduced, considering two important factors: the valley looks North and the very low insolation due to the height of the summits bordering the valley towards south-east and South-West which in the whole year prevent the insolation close to the cliffs. Finally, the detritus completely covering the glacier, keeps at its base a lower than outside temperature, so reducing the daily thermal variations effect.

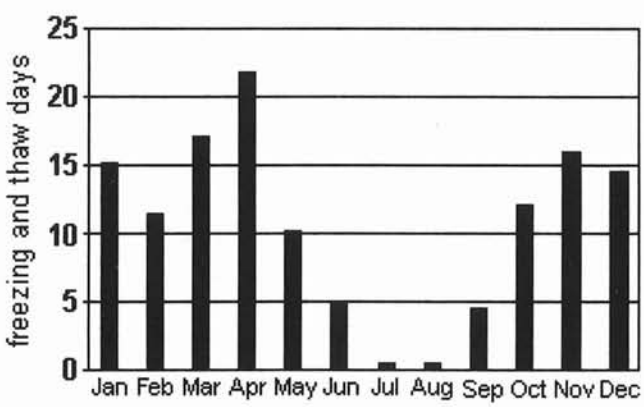

FIG. 3 - Monthly average of frost and thaw days during the 1985-1994 period at Punta Giatei (2183 m a.s.l.), near Giau Pass.

These specific local conditions have made possible the existence of a small glacier in the most western part of the Val d'Arcia with a relatively low level of its front (2140 m), despite the fact that the current level of snow-line has been estimated, on the basis of geomorphological considerations as well as of an analytical study of the existing bibliography (Del Longo, 1998), at about 2800-2900 m for the northern slope of Mt. Pelmo.

This glacier has reached its maximum recent expansion during the Little Ice Age. The frontal moraine of this last important glacial phase consists of two ridges, tightly leaning against each other, the external one being limited, downwards, by the Mt. Pelmo scree slope, exibiting conditions of discontinous permafrost in its upper part. Upstairs the front ridges there is a broad rough plain with dead ice topographically linked to a series of detritic fans and talus, from the foot of the slopes of Mt. Pelmo and Mt. Pelmetto. The extension of the hidden glacier of Val d'Arcia has been estimated 18 ha by the *World Glacier Inventory* (1982), and, according to the new data, 21,3 ha, with a minimum level at 2140 m (fig. 4, tab. 1).

The glacier is supplied not only by the avalanches but also by the melting water of seasonal snows, which refreezes below the detritus almost entirely covering the ice mass.

TABLE 1 - Comparison between the parameters of WGI (1982) and the ones obtained in 1999

	Val d'Arcia glacier World Glacier Inventory	New data
Area	18 ha	21.3 ha
Maximum length	0.40 km	0.58 km
Maximum width	0.65 km	0.80 km
Middle gradient	70 %	60 %
Basin maximum heigth	3168 m (Mt. Pelmo)	3168 m (Mt. Pelmo)
Glacier maximum heigth	2500 m	2500 m
Glacier minimum heigth	2220 m	2140 m
Prevailing exposure	NW	NW
Type	glacier	ice covered by detritus
Front	regular	regular
Longitudinal profile	regular	irregular
Main supplying	avalanches	snow & avalanches falling

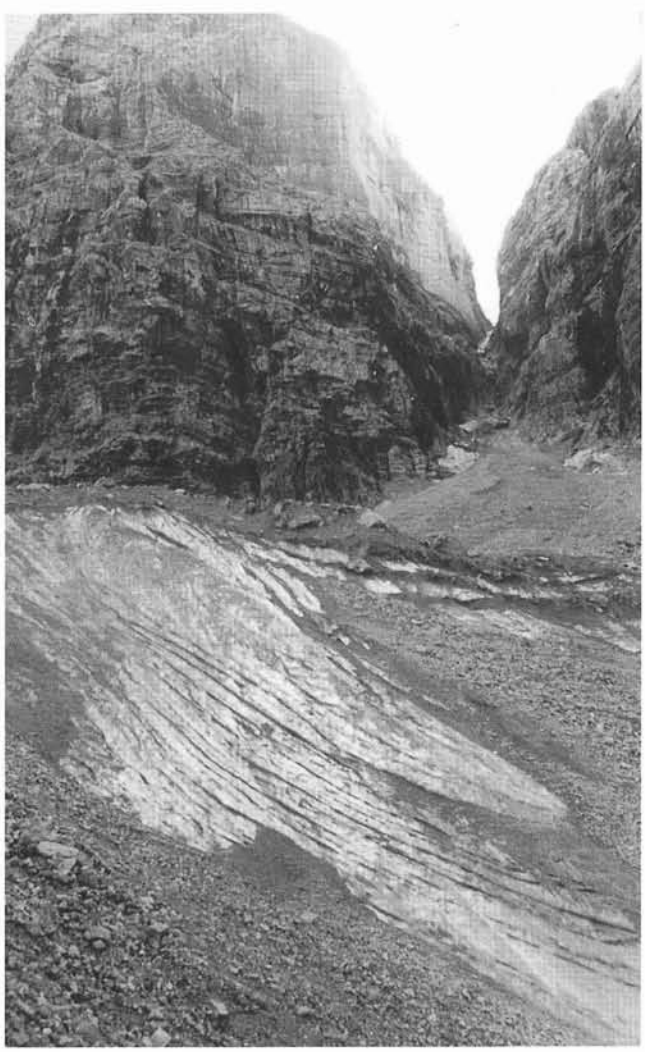

FIG. 4 - The Val d'Arcia glacier front, near the «Fessura», 2140 m a.s.l., just after the meteorological event of September 14, 1994 (photograph by M. Del Longo, 1995).

The part of the glacier next to its front, up the terminal moraine, is covered by a generally thin deritus. Since the '80s there has been a reduction of the total volume of the glacier, due to a fusion of the buried ice mass, inadequately supplied by winter accumulation.

As a consequence, the detritus surface covering the glacier has lowered, forming hollows, cracks and depressions. The movement of the detritus is, therefore, strictly linked to the activity of the underlying ice, which depends on the climate conditions occurring in the valley.

At the foot of the rocky walls, the detritus which has fallen upon the snow covered slopes, as well as the avalanche deposit creates a series of protalus remparts (fig. 5).

The melting of the buried ice mass causes slow displacements of the overlying detritus, made evident by the presence of recent undulations in the debris cover, giving to this area a morphology similar to the one of rock glaciers (fig. 6). Both the shape as well as the environment of the glacier of Val d'Arcia, especially in its eastern part, would, therefore, lead us to classify it as a rock glacier; nevertheless, other considerations, supported by the results of geophysical researches, suggest more articulate interpretation. The deposit covering the glacier in the Val d'Arcia (Zanon, 1990) consists at the moment in a thin detritus cover, underneath which there is an ice lens, locally 30 m thick, with, inside, frequent levels of detritic material.

The thickness of the ice lens gradually decreases, till a complete disappearance, starting from the terminal moraine toward the dolomitic slopes, where talus prevails. Similarly, advancing eastward from the western edge, corresponding to the couloir La Fessura, the thickness goes from its maximum value of about 30-40 m, till its complete extinction, while, at the same time, the amount of detritus included in the ice, increases.

The presence of this ice lens, evident next to the front, and the absence of any movement toward the valley of the entire detritus mass, induce us to conclude that this is not a rock glacier. In this case, since the Glacier of Val d'Arcia does not have the features of a real glacier, it would be more appropriate to classify it as «ice covered by detritus». These features allow us to suppose it may, in future, evolve, according to the models proposed by Evin (1984), into a rock glacier with an ice core.

Downstream the terminal moraines of the Little Ice Age a steep and thickly stratified talus has its origin: the North scree slope of Mt. Pelmo. The characteristics of this deposit are evident along the deep gully created by the debris flow (fig. 6). The higher part of the above mentioned talus, coinciding with the moraine of the L.I.A., is characterised by the presence of huge boulders apparently unstable, but firmly anchored to the ground by the permafrost.

THE DEBRIS FLOW OF THE NORTHERN SLOPE OF MT. PELMO

Every year the slope instability in this Alpine sector causes serious damages, not only for the casualty toll, but

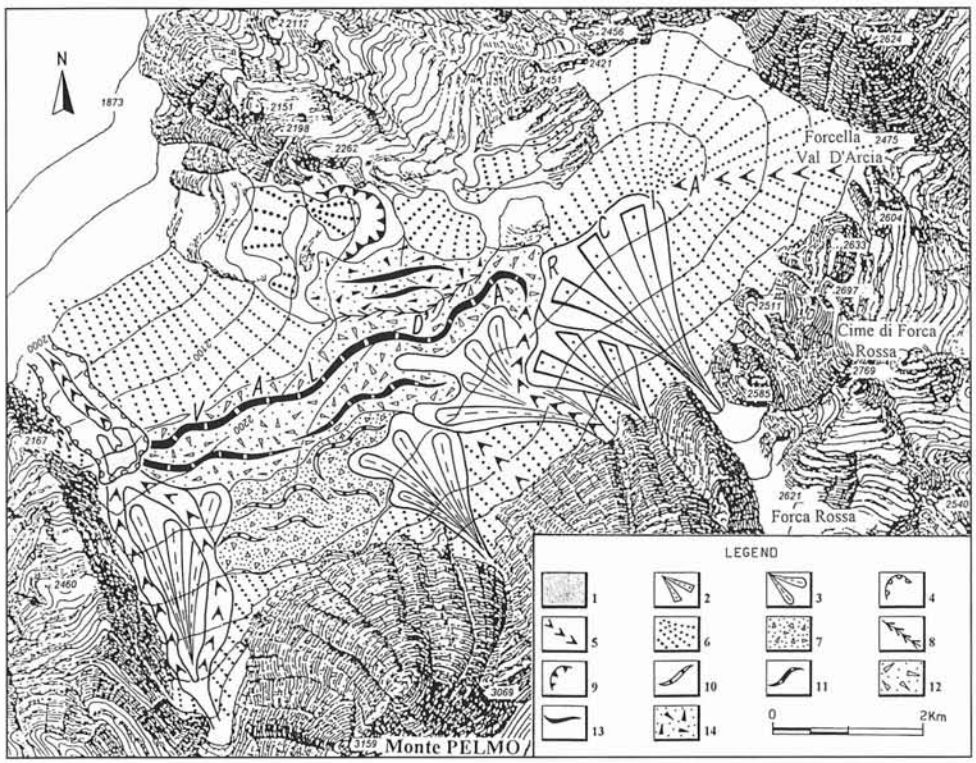

FIG. 5 - Geomorphological sketch of the Val d'Arcia. Legend: 1 - ice; 2 - talus cone; 3 - avalche cone; 4 - landslide scarp; 5 - debris flow; 6 - talus slope; 7 - talus slope with large blocks; 8 - small «V» shaped valley; 9 - nivation niche; 10 - winter-talus ridge; 11 - morainic ridge of the Little Ice Age; 12 - glacial deposits of the L.I.A.; 13 - Late Glacial morainic ridge; 14 - Late Glacial glacial deposits.

for its economic costs as well. In the Alpine area and especially in this sector of the eastern Dolomites, the most frequent and highly destructive events consist in mass movements in the shape of debris flow. This debris flow is among the most important natural processes for its influence on the morphological evolution of the hydrographic basins, as well as for the dangerous situations it creates. The data collection on them is therefore extremely important for the achievement and calibration of numerical models, as well as for a correct planning of the

FIG. 6 - The Val d'Arcia Glacier completely hidden by a large debris cover (Photograph by G.B. Pellegrini, 1996).

passive and active interventions to be carried out in high risk areas.

On September 14 1994 one of these debris flows originated in the upper part of the great detritic talus of the northern slope of Mt. Pelmo, at the level of the couloir La Fessura. The debris flow spread over an area which had never been occupied by similar previous events, as it is proved by the overlay of its debris to the Late Glacial moraines and to the preceding lateral levees of ancient phenomena of the same kind. An estimate of the volume of the detritus mobilised by this event, obtained through a series of profiles, transversal to the channel near the detachment zone, gives us a value of about 200 000 m^3 of moved material. During its movement the debris flow swept over the mule-track leading to Rifugio Città di Fiume, the S.S. n° 251 (connecting Zoldo and Fiorentina Valleys) as well as over the aqueduct supplying the settlements in the Upper Fiorentina Valley, luckily with no casualties.

The presence of the rocky slopes of Mt. Pelmo, at whose foot very steep merging detritic talus represents a geomorphological situation predisposing to the origin of such debris flows. The materials affected by this debris flow consist of a matrix whose grain sizes correspond with the ones of gravel and of sand, in which a great amount of boulders, sometimes several m^3 sized (fig. 7), is included. The presence of a lot of detritic deposits is linked to the tectonic and lithological conditions of the original rocks, to the orographic and exposure characteristics of the mountainside, as well as to the climate conditions.

The trigger of this flow took place during a highly intense though brief pluviometric event, which occurred upon contact of the rocky slopes with the detritic talus. Flowing, concentrated in the steep rocky couloir La Fessura, reached the underlying detritic talus which cover the buried ice. This caused the quick saturation of the detritic talus on the surface as well as the increment of its interstitial pressure with a consequent decrease of its shear resistance. This process also favoured the increase of the shear horizontal component of the detritic mass stress for the increased load, finally triggering the movement of a considerable amount of material rapidly flowing downwards.

The surface of the buried ice in proximity to the detachment zone, in metastable conditions for the partial melting due to the increased average temperatures during summertime (fig. 9), may have acted as a sliding plane as well as an impermeable surface favouring a quicker saturation of the material in the triggering area.

On September 14 1994, the effects of a long duration rainfall caused an elevated degree of geomorphologic risk in the whole northern area of the Belluno Province. The causative relationship between the rapid mass movement and the pluviometric situation at that time has been pointed out by a series of debris flow which occurred in the whole area involved in the meteoric event. The meteorological data concerning this event have been recorded by the Arabba Avalanches Centre (ARPAV, Belluno), by processing the data coming from a series of automatic thermopluviometric stations in this Dolomitic area, specifically in the Selva di Cadore station, 10 km from Val d'Arcia.

As for the state of the art in the analysis of the meteorological factors, since in the Alps the torrent processes and the debris flow processes usually occur during sum-

FIG. 7 - The debris flow on the northern slope of Mt. Pelmo (Photograph by A. Galgaro, 1998).

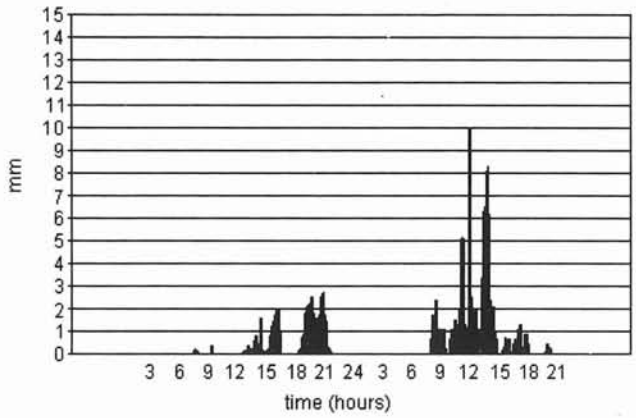

FIG. 8 - Precipitation at Selva di Cadore (1470 m a.s.l.) on September 13 and 14, 1994.

mer rains, brief and often very localised for the orographic conditioning of the stormy cells, it must be pointed out that, inside the involved basin, and especially at high altitude, a precipitation measuring station seldom exists. On the other hand, the possibility to extrapolate the data from neighbouring stations can be considered a good estimate of the critical amount rain and therefore of discharge able to trigger flow phenomena.

In September '94, the Selva di Cadore station recorded cyclic rain peaks of about 25-30 mm/day. The September 13 and 14 event, unlike the previous ones, after the night pause of the precipitations on September 13, was followed by a growth throughout the whole following day (fig. 8). During the September 14 event , the rain, alternately, reached a first peak, isolated but very intense (10 mm in 15 minutes) at 13:00, followed by a second, very intense (8.4 mm in 15 minutes) peak, at 14:45. The highest intensity of this second rainfall event, between 14:00 and 15:00, was 20 mm/h (fig. 8). The exhaustion of the second peak coincided with the activation of the debris flow, since the rain fallen over a material which had been completely soaked by the previous precipitations, producing, in La Fessura area, an amount of water such as to trigger the debris flow.

An analysis of the variations of the monthly average temperatures in 1994, in comparison with the average monthly values of the previous decade (fig. 9), concerning the nearby Punta Giatei station (2183 m), points out an increase of the summer temperatures in this area to such an extent to make us believe this could have favoured, although partially, the instability of the detritic mass. Nevertheless, not having at our disposal the thermometric data of the whole day, it was not possible to evaluate, precisely, the relations between the daily trend of this parameter and the fusion processes of the ice mass. Therefore, we cannot rule out the possibility that temperature peaks occurred such to favour the motion of the detritus resting on the upper levels of the ice mass.

THE GEOPHYSICAL ANALYSIS

The geophysical study was aimed to define the extension and thickness of the ice plate revealed by the event in September '94, and, in more general terms, to acquire likely data concerning the stratigraphies in the Val d'Arcia area.

The analysis has, as well, given a valid occasion to identify the methodologies, techniques and most appropriate instruments to be used in the specific morphological conditions typical of the deposits existing in this, as well as in other similar high altitude areas.

The survey has been carried out through GPR (georadar) profiles, combined with vertical electrical soundings (V.E.S.) and CMP test, which allowed us to calibrate the time-scale of radargrams.

The GPR prospecting method is fundamentally based on the measurement of the propagation times of electromagnetic waveform (in the frequency band of radio waves), sent into the subsurface by means of a proper transmitting antenna and sent to a recorder by means of a receiving antenna after being reflected while passing through layers (interfaces and objects) with different electrical characteristics.

The reflected signal is reconstructed by a sampling, with the possibility to collect as many as a few dozen scans per second, certainly enough to have the required resolution.

The GPR equipment consists of an electronic signal generator and of a transmitting-receiving antenna which, moving on the soil surface along transects, in real time gives back image-sections of the subsurface (radargrams), whose configuration strictly depends on the entity and position of the contrasts in electrical characteristics, encountered by the electromagnetic signal during its spreading.

The achievable penetration depth and the resolution capacity of the GPR method (that is the reciprocal of the minimum distance where it is still possible to separate, in

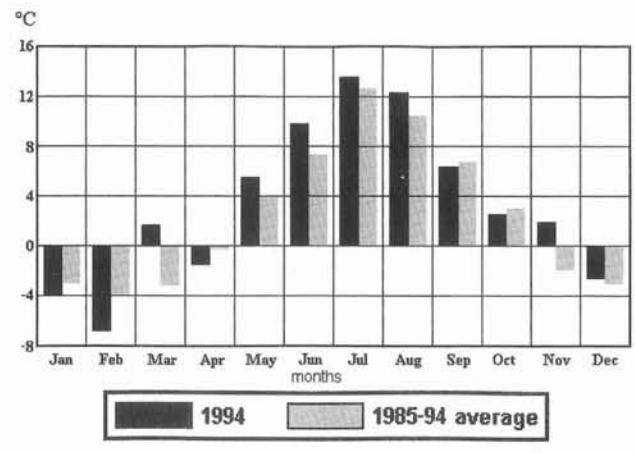

FIG. 9 - Monthly average temperatures for the 1985-1994 at Punta Giatei (2183 m a.s.l.) compared with monthly average temperatures of 1994.

the section, two close objects), depends, instead, also on the energy of the transmitted wave and on the central frequency of the transmitting antenna. In general, these two important characteristics of the system are opposed each other, and, therefore, the Val d'Arcia survey has been preceded by a series of tests of the most appropriate antenna, looking for the best compromise between the two parameters.

The implemented tests have demonstrated that, in our case, the best effectiveness could be obtained by means of antennae with central frequency of 100 and 400 MHz.

In 1997, 1998 and 1999 three field surveys have been carried out, the first two using only of the 400 MHz antenna, and the last one using also mono and bistatic 100 and 500 MHz transducers. The position of the georadar transects carried out in the three campaigns, and the VES one, are showed in fig. 10.

In general, in Val d'Arcia the recorded radargrams show a good signal to noise ratio and a stratified buried structure with few significant layers characterised by homogeneous electromagnetic properties. In the records obtained by means of the 400 MHz antenna (fig. 11 a, b, c, d), there is a clear image of the subsurface in the first 17-18 m as to the ground level (corresponding to an instrumental full scale of 200 ns, for an estimated average speed of 18 cm/ns); the cover, consisting of shallow snow (1-2 m) and of detritus as far down as 7-8 m from the g.l., is clearly visible. Below this covering, systematically, and down to the bottom of the scale, a layer characterised by a strong homogeneity, appears, which should certainly be recognised as an ice core.

In the records carried out by means of the 100 MHz bistatic transducer (fig. 12 e, f) and full scale of 500 ns (corresponding, according to our estimate, to a depth of about 40 m) it is instead very evident, in the lower part of the sections, the presence of a third stratigraphic unit, mostly likely attributable to the bedrock (fig. 12, e, f), which is situated at very variable depths (from little less than 30 m to more than 40 m from the g.l.). In some cases, within the first 20 m from the g.l., some interfaces, generated by reflecting levels of detritus inside the body indicated as ice core, possibly representing high temperature deposition phases, are clearly evident. The topographic corrections and the traces equalisation have been performed according to the different speeds of movement of the antenna. In the triggering area of the debris flow, it has been indispensable to predispose an accurate topographic survey in order to make the necessary corrections of the georadar data taken along the transects. This topographical survey has been supported by ARPAV, by means of an optical total station, with respect to the GPR trajectories, so obtaining an accurate series of topographic profiles with 2 meters sampling, which allowed the correct positioning of the georadar transects on the available cartography (1:10,000) as well as an accurate altimetric correction of the radar data.

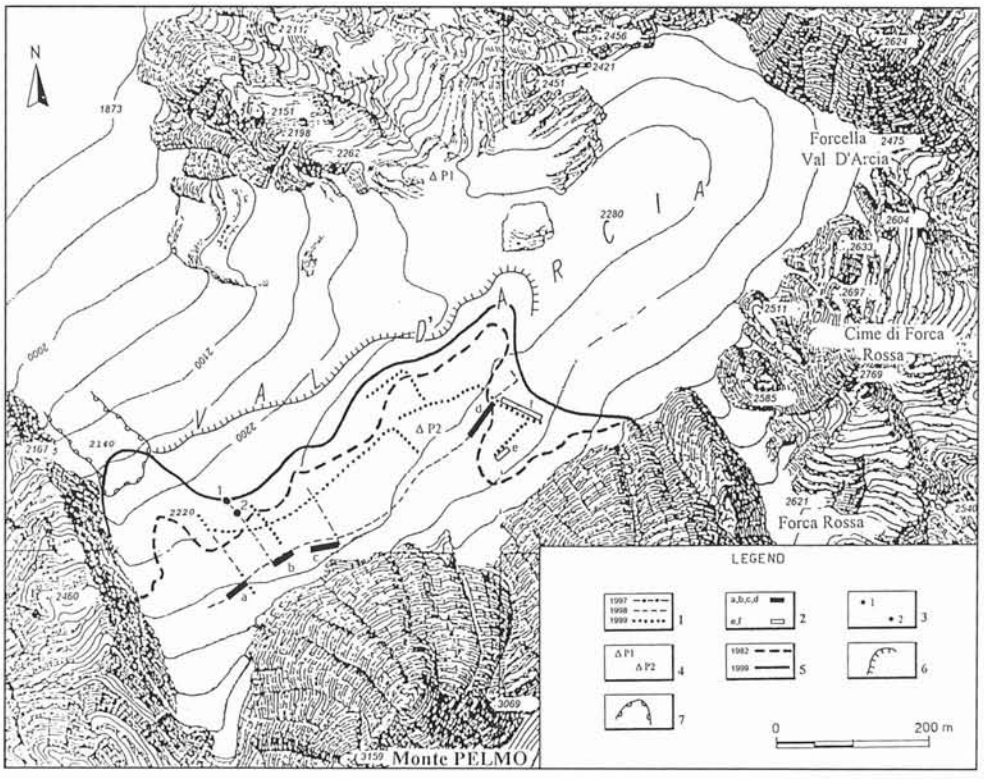

FIG. 10 - Planimetry of the G.P.R. transects and V.E.S. points. The Val d'Arcia Glacier in the W.G.I. survey (1982) and in the 1999 survey. Legend: 1 - 1997, 1998 and 1999 GPR transects; 2 - location of the transects whose radargrams are shown in fig. 11 and in fig. 12; 3 - location of V.E.S.; 4 - topographic survey base station; 5 - boundary of the Val d'Arcia Glacier (1982 survey) and of the ice covered by debris (1999 survey); 6 - scarp of the L.I.A. moranic ridge; 7 - debris flow scarp.

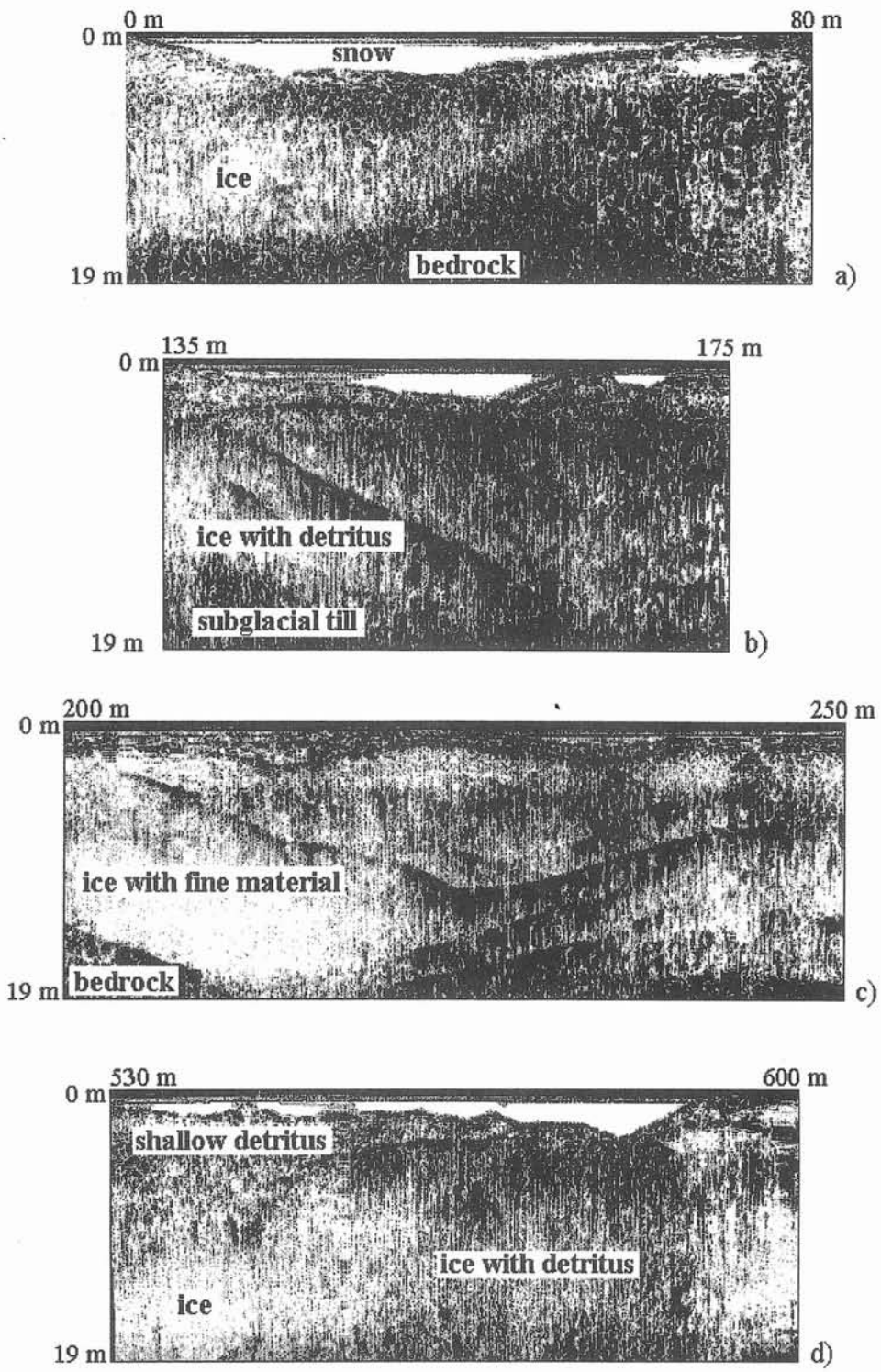

FIG. 11 - Radargrams recorded with a 400 MHz transducer. The tipologies of the different electromagnetic unities are pointed out. The location of the selected radargrams is marked in fig. 10 by a), b), c) and d) letters.

The geoelectric survey, carried out in the summer 1996, consists of two VES, located in proximity to the detachment zone of the debris flow, the first being at 2250 meters above sea level, the second one, a little to the South toward the rocky slope, at 2260 meters above sea level. VES have been carried out at a maximum of AB = 320 m, in this way obtaining stratigraphic information as far deep as several dozen meters. As expected, the interpretation of the VES plots (fig. 13) pointed out the existence of three electric layers:

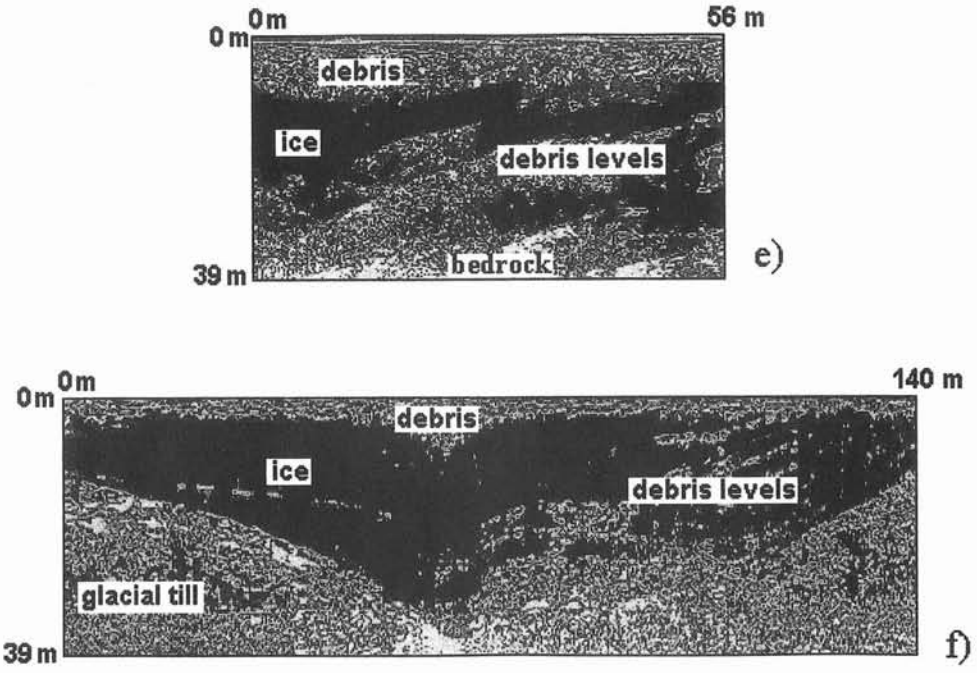

FIG. 12 - Radargrams recorded with a 100 MHz transducer. The tipologies of the different electromagnetic unities are pointed out. The location of the selected radargrams is marked in fig. 10 by e) and f) letters.

a) a shallow cover of coarse detritus probably partly included into the ice (ρ = 50 000-100 000 Ωm);

b) a second layer, quite different in the two VES. In the first sounding (VES 1) it is relatively conductive (ρ = 13 000 Ωm), 15 m thick and it can be interpreted as a sequence of coarse detritus mixed with ice; in VES 2 the layer is much more resistive (ρ > 6000 000 Ωm) a little more than 10 m thick, and, very likely, related to ice;

c) a third layer, with different characteristics in the two VES:

– in VES 1 the resistivity is ρ > 1000 000 Ωm and the thickness turns out indeterminate. This layer can be interpreted as ice;

– in VES 2, the resistivity is about 10 000 Ωm. Very likely, it corresponds to the rocky, dolomitic-calcareous bedrock.

CONCLUSIONS

The climate changes which occurred since Late Glacial up to nowadays in the Dolomites area and, specifically, in the Mt. Pelmo area, have determined such remarkable morphologic changes in the Val d'Arcia glacier, that at present it looks like an ice mass covered with detritus, rather than a real glacier.

A teamwork of specialists in different fields has made it possible to obtain an integrated vision of the processes in this area, especially from the Little Ice Age to nowadays, and to compose them in the palaeogeographic reconstruction of this Dolomitic area.

The geomorphological survey has pointed out glacial, periglacial and gravitative processes and deposits unknown in literature. Specifically, on the base of a detailed survey at 1:10,000 scale, the phases of the würmian degla-

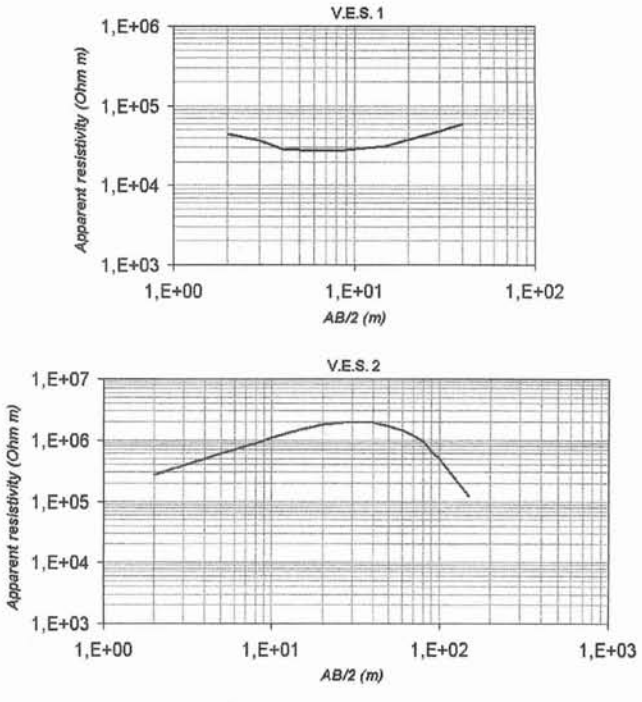

FIG. 13 - Apparent resistivity plots for VES 1 and VES 2.

ciation have been reconstructed, from the Late Glacial to nowadays, carefully paying attention to the morainic deposits of the Little Ice Age, delimiting Val d'Arcia to the West, opposite the great Mt. Pelmo detritic slope.

Val d'Arcia is settled along a tectonic line due to a southward backthrust which has affected only the Dolomia Principale.

The new detailed surveys, and the data emerging during the debris flow event on September 14 1994, allowed us to place the front of the Val d'Arcia glacier at 80 m deeper in comparison with the data obtained by WGI (1982), and 57 m in comparison with O. Marinelli's survey in 1909. Also the data on its length and width have turned out different (tab. 1) and the area of buried ice has been valued 21.3 ha.

The debris flow on September 14 1994 has left a deep channel in the Mt. Pelmo scree slope, a detailed topographic survey of which has been carried out (in a different publication) and the volume of the detritus involved in the rapid mass movement has been estimated in 200 000 m^3.

The meteorologic event which has provoked such an important phenomenon has been described at length using the pluviometric data coming from a series of stations, controlled by the Arabba Avalanches Centre, mainly the Selva di Cadore station, 10 km from the debris flow area. After a summer season characterised by frequent rain events of about 30 mm/day, there have been two days (September 13 and 14) with highly intense rains. Specifically, during the second day, there have been rain peaks of 10 and 8,4 mm in 15 minutes, with a peak of hourly intensity of 20 mm.

The amounts of rain fallen on September 13 and 14 have been, respectively, 34,4 mm and 81,2 mm, giving 115,6 mm in two days. These values, relatively modest (during the flooding on November 3-4 1966 in Agordino and in the nearby Val di Zoldo there was an average of 300 mm of rain in two days), prove that what has provoked these phenomenon of debris flow, was the high values of intensity in a short period following several days with intense precipitations, rather than the amount of daily rain.

On the basis of these investigations, we think that the decisive element in the debris flow phenomenon, must be recognised in the specific meteorologic conditions on September 13 and 14 1994, because the ice mass, buried under the detritus in Val d'Arcia was just a marginal factor, the contribute of the melting water being modest. The presence, instead, of a surface of ice highly inclined in the same direction of the mountainside, and in conditions next to the melting, has favoured the detachment of the water saturated detritus.

The geophysical survey has been carried out in three years, from 1996 to 1999, with the execution of three longitudinal profiles, and four transversal to the valley, for more than 2200 m in length, also including the parts of profile repeated with the various antennae. The recordings obtained with the GPR instrumentation, equipped with two 400 and 100 MHz antennae, made it possible to define, rather clearly, the area limits and the thickness of the ice buried in Val d'Arcia. The use of the 400 MHz antenna, besides confirming the data pointed out by the geomorphological investigation, gave a clear image of the first 17-18 m below the ground level. Below this covering, and up to the full scale, a very homogeneous unit, interpreted as ice core, appears systematically.

The records obtained through the 1000 MHz antenna and 500 ns full scale (fig. 12) show, very clearly, the presence, in the lower part of the sections, of a third unit, which has been assigned to the bedrock, located at 30-40 m depths. The areas with glacial deposits included in the ice core are frequent.

The data obtained along the georadar transects have been equalised with respect to the movement irregularities of the antenna, using the accurate topographic survey carried out along the 2200 m of profiling. Also the VES have pointed out the existence of the three main layers: the shallow cover, the detritus mixed with ice and the ice lenses with very high resistivity ($\rho > 6\ 000\ 000\ \Omega m$). The data obtained by the geophysical survey, besides confirming the geomorphological hypothesis, made it possible to estimate the new dimensions of the ice buried in the Val d'Arcia and to supply a first evaluation of its volume, valued in 4 million m^3. It is a remarkable water supply, which can probably be found also in other small glaciers buried in the Dolomites, which could, therefore, be the subject of specific surveys in the future.

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