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LATE PLIOCENE-HOLOCENE DEBRIS FLOW DEPOSITS IN THE IONIAN SEA (EASTERN MEDITERRANEAN)

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Riassunto. Dall'esame delle litologie rinvenute in depositi di debris flow carotati dal Mediterraneo Orientale si è constatato che esiste una relazione sistematica fra litologia e posizione fisiografica. Se da una parte gli alti morfologici sono sede di sedimentazione pelagica, dall'altra, nelle zone depresse, si alternano sedimentazione pelagica e processi di risedimentazione. Per quanto riguarda i processi di risedimentazione, le correnti di torbidità ed i debris flow sono i meccanismi di trasporto più comuni.

In questo lavoro presentiamo uno studio del meccanismo di debris flow nel Mare Ionio tramite descrizione visiva, analisi granulometrica, analisi calcimetrica e analisi mineralogica di carote di sedimento prelevate nel corso degli ultimi 20 anni. Distinguiamo tra i debris flows provenienti dai margini continentali (Nord Africa e Scarpata di Malta) e quelli avvenuti nei piccoli bacini che formano la topografia "Cobblestone" delle dorsali Calabra e Mediterranea. Come conseguenza della diversa posizione fisiografica, i primi coinvolgono una grande varietà di litologie e di età, mentre i secondi interessano i sedimenti pelagici che formano la tipica successione sedimentaria Plio-Quaternaria del Mediterraneo Orientale. Uno studio dettagliato delle strutture dei clasti e della matrice dei depositi di debris flow, ha reso possibile la loro descrizione nell'ambito delle esistenti classificazioni dei flussi gravitativi di sedimento e ha permesso di ipotizzare un meccanismo di supporto dei clasti. Infine, la biostratigrafia e la presenza di livelli marker aventi grande estensione ci ha permesso di datare la messa in posto dei depositi di debris flow e di ipotizzare i meccanismi che li hanno originati. Si possono quindi mettere in relazione tre di questi depositi con la deposizione dell'omogenite, una torbidite pelagica originata dall'eruzione esplosiva del vulcano Santorini (eruzione Minoica, circa 3500 BP). I depositi rimanenti hanno invece un'età variabile da 9000 BP a circa 70000 BP. Questi sono stati innescati sia da eventi sismici che da instabilità dei versanti che delimitano il Mediterraneo Orientale, in coincidenza con l'abbassamento del livello marino durante i periodi glaciali.

Abstract. Widespread coring of the Eastern Mediterranean Basin has outlined the existence of a systematic relation between lithology of debris flow deposits and physiographic setting. Whilst the topographic highs are characterized by pelagic sedimentation, the basin floors are alternatively subject to pelagic sedimentation and re-sedimentation processes. Amongst the latters, turbidity flows and debris flows are the most common transport mechanisms.

In this paper we present the study of the debris flow process in the Ionian Sea using visual description of cores, grain size, carbonate content and smear slide analysis carried out on gravity and piston cores recovered over the past 20 years. A distinction has been made between debris flow deposits originating from the continental margins (North Africa and Malta Escarpment) and those emplaced in the small basins amidst the Calabrian and Mediterranean ridges "Cobblestone Topography". As a result of the difference in setting, the former debris flow deposits include a great variety of lithologies and ages whilst the latter involve the pelagic sediments forming the typical Eastern Mediterranean Plio-Quaternary succession. A detailed study of clast and matrix structures makes it possible to describe the flows in terms of existing classifications of sediment gravity flows and to assume a clast support mechanism. Finally, biostratigraphy coupled with the presence of widespread marker beds enabled us to estimate the age of emplacement of the deposits and to hypothesize a triggering mechanism for flow initiation. Three flows are strictly related to the pelagic turbidite named homogenite, triggered by the explosive eruption of the Santorini volcano (Minoan eruption) and therefore have an estimated age of 3,500 BP. The other deposits have ages ranging from 9,000 BP to about 70,000 BP and were originated by debris flows triggered by events such as earthquakes and glacial low sea level stands.

Introduction.

In subaerial environments, highly concentrated, highly viscous sediment-fluid dispersions moving downslope under the pull of gravity can carry boulders up to several meters in diameter (Jahns, 1949, 1969; Johnson, 1970; Curry, 1966) and up to 2.7 million kg in weight (Takashi, 1981). These slurries have densities ranging from 2.0 g/cm^3 to 2.5 g/cm^3 and move with speeds of up to 20 m/s. In submarine environments similar flows can move for hundreds of kilometers on slopes having an inclination of less than 1° (Prior & Coleman, 1982; Damuth & Flood, 1984; Simm & Kidd, 1984; Thornton, 1984) and may carry (or push) enormous slabs weighing up to about 2300 million kg (immersed weight, Marjanac, 1985).

This process, known as debris flow, is described by Middleton & Hampton (1976) as "the sluggish downslope movement of mixtures of granular solids (e.g., sand grains, boulders), clay minerals and water in the response to the pull of gravity" and by Takashi (1981) as "a flow in which the grains are dispersed in a water or clay slurry with the concentration a little thin-

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FLOW BEHAVIOUR	FLOW TYPE		SEDIMENT SUPPORT MECHANISM
FLUID	FLUIDAL FLOW	TURBIDITY CURRENT	FLUID TURBOLENCE
		FLUIDIZED FLOW	ESCAPING PORE FLUID (FULL SUPPORT)
		LIQUIFIED FLOW	ESCAPING PORE FLUID (PARTIAL SUPPORT)
PLASTIC (BINGHAM)	DEBRIS FLOW	GRAIN FLOW	DISPERSIVE PRESSURE
		MUD FLOW OR COHESIVE DEBRIS FLOW	MATRIX STRENGHT MATRIX DENSITY

Tab. 1 - Sediment gravity flow nomenclature proposed by Lowe (1979). Fluidal flows are distinguished from debris flows on the basis of flow behaviour (fluid in fluidal flows and plastic in debris flows). A further distinction is made on the basis of the sediment support mechanism that keeps the larger particles above the substratum: turbulence in turbidity currents, escaping pore fluid giving full or partial support in fluidized and liquefied flows respectively, dispersive pressure due to grain collisions in grain flows and matrix strength and density in cohesive debris flows. These five flow types are to be considered end members and in most real sediment gravity flows more than one support mechanism will be important.

ner than in a stable sediment accumulation... [and] in which all particles as well as the interstitial fluid are moved by gravity".

Debris flows are part of the broader category named 'sediment gravity flows' which includes all flows consisting of sediment moving downslope under the action of gravity (Middleton & Hampton, 1976). A sediment gravity flow nomenclature was proposed by Middleton & Hampton (1973, 1976) and subsequently revised by Lowe (1976, 1979). The nomenclature after Lowe (1979) is summarized in Tab. 1 and will be used throughout this paper. Lowe (1982) also suggests that the sedimentological character of debris flow deposits depends upon both the particle support mechanism (buoyancy, dispersive pressure, matrix strength, ecc.) and the depositional mechanism (Fig. 1).

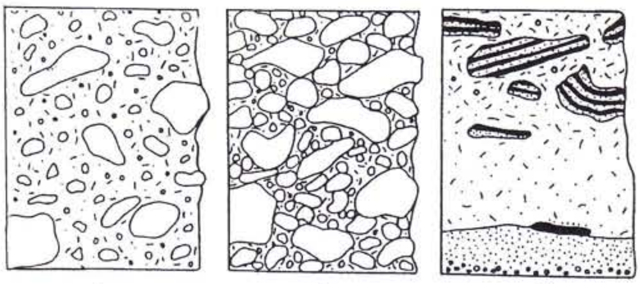


Fig. 1 - Cohesive debris flow deposits. A) Massive, structureless, matrix-supported pebbly mudstone deposited by a cohesive flow in which clasts were actually suspended in and supported by the matrix. B) Massive, structureless, clast-supported muddy conglomerate deposited by a flow in which the clasts were lubricated but not fully supported by or suspended within the matrix. C) Stratified deposit formed by suspension sedimentation of coarser quartz-density sand and gravel from the lower part of a turbulent cohesive debris flow followed by cohesive freezing of the upper part. The top of the flow deposit, from which the larger quartz-density grains have not settled, may have already been a rigid plug during accumulation of the basal suspension layer (Lowe, 1982).

The term debris flow is commonly used for both the flow process and the resulting deposit. The latter is sometimes termed debrite. In this work the term debris flow will be used to indicate the flow mechanism whilst the term debris flow deposit is going to be used to indicate the deposit. As a result of the en masse deposition process, debris flow deposits are poorly sorted, lack distinct internal layering but may have crude stratification (Hampton, 1975; Thornton, 1984; Aksu, 1984) and have poorly developed clast fabric (Lindsay, 1968; Aksu, 1984; Hiscott & James, 1985). Grading is generally poor, but both normal and inverse grading may occur (Naylor, 1980; Aksu, 1984; Shultz, 1984). The result of a submarine debris flow is therefore a coarse grained, muddy conglomerate known as pebbly mudstone in which larger clasts are embedded in a typically clay-rich matrix.

The purpose of this paper is to study the sedimentological characters of a number of Late Pleistocene to Holocene debris flow deposits recovered by piston and gravity coring in the Ionian Sea (Eastern Mediterranean).

The existing database.

In over twenty years of active exploration in the Eastern Mediterranean the Earth Sciences Department of Milan University recovered more than 250 piston and gravity cores coming from different geological and physiographic settings. A detailed micropaleontological study of the recovered sediments (Blechschmidt et al., 1982) combined with the presence of well distinguishable and widespread marker beds as Sapropels and Tephras (Cita & Grignani, 1982; McCoy, 1974; Keller, 1981) permits a high resolution stratigraphic control and basin wide correlations within the Eastern Mediterranean Quaternary pelagic sequence. These stratigraphic tools have proved to be essential in dating the debris flow deposits and thus in understanding the mechanism of flow initiation.

For the purpose of this paper, all cores in the database were considered. Only 32 cores contain debris flow deposits. Among these, seven were selected for the present study on the basis of their thickness (not less than ten centimeters) and of representativeness of a physiographic setting (only one debris flow was selected as representative of a discrete physiographic setting).

Core	Uncorrected Depth (m)	Latitude, N	Longitude, E	Sediment Recovery (cm)
East 78 12 PC	3625	36°14.90'	17°13.80'	1169
East 78 26 PC	3197	35°51.50'	20°50.40'	1115
East 78 32 PC	3243	35°51.03'	20°50.16'	1141
BAN 80 38 GC	3289	36°18.10'	15°37.10'	207
BAN 81 31 PC	3759	35°05.75'	21°27.25'	960
BAN 86 28 PC	3208	34°05.22'	19°53.04'	110
BAN 89 21 GC	3515	34°18.35'	20°01.00'	498

Tab. 2 - Latitude, Longitude, water depth and sediment recovery for the seven studied cores.

Core	Main sedimentological characteristics of the debrite
East 78 12PC	Highly homogeneous matrix Very high silt content in matrix Low $CaCO_3$ content in matrix
East 78 26PC	Strongly dishomogeneous matrix
East 78 32PC	Very small debris flow deposit Base of a very thick, homogeneous resedimentation unit
BAN 80 38GC	Evident structures in matrix and clasts Great variety of clast lithologies and ages Long distance travel
BAN 81 31PC	Very small debris flow deposit Base of a very thick, homogeneous resedimentaion unit
BAN 86 28PC	Very high sand content in matrix
BAN 89 21GC	Dark, anoxic sediment Gypsum crystals in the upper flow deposit

Tab. 3 - Brief summary of the main sedimentological characteristics of the studied debris flow deposits.

Materials and Methods.

The location of the seven cores (Tab. 2) is shown in Fig. 2. Detailed core logs are shown in Figure 3 whilst location maps and a brief description of the geological setting are given in Fig. 4. All seven cores were described and photographed aboard the ship or shortly after the end of the cruises. With a few exceptions, detailed core logs are contained in the unpublished Cruise Reports, (Cita et al., 1982a, 1982b; Kastens, 1984; Blechschmidt et al., 1982). Both the matrix and clasts of the debris flow deposits were sampled and in some cases sampling was extended to the over and underlying sediments. Overall, 38 samples were taken from the matrix of the debris flows deposits, 63 from the clasts and 29 from the overlying and underlying sediments.

After having determined the color of all samples (Munsell Soil Color Chart), the bigger samples (6-8 g) were wet sieved in order to obtain the relative abundan-

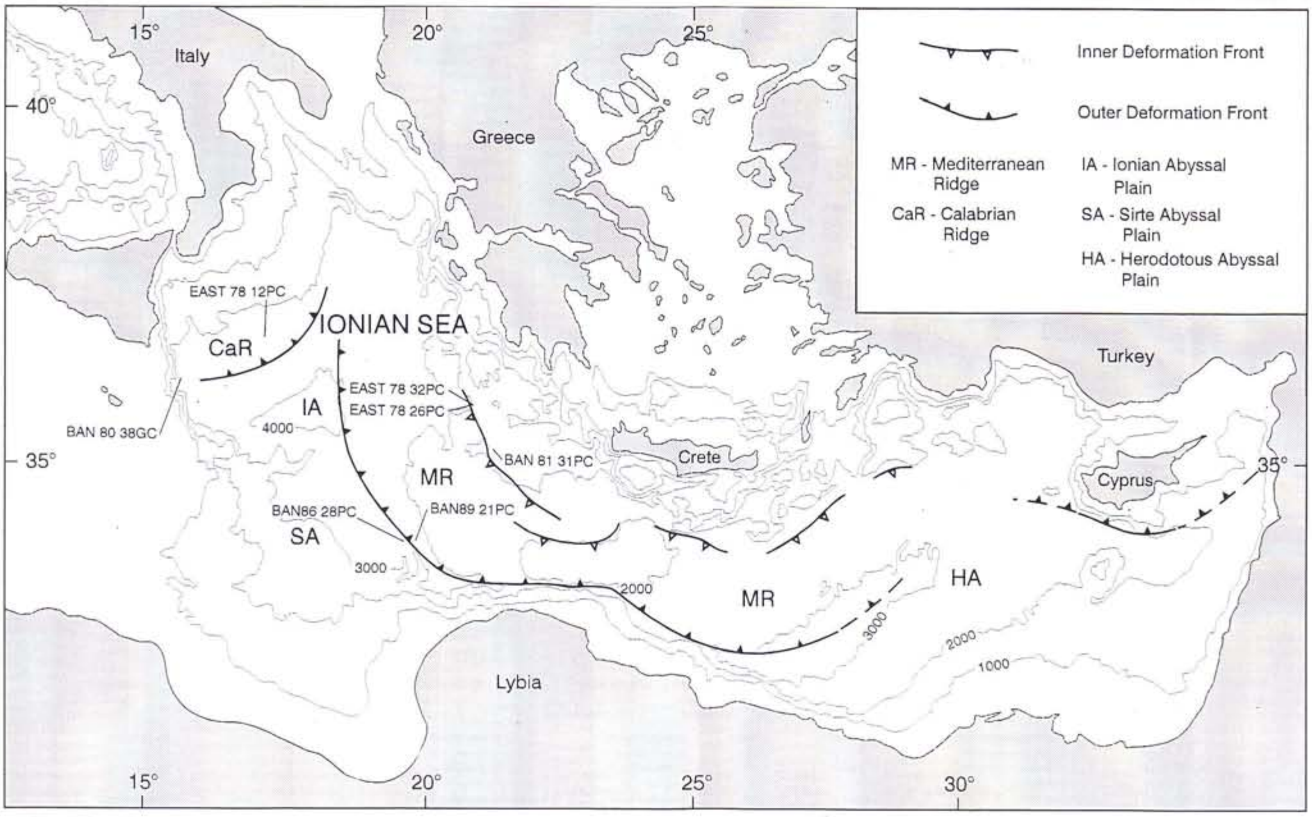


Fig. 2 - Location of the eight studied debris flow deposits within the Eastern Mediterranean basin. The Eastern Mediterranean is what remains of an ancient ocean nearly totally consumed by the subduction process created as a result of the Eurasian and North African plate convergence. The north verging subduction plane is associated with an arcuate accretionary ridge (the Mediterranean Ridge) where the non-subducted sediments of the Eastern Mediterranean abyssal plains form an imbricate structure with double vergence. In this context, the Hellenic Trenches are interpreted as fore-arc basins (Le Pichon et al., 1982), the Aegean Sea as a back-arc basin and the abyssal plains as sediment-filled subduction trenches (Cita & Camerlenghi, 1990).

Fig. 3 - Lithological core logs of the seven studied cores.

Fig. 4 - Detailed bathymetric maps with the location of the studied cores.

(i) EAST 78 12PC Beato Angelico Trough, base of slope.

The Beato Angelico trough is a NE-SW elongated basin part of the "Cobblestone topography", a seabed feature typical both of the Calabrian and Mediterranean ridges (Hersey, 1965) consisting of a series of parallel ridges and troughs having a wavelength ranging from 500m to 1000m and a depth ranging from 50m to 500m. The Calabrian and Mediterranean ridges are accretionary complexes (Le Pichon et al., 1982) with an arcuate shape and a vertical relief of up to 1500m. They are related to the subduction of oceanic crust under the Calabrian and Hellenic arcs along Benioff planes (Papazachos & Cominakis, 1971; Makris, 1977).

(ii) EAST 78 26PC Aphrodite Crater, base of slope and EAST 78 32PC Aphrodite Crater, basin floor.

The Aphrodite crater is a small basin of the "Cobblestone Topography" of the Mediterranean Ridge. Mud diapirs and mud volcanoes (Cita et al., 1981; Cita et al., 1982b; Camerlenghi et al., 1995) occur in this area.

(iii) BAN 80 38GC Base of Malta Escarpment.

This core comes from a relief separating a small basin from the abyssal plain at the foot of the Malta Escarpment. The Malta Escarpment is a N-S elongated feature (about 200km long) joining the Siculo-Maltese continental plateau to the Ionian abyssal plain, with a difference in altitude of over 3000m. This feature has a tectonic origin and has been modelled by submarine erosion (transversal canyons). It is currently interpreted as a passive continental margin (Casero et al., 1984).

(iv) BAN 81 31PC Mediterranean Ridge Cleft, basin floor.

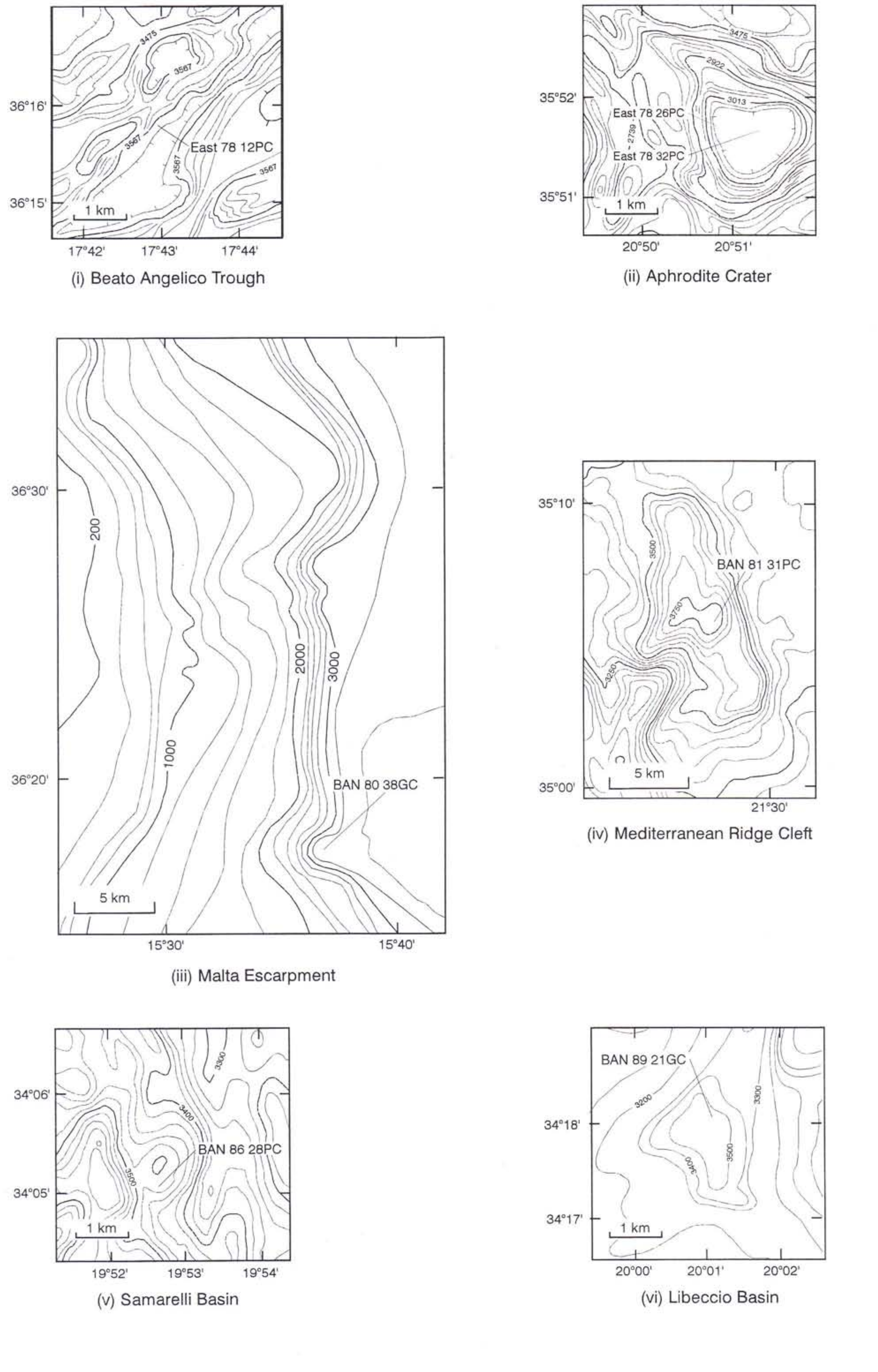
The Cleft is a NNW - SSE elongated basin lying near the Mediterranean's Ridge inner deformation front.

(v) BAN 86 28PC Samarelli basin, slope.

The Samarelli basin is a suspended basin near the outer deformation front amidst the "Cobblestone Topography", in an area where folds created after the recent deformation of the accretionary ridge underwent a change in direction.

(vi) BAN 89 21GC Libeccio basin, base of slope.

The Bannock basin, near the outer deformation front of the Mediterranean ridge, is a roughly circular depression about 15km in diameter and up to 700m deeper that the surrounding sea floor. This basin is subdivided in a series of sub-basins of which the Libeccio basin is the westernmost and deepest one (3520m). The origin of the Bannock basin depression is due to subsurface dissolution of the Messinian evaporites that caused the collapse of the overlying Plio-Quaternary pelagic deposits and the filling of the new basin with dense, anoxic brines (Cita et al., 1985; Cita et al., 1986).


36°16'
36°15'
3475
3567
East 78 12PC
1 km
17°42'
17°43'
17°44'
(i) Beato Angelico Trough
35°52'
35°51'
3475
2922
3013
2739
East 78 26PC
East 78 32PC
1 km
20°50'
20°51'
(ii) Aphrodite Crater
36°30'
36°20'
200
1000
2000
3000
BAN 80 38GC
5 km
15°30'
15°40'
(iii) Malta Escarpment
35°10'
35°00'
3500
3750
3250
BAN 81 31PC
5 km
21°30'
(iv) Mediterranean Ridge Cleft
34°06'
34°05'
3300
3400
3500
BAN 86 28PC
1 km
19°52'
19°53'
19°54'
(v) Samarelli Basin
34°18'
34°17'
BAN 89 21GC
3200
3300
3400
3500
1 km
20°00'
20°01'
20°02'
(vi) Libeccio Basin

ce of sand (>0,063 mm) and fine (<0,063 mm) fractions. Silt (between 0,002 mm and 0,063 mm) was then separated from mud (<0,002 mm) using the "Analysette 20", an optical apparatus that calculates the relative abundance of grain size fractions as a function of the amount of absorption of light passing through a settling sediment-water suspension.

All samples weighing more than 1g were then submitted to calcimetric analysis by means of reaction with diluted HCl (18%) in order to obtain the percentage of carbonates in the sediment. Finally, a semi-quantitative analysis of the non-biogenic and biogenic component of the sediment samples was carried out with the smear-slide method.

Analysis of piston cores.

A brief summary of the main sedimentological characteristics of the studied debris flow deposits is given in Table 3.

Core East 78 12PC - Calabrian Ridge, Beato Angelico trough, base of slope.

In this 90 cm thick debris flow deposit, numerous soft clasts up to 4 cm in diameter are embedded in a fine grained, uniformly colored, structureless matrix. The grain size distribution curve obtained for the matrix (Fig. 5) shows very limited vertical variations, a very high silt fraction content (average 90%) and very low sand and clay contents (4,5% and 5,4% respectively). The carbonate content is low (average 32%) compared with the other debris flow deposits (circa 40% or greater) and it does not vary downcore in a significant way. Smear slide analysis shows that the matrix is composed mainly by the calcareous biogenic fraction (the terrigenous fraction is not shown in Fig. 5) and that calcareous nannofossils are the dominant microfauna.

Calcimetric and smear slide analysis carried out on eleven clasts show how they do not vary much in composition and underline their highly variable carbonate content (from 9% to 63%).

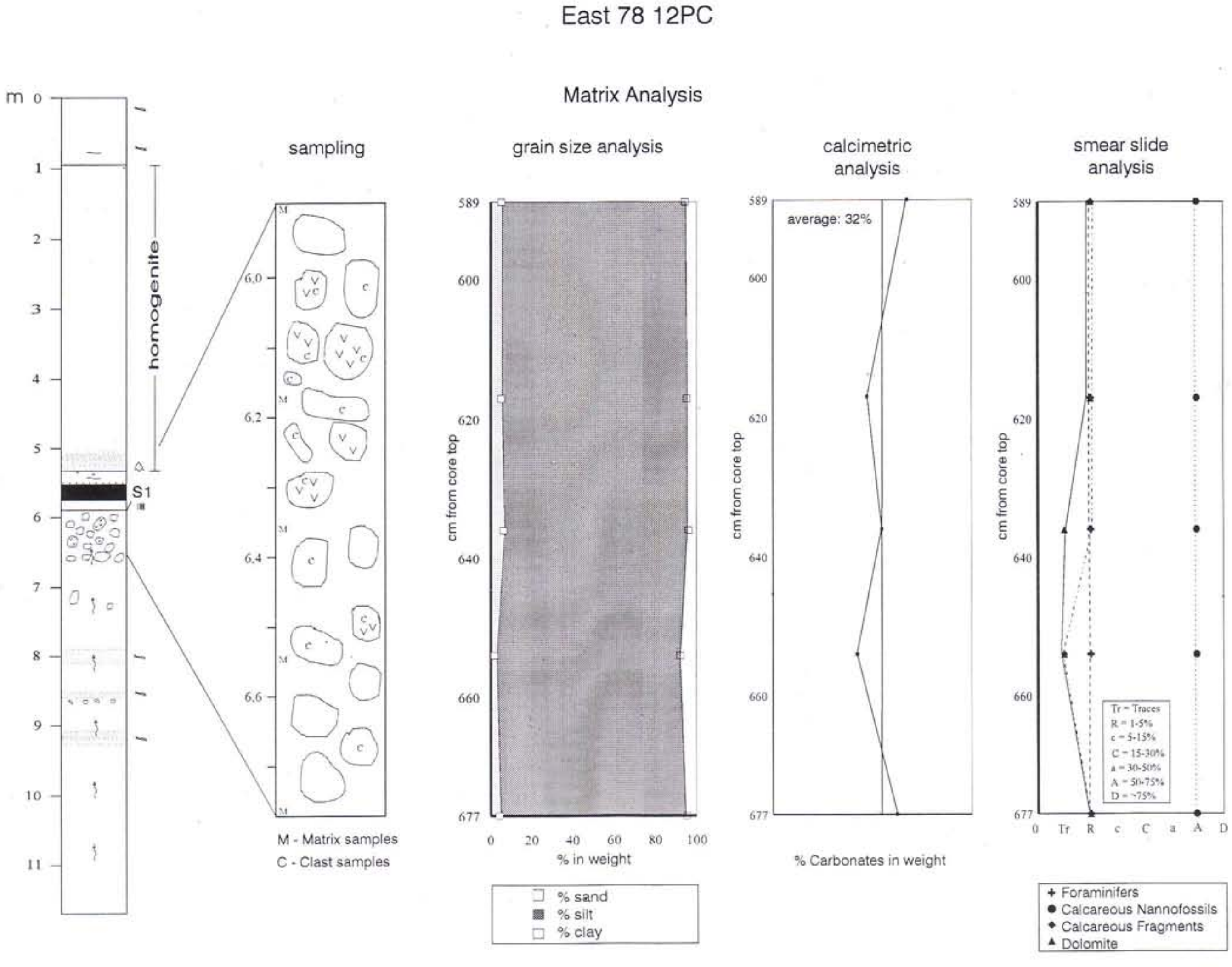


Fig. 5 - Results of the analysis carried out on the matrix of the debris flow deposit cored in the Beato Angelico Trough. All of the curves underline the homogeneity of this deposit. Note the high silt content, the low $CaCO_3$ content and its predominantly biogenic composition.

The very high silt content is certainly correlated with the great abundance of calcareous nannofossils that have dimensions that fall in the silt range. The relatively low carbonatic content is a result of the regional setting of the Beato Angelico Trough. This small basin in the Calabrian Ridge is nearer to the continent (the Calabrian arc) than the other basins in the Mediterranean Ridge are from the Greek mainland. The Calabrian Ridge therefore has a greater terrigenous sedimentary input which "dilutes" the biogenic fraction and causes a decrease in carbonate content per unit volume of sediment (Blechschmidt et al., 1982).

The highly homogeneous nature of the matrix suggests that there has been an efficient mixing of the original lithologies that now form the matrix, and therefore the duration and the distance traveled downslope by the flow are relatively high.

The overall aspect of this debris flow deposit, the absence of matrix and clast structures and the matrix support of the clasts suggest that this deposit is a type "A" cohesive debris flow (Lowe, 1982) (Fig. 1). Type "A" deposits are flows in which clasts are supported uniquely by the yield strength of the matrix while other mechanisms such as dispersive pressure and turbulence are not active.

Core East 78 26PC - Mediterranean Ridge, Aphrodite crater, lower part of slope.

This 220 cm thick debris flow deposit (Fig. 6) consists of a strongly disomogeneous matrix composed of several distinct parts. Embedded in this multicolored matrix, are clasts of different hardness and diameters up to 9 cm. The sand fraction can be locally important in the matrix although the silt fraction is still dominant throughout the deposit. The calcimetric curve shows an average value of 42%, greater than that typical of the Calabrian Ridge. Most of all, the grain size and calcimetric analysis emphasize the strongly dishomogeneous nature of matrix. The abundance of the sand fraction has a range of circa 80% (from 3% to 80%) while the carbonate content varies from 28% to 53%. These strongly diverse values are certainly due to the presence of different lithologies in the matrix. Smear slide analysis shows that although calcareous nannofossils are domi-

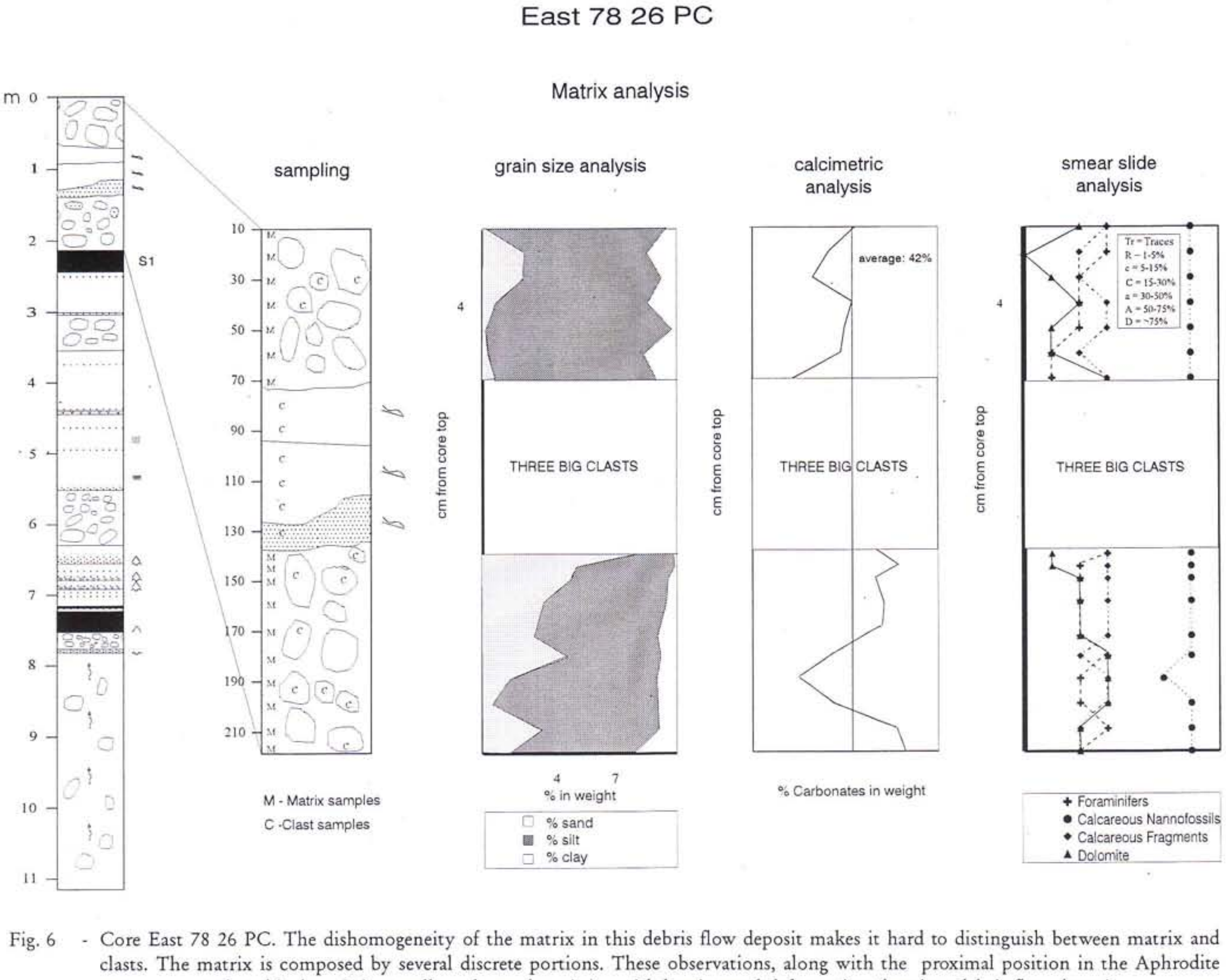


Fig. 6 - Core East 78 26 PC. The dishomogeneity of the matrix in this debris flow deposit makes it hard to distinguish between matrix and clasts. The matrix is composed by several discrete portions. These observations, along with the proximal position in the Aphrodite crater suggest that this deposit is actually a slump deposit i.e. with less internal deformation than in a debris flow deposit.

nant, other calcareous particles of greater dimensions such as foraminifers and calcareous fragments are common. Peaks of the sand fractions can be correlated with the abundance of foraminifers, which also give rise to high values in $CaCO_3$ content.

The highly dishomogeneous character of the matrix indicates that there has been a very small amount of mixing during flow and therefore that the distance traveled was relatively small. Furthermore, two of the big clasts have color, grain size character and carbonatic content very similar to those of discrete matrix portions. This indicates that no clear distinction can be made between matrix and clasts. This deposit does not show the typical features of a debris flow deposit as described by Lowe (1982), and therefore it can not be classified as such. The relatively low degree of internal deformation, instead, suggests that it should be classified as a slump deposit. These considerations are coherent with its proximal position in the Aphrodite crater (lower part of slope).

Core East 78 32PC - Mediterranean Ridge, Aphrodite crater, basin floor

This very small debris flow deposit (only 13 cm thick) (Fig. 7) was cored near the bottom of the Aphrodite crater. No samples of the matrix were taken, but following visual analysis, the homogeneity of the matrix (both color and grain size) and the matrix support of clasts suggest that it can be classified as a type "A" cohesive debris flow (Lowe, 1982).

The grain size distribution and the composition of the underlying sediments is very similar to that of the "normal" pelagic sediments typical of the late Quaternary in the Eastern Mediterranean Basin, while the average $CaCo_3$ content (circa 40%) is comparable with that of the matrix in core EAST 78 - 26PC (42%). The overlying sediments, instead, show evident signs of resedimentation. The grain size distribution and carbonate content curves indicate a normal grading probably due to the concentration of foraminifers and calcareous shell

East 78 32PC

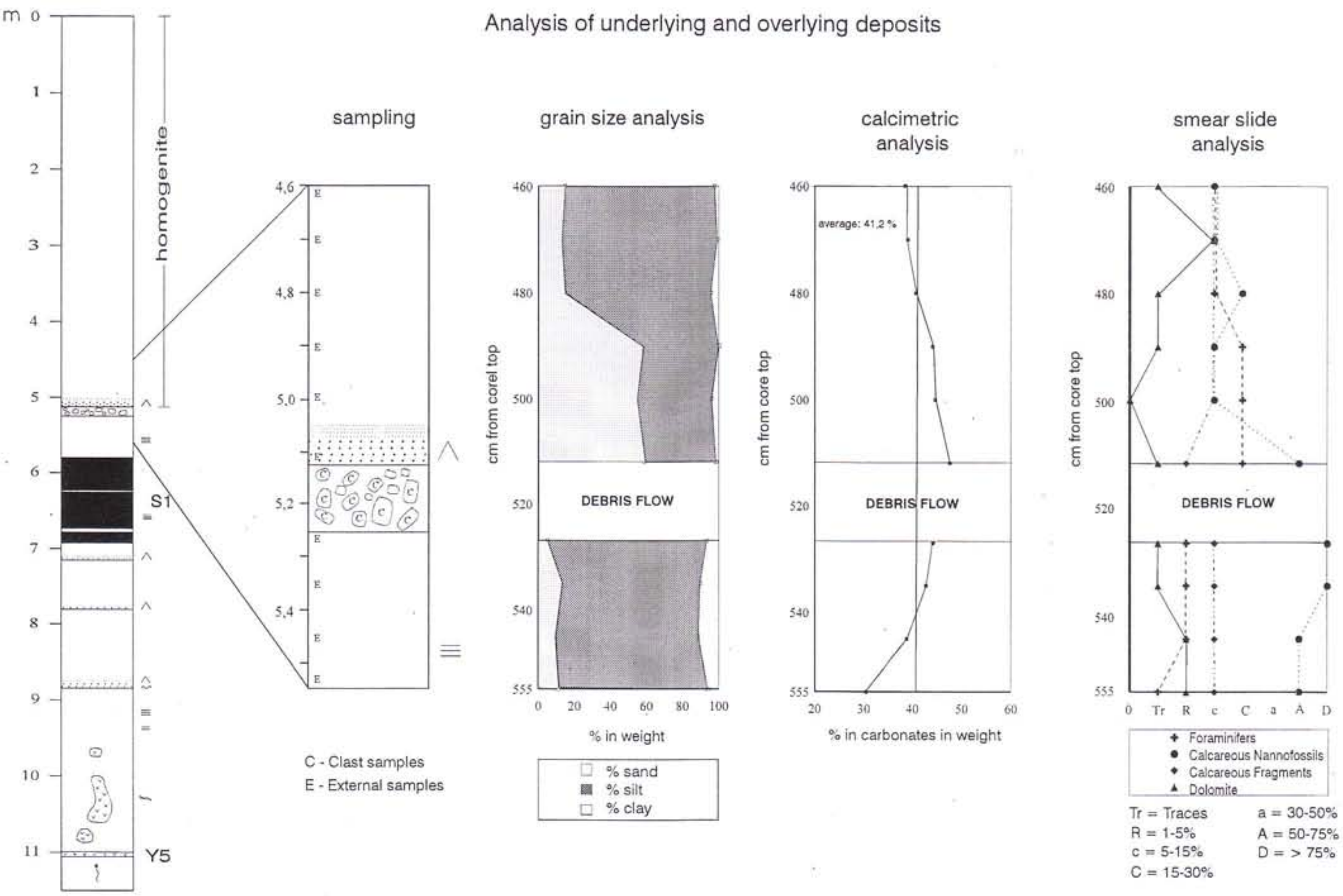


Fig. 7 - Core East 78 32PC. The grain size distribution and composition of the sediments underlying the small debris flow is very similar to that of the "normal" pelagic sediments typical of the late Quaternary in the Eastern Mediterranean Basin. The overlying sediments, instead, show evident signs of resedimentation (turbid flow). Above the base of this turbidite lays a great thickness (more than five meters) of a homogeneous, structureless marl known as "homogenite" (Cita et al., 1982c, Cita et al., 1984, Kastens & Cita, 1981). This pelagic turbidite represents a single sedimentation event whose emplacement is a consequence of the pressure pulse and bottom currents generated after the explosive eruption of the Santorini volcano, circa 3,500 y.a. (Minoan eruption).

SOFT OR INDURATED CLASTS

cm from core top	Lithology	Colour	Age	Environment
115	marl	white	Zanclean	pelagic
120	calcareous marl	white	Burdigalian	pelagic
146	marl	grey	Maastrichtian	pelagic
146	calcareous marl	white	Campanian	pelagic
153-156	marl	white	Late Paleocene - Early Eocene	pelagic
153,158,165	three small lumps		Late Paleocene Middle Eocene Late Oligocene	pelagic
160	calcareous marl	white	Campanian	pelagic
168	calcareous marl	white	Campanian	pelagic
171	marl	white	Middle Eocene	pelagic
176	marly limestone	whitish	Liassic ?	bathyal
194	marl	white	Aquitanian	pelagic

LITHIC CLASTS

Lithology	Roundness	Age
limestones	angular	middle Liassic - early Pliocene
basalts	sub - rounded	
volcanic breccia	angular	

Tab. 4 - The clasts in core BAN 38GC show a great variety of lithologies and ages. The presence of benthic microfauna typical of the shelf or upper slope environment indicate that the flow gradually "sampled" the outcropping lithologies of the Malta Escarpment as it travelled downslope.

fragments at the bottom of a turbidite (Fig. 7). Above the base of this turbidite lay more than five meters of a homogeneous, structureless marl (pelagic turbidite) known as "homogenite" (Cita et al., 1982c, Cita et al., 1984, Kastens & Cita, 1981), which represents a single sedimentation event emplaced as a consequence of the pressure pulse generated by the tsunami wave of the Santorini eruption, circa 3500 y.a. (Minoan eruption).

The Homogenite often shows a graded basal part and sometimes, as in this case, it overlies a thin debris flow deposit which represents the initial slope failure event.

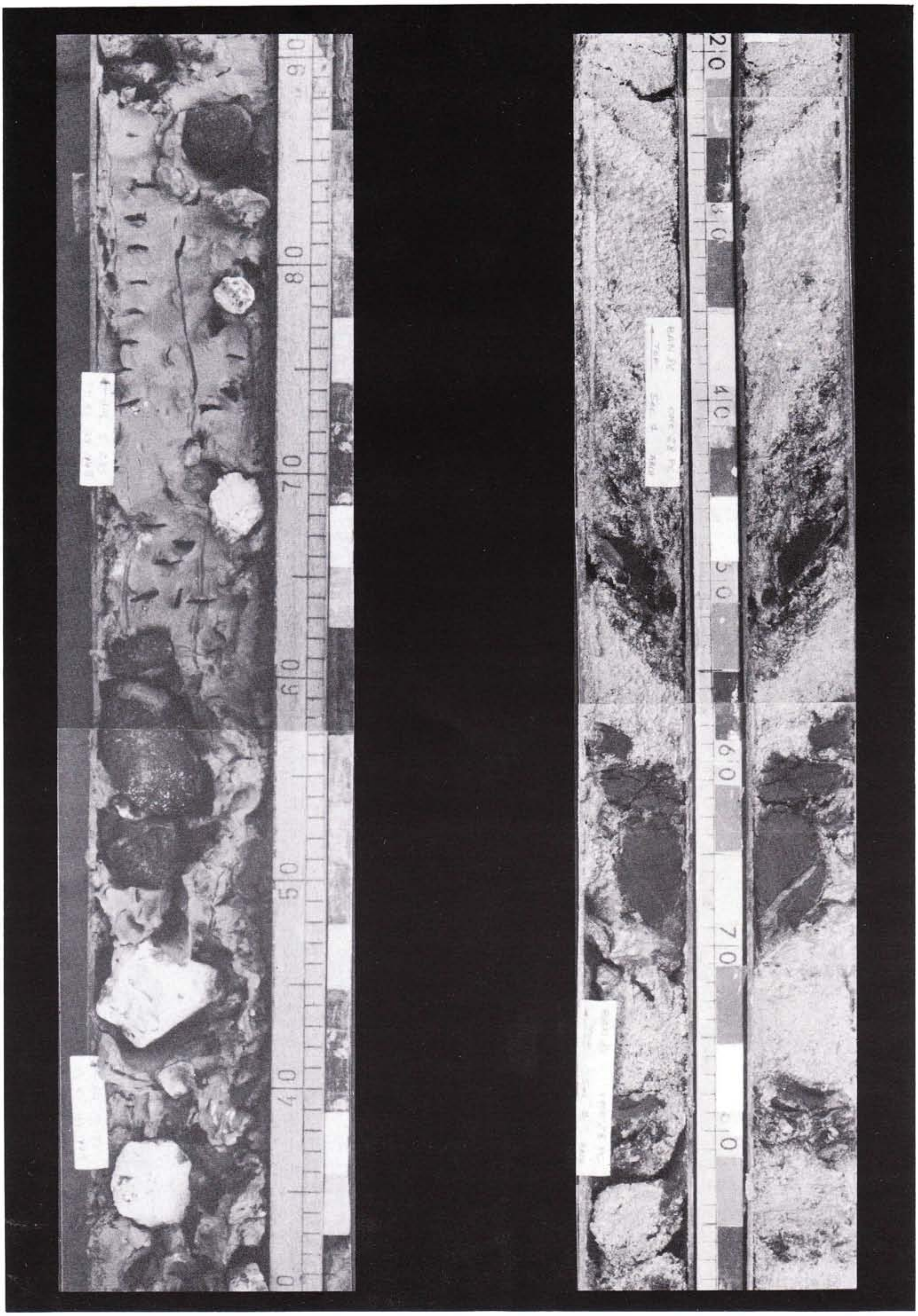
Core BAN 80 38GC - Base of Malta Escarpment.

The top 120 cm of this deposit (the bottom was not reached by the corer) show some lithological and sedimentological characters, not visible in any of the other studied debris flow deposits. The clasts are matrix supported except for a 30 cm clast-supported interval (from 152 cm to 192 cm from core top) where they form approximately 70 % of the sediment in volume giving rise to a crude inverse grading (Fig. 8, left). The upper part of the debris flow deposit (from 92 cm to 152 cm from core top) has a lower clast content (approximately 5% of the sediment in volume) and the matrix shows chaotic structures and convolute laminations (Cita et al., 1982a). Micropaleontological and diffractometric analysis of the matrix carried out by Cita et al. (1982a) (Fig. 9) underline that clay minerals make up more that 50% of the sediment in weight and that Quartz and Calcite are also important constituents (approximately 10 to 20 % in weight each). Six samples contain the typical late Pleistocene foraminiferal cold fauna. Associated with these planktonic species, benthic species indicate a shelf or upper slope environment.

The variability in clast lithologies, hardness and ages are the characters that make this debris flow deposit different from the other six considered (Tab. 4; Cita et al., 1982a).

The presence at 3289m water depth of benthic species in the matrix which are typical of shelf or upper slope environment implies that this flow has traveled a relatively long distance on the Malta Escarpment. Most of the pre-Quaternary clast lithologies correspond to those recovered during dredges carried out on the lower part of the escarpment (Cita et al., 1980; Scandone et al., 1981) whilst other lithologies were previously unknown.

The aspect of this debris flow deposit is of the "A" type cohesive debris flow of Lowe (1982) in which the clasts are fully supported by the matrix cohesiveness. Some lithological characteristics, however, indicate that other support mechanisms may have been locally important: the crude inverse grading in the lower part of the core is probably due to the generation of a dispersive pressure created by clast collisions, and directed upwards. This support mechanism, typical of pure grain flows, implies a high clast concentration and elevated slope inclinations. High values of both parameters (70% clast concentration in volume and inclinations of up to 60° in the lower part of the Malta Escarpment) suggest that an efficient dispersive pressure is probably the cause of the inverse grading. The convolute laminations in the matrix, instead, are a result of a local perturbation in the laminar flow regime that may have been locally turbolent. By definition (Middleton & Hampton, 1973,



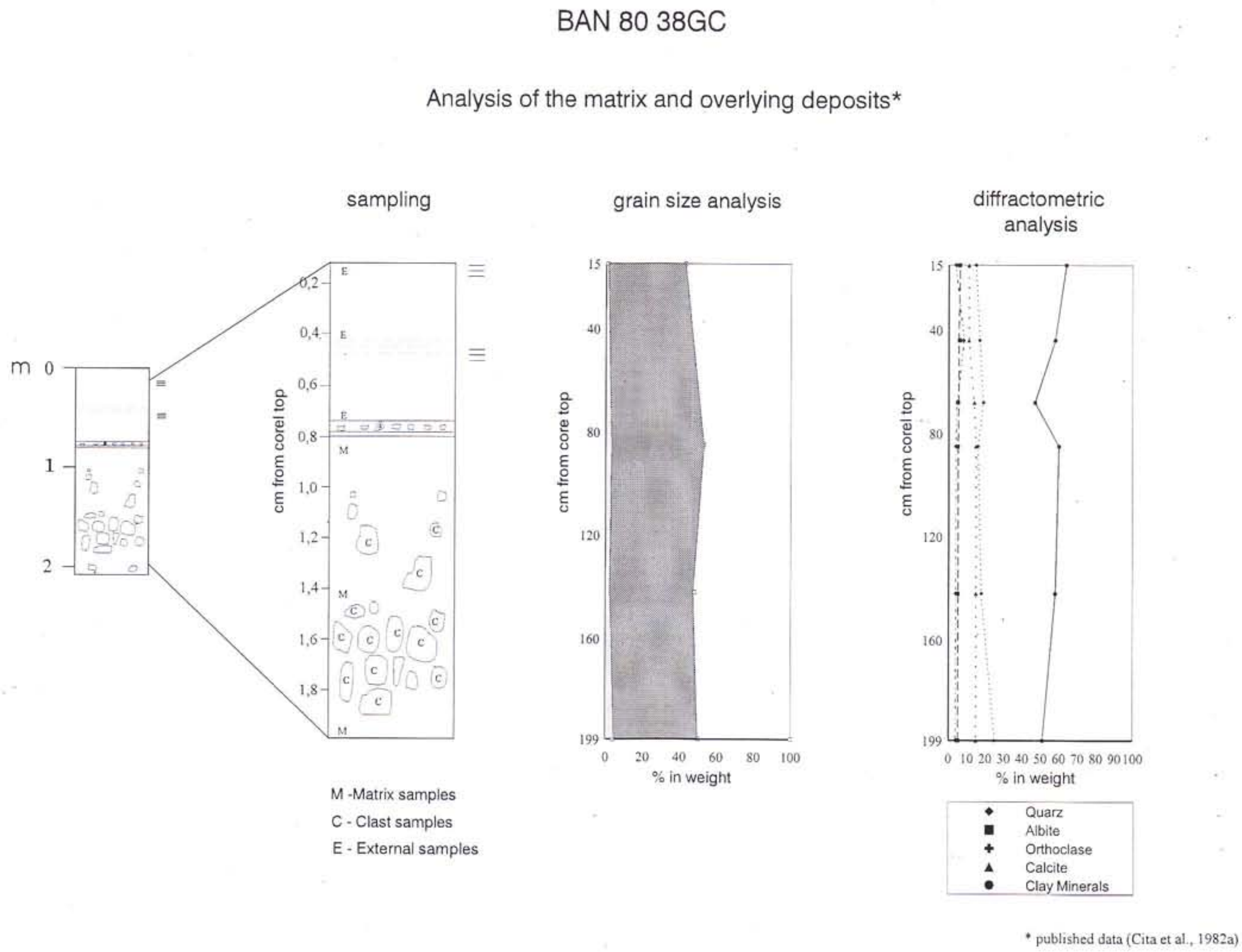


Fig. 9 - Core BAN 80 38GC by Cita et al. (1982a). Grain size and diffractometric analysis show that clay minerals make up about 50% (in weight) of the matrix in this debris flow deposit and that Quartz and Calcite are also important constituents. This debris flow deposit has a very strong terrigenous character as opposed to the other debris flow deposits where the biogenic component is dominant.

1976; Lowe, 1979), in a sediment gravity flow more than one sediment support mechanism may contribute in supporting the clasts above the substratum.

Core BAN 81 31PC - Mediterranean Ridge Cleft, basin floor.

This small debris flow deposit (Fig. 3) was cored from the bottom of the Mediterranean Ridge Cleft basin. It consists of centimetric clasts embedded in a homogeneous matrix. The homogeneity of the matrix (both color and granulometry) and the matrix support of clasts suggest that it can be classified as a type "A" cohesive debris flow (Lowe, 1982).

In both the Aphrodite crater and the Mediterranean Ridge Cleft, a variable thickness of pelagic sediments separates the S1 marker bed from a small debris flow (30 cm thick) at the base of the homogenite. As far as the last 8,000 years are concerned (post Sapropel S1), this core shows a sedimentation pattern very similar to that occurring in the Aphrodite crater (*Core East 78 32PC).* Although the geometries of the two basins are dissimilar (the Mediteranean Ridge Cleft is longer and

Fig. 8 - Left: High clast concentration interval in core BAN 80 38GC (from 152 cm to 192 cm from core top, lower half of photograph). In this interval clasts form about 70% of the sediment in volume giving rise to a crude inverse grading and offering clast support. The formation of the inverse grading could be the consequence of the action of a dispersive pressure generated by clast collisions during flow.

Right: Three sandy turbidites very rich is foraminifera contained in core BAN 86 28PC (Samarelli Basin). Bioclasts in the turbidites include faunas typical of the shelf environment such as *Elphidium crispum* and *Ammonia beccarii* benthic foraminifera indicating a source area located on the African continental margin.

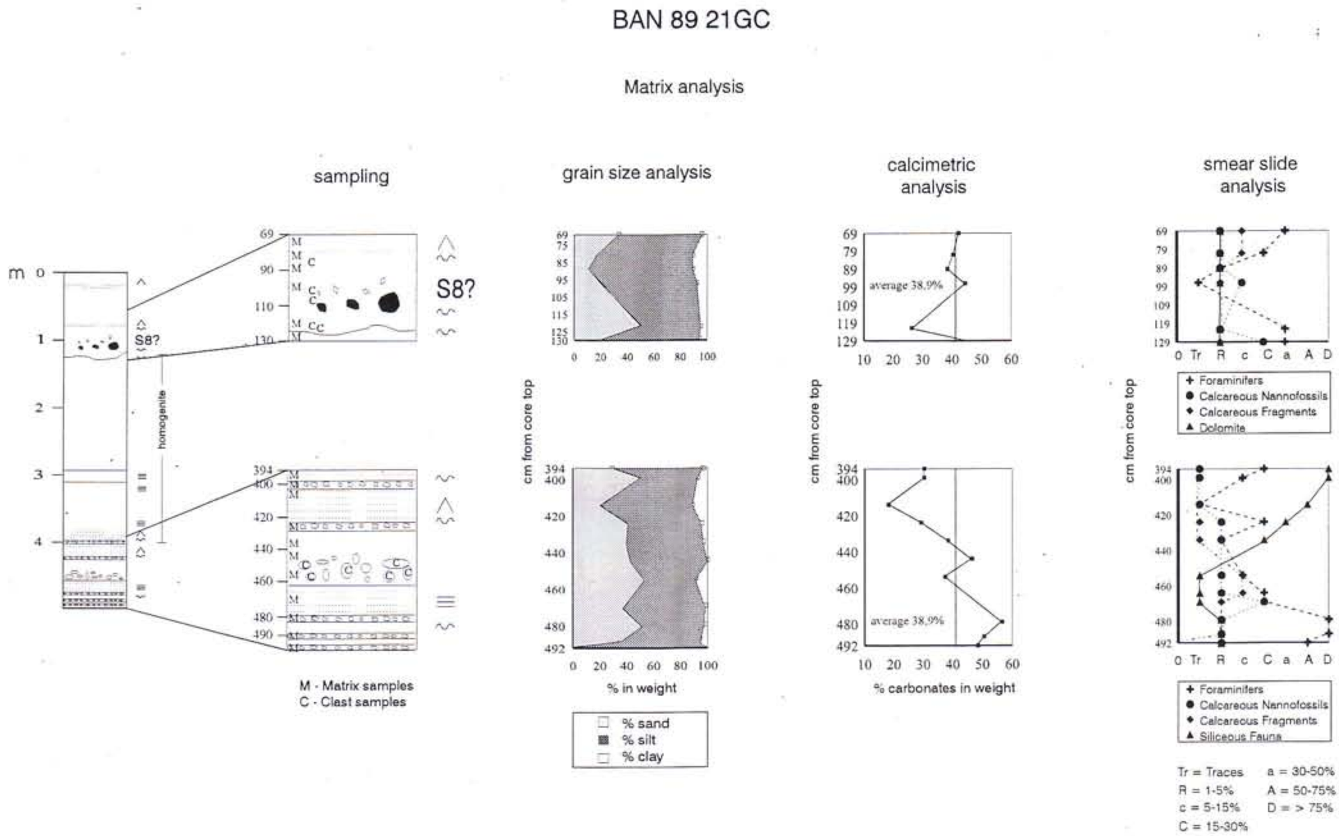


Fig. 10 - Smear slide analysis underline the difference in composition between the upper, debris flow and the lower one. An increase in siliceous fauna in the lower results in lower carbonate content values.

wider), the distance from the the Santorini caldera and the water depths are comparable. The high abundance of the silt fraction, 40 % of carbonates, and the dominant biogenic components in the matrix of the debris flow in core BAN 81 31GC supply further evidence that the resedimented material originally formed the normal pelagic succession typical of this part of the Eastern Mediterranean and that both debris flows deposits were emplaced by the tsunami generated by the Minoan eruption of the Santorini caldera.

Core BAN 86 28PC - Mediterranean Ridge, Samarelli basin, slope.

This short core is composed mainly by a coarse, carbonate rich, foraminiferal sand. Three evident re-sedimentation units contain pluricentimetric sapropel clasts which are at the base of three normally graded beds (Fig. 8, right). The coarse nature of this deposit is caused by a very high foraminiferal content which also gives rise to the unusually high value in carbonate content (71 %). The black sapropel clasts are fine grained and contain only 22 % of carbonates.

The three very evident normal grading structures and the lack of clasts in the middle - upper portions of the core indicate that the sediment gravity flow mechanism responsible for their emplacement was most probably a turbidity current. A cohesive debris flow mechanism (Lowe, 1982 - type "A") could be identified in the lower part of the three intervals, where the sapropel clasts are concentrated.

The sediment in this core has an age of less that 70,000 years (limit between *E. huxleyi* and *E. huxleyi Acme* nannofossil zones). Bioclasts in the turbidites include faunas typical of the shelf environment such as *Elphidium crispum* and *Ammonia beccarii*. The most probable source area for this extrabasinal turbidite is the North African continental margin. The Samarelli basin is fully exposed to Africa's northern continental margin and flows originating from it can climb for several hundred meters on the southern flank of the Mediterranean Ridge. Evidence of such "upslope turbidites" already exists for this part of the Eastern Mediterranean basin (Rimoldi, 1989). Northwards of the Samarelli basin, the Mediterranean Ridge is too deep (circa -1000 m at the least) to host shelf facies sediments.

Core BAN 89 21GC - Mediterranean Ridge, Bannock Basin (Libeccio sub-basin), base of slope.

This core contains two major debris flow deposits (35 and 60 cm thick) and three smaller ones (Fig. 3). Due to the anoxic environment in the Bannock basin (the bottom of this basin is permanently filled with a high density, anoxic brine) the sediments in this core are prevalently dark gray in color, and precipitation from an oversaturated solution has formed centimetric gypsum crystals which are embedded in the matrix of all debris flow deposits.

The matrix grain size of the two major debris flow deposits is made of up to approximately 90% of sand and silt. The high values and high vertical variability of the sand fraction are due to the variable abundance of foraminifers. The relation between sand fraction and foraminiferal content is clear in the upper debris flow deposit (from 69 cm to 115 cm) (Fig. 10).

The average carbonate content in this core (38,9 %) is typical of the pelagic sediments in this area (circa 40%) but this parameter shows a very high vertical variability, especially in the lower resedimented unit. The upper debris flow deposit is in fact composed entirely by the calcareous microfauna whereas the lower debris flow deposit is composed by siliceous fauna (mainly Radiolarians and lesser Diatoms) with increasing abundance moving upcore reaching a percentage >75% in two samples near the base of the homogenite (394 cm and 400 cm).

The increase in the siliceous fauna (mainly Radiolarians and to a lesser extent, Diatoms) is a consequence of the anoxic conditions in the water column, an environment in which the preservation of siliceous microfossils is favored.

Both major flows can be classified as type "A" cohesive debris flows (Lowe, 1982) whilst the minor debris flow deposits are too thin to be interpreted.

Of the two major debris flow deposits, the smaller one is older than the homogenite whilst the thicker one is younger and erodes the top of the homogenite. The lesser debris flow deposits form the base of normal graded beds (in one case the thin debris flow deposit is at the base of the homogenite) indicating that the debris flows evolved into turbidites.

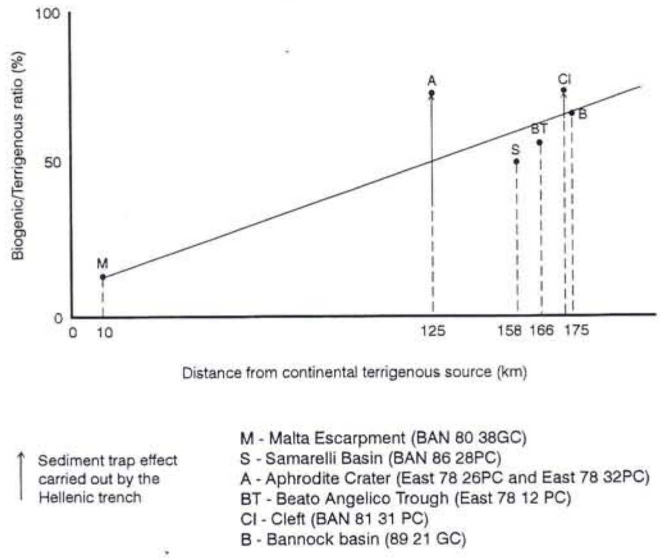


Fig. 11 - Distance from continent - biogenic/terrigenous component relationship for the studied cores in the Ionian Sea. The biogenic/terrigenous ratio in the matrix increases with the distance from the terrigenous source following a direct relation. Two exceptions (Aphrodite Crater and Cleft basin) are the debris flow deposits closest to the Hellenic Trench, where terrigenous sediments being transported southwards from the Peloponnesus and Crete towards the Mediterranean Ridge are trapped in the deep and narrow basins forming the trench. The result is a higher than expected biogenic/terrigenous ratio, similar to that of the Bannock basin.

Discussion.

Lithology.

The studied debris flow deposits can be subdivided into two distinct lithological types. The deposits occurring in the small basins amidst the cobblestone topography of the Calabrian and Mediterranean ridges (Beato Angelico trough, Aphrodite crater, Mediterranean ridge Cleft, Bannock basin) are composed by sediments that form the "normal" pelagic succession of the Eastern Mediterranean (calcareous nannofossil ooze with foraminifera and minor terrigenous fraction). Minor lithologies include organic rich layers (sapropels) and layers rich in volcanic ash (tephras). The age of the sediments forming the matrix and the clasts of these debris flow deposits is recent (late Pleistocene - Holocene) and the clasts are soft. This demonstrates that the sediments were originally part of an unconsolidated substratum before being transported and deposited. The Samarelli basin is an exception to this pattern for it lies in the proximity of the Mediterranean Ridge deformation front, facing the north African continental margin.

The second litological type includes the debris flow deposits occurring in the vicinity of a continental terrigenous source. These (BAN 80 38GC and BAN 86 28PC) involve a great variety of lithologies and ages, both in the matrix and in the clasts, and generally they are produced by debris flows that have traveled a great distance (tens of km or more).

It is therefore clear that we are considering two processes having a different scale. In the first case we are dealing with a local resedimentation phenomenon that involves a small area and a small volume of sediments (late Pleistocene - Holocene) whilst in the second case the processes happen in the continental shelf - slope - abyssal plain environment thus involving a great variety of lithologies and ages.

This strong dependence of debris flow deposit composition from the physiographic setting of the deposit within the Ionian Sea can be summarized graphically (Fig. 11). The biogenic/terrigenous ratio in the matrix increases with the distance from the terrigenous source roughly following a relation of direct proportionality. Two exceptions (Aphrodite Crater and Cleft basin) are the debris flow deposits closest to the Hellenic Trench, where terrigenous sediments being transported southwards from the Peloponnesus and Crete towards the Mediterranean Ridge are trapped in the deep and narrow basins forming the trench. The result is a higher than expected biogenic/terrigenous ratio, similar to that of the Bannock basin.

Flow type and clast support mechanism.

Most of the studied flow deposits have been classified as type "A" cohesive debris flows (Lowe, 1982). These deposits are matrix supported and, during flow, the clasts are sustained over the substratum entirely by matrix strength and cohesiveness. When these flows involve large quantities of sediment moving at relatively high speeds along steep slopes (as in the Malta Escarpment), other mechanisms such as fluid turbulence and dispersive pressure may contribute in sustaining the clasts. In particular, fluid turbolence is a consequence of water - sediment mixing on the top of the debris flow as it moves downslope and is favored by high speed. The generation of dispersive pressure is favored by high clast concentrations and steep slopes.

One deposit (core East 78 26PC) has a low degree of mixing so that it is hard to distinguish the matrix from the clasts. It has been classified as a slump deposit, although it may well represent an initial stage of debris flow because there is a strict distance traveled/internal deformation relationship for sediments moving downslope.

Finally, one deposit (core BAN 89 21GC) was interpreted as deposited from three turbidity currents with possible debris flow mechanisms at the their bases.

Age of the deposits and triggering mechanisms.

Dating of the pelagic sediments in the Eastern Mediterranean basin can be obtained with calcareous nannofossil zonations (Gartner, 1977) and foraminifera zonations (Cita, 1973, 1975). As far as the Plio - Quaternary is concerned, nannofossil zones offer a greater resolution. The problem of accurately dating the upper few meters of the pelagic succession (late Quaternary), can be overcome combining biostratigraphy with correlation of widespread marker beds such as Tephras and Sapropels.

Three of the seven studied debris flow deposits occurring in the small basins amidst the cobblestone topography are associated to the Homogenite and therefore have an age of 3500y b.p. Two such debris flow deposits (BAN 81 31GC and East 78 32PC) form the base of the homogenite (the upper debris flow deposit in core BAN 89 21 GC is younger than the homogenite). Although the third debris flow deposit (East 78 26 PC) does not lie at the base of the homogenite and no pelagic sediments separate it from sapropel layer S1 (Circa 8,000y) it was probably emplaced by the same tsunami event. In fact, this core is not in a basinal setting but it lies in the lower portion of the slope where debris flows still have erosional power. The small amount of sediments separating the flow from sapropel S1 may well have been eroded by the flow itself, because the clasts and matrix show lithologies that are very similar to those of the pelagics separating S1 from the flow at the base of the homogenite in core East 78 - 32 PC (also in the Aphrodite crater. Finally, the lack of the homogenite above this debris flow deposit can be explained by considering that the homogenite typically pinches out laterally on the small basin slopes (Cita et al., 1982c). Therefore, the difference in height between the basin floor and core East 78 26 PC (about 46 m) is sufficient to place this core in a position higher than the top of the homogenite.

Twenty-five centimeters of resedimented pelagics separate the base of the homogenite from two thin centimetric debris flows separated by one 20 cm turbiditic flow in core BAN 89 21 GC. It is therefore hard to express this thickness in terms of a time interval. The small thickness of the two debris flow deposits suggests that they did not have a great erosional power. Therefore they must not be much older than 3500 y.

The debris flow deposit in core East 78 12 PC lies under Sapropel S1 and therefore has an age older than 9000 y (lower age limit of Sapropel S1 obtained with radiometric dating). Kastens (1984) studied turbidites and debris flows deposits in the Calabrian ridge between Tephra layer Y1 (circa 14000 y) and Sapropel layer S1. She observed that in this time period these resedimentation events had a repeat time of about 1500 y. By studying the seismicity of the Hellenic arc she extrapolated that the earthquake with a frequency of 1500 y is geologically possible and has sufficient energy to trigger the observed flows. In this context, the debris flow deposit in core East 78 12PC may have been triggered by the last earthquake before the deposition of sapropel layer S1 and therefore should have an age of approximately 9,500 y.

The pelagic sediments overlying the debris flow deposit in core BAN 80 38 GC do not contain marker beds and therefore a relative dating is not possible. However, the sediments that make up the matrix of this debris flow deposit contain the 'cold' foraminiferal fauna typical of the late Pleistocene (Cita et al., 1982a). Hence, this debris flow was probably triggered during the last glacial period when low sea level stands favored slope failures on the margins of the Eastern Mediterranean (Embley, 1980).

The sediments in core BAN 86 28PC contain calcareous nannofossils that suggest an age younger than 70,000y (limit between *E. huxleyi* and *E. huxleyi Acme* zones).

Conclusion.

The lithological and sedimentological character of debris flow deposits in the Ionian Sea is strongly dependent on physiographic setting. An important distinction can be made between local debris flows emplaced in the small basins within the cobblestone topography and those coming from the passive continental margins that border the Ionian Sea to the east and to the south. These large scale debris flows include a wide range of lithologies and ages and are triggered by regional phenomena such as changes in sea level whereas the smaller debris flows occurring in the tectonically active Calabrian and Mediterranean ridges involve the young sediments that form the "normal" pelagic succession of the Eastern Mediterranean and are mostly triggered by seismic events or related events such as the tsunami wave of the Minoan eruption of the Santorini Volcano.

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