Quantification of neogene and quaternary sediment input to the Madeira Abyssal Plain

Cuantificación de los aportes sedimentarios neogenos y cuaternarios a la Llanura Abisal de Madeira

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ABSTRACT

Cruises Tydeman 80, Tyro 82 and ODP Leg 157 provided 7000 km of single-channel seismic profiles and three drilling sites with a total of 1158 m of core in the Madeira Abyssal Plain. Merging of the lithological records and conventional logs into the seismic units and subunits defined, allowed their 3D mapping and calculation of both the sediment volume and approximate accumulation rates in the Great Meteor East area (central subbasin of the Madeira Abyssal Plain) since the Middle Miocene. The total volume is around 19327 km^3 and the accumulation rates are 22.66 m/myr for the Upper-Middle Miocene, 68.78 m/myr for the Lower Pliocene, 49.23 m/myr for the Upper Pliocene and 54.93 m/myr for the Quaternary.

RESUMEN

Durante las campañas Tydeman 80, Tyro 82 y el "leg" 157 del Ocean Drilling Program (ODP), se obtuvieron 7000 km de sísmica de monocanal y tres sondeos de unos 350 m cada uno en la zona central de la Llanura Abisal de Madeira. A partir de los perfiles sísmicos se han diferenciado dos grandes unidades sísmicas y cuatro subunidades. La cartografía 3D de las mismas, junto con el estudio de las columnas litoestratigráficas y las diagrafías de los sondeos, ha permitido calcular el volumen de sedimento depositado en la cuenca desde el Mioceno medio hasta la actualidad. La correlación de las unidades sísmicas con la litoestratigrafía de los sondeos ha posibilitado el cálculo de las tasas de acumulación aproximadas para dicha cuenca. El volumen total depositado desde el Mioceno medio hasta la actualidad es de 19327 km^3 y las tasas de acumulación son de 22.66 m/Ma para el Mioceno superior y medio, 68.78 m/Ma para el Plioceno inferior, 49.23 m/Ma para el Plioceno superior y 54.93 m/Ma para el Pleistoceno.

Key words: *Madeira Abyssal Plain (MAP), Great Meteor East (GME), Ocean Drilling Program (ODP), seismic unit, sediment volume calculations, decompaction, sediment accumulation rates.*

Geogaceta, 20 (2) (1996), 394-397
ISSN: 0213683X

Geological and physiographic setting

The Madeira Abyssal Plain (MAP) is situated at the centre and deepest part of the Canary Basin, and shows a NNE-SSW shape almost parallel to the Mid-Atlantic Ridge. It limits to the west with the Irving/Cruiser/Hyeres/Great Meteor seamount chain, and to the east by a distinct break of slope that marks the foot of the African Continental Rise (Fig 1).

The MAP can be divided into three sub-basins: the southern sub-basin, which lies at a water depth of approximately 5350m.,the central sub-basin which is deeper, around 5440 m depth, and the northern sub-basin which lies slightly above the central sub-basin at around 5423 m.

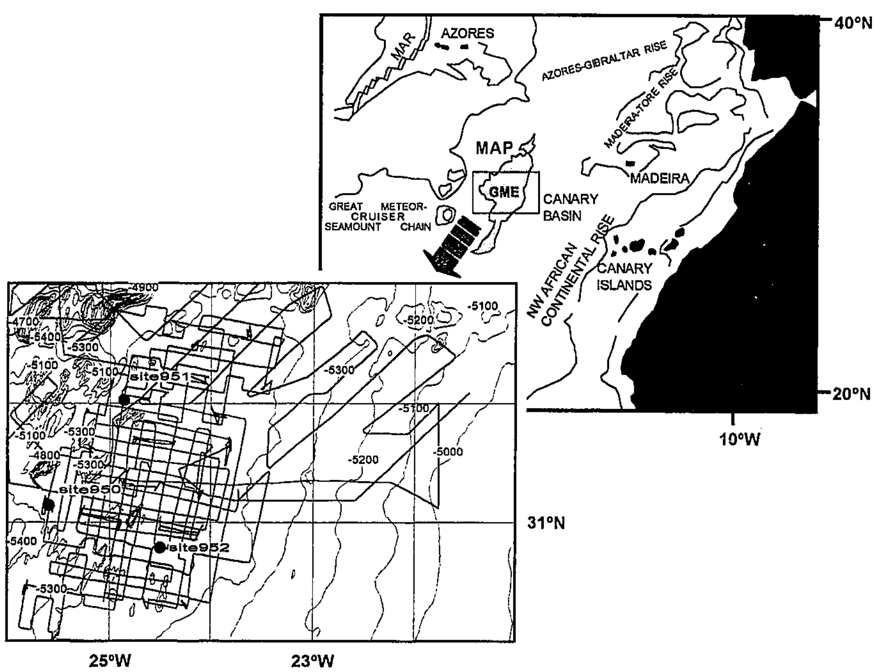

Fig. 1.- Geographic setting of the GME, seismic lines and ODP Leg 157 Sites.

Fig. 1.- Situación geográfica de la GME, líneas sísmicas y sondeos del "leg"157.

Our study focus on the central sub-basin of the MAP, which constitutes a broad area of 57187 km^2 that has been called Great Meteor East (GME) after a seamount situated to the west. This is a flat area occasionally interrupted by small abyssal hills of a few hundred meters in height which become more frequent to the north, south and west forming the boundaries of the GME area. The northern seamounts represent the outcropping above the plain of the southern-wall of the Cruiser Fracture Zone. The seamounts to the south mark the southern wall of the Charis Fracture Zone, while the western ones feature the begin ning of the lower flank of the Mid-Atlantic Ridge.

The MAP area and especially the GME have been deeply studied since the Nuclear Energy Agency's Seabed Working Group (Anderson, 1980) selected the MAP as a site study for possible disposal of heat-emitting radioactive waste.

Data and methodology

For our study we used around 7000 km of single channel seismic lines acquired by the Dutch Geological Survey during two cruises, Tydeman 1980 and Tyro 1982, and core data from three holes drilled during ODP Leg 157 in 1994 (Fig. 1).

Apparent reflectors from the seismic profiles were defined as unit boundaries and digitised in order to produce the depth and thickness contour maps of each seismic unit.

The travel times were converted to depths using a smoothed velocity-depth function for each site and an average for the whole GME. Assuming that velocity increases linearly with depth, $v=v_0+cz$, with v_0 the velocity at 0 mbsf, c the velocity increase and z the depth, the best fit was with functions of the type $TWT=(2000/c) \times \ln(1+cz/v_0)$, namely: $TWT=2.13 \times \ln(1+0.00059 z)$; $v=1584+0.937 z$ for Site 950 and $TWT=2.10 \times \ln(1+0.00065 z)$; $v=1460+0.953 z$ for site 952 (Lykke-Andersen, pers.com.).

The average, $TWT= 2.115 \times \ln(1+0.00062 z)$, was used as regional velocity function for the GME area when calculating depth from traveltime and to convert the time contour maps to meters.

Sediment types and lithological units

Sediments in the MAP fall into two basic types: alternating turbiditic and pelagic sediments. Most of the turbidites found in the three sites are distal and thus only rarely present coarse grained bases grading upwards. The main body of these turbidites consist of structureless silty-clay and show thickness up to 11 m. Previous studies have divided the MAP turbidites into 3 groups: (1) grey volcanic turbidites, (2) green organic-rich turbidites and (3) white calcareous turbidites (Jarvis and Higgs, 1987), derived respectively from: (1) northeastern Atlantic volcanic islands (Canaries and Madeira), (2) NW African continental margin (N Canaries off Morocco, S Canaries off Senegal), (3) nearby seamounts to the west of the MAP (Great Meteor-Cruiser chain) (Weaver and Rothwell, 1987; Weaver *et al.*, 1989b). During ODP Leg 157, two additional types of turbidites have been found, and provisionally called: 1) green-grey turbidites which differ from the traditional volcanics on their low magnetic susceptibility signature and from the organics in their higher calcium carbonate content and 2) brown turbidites. Their sources are still a matter of study and in this work we call them "intermediate turbidites". The pelagic layers are relatively thin (up to 50 cm) and consist of calcareous ooze, marl or clay, depending on the depth of the Carbonate Compensation Depth (CCD) at the time of deposition.

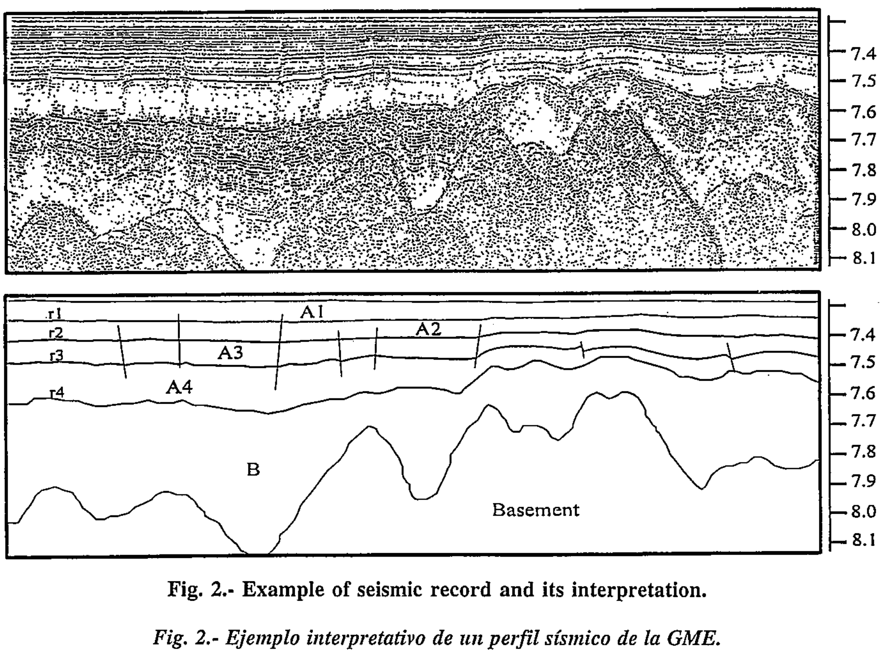

Fig. 2.- Example of seismic record and its interpretation.

Fig. 2.- Ejemplo interpretativo de un perfil sísmico de la GME.

SEISMIC UNITS AND REFLECTORS			AGE
Searle 1987	Duin & Kok 1984	This Work	
AB	A	A1	*Pleistocene*
		r1	
		A2	*Upper Pliocene*
		r2	
		A3	*Lower Pliocene*
		r3	
	B	A4	*Upper-Midle Miocene*
		r4	
C/D	C	B	*Paleogene*
	D		
Basement			*Upper Cretaceous*

Table.1.- Seismic units defined in the GME.

Table 1.- Unidades sísmicas definidas en la GME.

During ODP Leg 157 three Sites were drilled in the GME:

Site 950 (372 meters of recovery) is situated in the western part of the GME in the Cruiser Fracture Zone Valley (Fig. 1). The sedimentary sequence can be divided into four descriptive lithologic units: Unit 1 (Pleistocene to Middle Miocene) which consists of turbidites interbedded with pelagics, Unit 2 (Early Miocene) which consists of massive calcarenites, Unit 3 (Oligocene to Late Eocene) which consists of red pelagic clays with thin interbedded turbidites and Unit 4, formed by two depositional units of volcaniclastic siltstone and sandstone (Shipboard Scientific Party, 1996).

Site 951 (351.4 m of recovery) is located in the north-western part of the GME in the Charis Fracture Zone (Fig. 1). The sedimentary sequence consists of only one lithologic unit (Pleistocene to Early Miocene) which is equivalent to Unit 1 at Site 950 (Shipboard Scientific Party, 1996).

Site 952 (425.24 m of recovery) lies in the south-eastern part of the GME in the Cruiser Fracture Zone Valley. It comprises one lithologic unit (Pleistocene to Early Miocene) comparable to Unit 1 of site 950 and 951, which consists of turbidites interbedded with pelagics (Shipboard Scientific Party, 1996).

Results

Seismic units: Interpretation of the seismic records led us to differentiate 2 seismic units, B and A from base to top. Unit B lies directly over the oceanic basement and Unit A is divided into subunits A4, A3, A2 and A1, again from base to top (Fig. 2). Table 1 shows the correspondence between units previously defined by Duin and Kok (1984) and Searle (1987), partially based on the same profiles, and the units presented in this work. During ODP Leg 157, on approaching the sites, three short seismic lines were acquired and

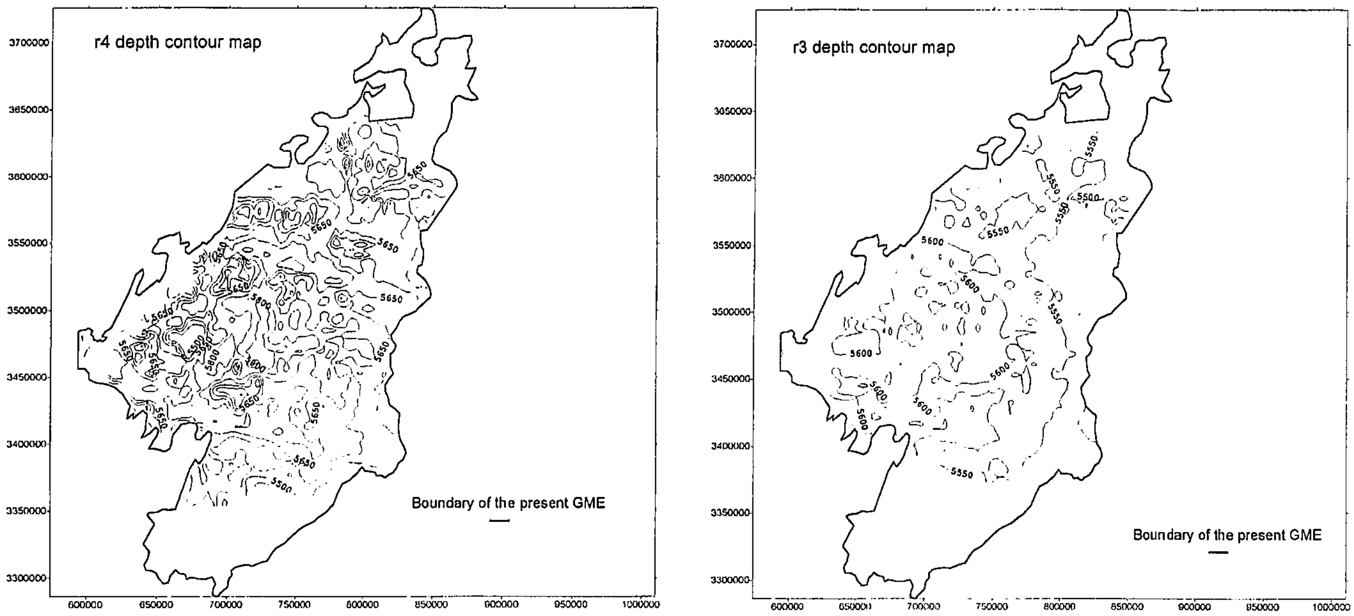

Fig. 3.- Isobath maps of reflectors r4 and r3 in the GME. Contours in meters.

Fig. 3.- Mapas de isobatas de los reflectores r4 y r3

the onboard working units (A and B) coincide with the two main units here considered.

The basement has a very abrupt topography as a consequence of its tectonic evolution. It is formed by NNE-SSW lineated valleys and ridges which represent the inactive traces of the Charis and Cruiser Fracture Zones. The present-day abyssal hills represent the shallowmost elevations of the basement ridges.

Seismic unit B forms a drape over the basement, although it onlaps or abuts sharply against it at steep basement slopes. This unit grades vertically from moderately transparent to strongly layered, and laterally from stratified over the basement lows to chaotic-transparent over the basement highs.

Unit B is separated from unit A by reflector r4, a major unconformity that can be traced all across the GME. This unconformity is time transgresive occurring earlier deeper in the section (Searle, 1987).

Subunit A4 has a thickness between 50-300ms.It usually appears as transparent, probably due to attenuation of the seismic signal with depth, since sometimes it appears as stratified, although reflectors are not as strong and continuous as in the upper units A3-A1.

Subunit A3 ranges between 50-110 m in thickness and has a transparent upper part and a stratified lower part in which reflectors are more continuous, parallel and largely spaced than the upper subunits.

Subunit A2 has a thickness between 50-100 m it is stratified and its reflectors are parallel and continuous with their spacing increasing with depth.

Subunit A1's thickness varies between 50 and 80 m it is well layered and reflectors are parallel and continuous. Spacing between relectors decreases with depth.

During ODP Leg 157, core drilling penetrated the seismic units up to r4, and revealed that the differences between seismic units A1-A4 are probably caused by large scale changes in thickness and lithology of individual turbidite layers.

Contour maps: The contour maps monitor the depositional evolution of the basin since the initial deposition of turbidites over a rough basement topography to the present-day flat floor abyssal plain. Two examples, the r4 depth contour map and the r3 depth contour map, show how the seafloor morphology evolves from an irregular topography that still reflects the basement valleys and ridges to an almost flat topography after the first significant turbiditic events (Fig.3).

Decompaction: Sedimentary units are affected by compaction after deposition so that the thickness of the units we see today is smaller than the unit thickness at the time of deposition. In order to restore the initial volume of sediment is necessary to decompact each unit to the time of deposition.

The thickness of a unit at the time of deposition (T_0) and any time thereafter is related to the change in porosity of the sediment during burial; therefore, the original thickness is related to the present-day thickness as follows (Van Hinte, 1978):

$$T_0 = (1-f_N)\, T_N / (1-f_0),$$

Being f_N and T_N the present-day porosity and thickness, and f_0 the original porosity at the time of deposition.

The present-day porosity was measured from discrete samples of approximately 10-12 cm^3 taken from layers of changing lithologies, using a dry volume (Shipboard Scientific Party, 1996). The original porosities were estimated from the porosity measured close to the surface. These are 0.7 for intermediate turbidites, 0.68 for calcareous turbidites, 0.76 for organic-rich turbidites, 0.82 for volcanic-rich turbidites and 0.7 for the pelagic layers.

Decompaction was calculated for each lithologic layer and the results indicate that compaction has been consistent across the plain, around 40% for the three sites. Decompacted depth and present depth are related by the following equations: $y = 0.64406 * x^{(1.167)}$ for Site 950, $y = 0.72738 * x^{(1.1469)}$ for Site 951 and $y = 0.72102 * x^{(1.1383)}$ for Site 952, resulting in a decompacted thickness of 620.76 m for Site 950, 597.980 m for Site 951 and 705.734 m for Site 952.

The average, $y = 0.6974 * x^{(1.1507)}$, will be used as standard equation for the GME area.

Correlation of seismic units and lithological column: Attributing reflectors to lithologic horizons is not so obvious since the vertical resolution changes depend on the interval velocity and of the wavelet frequency. In order to relate the defined seismic units, B and A4-A1, with the lithological record, the seismic unit boundaries were computed using the time-depth equation and were readjusted with the lithodensity log and sonic log. Therefore, seismic unit A1 sediments corres- pond to the Pleistocene, A2 to the Upper Pliocene, A3 to the Lower Pliocene sediments and A4 to the Upper-Middle Miocene (Tab. 1).

The percentage of the different sediment types varies through time and has been calculated for each seismic unit. There are small differences between the three sites depending on their geographic situation, but they reflect mainly the same trends (Fig. 4).

There is an increase in thickness and number of units of the volcanic turbidites from A4 to A1, presenting 3.2 m of accumulated thickness in unit A4 and 25.95 m in unit A1 for Site 950. The organic turbidites are very abundant and there is a decrease in the total accumulated thickness from A4 to A1, from 63.5 m in A4 to 29.6 m in A1 for site 950. The thickness of the calcareous turbidites remains constant along the seismic units, around 7 m of accumulated thickness for Site 950, but slightly more abundant in unit A2. The intermediate turbidites are more abundant in units A4 and A3, around 16 m of accumulated thickness for Site 950's unit A4, as opposed to the pelagic layers which are more abundant in units A1 and A2, around 6 m of accumulated depth.

Volume calculations and accumulation rates: The mapping of the units throughout the study area enables estimation of their total volume. It must be emphasized that these estimates are restricted to the study area which is a subbasin of the MAP and that the area covered with the seismic lines is not all of the GME (57187 km^2), but approximately 48625 km^2, and thus these calculations will be underestimated.

The present volume and the volume that was deposited, that is before the process of compaction, for each unit are: Unit A1 (Pleistocene) has a compacted volume of 2790.17 km^3 and a decompacted volume of 3863.54 km^3; Unit A2 (upper Pliocene) has 2302.51 km^3 vs 3664.43 km^3; Unit A3 (lower Pliocene), has 2470.71 km^3 vs 4250.46 km^3; and finally Unit A4 (upper and middle Miocene), has 4311.61 km^3 vs 7997.97 km^3 (Fig. 5).

Combining the area covered by each unit, the time of its deposition and its decompacted volume, we can estimate the accumulation rates for each seismic unit. These values are only approximate at this moment because the ages are still not definitively constrained. The accumulation rate for unit A1 is 54.93 m/myr, 49.23 m/myr for unit A2, 68.78 m/myr for unit A3 and 22.66 m/myr for unit A4 (Fig. 5).

Conclusions

The detailed analysis of the logs, physical properties and general variations in turbidite thickness and lithology allows us to correlate the seismic units with the drillholes and thus know the lithology and approximate age of each seismic unit. This job is, however, not obvious since the variability and high frequency of lithological units throughout the section complicate a correlation with the seismic units at first sight.

The computed decompacted volumes indicate that during the Pleistocene and the Lower Pliocene the input of turbidites per million years was higher (2329 km^3/myr during the Pleistocene and 2477.5 km^3/myr during the Lower Pliocene) than during the Upper Pliocene (1877.5 km^3/myr) and three orders of magnitude higher than during the Upper-Middle Miocene (715.65 km^3/myr).

The variation in thickness and number of volcanic turbidite layers can be linked to the volcanic history of the Canary Islands and Madeira, with the sudden increase after unit A4 probably representing the end of the major hiatus in volcanic activity on Gran Canaria (Schmincke, 1987). The organic turbidites are very abundant, although their volume decreases since the Middle Miocene to the present. Therefore, the erosion of the NW African continental margin, which is known to occur by large scale mass wasting events (Embley, 1982), must have decreased since the Middle Miocene. The calcareous turbidites reflect the sealevel history, being more abundant during sea level lows in which the seamounts to the west could be eroded. And, finally, the pelagics are more abundant when the frequency of the turbiditic events is lower, that is longer periods of free-erosion and deposition, or when the preservation is enhanced. Hence, the pelagics are more abundant during the Upper Pliocene and Pleistocene, which are periods of high accumulation rates, for which the frequency of the turbiditic events are unknown.

Further research will help to link the erosional history of the source areas with the volumes of sediments deposited in the GME since the Middle Miocene.

Acknowledgements

This study is being funded by the European project STEAM (ref. MAS2-CT94-0083) and by the CICYT Spanish projects CRESCENT and MAYC (refs. AMB94-0323 and AMB95-0196). The GRQ "Geociències Marines" of the University of Barcelona has been supported by grants GRQ94/95-1026 of the "Generalitat de Catalunya". Assistance provided by the Foundation "Bosch y Gimpera" is also acknowledged. We are grateful to our Dutch colleagues of the "Rijks Geologische Dienst" and to the ODP Leg 157 Sientific Party for providing the data used in this study.

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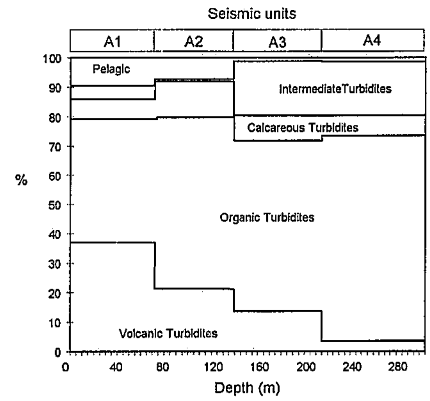

Fig. 4.- Percentage of each sediment type calculated for seismic units A1 to A4 on Site 950.

Fig. 4.- Porcentaje de cada tipo de sedimento calculado para las unidades sísmicas A1-A4 en el sondeo 950.

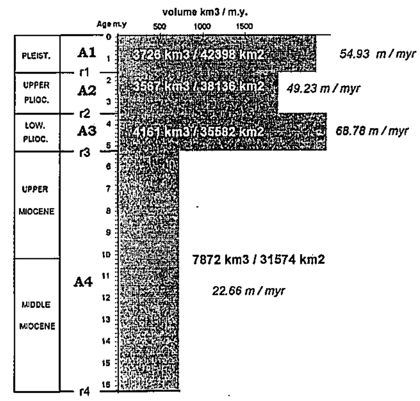

Fig. 5.- Volumes, extension, ages and accumulation rates for seismic units A1-A4.

Fig. 5.- Volúmenes, áreas, edades y tasas de acumulación de las unidades s´smicas A1-A4.