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Messinian palaeorelief from a 3-D seismic survey in the Tarraco concession area (Spanish Mediterranean Sea)

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Abstract

The 3-D seismic survey shot in the Tarraco concession area enables a very detailed analysis of the Messinian unconformity in that area. The revealed palaeomorphological features in combination with well data confirm that during the Messinian the sea level dropped rapidly and substantially, resulting in the erosion of a pre-Messinian shelf and slope sequence under subaerial conditions. The magnitude of the sea level drop is estimated to be about 2000 m. The nature of the infill of the Messinian valleys indicates a rapid return to normal global sea level.

Introduction

The Messinian salinity crisis in the Mediterranean Basin has been the subject of numerous publications, mainly since the drilling campaign (Leg 13) of the Glomar Challenger in 1970 (Ryan et al., 1973). It was suspected that the Mediterranean Basin had dried up during the latest Miocene as a consequence of its disconnection from the Atlantic Ocean, resulting in the deposition of a thick sequence of evaporites including salt over a large part of the whole basin as discovered by the wells of Leg 13. In 1975 a second drilling campaign (Leg 42) was mounted in the Mediterranean to gain more information on this rather unique geological event; the conclusions from this leg are given by Hsü et al. (1978).

These authors postulated a total desiccation of the Mediterranean, which in some areas would imply a drop in sea level in excess of 3 or even 4 km. However, this model has remained controversial. Discussions include the question as to whether the Late Miocene Mediterranean Basin had a bathymetry similar to that of the modern basin or alternatively consisted of a number of shallow restricted basins. Debenedetti (1982) argues that the salt layer may have been deposited by precipitation in such shallow seas, and that it was not necessarily associated with a drop in the sea level. He also demonstrates that total desiccation is impossible under current conditions of fluvial discharge into the Mediterranean Sea. The relative scarceness of complex salts in the Messinian evaporite sequence would support this view.

To date, evidence for a substantial sea level drop in a several kilometre deep Mediterranean Basin has been collected from numerous records of deep erosional features in marginal areas. The Messinian unconformity can be traced from onshore outcrops to offshore seismic data which show it cutting into thick Miocene shelf sequences and being the lateral equivalent of the abyssal Messinian evaporites. Cita & Ryan (1978) give a general account of these observations, which, together with sedimentological and palaeontological data, confirm the validity of, at least, a partial desiccation of the Mediterranean. The most striking observations on Messinian palaeo relief were reported by Barber (1981) and Bentz & Hudges (1981) from the Nile delta. However, in both cases a detailed interpretation was hampered by a rather poor horizontal resolution of the seismic data.

In the present paper an example is given of how 3-D seismic data acquired in the Tarraco concession area, offshore Tarragona, Eastern Spain, have provided additional and more detailed information in support of the subaerial character of the Messinian erosional surface. Additionally, a minimum range of the Messinian sea level drop is derived.

To explain the isolation of the Mediterranean Sea from the world oceans, tectonic movements or a eustatic fall in sea level have been envisaged. Because the Mediterranean Basin is surrounded by rising mountain ranges in Miocene times, a control by vertical movements in the Gibraltar area cannot be excluded. However, there is also evidence for a worldwide sea level low during the Messinian being related to a glaciation episode (Cita, 1982).

The Messinian unconformity in the Tarraco concession area

The Tarraco 3-D survey (Fig. 1) was shot in 1981 with a line spacing of 60 m and a trace spacing of 12.5 m, and covered an area of approximately 4.7 by 8 km. After 3-D processing the data set was interpreted on a Landmark III workstation.

The Messinian unconformity is a conspicuous seismic event, certainly in valley positions where it is associated with amplitude anomalies. Figure 2 shows the Messinian unconformity separating Miocene and Pliocene shelf sequences. The Miocene shelf prograded eastward during a rising sea level stage following a prominent sea level fall in the Upper Oligocene. Accordingly, the Miocene sedimentary sequence consists of bathyal deposits at the base overlain by prograding slope sediments (Castellon Clay). The thick topsets are represented by the shallow marine to deltaic Castellon Sandstone Formation. The original thickness of the Miocene prograding shelf sequence exceeds one kilometre and is locally reduced by the Messinian erosion. Pliocene sedimentation started with deep-water clays and mass-flow deposits (*Sphaeroidinellopsis* spp zone) filling and overstepping the Messinian relief. The overlying prograding shelf sequence is associated with the modern Ebro delta after which the Pliocene to Quaternary group is named.

The Messinian unconformity has the following seismic characteristics. In the valleys it corresponds to the strong negative amplitude reflection (horizon H1) below a large positive amplitude reflection (Fig. 2). Outside the valleys it is a rather faint event in terms of amplitude as the impedance contrast between pre- and post-Messinian slope deposits is very low. However, it is usually easy to pick because of the differing reflector geometries in both sequences. The H1 horizon was digitised on all lines, and an isochrone map of the unconformity was produced (Fig. 3). The picture that emerges is one of a rugged erosive landscape with broad ridges and varying valley profiles. Slopes show different gradients: they are rather gentle above 1.45 ms, relatively steep between 1.45 and 1.60 ms and gentle again in deeper regions. In the deeper regions in particular, the slope shape is dominated by numerous erosive entrenchments. These local drainage systems have V-shaped valley profiles. In contrast, the broad valley crossing in the northern half of the study area from trace 460 to line 160 is part of a more regional drainage system and has a rather flat bottom. At the eastern margin of the study area, the morphological character changes to that of piedmont plain which received a large volume of unconsolidated sediments eroded during Messinian times.

The overall morphology is clearly generated by subaerial erosion. The close similarity to recent badlands suggests that the vegetational cover was poor or lacking. Local variations of the morphological style are closely related to the eroded lithology: rather steep-sloped ridges are formed by the Castellon Sandstone formation, the uppermost Formation of the Miocene shelf sequence with a base around 1.60 ms. Owing to the relatively high carbonate content, these sands may have achieved

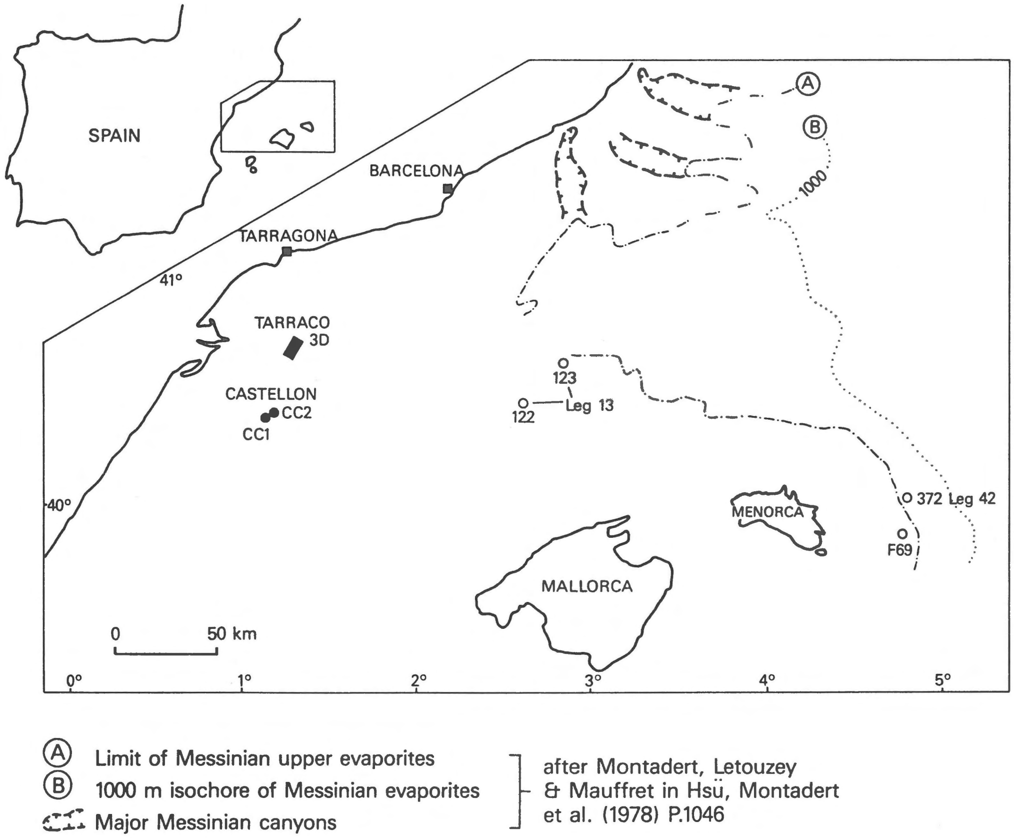

Fig. 1. Location map of the Tarraco 3D seismic survey.

a considerable physical resistance to erosion shortly after deposition. In terms of slope morphology, the boundary to an underlying shale-rich sequence coincides with the upper limit of many small valleys. Possibly a spring horizon had been caused by the permeability contrast between these lithologies. More gentle slopes below the 1.60 ms boundary coincide with a physically less resistant shale-rich lithology. Instability of the shales may be increased by abnormally high fluid pressures after the rapid drawdown of the sea level, triggering sliding and slumping phenomena.

From the flat bottom of the main northern valley it can be concluded that the base level of this valley has not been much deeper than the valley bottom itself. However, this conclusion does not necessarily have a direct implication for the position of the Messinian sea level: the base level of the mountain valleys seems to be controlled more by the piedmont surface in the east than by the Messinian sea level.

Infill history of the Messinian valleys

Well data show that sands and conglomerates were deposited in Messinian thalweg positions before deep marine sedimentation recurred. To analyse the nature and distribution of these Messinian valley fills, amplitudes have been extracted and mapped along the unconformity (H1 in Fig. 2) and along a stratigraphically higher horizon (H2) representing the first infill of valleys. The resulting maps are provided as Figures 4 and 5 with an interpretational sketch in Figure 6. High amplitudes occur in all thalwegs and also on slopes at the foot of sand-

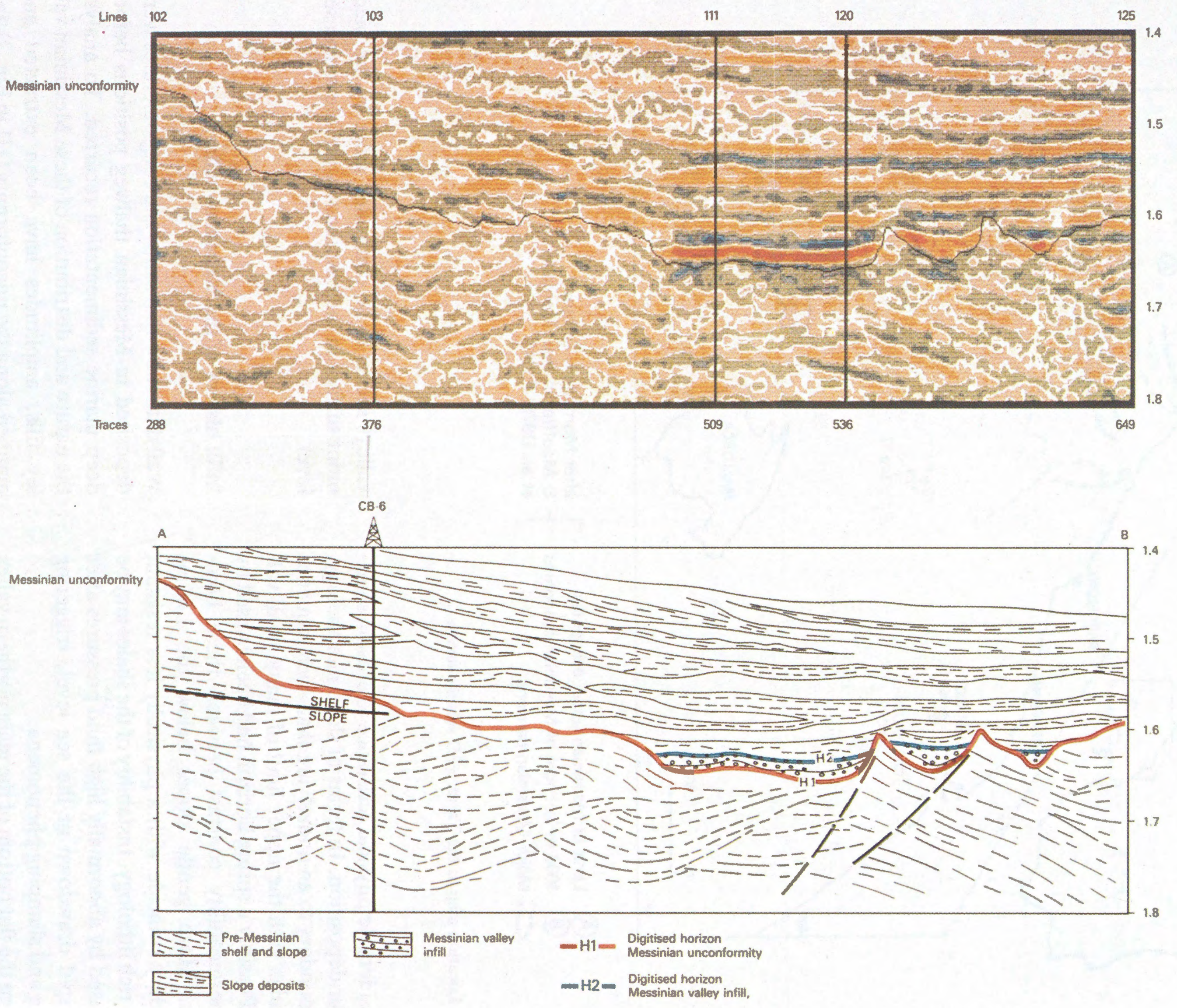

Fig. 2. Section A–B.

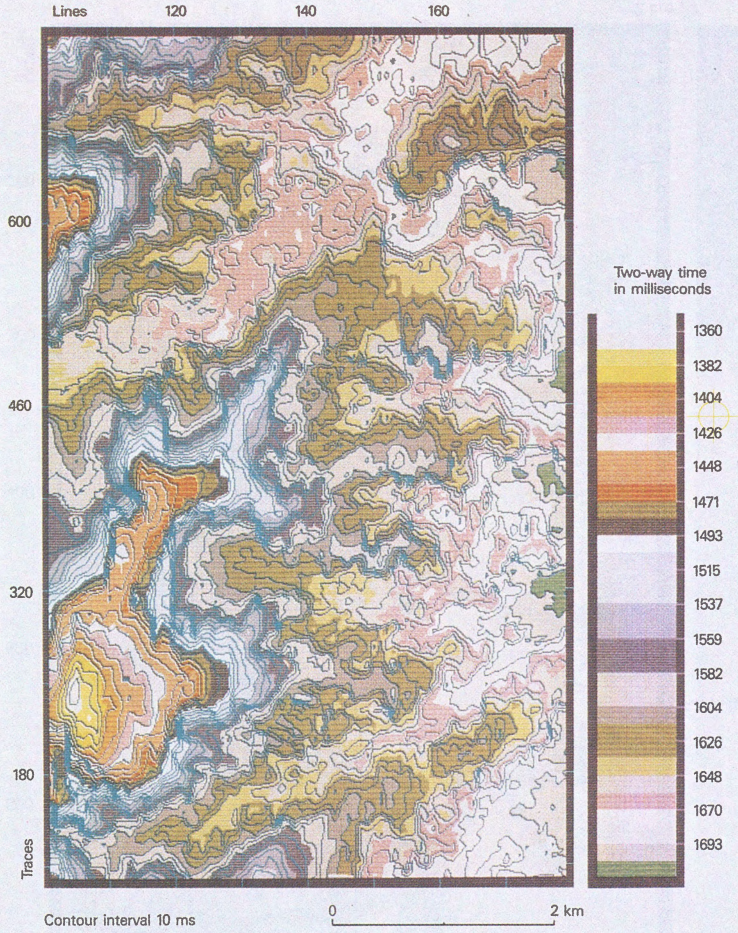

Fig. 3. Messinian unconformity, isochrone map.

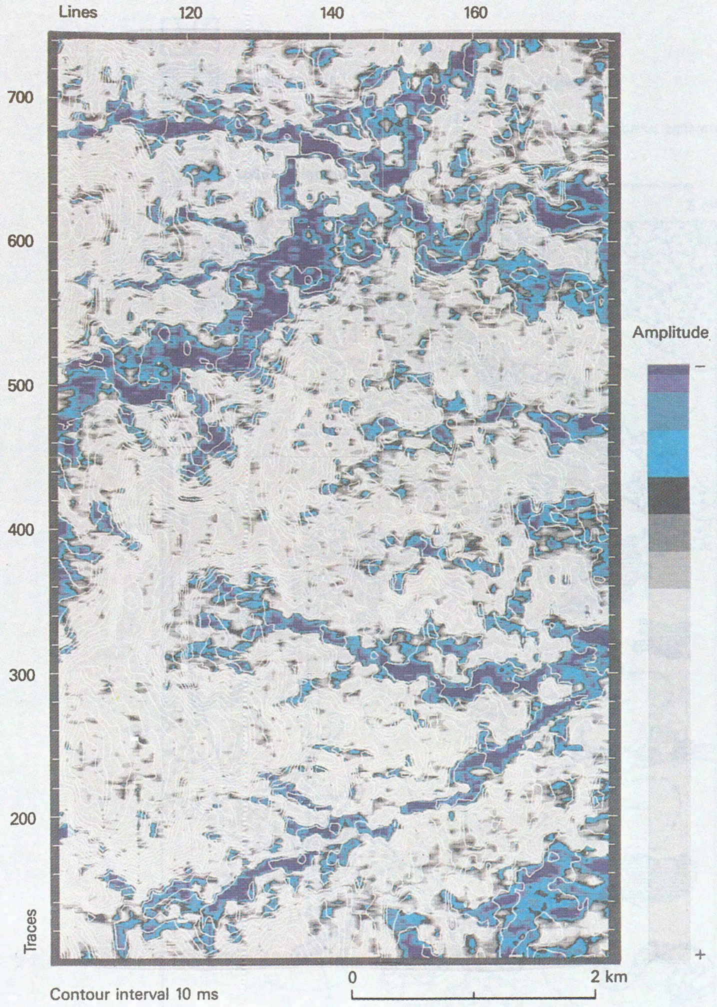

Fig. 4. Messinian unconformity, amplitude extraction and isochrones.

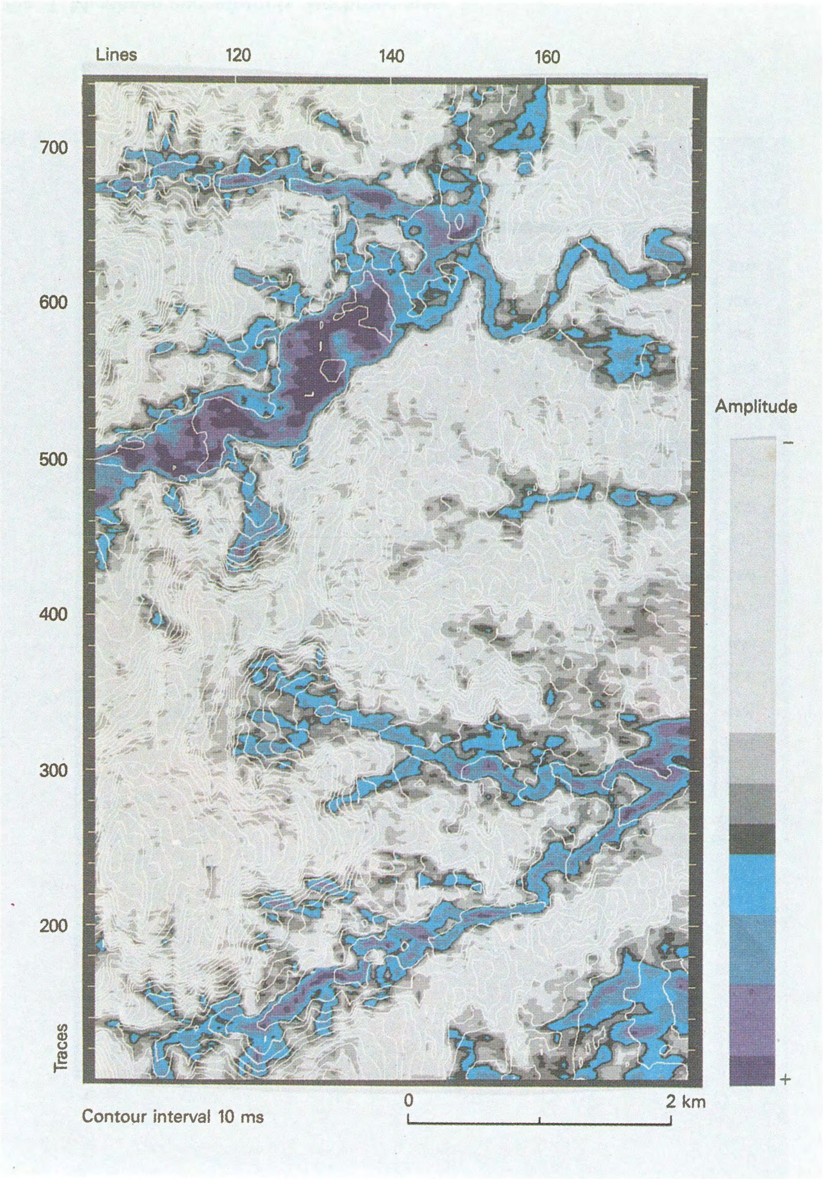

Fig. 5. Messinian valley fill, amplitude extraction and isochrones.

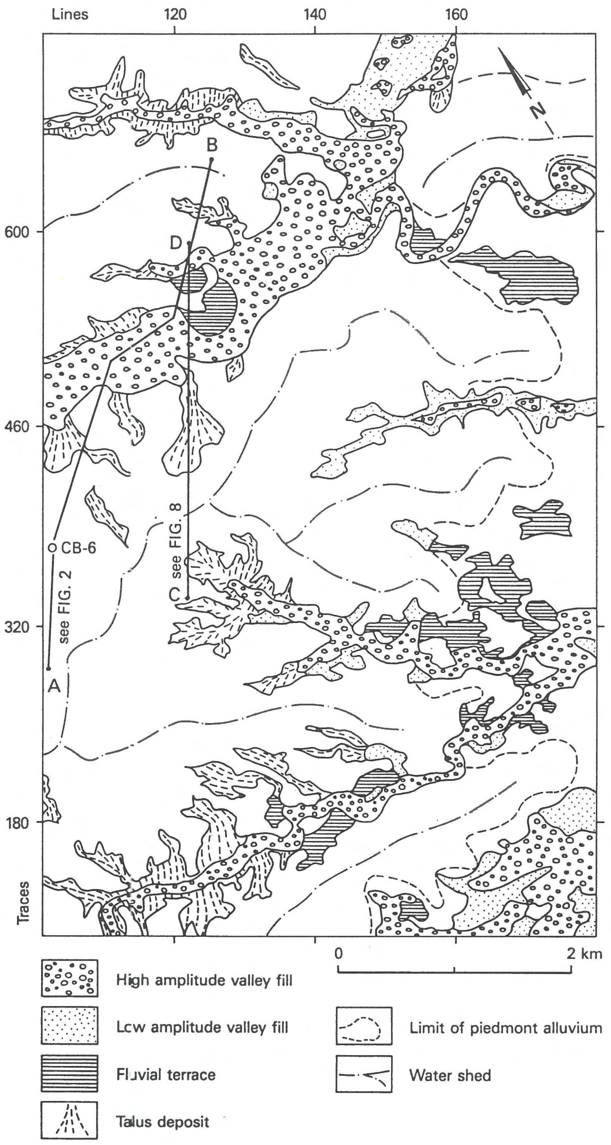

Fig. 6. Messinian valley fill, interpretation of amplitude extraction.

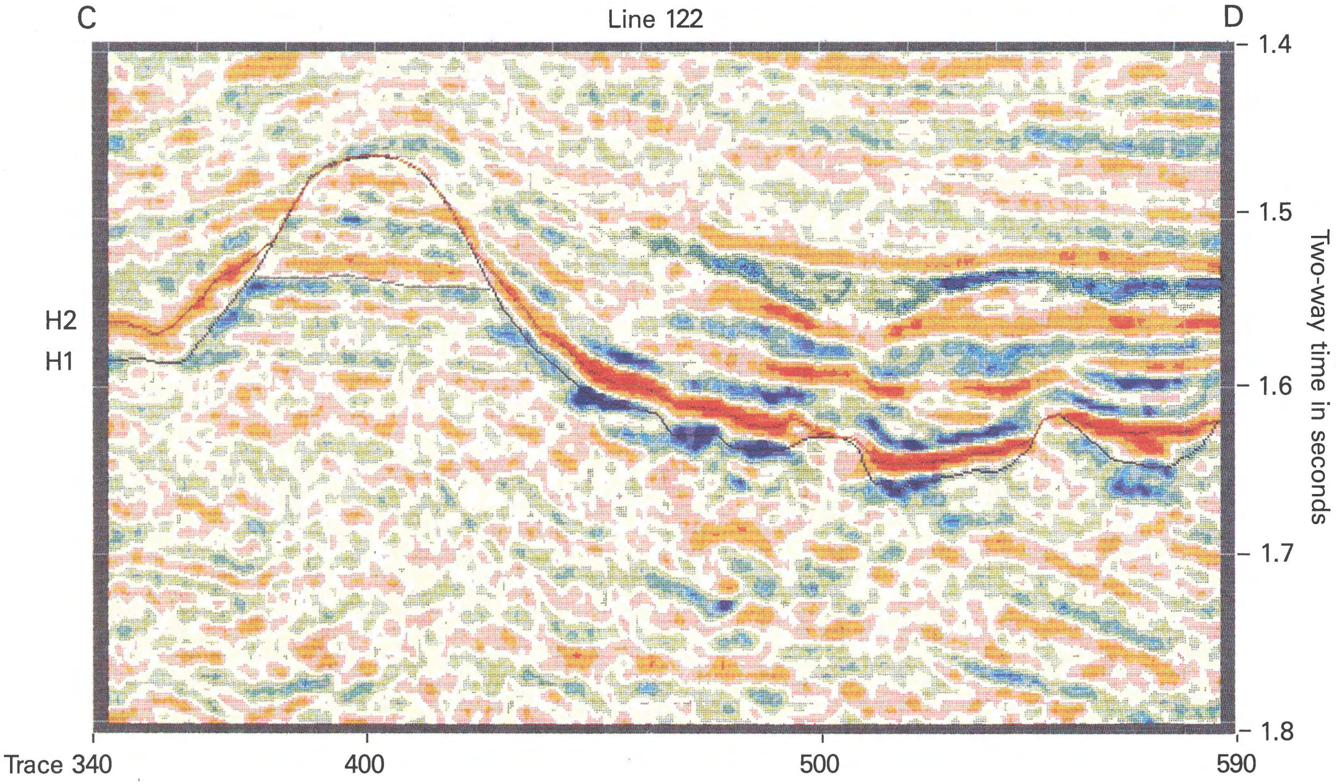

Fig. 7. Section C–D.
Reflectivity section. See Fig. 6 for location.
H1 Digitised horizon Messinian unconformity, see Fig. 4.
H2 Digitised horizon Messinian valley infill, see Fig. 5.
A third line in the hill of Castellon Formation indicates the boundary between slope and shelf facies.
Note that valley infills are represented by sub-horizontal reflectors while reflectors of talus deposits are inclined with an upper limit around the slope/shelf boundary of the underlying strata.

stone 'cliffs' of the Castellon Formation and appear to be lithology-related.

To calibrate the seismic response to lithological features, core information from two nearby wells, CC-1 and CC-2 (Fig. 1), was used. Both wells are positioned in Messinian thalwegs and encountered tight conglomerates overlying grey clays with irregular microfractures filled with calcite. The polymict conglomerates are interpreted as Messinian fluvial deposits derived from Mesozoic formations of the onshore Tarragona area. Strong cementation by calcite may be understood as being related to surficial processes in an arid climate; the calcitic microfractures in the deep sea clays may also be of pedogenic origin. It is assumed here that high amplitudes at the unconformity level reflect cemented siliciclastics (i.e. conglomerates in main valleys coming from more landward areas or sandstones in local valleys). Because the overlying shales are rather monotonous, lateral changes in amplitude will be related to variations in the lithology of the Messinian sediments.

Based on these data and on morphological considerations, a lithological interpretation of the amplitude anomalies of Messinian valley fills is proposed in Fig. 6. Sediments in a true thalweg position are split according to the reflection amplitude into 'high-' and 'low-amplitude valley fills'. Similar flat-lying deposits in somewhat elevated positions above the main thalweg are interpreted as 'fluvial terraces'. Anomalous amplitudes in slope positions occur mainly in the western part of the area and are interpreted as reflections of 'talus deposits'.

To some extent the erosional and depositional history of the Messinian valleys can be extracted from the distribution of the four facies inferred. In general, sinuous meandering patterns dominated during fluvial erosion and these are also common as depositional patterns visible in the amplitude maps (Figs. 4 and 5). An excellent example of the erosional movement of a single meander loop is located at line 155/trace 590. It illustrates synchronous erosion at the river bed and the cut bank leaving behind fluvial terraces at the concave bank (compare Figs. 3, 5 and 6). This river has changed its course completely at least once, as evidenced by the isolated terrace to the southeast.

Another major change of fluvial pattern may be indicated by the amplitude distribution in the broad main valley which crosses the northern part of the study area from west to east. At the H2 infill level there is a distinct contrast between a western upstream part, with a continuous high-amplitude facies, and an eastern downstream part with a spot-like distribution of this seismic facies (Figs. 5, 6). Instead, high amplitudes continue towards the southeast in the highly sinuous narrow valley. It could be argued that here the phenomenon of river capture took place: erosion in the narrow secondary valley proceeded until the ridge towards the main valley was removed. Thereafter the main river flowed to the southeast, the eastern part of its course being abandoned.

At the margin of the piedmont plain, further weak amplitude anomalies occur on top of gentle ridges. These anomalies are roughly confined to certain isochrones and may therefore represent relics of former thalweg deposits. After the previous relief in this area was levelled by progressive erosion, the rather hard thalweg deposits may have caused an inversion of morphology. However, locally these anomalies are related to subcropping harder lithologies of the Miocene sequence.

Well-developed talus deposits are clearly associated with occurrences of the Castellon sands which form the top part of the Miocene sediments. The distinct seismic expression of these bodies (Fig. 7) may result from a combination of two features, both related to the Castellon sands as source of the talus deposits: the sandy to conglomeratic clastic composition and a likely cementation by calcium-rich solutions seeping down from the inferred spring horizon at the base of the Castellon calcareous sands.

In conclusion, the overall morphological character of the Messinian surface and the distribution of seismic facies in valleys accentuate the subaerial nature of erosion and deposition. While meandering patterns dominated during erosional stages, leaving behind fluvial terraces, the fill of the broad northern valley also shows features of a braided stream environment.

The sharp transition from subaerial to deep-water depositional conditions demonstrates that the final rise in sea level was very rapid. A number of intermittent sea level rises during the Messinian have been concluded from the volume of evaporites accumulated (Hsü et al., 1978) and from observations made on Messinian reef complexes of the Western Mediterranean (Esteban, 1979). Similar to the final sea level rise, such rapid marine incursions would not leave distinct traces of their passage.

Estimation of the sea level drop during the Messinian salinity crisis

The range of the Messinian sea level drop in the western Mediterranean Sea can be estimated from the relief between the top of the Miocene shelf and the evaporites or salt in the abyssal basin, corrected for the effects of post-Messinian vertical movements and compaction. However, only some of the necessary data are available for the area under study. The 3-D seismic data cover only a rather limited area, in which no Messinian evaporites were recorded. Therefore, only a minimum range of sea level drop can be directly inferred from the seismic data in the Tarraco concession. The shallowest position of the Messinian surface is around 1500 m subsea, the deepest contact between Miocene slope sediments and Messinian valley fills is recorded around 2150 m giving a range of 650 m. In the CC wells to the south (Fig. 1), the unconformity has been penetrated at 2750 m subsea; east of the CC wells, regional seismic lines show the unconformity at about 3400 m subsea, resting directly on the Miocene base-of-slope sediments. This proves that the sea level drop was at least as large as the original thickness of the Miocene shelf sequence. Going further east towards the abyssal plain, Messinian evaporites – as the lateral equivalent of the unconformity – are reported from depths between 2400 m and 2800 m subsea (Montadert et al., 1978; Rios, 1978), often shallower than in the CC wells. This configuration illustrates the difference in post-Messinian subsidence between shelf and abyssal plain.

To obtain an estimate of the Messinian palaeorelief, the actual relief measured on seismic data has to be corrected for the effects of post-Messinian compaction and differential subsidence. We have measured a relief of 1950 m in the area surrounding the actual Tarraco 3-D seismic survey area; this agrees closely with data reported by Ryan (1976) from the Gulf of Lions. If corrected for post-Messinian compaction according to Baldwin & Butler (1985), this relief must have been about 2170 m in Messinian time. However, the areas with a deep position of the unconformity have received thicker packages of Pliocene-Quaternary sediments and have therefore experienced more post-Messinian subsidence than areas where the unconformity is shallower. It is assumed here that the opposite effects of compaction and differential subsidence are of the same order of magnitude. Consequently, a minimum value of nearly 2000 m for the Messinian sea level fall can be assumed. The question of whether deeper parts of the western Mediterranean Basin actually dried up remains unanswered and requires further investigation.

Conclusions

The interpretation of 3-D seismic surveys can be regarded as a major tool for geological investigations. The detail extracted from the example described here, proves the powerful lateral resolution of the method. It certainly enables a much more accurate structural interpretation and also provides the geologist with ready-made models such as that of the Messinian river system introduced here.

Careful use of seismostratigraphy (calibrated by well information) leads to refined geological models. It is demonstrated by the application of these methods that the Messinian erosion was of subaerial character in this area. The history and controlling features of the Messinian erosion can be inferred from morphological features such as terraces, and the nature of Messinian valley fills can be unravelled. It must, however, be stressed that the above observations were helped by the largely unequivocal seismic expression of the Messinian valleys, which in itself is an outstanding phenomenon.

We calculated that the Messinian sea level drop in the Mediterranean Basin may have been of the order of 2000 m. The deepening of the sea during the return to the global level was very fast. However, it is realised that little can be said on sea level fluctuations during the salinity crisis.

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