

## 3-D Seismic interpretation and lateral prediction of the Amposta Marino field (Spanish Mediterranean Sea)

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### Abstract

The objectives of a seismic study of the Amposta Marino field, offshore Spain, were threefold: firstly, to map the top of the main karstified reservoir (C horizon) accurately in order to identify any possibly remaining attic oil; secondly, to map and interpret a sub-horizontal, semi-continuous anomalous reflection (C2 horizon) within the karstified Montsia carbonate reservoir; thirdly, to assess the feasibility of predicting porosity in karstified reservoirs.

1. The acoustic impedance at the interface between cap rock and top reservoir can be increasing or decreasing, depending on the degree of karstification. Hence, the top reservoir reflection can be positive or negative. This interpretation problem, once recognised, could be solved and led to improvements in the structural map.
2. The synthetic seismogram, logs and drilling records of well AMB-10 indicate that the C2 horizon represents a porous karstic layer. It occurs as a semi-continuous, sub-horizontal feature around the flanks of the structure. Distribution of the C2 marker and also the reservoir performance data and geological history of the Amposta Marino field indicate that the actual porosity system in the Montsia reservoir could be the product of an originally compartmentalised porosity network (resulting from karstification) with greatly increased lateral communication as a result of subsequent mixing-zone corrosion. The C2 event is interpreted as a high-porosity layer caused by a sea level stillstand which allowed intense mixing-zone corrosion to occur.
3. The areal distribution of collapse breccia and cave development can be mapped by displaying the root mean square of the amplitude measured in a window corresponding to the karstified reservoir. Qualitatively, areas with high amplitudes correspond to the most enhanced porosity zones.
4. Although very thin compared to total reservoir thickness, enhanced porosity zones, created as a result of mixing-zone corrosion, could contain the bulk of the oil and may therefore represent an important exploration/production target.

### Introduction

The Amposta Marino oil field was studied as part

of Shell research on 3-D surveys and geological modelling of carbonate reservoirs. The field is situated in the Mediterranean Sea, some 30 km off

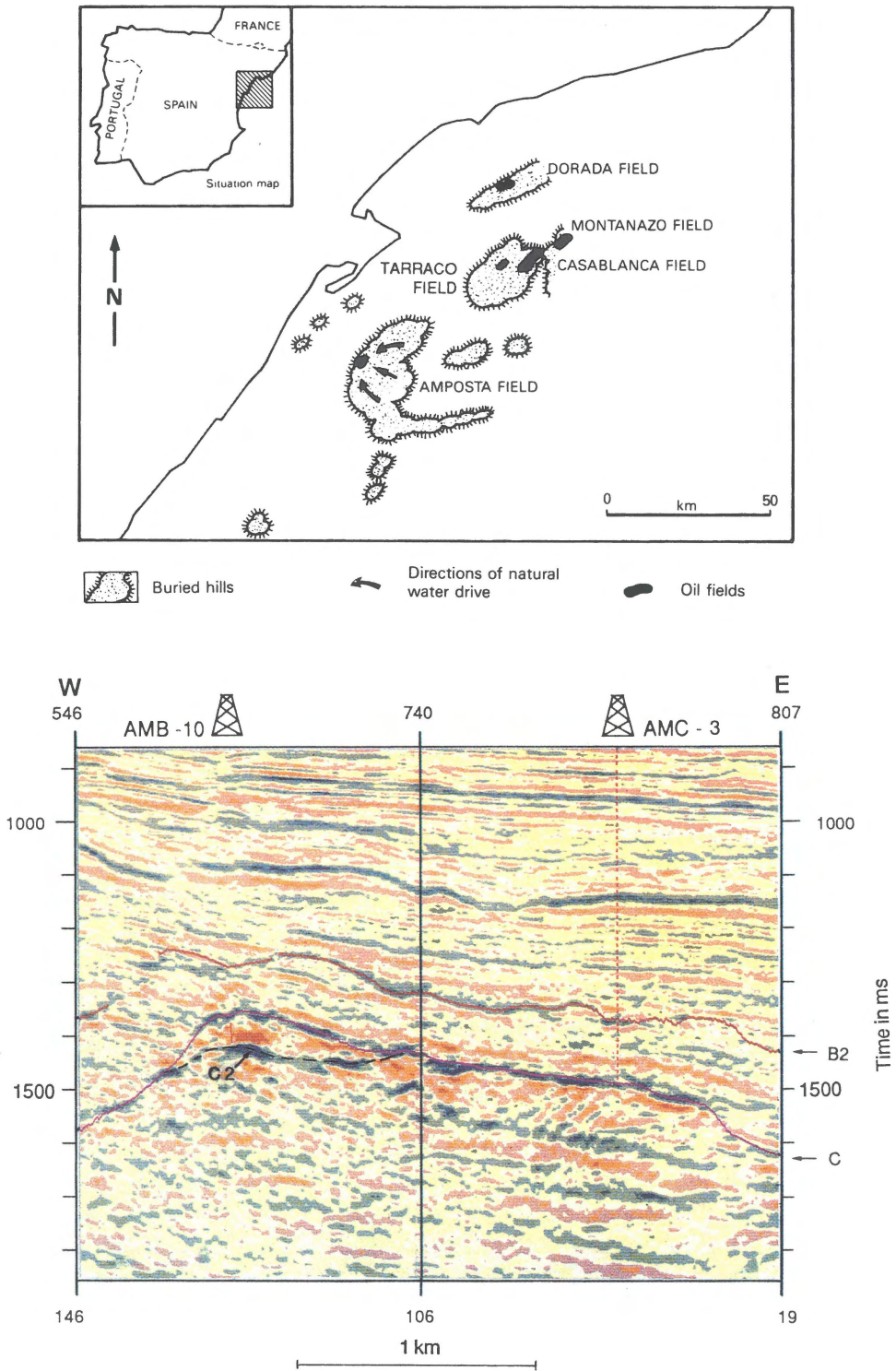


Fig. 1. (a) Buried hills with karstified Mesozoic carbonates and oil fields, offshore Castellón area. (b) Representative interpreted line across the Amposta Marino structure. Interpreted section shows the 'B2', 'C' and 'C2' horizons indicated by arrows. (See Fig. 6 for location).

the Ebro river mouth along the east coast of Spain (Fig. 1a). The discovery well (AMC-1) was drilled in 1970 by Shell España and encountered a large buried hill of partly karstified Mesozoic carbonates. The structure trends NE-SW, and is some 40 km long and 20 km wide; the actual field covers an area of approximately 8 km<sup>2</sup> located at the structurally highest part of the buried carbonates. It is bounded to the west by a steep (around 40°) major scarp some 500–800 m high. The surface of the paleorelief is tilted gently towards the southeast, reflecting the structural dip (approx. 6°) of the Lower Cretaceous Montsia Formation (Figs 1b & 6). It is on trend with the abandoned Tarraco field (Shell), the Dorada, Montanazo and Casablanca fields, which represent a total of approximately 175 MMSTB reserves.

The main reservoir is the Montsia karstified carbonate. It is estimated that the porosity related to the karst ranges from 0.2% to as high as 5% (with an average of 2% bulk volume). The matrix porosity of the carbonate reservoir amounts to some 3% with a correspondingly low permeability (0.1–3 mD). To date, 55.7 MMSTB of oil have

been produced and the field is believed to be close to the end of production (Seeman, 1988).

### Seismic data, seismic to well match

A 3-D seismic survey was shot in 1983 over the Amposta Marino field in a NW-SE direction (dip direction), covering an area of 6.7 by 9.7 km (65 km<sup>2</sup>). Trace spacing is 5.25 m and line spacing is 20 m. The seismic data were reprocessed in KSEPL\*, with a 3 ms sampling rate; the final display filter, at reservoir level is a zero-phase Butterworth filter with corner frequencies: 6-10-60-80 Hz. The zero-phase reflectivity seismic data were loaded onto a Landmark seismic workstation with the following convention: an increase in acoustic impedance is a negative trough and displayed in blue.

Synthetic seismograms for all Amposta wells (except for the AMB-11 well) were generated to

\* KSEPL: Koninklijke/Shell Exploratie en Productie Laboratorium.

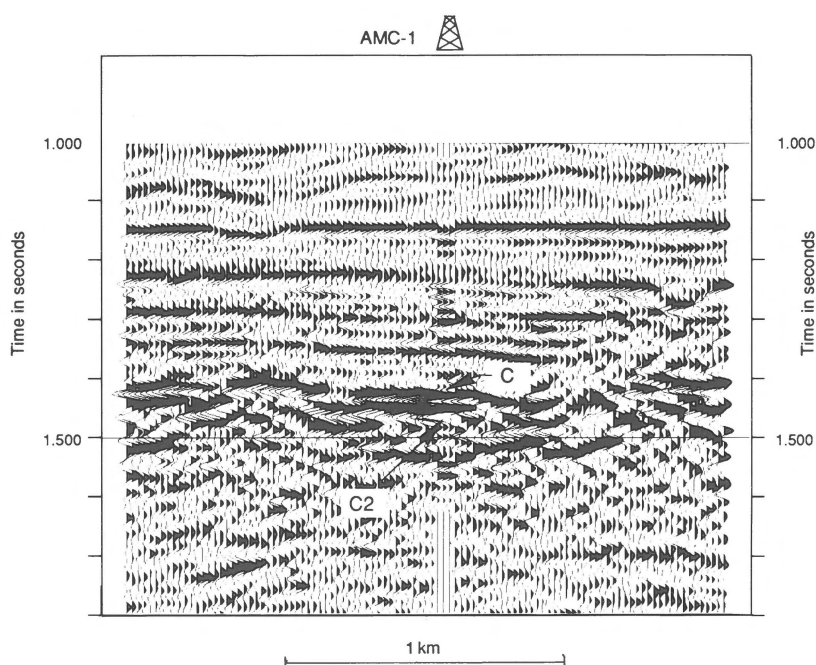


Fig. 2. AMC-1 seismic-to-well match. The identification of the various loops is possible above the top reservoir (C horizon, black positive loop) and locally at the C2 horizon level (white negative trough). (See Fig. 6 for location).

pick the exact position of the top reservoir (C horizon) and the sub-horizontal, semi-continuous anomalous reflection within the karstified Montsia reservoir (C2 horizon).

For seismic-to-well matching, the sonic and density logs needed editing in the zone of intensive karst development as the logging tools are reading mud properties rather than formation. The resulting seismic-to-well match was fairly good in the clastic section down to the top of the Montsia reservoir (Fig. 2), and allowed reliable picking of the C horizon. The match in the Montsia reservoir, where heavily karstified zones were encountered, was generally less satisfactory but sufficient to pick the C2 horizon.

Interpretation of the synthetic seismograms indicates that the acoustic impedance contrast between the Montsia carbonate reservoir and the overlying clastic Castellon Formation changes from positive to negative with increasing cavernous/breccia karstification (Martinez del Olmo et al., 1983) (Fig. 3b). In terms of reflectivity, this corresponds to a change from a negative loop to a positive loop (Fig. 3c). Within the Montsia interval, only cavernous/breccia karst development significantly affects the seismic response (not fissure and cavity), giving rise to anomalously high amplitudes (positive and/or negative). Fig. 4 shows two examples of synthetic seismograms with and without cavern/breccia karstification.

## Seismic interpretation

### Interpretation objectives

For this study, the following objectives were identified:

1. Accurate mapping of the top karstified carbonate reservoir (C horizon).
2. Mapping and interpretation of a sub-horizontal, semi-continuous anomalous reflection (C2 horizon) within the karstified Montsia reservoir.
3. Feasibility of predicting porosity in karstified reservoirs. In addition, the Messinian unconformity (B2 horizon) was also mapped.

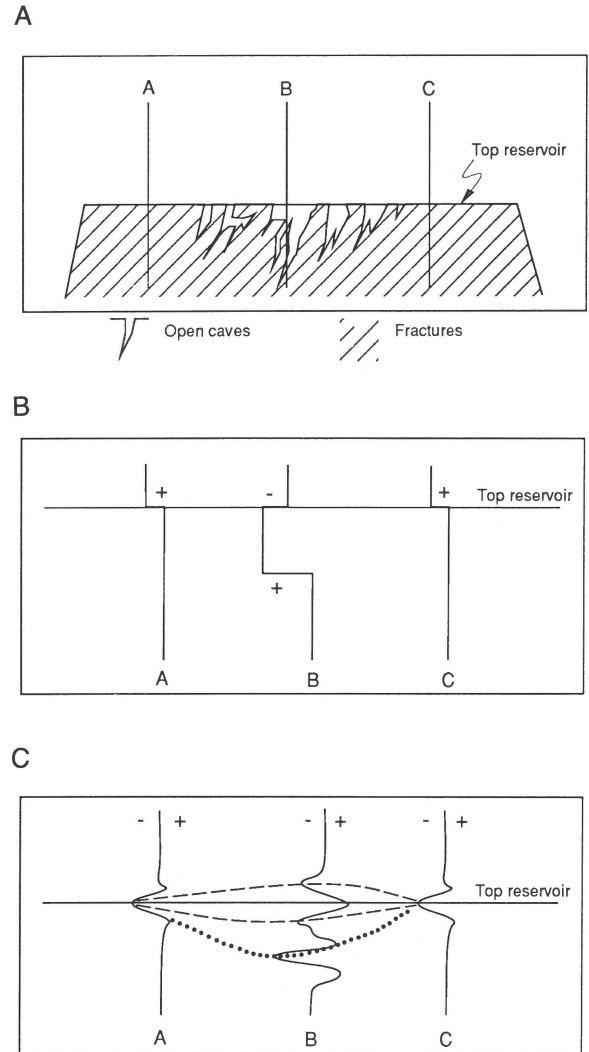


Fig. 3. (a) Conceptual depth model. (b) Acoustic impedance model. Top reservoir acoustic impedance contrast varies from positive to negative to positive. (c) Reflection traces model. Top reservoir signature varies from negative to positive loops (solid, horizontal line). Mapping the top reservoir considering only negative loops would be incorrect:

- the dashed lines are above or below the top reservoir in well B
- the dotted line indicates the base of cavernous karst development in well B.

### Accurate mapping of the top karstified carbonate reservoir

As a result of seismic-to-well calibration, the top of the karstified carbonate reservoir (C horizon) was mapped as a positive loop on reflectivity when high amplitudes underlaid it, indicating that it directly overlies collapse breccia/cave development; else-

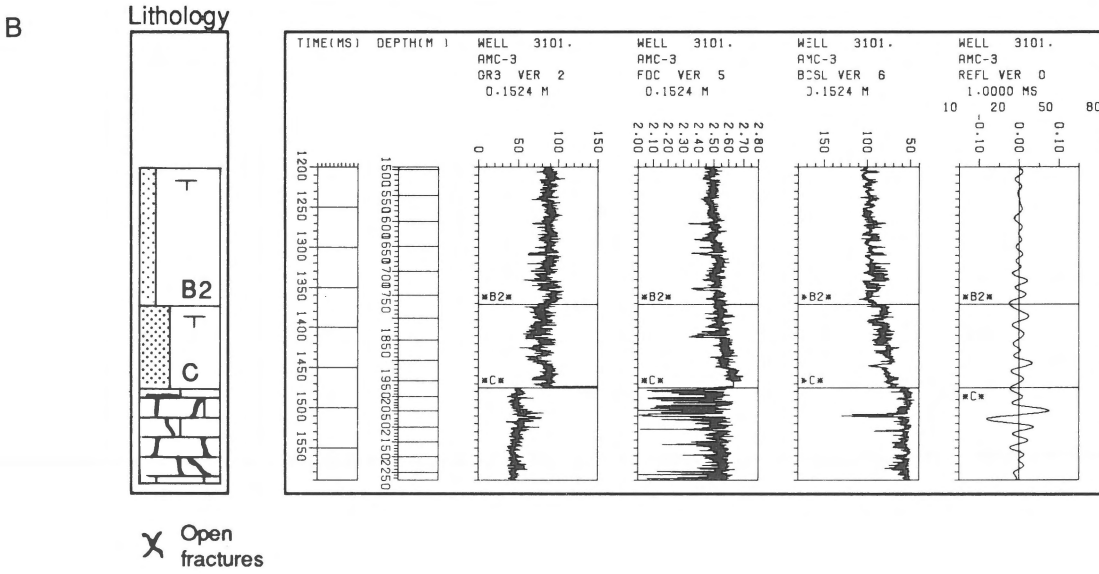
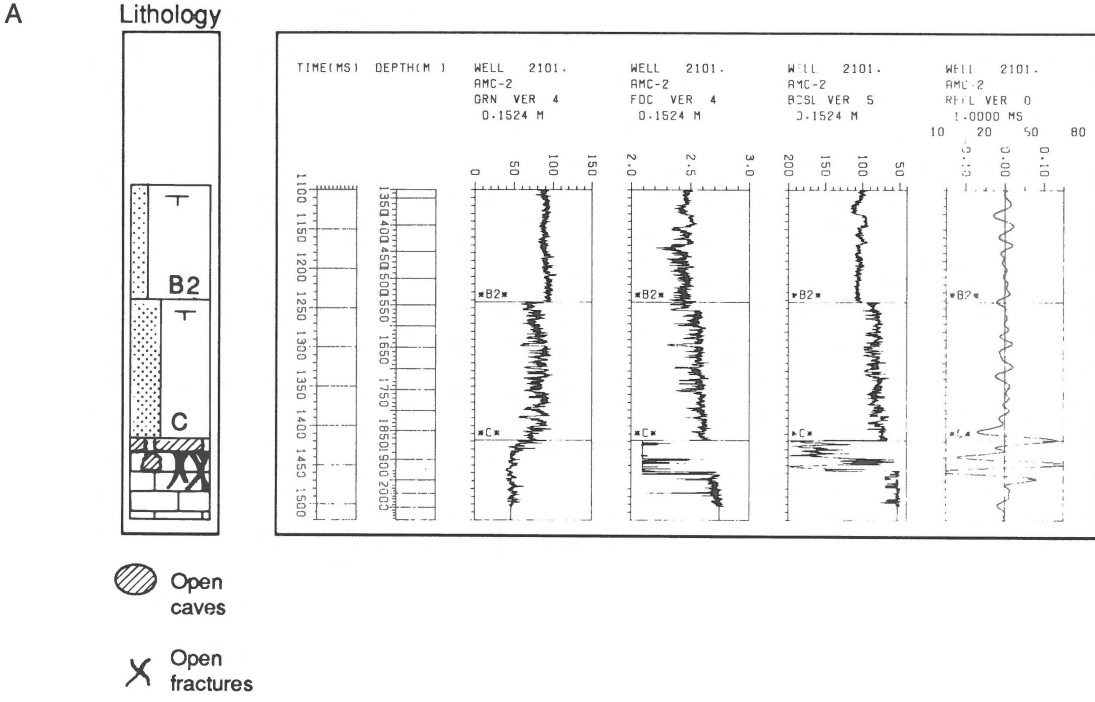


Fig. 4. (a) Synthetic seismogram for well AMC-2 showing that the top of the cavern/breccia karstified reservoir corresponds to a strong positive loop. (b) Synthetic seismogram for well AMC-3 showing that without cavern/breccia karstification top reservoir corresponds to a weak negative loop.

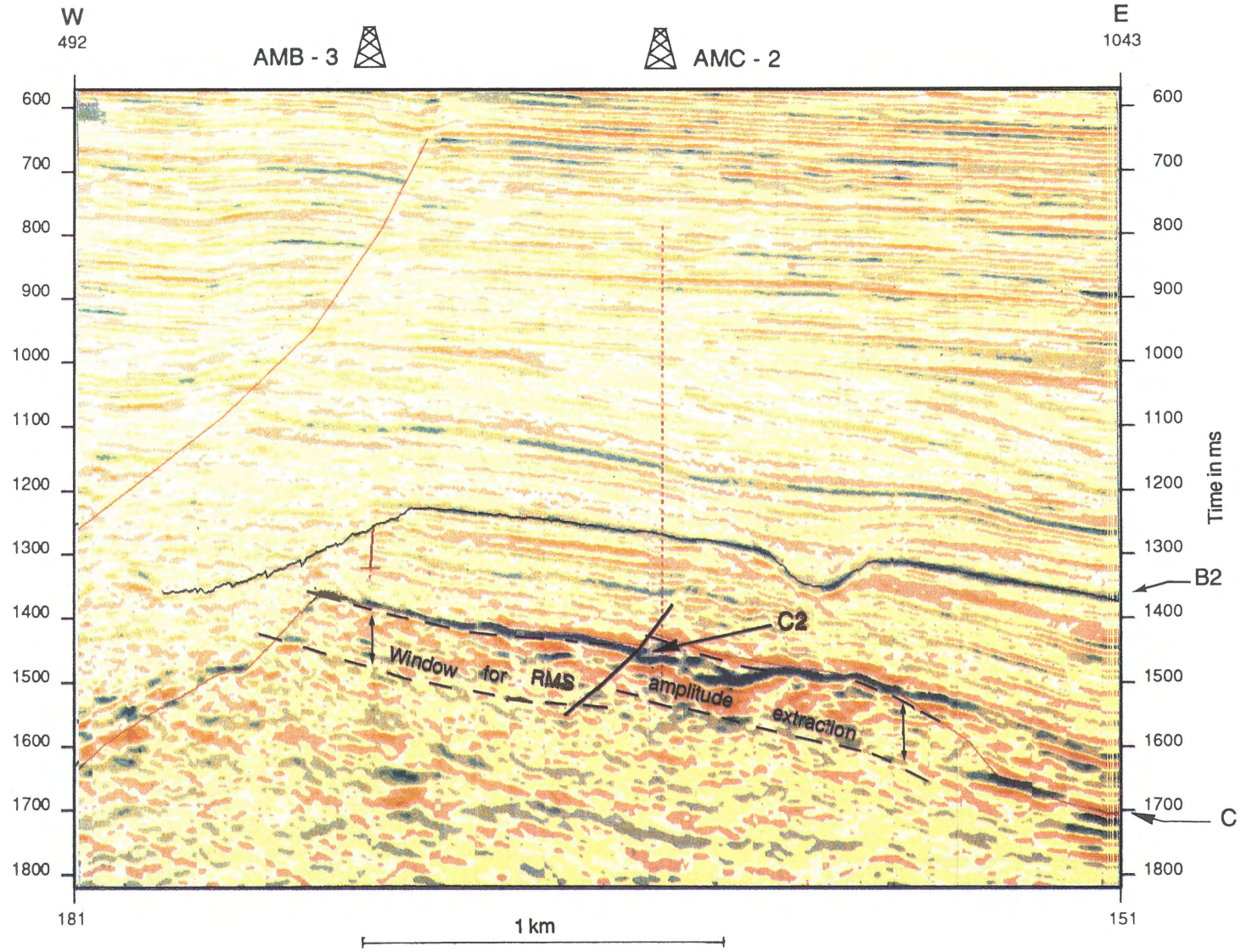


Fig. 5. Seismic section across wells AMB-3 and AMC-2 (See Fig. 6 for location).

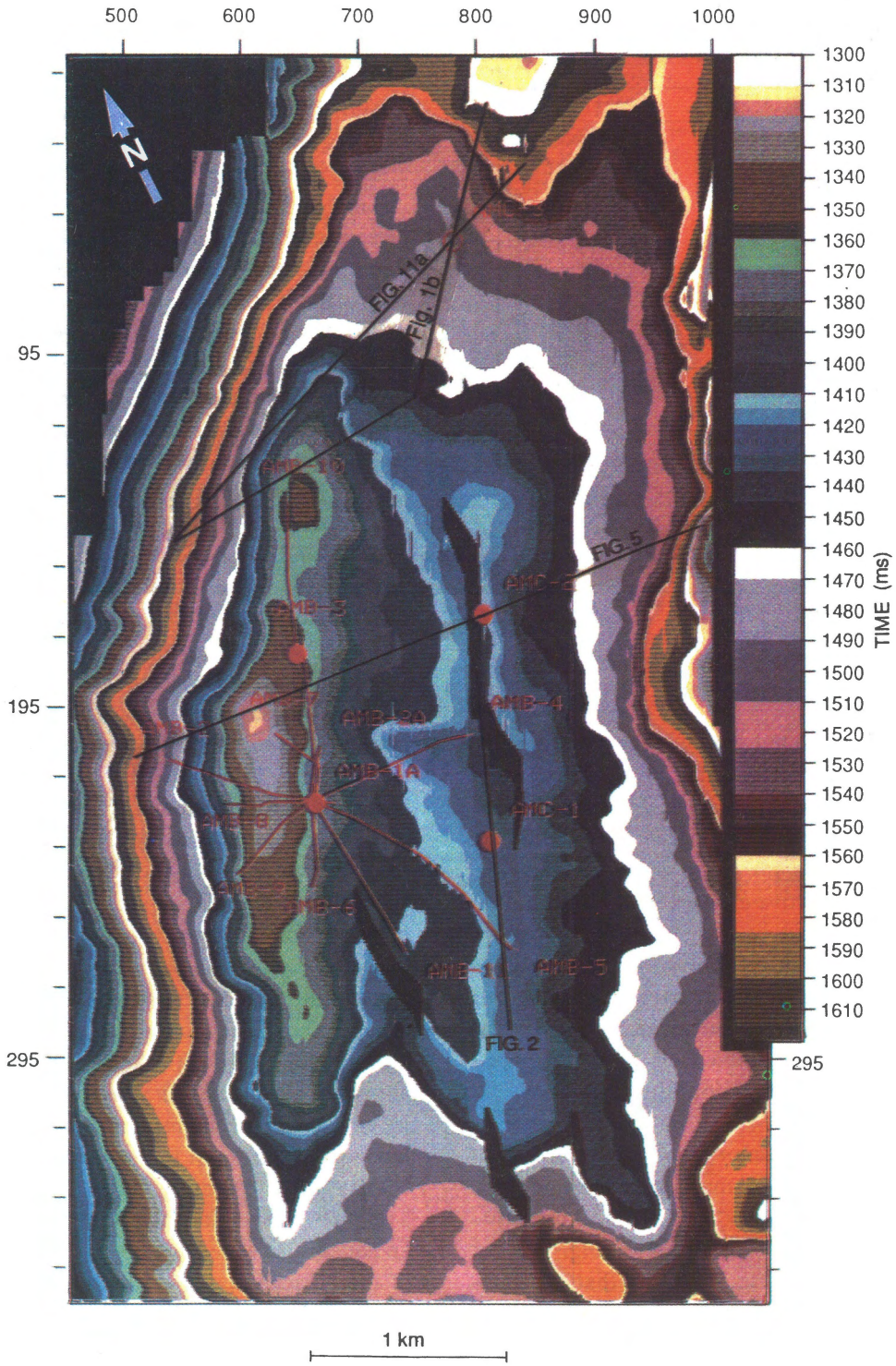


Fig. 6. Isochrone map. Top reservoir level (C Horizon).

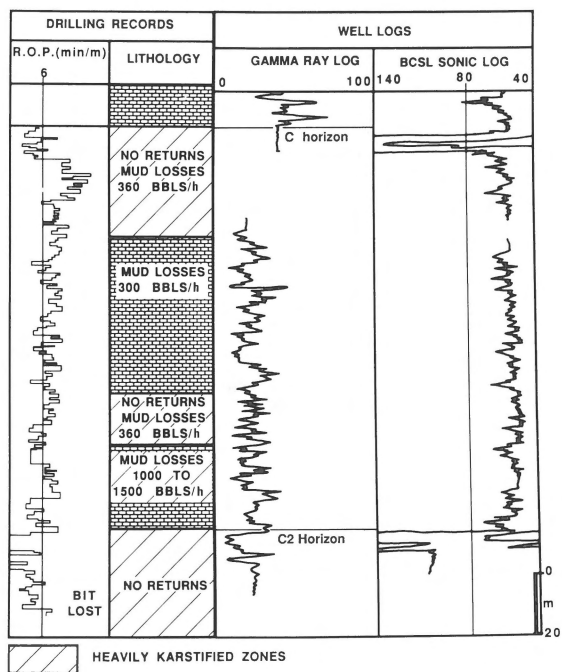


Fig. 7. AMB-10 well data.

where it was interpreted as a negative loop (Fig. 3). Figure 5 shows a seismic line through two wells together with the interpretation. Ignoring the polarity change can result in errors of up to 20 ms (some 35 m), which may well be more than the relief of the prospective attic oil pool. For Amposta, the improvement in the structural map as a result of the re-interpretation of the 3-D data is minor owing to the dense structural control from well data. There was, however, a significant change in the area around well AMB-11 where closure is now considered doubtful (Fig. 6).

#### Mapping and interpretation of the C2 horizon

In well AMB-10, the 'C2' marker corresponds to a drilling break followed by severe mud losses, indicating a (karstic) porosity zone (Fig. 7). Its mapped distribution (Fig. 8) shows that it occurs somewhat discontinuously, around the western margin of the structure, and fairly continuously around the eastern margin of the structure, forming a 'rim'-type feature around the flanks of the 'buried hill'.

Distribution of porosity (and therefore productivity) in a 'buried hill' type of karstified carbonate

such as Amposta can be described by invoking a model of authigenic karstification (Fig. 9). Such a karst network (Jennings, 1985) will typically follow a dendritic pattern with the crest of the structure being dominated by abundant, small pipes/caves and the flanks of the structure by larger, but fewer, channels and caves. Collapse of these large channels/caves results in the down-flank areas being dominated by breccia porosity. In the crestal areas, where there were smaller pipes/channels, fissure and cavity porosity are dominant. In this type of setting the overall resultant karst porosity distribution would be highly compartmentalised (Fig. 9a). However, for Amposta Marino, reservoir performance data indicate that the main karst-related porosity system is extremely well connected, as shown by the perfect pressure support from the downdip aquifer, and the fact that the bulk of the reserves was drained by only five wells, one of which produced nearly half of the total production.

Several studies (Lohman, 1988, Smart et al., 1988; Plummer, 1975) have shown that in coastal or island settings, porosity in carbonate rocks can be increased along the contact between seawater and the overlying brackish/fresh-water lens, as a consequence of mixing-zone corrosion (Fig. 9b). This process can pervasively increase existing porosity, regardless of whether the porosity is matrix, karstic, or fracture in character. Most importantly, however, mixing-zone corrosion will tend to create laterally extensive, sub-horizontal zones of well-connected, enhanced matrix porosity as a rim around the flanks of a 'buried hill' structure. Hence, to explain the observations described above for the Amposta Marino field, both porosity-generating mechanisms are combined in the following description of the geological history.

From the late Cretaceous till the Early Miocene, a relative sea level fall of around 800 m, followed by an equal relative sea level rise, occurred as a result of the African plate moving northwards. Considerable faulting took place during that period and, as a result, the Montsia Formation in Amposta became exposed and was affected by intensive karstification. Karst porosity was developed to a depth of 150–200 m below the top of the carbonate, with its base approximately parallel to the structural



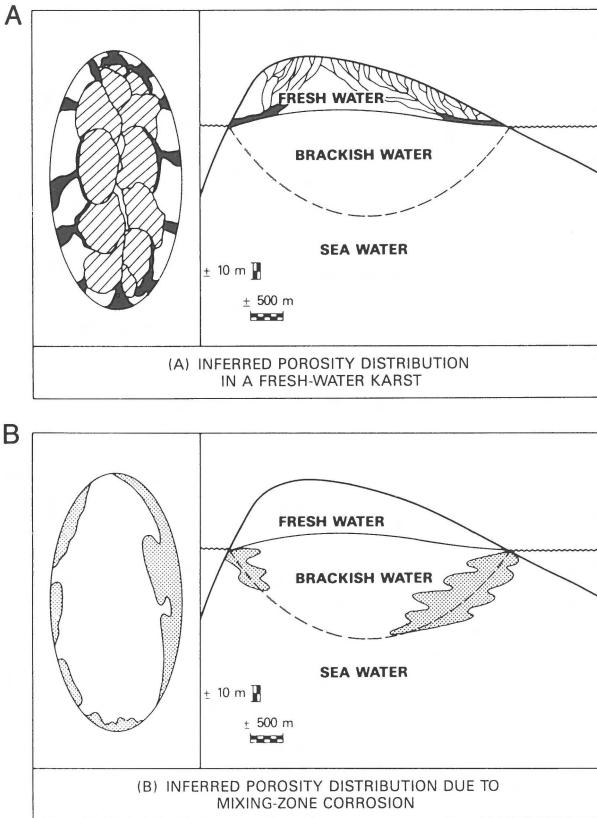





Fig. 9. Conceptual model of porosity development. (a) A karst network typically follows a dendritic pattern. In the crestal areas fissure and cavity porosity are dominant . The down-flank areas are dominated by cave and breccia porosity . The overall porosity distribution is highly compartmentalised. (b) Mixing-zone corrosion can enhance both cave and matrix porosity at depth in the phreatic zone . This process results in a far less compartmentalised porosity distribution, especially around the edges of the structure.

dip. The Amposta hill was further tilted (approximately  $6^\circ$ ) (Fig. 10a) before sea level began to rise again during the Early Tertiary. When the sea reached the level of the karst system (Fig. 10b), marine and meteoric waters could mix in the cavernous karst porosity. The resulting corrosion increased the communication, and the lateral conti-

nunity of the originally compartmentalised karst porosity. Then a sea level stillstand allowed intensive mixing-zone corrosion to occur around the flanks of the Amposta buried hill, forming an extensive, laterally continuous porosity zone – the ‘C2’ horizon – locally associated with terrace development (Fig. 10b). (A stillstand in sea level for 5,000 to 10,000 years would be sufficient for extensive porosity enhancement and development, such as observed in the present-day Bahama Banks). Continued rising sea level increased the karst porosity above the level of the ‘C2’ horizon, until the entire structure was drowned in the Mid to Late Miocene, and deposition resumed with the chalky coral-algal Amposta Limestone and its deep-water equivalent the Alcanar Formation (Fig. 10c).

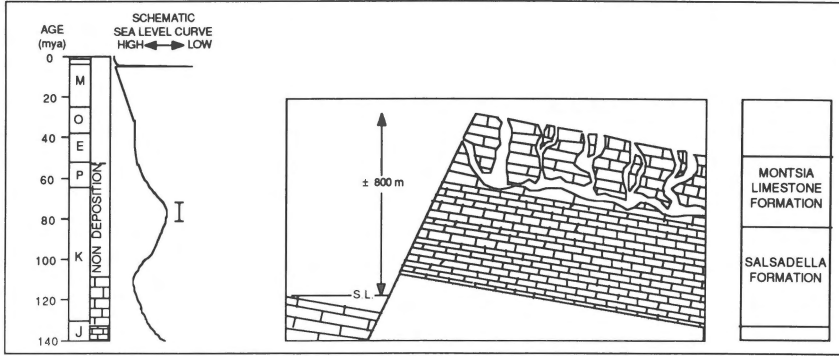
This interpretation is corroborated by the presence of a bench-like break in slope in the upper surface of the Montsia carbonates. This bench which occurs laterally from the C2 horizon (Fig. 11a) marks a sea level stillstand beach terrace. A similar feature has been encountered in a Miocene reef exposed in southeast Spain (Dawans, 1988) (Fig. 11b).

#### *Feasibility of predicting porosity in karstified reservoirs*

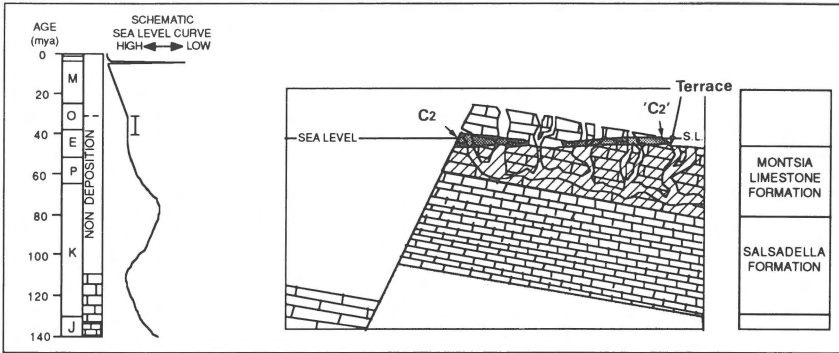
With the use of Shell proprietary seismic software, the average (root mean square) seismic amplitudes were extracted in a window covering the interval 10–100 ms below the top karstified carbonate to include the deepest karst development within the Montsia Formation (Fig. 5). The map in Fig. 12 represents areas of anomalously high amplitudes in red-purple. Well calibration indicates that these areas correspond to intervals of cavernous karst development (increased by mixing-zone corrosion) approximately 15 m to 60 m thick. Low amplitudes (blue colour) are predominant at the crest of the Amposta structure where fissure porosity prevails, as expected for an authigenic karst. The best ca-

Fig. 10. Geological history of the Amposta Marino structure. (a) Late Creacetus. Large drop in sea level ( $\pm 800$  m) leads to extensive karst development in the Montsia Limestone Formation. (b) Lower to mid Tertiary. As the sea level rises mixing with fresh water increases the karst porosity. A sea level stillstand occurs, resulting in intensive corrosion and terrace development at the ‘C2’ level. (c) Mid to late Miocene. The remainder of the karst porosity is increased by mixing-zone corrosion, as sea level resumes. Amposta Limestone and Alcanar Formation are deposited.

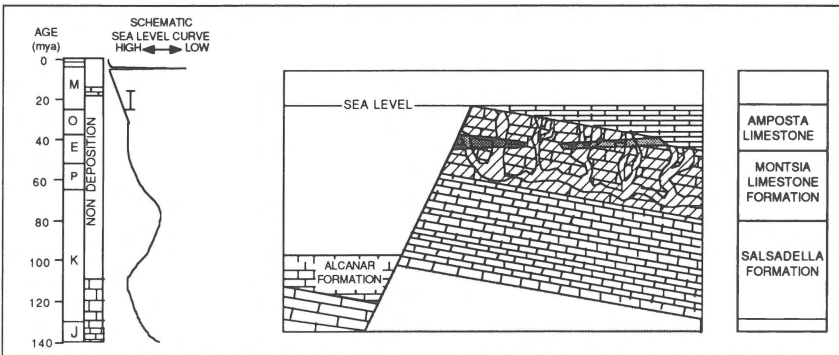
A




B





C



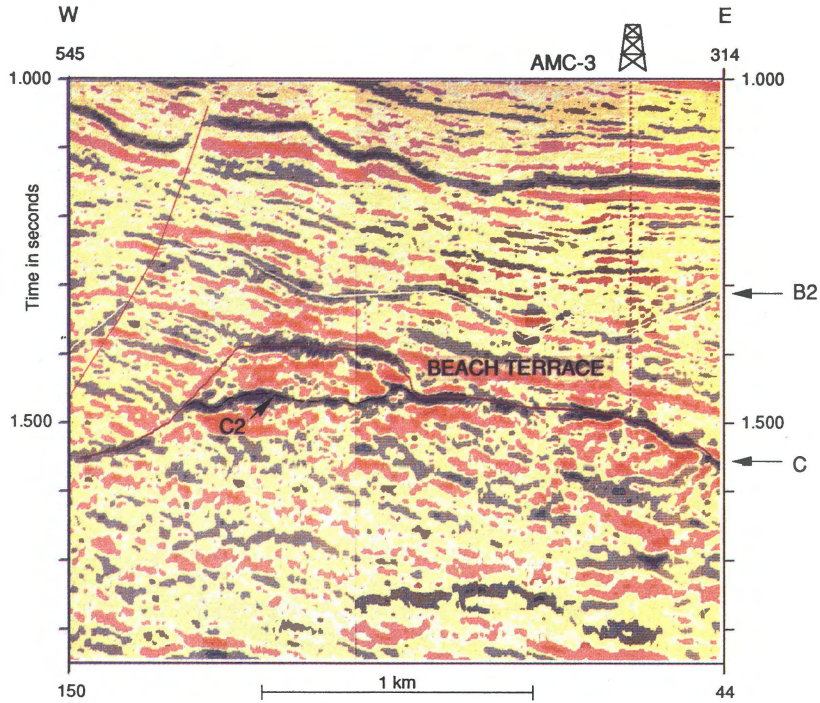
LEGEND:

-  Amposta Limestone/Alcanar Fm.
-  Montsia Limestone Fm.
-  Salsadella Fm.
-  Trias

 ∅ increased by mixing-zone corrosion.

 Zone of intense porosity enhancement by mixing-zone corrosion as a result of sea-level stillstand

A



B

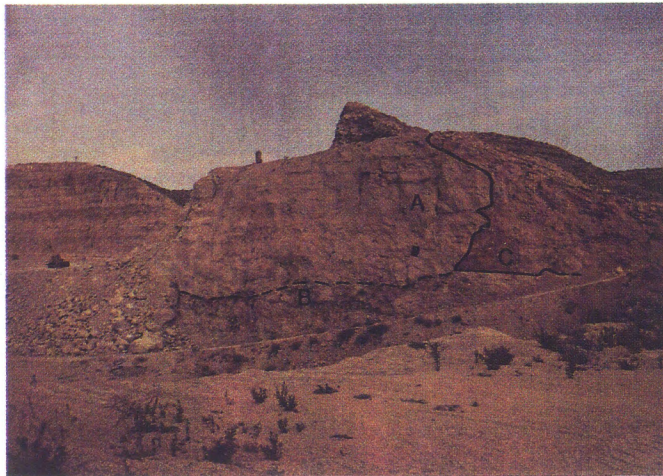


Fig. 11. (a) Seismic section across well AMC-3 showing the interpreted beach terrace corresponding to the horizon 'C2' (See Fig. 6 for location). (b) Outcrop view of eroded Miocene reefs (A and B) showing subhorizontal vug/cave (B) development, interpreted as the result of mixing-zone corrosion, laterally corresponding to a beach terrace (C). (From Smart et al., in preparation).

vernous/breccia karst development (red-purple colour) occurs on the flanks where circulation of water in a karst system is predominantly subhorizontal. The asymmetric distribution of the cavernous karst development is consistent with the paleo-structural dip to the east (main drainage direction).

An attempt was made to quantify the degree of karstification from the average amplitudes using available well data for calibration. To this end, the approximate thickness (in metres) of the interval with karst development (either cavern/breccia type or other type, Fig. 13) was established from well

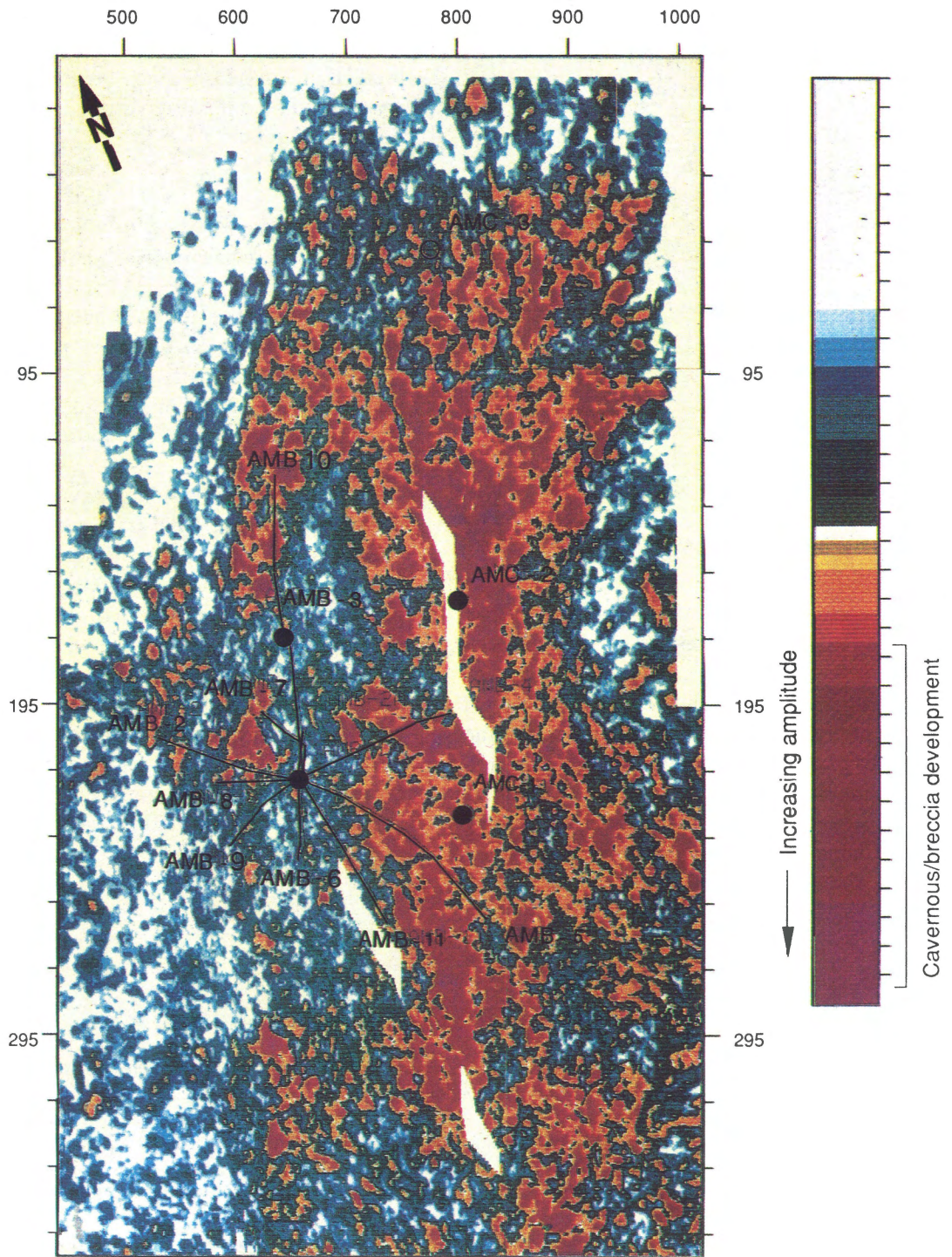


Fig. 12. Average (RMS) amplitude karstified reservoir.

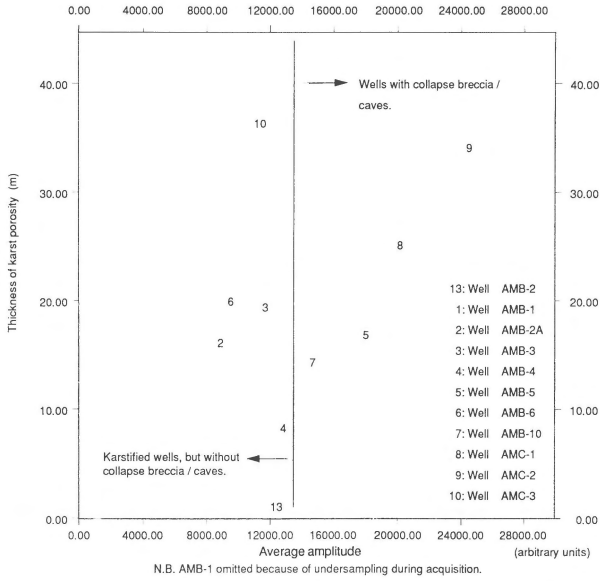


Fig. 13. Thickness of karst versus average (RMS) amplitude.

logs and cores, and plotted against the average amplitudes value from 25 traces around the well location. It was found that the average value increases with increasing thickness of the interval with cavernous/breccia karst development. For the other types of karst development, the average amplitude remains constant, irrespective of karst interval thickness (Fig. 13). Although it is tempting to infer a linear trend between average amplitudes and total thickness of breccia/cave development from Fig. 13, the standard deviation in the average

amplitudes is such (50%) that the resulting regression has little statistical significance and a realistic prediction can be only qualitative: thicker cavernous/breccia karst will give rise to higher amplitudes on seismic.

### Mixing-zone corrosion porosity in carbonate reservoirs; its impact on prospect/field evaluation

Enhanced porosity zones created as a result of mixing-zone corrosion, although typically very thin compared to total reservoir thickness, could contain the bulk of the oil in a prospect/field reservoir and may therefore represent an important exploration/production target.

If mixing-zone corrosion porosity zones are connected with an overlying fractured/fissured reservoir, crestal wells should be produced at low rates to avoid premature water breakthrough along high permeability conduits; alternatively wells could be drilled on the flanks to tap the oil in the enhanced porosity zone (Fig. 14a) directly. If separated from a crestal karst/fracture system by, for instance, tight carbonates, mixing-zone corrosion porosity development could form quite separate extensive downflank stratigraphic traps (Fig. 14b) representing prospective exploration targets.

Fig. 14. Conceptual models illustrating the implications of mixing-zone corrosion for prospect/field evaluation.

(a) Schematic section of a 'buried hill' carbonate reservoir with extensive fissure/fracture system at the crest connected with enhanced matrix porosity zones downflank as a result of mixing-zone corrosion occurring at palaeo sea level (MSL).

#### Early field development:

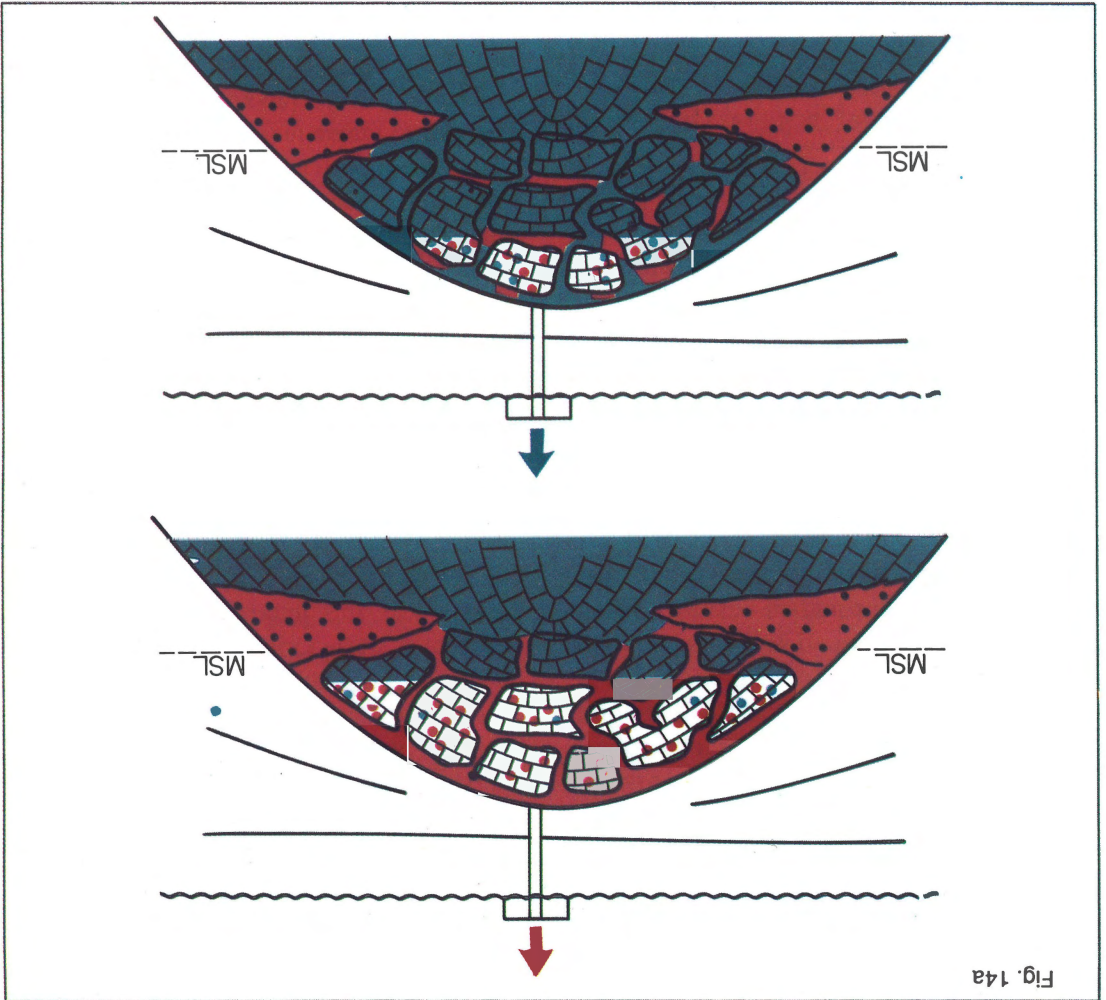
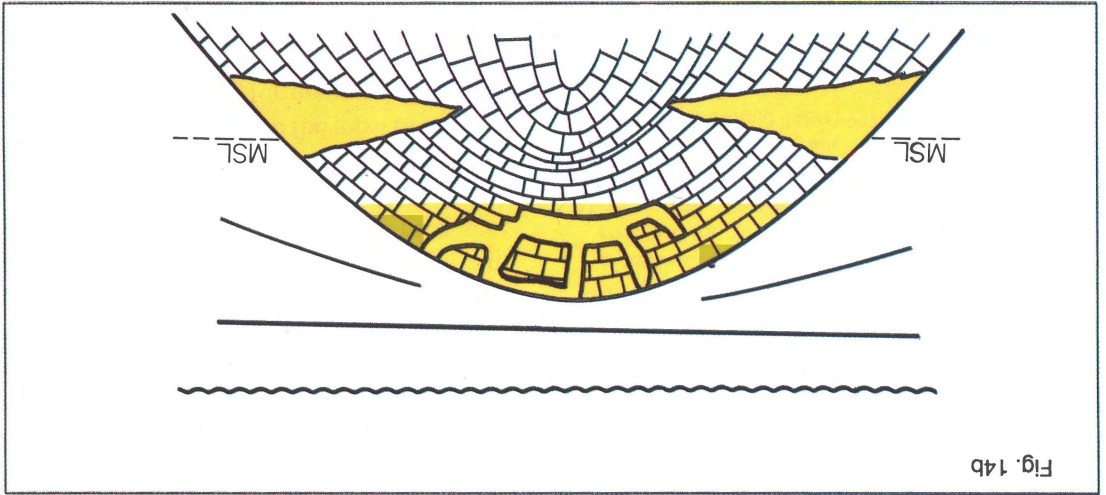
Hydrocarbons (in red) are produced from the karst system at the top of the structure. Note, however, that the hydrocarbon-water contact may be significantly deeper on the flanks of the structure where the high matrix porosity zones occur. The hydrocarbon distribution reflects the capillary characteristics of the reservoir rocks. Tight matrix blocks in the karst system have high entry pressures and are therefore mostly water-bearing.

Karstic conduits and high matrix porosity zones have much lower entry pressures, and hence are hydrocarbon-filled.

#### Late field development:

High water-cut production may be reached quickly at the top of the structure as water (in blue) migrates rapidly upwards through high-permeability karstic conduits. Note that a significant volume of hydrocarbons could thus remain on the flanks of the structure.

(b) Schematic section of a 'buried hill' carbonate reservoir with a prospective yellow fissure/fracture system at the crest separated from a prospective yellow matrix porosity zone downflank as a result of mixing-zone corrosion occurring at the palaeo sea level (MSL).



## Conclusions

The acoustic impedance contrast at top reservoir level (i.e. between the karstified Montsia Formation and the overlying clastic Castellon Formation) varies from positive to negative with an increasing degree of karstification. This observation is likely to apply to either karst fields in the world.

Well logs, synthetic seismograms and drilling records of well AMB-10 indicate that the C2 horizon corresponds to a porous (karstic) layer. It forms a semi-continuous, sub-horizontal rim around the flanks of the Amposta Marino buried hill. When this distribution, which is not expected in an authigenic karst system, is combined with reservoir performance data and the geological history of the field, it suggests that the present-day porosity distribution in the Montsia reservoir reflects a karst network which, at the level of the C2 horizon has been overprinted and laterally enhanced by mixing-zone corrosion processes.

The distribution of collapse breccia and cave development could be mapped for the whole reservoir interval by displaying the average (root mean square) amplitudes measured in a window covering the karstified interval. The areal extent of this development confirms the model of an authigenic karst proposed for Amposta in earlier studies. Qualitatively, areas with high average amplitudes correspond to breccia/cavern karst development with enhanced porosity. Recognition of the areal extent of such karst development can contribute to a better understanding of the karst porosity distribution and can be essential for the positioning of appraisal/development wells.

Enhanced porosity zones created as a result of mixing-zone corrosion, although typically very thin compared to total reservoir thickness, could contain the bulk of the oil and may therefore represent an important exploration/production target.

Detailed seismic investigation (preferably using 3-D seismic data) appears to be the most promising technique available to date for mapping the distri-

bution of mixing-zone corrosion porosity zones in subsurface carbonate reservoirs.

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