REPORT

How the Mediterranean dried up

Summary of lecture presented to the Society on Saturday 4th December 1999 by Dr Rob Butler, of Leeds University.

The Salinity Crisis in the Mediterranean represents one of the most dramatic examples environmental change outside of glaciated areas in the relatively young geological record. In the 1970s, deep sea drilling confirmed that sediments beneath the floor of the Mediterranean included a layer of salt. For these researchers, the salt layer, sandwiched between sediments that had been deposited under very deep water conditions, implied one thing: the Mediterranean had once dried up. It was well known from plate reconstructions that Africa and Europe had moved together to isolate what was once the open Tethys ocean into the restricted Mediterranean by the end of Miocene times (the Messinian stage, about 7-5 million years ago). The isolation was completed by a sea-level fall of world-wide extent (linked to a resurgence in glaciation) that cut off the Mediterranean from the Atlantic. The isolated sea was then thought to have dried out, only filling when the world sea-level rose again during global warming at the start of Pliocene times. Rough calculations indicate that, with no river input, an isolated Mediterranean would evaporate in a few tens of thousands of years, given the arid climates that characterise glacial maximums. Refilling by the Atlantic pouring back in through a breached Gates of Gibraltar might take a little longer.

Evaporites in Sicily

Central to the development of these dramatic models were the on-land outcrops of Miocene strata on the island of Sicily. Messinian halite and potash salts, together with gypsum, had long been exploited commercially from more than 800m of salt thickness in some basins. These deposits are classically separated into two cycles separated by a sub-aerial unconformity. The First Cycle includes chloride salts and organic-rich facies while the Second Cycle contains clastic evaporites and gypsum. Linked structural and stratigraphic studies in central and southern Sicily show that the evaporites accumulated in synclines related to underlying thrust structures of the frontal part of the Maghrebian orogenic belt. This orogen runs through north Africa (geologically, southeastern Sicily is part of the African foreland) and links into the southern Apennines of Italy. Prior to the Salinity Crisis these basins were hydrodynamically linked through the foredeep to the Mediterranean.

The precursor sediments, of the Terravecchia Formation, formed a delta, sourced from the north.

The crests of anticlines have late Tortonian to early Messinian patch reefs upon them. The synclines that host the Mesinian evaporites formed a tiered system, with originally shallow water in the north to progressively deeper water in the south. Thus Sicily provides an ideal 'tide gauge' for charting how the level of the Mediterranean sea fell during the Messinian. The prediction is that the northern synclines experienced more restricted sea water circulation, while those in the south were submerged beneath open water. Consequently the first evaporites should form in the north, getting progressively younger to the south (Fig. 1).

The evaporite facies vary over very short distances across the Sicilian folds. Anticline crest show evaporitic carbonates with lime muds and local sabbkha-like textures. In general these successions are about 10m thick and show bed-by-bed brecciation and collapse. These features suggest that sea level was oscillating, leaving anticline crests sometimes a few metres below sea level and at other times exposed to rainfall and karstification. In contrast, mine data show that the synclines locally contain over 500m, of halite and potash salts. The flanks of the folds commonly contain gypsum. Thus the evaporitic facies are fractionated, depending on their structural position. The simple explanation is that outlying anticlines act as a porous barrier within which the less soluble salts accumulate, leaving water enriched in the more soluble halite and potash salts to pass into the syncline where they are deposited. Structural architecture and evolution of the Messinian basins on Sicily exerts a fundamental control on the stratigraphy. Thrusting provides accommodation space for evaporites and also controls the water pathways into the desiccating basins.

Mine and outcrop data show that the Messinian evaporites contain an important inter-regional unconformity. This surface separating First and Second Cycle evaporites is related to the forced regression associated with the acme of Mediterranean desiccation, an interpretation supported by local ravinement and incised valley fills. The overlying Second Cycle evaporites are a combination of detrital, reworked First Cycle material and primary gypsum formed under brackish water. Regional onlap relationships and bed continuity suggest that this water body was of regional extent, with a systematically rising baselevel. The Second Cycle evaporites mark the replenishment of baselevel to near normal sea levels. However, normal sea water conditions, as charted by a rich fauna, only occurs later, at the onset of the Pliocene. These younger strata are typically chalks (the Trubi Formation) that show regional transgressive behaviour on substrata.

Establishing the chronology

By linking tectonic and sequence stratigraphic analyses to facies distributions across the Sicilian basins it is possible to build up a picture of sea level variations and climatic fluctuations. However, the absolute timing of these events and the rates of the processes requires additional data. As part of a regional study of deformation rates (The Central Sicily Basins Project), high resolution stratigraphic data were collected. For these types of problems, traditional fossil studies are of little use, as they rarely provide adequate temporal resolution and are environmentally sensitive; not much lives in the saline world of a halite basin. So our approach relies on linking magneto-stratigraphy to depositional cyclo-stratigraphies. Sediments can record reversals

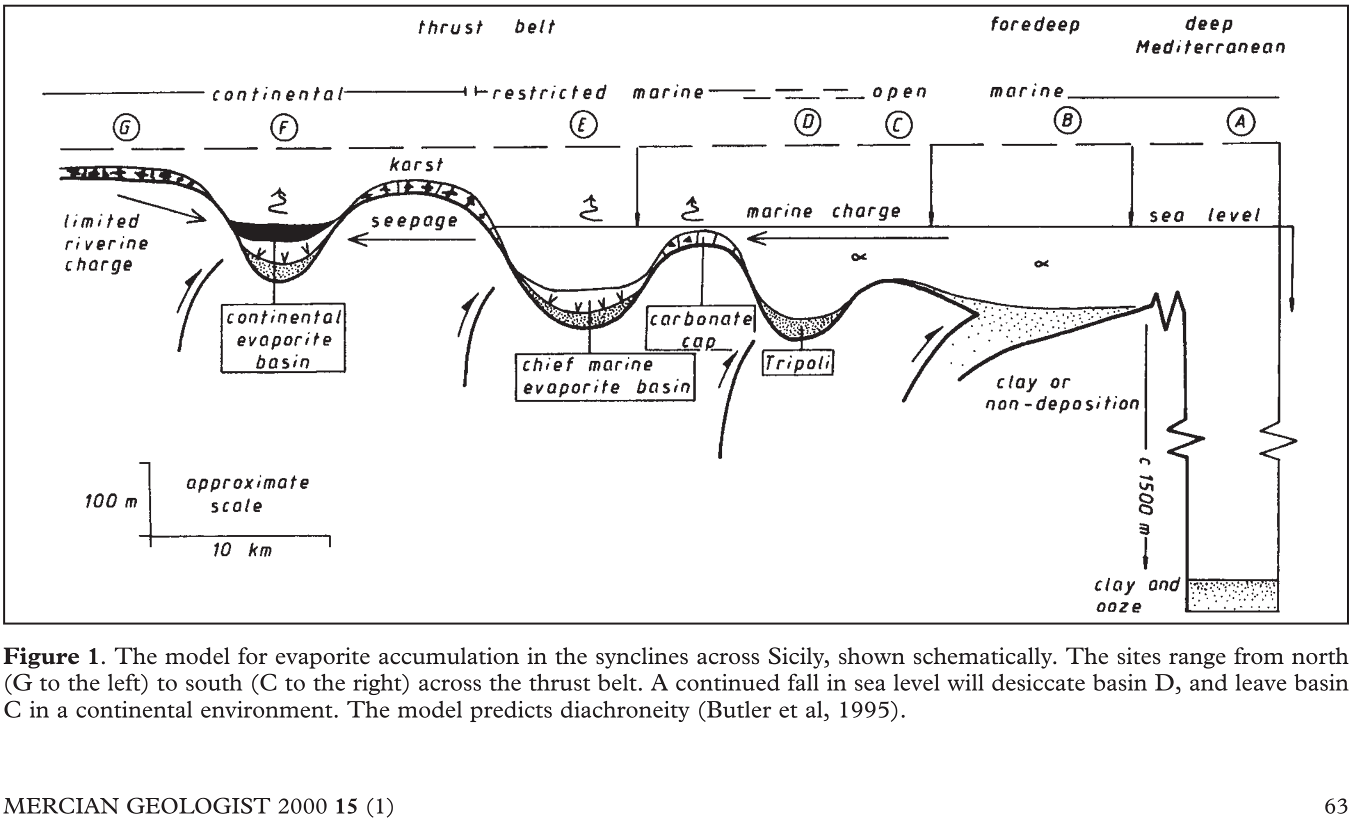

Figure 1. The model for evaporite accumulation in the synclines across Sicily, shown schematically. The sites range from north (G to the left) to south (C to the right) across the thrust belt. A continued fall in sea level will desiccate basin D, and leave basin C in a continental environment. The model predicts diachroneity (Butler et al, 1995).

in the polarity of the Earth's magnetic field (rather like ocean floor magnetic anomalies chart sea-floor spreading). However, to calibrate reversals in measured sections with the world-wide reversal record requires additional controls. We use the fact that reversals represent different periods of time. Neogene marine sediments in the Mediterranean commonly show cyclic variations that have been matched to regular fluctations in earth orbit. These precession cycles have a period of about 24,000 years. Consequently by counting cycles we can sum the duration of time and calibrate the duration of our measured magneto-stratigraphic section. This can then be matched to the global record (Fig. 2). Potentially, the method can give a temporal resolution of a single precession cycle (24,000 years) even for sediments several million years old.

Our results from a range of sites across Sicily show that the onset of evaporite accumulation was

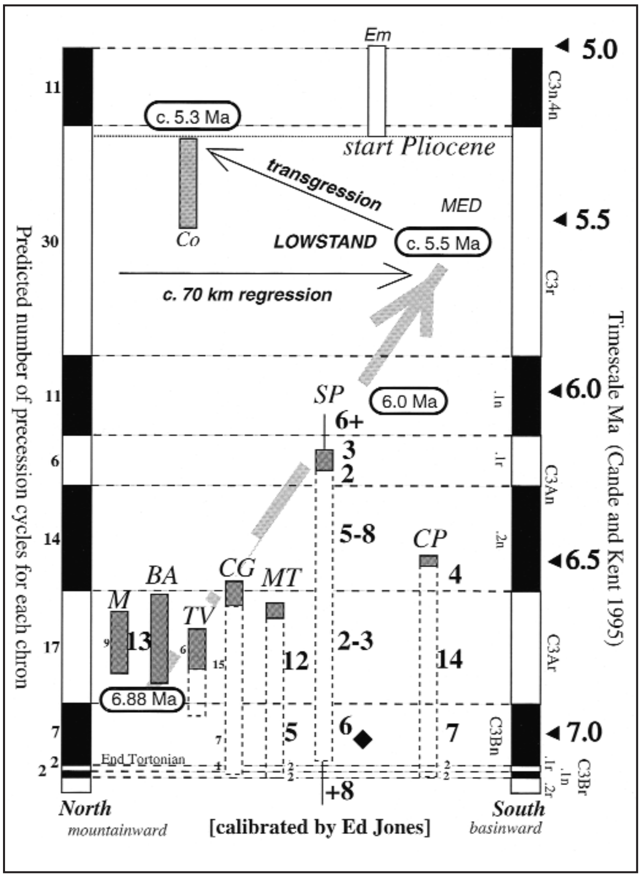

Figure 2. Results of the magneto-stratigraphic studies of Messinian sites on Sicily. This complex diagram shows a number of stratigraphic columns (M, BA, TV, CG, MT, SP and CP) with an upward transition from pre-evaporitic beds of the Tripoli Formation (unornamented), to basal evaporites of the Calcare di Base (shaded). The number next to each column is the number of observed depositional cycle in each chron at each site; these should always be equal or fewer in number than the predicted number. The resulting calibration charts the diachronous onset of evaporite precipitation across Sicily from which the rate of sea level fall (regression) may be established. Note that the marine transgression is much more rapid than the regression (Butler et al, 1999).

diachronous. Calibrating the magnetostratigraphy shows that the fall of Mediterranean sea level was protracted. The earliest evaporites in our study accumulated early in chron C3Ar (pre 6.88 Ma) and the youngest accumulated late in chron C3An (post 6.0 Ma). During this period the basinward (southward) shift in coastline was 70 km and in vertical section implies a relative fall in sea level at 0.3-0.4 m/ka. The lowest point in the level of the Mediterranean (the so-called lowstand) probably occurred at 5.8-5.5 Ma.

Transgression marked by accumulation of the 'second cycle' deposits, which all record reversed magnetisations (C3r), apparently occurred far more rapidly (200 ka), prior to the return to 'normal' marine conditions in the central Mediterranean (Trubi deposition) late in chron C3r.

So far a unified bio-astro-magneto-stratigraphy has proved impossible. Assuming depositional cyclicity in the first cycle and precursor sediments are eustatic in origin and forced by precession, they provide an absolute calibration of magneto-stratigraphy. Discrepancies with conventional biostratigraphy require diachronous colonisation and extinctions between sub-basins. Such diachroneity in biological 'events' should be expected during large magnitude sea level fluctuations and their associated local variations in water chemistry within isolated basins.

Debate over the Messinian event

The Sicily study then gives a new insight onto the salinity crisis. For most of the Messinian the level of the Mediterranean fell slowly, linked to the fall in world ocean level caused by a sharp glacial event. The seaways stayed open. If the Mediterranean itself dried up then this happened only for a short period in the late Messinian. However, much of the evidence for the nature of the Mediterranean basin floor during this time came from Sicily – clearly an area that never resided at these depths. Although the water returned across Sicily in the latest Messinian at a much higher rate than it fell, it still did so over a protracted period. There no evidence for a catastrophic flooding at the start of the Pliocene. Rather, this time represents a change in water chemistry accompanied by a sea level rise and recolonisation by a richly diverse fauna. The nature of the Mediterranean water body during the late Messinian is controversial Our existing studies suggest that it was not normal world ocean water but had a significant component of river input. It was however homogeneous across the Sicilian basins suggesting that these synclines had good communication with the broader sea.

This story of structure and sedimentation illustrates how a multidisciplinary approach to basin analysis can yield high-resolution results. It is now possible to quantify rates of geological processes with surprisingly high precision. However, to have much further faith in these models and results requires a broader view and the application of these methods to other sites around the Mediterranean. Fortunately there are many to target, and work is continuing apace.

Acknowledgements

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