A comprehensive review of the MSC facies and their origins in the offshore Sirt Basin, Libya

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ABSTRACT: Interpretation of 2D long-offset multi-client seismic data acquired by CGVVeritas in 2004–5 has allowed the distribution and composition of the Messinian salinity crisis (MSC) facies to be mapped across the offshore Sirt Basin, Libya. The results reveal that only the Lower and Upper Evaporites are present within the marginal offshore Sirt Basin, with the middle halite unit confined to the deeper basin. The Upper Evaporites, ‘Lago Mare’, are characterized by a period of fluctuating base level and strong water salinity changes controlled by astronomical precession. They consist of interbedded evaporites and clastics with a total of seven precessional cycles recognized, each associated with erosional sub-aerial channels interpreted to have been created by the Eosahabi rivers sourced from the flooding of Neogene Lake Chad. The Lower Evaporites display a high relief, irregular topography which strongly controls the distribution of the overlying Lago Mare facies. They have an overall chaotic high amplitude response with very little internal structure and are interpreted to represent mass transport complex deposits of the Re-sedimented Lower Gypsum unit. There is a strong correlation between the distribution and composition of the MSC facies and the quality of seismic imaging.

INTRODUCTION

The Messinian Salinity Crisis (MSC) has long been a subject of immense fascination and controversy since it was first recognized following Deep Sea Drilling Project (DSDP) Leg 13 in 1970. However, the majority of studies are based on outcrops located in peripheral basins, such as Morocco, Spain and Cyprus, although uplifted outcrops in Sicily and the Apennines may offer deep basin analogues (Lofi et al. 2007). The aim of this study is to present observations from regional 2D seismic data of the MSC facies in the offshore Sirt Basin, Libya, and attempt to interpret them in the context of previous studies within other Mediterranean basins, with particular reference to the work undertaken by Roveri et al. (2008a; b) in the Sicily foreland basin.

There have been very few studies focusing on the offshore Sirt Basin, largely due to a lack of good quality seismic data and sparse well penetrations. However, this has recently changed following a series of licensing rounds which saw the majority of the Libyan offshore licensed to global oil majors and national oil companies. In 2004–5 CGVVeritas acquired 38 000 km of 2D long-offset multi-client seismic data across the whole of offshore Libya in support of these licensing rounds (Fig. 1). The majority of these data within the offshore Sirt Basin were re-processed in 2007–8 leading to a significant uplift in data quality with improved imaging particularly below the MSC facies.

Understanding the composition and distribution of the MSC facies is crucial for seismic acquisition and processing. The MSC facies can vary significantly both vertically and laterally with the Messinian evaporites representing a significant velocity inversion in the shallow subsurface above the main Eocene and Cretaceous target intervals. The MSC facies also represent a significant barrier to the penetration of seismic energy due to a combination of their high impedance contrasts, often chaotic nature, and energy scattering due to erosional surfaces. If accounted for, however, these effects may be reduced during seismic acquisition by using, for example; a larger source, broadband seismic, long-offset streamers, deeper and variable depth towed streamers, and multi-azimuth or wide-azimuth shooting configurations.

GEOLOGICAL BACKGROUND AND PREVIOUS WORK

In simple terms the MSC facies can be subdivided into three units, the ‘Messinian trilogy’, comprising the Lower Evaporites, Halite (or Mobile Unit) and the Upper Evaporites (Montadert et al. 1970; Decima & Wezel 1971) (Fig. 2). The MSC facies encountered in the western Mediterranean comprise the full suite of the Messinian trilogy whilst those encountered in the eastern Mediterranean comprise a thick layer of halite only which is often strongly deformed and diapiric (Hübscher et al. 2007; Bowman 2011). The offshore Sirt Basin can be considered as part of the western Mediterranean MSC facies based upon the recognition on seismic data of both the Lower and Upper Evaporites.

The Lower Evaporites were deposited at the onset of the MSC, dated at 5.96 Ma based on astronomical tuning (Krijgsman et al. 1999). They are believed to have been deposited in relatively shallow waters at a maximum depth of 150–200 m whilst the Mediterranean was still a deep-water basin (Krijgsman et al. 1999; Krijgsman & Meijer 2012; Roveri et al. 2008a).
The Lower Evaporites are composed of gypsum interbedded with thin euxinic shales (Lugli et al. 2007) with deposition controlled by astronomical precession with a total number of 16 cycles recorded in Italy and 17 cycles recorded in Spain (Krijgsman et al. 1999). The average periodicity for precession in the Neogene is 21.7 ka, implying a duration of 350–370 ka for the deposition of the Lower Evaporites (Krijgsman et al. 2007).

The Lower Evaporites can be subdivided into two distinct stratigraphic units, Primary Lower Gypsum (PLG) and Re-sedimented Lower Gypsum (RLG) (Roveri et al. 2008a) (Fig. 2). The PLG was deposited in situ in marginal settings and typically overlies shallow-water to shelfal deposits (Roveri et al. 2008a). The RLG deposits are not in their original stratigraphic position due to large-scale mass-wasting processes and commonly overlie deep-water deposits (Roveri et al. 2008a). The PLG was deposited while the Mediterranean sea-level was still high, and the RLG was deposited during the drawdown of the Mediterranean and hence the two stratigraphic units are not contemporaneous (Roveri et al. 2008a).

Deposition of halite occurred at approximately 5.59 Ma (Krijgsman et al. 1999) following the isolation of the Mediterranean from the Atlantic which led to a substantial fall in sea-level estimated at approximately 1500 m (Ryan 1976; Maillard et al. 2006). The presence of halite is, therefore, confined to the deeper basins whilst the continental shelves and marginal basins were sub-aerially exposed and eroded forming the Messinian erosional surface (MES) (Roveri et al. 2008a) (Fig. 3). The halite records a shallowing-up sequence (Lugli et al. 2007) as sea-level continued to fall and the accumulation of halite out-paced the rate of subsidence, causing the basins to become infilled (Roveri 2007). The thickness of the halite body is variable but it is up to 1 km thick in the Ionian Basin (Lofi et al. 2007; Sabato Ceraldi et al. 2008), and up to 2 km thick in the Levantine Basin (Hübscher et al. 2007). The entire halite sequence is estimated to have been deposited in a short period of only 90 ka, the ‘Messinian Gap’, calculated as the time interval between the astronomically tuned Lower and Upper Evaporites (Krijgsman et al. 1999).
The onset of deposition of the Upper Evaporites, also known as the ‘Lago Mare’ event, occurred between 5.50 Ma (Krijgsman et al. 1999) to 5.53 Ma (Roveri et al. 2008b). They conformably overlie the halite unit in deep basinal areas and onlap the MES in shelfal areas and marginal basins (Lofi et al. 2007). The Upper Evaporites are characterized by a period of fluctuating base level and strong water salinity changes with a gradual return to marine conditions (Orszag-Sperber 2006; Roveri 2007) once again controlled by astronomical precession (Krijgsman et al. 1999). They were deposited in shallow-marine and brackish to lacustrine waters and consist of conformable cyclic alterations of sandstones, conglomerates, marls and gypsum deposited in a dominantly non-marine environment (Roveri et al. 2008b; Wells 2010). There is a debate regarding the total number of precessional cycles recorded within the Lago Mare facies, with some authors reporting 7–8 cycles (Vai 1997; Krijgsman et al. 2001; van der Laan et al. 2006), whilst others report as many as 9–10 cycles (Roveri et al. 2008b). This is an important distinction because the age for the
onset of the Lago Mare facies is defined by counting back the number of precessional cycles from the astronomically well-tuned Miocene–Pliocene boundary at 5.33 Ma.

Roveri et al. (2008b) subdivided the Lago Mare facies into two sub-units, p-ev1 and p-ev2 (Fig. 2). The lower sub-unit, p-ev1, is defined as being more localized and occurring in deeper and/or strongly subsiding basins commonly having a regressive depositional trend. The upper sub-unit, p-ev2, is defined as having a more basin-wide distribution and records the generalized periodic activation of catastrophic flood-dominated fluvio-deltaic systems, indicating important modifications in the drainage areas and/or fluvial runoff. A total of 4–5 precessional cycles have been recognized within the p-ev2 unit, which would place its basal age at approximately 5.42 Ma (Roveri et al. 2008b).

The occurrence of channels within the Lago Mare facies, interpreted as having a sub-aerial origin, have been reported in the offshore Sirt Basin (Sabato Ceraldi et al. 2008; Wells 2010) (Fig. 3). They are up to 4 km in width (Wells 2010) and deeply incised and were later infilled by seismically transparent clastic sediments (Sabato Ceraldi et al. 2008). Recently acquired 3D seismic data show evidence of dendritic and braided ephemeral channel systems, providing further evidence for sub-aerial exposure (Wells 2010). The occurrence of a large fossil drainage system, named the Sahabi channel, of Upper Miocene age has been reported in the onshore Sirt Basin (Fig. 4). It has been mapped over about 340 km from near the town of Gialo to the present-day coastline and has a width of between 1 and 5 km and is steep-sided with a maximum depth of up to 750 m near Marsa al Brega, located along the coastline (Barr & Walker 1973; Nicolai 2008). The Sahabi channel is infilled with unconsolidated quartz sand, silt and clays with relatively slow interval velocities of 1800–1900 m s⁻¹ (Barr & Walker 1973; Nicolai 2008). Deeply incised canyons are also reported along other Mediterranean margins corresponding to the Rhone, Ebro, Po, and Nile rivers (Krijgsman et al. 2007).

The MSC ended at 5.33 Ma, terminating in the Zanclean flood which marks the Miocene–Pliocene boundary (Krijgsman et al. 1999). The Zanclean flood represents a return to fully open-marine conditions as a connection between the Mediterranean and Atlantic Ocean was re-established through the Gibraltar Strait (Hsü et al. 1973). It does not coincide with any major deglaciation (van der Laan et al. 2006) but is instead thought to correspond to headward erosional incision of the Gibraltar strait (Garcia-Castellanos et al. 2009).

**OBSERVATIONS FROM SEISMIC DATA**

The interpreted Upper Messinian Lago Mare facies can be clearly imaged on CGGVeritas’ 2D long-offset multi-client seismic data. They are extensive within the offshore Sirt Basin, covering an area of approximately 45 000 km² with a maximum thickness of around 550 m. The landward extent of the interpreted Lago Mare facies roughly coincides with the present-day base of the continental slope at around 400 m water depth, whereas their basinward extent corresponds to the Ionian abyssal plain at around 3600 m water depth.

The interpreted Lago Mare facies are instantly recognizable on the seismic data due to their interbedded nature, with alternating high and low amplitudes and the presence of several major channels (Fig. 5). The high amplitude reflectors are interpreted to correspond to the deposition of evaporites, gypsum or anhydrite, whereas the low amplitude reflectors correspond to
Fig. 5. Re-processed seismic section showing the typical Lago Mare facies observed in the offshore Sirt Basin. Three versions of the same line are displayed: (a) uninterpreted; (b) interpreted; (c) schematic. The cyclical and channelized nature of the Lago Mare facies can be observed clearly, with seven individual units, 1–7, identified.
periods of low-energy clastic deposition in a fluvial or lacustrine setting. This alternating sequence is repeated several times within the Lago Mare facies. The evaporite interbeds are very well imaged, particularly on the re-processed data, and display a high amplitude response due to their large impedance contrast to the surrounding clastic deposits. Each evaporite interbed can be mapped regionally across the offshore Sirt Basin even on 2D seismic data with line spacings of 10–15 km.

A total of six regionally extensive evaporite interbeds have been mapped across the offshore Sirt Basin subdividing the Lago Mare facies into seven distinct units (Fig. 5). Each unit is interpreted as consisting of a relatively thick clastic sequence up to 100 m thick (locally up to 200 m) overlain by a thin evaporite layer not likely more than 20 m thick. The dominant frequency for the whole of the Lago Mare facies is approximately 40 Hz, giving a vertical resolution of approximately 16.25 m. The only exception to the above is the seventh unit which consists of a clastic sequence only as the onset of the Zanclean flood prevented the deposition of evaporites. Each unit is associated with the presence of erosional, generally seismically transparent, clastic-filled channels. Units 1–4 are associated with relatively minor channels which have a maximum width of 4 km and a maximum thickness of 130 m. Units 5–7 are associated with major channels which have a maximum width of 7.5 km and a maximum thickness of 350 m and are capable of eroding through to the base of the earlier Lago Mare facies.

The major channels present within Units 5–7 can be regionally mapped across the offshore Sirt Basin and can be traced back to a single channel pathway sourced from the present-day southern Gulf of Sirt (Fig. 1). They are orientated NW–SW and are steep-sided and deeply incised, suggesting that they coincide with a significant drop in base level. There is a second, smaller, channel pathway which is sourced from the SW towards the city of Misratah (Fig. 1). The channels are orientated NE–SW and have a maximum width of 2 km and a maximum thickness of 110 m. They are located outside the main Lago Mare facies depocentre and, as such, are associated with a thinner succession consisting of only three individual units. It is, therefore, not possible to correlate these channels to individual units. Evidence of channel incision and channelized facies can also be observed on some seismic lines within the Lower Evaporite sequence, although these are poorly imaged due to the chaotic nature of the Lower Evaporite facies and cannot be traced from line to line.

The distribution of the Lago Mare facies is controlled by the underlying topography of the Lower Evaporites and Oligo-Miocene clastics as well as older structural lineaments (Figs 5, 6). The Halite Unit is absent within the marginal Sirt Basin, occurring only in the deeper part of the basin beyond the Cyrenaica Ridge corresponding to present-day water depths of approximately 2400 m (Fig. 6). The Lower Evaporite and Oligo-Miocene topography is extremely irregular and has a large influence on the distribution of the Lago Mare facies, particularly the earlier units (Fig. 5). The Lago Mare facies have a largely aggradational stacking pattern linearly onlapping the MES on the basin margins.

Within the basin centre a series of NW–SE-trending structural highs and lows are present, causing the early Lago Mare facies (Units 1 and 2) to be present only locally within disconnected structural lows. As the structural lows became infilled each progressive unit would have become more widespread, with the intra-basinal highs becoming buried. Units 1–4 are confined to the Sirt Trough, bounded to the north by the Cyrenaica Ridge. Units 5–7 extend beyond the Sirt Trough over the Lower Sirt Slope towards the Ionian Abyssal Plain where they appear to be more clastic dominated. An interesting observation is that Unit 5 is regressive, onlapping on to Unit 4 along the landward basin margin, suggesting either a large drop in base level or a reconfiguration of accommodation space within the basin. Units 6 and 7 are once again largely aggradational, onlapping the MES along the landward basin margin.

Recent published studies have drawn attention to the importance of gravitational collapse and slumping within Oligo-Miocene deposits in the offshore Sirt Basin (Slack et al. 2009; Cund 2010; Sabato Ceraldi et al. 2010). Mass transport complexes (MTCs) make up a large proportion of the Oligo-Miocene succession, locally up to 80% (Cund 2010). The majority of the structural highs within the basin centre which affect the distribution of the Lago Mare facies are interpreted to represent MTCs, consisting of large slide blocks, slumps, and debris flows. The individual MTCs within the basin centre are generally 10–15 km in width with a maximum thickness of approximately 500 m. They are generally poorly imaged with a very noisy response on the seismic data – likely due to their intensely deformed and
chaotic internal structure (Figs 5, 7). Some stratal reflections can, however, be imaged within the larger slide blocks.

Along the eastern basin margin offshore Benghazi, a much larger MTC is observed corresponding to the retrograde collapse of the Oligo-Miocene shelf (Figs 7, 10). It is a concave structure with its headscarp cutting down into the Oligo-Miocene shelf. It has a width of over 110 km, over 200 km along strike, with a maximum thickness of over 700 m and volumetrically may represent one of the largest known submarine slides in the world. Its morphology is indicative of a deep-seated slide, maintaining a high degree of post-failure cohesion with several slide blocks observable, suggesting that the sediments were over-consolidated with a high material strength (McAdoo 1999, 189–205).

The retrograde collapse of the Oligo-Miocene shelf can also be observed along the whole of the Sirt Basin landward margin, particularly in the western Gulf of Sirt, where steep fault scarps are present. Unlike offshore Benghazi, however, the resulting MTC deposits are not as spectacular and it is difficult to map individual MTCs. Instead the resulting MTC deposits appear to be more continuous and homogeneous, indicative of a series of shallow-seated slides suggesting that the sediments had a lower material strength, perhaps as a result of high fluid pressures (McAdoo 1999, 189–205).

The MSC facies are overlain by a poorly reflective Plio-Pleistocene facies which has a maximum thickness of approximately 800 m in shelfal areas and 200 m in basinal areas (Fig. 7). Within the shelfal areas the facies display a typical 'sea-slug' morphology representative of a prograding deltaic complex with clearly imaged sigmoidal reflectors onlapping the Messinian unconformity updip and downlapping on to the slope downdip. Distinct sediment packages can be mapped which correspond to lowstand system tracts (LST), transgressive system tracts (TST), highstand system tracts (HST), and shelf-margin wedge system tracts (SMWT), corresponding to third-order depositional sequences as defined by Vail (1987). Within the deeper basin a condensed section of hemipelagic shales is observed which is conformable with the underlying Messinian 'unconformity'.

**DISCUSSION**

**Lago Mare facies**

The interpreted Lago Mare facies would likely have been deposited in a dominantly brackish to lacustrine environment, with supporting evidence coming from mollusc, ostracod, gastropod and dinoflagellate fossil assemblages (Abbazzi et al. 2008; Roveri et al. 2008). However, the presence of the interbedded evaporite layers indicates that there was also periodic marine flooding of the offshore Sirt Basin which may explain the presence and origin of benthic and planktonic foraminifers which have previously been explained as being reworked from older sediments (Iaccarino & Bossio 1999).

A total of seven individual units have been identified within the Lago Mare facies, with each unit consisting of a relatively thick clastic sequence overlain by a thin evaporite layer and associated with the presence of erosional clastic-filled channels (Fig. 5). These units appear to be representative of fluctuating baselevel changes as a result of precession-induced climate change, with each unit corresponding to a precessional cycle. Given that the average periodicity for precession during the Neogene is 21.7 ka (Krijgsman et al. 1999), this would imply that the Lago Mare facies within the offshore Sirt Basin had a duration of less than 152 ka, with the onset of deposition at approximately 5.48 Ma.

The following sequence of events is proposed for each precessional cycle within the Lago Mare facies:

1. sub-aerial exposure and channel incision;
2. fresh-water inflow and flooding from Eosahabi rivers;
(3) brackish/lacustrine conditions established;
(4) deposition of channel sands and lacustrine silts and muds;
(5) marine flooding;
(6) evaporation and drop in base level;
(7) deposition of evaporites, gypsum/anhydrite;
(8) sub-aerial exposure and channel incision . . . start of new precessional cycle.

During precession minima and relatively wet periods high freshwater runoff (Krijgsman et al. 1999) would have flooded the marginal Sirt Basin, creating a brackish or lacustrine environment with deposition of channel sands, silts and clays sourced primarily from the Eosahabi rivers. Evaporite deposition would have occurred following marine flooding during precession maxima, during relatively dry periods when evaporation exceeded precipitation (Krijgsman et al. 1999). This would have resulted in the drying out of the marginal Sirt Basin and a lowering of the base level, leading to channel incision.

Units 1–4 are confined to the offshore Sirt Trough bounded to the north by the Cyrenaica Ridge. Their distribution and thickness, especially Units 1 and 2, is strongly influenced by the underlying topography of MTCs, confining them to the structural lows. Their associated channel systems are relatively small and are not as erosive as the channels associated with Units 5–7, making it very difficult to map and correlate them across the offshore Sirt Basin – especially as they have been superimposed by the much larger channels of Units 5–7 in places. Units 1–3 can be correlated to the p-ev1 lower sub-unit of Roveri et al. (2008b). Unit 4 is considered as being somewhat transitional due to its more basin-wide distribution and greater thickness and is assigned to the p-ev2 upper sub-unit of Roveri et al. (2008b).

There are a number of significant changes in basin configuration observed within Units 5–7 and their associated channel systems which become much larger and more erosive. The channel system associated with the regressive Unit 5 extends the furthest into the Sirt Basin, whereas Unit 6 and 7 channel systems progressively step back in a landward direction (Fig. 1). This would imply that the magnitude of the fall in base level was diminishing, causing an overall increase in the base level and hence explaining the reduced extent of the channel systems. This pattern is thought to be representative only in Units 5–7 and is not reflected through-out the whole Lago Mare facies. The large magnitude of base-level
MSC facies, offshore Sirt Basin, Libya

The major channel systems within the interpreted Lago Mare facies have been traced back to the southern Gulf of Sirt (Fig. 1). However, there is currently no active drainage system within this region which raises the question of what is the origin of these major channel systems? Published literature must be relied upon in order to answer this question as no onshore data...
were available as part of this study. Barr & Walker (1973) mapped a large fossil drainage system located between the ruins of Qasr as Sahabi and the town of Gialo, to which they assigned a probable Upper Miocene age. They traced the channel over a distance of approximately 150 km and referred to it as the Sahabi channel (Fig. 1). Using a combination of modern 2D and 3D seismic data and aeromagnetic data, Nicolai (2008) traced the Sahabi channel system south of the ruins of Qasr as Sahabi to the coastal town of Marsa al Brega over a further distance of 200 km (Figs 1, 4).

The characteristics of the Sahabi channel and its probable Upper Miocene age correlate well with the major channel systems within the Lago Mare facies, which are observed as an offshore continuation of the onshore Sahabi channel system as mapped by Nicolai (2008) (Fig. 1). An onshore link has now been established but the question regarding the origin of the Sahabi channel and its offshore extent still remains. Satellite imagery has been used by several authors to map the geomorphology of northeastern Chad, southern Libya, and the Western Desert of Egypt (Griffin 2006; Carmignani et al. 2009). The results define two possible pathways for the Sahabi channel system between the southern Gulf of Sirt and either Neogene Lake Chad (Griffin 2006) or as a western extension of the Nile River originating from nearby the city of Asyut (Carmignani et al. 2009) (Fig. 8).

The preferred model within this study is for the Sahabi channel system predominantly originating from Neogene Lake Chad; however, in reality it may be that both models are valid. Griffin (2002; 2006) defined three river systems, the Sahabi, Eosahabi and Palaeosahabi (Fig. 8). The Sahabi rivers are defined as those of Pliocene age that followed the MSC, the Eosahabi rivers are defined as those of late Messinian age that followed the drawdown of the Mediterranean, and the Palaeosahabi rivers are those that flowed during the early to mid Messinian (Griffin 2002; 2006). The Eosahabi rivers, therefore, correspond to the Sahabi channel as mapped by Barr & Walker (1973) and Nicolai (2008) and the major channel systems mapped offshore within the Lago Mare facies.

Neogene Lake Chad was much larger than the present-day Lake Chad, covering a maximum area of approximately 700,000 km² (Griffin 2006) (Fig. 8). It fluctuated in size in response to precessional climate change and, at times, overflowed to the east, northeast or north, giving rise to the Palaeosahabi, Eosahabi and Sahabi rivers (Griffin 2006). During precession maxima and relatively dry periods, Neogene Lake Chad would have receded and the flow of the Eosahabi rivers would have ceased, allowing a fall in base level and uninterrupted deposition of evaporites within the Lago Mare facies in the offshore Sirt Basin. During precession minima and relatively wet periods, Neogene Lake Chad would have become enlarged and flooded, allowing for the flow of the Eosahabi rivers into the Gulf of Sirt and causing a gradual change to a brackish to lacustrine depositional environment. Significant clastic deposition would have occurred during...
this time, with the Eosahabi rivers delivering sands, silts, and clays which make up the majority of the Lago Mare facies.

The Eosahabi river system has a total length of approximately 2000 km. Sabato Ceraldi et al. (2008) postulated the presence of an alluvial fan beyond the termination of the interpreted Lago Mare facies on the present-day Ionian Abyssal Plain. However, no such observation is made on the seismic data, with the Eosahabi river systems seen terminating within the Lago Mare facies. Instead it is hypothesized that the sediments transported by the Eosahabi rivers were deposited within the Lago Mare facies themselves as a series of overlapping depositional lobes. This is supported by observations from seismic lines (Fig. 9) and the use of isopach maps which show clear thinning and downlapping of clastic sediments away from the Eosahabi channel axis. The Eosahabi rivers would have become less erosive in a basinward direction as they lost energy and the location of their depositional lobes can be used as a proxy for the magnitude of the fall in base level for each of the individual units, particularly 5–7, as they were most likely deposited as the Eosahabi rivers entered the brackish to lacustrine waters of the Sirt Basin.

Evidence for the extent of Neogene Lake Chad comes from work undertaken by the ‘Mission Paleontologique Franco-Tchadienne’ (MPFT) within the Djourab desert at four localities: Toros-Menalla, Kossom-Bougoudji, Kollé and Koro-Toro (Fig. 8). Sediments comprising clays, diatomites, argillites, siltites and poorly cemented sandstones were deposited at these localities during wet periods, accompanied by major lacustrine extension in an area that was otherwise characterized by a recurrent desert climate (Lebatard et al. 2008). Each of the four localities also contain rich fossil assemblages, including leguminous plants, fish, snakes, crocodiles, rodents, horses, hippos, elephants, giraffes and rhinos, further confirming the presence of a lacustrine and peri-lacustrine environment (Brunet & MPFT 2000; Vignaud et al. 2002).

**Post-Messinian drainage patterns**

The Eosahabi rivers became extinct at the end of the MSC as the Mediterranean reflooded (Griffin 2006). Following the Messinian, the Sahabi rivers continued to flow during the Pliocene until they too became extinct at 4.6 Ma (Griffin 2006) as the drainage patterns across North Africa were reorganized following the MSC; the Nile captured most of the Sirt drainage, diverting clastic sedimentation away from the offshore Sirt Basin (Slack et al. 2000). The offshore extension of the Sahabi river system has also been mapped as part of this study. It has the same entry point into the offshore Sirt Basin as the Eosahabi river system and follows a similar path, although it is shifted towards the SW following the same progressive trend of Units 5–7 within the Lago Mare facies (Figs 1, 5). It is interpreted to have been formed under submarine conditions based on the recognition of channel levee systems (Sabato Ceraldi et al. 2008), which is consistent with its Pliocene age proceeding the reflooding of the Mediterranean.

**Mass transport complexes**

Several MTCs are observed within the offshore Sirt Basin along the shelf and within the basin centre. Slumping and gravitational collapse appears to have begun during the Oligocene prior to the MSC involving deltaic clastics. Multiple detachment surfaces can be observed, indicating that the slumping and gravitational collapse of Oligo-Miocene sediments was an ongoing process (Fig. 7). Seismic observations indicate the presence of a negative impedance reflector below the Upper Messinian Lago Mare facies, with MTCs observed both above and below the reflector (Fig. 5). The reflector is generally poorly imaged and cannot be picked in places. The overlying facies below the Lago Mare facies display a high relief, irregular topography and have an overall chaotic high amplitude response with very little internal structure except where large slide blocks are interpreted to be present.

This facies is interpreted to be made up almost entirely of MTCs and is likely to represent a combination of the RLG of the Lower Evaporites and mixed clastics. This would explain the negative impedance response at the base of the facies as seismic energy passes from the higher velocity gypsum-bearing RLG and into the lower velocity Oligo-Miocene clastics. Outcrop studies of the RLG deposits in the northern Apennines and Sicily show that they consist of a complete suite of gypsum-bearing deep-water gravity deposits ranging from olistostromes to thin-bedded turbidites (Manzi et al. 2005). The RLG deposits in outcrop show a common vertical organization, with thin-bedded turbidites at the base and disorganized deposits towards the top, often containing kilometre-scale and undeformed PLG blocks or slabs, suggesting large-scale collapse of primary evaporite basins (Roveri et al. 2008a).

This observation is replicated in the offshore Sirt Basin where the much larger MTCs (e.g. offshore Benghazi) appear to have been deposited towards the end of the RLG deposition. The age of the RLG in the offshore Sirt Basin would appear to correspond to the ‘Messinian Gap’ between 5.50 and 5.59 Ma, given that they post-date the PLG but pre-date the Lago Mare facies. This raises an interesting question: where to place the MES, above or below the RLG? Roveri et al. (2008a) consider the MES as a basal surface of forced regression and, as such, place it above the PLG deposited during a HST but below the RLG which is interpreted to have been deposited during a LST (Fig. 2). Therefore, given the absence of the in situ PLG within the offshore Sirt Basin, the MES actually represents the base of the MSC facies.

There are multiple origins for the formation of MTCs, including sediment over-pressuring, rapid sedimentation rates, gas-hydrate decompression and sublimination, and earthquakes (Weimer & Slatt 2004). The large fall in sea-level during the mid-Messinian drawdown may also have destabilized unconsolidated shelfal areas (Sabato Ceraldi et al. 2010). The most likely origin for the MTCs within the Sirt Basin is rapid sedimentation rates causing an overdeepening of the shelf, with gravitational collapse triggered by a large fall in sea-level and/or tectonic activity associated with the collision of the African and Eurasian plates.

**Zanclean flooding**

The MSC ended at 5.33 Ma, terminating in the Zanclean flood. The latter marks the Miocene–Pliocene boundary (Krijgsman et al. 1999) and a return to fully open-marine conditions as a connection between the Mediterranean and Atlantic Ocean was re-established through the Gibraltar Strait (Hsi et al. 1973). The Zanclean flood has been interpreted as a catastrophic event with a maximum duration of two years (Garcia-Castellanos et al. 2009). This is consistent with seismic observations from the offshore Sirt Basin where deep-water hemipelagic Plio-Pleistocene sediments are observed sitting directly and conformably above the shallow-water Lago Mare facies, indicating a sudden change in depositional environment with no apparent transitional facies or erosional hiatus (Fig. 5).

**Implications for seismic imaging**

The quality of seismic imaging within the offshore Sirt Basin is extremely variable, ranging from good to very poor (Fig. 6). The MSC facies have long been understood to be the cause of the poor imaging quality. However, the MSC facies are widely
distributed within the offshore Sirt Basin and, in places, the imaging quality below them is good, indicating that there is no simple correlation between imaging quality and the presence of MSC facies. This study has thus far attempted to understand the composition and distribution of the MSC facies within the offshore Sirt Basin and now that a framework is in place a correlation between imaging quality and the individual MSC facies can be made.

A map of the MSC facies was created which describes the different depositional and erosional environments that were active during the MSC (Fig. 10). A total of eight facies environments have been recognized. Some of the best seismic imaging is observed below the eroded shelf slopes, where the MSC facies are absent and karstification has not occurred, and the marginal Lago Mare and sabkha depositional environments where the MSC facies are relatively thin at less than 150 m. The worst seismic imaging is observed below the karstified shelf margins, which cause a ‘ringing’ effect in the data due to multiple energy, and the RLG and Benghazï MTC which display a chaotic internal structure and record rapid facies and thickness changes. Imaging below the Halite unit, located within the ultra-deepwater zone, is generally poor to very poor, in contrast to the eastern Mediterranean where imaging below the Halite is generally very good (Bowman 2011). No simple relationship can be made between the presence of the large, erosional, clastic-filled channels and imaging quality, although imaging does undoubtedly improve in areas below some of the major channels. When acquiring future seismic surveys, either 2D or 3D, the distribution and composition of the MSC facies should be considered as the acquisition parameters can be specifically tailored to minimize seismic imaging problems. The use of a larger source, broadband seismic technology, long-offset streamers, deeper and variable depth towed streamers, and multi-azimuth or wide-azimuth shooting configurations may help to improve imaging of the deeper target intervals below the MSC facies.

CONCLUSIONS

This paper has attempted to provide a comprehensive review of the MSC facies and their distribution in the offshore Sirt Basin based on seismic interpretation and through the use of onshore analogues, particularly the Sicily foreland basin. The Lower Evaporites of the ‘Messinian trilogy’ are present across the entire offshore Sirt Basin with the exception of the shelf margins and slopes. However, they are not present as the in situ PLG but instead as the RLG deposited as a result of large-scale masswasting processes along the shelf margins and slopes following the Messinian drawdown. A large MTC offshore Benghazï, 110 km in width and over 700 m in thickness, was deposited as part of the RLG and volumetrically may represent one of the largest known submarine slides in the world. The middle Halite unit is absent within the Sirt Basin and is instead confined to the abyssal plain to the north beyond the Cyrenusica Ridge.

The Lago Mare facies of the Upper Evaporites are restricted to the deeper central parts of the offshore Sirt Basin. They are characterized by fluctuating base level and strong water salinity changes (Orszag-Sperber 2006) as a result of precession-induced climate change. A total of seven individual cyclical units have been mapped on seismic data, with each unit consisting of a thick clastic sequence and a thin evaporitic layer. Each unit is associated with erosional, clastic-filled channels, all of which can be traced back to a single channel pathway in the southern Gulf of Sirt. The onshore Sahabi channel, as mapped by Barr & Walker (1973) and Nicolai (2008), is shown to represent part of the same drainage system and using satellite imagery this has been traced back to an origin corresponding to Neogene Lake Chad (Griffin 2006).

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