

# Stratigraphic variations control deformation patterns in evaporite basins: Messinian examples, onshore and offshore Sicily (Italy)

Robert W.H. Butler<sup>1\*</sup>, Rosanna Maniscalco<sup>2</sup>, Giovanni Sturiale<sup>2</sup> & Mario Grasso<sup>2, †</sup>

<sup>1</sup> Geology and Petroleum Geology, School of Geosciences, University of Aberdeen, King's College, Aberdeen AB24 3UE, UK

<sup>2</sup> Department of Biological, Geological and Environmental Science, University of Catania, Corso Italia, 57, 95129 Catania, Italy

† Deceased.

\* Correspondence: [rob.butler@abdn.ac.uk](mailto:rob.butler@abdn.ac.uk)



**Abstract:** Three-dimensional seismic data are increasingly resolving original compositional heterogeneity and structural complexity in evaporitic successions within sedimentary basins. The relationship between basin structure, evaporite composition and its influence on subsequent deformation are investigated here using Messinian examples from the Maghrebian thrust system of Sicily and applied to the adjacent Ionian sea-bed. By integrating outcrop and onshore subsurface data, we demonstrate variations in evaporite stratigraphies deposited across thrust-top basins, and how these variations have controlled subsequent deformation of these basins. Gypsum and carbonate units develop broad single-layer buckle fold trains, with wavelengths reflecting layer thickness. The development of deformation appears limited by bending resistance at fold hinges, which can be overcome by syntectonic erosion. In contrast, the thick halite and K-salt accumulations in growth synclines have deformed with short-wavelength folds and distributed strain. These structures can display rapid lateral variations (on a scale of hundreds of metres). Similar structural styles, with buckle fold trains passing laterally into more homogeneously shortened, short-wavelength folding, are evident on seismic data from the buried Messinian interval beneath the Ionian Sea. Using the Sicilian outcrop as analogues, the structural styles for the Ionian may be used to infer evaporite type in these subsurface examples.

Received 28 February 2014; accepted 3 September 2014

The aim of this paper is to demonstrate lateral variations in evaporite stratigraphies deposited in thrust-top basins and how these variations have controlled subsequent deformation of these basins. Evaporitic formations are common components of many sedimentary basins and their mobility can create bewildering structural complexities (e.g. Jackson *et al.* 1995; Hudec & Jackson 2007). With improvements in seismic imaging, it is increasingly evident that original stratigraphic variations in evaporite formations can play important roles in their deformation (e.g. Fiduk & Rowan 2012). Critical in this regard is the relative abundance of halite, together with other high-solubility salts, and the less soluble calcium sulphates (gypsum and anhydrite). In this contribution we present new structural interpretations that combine outcrop observations with extensive subsurface data from Sicily. These Messinian basins are excellent sites for studying lateral variations in evaporite successions and their subsequent deformation. We go on to use these results to interpret seismic data from the nearby Ionian Sea.

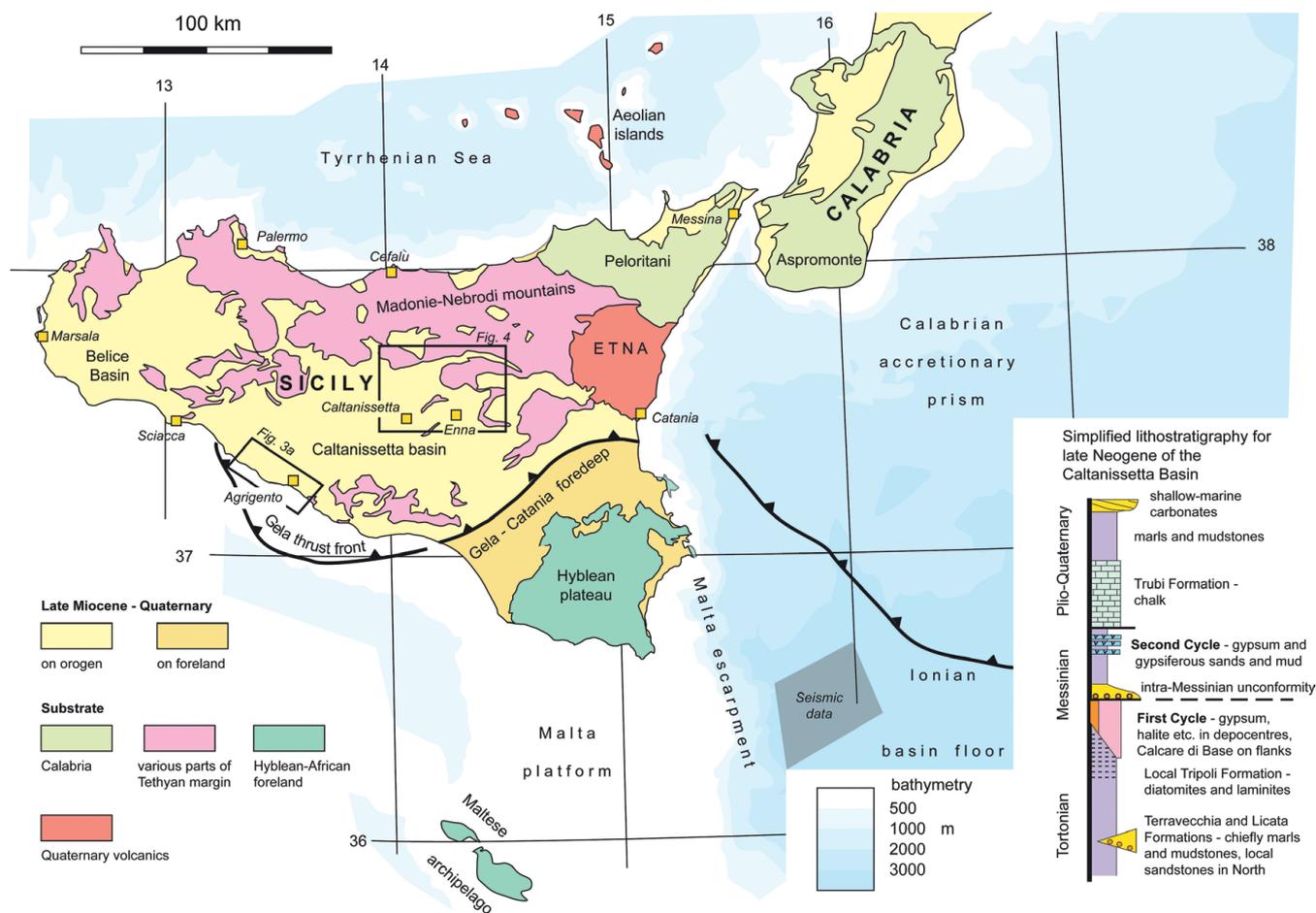
Evaporite formations can exert a strong control on the distribution and geometry of deformation structures in sedimentary basins (e.g. Jackson *et al.* 1995). In compressional tectonic regimes, numerous studies interpret the role of evaporite formations, especially those formed principally of halite, as acting as regional detachment surfaces. In these settings halite (especially wet halite) is assumed to behave as a mechanically weak horizon, in accordance with its measured shear strength at geological strain rates compared with other sedimentary rocks (e.g. Jackson & Vendeville 1994). However, other evaporites show less extreme behaviour. Although gypsum–anhydrite can show transient weakening (e.g. Olgaard *et al.* 1995) owing to dehydration, in general it is stronger than poorly lithified sedimentary rocks. As many basins contain

spatially varying evaporitic assemblages, natural zones of deformation might be expected to display significant variability in structural geometry and evolution.

Messinian evaporites in the sea-bed of the modern Mediterranean are generally inferred to influence the structure of the overlying Plio-Quaternary sediments (Minelli & Faccenna 2010). Hummocky deformation of these sediments (so-called ‘cobblestone’ morphology; Hersey 1965; Hsü & Cita 1973) characterizes much of the Mediterranean sea floor (Costa *et al.* 2004). Modern seismic data reveal a range of behaviours. Messinian evaporites provide detachment surfaces for major gravitational deformations from the Levantine continental margin (e.g. Cartwright *et al.* 2012). Complex inherited variations in evaporite thickness are inferred to influence deformation within the outer part of the Mediterranean Ridge subduction–accretion complex, to the east of our study area (e.g. Tay *et al.* 2002; Hieke *et al.* 2009). However, these seismic-based studies have very little well control on the nature of the evaporites. Furthermore, there is a basic assumption in some modelling of Messinian evaporites that any composition variations are unimportant in controlling deformation (e.g. Costa *et al.* 2004). The lack of substantial well control is partially overcome by interpreting seismic reflector character and linking this to the variations in Messinian evaporites found onshore (e.g. Valenti 2010). The approach here is to extend such comparisons, using deformation style as a further tool to assist interpretation of evaporites beneath the sea-bed of the Mediterranean.

## Salt on Sicily

The greatest range of evaporitic units and the most complete onshore Messinian rock record in the circum-Mediterranean region



**Fig. 1.** Regional map showing the setting of Sicily in its central Mediterranean context (after Bigi *et al.* 1991). Inset: stratigraphy of late Neogene–Quaternary strata in central–southern Sicily (after Butler & Grasso 1993).

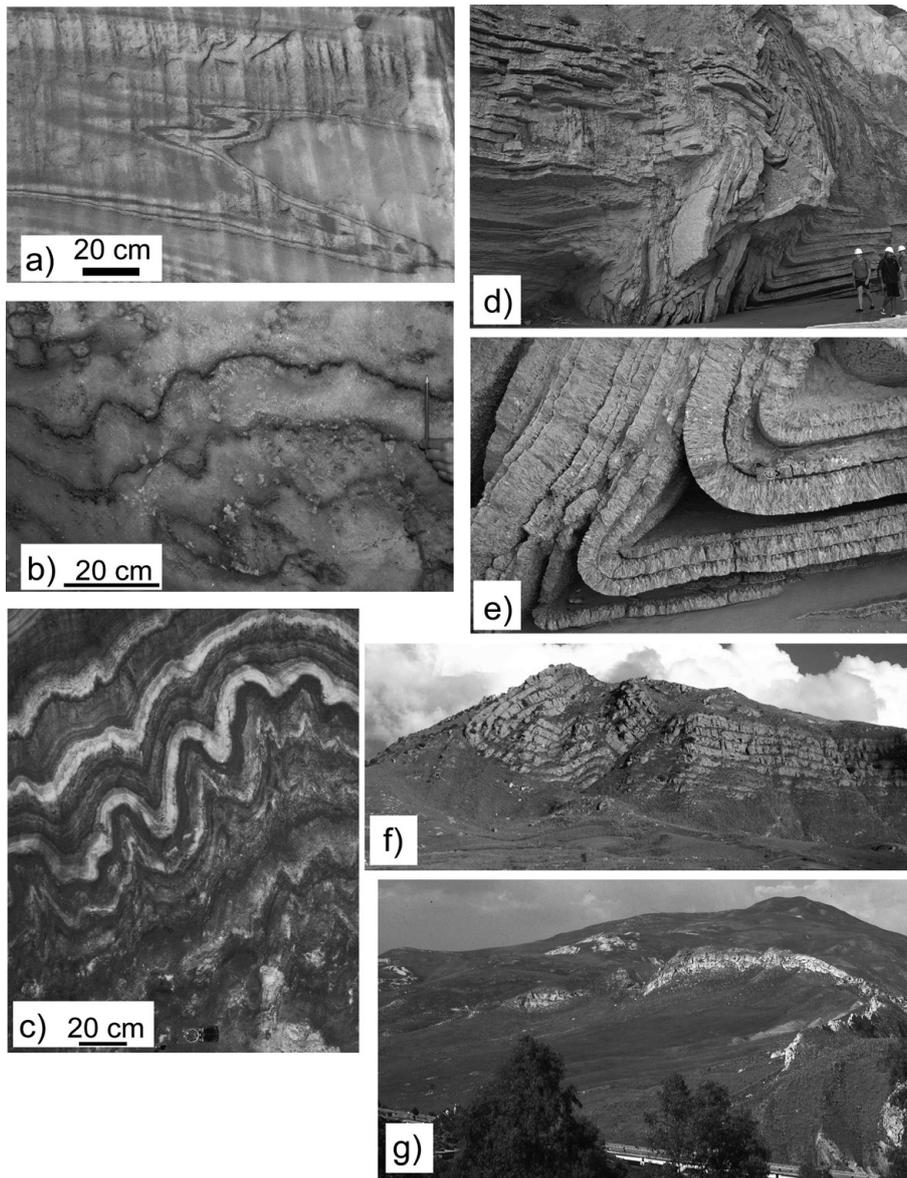
is in central and southern Sicily (Fig. 1). Extensive linked stratigraphic–sedimentological–structural studies have established that the Mio-Pliocene strata of central Sicily, informally known as the Caltanissetta Basin, were deposited on a deforming orogenic wedge (e.g. Butler & Grasso 1993; Jones & Grasso 1997; Lickorish *et al.* 1999; Gugliotta 2012). This thrust belt formed the eastern part of the Mahgrebian system that continues through the central Mediterranean into northern Africa. This thrust belt setting for central–south Sicily is confirmed by seismic reflection profiles across the island and in the offshore (Ghisetti *et al.* 2009; Catalano *et al.* 2013). The Messinian strata of the Caltanissetta Basin (Fig. 1c) form part of the thrust-wedge-top depositional system. The evaporitic strata and time-equivalent carbonates (the so-called Calcare di Base; Ogniben 1957) are generally sandwiched between fine-grained units (Decima & Wezel 1973; Butler & Grasso 1993). They are capped by Pliocene chalks (the Trubi Formation) and underlain by diatomites, local sandstones, silt and laminated mudrocks (the Tripoli, Terravecchia and Licata formations). Active mud volcanoes (Bonini 2009) testify to the poor lithification state of at least some parts of the thrust wedge. Collectively the sedimentary sequence provides a mechanical stratigraphy that we will infer to be broadly similar to that beneath the modern Ionian Sea when we draw comparisons with the onshore geology.

Early studies on Sicily (Decima & Wezel 1973) charted long-range variations in Messinian stratigraphy across the island and established that halite accumulations preserved in the subsurface achieved thicknesses in excess of 1 km. Subsequently, Butler *et al.* (1995) described lateral variations in both facies and thickness of Messinian strata across thrust-wedge-top minibasins, using

subsurface and outcrop data. Significant stratigraphic and sedimentological studies of the Messinian strata of Sicily have followed (e.g. Kouwenhoven *et al.* 2003; Londeix *et al.* 2007; Roveri *et al.* 2008; Manzi *et al.* 2009), largely aimed at long-range correlations and their implications for Mediterranean palaeoenvironmental change (see Pedley *et al.* 2007), although few of these used subsurface data.

Since the work of Decima & Wezel (1973), the Messinian evaporites have been divided into two distinct units, termed the ‘First’ and ‘Second’ Cycle. The two cycles are separated by a major, commonly angular unconformity. Butler *et al.* (1995) established a sequence stratigraphic framework for these units on Sicily, interpreting the unconformity as representing a major forced regression that correlates with the lowstand of water level in the Mediterranean (e.g. Zecchin *et al.* 2013). Onshore Sicily it therefore represents a significant period of non-deposition and emergence. Butler *et al.* (1999) estimated the duration of this emergence in some locations to have exceeded 1 myr, although elsewhere this time-gap was probably 400–500 kyr.

There are important differences in the stratigraphy between the two cycles. The younger, Second Cycle evaporites are exclusively gypsum and rarely reach bed-set thicknesses in excess of 10–15 m. They are interbedded with detrital mud, silt, sandstones and conglomerates that rework earlier Messinian strata. In contrast, detrital input in the First Cycle strata is rare, and limited to mud and silt-grade material. It is in the First Cycle that evaporitic facies show their greatest variations, from Mg- and K-salts with thick halite that are exploited in mines located in specific structural settings, to gypsum and carbonates with bed-by-bed dissolution



**Fig. 2.** Fold styles in Messinian strata onshore Sicily. (a) Intrafolial similar folds in halite, Realmonte mine; (b) interfacial buckles of evaporitic crusts in halite, Realmonte mine; (c) polyharmonic multilayer buckle folds in interlayered halite and K-salts, Realmonte mine; (d) asymmetric fold pair developed in *c.* 5 m of bedded selenitic gypsum, embedded in mudstone and gypsiferous siltstone–fine sandstone (all Second Cycle Messinian), Eraclea Minoa; (e) detail of (d) folding in multi-layered selenitic gypsum (with thin interbedded mudstone) showing layer thickness control on hinge curvature (compass is 20 cm long for scale); (f) tight, inclined and upright folding in well-bedded Calcare di Base defined by *c.* 2 m carbonate units with separated by thin mudstones, Monte Grande (cliff height up to *c.* 50 m); (g) the Mucciarello anticline (see Figs 4, 5 and 6) with wavelength of *c.* 1200 m, developed in Calcare di Base characterized by amalgamated beds of limestone (total *c.* 15 m thick).

breccias (Calcare di Base) that dominate the outcrop of the First Cycle.

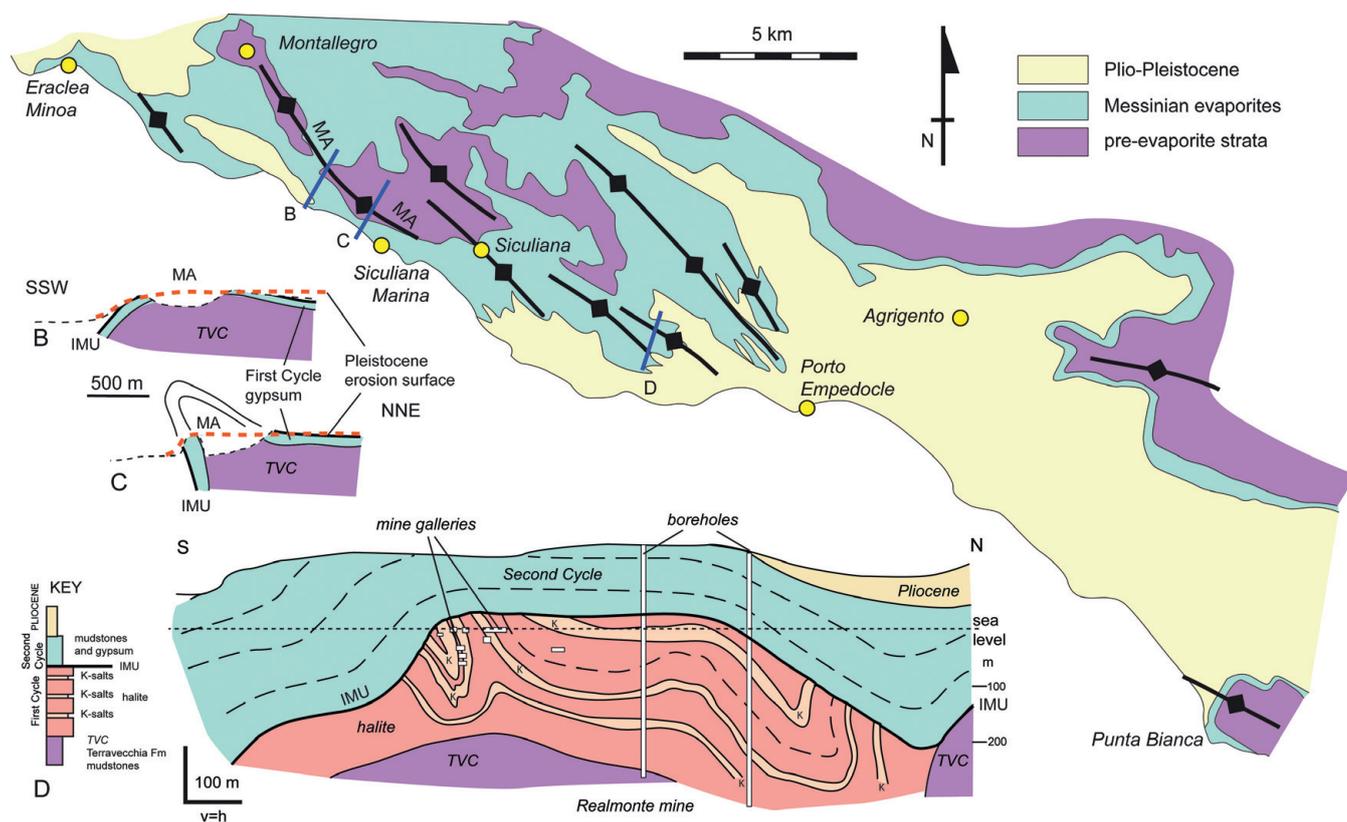
It is generally accepted that Messinian successions in Central Sicily are deformed by late Messinian to early Pleistocene fold and thrust tectonics. Lentini *et al.* (1996) proposed that the enhanced thickness of evaporites preserved in synclines was achieved by tectonic thickening ahead of advancing thrust sheets. These structural settings generally remain in the subsurface and many have been exploited commercially for halite and potash together with native sulphur. These mine workings together with exploration drilling are essential, when integrated with outcrop studies, in developing understanding of Messinian geology on Sicily. The mine plans, well logs and other subsurface data reprised here are provided by Italkali and Ente Minerario Siciliano, following our initial collaboration (Butler *et al.* 1995). They show that although there is deformation within the halite-rich synclinal settings, there are also considerable stratigraphic thickness increases and distinct primary facies variations that are controlled by active thrust and fold structures at the time of deposition.

The Messinian strata are involved in a wide range of visible fold structures (Fig. 2). These range from structures with kilometre-scale wavelengths to smaller-scale buckles and interfacial folds on

the centimetre scale. Our aim here is to show how these variations relate to the larger-scale fold–thrust belt structure and hence to the depositional setting. Two areas of the Sicilian thrust system are used here (Fig. 1), linked to three major mine areas. These are Realmonte (on the south coast) together with Corvillo and Mandre in the centre of the island.

### Siculiana and the south coast

The south coast of Sicily (Fig. 3) is classic ground for Messinian studies. Mio-Pliocene strata are folded and capped by only weakly deformed Pleistocene shallow-marine deposits. This Siculiana fold belt is portrayed on 1:50000 geological mapping (Decima *et al.* 1972) that provides stratigraphic context and underpins previous interpretations (Butler *et al.* 1998). The First Cycle evaporites that crop out are massive-bedded selenitic gypsum (the ‘Gessi di Cattolica Eraclea’ of Decima *et al.* 1972), *c.* 100 m thick. This unit defines folds with a wavelength of 5–8 km, which separate synclines that host commercially exploited evaporite successions dominated by halite. The gypsum unit is underlain by kilometre-thick mudstone-dominated successions that include the Miocene Licata Formation and older claystones. The gypsum unit is overlain



**Fig. 3.** The Siculiana fold belt displayed as a simplified structural map (based on Decima *et al.* 1972) and sections. B and C are profiles through the Montallegro anticline. D is a profile through Realmonte mine and adjacent areas based on mine plans and well penetrations. MA, Montallegro anticline; IMU, Intra-Messinian unconformity.

by an upper Messinian succession chiefly comprising mudstones, with thin sandstone and sparse 1–4 m thick gypsum beds. Collectively these constitute the Second Cycle of Decima & Wezel (1973; ‘Upper Evaporites’ of Manzi *et al.* 2009; Fig. 1b). They pass abruptly up into chalks (Trubi Formation) and marls (Narbone Formation) of Pliocene–Pleistocene age. Neglecting the thin (<4 m) gypsum layers in the Second Cycle succession, the overall mechanical stratigraphy is therefore assumed to constitute a single competent beam (the ‘First Cycle’ gypsum, *c.* 100 m thick) embedded in relatively incompetent units.

### The Montallegro anticline

For 5 km either side of Siculiana Marina (Fig. 3), the coastal section is defined by a SSW-dipping dip panel of massive First Cycle gypsum that represents the seaward limb of the Montallegro anticline. This is one of a train of folds with wavelengths of 1–3 km. The NNE limb dips more gently landward so that the fold is inclined. The fold interlimb angle varies along axis, from *c.* 120° to *c.* 80°, with much of this variation caused by dip changes along strike in the forelimb. These dip changes occur abruptly, commonly across axis-perpendicular faults that act to segment the fold. Although the Montallegro anticline is deeply incised it is possible to reconstruct a Pleistocene marine erosion surface across the structure (Decima *et al.* 1972) and to trace the continuity of this unconformity into Pleistocene shallow-marine growth strata on the seaward limb. Thus at least the later part of the folding was coeval with erosion and marine regression. Butler *et al.* (1998) deduced that variations in the tightness of the anticline corresponded to the amount of erosion of the fold hinge along the Pleistocene unconformity, and that bending resistance in the hinge area of the fold had been overcome by reduction or loss of the competent gypsum layer. Therefore, deformation within this sector of the fold belt was

controlled by the mechanical properties of the 100 m thick First Cycle gypsum relative to the surrounding mudrocks.

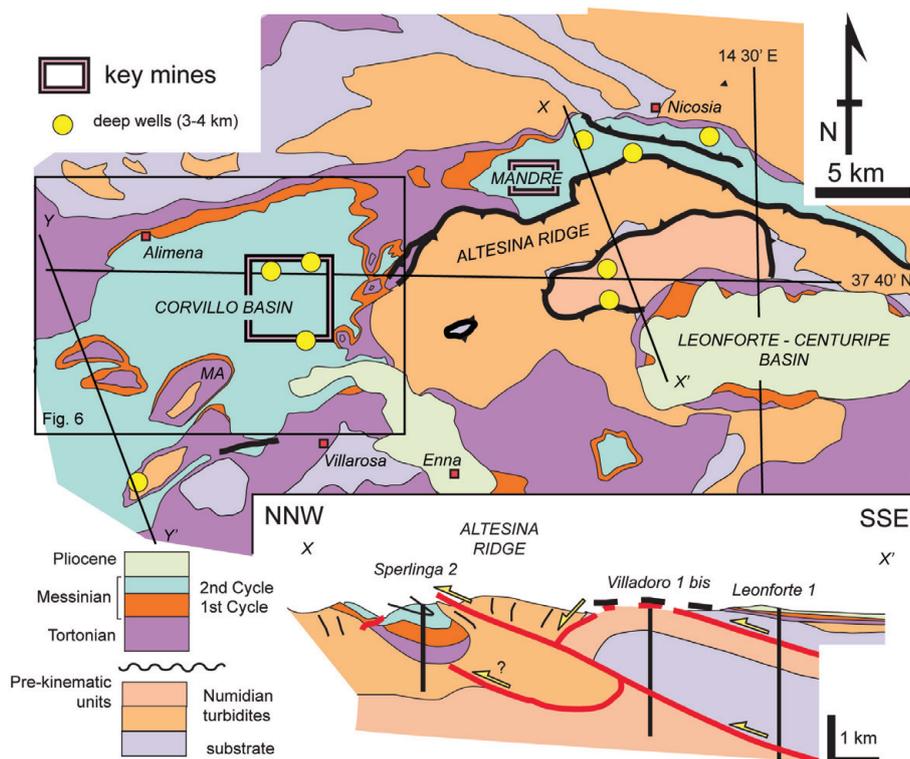
### Realmonte

The Montallegro anticline plunges ESE into a synformal Messinian basin that hosts the Realmonte mine (Fig. 3, profile D). Extensive well and gallery plans show that Messinian strata at Realmonte are chiefly halite, together with seams of potassium salts and only local gypsum layers. This First Cycle stratigraphy has an expanded thickness of over 300 m and is deformed into a series of upright folds (Lugli *et al.* 1999). These are truncated by the intra-Messinian unconformity, which effectively seals the synform.

Based on mine plans from galleries and borehole data, on the scale of the minibasin, deformation within the First Cycle evaporites is more intense than for the Montallegro anticline. Folds are tighter and of a shorter wavelength. However, this cross-section-scale deformation hosts smaller-scale structures evident on mine gallery walls. In volumes of near-pure halite, evidence of penetrative layer-contractional deformation is provided by crenulated partings. Where solution crusts (Fig. 2b) and more complex inter-layered halite and K-salts are present (Fig. 2c), layer buckles with wavelengths of tens of centimetres are evident. Elsewhere, tight, intrafolial folds of similar geometry (Fig. 2a) are present in halite, evidencing significant ductile deformation.

### Deformation of Second Cycle gypsum

Discussions of the south coast area here have thus far concentrated on deformation of First Cycle evaporites. In both the Montallegro fold belt and its correlative sections in the subsurface at Realmonte, the First Cycle evaporitic strata are essentially devoid of detrital material. Consequently, the gypsum units in the Montallegro fold belt appear to have deformed as a single competent layer. Within



**Fig. 4.** Simplified map of part of central Sicily showing the location of major halite basins in the Altesina syncline (based on Sturiale *et al.* 2010, and syntheses by the authors). The location of the contextual cross-section (X–X') is shown on the map. Y–Y' is the line of section for Figure 5. MA, Mucchiarello anticline (see Fig. 2g).

the halite-rich successions of the Realmonte mine, the evaporites again behave coherently, albeit with local heterogeneity promoting short-wavelength (tens of centimetres) folds. This behaviour contrasts with deformation of Second Cycle evaporites. These units are exclusively gypsum, with local, millimetre-scale carbonate crusts. The gypsum is chiefly selenitic and is deposited in bed-sets of up to *c.* 10 m. These bed-sets themselves comprise gypsum layers of 10 cm to *c.* 1 m thickness, commonly separated by a few centimetres of mud. Collectively then the gypsum bed-sets contain an internal mechanical layering that facilitates folding at shorter wavelength (e.g. Fig. 2e and f) than bed-sets (e.g. in the First Cycle at Montallegro) where layers are apparently well-bonded.

### The Altesina syncline and basin system

The structure of central Sicily is marked by a major north-vergent thrust system, referred to here as the Altesina backthrust. In the footwall to this is preserved a tract of Messinian strata, with an along-strike extent in excess of 40 km. This is described in recent mapping (Maniscalco *et al.* 2010; Sturiale *et al.* 2010), synthesized here into a summary geological map (Fig. 4a). A suite of deep hydrocarbon exploration wells constrain subsurface structure and define a regional cross-section (Fig. 4b). Unlike the Miocene basins of southern Sicily, which prior to evaporite precipitation were characterized by open marine conditions (the Licata and Terravecchia formations), in the Corvillo area the Tortonian strata locally record subaerial fluvial deposition (Butler & Grasso 1993; Jones & Grasso 1997) and local patch-reef development (Grasso & Pedley 1988). Consequently, the facies and thickness variations in Messinian strata chart differential subsidence across this part of the thrust belt, linked with active folding (Butler *et al.* 1995) and presumably enhanced flexural subsidence driven by long-wavelength tectonic loading (Butler & Grasso 1993).

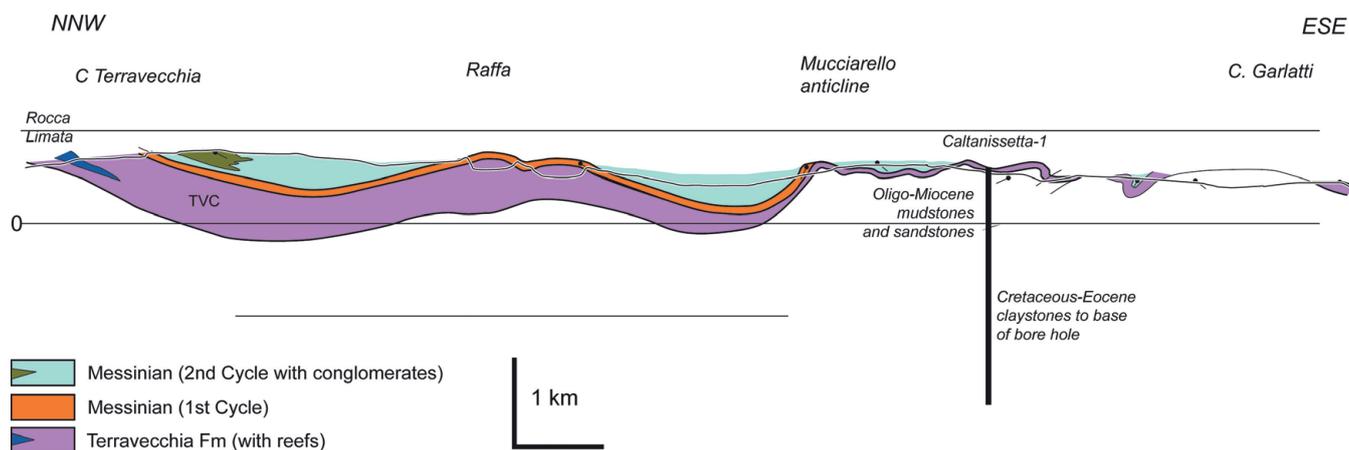
There are two important accumulations of halite and K-salts along the north side of the Altesina backthrust and its continuation.

These form the Corvillo and Mandra mine concessions, which have substantial well penetrations that are used later in this paper to develop structural interpretations. First we consider the structure adjacent to these subareas.

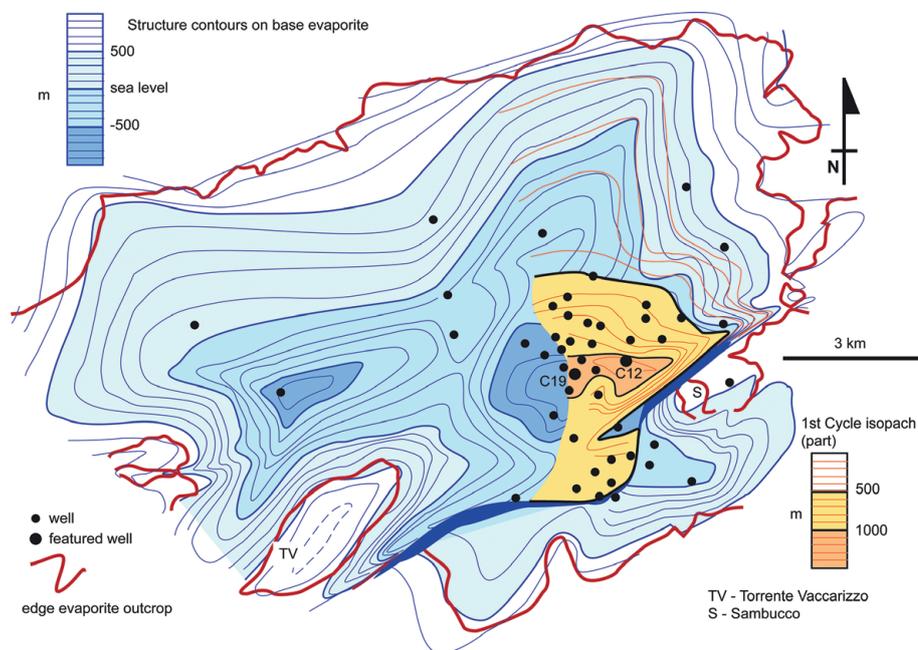
### Western transect

To the west of the Corvillo concession, the First Cycle Messinian strata are chiefly represented by a multi-bed carbonate unit, the Calcare di Base. It contains the usual bed-by-bed brecciation textures with halite pseudomorphs encased in lime mudstone. In general, the Calcare di Base directly overlies mudstones and local diatomitic laminites (Tripoli Formation) of latest Tortonian to Early Messinian age (e.g. Pedley & Grasso 1993; Pedley & Maniscalco 1999) that pass upwards from the shallow-water units of older Tortonian age (Jones & Grasso 1997). These overlie older, chiefly mudstone-dominated strata. Overlying the Calcare di Base, and preserved in synclines, are Second Cycle Messinian strata consisting of detrital muds, gypsiferous sandstones and local primary gypsum beds (Butler *et al.* 1995). A distinct angular unconformity between strata of the two cycles is evident, especially along the northern edge of the cross-section (Butler *et al.* 1995). The Second Cycle strata in turn are overlain by the ubiquitous Trubi chalk of Pliocene age, although erosion has largely removed this from this area.

The structure of Messinian and younger strata to the west of Corvillo is shown here on a cross-section through the Raffa area (Fig. 5). It is dominated by an upright, open fold train defined by the Calcare di Base. The profile can be divided into two distinct parts: a southern segment, where folds have a wavelength of *c.* 250–500 m, and a much more broadly folded northern segment. The reason for these differences is unclear but may relate to the thickness of the Second Cycle, which is up to 600 m thick in the north and may locally have been just a few tens of metres thick in the south. Nevertheless, the folds defined by the Calcare di Base



**Fig. 5.** Cross-section through the western edge of the Corvillo basin (Y–Y' in Fig. 4), showing the structure of the synkinematic strata developed above the thrust wedge in central Sicily. It should be noted that the folding defined by the beam of Messinian First Cycle strata (here Calcare di Base) is superimposed upon a longer-wavelength syncline that hosts pre-Messinian strata (Terravecchia Formation). The flanks of this earlier syncline (which hosts the Corvillo basin along strike; see Fig. 6) are defined to the NNW by a limestone reef and by a thin veneer of Terrevecchia Formation south of the Mucciarello anticline.



**Fig. 6.** Subsurface map of the Corvillo Basin, with interpreted structure contours on the base of the Messinian evaporites (using well and outcrop data) together with a partially displayed isopach map for the First Cycle evaporites in the basin. Contour spacings are 100 m. Location of the map area is shown in Figure 4. Well C12 is used in Figure 7 and well C19 is used in Figure 8.

are superimposed on a much longer (>6 km) wavelength fold, preserved as a syncline that hosts the pre-evaporitic strata. These long-wavelength folds were reported by Butler & Lickorish (1997) and are interpreted as reflecting the spacing of the main foreland-directed thrusts within the orogenic wedge.

### The Corvillo Basin

Fold structures in the Calcare di Base, identified on the Raffa section (Fig. 5), can be mapped laterally to the east, where they plunge beneath the Second Cycle Messinian and Pliocene strata that represent the younger part of the sedimentary fill to the Corvillo Basin (Fig. 6). Carbonates of the Calcare di Base rim the Corvillo Basin. The basin itself is penetrated by 47 boreholes, which were used to define the Corvillo mine concession. They are used here to create a structure contour map on the base of the First Cycle deposits, tied to the outcrop data. Using the outcrop sections as a guide, the two cycles of Messinian strata can be distinguished in well logs, as Second Cycle evaporites are exclusively gypsum and are encased in thick detrital mudstones and gypsiferous sandstones. In some

well logs there is a sufficient dip-meter record to chart the angular unconformity between the cycles.

By combining borehole depths to base evaporite and base Second Cycle, an isopach map for the First Cycle can be constructed. Here it is represented only for the eastern part of the Corvillo Basin (Fig. 6). In the depocentre area, First Cycle thicknesses exceed 1100 m. These thicknesses do not simply represent stratigraphic values, as dip-meter data indicate tracts with significantly steep layer inclinations. However, reconstruction of these data, matched against borehole segments with only gentle dips, indicates that depositional thicknesses must exceed 600 m for First Cycle strata within the Corvillo Basin. This contrasts with the broadly time-equivalent Calcare di Base on the flanks, which achieves thicknesses of only 12–25 m (Fig. 7). These variations in stratigraphic thickness and facies for First Cycle strata occur over a present-day across-strike distance of <1500 m. This distance has been telescoped by later deformation but probably did not exceed 3 km distance at the time of deposition. The distance along strike, in a direction that has unlikely to have been telescoped by deformation, between the Calcare di Base at outcrop and the halite and

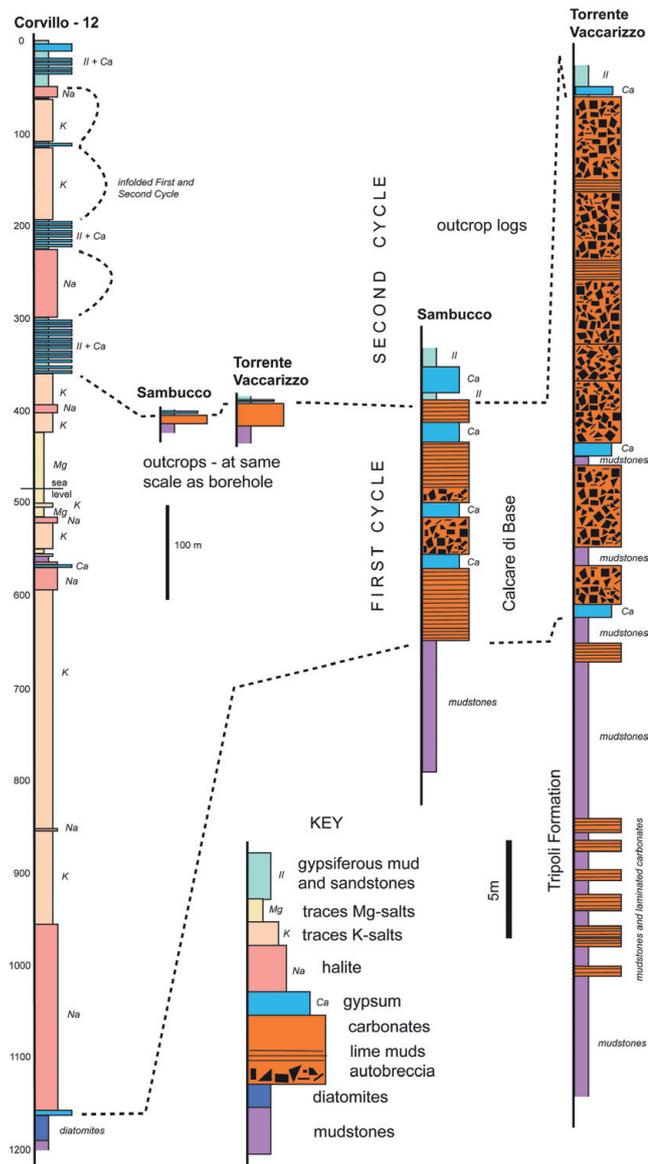


Fig. 7. Vertical sections for the Corvillo subsurface and adjacent outcrops to show thickness and facies variations in First Cycle Messinian strata. Locations are shown in Figure 6.

higher-order salts with stratigraphic thicknesses in excess of 600 m, is <5 km. Thus, regardless of the subsequent deformation, at the time of deposition the Corvillo Basin exhibited dramatic variations in facies and thickness on the scale of a few kilometres.

The southern flank of the Corvillo Basin is defined at depth by a major monocline with an amplitude that locally exceeds 1 km (Fig. 6). This structure is the lateral continuation of the Altesina backthrust (Fig. 4b). Well logs for boreholes in the Corvillo Basin adjacent to the monocline show complex variations in stratal dip, although chiefly dips are very steep. This finding, together with alternations in logged evaporitic compositions, is consistent with the First Cycle deposits having been folded on broadly sub-recumbent folds. Fold wavelengths for the structures resolved in these records are probably of the order of a few hundred metres. An example is shown in Figure 8. It should be noted that the dip-meter data are derived from core. However, as the boreholes are vertical and not otherwise calibrated, the dip direction cannot be established from well logs. Therefore structural interpretations shown here are non-unique. Further analysis is the subject of continuing research, but it is not expected to affect the broad deductions drawn here. The deformation of First Cycle strata in the Corvillo Basin is

significantly more intense and complex than in the surrounding rim of time-equivalent Calcare di Base.

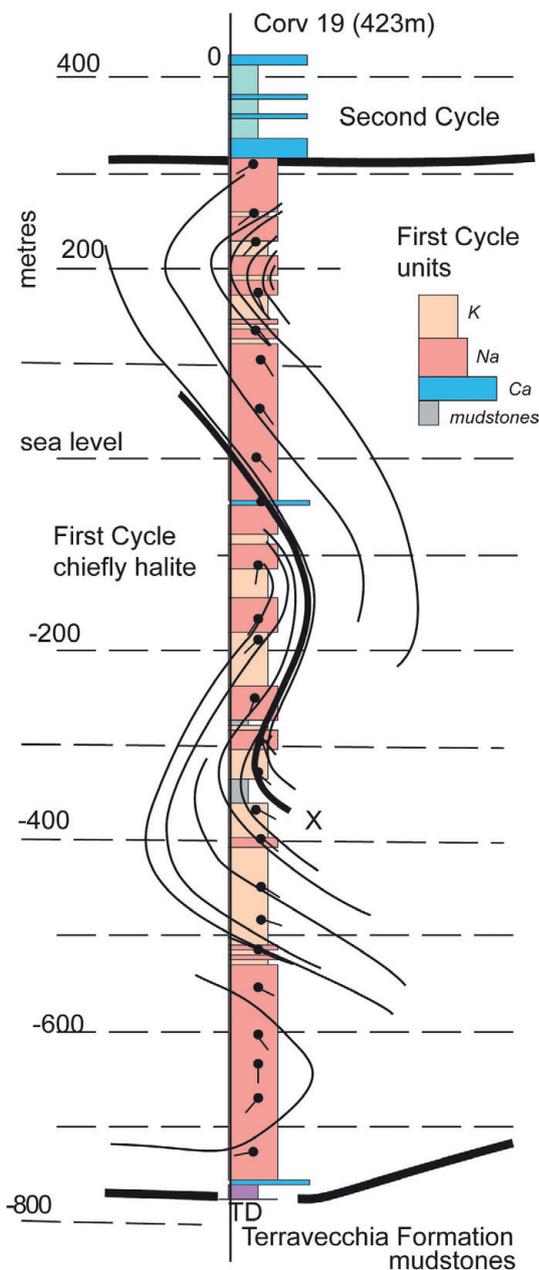
### The Mandre Basin

The Corvillo Basin passes laterally to the NE into a narrow fold belt, defined by Calcare di Base that forms a continuous outcrop. However, 12 km to the ENE of the Corvillo depocentre, the Second Cycle Messinian strata overstep onto the older Terravecchia Formation, masking a subcrop of First Cycle deposits that lie in a second minibasin that hosts the Mandre mine concession. Ten boreholes were available for our study and these are used to construct a simple fence-diagram illustrating an interpretation of the structure of this basin (Fig. 9).

As with Corvillo, the First and Second Cycle Messinian successions can be readily distinguished by virtue of the detrital content of the younger unit. The unconformity between these is less apparent at Mandre, there being no clear discordance between the cycles. Both First and Second Cycle strata are folded together along the southern side of the Mandre Basin. These structures are readily interpreted as relating to the Altesina backthrust. The boreholes show tight interleaving of the two cycles and of the internal compositional layers in the First Cycle into tight, presumably similar folds with wavelengths of *c.* 100 m (Fig. 9). The limitations in this interpretation are similar to those for Corvillo, in that there may be smaller-scale deformation, but this is not recorded in the commercial records. Given the deflection of the intra-Messinian unconformity into a broad pillow-like antiform ahead of the highly deformed section (Fig. 9) it is likely that the Mandre strata contain significant, broadly distributed, ductile strain.

### Onshore deformation

The large-scale stratigraphic variations in Messinian strata occur over distances of 5–10 km presumably reflecting the spacing of the minibasins that hosted these deposits. These in turn would reflect the broad spacing of thrusts and their related anticlines in the orogenic wedge on Sicily. Folding of the Calcare di Base is generally on a shorter wavelength. A conclusion of linked magnetostratigraphic and cycle stratigraphic analysis of the Calcare di Base and underlying strata by Butler *et al.* (1999) was that deposition of this unit was over the course of a few precession cycles (*c.* 24 myr each). Thus across areas of the orogenic wedge with little differential growth, the Calcare di Base was probably deposited in 100–150 kyr, a short duration compared with that of deformation within the thrust wedge. The Calcare di Base Formation is encased in poorly consolidated muds and silts, and presumably therefore behaved as a strongly competent beam during subsequent deformation (Fig. 10a–c). As the Calcare di Base is folded across arrays of pre-existing anticlines and synclines it suggests that at least this part of the orogenic wedge has undergone subhorizontal compression on a broadly NNW–SSE axis. In this regard, the First Cycle gypsum units that are the equivalent to the Calcare di Base in the Montallegro fold belt on the south coast of Sicily have behaved in a similar fashion. Presumably this reflects the significant competence contrast between thickly bedded, coarse-grained gypsum and poorly consolidated muds and silts. It is this contrast in rheology that, for this example, is more important than any contrasts between carbonates and gypsum. The notion that the composite carbonate and thick gypsum of the First Cycle behaved as an end-loaded buckling beam is supported by the interpretation of the eroded part of the Montallegro anticline. That limb-tilting rates increased after the crest of the anticline was breached through erosion indicates that deformation is limited by bending resistance, a feature of amplifying buckle folds (Casey & Butler 2004). The addition of a strong layer (First Cycle Calcare di Base and thick First Cycle gypsum) across the region may have acted to increase the bulk strength



**Fig. 8.** Interpretation of the structure developed in First Cycle Messinian evaporites within the Corvillo Basin revealed by dip-meter data and evaporite composition for borehole Corvillo 19 (location shown in Fig. 6).

of the thrust wedge, albeit transiently, until buckling instabilities had developed sufficiently to weaken this layer. Presumably this would serve to enhance slip rates transiently on the base of the thrust wedge. An alternative mechanism for perturbing the mechanical strength of the thrust wedge, by the deposition of encasing strata across the thrust wedge acting as a top-seal trapping significant overpressures below, is not considered here to be a likely option. The Calcare di Base is highly porous and an unlikely candidate for an effective top-seal. Halite, which could have acted as an effective seal, accumulated in synclines and therefore does not cap structures that might have trapped buoyant overpressuring fluids.

A key result from the studies of mine data from the two study areas on Sicily is that the halite-rich successions preserved in the subsurface have deformed on a finer scale and more intensely than their counterparts of the Calcare di Base or gypsum in the First Cycle at outcrop. The implication is that a combination of the thickness of these basins together with the weakness of the fill

(halite) in comparison with the gypsum and carbonate units elsewhere has promoted more deformation in these parts of the thrust wedge (Fig. 10d and e). These halite basins on Sicily represent only local weak patches (<10 km across) in the stiff layer of First Cycle Messinian strata and so presumably did not influence the large-scale evolution of the thrust wedge. However, they would serve to generate local structural complexity, especially significant plunge variations in folds.

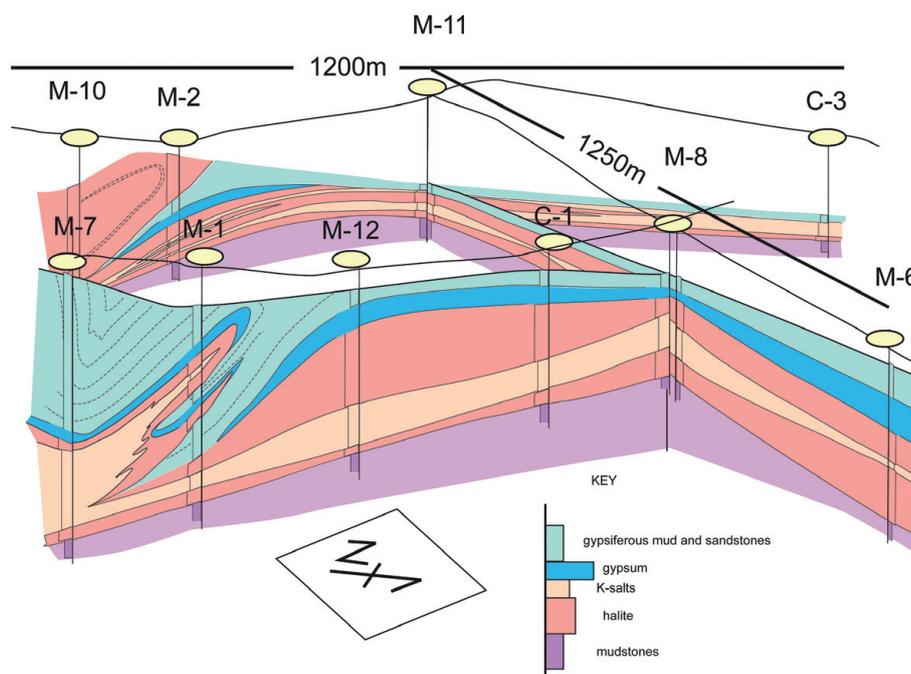
### Interpreting Messinian strata and deformation in the Ionian Sea

Messinian evaporites have been extensively imaged beneath much of the floor of the Mediterranean Sea and encountered in boreholes. Seismic investigations of the Mediterranean Ridge accretionary complex, to the east of our study area, show complex thickness distributions of Messinian evaporites that reflect both original stratigraphic variations and heterogeneous tectonic thickening (Tay *et al.* 2002; Hieke *et al.* 2009). Costa *et al.* (2004) argued that the hummocky 'cobblestone' form of the top Messinian reflector in the Mediterranean Ridge area represents short-wavelength folds. Similar patterns have been described from the Calabrian accretionary complex (Fig. 1) on the floor of the Ionian Sea (Sartori 2003), where cobblestone morphology has been attributed to deformation in front of the subduction zone along shallow, blind thrust faults controlled by the presence of Messinian evaporites.

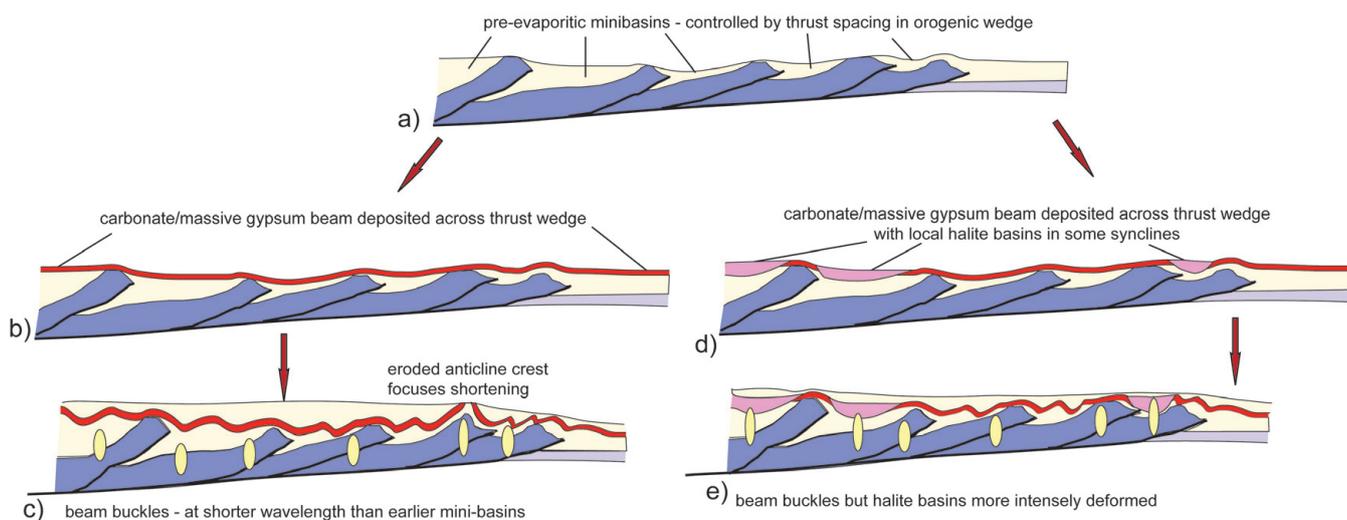
Here we use commercial seismic data from the Ionian Sea acquired by Fugro Multiclient Services in 2007 (Malta Escarpment Margin survey) made available through the Virtual Seismic Atlas ([www.seismicatlas.org](http://www.seismicatlas.org)). These data are of excellent quality as they were acquired using a 7 km streamer and a large source giving good penetration and relatively low signal-to-noise ratio. The data are displayed as migrated time sections. Commercial sensitivities mean that we cannot give the precise location of the seismic data and thus we cannot tie profiles to the sparse well coverage in the Ionian basin. Rather, we use the seismic stratigraphy of Valenti (2010) derived from the CROP marine seismic experiments, described here in a sample panel (Fig. 11a). Valenti placed the base of the Messinian evaporite sequence at the top of the well-layered reflector package, which shows the opposite reflector polarity to the sea-bed (historically designated the 'T-reflector'; e.g. Costa *et al.* 2004) and therefore corresponds to a downward decrease in seismic velocity. The top of the evaporites is marked by a prominent reflection (historically designated the 'M-reflector' on seismic data from the Mediterranean; e.g. Costa *et al.* 2004) with the same polarity as the sea-bed. This M-reflector is complex and irregular. Stratal reflectors above the evaporites have high frequency. They both onlap and are tilted around irregularities in the M-reflector, demonstrating that the evaporites and their overburden have been deformed.

Seismic character within the evaporites is variable but generally discontinuous. The lower part is commonly represented by an almost transparent seismic facies with short, discontinuous internal reflections. Above this there is a highly reflective, if contorted, intra-evaporite layer overlain by a further, broadly transparent layer. Collectively, these units are represented in the simple section of Figure 11a by 1 s of seismic two-way time. Assuming an average velocity of  $4 \text{ km s}^{-1}$ , this travel time equates to a thickness of over 2 km.

The seismic stratigraphy from Figure 11a is now applied to two 2D profiles through the western margin of the Ionian basin. In both cases the profiles abut against the Malta escarpment, the tectonic boundary between the floor of the Ionian basin and the Maltese platform (offshore continuation of the Hylean plateau of SE Sicily; Fig. 1). The sections are presented in clean and interpreted form.



**Fig. 9.** Fence diagram of three cross-sections for the Mandre mine concession (see Fig. 4 for general location), showing the structure and stratigraphic variations within the Mandre minibasin. The view is towards the WSW, with north indicated by the plan-view arrow. The vertical and horizontal scales are equal and given by the measured distances as portrayed.

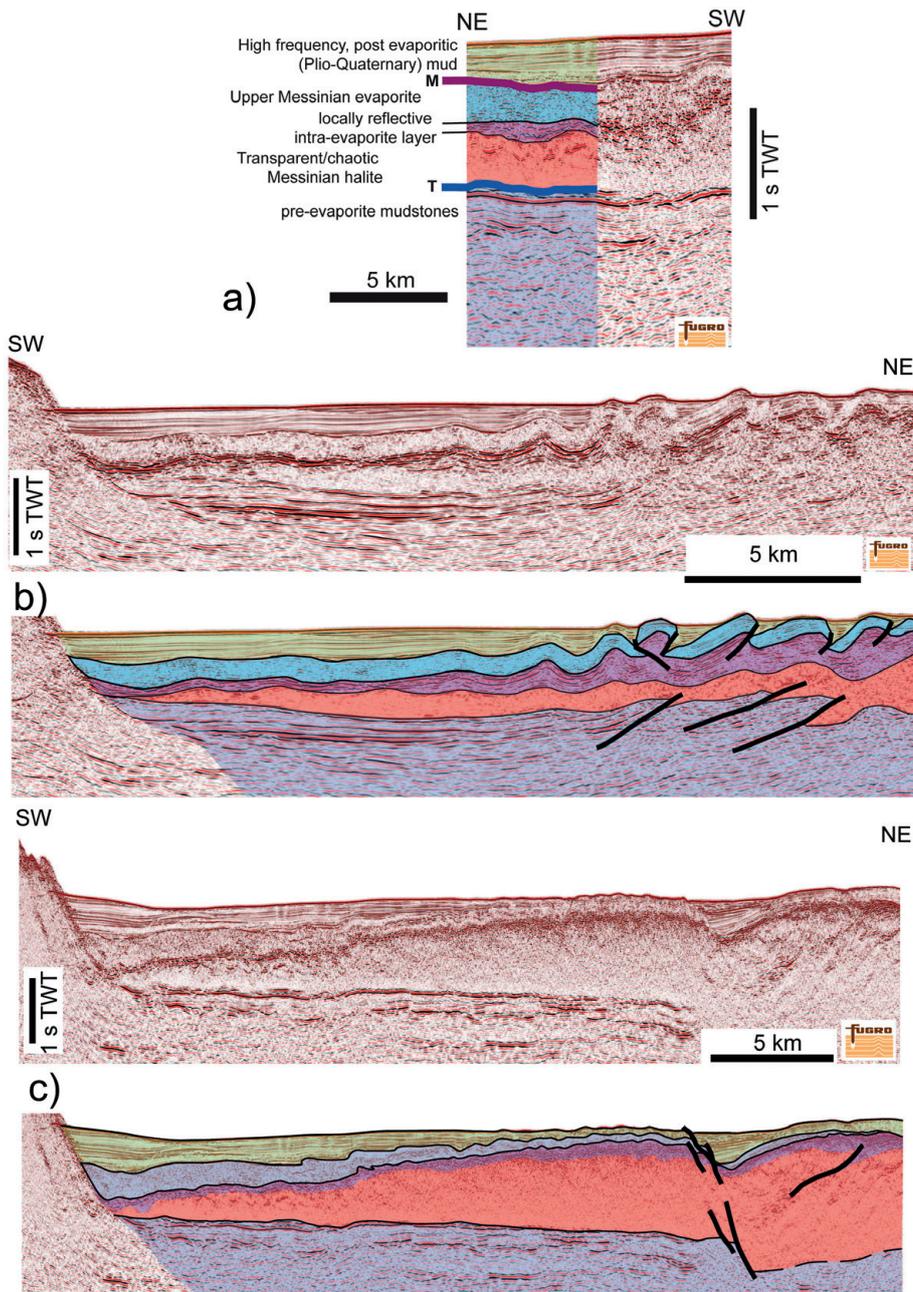


**Fig. 10.** A general model for thrust wedge development through central-southern Sicily, showing the stratigraphic controls on deformation through the deposition of a continuous competent beam of carbonate and massive gypsum across the thrust belt (a–c in time) in contrast to a beam that is interrupted by halite basins (a–d–e in time). The schematic sections are drawn with vertical and horizontal scales equal and the horizontal distance represented is *c.* 70 km.

In profile B (Fig. 11b), the T-reflector at the base of the Messinian evaporites and the underlying stratal reflectors are gently inclined. However, the M-reflector and uppermost seismic facies unit in the evaporites is folded. These folds emerge to have a sea-bed expression at the NE end of the section. Collectively they have a buckle form and therefore imply that the upper evaporitic facies is significantly more competent than the overlying (post-Messinian) sediments and the lower part of the evaporites. We deduce therefore that the upper evaporitic facies on this section line consists largely of gypsum. The lower evaporitic unit presumably consists of halite and higher-order salts.

In profile C (Fig. 11c), again the T-reflector at the base of the Messinian evaporites has a simple form. The M-reflector at the top of the evaporites is crenulated, albeit at a much shorter wavelength

than in profile B (Fig. 11b). However, the seismic facies of the evaporitic intervals in the two profiles (Fig. 11b and c) are broadly comparable, although the deformation style is rather different. If the upper evaporitic interval in profile C is gypsiferous, presumably it has strong mechanical layering so that it has folded on a much shorter wavelength, or even, at the scale of the seismic profiles, simply shortened internally. It appears that, for profile C, the buckling tendency of the upper evaporite is low, and consequently it has thickened in parallel with the lower evaporites that lie below. It is the short-wavelength buckling at the top of the evaporites that, in this part of the Mediterranean, generates the hummocky cobblestone morphology. The downward passage of this distributed deformation into localized thrusts (e.g. Fig. 11) remains speculative.



**Fig. 11.** Seismic data from the western Ionian Sea. These images are provided courtesy of Fugro MCS and the Virtual Seismic Atlas ([www.seismicatlas.org](http://www.seismicatlas.org)), where high-resolution images are available. It should be noted that precise location information for these data is not publicly available but the general location is shown in Figure 1. The data are displayed in migrated two-way time profiles. As shown, the approximate vertical exaggeration for the evaporite levels is *c.* 2.5:1. (a) Partly interpreted seismic panel showing interpretation, based on the velocity and facies model of Valenti (2010). (b) Profile B, shown in clean and interpreted form. (c) Profile C, shown in clean and interpreted form.

In summary, the Messinian evaporites beneath the bed of the western Ionian Sea display deformation styles that vary with depth and spatially. These variations imply that the evaporites have a gross mechanical stratigraphy, most probably halite-dominated at depth but overlain by gypsum. The strongly reflective intra-evaporitic unit remains somewhat enigmatic. It is unlikely to be gypsum or carbonates as it behaves as a detachment beneath the buckle folds (Fig. 11b), and consequently is interpreted here as being significantly weaker than the thick beam of gypsum. Plausibly, these intra-evaporite reflectors represent muddy sediments. If so, the offshore evaporite stratigraphy may closely correlate with that onshore Sicily. The lower evaporites offshore would be broadly correlative with the First Cycle of Sicily, though presumably younger and dating from the pan-Mediterranean lowstand in water level (Butler *et al.* 1995). The detrital material and gypsum of the upper evaporitic levels offshore would correlate with the Second Cycle onshore Sicily. However, the inferred gypsum unit interpreted from Figure 11b is significantly thicker (200ms TWT, equivalent to *c.* 400–500m) than its counterparts onshore. Further research, ideally tied to well

penetrations in the offshore, is needed to corroborate these correlations.

## Discussion

Messinian evaporites on Sicily show complex lateral variations in both thickness and composition. These relate to the pattern of thrust-top minibasins. Integrating data from subsurface with outcrop confirms the general findings of Butler *et al.* (1995) that recognized this primary basin structural control on Messinian stratigraphy. These stratigraphic variations went on to influence deformation styles in the thrust wedge.

For much of the study area, the Messinian strata form a competent beam generally composed of carbonates of the Calcare di Base. In the Montallegro fold belt the equivalent strata are massive gypsum units, and these too behaved as a competent beam encased in mud. Both units represent the First Cycle Messinian strata on Sicily, which accumulated during the protracted regression of palaeo-Mediterranean sea level. They are deformed in folds at a wavelength significantly reduced (*c.* 1 km) from the original

spacing of thrust-related folds (*c.* 5–10 km) across the thrust belt. The carbonate–gypsum beam behaves as a single competent layer that buckled. The amplification of this type of folding is limited by bending resistance at fold hinges (e.g. Casey & Butler 2004). Consequently, erosion across the crests of upright anticlines promotes accelerated fold amplification and associated limb rotations. From seismic examples offshore Brazil, Fiduk & Rowan (2012) described intra-evaporite buckled layers that they inferred to be anhydrite, embedded in halite. In the Sicilian case, the competent beam is encased in poorly consolidated, low-competence, mudstone-dominated clastic deposits.

In some parts of the thrust belt, bathymetric patterns in minibasins allowed halite to accumulate. These minibasins show differential deposition owing to amplification of bathymetry during deposition. In the case of the Corvillo Basin (Fig. 6) many hundred metres of halite and K-salts pass laterally to *c.* 15 m of carbonates (Fig. 7) in less than 2 km, direct evidence for continuing deformation during the Messinian in the thrust belt. These basins continued to deform after halite accumulation, during the regional lowstand in late Messinian times through the Mediterranean and subsequently during late Messinian–early Pliocene transgression.

Deformation in the halite-dominated basins is significantly more intense, with folding on scales of a few hundred metres to centimetres. Therefore these basins presumably act to localize deformation within the thrust wedge. A similar pattern can be interpreted in seismic data from the floor of the Ionian Sea. Halite deposits show significant thickening that in turn influenced Plio-Quaternary deposition. Above thickened halite, these younger units are thinner than in the areas to the flanks.

It is interesting that massive First Cycle gypsum on Sicily (Fig. 3) behaves in a similar fashion to carbonates of the Calcare di Base, in marked contrast to halite. Such behaviour is predicted by classical low-temperature rock deformation experiments (e.g. Handin & Hager 1957). However, it is at odds with the assumptions of Costa *et al.* (2004), who considered gypsum–anhydrite to have a similar competence to halite and thus act incompetently during deformation. Perhaps the difference lies in the depth of burial, and hence ambient temperature, at the time of deformation on Sicily compared with the Costa *et al.* (2004) study area of the Mediterranean Ridge. Costa *et al.* suggested that deformation in their example occurred under a blanket of 1000 m of post-Messinian strata. The implication from Sicily is that shallowly buried gypsum need not form a weak layer within sedimentary successions, which may be important when considering mobilization of evaporitic successions soon after their deposition. The buckle folds imaged seismically beneath the floor of the western Ionian Sea (Fig. 11b) may suggest that the evaporites here deformed under burial conditions more like those onshore Sicily than those that pertain to the Mediterranean Ridge. Certainly, the overlying sediments show onlap onto the flanks of the folded evaporites (Fig. 11b), indicating that deformation initiated when the evaporites were on the sea-bed. However, presumably if further sedimentation occurred above these folds the inferred gypsum layer would reduce in strength, as it warms and dehydrates to anhydrite, leading to a change in rheology. If temperature simply increases with depth in the overburden then this transition in rheology would initiate in the syncline axes, so the gypsum beam could develop strongly heterogeneous deformation. It would be interesting in the future to test this deduction on examples of progressively buried and deforming gypsum units elsewhere.

Seismic profiles from the floor of the Ionian Sea show variable structural styles, with different fold wavelengths. These fold geometries, hitherto thought to produce the hummocky cobblestone morphology seen seismically along the upper contact of Messinian evaporites elsewhere beneath the Mediterranean, may reflect lateral changes in evaporite composition. Using the structure of evaporitic units onshore

Sicily as an immediate analogue, longer wavelength folding in the offshore may reflect deformation of competent gypsum layers whereas short-wavelength crenulated folds and apparently homogeneously thickened tracts may be chiefly halite-bearing. Similar variations in folding patterns may be expected in other weakly buried mixed evaporite successions elsewhere in the global geological record.

## Acknowledgements and Funding

We are grateful to Ente Minerario Siciliano and Italkali for the provision of extensive subsurface data from Realmonte, Corvillo and Mandre areas. We thank F. Peel and an anonymous referee for comments. Seismic reflection data are available for inspection and interpretation at the Virtual Seismic Atlas (www.seismicatlas.org). R.M. acknowledges a MIUR Cofin-PRIN 2010–2011 grant.

*Scientific editing by Stuart Jones*

This paper is in memory of our co-author and friend Mario Grasso.

## References

- Bigi, G., Cosentino, D., Parotto, M., Sartori, R. & Scandone, P. 1991. *Structural Model of Italy at 1:5000,000*. Società Elaborazioni Cartografiche, Firenze.
- Bonini, M. 2009. Mud volcano eruptions and earthquakes in the Northern Apennines and Sicily, Italy. *Tectonophysics*, **474**, 723–735.
- Butler, R.W.H. & Grasso, M. 1993. Tectonic controls on base level variations and depositional sequences within thrust-top and foredeep basins: examples from the Neogene thrust belt of central Sicily. *Basin Research*, **5**, 137–151.
- Butler, R.W.H. & Lickorish, W.H. 1997. Using high resolution stratigraphy to date fold and thrust activity: examples from the Neogene of South-central Sicily. *Journal of the Geological Society, London*, **154**, 633–643.
- Butler, R.W.H., Lickorish, W.H., Grasso, M., Pedley, H.M. & Ramberti, L. 1995. Tectonics and sequence stratigraphy in Messinian basins, Sicily: constraints on the initiation and termination of the Mediterranean ‘salinity crisis’. *Geological Society of America Bulletin*, **107**, 425–439.
- Butler, R.W.H., Keogh, S.M. & Lickorish, W.H. 1998. Evolution of the Agrigento thrust-top basin, Sicily: Sedimentation and the tectonics of orogenic wedges. *Annales Tectonicae*, **12**, 28–50.
- Butler, R.W.H., McClelland, E. & Jones, R.E. 1999. Calibrating the duration and timing of the Messinian Salinity Crisis in the Mediterranean: linked tectono-climatic signals in thrust-top basins of Sicily. *Journal of the Geological Society, London*, **156**, 827–835.
- Cartwright, J., Jackson, M., *et al.* 2012. Strain partitioning in gravity-driven shortening of a thick, multi-layered evaporite sequence. In: Alsop, G.I., Archer, S.G., Hartley, A.J., Grant, N.T. & Hodgkinson, R. (eds) *Salt Tectonics, Sediments and Prospectivity*. Geological Society, London, Special Publications, **363**, 449–470.
- Casey, M. & Butler, R.W.H. 2004. Modelling approaches to understanding fold development: implications for hydrocarbon reservoirs. *Marine and Petroleum Geology*, **21**, 933–946.
- Catalano, R., Valenti, V., *et al.* 2013. Sicily’s fold–thrust belt and slab roll-back: The S.I.R.I.PRO. seismic crustal transect. *Journal of the Geological Society, London*, **170**, 451–464.
- Costa, E., Camerlenghi, A., *et al.* 2004. Modelling deformation and salt tectonics in the eastern Mediterranean Ridge accretionary prism. *Geological Society of America Bulletin*, **116**, 880–894.
- Decima, D. & Wezel, F.C. 1973. Late Miocene evaporites of the central Sicilian Basin, Italy. Initial Reports of the Deep Sea Drilling Project, **13**, 1234–1241.
- Decima, D., Bommarito, S., La Rosa, N. & Aiello, R. 1972. *Foglio 636, Agrigento 1:50,000*. Carta Geologica d’Italia, Servizio Geologico d’Italia, Rome.
- Fiduk, J.C. & Rowan, M.G., 2012. Analysis of folding and deformation within layered evaporites in Blocks BM-S-8 and -9, Santos Basin, Brazil. In: Alsop, G.I., Archer, S.G., Hartley, A.J., Grant, N.T. & Hodgkinson, R. (eds) *Salt Tectonics, Sediments and Prospectivity*. Geological Society, London, Special Publications, **363**, 471–487.
- Ghissetti, F.C., Gorman, A.R., Grasso, M. & Vezzani, L. 2009. Imprint of foreland structure on the deformation of a thrust sheet: The Plio-Pleistocene Gela Nappe (southern Sicily, Italy). *Tectonics*, **28**, TC4015, <http://dx.doi.org/10.1029/2008TC002385>.
- Grasso, M. & Pedley, H.M. 1988. The sedimentology and development of Terravecchia Formation carbonates (Upper Miocene) of North Central Sicily: possible eustatic influence on facies development. *Sedimentary Geology*, **57**, 131–149.
- Gugliotta, C. 2012. Inner vs outer wedge-top depozone ‘sequences’ in the Late Miocene (late Tortonian–early Messinian) Sicilian Foreland Basin system; new data from the Terravecchia Formation of NW Sicily. *Journal of Geodynamics*, **55**, 41–56.
- Handin, J. & Hager, R.V. 1957. Experimental deformation of sedimentary rocks under confining pressure: Tests at room temperature on dry samples. *AAPG Bulletin*, **41**, 1–50.
- Hersey, J.B., 1965. Sedimentary basins of the Mediterranean Sea. In: Whitard, W.F. & Bradshaw, W. (eds) *Submarine Geology and Geophysics*.

- Proceedings of the 17th Symposium of the Colston Research Society, London*. Butterworths, London, 75–91.
- Hieke, W., Camerlenghi, A., *et al.* 2009. Bannock Basin, Sirte Abyssal Plain and Conrad Spur: Structural relationships between Mediterranean Ridge and its western foreland and implications on the character of the accretionary complex (eastern Mediterranean). *Marine Geophysical Letters*, **30**, 161–192.
- Hsü, K.J. & Cita, M.B. 1973. The origin of the Mediterranean Evaporite. Initial Reports of the Deep Sea Drilling Project, **13**, 1203–1231.
- Hudec, M.R. & Jackson, M.P.A. 2007. Terra infirma: Understanding salt tectonics. *Earth-Science Reviews*, **81**, 1–28.
- Jackson, M.P.A. & Vendeville, B.C. 1994. Regional extension as a geologic trigger for diapirism. *Geological Society of America Bulletin*, **106**, 57–73.
- Jackson, M.P.A., Roberts, D.G., & Snelson, S., (eds) 1995. *Salt Tectonics: A Global Perspective*. American Association of Petroleum Geologists, Memoirs, **65**.
- Jones, R.E. & Grasso, M. 1997. Palaeotectonics and sediment dispersal pathways in north–central Sicily during the Late Tortonian. *Studi Geologici Camerti, Volume Speciale*, **2**, 279–291.
- Kouwenhoven, T.J., Hilgen, F.J. & van der Zwann, G.J. 2003. Late Tortonian–early Messinian stepwise disruption of the Mediterranean–Atlantic connections: constraints from benthic foraminiferal and geochemical data. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **198**, 303–319.
- Lentini, F., Catalano, S. & Carbone, S. 1996. The external thrust system in southern Italy: a target for petroleum exploration. *Petroleum Geoscience*, **2**, 333–342.
- Lickorish, W.H., Grasso, M., Butler, R.W.H., Argnani, A. & Maniscalco, R. 1999. Structural styles and regional tectonic setting of the ‘Gela Nappe’ and frontal part of the Maghrebian thrust belt in Sicily. *Tectonics*, **18**, 655–668.
- Londeix, L., Benzakour, M., Suc, J.-P. & Turon, J.-L. 2007. Messinian palaeoenvironments and hydrology in Sicily (Italy): the dinoflagellate cyst record. *Geobios*, **40**, 233–250.
- Lugli, S., Schreiber, B.C. & Triberti, B. 1999. Giant polygons in the Realmonte mine (Agrigento, Sicily): Evidence for the desiccation of a Messinian halite basin. *Journal of Sedimentary Research*, **69**, 764–771.
- Maniscalco, R., De Guidi, G., Pedley, H.M., Sturiale, G. & Grasso, M. 2010. Geological map of the Corvillo and Mandre Basins (Caltanissetta Basin, Central Sicily): Explanatory notes. *Italian Journal of Geoscience*, **129**, 316–326.
- Manzi, V., Lugli, S., Roveri, M. & Schreiber, B.C. 2009. A new facies model for the Upper Gypsum of Sicily (Italy): Chronological and palaeontological constraints for the Messinian salinity crisis in the Mediterranean. *Sedimentology*, **56**, 1937–1960.
- Minelli, L. & Faccenna, C. 2010. Evolution of the Calabrian accretionary wedge (central Mediterranean). *Tectonics*, **29**, TC4004, <http://dx.doi.org/10.1029/2009TC002562>.
- Ogniben, L. 1957. Petrografia della Serie Solfifera Siciliana e considerazioni geologiche relative. *Memorie Descrittive della Carta Geologica d'Italia*, **22**, 275pp.
- Olgaard, D.L., Ko, S.C. & Wong, T.F. 1995. Deformation and pore pressure in dehydrating gypsum under transiently drained conditions. *Tectonophysics*, **245**, 237–248.
- Pedley, H.M. & Grasso, M. 1993. Sedimentology and palaeoenvironment of the Tripoli and Calcare di Base Formations. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **105**, 337–360.
- Pedley, H.M. & Maniscalco, R. 1999. Lithofacies and faunal succession (faunal phase analysis) as a tool in unravelling climatic and tectonic signals in marginal basins; Messinian (Miocene), Sicily. *Journal of the Geological Society, London*, **156**, 855–863.
- Pedley, H.M., Grasso, M., Maniscalco, R. & Esu, D. 2007. The Monte Carrubba Formation (Messinian, Sicily) and its correlatives: New light on basin-wide processes controlling sediment and biota distributions during the Palaeomediterranean–Mediterranean transition. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **253**, 363–384.
- Roveri, M., Lugli, S., Manzi, V. & Schreiber, B.C. 2008. The Messinian Sicilian stratigraphy revisited: New insights for the Messinian salinity crisis. *Terra Nova*, **20**, 483–488.
- Sartori, R. 2003. The Tyrrhenian back-arc basin and subduction of the Ionian lithosphere. *Episodes, Journal of International Geoscience*, **26**, 217–221.
- Sturiale, G., Maniscalco, R., De Guidi, G., Pedley, H.M. & Grasso, M. 2010. *Carta Geologica dei Bacini di Corvillo e Mandre (Sicilia Centrale at 1:50.000)*. Società Elaborazioni Cartografiche, Firenze.
- Tay, P.L., Lonergan, L., Warner, M. & Jones, K.A. & IMERSE Working Group 2002. Seismic investigation of thick evaporite deposits on the central and inner unit of the Mediterranean Ridge accretionary complex. *Marine Geology*, **186**, 167–194.
- Valenti, V. 2010. Shallow structures at the outer Calabrian accretionary wedge (NW Ionian Sea): New insights from recently migrated reflection data. *Terra Nova*, **22**, 453–462.
- Zecchin, M., Civile, D., Caffau, M., Muto, F., Di Stefano, A., Maniscalco, R. & Critelli, S. 2013. The Messinian succession of the Crotona Basin (southern Italy) I: Stratigraphic architecture reconstructed by seismic and well data. *Marine and Petroleum Geology*, **48**, 455–473.