I| DECLARATION OF ORIGINALITY

I declare that this thesis entitled:

STRATIGRAPHY AND STRUCTURAL EVOLUTION OF THE MESSINIAN EVAPORITE COMPLEX IN THE EASTERN MEDITERRANEAN...

...is my own research under the supervision of Prof. Alastair J. Fraser and Dr. Christopher A.-L. Jackson. The research was carried out in the Department of Earth Science and Engineering at Imperial College London. All material used in this thesis has been given full acknowledgement. None of the work has previously been submitted to this or any other academic institution for a degree or diploma, or any other qualification.

Signed,

HAYLEY ALLEN (23.06.2014)
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V | ABSTRACT

The offshore Eastern Mediterranean constitutes an area of c. 250,000 km\(^2\) and is located on the northern margin of the subducting African plate. It is a region of numerous tectonic domains that have resulted in a complex, high-relief crustal structure of sub-basins and highs. Superimposed on this complicated structural framework and Mesozoic-Cenozoic sedimentary fill is a vast salt succession, which we term the Messinian Evaporite Complex (MEC), that is locally >3 km thick and has a total volume of ~1 million km\(^3\). The evaporites were deposited between c. 5.96-5.33 Ma as a result of the Messinian Salinity Crisis, a major evaporitic drawdown event affecting the Mediterranean basins, resulting in the deposition of this vast salt deposit in the deep basins and widespread incision at the margins.

The overwhelming majority of previous research conducted on the MEC has focused on isolated outcrop or sub-surface studies from relatively marginal settings, despite the fact that much of the salt sits out in the deep basin. This has led to confused stratigraphic schemes and much debate over the origin, extent and timeframe for the deposition of the MEC.

This thesis aims to progress understanding of the structural and stratigraphic development of the MEC in the deep basin by utilizing regional 2D seismic surveys and a high-resolution 3D seismic cube (covering a total area of c. 180,000 km\(^2\)) underpinned by marginal well data to perform comprehensive seismic facies and structural analyses of evaporites across the eastern Mediterranean sub-basins.

For the first time in the literature, we present systematic interpretations of the variability of seismic facies and structural styles of the MEC at a regional scale across the Eastern Mediterranean. Our research has revealed a thick succession of up to seven alternating high to low amplitude, laterally persistent seismic sequences in the Levantine Basin, which display high levels of internal deformation. These stacked sequences pass abruptly into an evaporite interval dominated by
transparent seismic facies, with high levels of mobility, producing classical salt-tectonic structures affecting both the salt and overburden in the Herodotus Basin. A series of structural domains have also been identified that are related to on-going, thick-skinned, collisional tectonics in the region and thin-skinned, gravity processes associated with the Nile Delta and Levant margin.

The project therefore offers a unique opportunity to study the impact of major sea-level fall on facies and depositional patterns during the early stage tectono-stratigraphic evolution of a saline giant. This has led us to propose new models for the stratigraphic and structural development of the region, and poses new questions regarding the effect of these facies variations on calculated velocities and therefore, depth migration and conversion attempts.

The relative youth of this saline giant makes it an excellent natural laboratory, offering exciting new insights into the structural and stratigraphic complexity of evaporite-bearing successions. In terms of its youth and depositional timeframe, the MEC is unique, although the processes we document here may be applicable to other salt-bearing sedimentary basins worldwide.
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The last thirty years have seen significant advancement in our understanding of salt tectonic processes, with over half the total number of publications on the subject being written since 1990 (Hudec and Jackson, 2007). This is largely a consequence of more sophisticated geophysical data acquisition and processing techniques that have allowed petroleum industries to pursue exploration opportunities in progressively deeper-water settings. As a by-product, academic research has benefitted from an influx of high-quality 2D and 3D seismic datasets that have increasingly emphasised the influence of salt on the structural and stratigraphic development of sedimentary basins and therefore, the petroleum systems within them (e.g. Jenyon, 1986; Jackson & Talbot, 1991; Jackson et al., 1994; Stewart & Coward, 1995; Jackson et al., 1996; Spathopoulos, 1996; Ge et al., 1997; Hudec & Jackson, 2007; Brun & Fort, 2011; Alsop, 2012; Rowan, 2014).

Salt-involved margins often display higher levels of deformation when compared to their salt-free counterparts, with increased up-dip extension and down-dip shortening (e.g. Jackson and Vendeville, 1994, 1997; Hudec and Jackson, 2007; Loncke et al., 2006; Brun and Fort, 2011). This is primarily due to the distinct difference in the mechanical properties of salt compared to the rocks that surround it in a typical sedimentary basin fill. Over geological time scales and under relatively modest strain rates, salt flows like a fluid in the subsurface and at the free surface (i.e. seabed) (Hudec & Jackson, 2007). Salt flow can either be initiated through tectonic forces (gravity gliding) or differential load-driven (gravity spreading) processes (sensu. De Jong & Scholten, 1973; Jackson & Talbot, 1991). This susceptibility to flow and therefore, intense deformation, means that salt is typically seismically transparent, thus reflection-free and notoriously difficult to image internally. However, on occasion, salt bodies can display lithological heterogeneities that enable interpretation of laterally continuous reflections, which act as key markers for deformation styles and intensity. These
exceptions include the Aptian Ariri Formation Santos Basin, offshore Brazil (Cobbold et al., 1995; Fiduk and Rowan, 2012; Jackson et al., 2014); The Permian Zechstein Group, NW Europe (Van-Gent et al., 2011; Strozyk et al., 2012), and the Late Miocene (Messinian) Evaporite Complex (MEC), offshore Eastern Mediterranean (Bertoni and Cartwright, 2006; Cartwright et al., 2012; Allen et al., 2014).

This thesis centres around the aforementioned MEC in the offshore Eastern Mediterranean basins; a rare example of an ancient saline giant where, in places, the exquisite preservation of intra-salt reflections permits spectacular imaging of the complex structural styles that have occurred as a result of salt flow. The MEC was deposited as a result of the Late Miocene (Messinian) Salinity Crisis (MSC, 5.96-5.33 Ma), a major drawdown event triggered primarily by the temporary closure of the marine gateway with the Atlantic Ocean, which was, and is still, located at the Straits of Gibraltar. Consequently, the Mediterranean Sea experienced almost total desiccation, initiating widespread canyon incision at the basin margin and the deposition of a vast (up to 3 km thick, c. 1 x 10⁶ km³ in volume) salt giant (sensu Hűbscher et al., 2007) in the deep basin (Hsü et al., 1973; Ryan and Cita, 1978; CIESM, 2008).

Although the MEC has undergone numerous studies and stratigraphic models are well established for certain areas, there are still clear disparities within the data. At present, the majority of previous research has focussed on outcrops or shallow, marginal basins such as those in southern France, Spain, Italy and Cyprus (e.g. Savoye and Piper, 1991; Riding et al., 1998; Roveri et al., 2001; Orszag-Sperber et al., 2009), despite the fact that the majority of the salt is preserved in the deep basin. Additionally, the aforementioned studies show a tendency to overlook the regional perspective, favouring instead, a focused approach within individual sub-basins or localised outcrops. This has led to confused stratigraphic schemes and much debate over the origin, nature of onset, timing and composition of this unique saline giant.
Furthermore, these marginal deposits are likely to pre-date or post-date the major drawdown and are therefore, are not age-equivalent to the deep basin evaporite deposition. Consequently, there is an underrepresentation of the deep basin evaporite series in the literature, from both a localised and regional standpoint. This is largely due to the lack of direct and/or complete subsurface calibration, thus broad, regional, seismic studies coupled with the minimal, but crucial marginal well data available, offer the best opportunity to bridge the gap in knowledge between the marginal and deep basin characterisation of the MEC until such a time when the complete successions are drilled. The relative youth and shallow burial of the Messinian saline giant is a crucial aspect that enables such detailed mapping of the structural and compositional variability of this enigmatic salt province, thereby offering a valuable window into its early-stage depositional and deformational development that may be applicable to other saline giants worldwide.

1.2 Aims

A key aim of this thesis is to evaluate and incorporate our observations of evaporite seismic stratigraphy and salt-related structural styles, into existing conceptual models relating to; (i) the stratigraphic and structural development of the Messinian Salinity Crisis; and (ii) the triggers, drivers and mechanics of prolonged salt tectonics. We also attempt to answer pertinent questions regarding the stratigraphic and structural development of the Messinian saline giant. Specifically, this thesis aims to further the understanding of:

- The spatial and temporal distribution of Messinian seismic facies across the eastern Mediterranean sub-basins
- The local and regional controls in terms of tectonics and climate on the observed seismic facies distributions.
• The variability and controls of salt-related structural styles across the eastern Mediterranean sub-basins (i.e. Nile/Herodotus and Levantine Basins).

1.3 Thesis Overview and Structure

This thesis investigates the seismic facies and structural styles of the Messinian evaporite complex of the Eastern Mediterranean using a combination of 2D/3D seismic, well, borehole and outcrop data from a c 180,000 km² study area in the eastern Mediterranean. The thesis is divided into seven chapters. Chapter one provides a general introduction to the topic under investigation. It also serves to outline the rationale and specific research aims. Chapter two reviews literature on key themes and summarises relevant concepts to provide a context for the following results chapters. The main body of original research is presented in chapters three, four and five as three standalone, but closely linked journal style articles. Chapter six synthesises the findings of the preceding results chapters, highlighting the over-arching narrative to the work and the wider implications envisaged, before chapter seven concludes with the main findings from each of the preceding results chapters.

1.4. Publication/submission status and contribution from co-authors

Chapters three and four and five are presented as stand-alone journal-style manuscripts in this thesis. These are yet to be submitted for publication. Chapter five is presented as a case study based on work initially carried out by Miss Dana Tolessin; an Imperial College MSc Petroleum Geoscience student under my co-supervision with Prof. Alastair Fraser (Imperial College) and external collaborators Andrei Belopolsky and Matthew Plummer of Premier Oil, London. The author of this thesis is the first author on the chapter three, four and five manuscripts, and is responsible for all the observations, interpretations and discussions presented therein. Contributions to primary observations and interpretations
in the case study presented in chapter five were made by Miss Tolessin and are referenced appropriately.
1.5 References


2. |CHAPTER TWO | LITERATURE OVERVIEW
(i) Foreword:

This chapter aims to synthesise the key literature and models pertinent to this thesis in order to provide a context for the subsequent chapters. An emphasis is placed upon the general development of a saline giant and how the Messinian Saline giant remains a unique example. We also outline the importance of studying such environments from both an academic and applied perspective. Additional background, focused specifically at research aims, is presented in chapters 3, 4 and 5. The review is divided into four sections, which address: i) marine saline giants worldwide; ii) the importance of studying these environments; iii) The Messinian Salinity Crisis (MSC) and Messinian Evaporite Complex (MEC) of the eastern Mediterranean; and iv) key regional discrepancies to be addressed.

2.1. Marine Saline Giants

The successful precipitation of an evaporite deposit requires the liquid water loss from a brine mass to exceed inflow rates and the driving force behind this concentration process should be solar evaporation (Warren, 2010). With this in mind, there are certain areas of the world that we would expect to see such deposits such as the discrete climatic belts where global evaporation rates are at their highest. These are known as the ‘horse latitudes’ and they lie roughly 30° either side of the Equator where cold, dry air descends within the Hadley circulation cells to create arid and semi-arid conditions (Hudec and Jackson, 2007). Over oceans, these latitudes correspond to areas of maximum evaporation whilst over land they sit above many of the world’s great deserts. With the exception of a few localised examples, this is indeed where evaporite deposits have formed in the past and are forming present day.

Although evaporite basins can form in both marine and continental settings, this review will focus on marine fed, basin-wide evaporite systems, which are typically dominated
by thick halite and anhydrite successions (i.e. >1km) along with varying amounts of evaporitic carbonates and potash deposits. The latter is dependent on the severity of saline concentration taking place within the basin and the chemical composition of the original water that supplied it (Warren, 2010).

Evaporite basins typically show an ‘ideal’ sequence of evaporite deposition (sensu. Richter-Bernburg, 1955 as cited in Taylor, 1990). This reflects the lithological changes that occur in response to progressive evaporation as a basin undergoes prolonged restriction and thereby increasing salinity. It begins with a thin clastic member, passing upwards through limestone, dolomite, anhydrite, and halite; culminating with the highly soluble magnesium and potassium (bittern) salts (Fig. 2.1) This simplistic model offers a useful framework for interpretation, but in reality these environments are likely to be more complex due to the interplay between changing climate, run-off, oceanic exchange, water depth, sedimentation rate and subsidence (Taylor, 1990)

There are many examples preserved in the geological record of extremely thick basin centre evaporite deposits that occupied extensive areas at various times throughout the past; known as ‘saline giants’ (sensu. Hübscher et al., 2007), their deposition would require severe restriction to total isolation from the open ocean and are therefore, thought to be the result of the juxtaposition of favourable eustatic, climatic and tectonic conditions (Warren, 2010). In the case of the Zechstein Supergroup, the basin centre evaporitic cycles that accumulated over the last 5 million years of the Permian, reached thicknesses in excess of 1500m (Olsen, 1987).

At the other end of the time spectrum, the youngest saline giant deposits constitute the various Messinian basins of the Mediterranean region. The gradual restriction and isolation of the Mediterranean that led to the Messinian Salinity Crisis was predominantly under a tectonic control (Sierro et al., 1999) following the temporary closure of the Gibraltar
Straits. This led to a dramatic drawdown and the deposition of an evaporite body with a volume of approximately 1 million km$^3$ (Ryan, 2009) and halite successions alone exceed 1km vertical thickness in the deepest parts of the basins (Ryan and Cita, 1978).

**Figure 2.1:** Model of ‘Bull’s-eye’ evaporite deposition in a basin experiencing total isolation. The concentric pattern of deposition represents increasing restriction and therefore salinities toward the basin centre. Note the severity of concentration required for bittern deposition, which have been sampled in Sicily. (NMSC = Normal Marine Seawater Concentrations). Modified from: Taylor. (1990) and Hsü et al. (1973a)

The Zechstein and Messinian basins share certain similarities regarding their scale (in terms of salt volume and area) and composition of their evaporite facies. However, whilst the Zechstein cycles accumulated over millions of years, the deeper Messinian basins filled within a maximum time interval of 300 kyrs (Zharkov and Yanshin, 1981; Krijgsman et al., 1999). This implies that the development of the Messinian saline giant was more complex, involving a number of factors including fluctuations of the circum-Mediterranean climate and glacio-eustatic influences in the early stages of the crisis (Rouchy and Caruso, 2006). For example,
Hodell et al., (2001) document the increase in volume of the Antarctic ice cap during the Late Messinian which lowered world sea level and may have influenced the restriction of the Mediterranean prior to the total isolation at the Gibraltar Straits.

One of the greatest remaining challenges faced in interpreting these environments is the lack of any modern day counterparts. These ancient examples of saline giants are several orders of magnitude larger than any modern day evaporitic basin (Fig. 2.2). There is no single scenario that promotes the development of a saline giant, but as aforementioned, they require the alignment of many inter-related factors that, for one reason or another, do not exist on the Earth’s surface today. For example, many of the larger examples of saline giants accumulated at times of high continent-continent proximity such as the accretion and disaggregation of super-continents. The largest modern day example of a marine fed evaporite system is Lake Macleod, Western Australia with an area of 2066 km² and a maximum halite and gypsum thickness of just 12 m (Warren, 2010). Today global tectonics are relatively quiescent and our continents dispersed so any attempt at interpretation of ancient saline giants is largely speculative, thus we cannot rely on modern analogues alone.

2.2 Importance of Studying Marine Saline Giants

Prior to the 1990’s, salt tectonics received limited attention as data quality was often poor and salt is notoriously difficult to interpret seismically. More recently, significant advances in geophysical processing techniques have resulted in much higher data quality, which allows petroleum companies to pursue exploration opportunities in progressively deeper water settings. This influx of new and improved seismic data has put salt in the spotlight and of the 5500+ publications on topic, over half were written post 1990 (Hudec & Jackson, 2007).
Saline giants have formed in a variety of tectonic settings from craton to passive margin (Figure 2.3) and this exerts a fundamental control on the resultant evaporite stratigraphies and structural styles and subsequent deformation observed within them. Salt containing basins tend to show a much greater degree of deformation and lateral variation in

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**Figure 2.2**: Comparison of ancient saline giant with modern day examples of evaporite basins drawn to the same scale. Ancient examples, clockwise: Cretaceous Santos and Campos saline giant, Offshore Brazil; Permian Zechstein saline giant, Northern Europe; Neogene Eastern Mediterranean, Ionian and Balearic Saline giants, Eastern and Western Mediterranean (Modified from Warren, 2010).
facies distributions owing to the unique mechanical properties of the halite. Salt’s rheology and incompressibility make it inherently unstable under a wide variety of conditions and this makes salt basins an extremely interesting environment to study, both from an applied and academic point of view.

**Figure 2.3:** Saline Giant Tectonic Settings. Variability in tectonic settings for halite-containing saline giants worldwide. (collated and modified from Hudec & Jackson, 2007).

### 2.2.1. Key Applied Implications

- Salt exerts a strong influence on almost all aspects of a developing petroleum system, largely due to its relative mechanical weakness, which over geological timescales means that salt deforms visco-elastically and begins to flow (Hudec & Jackson, 2007). This is either initiated through tectonic forces or gravity driven processes. As a result, salt can quickly compartmentalise a basin, becoming a strong controller of reservoir distribution and structural trap formation as well as providing an effective seal to migrating hydrocarbons.

- Salt is also an effective thermal conductor thus, around a salt body, the geothermal gradient shallows promoting maturation of overlying rock units but cooling of sub-salt
lithologies (Hudec & Jackson, 2007). Consequently, sub-salt rocks need to be buried deeper in order to enter the ‘petroleum kitchen’ where heat flow is optimum for the essential maturation of potential hydrocarbon bearing rock units. An understanding of salt tectonics is therefore essential for effective hydrocarbon exploration in salt-containing basins.

2.2.2. Key Academic Implications

• Salt’s capacity to deform relatively easily makes it a very sensitive strain gauge, which is particularly useful for recording the growth histories of salt structures and thus, the evolution of salt-containing passive margins or compressional systems. Such studies have been carried out in the Nordkapp Basin (Nilsen et al., 1995), offshore Angola (Hudec and Jackson, 2007); Santos basin, Brazil (Jackson et al., 2014) and the Levantine Basin (Cartwright et al., 2012)

• A salt layer often deforms independently from surrounding lithologies, which serves to decouple the structural styles of sub, intra and suprasalt layers. Typically, the upper and lower boundaries of the salt body act as decollement surfaces along which, gravitational mass transport processes and raft tectonics can occur in the suprasalt sections.

• Studying salt/sediment/fault interactions through processes such as diapirism and salt withdrawal can not only help forward understanding in salt tectonics but also other areas of research such as shale tectonics (e.g. Cohen and McClay, 1996; Morley and Guerin, 1996), or even, extra-terrestrial geology (e.g. Schenk and Jackson, 1993).

• The relative fluidity of salt means that new accommodation space is constantly being created, allowing stratigraphers to analyse basin fills in high resolution thus
monitoring the relationship between tectonics, sea level change and facies distributions (Beaubouef and Friedmann, 2000).

2.3. Messinian Salinity Crisis: Controversy to (near) Consensus

2.3.1 Tectonic Evolution of the Eastern Mediterranean Basin

The offshore Eastern Mediterranean forms the focus of this study and occupies an area of c. 180,000 km² (Fig. 2.4). The area is tectonically complex, characterised by an intricate mosaic of active, thick-skinned, crustal-scale structures formed in response to the on-going collision between the African and Eurasian plates (Mascle et al., 2000; McClusky et al., 2000; Robertson and Mountrakis, 2006).

The Eastern Mediterranean initially formed in the Early Mesozoic, along the northern passive margin of Gondwana, and it is widely accepted to represent a relic of the Mesozoic Neotethys Ocean (Robertson and Dixon, 1984; Garfunkel, 1998). Remnants of this oceanic crust are still preserved in the deepest parts of the Ionian, Herodotus and Levantine basins.

Since the Middle to Late Cretaceous, northward movement of Africa has progressively isolated the Mediterranean Sea in a largely compressional setting. However, Cenozoic tectonics have modified this overall compressional setting to create domains of extension and transpression. Notable examples include the reworking of Alpine orogenic belts, which led to back-arc extension and seafloor spreading in both the Aegean and Tyrrhenian Seas (Avigad et al., 1997). This has sufficiently thinned the crust to allow the development of new Miocene-Pliocene oceanic crust in the Tyrrhenian Sea. Areas of strike-slip and transpressive motions are observed along the DSTZ as the rotating Arabian plate interacts with Africa and Eurasia.
Figure 2.4: Base map illustrating the confining structural elements affecting the Messinian salt basins under investigation in this study (The Herodotus and Levantine specifically) and furthermore, how deformation is transmitted through the salt and overburden; areas with no colour indicate undeformed strata - i.e. a translational province. (see inset for continental context of the study area). Base map generated using GeoMapApp. (2012). Structural trends compiled after McCluskey et al. (2000); Abdel Aal et al. (2000); Robertson & Mountrakis. (2006); Loncke et al. (2006) and Gardosh et al. (2008).

2.3.2 Discovery and Early Hypotheses

During the late Miocene ‘Messinian Salinity Crisis’ (MSC), an unprecedented evaporitic sea level drawdown affected the Mediterranean Basins (Hsu et al., 1973). This event
constitutes one of the most dramatic hydrological episodes to affect the Earth during the Cainozoic and is thought to have been caused, at least in part, by the closure of the marine gateway to the Atlantic Ocean at the Gibraltar Straits (CIESM, 2008). The drawdown resulted in extensive erosion and incision of the Mediterranean margins and the accumulation of a thick evaporite succession within the deep basins. The event culminated with the restoration of normal marine conditions after a period of just 630 kyrs between 5.96-5.33 ma (Krijgsman et al, 1999).

Early seismic reflection profiles taken across the Mediterranean (Hersey, 1965) revealed a regionally correlative and prominent reflection event later termed the ‘M reflector’\(^1\) (Ryan, 1969; Ryan, 1973; Ryan and Cita, 1978; Hsü et al., 1973a) as well as distinctive diapiric structures, thus the discovery of evaporites in the first DSDP expedition to the region in 1970 was not unexpected. However, a later DSDP expedition (leg 13, 1973) recognised their true extent and thickness and recovered cores containing dolomite, gypsum, anhydrite and halite from numerous locations across the region (Hsu et al, 1973, Ryan, 2009). It soon became clear that a vast salt layer, varying in thickness from 1500-3000 m and covering an area of approximately 1 million km\(^3\) had been laid down across the whole Mediterranean basin at the end of the Miocene (CIESM, 2008, Figure 2.5).

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\(^1\) The ‘M’ reflector was the first name assigned to the regionally correlatable unconformity that led to the proposition of a major drawdown event, and thus the MSC. However, the complexity of this surface and the numerous studies on the MSC over the years has meant that the name given differs depending on the author and their interpretation of it. Other popular names are the Messinian/Marginal/Top erosional surface. In an attempt to synthesise and produce a global and coherent terminology for the crisis, the CIESM meeting in 2007 use the term ‘Intra Messinian Unconformity’ (IMU). We use the original term ‘M reflection’ in this thesis though this is a term largely reserved for use in marginal settings.
Following the discovery of this saline giant, considerable debate ensued prompting the presentation of numerous and highly varied scenarios all with the aim of defining the origin, spatial extent and the timeframe of deposition for the evaporites. The following sections will discuss some of the key scenarios and follow their progression to the near consensus model that exists today regarding what is widely accepted, but equally, where the gaps in our knowledge still exist.

The earliest proposals focussed around two main hypotheses: 1) The ‘deep-water, deep basin’ model (Schmalz, 1969) assumes deposition took place in a deep-water setting where the Mediterranean did not experience total isolation but marine circulation was severely restricted due to a shallow sill. Eventually, carbonates, sulphates, and halite were crystallized out of brine and accumulated on the deep basin floor. 2) The ‘shallow water desiccated basin’ model (Nesteroff, 1973). This model suggests that a shallow, rapidly
subsiding basin was able to create accommodation for shallow-water to supra-tidal evaporite accumulation.

However, these initial scenarios failed to take into account discoveries made in the late 1950’s and early 1960’s of age-equivalent, deeply incised valleys (≥ 1km) on the basin margins. These ancient drainage networks were recognised in various places around the Mediterranean, including Egypt, Libya and France, with knickpoints located up to 300 km inland of the present Mediterranean coast (Loget et al., 2006). This led to the proposition of the third, and widely accepted model of the ‘deep, desiccated basin’ (Hsü and Cita, 1973). This model envisages a pre-existing deep basin that underwent temporary isolation from normal marine oceanic circulation systems resulting in a dramatic sea-level drawdown of at least 1500 m, widespread canyon incision at the basin margins and the deposition of shallow-water to hyper-saline facies in the deepest parts of the basin (Fig. 2.6).

2.3.3 Drawdown Models

In the years following Hsu’s early model, significant developments were made in the understanding of Messinian palaeoclimate in the Sicily region (e.g. Suc and Bessais, 1990) along with detailed biostratigraphy and magnetostratigraphy of the Messinian evaporites (Colalongo et al., 1979; Gautier et al., 1994). The majority of researchers remained broadly in favour of the Hsu and Cita (1973) ‘deep desiccated basin’ model for total basin isolation with much of the basin fill accumulating during the post-drawdown transgressive phase (Rouchy and Caruso, 2006). However, debate was renewed in the late 1990’s following the production of a very accurate astronomically calibrated timescale (Krijgsman et al, 1999). This led to the proposal of new models that rejuvenated and modified the classic model of Hsü et al. (1973a) and Hsü et al. (1973b) to answer pertinent questions related to timing, the nature of onset and the extent of drawdown.
**Fig. 2.6:** Schematic diagram of sedimentary, hydrological, and erosional processes in an evolving evaporitic basin. This is based on the widely accepted ‘deep desiccated basin’ filling model where much of the evaporite fill in the deep basins accumulated during the transgressive phase following the major drawdown event of 5.6ma. (a) Phase 1: Initial drawdown. Marginal erosion follows the increasingly saline brine down into the basin. At 5-6 times normal marine seawater concentrations of salt, gypsum deposition commences along the margin of deep basins. The previously deposited marginal marine sediments, e.g., the carbonate platforms are sub-aerially exposed and eroded. (b) Phase 2: cycles of marine influx and evaporative drawdown lead to salt accretion and the periodic deposition of the Lago Mare in phase 3. As salt deposition progresses, halite onlaps the earlier gypsum deposits and eventually fills the deep basins. (C) Regional relationships between the three depositional phases of the MSC and key erosional surfaces. Seismic horizon M is an erosional surface seen truncating the margins surrounding the Mediterranean. (After Rouchy and Caruso, 2006; (Fiduk, 2009); Hsu & Cita, 1973).

One of the key areas of debate exists around the timing and nature of onset for evaporite deposition. Fig. 2.7 summarises the key scenarios, which historically, were divided into two main groups; those that propose a synchronous onset and those that argue in favour
of a diachronous onset. The principal differences between the models are that Butler et al. (1995); Clauzon et al. (1996); Riding et al. (1998) (a, b, and c), all propose a diachronous onset, with evaporite deposition occurring firstly in marginal basins and later in deeper basins. Whereas Krijgsman et al. (1999) and Rouchy and Caruso. (2006) (d & e) propose that a single evaporite suite was deposited synchronously across margins and deep basins.

Attempting to apply any one of these models to the whole of the Mediterranean presents a problem in that each one was constructed based upon individual and isolated study locations. The complex tectonic configuration of the Mediterranean region often means that where one scenario works, another will not, therefore no single scenario is applicable across the whole Mediterranean region as the expression of the MSC will vary where sub-basins have different initial elevations and depths.

In an attempt to rectify this problem, more recent studies have postulated an integrated scenario, which envisages a largely synchronous onset but different facies associations for marginal and deep basin settings (Rouchy and Caruso, 2006; Roveri and Manzi, 2006; CIESM, 2008); Fig. 2.7 (f) and 2.8)).
2.4 Messinian Stratigraphy

The stratigraphy of this event will be termed the Messinian Evaporite Complex (MEC), and although rare, previous attempts at Mediterranean scale (i.e. multi-site) analysis of the MEC (e.g. CIESM, 2008 and references therein; Lofi et al., 2011) have noted a clear disparity between the thickness and stratigraphic architecture of the deep basin MEC in the offshore western Mediterranean compared to that of the offshore eastern Mediterranean.

In the west, the Messinian subsurface expression largely adheres to a well-established trilogy commonly referred to as the Lower Unit (LU), Mobile Unit (MU) and Upper Unit (UU) (Montadert et al., 1970; Lofi et al., 2011), which are thought to represent aggrading facies, delineating an idealised, single cycle of evaporite deposition; i.e. the onset, acme, and cessation of the MSC respectively (Rehault et al., 1984). In the eastern Mediterranean, this tripartite division is not recognised. The LU and UU are presumed to be absent or post-
depositionally removed, with the succession characterised by a thicker, multi-layered MU, of predominantly halite composition (Bertoni & Cartwright, 2006; Netzeband et al., 2006; Hübscher et al., 2007).

### 2.4.1 Western Mediterranean Stratigraphy

The Western basin is generally recognised to consist of the phases and lithologies summarised in figure 2.8 and described in detail in sections 2.4.1.1-2.4.1.4.

#### 2.4.1.1 Pre-cursor Unit. (PcU) ~7.2-5.96 Ma

There is a good deal of evidence to suggest that the initial restriction of the Mediterranean basin was a gradual process, which began well in advance of the onset of the MSC proper (i.e. prior to total tectonic isolation). Deposition of diatomites and black shales as well as faunal and isotopic changes began as early as 7.2 Ma in the deeper basins (Kouwenhoven et al., 2003). A later study by Kouwenhoven et al. (2006) revealed a marked transition to a more adverse environment occurred ~ 6.7 Ma when a dominance of microfossils typical of low oxygen conditions (brought about by stagnation and hyper-salinity) were sampled in the Pissouri Section, Cyprus. This progressive shift to more mono-specific assemblages within microfossil groups continued and results indicated that severely stressed environments existed after ~6.4 Ma.

#### 2.4.1.2 Lower Evaporites and Primary Lower Gypsums (PLG) ~5.96-5.6 Ma

The Lower Evaporite unit is thought to represent the onset of the Messinian Salinity Crisis. At 5.96 Ma the deposition of Primary Lower Gypsums (PLG) largely consisting of selenites is thought to have taken place across the Mediterranean region in a variety of geological settings. These include the perched wedge-top basins of the Maghrebian Chain (Butler et al., 1995) the pull-apart basins of the Betic Cordillera such as the Nijar Basin,
Figure 2.8: Stratigraphic model for Messinian Salinity Crisis based on the general consensus regarding timing, nature of onset and recognised phases of evaporite deposition. The model highlights the proposed spatial and temporal facies variations from margin to deep basin (Modified from CIESM, 2008). Note: the side column which contains names for units proposed to be the deep basin seismic counterparts as correlated by Lofi et al., 2005; Lofi et al., 2011). It should once again be stressed that this model is constructed largely on the basis of marginal outcrop studies with the assumption that the succession of ‘deep basin’ evaporites on Sicily is representative of deep basin stratigraphy basinwide.

(Lu, 2006) and in minor outcrops of the Hellenic and Cyprus arcs (e.g. Kontopoulos et al., 1997; Maillard et al., 2011). Selenite commonly precipitates at the bottom of restricted marginal basins less than 200m deep (Lugli et al., 2010). The lack of evidence for sub-aerial exposure and the common facies associations for sections located thousands of kilometres apart indicate a modest depositional depth but not extremely shallow at this stage (CIESM, 2008). Nevertheless, this points towards a significant change in hydrological circulation patterns within the Mediterranean at this time.
The deep basins show little change in lithology from the underlying PcU, which suggests that this still remains a restricted, but largely deep-water marine environment. The PLG unit has an average thickness of 150m but the deep-water counterpart shows more thickness variability ranging from <10-60m (CIESM, 2008). There are 16-17 gypsum cycles within the PLG rhythmically intercalated with shales suggesting periodic changes in salinity that are thought to be related to precession-driven climate changes (Krijgsman et al, 1999). One of the problems we have with interpreting this early stage is that records are likely to have been eroded during the relative sea level fall of the subsequent stage, though there is a possibility that some areas escaped this and if found, could unlock new ideas on chronology of the MSC.

### 2.4.1.3 Resedimented Lower Gypsums (RLG) and Main Salt Unit – ~5.6-5.55 Ma

This phase is characterised by abundant evidence for a major drop in relative sea level within the Mediterranean basin. The drawdown led to the sub-aerial exposure of the PLG’s and the development of new karst systems as well as rejuvenation of older ones of Cretaceous age (Audra et al., 2004). The main valleys were entrenched as canyons and fluvial systems were revived leading to the development of the regionally correlative marginal Intra Messinian Unconformity (IMU). It is fair to say that such a rapid removal of the Mediterranean seawater would have undoubtedly affected the stability of the margins themselves and coupling of this with the erosion evidenced by the IMU, we would expect to see gravitational collapse events and re-sedimentation of marginal evaporites from phase one.

Indeed, this has been suggested more recently for the interpretation of a unit originally believed to represent the deep basin counterpart of the PLG’s of the Lower Evaporites. (Lofi et al., 2005) recognise a unit in the Apennines and Sicily where abrupt activation of turbidity flows are observed. These contain a range of heterogeneous, chaotic
bodies interpreted as resedimented PLG’s of the Lower Evaporite phase delivered to the deep basin through mass gravitational transport mechanisms. This unit is known as the Resedimented Lower Gypsum (RLG) and is therefore a later deposit found intercalated with the basinal halite and not part of the Lower Evaporite sequence. (Roveri et al, 2008). Its thickness varies considerably depending on local basin floor topography but can reach up to 300m (CIESM, 2008).

The Main Salt Unit is particularly impressive as it reaches thicknesses of 1000m and is thought to have accumulated in as little 50kyrs (Roveri et al., 2008; Schreiber and Hsü, 1980). This is in agreement with cyclic depositional studies from (Meijer and Krijgsman, 2005), who suggest that the rhythmic layering of salt/anhydrite/shales represent annual seasonal cycles (i.e. salt in the summer and shales in the winter). Assuming a 10-15 cm cycle thickness, it is plausible that the succession could have been deposited in the timeframe predicted. Also in line with this is the geophysical evidence. The transparent appearance of the salt in seismic suggests it is a ‘clean halite’ with little or no interference from clastic systems further supporting the idea of its rapid deposition (CIESM, 2008).

2.4.1.4 The Upper evaporites and Lago Mare Facies – ~5.55- 5.33 Ma

The Upper evaporites record the gradual return to normal marine conditions and contain a much stronger fresh-water signature. Once again, the topographic and bathymetric relief controls thickness and they range anywhere between 10-1000m (CIESM, 2008). (Roveri et al., 1998) divided the vertical succession into 2 distinct lower and upper units (p-ev1 and p-ev2 respectively). The lower unit (5.55-5.42 Ma) is characterised by primary precipitated gypsums, cyclically inter-bedded with shales. Strontium isotope values are lower in these gypsums indicating a greater freshwater input and similarly, the shales also contain brackish faunas (Lugli et al., 2007).
The upper unit (5.42-5.33 Ma) is dominated by the so-called “Lago- Mare” facies (Orszag-Sperber, 2006; Rouchy and Caruso, 2006). This term is used to describe the brackish to freshwater environment characterized by the reappearance of marine mollusc faunas (“Congeria beds”, or “Melanopsis beds”, (Orszag-Sperber, 2006) in sediments deposited during the final stage of the MSC, immediately prior to Pliocene marine re-flooding. It records the freshwater dilution of this previously desiccated deep basin before the final Pliocene re-flooding. At 5.33 Ma, the ‘Zanclean flood’ event marked the end of the crisis as the Gibraltar Straits were breached and a catastrophic flooding event returned the Mediterranean basin to pre-drawdown salinities (Garcia-Castellanos et al., 2009).

2.4.2 Eastern Mediterranean Stratigraphy.

The stratigraphic model in figure 2.8 attempts to link outcrop stratigraphy with that of the deep basin seismic units identified through subsurface studies. It is generally used as a guide for interpretation basinwide although it has become increasingly apparent that a more complex situation exists and this model cannot be applied to the Eastern Mediterranean. Whilst a clear deep basin stratigraphic trilogy is observed in the western basin; a multi-layered mobile unit, eroded at its top, is observed in the east.

High-resolution 2D and, more recently 3D seismic analysis of the MEC in the Levantine Basin (Eastern Mediterranean) has allowed the distinction between 6 seismic sequences, distinguished from each other by sharp changes from seismically transparent to highly reflective layers (Fig. 2.9). The sequences have a combined thickness of up to 2000 m and are mapable over large areas of the Levantine Basin; Gradmann et al. (2005) (Netzeband et al. (2006); Bertoni and Cartwright. (2005; 2006; 2007); Hübscher et al. (2007); Cartwright et al. (2012); Reiche et al. (2014); Allen et al. (2014. this thesis).
Fig. 2.9: Seismic and line drawing summarising the most up-to-date seismic stratigraphic architecture of the MEC in the Levantine Basin inclusive of nomenclature and divisions proposed from other authors. Intra-salt sequences are labelled ME-I to ME-VI after Netzeband et al. (2006). TES and BES represent the Top and Base Erosional Surfaces respectively (Modified from Reiche et al., 2014). Horizons are labelled ME20 to ME60; M denotes the M-reflection and top of the Messinian evaporites, and N marks the base according to Bertoni and Cartwright (2007). (See Fig. 2.4 for location of regional profile).

Sequences ME-I, ME-II, ME-IV and ME-VI are seismically transparent and presumed to consist predominantly of halite (Bertoni and Cartwright, 2007a; Hübscher and Netzeband, 2007). The high-amplitude units (ME-III and ME-V) have previously been interpreted as interbedded clastics (Garfunkel and Almagor, 1984) and/or sulphate-rich deposits (e.g. Gradmann et al., 2005; Netzeband et al., 2006; Cartwright and Jackson, 2008; Allen et al., chapter three, this thesis), the latter being a typical component of an evaporitic cycle (Warren, 2010). The strong support for the sulphate-rich interpretation is based on: (i) the basin-wide distribution and relatively uniform thickness of the reflective sequences; (ii) their correlation
to anhydrite-rich units penetrated by marginal wells (e.g. Hannah-1; Gardosh et al. (2008); and (iii) their distinctly different deformation style, i.e. brittle compared to the ductile properties of the inferred halite (see also Cartwright et al., 2012).

However, it is recognised that precise calibration of the Messinian evaporite in the deep basin will remain uncertain until it is drilled. Nevertheless, velocity analysis may provide an additional insight into their composition in the absence of direct well calibration. Relatively high interval velocities of the acoustically transparent sequences (3850-4240 km/s) are consistent with halite, whereas lower velocities of reflective sequences (3650-4030 km/s) may point towards the presence of low-velocity evaporite facies like gypsum (Reiche et al., 2014).

2.5 References


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3. | CHAPTER THREE | MANUSCRIPT I

Charting the Stratigraphic Evolution of a Youthful Saline Giant: New Insights from Regional 2D Seismic Facies Analysis of the Messinian Evaporite Complex in the Offshore Eastern Mediterranean

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Abstract

The Late Miocene Messinian Salinity Crisis (MSC; 5.96-5.33 Ma) involved a major drawdown (c. 2000 m) of Mediterranean Sea level, initiating widespread, marginal canyon incision and the deposition of a vast saline giant across the deep, ocean crust floored basins. The resulting Messinian Evaporite Complex (MEC) reaches thicknesses of >3km and total salt volumes are estimated at c. 1 million km$^3$. The youth, short depositional timeframe and shallow burial of the MEC lends itself to excellent seismic imaging, providing a unique opportunity to re-evaluate the possible impacts of a major base level fall on facies variability and distributions.

The majority of previous research on the MEC has focussed on the basin margins despite the fact that the majority of the evaporite deposits are preserved in the deep basin. This sub-surface seismic study centres around the eastern Mediterranean region and aims to characterize the stratigraphic evolution of the MEC in the deep basin setting through comprehensive mapping of seismic facies across a regional multi-client 2D seismic dataset supported by key marginal wells and borehole data. To date, no wells have penetrated the deep basinal evaporite thus regional subsurface seismic-based studies offer a unique opportunity to bridge the gap between onshore and offshore characterization of the MEC.

The seismic facies analysis has provided valuable insights into the intrasalt seismic facies variability of the MEC across the study area. We recognise up to eight discrete seismic facies, which have provided the framework for the construction of a series of palaeo-facies distribution maps. These maps attempt to chart the likely lithological and palaeo-environmental progression of the crisis from onset through acme to the final abrupt return to normal deep-water marine conditions following the Zanclean flood.

Our work supports previous suggestions that the layering observed (especially in the Levantine basin) represents a cyclicity of evaporite deposition from halite to
gypsum/anhydrite. Up to 4 cycles are observed in the Levantine basin, which are thought to reflect changes in brine salinity. It is further proposed that orbital perturbations could be driving alternating dry and wet climate periods, influencing river discharge rates and therefore, freshwater input to the basin from the palaeo River Nile. We envisage that, following the major drawdown at 5.6 Ma, cycles of marine and freshwater influx and evaporative drawdown led to salt accretion. As the basin fills, freshwater dilution dominates resulting in the brackish, ponded, lake deposits of the 'Lago Mare' before the final Pliocene re-flooding at 5.33 Ma.
3.1. Introduction

3.1.1 The Messinian Salinity Crisis

During the Late Miocene (5.96-5.33 Ma) Messinian Salinity Crisis (MSC), the Mediterranean Sea (see Fig. 3.1 for location) experienced almost total desiccation following the temporary closure of the marine gateway with the Atlantic Ocean, which was and is still located at the Strait of Gibraltar. Sea-level drawdown initiated canyon incision at the basin margin and the deposition of a vast (up to 3 km thick, c. 1 x 10⁶ km³ in volume) salt giant (sensu Hübischer et al., 2007) in the deep basin (Hsü et al., 1973a; Ryan and Cita, 1978; CIESM, 2008). The areal extent of this deep basin evaporite was only revealed during drilling of Deep Sea Drilling Project (DSDP) leg 13 in 1973 and, since then, an intense debate has ensued regarding the thickness, composition and depositional timeframe for the Messinian Evaporite Complex (MEC), and the magnitude of the associated sea-level drawdown.

Two key models have been proposed for the deposition of the MEC: (i) the ‘deep-water, deep basin’ model (Schmalz, 1969), which states that the Mediterranean did not experience total isolation and that marine circulation was severely restricted due to a shallow sill near the Strait of Gibraltar. Deposition on the deep basin floor took place in a deep-water setting, with carbonates, sulphates and halite precipitated out of the brine; and (ii) the ‘shallow water desiccated basin’ model (Nesteroff, 1973), which suggests that a shallow, rapidly subsiding basin was able to create accommodation for shallow-water to supratidal evaporite accumulation.

These initial scenarios failed to take into account discoveries made in the late 1950’s and early 1960’s of age-equivalent, deeply incised valleys (≥ 1km) on the basin margins. These ancient drainage networks were recognised in various places around the Mediterranean, including Egypt, Libya and France, with knickpoints located up to 300 km inland of the present
Mediterranean coast (Loget et al., 2006). This led to the proposition of the third, and widely accepted model of the ‘deep, desiccated basin’ (Hsü and Cita, 1973). This model envisages a pre-existing deep basin that underwent temporary isolation from normal marine oceanic circulation systems resulting in a dramatic sea-level drawdown of at least 1500 m, widespread canyon incision at the basin margins and the deposition of shallow-water to hyper-saline facies in the deepest parts of the basin. Following fairly widespread acceptance of this model, debate shifted to the nature of onset of evaporite deposition. Two scenarios have been proposed; (I) diachronous onset of deposition (Butler et al., 1995; Clauzon et al., 1996; Riding et al., 1998) (Fig. 3.2 a-c); and (ii) synchronous onset of deposition (Krijgsman et al., 1999; Rouchy and Caruso, 2006) (Fig. 3.2 d-e).

The intricate tectonic configuration of the Mediterranean basins, coupled with the fact that these models were primarily constructed from isolated locations, typically at the basin margin, means that it is likely that no single model can be applied to the entire basin. Similarly, the stratigraphic record of the MSC will presumably vary considerably where sub-basins have different elevations and depths at the onset of evaporite deposition. In an attempt to rectify these problems, more recent studies have postulated an integrated scenario in which deposition is largely synchronous at the onset of the crisis, but that different stratigraphies developed in marginal and deep basin locations (Fig. 3.2) (Roveri et al., 2008) and references therein. A three-stage model has been proposed that envisages gradual restriction of the basin (Stage 1a-b) before dramatic drawdown led to pan-Mediterranean incision of the basin margin and coeval basinal salt deposition (Stage 2). Gradual freshwater dilution by fluvial systems ensued during Stage 3, before an abrupt return to normal marine conditions after the Zanclean flood event at 5.33 Ma (latest Messinian), when the Atlantic-Mediterranean gateway at the Strait of Gibraltar was breached (Garcia-Castellanos et al., 2009).
The timescale for these more recent scenarios is based on Krijgsman et al. (1999), who conducted high-resolution stratigraphic analysis of the MEC in marginal basins in Spain, Sicily and Greece. They were able to demonstrate that lithological variability across the depositional cycles recorded could be astronomically calibrated to circum-Mediterranean climate changes driven by the ~26 Kyr cycles of axial precession. This led to the provision of a reliable, high-resolution stratigraphic framework for the MEC in these marginal settings, which we adhere to as a guide for this study.

3.1.2 Rationale

Although a general consensus now exists in terms of the chronology and dynamic, likely three-stage progression of the MSC, there is still a clear disparity within the data. At present, the overwhelming majority of previous research has focussed on exposures of the MEC preserved in marginal basins such as those in France, Spain, Italy and Cyprus (e.g. (Savoye and Piper, 1991; Riding et al., 1998; Roveri et al., 2001; Orszag-Sperber et al., 2009), despite the fact that the majority of the salt is preserved in the deep basin. Furthermore, deposition in marginal basins likely pre- or post-dates the major period of drawdown and, therefore, the stratigraphy in these basins is not time-equivalent with, or representative of, the deposits found in the deep basin. Limited documentation of the stratigraphy of the deep basin evaporite reflects the lack of direct and/or complete subsurface calibration. Consequently, until such a time when the complete successions are drilled, perhaps during scientific drilling campaigns (i.e. IODP; Hübscher et al., 2007), seismic reflection studies, coupled with what limited well data are available, offer a unique opportunity to bridge the gap in knowledge between the stratigraphic framework of the MEC in marginal and deep basin locations, and the overall dynamics of the MSC.

The current model for deep basin stratigraphy is outlined in Fig. 3.2b and is primarily based on outcrop studies from the island of Sicily. Key similarities were noted between the
Upper Messinian stratigraphy of the Caltanissetta Basin (Gessoso Solfifera Formation), and the seismically imaged and partially drilled evaporites of the deep Western Mediterranean ‘trilogy’ (Lower Evaporites, Salt and Upper Evaporites) (Decima and Wezel, 1973) or alternatively known as the LU, MU and UU respectively by more recent studies (e.g. Lofi et al., 2011). This tripartite division of the evaporites is thought to record initial restriction of the Mediterranean (Lower Evaporites (LU)), the acme of salt deposition during major sea-level drawdown (Main Salt Unit (MU)), and flooding and basin dilution (Upper Evaporites (UU)). This led some to suggest that the Sicilian successions represented exhumed parts of the deep basin stratigraphy (Hsü et al., 1973b).

This interpretation gained support as an analogue for the western Mediterranean deep basin composition (e.g. Lofi et al., 2011; Geletti et al., 2014); however, as we will show throughout this article, the proposed ‘trilogy’ shows little relationship to the seismic-stratigraphic architecture observed in the offshore eastern Mediterranean sub-basins (see also Gradmann et al., 2005; Netzeband et al., 2006; Bertoni & Cartwright, 2006; Hübscher et al, 2007; Roveri et al., 2014). In the eastern Mediterranean, the LU and UU are presumed to be absent or post-depositionally removed, with the succession characterised by a thicker, multilayered MU, of predominantly halite composition (Bertoni & Cartwright, 2006; Netzeband et al., 2006; Hübscher et al., 2007).

High-resolution 2D and, more recently 3D seismic analysis of the MEC in the Levantine Basin has allowed the distinction between 6 seismic sequences, distinguished from each other by sharp changes from seismically transparent to highly reflective layers. Sequences ME-I, ME-II, ME-IV and ME-VI are seismically transparent and presumed to consist predominantly of halite (Bertoni and Cartwright, 2007a; Hübscher and Netzeband, 2007). The high-amplitude units (ME-III and ME-V) have previously been interpreted as interbedded clastics (Garfunkel and Almagor, 1984) and/or sulphate-rich deposits (e.g. Gradmann et al., 2005; Netzeband et al., 2006; Cartwright and Jackson, 2008; Allen et al., chapter three, this thesis).
3.1.3 Aims and Objectives

The principal aims of this study are: (i) to examine the temporal and spatial variability in the seismic facies of the MEC across the offshore Eastern Mediterranean sub-basins; (ii) to determine the likely mechanism(s) and/or processes responsible for the deposition of strongly layered evaporites in the Levantine Basin and further afield; and (iii) to regionally correlate seismic sequences and associated facies, thereby allowing us to produce basin-wide palaeo-facies reconstructions for the eastern Mediterranean. These reconstructions will incorporate data from other studies in order to chart the basin-wide stratigraphic evolution of the MEC and the anticipated palaeoenvironmental settings responsible for the variability, and apparent cyclicity of seismic facies observed across the study area and beyond.

To achieve these aims, we have carried out a comprehensive regional analysis of seismic sequences and facies across a multi-client suite of 2D seismic reflection datasets covering c. 180,000 km$^2$ of the offshore Eastern Mediterranean. We demonstrate that these seismic facies, mapped at an unprecedented level of detail, reveal numerous depositional sequences with a high degree of variability, in terms of thickness, extent and styles of deformation, over short distances. However, at the basin-scale, these sequences, although subjected to differing levels of post-depositional halokinesis, show a broader correlation between sub-basins. This may suggest the synchronous deposition of a single ‘salt giant’ across the entire Eastern Mediterranean offshore domain.

3.2. Geological setting

The offshore Eastern Mediterranean forms the focus of this study and occupies an area of c. 1,250,000 km$^2$ (Fig. 3.1). The area is tectonically complex, characterised by an intricate mosaic of active, thick-skinned, crustal-scale structures formed in response to the ongoing collision between the African and Eurasian plates (Mascle et al., 2000; McClusky et al.,
2000; Robertson and Mountrakis, 2006). The Eastern Mediterranean initially formed in the Early Mesozoic, along the northern passive margin of Gondwana, and it is widely accepted to represent a relic of the Mesozoic Neotethys Ocean (Robertson and Dixon, 1984; Garfunkel, 1998). Remnants of this oceanic crust are still preserved in the deepest parts of the Ionian, Herodotus and Levantine basins. Since the Middle to Late Cretaceous, northward movement of Africa has progressively isolated the Mediterranean Sea in a largely compressional setting. However, Cenozoic tectonics have modified this overall compressional setting to create domains of extension and transpression. Notable examples include the reworking of Alpine orogenic belts, which led to back-arc extension and seafloor spreading in both the Aegean and Tyrhrenian Seas (Avigad et al., 1997). This has sufficiently thinned the crust to allow the development of new Miocene- Pliocene oceanic crust in the Tyrhrenian Sea. Areas of strike-slip and transpressive motions are observed along the DSTZ as the rotating Arabian plate interacts with Africa and Eurasia.

The MEC and post Messinian Plio-Pleistocene deltaics of the Nile Deep Sea Fan (NDSF) were deposited in this complex basin setting, draping the former Egyptian passive margin and extending northward to the subducting Tethyan oceanic domain, offshore Cyprus. Further structural complexity arose in the Eastern Mediterranean during the Neogene-Quaternary due to halokinesis of Messinian salt (Gaullier et al., 2000; Loncke et al., 2006; Lofi et al., 2011). Despite the numerous tectonic phases the basin has experienced since the Cretaceous, the continuity of its passive margins and original configuration has remained broadly similar over the last 5 Myrs, thereby providing a rare opportunity to examine the depositional history of a salt giant that has undergone relatively little halokinesis. Most other salt giants (e.g. Louann Salt, Gulf of Mexico; Wu et al., 1990b; Peel et al., 1995; Zechstein Supergroup, NW Europe; (Van-Gent et al., 2011; Strozyk et al., 2012); Ariri Formation, offshore Brazil; Jackson et al., 2014) have been extensively deformed due to post-depositional flow, thus constraining the palaeogeographic setting and evolution of these basins is very difficult. Furthermore, because
the deposits are deeply buried (e.g. Zechstein Supergroup) or because massive salt flow had led to the emplacement of allochthonous structures (e.g. Louann Salt) these deposits are poorly imaged on seismic reflection data. Therefore, the Messinian salt is somewhat unique in that its internal architecture remains relatively undisturbed owing to its comparative youth and short depositional timeframe.

3.3. Dataset

This study utilizes a regional, multi-client, pre-stack, zero-phased, time-migrated 2D seismic dataset supplied by BP Egypt. It covers an area of approximately 180,000 km² in the offshore Eastern Mediterranean and was acquired between 2000 and 2005. The dataset is bound to the south by the Mesozoic Egyptian passive margin and the Miocene Suez Rift, the Dead Sea Transform zone (DSTZ) to the east, and the Cyprus and Hellenic arcs to the north (Fig. 3.1). The seismic grid is irregular, with line spacing varying between 7 and 50 km and an average of c. 10 km. The data have a record length of 8 seconds two way time (TWT) in the Herodotus Basin, distal Nile cone and Eratosthenes Seamount, to 12 seconds (TWT) in the Levantine Basin. In addition, there are a few ultra-deep lines over the proximal Nile cone with a record length of 14-20 seconds, thereby allowing imaging of crystalline basement. The vertical seismic resolution is c. 30 m, as indicated by wavelet extraction. Data are displayed with normal polarity (a downward increase in acoustic impedance is represented by a positive reflection; SEG European convention, see Brown, 2011). Despite some discrepancies in the acquisition and processing parameters between vintages, seismic imaging of the Messinian section is generally very good and consistent in terms of amplitude, phase and frequency.

Four exploration wells penetrate the Messinian interval (Fig. 3.1). Data from these wells is limited to time/depth and nanno-fossil zone boundaries, however, in some cases (e.g. Marakia-1 and North Sinai-1), they allow us to tie our seismic data to the Messinian/Pliocene boundary (top salt), which is marked by the nanno-fossil zone boundary NN12. Published
documentation of wireline log data and cuttings information from four additional wells were integrated with our dataset; these wells were drilled for scientific drilling purposes in the Nile Delta and Levantine Basin (e.g. DSDP legs 13 and 42A: Hsü et al., 1973b; Proceedings of the ODP Leg 160: Emeis et al., 1996; Gardosh et al., 2008a; Fig. 3.1). The locations of these wells are intermediate (i.e. deeper than marginal exposures but not fully penetrative of the complete Messinian deep basin succession). Areal coverage provided by these wells is somewhat limited but they do allow confident, albeit one-dimensional constraints on the lithology of the Messinian in an intermediate depth setting, permitting a more confident extrapolation into the deep basin.

3.4. Results

3.4.1. Regional Messinian Seismic Characterisation

Before considering the internal organisation of the MEC, it is first important to understand its’ basinwide distribution, external morphology and thickness. Our dataset allows us to generate a basin-wide time isopach map for both the gross salt interval (Fig 3.3a) and the Plio-Pleistocene overburden (Fig 3.3b). For illustrative purposes, a selection of accompanying regional composite seismic lines is also presented (Fig. 3.3c). These maps show a near-perfect inverse thickness relationship, with areas of thin-to-locally absent salt corresponding to areas of thick overburden. Lateral changes in salt thickness facilitate the division of the evaporite into three tectono-morphological domains; (i) D1, characterised by thick, highly deformed salt; (ii) D2, characterised by thin-to-locally absent (welded) salt; and (iii) D3, characterised by thick, largely undeformed salt. The domains clearly demarcate the limits of the Plio-Pleistocene NDSF, and their external geometry and thickness also show a close relationship with the enclosing basin morphology and structural elements (i.e. the deeper the basin, the thicker the salt).
3.4.1.1. Domain 1 (D1)

The top and base of the MEC in D1 are highly reflective, despite the unit itself being largely seismically transparent. Occasionally, areas of chaotic and/or highly contorted bedding are also observed but these are not laterally extensive (see table 1). Along the southern limit of D1, the salt pinches-out onto the Egyptian passive margin and passes landwards into a single erosional surface known as the ‘M-reflection’ (Ryan et al., 1973). From here, the MEC thickens downdip to the NW, reaching a maximum thickness of >3 km in the deepest parts of the Herodotus basin, before thinning again onto the eastern arm of the Mediterranean Ridge accretionary complex. Coincident with the MEC’s contact with the accretionary complex, is an abrupt degradation of seismic imaging of the salt and sub-salt stratigraphy. The base salt becomes difficult to map in this area, but the top salt horizon and overburden reflectivity remain continuous and provide a reliable guide for base-salt interpretation. The salt layer shows a sharp structural change as it comes into contact with the active MR, from a relatively undeformed but gently dipping interval to a domain of upright, progressively tightening folds.

The overburden in D1 progressively decreases in thickness northwards from the Egyptian passive margin, where up to 3 km of Nile-derived clastics have accumulated, to the MR foredeep, where it is relatively isopachous (typically <1 km thick) but highly deformed. Overburden deformation in D1 near the Mediterranean Ridge is complex but the dominant structural styles are characterised by northerly-dipping thrusts, which produce a series of NE-trending, short wavelength (< 2 km), 300 ms (TWT) amplitude anticlines that are expressed at the present seabed. These folds are upright to moderately inclined southwards, although we also observe some areas where underlying thrusts dip towards the south and folds verge northwards. These folds are subtle on the isochron maps due to the coarse seismic grid but are very clearly defined on seismic profiles (e.g. Fig.3.3c). It has been suggested that the intensity of deformation across the post-Messinian Mediterranean Ridge toe exceeds what is
expected to occur in response to deep-seated tectonics and that the intense deformation reflects the presence of décollement surfaces at multiple levels within the overlying evaporites (Chaumillon et al., 1996). Consequently, much of the accreted outer wedge of the Mediterranean Ridge is attributed to the thin-skinned thrusting and imbrication of Messinian evaporites and overlying Plio-Pleistocene sediments along these detachment surfaces, rather than deep-seated shortening.

3.4.1.2. Domain 2 (D2).

The salt layer of D2 is recognisable by its well-defined, sharp boundaries with adjacent domains and largely transparent interior. The up-slope pinch-out coincides with the northern limit of the pre-Messinian (now heavily incised) shelf, where all that remains are a few, small, isolated salt rollers located in the footwalls of seaward-dipping growth faults. Downslope, there is a general increase in salt thickness, although post-depositional flow has generated dramatic lateral thickness variations, with salt welds being present immediately adjacent to large diapirs exceeding 1 s (TWT). Although our dataset does not cover the salt’s northernmost extent in D2, it is reasonable to assume that it would come into contact with the southern edge of the MR (Loncke et al., 2006).

The overburden is dominated by the Plio-Pleistocene clastics derived from the NDSF, which cover an area of c.100, 000 km² and reach up to 2.5 km in thickness (Loncke et al., 2006). The sediment wedge thins basinward and contains structures that display a radial pattern of distribution in plan view. The sediments of the proximal Nile Cone remain relatively isochronous and undeformed due to the absence of underlying, mobile MEC evaporites. At the distal edge of the arcuate pre-Messinian shelf area, a sharp escarpment marks the initiation of shelf collapse accommodated along large, seaward-dipping normal faults. This change from a stable to unstable overburden coincides with the proximal edge of the salt basin.
The interaction between the overburden and salt layer is particularly evident in this domain. Differential loading of the salt initiates basin-ward flow, creating an array of classical salt tectonic structures (e.g. diapirs and pillows) with related deformation in the overburden (e.g. crestal collapse structures and salt-withdrawal mini-basins). This activity appears to be ongoing as evidenced by the deformation of the present day seabed.

3.4.1.3. Domain 3 (D3).

D3 is the Levantine basin and this domain differs considerably from the central and western domains; here the basin geometry is relatively simple, allowing the deposition of a thick, largely tabular salt body. The evaporites have a maximum thickness of c. 1.6 km (depth converted value; Netzeband et al., 2006) in the basin centre and a high, up-dip pinch out that remains parallel with the continental margin as it swings from E-W along the Egyptian coast to trend NNE-SSW forming the Levantine margin. The salt body thins onto the Eratosthenes Seamount, which is thought to have remained above the Messinian sea level or evaporite deposition depth owing to the absence of any evaporite deposits on the top of the seamount (Neev et al., 1976; Montadert et al., 1978; Kempler, 1998). The seismic section in Fig. 3.3(d) shows presence of a moat-like depression around the edges of the ESM. Several authors have noted this feature (Robertson et al., 1996; Major, 1998), with the former suggesting it formed as a result of dissolution of a thick evaporite sequence as fluids escaping from over-pressured sediments percolated up the flanks of the seamount. The salt in our dataset thins towards its northernmost limit as it comes into contact with the Latakia Ridge, which represents the easternmost arm of the Cyprus Arc subduction zone.

Despite its outwardly tabular appearance, internally, the salt is comprised of alternating transparent and highly reflective, layered units. These more reflective units accommodate numerous compressional features such as folding, thrusting and pop-up structures, which are widespread and generally intensify basinward.
The overburden in D3 thins basinward although it is comparably thinner (c. 1 km) than in D1 and 2. This Plio-Pleistocene wedge spans the length of the Levantine margin and is composed mainly of sand in its basal part, and hemipelagic turbiditic claystones, alternating with sandstones, siltstones and marls in its upper part (Frey Martinez et al., 2005). Thin-skinned deformation has affected these deposits causing them to be rotated to dip landward via moderate displacement (200 ms TWT), listric normal faults that sole-out onto the base-salt. Beneath these structures, the evaporites are very thin and locally absent, which, in part, reflects the original depositional pinch out of these units onto the eastern basin margin, in addition to basinward flow of salt driven by sedimentary loading and margin tilting (Tibor and Ben-Avraham, 1992; Bertoni and Cartwright, 2006).

3.4.2. Seismic Facies Analysis and Seismic-Stratigraphic Framework

A seismic facies is defined as a sedimentary unit which is different from adjacent units in terms of its seismic characteristics or expression (Roksandić, 1978). These characteristics include: (1) reflection configuration; (2) reflection continuity; (3) reflection amplitude and frequency; (4) bounding relationships, that is, types(s) of reflection termination or lateral change; and (5) external geometry of the reflection package (Brown and Fisher, 1980; Fontaine et al., 1987; Mitchum, 1977). The seismic-stratigraphic framework employed here largely adheres to the seismic stratigraphic principles outlined in by Brown and Fisher (1980); Catuneanu et al. (2009); Fontaine et al. (1987); Sangree and Widmier (1979); Sheriff (1977); Vail and Mitchum (1977), where a seismic sequence is defined as; “a relatively conformable succession of genetically related strata bounded by unconformities or their correlative conformities”. In this study, a ‘sequence’ refers to a relatively conformable succession of genetically related strata defined by a single seismic facies and bound by unconformities or their correlative conformities.
The basal and upper bounding surfaces of MEC are correlated to Horizons N and M respectively; two regional, deep basin seismic events traditionally interpreted to mark the confines of the Messinian evaporites in the Mediterranean basin (Ryan et al., 1973). Up-dip, these horizons merge to become a singular, erosional surface (M reflection) where no salt deposition occurs. Offshore, these horizons are clearly recognised by their continuous, high amplitude character and the conspicuous change in seismic facies generated by, in the case of the N horizon, the transition from finely layered Middle-Upper Miocene strata to the overlying chaotic salt layer and for the M horizon, the change from chaotic salt to the overlying finely layered Plio-Pleistocene strata.

The MEC displays significant lateral and vertical variability in terms of bulk thickness, seismic sequence number and individual thickness, seismic facies and structural styles. Constituent seismic facies range from those that are thick, transparent and chaotic with high degrees of internal (intrasalt) deformation to well-stratified, highly reflective, and relatively undeformed seismic facies (see also Gradmann et al. 2005; Bertoni and Cartwright, 2006; Cartwright et al., 2012). In total, we document eight distinct seismic facies, the characteristics of which, according to the parameters set out above, are summarised in Table 1. Detailed descriptions of these seismic facies, which form the building blocks of the MEC, are provided in sub sections 4.3.1-4.3.8.

The seismic facies and the seismic-stratigraphic architecture of the MEC is particularly clear in the easternmost Levantine Basin (D3), largely because of relatively limited amounts of halokinesis (Gradmann et al., 2005; Netzeband et al., 2006b; Cartwright et al., 2012). This allows for construction of a detailed seismic and mechanical stratigraphy for the MEC in this sub-basin (Fig. 3.4), which is then used as a comparative type section for extrapolation of seismic facies interpretation across the study area and into other sub-basins. Up to eight seismic sequences comprising five of the eight seismic facies (SF) catalogued can be observed in this basin alone and regionally mapped (Fig 3.5). SF I, II and IV are also observed
intermittently in D1 and D2, whereas SF V, VI, VII and VIII are confined to D1 and D2 and cannot be related in seismic character to those observed in D3.

Owing to the lack of direct well calibration of lithology in the deep basin domain, interpretation of lithology and depositional environment from seismic facies alone is approached with caution. It is possible that the seismic expression of different sedimentary units could be similar depending on the depositional environment (Janson et al., 2011). For this study, we utilise lithological interpretations and nannofossil picks from marginal wells available in the public domain and extrapolate these out into the deep basin. We combine this offset well data with a general understanding of sedimentation processes within typical evaporitic systems (i.e. expected lithologies associated with increasing salinities; e.g. carbonate-anhydrite-halite-bitterns, Richter-Bernburg, 1955 as cited in Taylor, (1990). This pattern has been demonstrated in many other salt giants such as the Zechstein of Northern Europe (Stewart, 2007; Taylor, 1990) and the Cretaceous Santos Basin, Offshore Brazil (Davison, 2007; Fiduk and Rowan, 2012) and allows us to achieve a reasonably confident correlation between seismic reflection character and lithology.

3.4.3. Intra-Messinian Seismic Facies (SF) Characterisation

Detailed descriptions and images of each seismic facies are presented in Table 1. Selected examples from seismic profiles illustrating the basinal context and external geometry of the facies, sequences and features described in the following text are displayed in Figures 3.6, 3.7, 3.8, 3.9 and 3.10, which the reader is referred to for visual support of the following observations and interpretations.
3.4.3.1: SF I: (Sequence 1, Levantine Basin).

Observations:

This facies is observed in numerous locations across the study area and is characterised by high-amplitude, continuous bounding surfaces and a semi-transparent interior. It is best imaged in the Levantine basin (D3), where it can be regionally mapped. Here, it forms the basal unit of the evaporite series and displays a relatively constant thickness across the basin floor (c. 40-60 ms), with thinning observed along its marginal pinch outs. Its lower bounding surface is correlated to the N horizon through extrapolation from up-dip marginal wells (e.g. Hannnah_1, Yam-Yafo-1, Yam-West-2, (Gardosh et al., 2008)), where it is represented by a high-amplitude unconformity with erosion estimated to be between 50 and 200 m (Tibor and Ben-Avraham, 1992). This surface also marks a major lithological boundary related to the abrupt drop in sea level at the start of the MSC. The uppermost boundary of sequence 1 is characterised by a sharp change to high-amplitude parallel reflections of sequence 2 (SFII) that unconformably overlie this sequence truncating dipping surfaces within sequence 1 (SFI).

Although dominantly transparent internally, local packages of stratified, reflective material is observed, in addition to low-relief mounds and low displacement normal faults, just above the basal detachment (Table 1). Its occurrence elsewhere is limited to windows of good imaging in the deep Herodotus Basin of D1 (Fig. 3.6a). Furthermore, the Virtual Seismic Atlas (Butler, 2012, pers. comm) also images this seismic facies in the deep Ionian Basin (Fig 3.6b), which could suggest a more widespread occurrence beyond what is currently imaged.

Interpretation:

The general lack of reflectivity observed in this unit points towards a largely homogenous composition; however, as the first depositional unit of the MSC in the Levantine basin, the lithological composition of SF1 is likely to be varied due to previous and on-going
collapse of the margins following drawdown. Gardosh et al., (2008) interprets an analogous facies recorded in the Hannah-1 well as ‘reef debris’, possibly resedimented from earlier basin margin carbonate deposits. The mounded geometries could be preserved rafts of such reef systems or marginal salt deposits (e.g. PLG’s, Fig.3.2) that have later been translated downslope following the major drawdown at 5.6 Ma, which destabilized the shelf/slope and led to its collapse. In the stratigraphic model presented in Fig. 3.2, SF1 could be analogous to the ‘Resedimented Lower Gypsum’ unit described by CIESM (2008). It is therefore interpreted that this basal unit could represent a ‘dirty halite’ that contains primary precipitates of halite, punctuated by resedimented lower gypsums and clastics shed from the margin following major drawdown and incision at 5.6 Ma.

3.4.3.2: SF II (Sequence 2, Levantine Basin).

Observations:

This seismic facies constitutes sequence 2, which unconformably overlies sequence 1 in the Levantine basin and is bound by the top surface of sequence 1 (SFI) and the base of sequence 3 (SF3). It is characterised by between two and five very high-amplitude, parallel, continuous reflection events with sub-ordinate transparent intervals and has been assigned a separate seismic facies from SF IV (see below) due to the lower frequency of reflection events. The basal contact with sequence 1 is unconformable, truncating dipping surfaces within it. The gently undulating uppermost boundary is onlapped by subtle reflections in SFIII (see table 1). It is widespread across D3, locally imaged in D1 and absent in D2.

Interpretation:

This composition and origin of this seismic facies is difficult to tie to any stratigraphically comparable lithological unit interpreted in onshore wells so it is possible that this unit was deposited only in the deep basin or it was deposited but then subsequently
eroded and thus not been preserved in marginal locations. However, based on its seismic character, distribution, lateral continuity and polarity of contained reflections, we can speculate as to its composition. Parallel, laterally continuous, high-amplitude reflections imply SFII is more heterogeneous than the transparent SFI. The high continuity and relatively uniform time-thickness of this facies suggests the strata were deposited in an aerially extensive, environmentally uniform location, perhaps conducive to chemical sedimentation processes or, alternatively, a clastic drape of deep marine shales. If we assume that these deposits are evaporitic, SF II could plausibly represent interbedded halite, anhydrite and, perhaps, Mg-K salts and carbonates. Alternatively, if we assume that these deposits are clastic, a deep marine shale drape may be more likely. However, the former is further supported by the positive acoustic impedance contrast between SFI and II. In evaporitic settings this type of seismic response generally indicates the juxtaposition of halite on anhydrite or limestone facies (Bertoni and Cartwright, 2007).

3.4.3.3: SF III: (Sequences 3, 5 & 7, Levantine Basin)

Observations:

SF III is characterised by an abrupt transition from the high-amplitude parallel reflection events to a seismically transparent unit. SFIII occurs at different stratigraphic levels in D3, forming sequences 3, 5 and 7 in the Levantine basin with the uppermost sequence 7 being truncated by the top salt reflection. This facies is mapable across D3 and is largely transparent with some reflectivity locally observed. These more reflective areas contain chaotic and discontinuous reflections with variable dips and complex patterns of truncation. SF III displays some lateral variations in thickness, which appears related to deformation in the underlying and overlying units. These sequences exhibit a progressive upwards decrease in thickness from 150 ms TWT (s3) to 50 ms TWT (s7). Calculations of the interval velocity within similar transparent units revealed velocities of up to 4.6 km/s (Hübscher et al., 2007).
Interpretation:

High seismic velocities, the absence of internal reflections and/or lack of evidence for brittle deformation (i.e. faulting) are all consistent with our interpretation that these units are dominated by mobile halite. The minor thickness changes observed are not thought to be depositional, but instead, a result of flow of the mobile unit to solve the space problem created by brittle deformation in the bounding units (S2 & S4). Well data from onshore reveals halite occurs in both laminated and massive form (Cohen, 1993). We suggest that reflective material in D3 may represent; a) resedimented laminated halite originally deposited upslope; and/or b) primary precipitated laminated halite, which has subsequently undergone post-depositional deformation during halokinesis. Further geophysical evidence also supports a halite composition, as we observe an increase in acoustic impedance (waveform deviates to the right) across the boundary from SF II (high amplitude) to SFIII (low amplitude).

3.4.3.4: SF IV: (Sequences 4 and 6, Levantine Basin).

Observations:

This seismic facies is well imaged throughout the deep basin domain of D3 and can be mapped regionally; however, correlation with similar units imaged in D1 is also proposed (e.g. Fig. 3.6a). This facies is characterised by high-amplitude, high frequency, flat-lying reflection events that are gently inclined to sub-parallel in the basin and more discontinuous towards the basin margin. This facies is set apart from SF II as the frequency of internal reflections is higher. It occurs at two discrete stratigraphic levels within the MEC in D3 (sequences 4 & 6), which show a similar internal seismic character but display varying intensities of deformation. These sequences alternate with the transparent sequences 3, 5 and 7, which are comprised of SF III. The interspersed reflective units of sequences 2, 4 and 6 have seismic velocities that range from 2.95 to 3.75 km/s (Ryan and Cita, 1978; Gardosh et al., 2008). Figure 3.7 includes a time-thickness map of sequence 4, which, despite its strong post-depositional deformation...
signature, shows a relatively narrow range of thicknesses with c. 90% of the mapped area falling between 100-200 ms TWT thickness.

**Interpretation:**

Interpretations of these more reflective units include: i) a vertical (stratigraphic) change from evaporites to over-pressurized clastics (Garfunkel and Almagor, 1984), ii) trapped fluids (CIESM, 2008) or iii) vertical (stratigraphic) evaporite change (Cohen, 1993; Netzeband et al., 2006). We are in favour of the latter interpretation due to the high lateral continuity of seismic reflections within SF IV, which might be indicative of chemical sedimentation processes rather than a point-sourced clastic input (Bertoni and Cartwright, 2007).

Furthermore, the recorded interval velocities are also consistent with this interpretation in addition to the uniformity in time-thickness of these sequences (e.g. Fig. 3.7). As aforementioned, one might expect a point source in a clastic scenario, and thus a thinning of the unit towards the basin centre. However, despite the coarse nature of our 2D seismic grid, thicknesses do not reveal any obvious lobate geometries emanating from the basin margin. The thickness variability that is observed is likely a reflection of the intra-salt deformation taking place along these more competent units. This can cause stratal repetition through imbricated stacking within the sequence. We also speculate that the acoustic impedance contrasts leading to the enhanced reflectivity in SF IV reflect the progressive phases of evaporite deposition as described by Cohen (1993); e.g. tripartite units composed of marine clay, gypsum/anhydrite, and halite. In the case of the Levantine Basin (D3), borehole data presented by Cohen (1993) reveal that clay layers and couplets of halite–gypsum/anhydrite are present in the MEC. We suggest that this stratigraphic cyclicity may be controlled by several transgressive-regressive cycles triggered by periodic marine or freshwater incursions.
3.4.3.5: SF V (Sequence 8, Levantine Basin).

Observations:

SF V is primarily confined to the marginal areas of the Levantine basin in D3 and has a semi-lobate external geometry (Fig. 3.5). A small arm of this unit extends out down the slope into the deep basin. In proximal locations, SF V overlies and onlaps or downlaps onto the M reflection but becomes concordant distally. It is comprised of alternating high- and low-amplitude, parallel reflection events, dissected by low displacement (i.e. sub 10 ms (TWT)) normal faults, and its upper surface has undergone deep 100 ms (TWT), wide (> 0.75 km), angular incision.

Interpretation:

Although not part of the Messinian evaporite sequence sensu stricto, we nonetheless interpret SF V to be intimately related to the crisis. Seismically, this unit is very similar to the lowermost Pliocene Yafo Formation described by (Frey Martinez et al., 2005) in the southern Levantine basin. In this location this unit was interpreted as being deposited as a basin-floor fan after the marine transgression that ended the MSC. Similarly, a sedimentary sequence that extends along the continental margin of the southeast Mediterranean is referred to as the Yafo Formation (Plio-Pleistocene) (e.g. (Gvirtzman, 1970; Mart and Ben-Gai, 1982; Cohen, 1993; Bertoni and Cartwright, 2006; Gardosh et al., 2009; Hawie et al., 2013). The unit is composed mostly of sand and/or sedimentary breccia in its basal Pliocene part and interbedded marls, shales, and sandstones in its upper Pleistocene part (Hof Ashdod-1 well, Cohen, 1993). The mounded and channelized facies observed at the base of this unit have been drilled and are producing gas in the southern Levant Basin (3Tcf) offshore Israel. These were referred to as clastic mounds by Gardosh et al. (2009). The deposition of this unit is likely a result of marginal uplift, which may have been triggered by isostatic rebound of the marginal areas in response to re-loading of the basin centres during the Pliocene reflooding. The
uppermost hemipelagics of the Pleistocene-age Yafo Fn. then drape the basin floor fan resulting in exquisite preservation of the rugose top surface.

3.4.3.6: SFVI

Observations:

This facies dominates the Messinian section throughout D1 & D2. It is characterised by distinctive, high amplitude top and basal reflection events and a dominantly transparent interior (Table 1). Occasionally, small windows of reflectivity are observed, within which beds can be chaotic, displaying sub-vertical, strongly deformed geometries (e.g. Table 1). The transparent facies is associated with a variety of salt structures (e.g. diapirs, salt pillows, and salt rollers) and seismic pull-ups are common beneath such structures (e.g. Fig. 3.9). The deformation in this unit creates abrupt lateral thickness variations which influence structural styles in the overburden with crestal collapse grabens and salt-withdrawal mini-basins being commonplace throughout D2 (Fig. 3.10).

Interpretation:

This facies bears all the characteristics of a relatively clean, mobile halite. This is consistent with the apparent ductile behaviour, mounded external geometry, internal reflection-free character and geophysical artefacts created by the high velocity contrast between the salt and surrounding sediments (i.e. seismic pull-ups below the diapirs). Localised areas of more reflective material within the unit (Table 1) further highlight considerable mobility and the high levels of internal strain that these deformed beds have experienced.

3.4.3.7: SF VII:

Observations:

This facies occurs in ponded, isolated pockets, up to 200 ms deep, in up-dip, shelfal areas beneath the Nile Cone within D2. It is possible to map these seismic facies in two areas,
which together cover c. 5000 km² (Fig. 3.8a). The unit is comprised of high amplitude, horizontally bedded and continuous reflection events which onlap subtle fringing highs.

**Interpretation:**

Various sample locations from both DSDP core and outcrop describe an analogous facies as being indicative of a low-energy brackish environment, consisting of laminated gypsums, marls and carbonates (e.g. (Ruggieri, 1962; Rouchy, 1982; Vai, 1997; Orszag-Sperber, 2006). This facies was interpreted as the resulting deposits of the “Lago-Mare event”; a very short period of time, lasting only c. 75 kyrs at the end of the MSC, when a mainly brackish to fresh water environment existed prior to the Pliocene marine refilling of the basin at 5.33 Ma (Krijgsman et al., 1999). More recent subsurface studies in the Sirt Basin, offshore Libya also mapped ponded, high-amplitude, laminated facies with identical seismic properties and stratigraphic relationships to surrounding units as our SFVII (Ceraldi et al., 2010; Bowman, 2012). This distinctive facies was termed ‘Lake Sirt’ and has been tied to well data and interpreted as the Libyan equivalent to the ‘Lago Mare’. We therefore propose that our seismic data provide further seismic examples of the type of deposits that were associated with fresh-water dilution of lakes during the final stages of the MSC.

**3.4.3.8: SF VIII**

**Observations:**

This seismic facies is only locally apparent at the base of the Messinian slope beneath the Nile Cone (Fig. 3.8b). Its external geometry is difficult to constrain due to the sparse nature of our 2D seismic grid, but our mapping suggests that it has a semi-lobate form covering an area of c. 1200 km² and thickens basinward to c. 1 s (TWT). Internally, SF VIII is chaotic, with a mix of seismic facies, ranging from transparent to high-amplitude, semi-continuous reflections, which are faulted. These more reflective areas permit excellent
imaging of the intrasalt deformation, which is characterised by imbricated thrust sheets that become steeper down-dip, creating a tectonically thickened wedge of sediments at the unit’s distal limit. This unit conformably overlies the base salt surface, with abrupt lateral and vertical transitions into the seismically transparent SF VI that occurs adjacent to and above it.

**Interpretations:**

Lofi et al., (2011) defines a seismic unit with strong similarities to our SFVIII in terms of geometry, internal reflection configuration and stratigraphic relationships to surrounding units. This was termed the ‘Complex Unit’ by these authors and it is documented in numerous locations within the Mediterranean Basin. It is believed to represent the products of upslope incision and basinal resedimentation following the initial drawdown at 5.6 ma. These products are likely to include resedimented clastics and evaporites analogous to the Resedimented Lower Gypsums (RLG’s, Fig. 3.2) described by Roveri et al., (2008), which form lobate, basin floor deposits, emplaced by sediment gravity flows. Because of seismic and geometric similarities to the Complex Unit of Lofi et al. (2011), we interpret that SFVIII is the seismic expression of resedimented slope deposits. However, in our data, this unit appears to have undergone considerable post-depositional deformation, which we interpret to be the result of preferential flow of interbedded, more mobile, pure halite units during halokinesis.

**3.5. Discussion**

This integrated study of seismic facies, and primary and literature-sourced well and outcrop data has provided valuable insights into the vertical and lateral variability in salt composition, mechanical behaviour and depositional patterns across the Eastern Mediterranean Messinian sub-basins. We discuss our findings at both regional and local scales in an attempt to reconstruct the palaeo-facies distributions at each discrete phase of the MSC using the temporal framework outlined in Fig. 3.2b. On a regional scale, we divide our dataset
into three structural domains (D1, D2 & D3) demarcated by abrupt changes in salt thickness, reflective character and mechanical behaviour. These domains are mirrored in the overburden, where typically we observe an inverse thickness relationship (i.e. increasing salt layer thickness is associated with thinner overburden thickness) as described previously and shown in Fig. 3.3.

Although a full analysis of the structural styles within salt and the overburden are beyond the scope of this study, an overview can be found in Netzeband et al. (2006), Loncke et al. (2006) and Allen et al. (2014; this thesis.). However, it is necessary to explore some of the key drivers for the observed lateral salt thickness changes at the basin scale in order to determine the link, if any, that exists between the internal character of the evaporite and the structural styles observed. This is also important for the reconstruction of Messinian facies distributions throughout the MSC.

3.5.1 Evaporite Layering

The Levantine Basin is often set apart from other eastern Mediterranean sub-basins as a unique example of where repeated cycles of salt deposition are preserved. However, our work suggests this layering may not be exclusive to this basin, but in fact, more widespread than previously acknowledged. Figure 3.6 highlighted the similarities in thickness, reflection configuration and mechanical behaviour between several seismic facies observed in the Levantine Basin, with those interpreted in the Herodotus (our dataset) and Ionian basins (Virtual Seismic Atlas; Butler, 2012).

These more isolated examples from the Herodotus and Ionian basins offer a valuable insight into the evolution of the eastern Mediterranean’s relatively under-represented depocentres and could be explained by the synchronous development of the Ionian, Herodotus and Levantine basins as a single saline giant. Naturally, some facies variations are expected between these sub-basins, depending on their pre-salt structural setting and the
syn-and post-salt deformation that have affected them. The lack of such prominent imaging of layering outside of the Levantine Basin may result from simply a more homogeneous primary composition of the salt layer. Alternatively, we suggest strong syn-and post-salt deformation resulting from the flow of mobile evaporites may have destroyed the primary stratigraphic layering in these areas.

As we have demonstrated, the salt in D1 and D2 has undergone significant mobilisation resulting in intensive flow-induced deformation. Furthermore, we also note the presence of sheath folding (see SFVI, Table 1), which is characteristically indicative of high strain environments (Alsop et al., 2007). However, deformation in the Levantine Basin appears less mature, which could be due to a number of reasons including; lower levels of strain, minor basinward salt flow or strong partitioning of deformation due to less mobile anhydrite intervals. Indeed, a re-emergence of clearer internal reflections is noted in the Ionian Basin, away from the influences of the Nile Cone loading and Mediterranean Ridge tectonics (Butler, 2013; VSA), which are likely to be key drivers for salt mobilisation across D1 and D2.

At the regional scale, the differences highlighted between the eastern and western Mediterranean Messinian successions indicate depositional synchronicity is unlikely. Indeed, numerical modelling that reproduces the drawdown, basin isolation and reflooding events have emphasised the role that the Sicily sill played as a barrier to significant hydrological exchange between the west and east Messinian basins (Ryan, 2008). This leads to diachronous halite deposition, firstly in the Eastern Basin and later the Western Basin (Blanc, 2000; Ryan, 2008). In line with this, we suggest the existence of two main salt depocentres, separated by the Sicily sill. These are expected to have experienced differing fill histories, probably controlled by several, more localised changes in climate, base-level dynamics, hydraulic budgets, intra-basinal highs and connections with the global ocean. The role of the Sicily Sill is discussed in more detail in section 3.5.3 with respect to the specific drivers for the documented layering.
3.5.2 Salt Composition and Genesis of Layering

In the absence of a direct well calibration for the deep basin stratigraphy, it is difficult to offer any definitive lithological interpretations at this stage. Nevertheless, it is possible to compare our scenario to other salt basins worldwide where analogous seismic facies have been interpreted and, more crucially, lithologically calibrated. The vertical alternation of transparent to high amplitude, bedded seismic facies is not unique to the Messinian evaporite. Other notable examples from the Permian Zechstein of Northern Europe (e.g. Stewart, 2007; Taylor, 1990), the Cretaceous Santos Basin, Offshore Brazil (Davison, 2007; Fiduk and Rowan, 2012) and the Carboniferous Paradox Basin, USA (Trudgill, 2011) display a similar cyclic configuration of strata.

The Zechstein Basin of Northern Europe is arguably the best studied of all the ancient saline giants. The basin centre evaporitic cycles were deposited over the last 5 million years of the Permian and reached thicknesses in excess of 1500 m (Olsen, 1987). These cycles (up to five in total), were distinguished using the concept of an ‘archetypal’ sequence of evaporite deposition (Richter-Bernburg, 1955 as cited in Taylor, 1990). This reflects the lithological changes that occur in response to progressive evaporation as a basin undergoes prolonged restriction and thereby increasing salinity. It begins with a thin clastic member, passing upwards through limestone, dolomite, anhydrite, and halite; culminating with the highly soluble magnesium and potassium (bittern) salts.

This simplistic model is similar to that proposed for the MEC and offers a useful framework for interpretation, but in reality, as we have seen in the Levantine basin, the Zechstein cycles are more complex with some parts of the cycle missing or reversed. Likewise, these omissions were also attributed to the interplay between changing climate, run-off, oceanic exchange, water depth, sedimentation rate and subsidence (Taylor, 1990). Similarly, a typical Santos Basin cycle consists of anhydrite, halite, complex salts, halite and finally
anhydrite (Davison et al., 2012; Rodriguez, 2013; Pers. Coms). Twenty-two such cycles of increasing and decreasing salinity have been recognised here and tentatively linked to the 22 and 37 ka Milankovich cycles.

The cyclic deposition of evaporites in the Paradox basin produced a repetitive sequence of primarily halite, with minor clastics, organic shales and anhydrite between c. 313-306 Ma. Global Pennsylvanian glacio-eustatic sea-level change is favoured as a primary controller of Paradox cyclicity (Trudgill, 2011; Hite and Buckner, 1981). However, more localised tectonic and climatic controls including Milankovich cycles, may also have been key contributors to the complex spatial distribution of cycles across the Paradox Basin (Goldhammer et al., 1994).

The dominant lithology throughout our study area is interpreted to be halite; however, in the Levantine Basin, several ideas surrounding the composition of the intra-salinar reflections have been proposed. These range from inter-beded clastic sediments (Mart and Ben-Gai, 1982), over-pressured shales (Garfunkel and Almagor, 1984), microbialitic clays (Cohen, 1993) and anhydrites (Bertoni and Cartwright, 2007; Gardosh and Druckman, 2006; Gardosh et al., 2008). Our interpretation of a cyclic alternation between halite and anhydrite, with possible subordinate amounts of carbonates/clastics is largely based on seismic character (i.e. reflection continuity, amplitude, frequency), the lithology-controlled rheology of the units inferred from the observed structural style, mechanical behaviour, and lithology information obtained from marginal wells. Although we acknowledge that shales and sands are likely to feature in this basin, the brittle deformation style, positive acoustic impedance contrasts with respect to enclosing halite facies and analogous seismic character of units within the Hannah-1 well all point towards a predominantly anhydrite composition for the reflections of SFIV.
3.5.3 Drivers for evaporite cyclicity

There is a broad consensus within the literature that the rhythmic depositional nature of the Messinian evaporites (at least at the outcrop scale) is almost certainly linked to lithological changes driven by Mediterranean climate oscillations (e.g. Cohen, 1993; Krijgsman et al., 1999a; Griffin, 2002; Gradmann et al., 2005; Bertoni & Cartwright, 2006; Netzeband et al., 2006; Orszag-Sperber, 2006 Ryan, 2008; Bowman, 2012). It has been demonstrated that these lithological changes correlate well to records of certain Milankovich cycles; more specifically, orbital precession (21 Kyr component) and eccentricity (400 Kyr component) (Krijgsman et al., 1999a; Sierro et al., 1999). Orszag-Sperber (2006) attributed variations in the composition of the uppermost Messinian successions to oscillations between dry and humid periods (e.g. the alternation of fluvial conglomerates and gypsiums in the Pissouri and Polemi basins, Cyprus). Similarly, Griffin, (2002) supports the idea that Messinian evaporitic couplets (i.e. halite overlain by anhydrite/clastics) are a consequence of a transition from a dry to a more humid climate. This was previously demonstrated for the change from halite of the Tortonian South Gharib Formation to overlying clastics and anhydrites of the Zeit Formation in the Gulf of Suez and Red Sea (Griffin, 1999). However, we extend this interpretation and propose that this oscillation between dry and humid periods would also impact on the freshwater budget in the Eastern Mediterranean from the Nile River, and possibly, the ancient Sahabi River to the west (see Fig. 3.11 for location). This could lead to fluctuating Messinian lake levels, changes in brine concentration and therefore, evaporite lithology, thus accounting for the vertical seismic facies variability encountered in numerous locations across the study area.

Considering the regional nature but short depositional timeframe for evaporite deposition in the deep basins (i.e. less than 300 kyrs), an interplay between two main controls are considered key drivers for fluctuations in the Eastern Mediterranean Messinian lake level;
(i) freshwater inflow and (ii) evaporation rate. During the proposed humid climate intervals, the former may be greater due to increased precipitation and the latter may decrease. The successful precipitation of an evaporite deposit requires the liquid water loss from a brine mass (through solar evaporation) to exceed inflow rates (Warren, 2010). When lake level is higher, and thus more dilute, less concentrated salts such as anhydrites may precipitate whereas halite precipitation coincides with dryer periods, less inflow and higher salinities. Numerical modelling conducted by Ryan. (2008) indicated that changes in rainfall over the Mediterranean at insolation maxima can triple the rate of freshwater supply to the basin for prolonged periods, leading to rising water levels even with the same rates of evaporation. This effect is amplified in the eastern Mediterranean due to the Nile River input.

Examination of sedimentation rates in the Nile area reveals a sharp drop in sedimentation from c. 300 m/Myr⁻¹ to c. 75 m/Myr⁻¹ at the onset of the MSC (Aal et al., 2000). This reduced rate is inferred to have continued throughout the crisis. However, we propose that finer-scale alternations during this time are also likely a response to Milankovich-driven climate oscillations in both North and Central Africa, which both represent source regions for the River Nile. Higher resolution data is difficult to obtain from the literature but overall sedimentation rates have shown great variation since the Oligocene (<10 m/Myr⁻¹ to >600 m/Myr⁻¹) due to various tectonic and climatic events that occurred in the hinterland (Macgregor, 2012 and references therein).

Although precession is often cited as the main driver for lithological variations within the evaporitic successions in the Western Mediterranean basins, these studies are calibrated to high frequency cycles in the uppermost or lowermost evaporites in marginal settings. For example, up to 17 marl/sapropel and evaporite/sapropel cycles are recognised within the Lower Evaporites and 7 to 8 cycles are documented within the Upper Evaporites across the various sections exposed in the Sorbas, Gavdos and Caltanissetta basins (Krijgsman et al., 1999a). These outcrops are c. 125 m thick, which is likely to fall below the resolution of our
seismic data. Therefore, the 2-4 halite-anhydrite couplets we infer from seismic facies analysis may reflect lower-frequency climate oscillations, such as the 100 Kyr component of eccentricity. Indeed, the occurrence of up to three cycles of halite-anhydrite would fit the eccentricity periodicity of c.100 Kyrs, covering the time interval for the MSC in our study area of between 5.6 and 5.33 Ma.

In much the same way as inflowing water salinity may vary due to circum-Mediterranean climate change affecting fluvial activity; basin physiography may play an equally important role in controlling the nature of salt deposition. As aforementioned, the Sicily Sill (Fig. 3.1 and 3.10) acts as a physical separator between the east and western basins but could still permit hydrological exchange via a subsurface seepage mechanism.

The deposition of the almost 2 km of salt that fills the Levantine Basin would require multiple recharge events, which are typically thought to result from the periodic over-spilling of a barrier by large volumes of ocean water (Hsu et al., 1973; Meijer and Krijgsman, 2005). Through quantitative analysis of the processes of desiccation and re-filling, Meijer and Krijgsman (2005) predicted that a single cycle of desiccation and refilling would produce an evaporite layer of c. 24-41 m in thickness. This is merely a fraction of the total estimated thickness of the MEC in the eastern Mediterranean supporting the idea of multiple cycles of desiccation and refilling.

In the case of the eastern Mediterranean basin specifically, it could also be proposed that water inflow was more continuous and occurred from the western basin to the eastern basin through the Sicily Sill as well as across it during times of higher water levels in the western basin. In this scenario, one may envisage the Sicily Sill acting as a distillery serving to increase the concentration of solutes so the inflow to the eastern basins would not necessarily be seawater with Normal Marine Seawater Concentrations (NMSC) (Hübscher, 2014, pers. comms).
Numerical simulation modeling of water and salt flux in and out of a basin via a seepage mechanism has been tested for the main Mediterranean-Atlantic sill at the Gibraltar Straits gateway (Nunn and Harris, 2007). It was concluded that although a seepage mechanism cannot provide sufficient water to maintain very large water bodies such as the Mediterranean; it can provide a viable source of solutes that serve to increase saline concentrations of inflowing water.

3.5.4 Regional Palaeo-facies Reconstruction for the Messinian Salinity Crisis

The seismic facies analysis has provided valuable information on the variability of the Messinian evaporite across the Eastern Mediterranean sub-basins permitting the generation of a series of palaeo facies maps that attempt to chart the temporal and spatial evolution of the crisis from early restriction through major drawdown and salt deposition, to cyclic freshwater dilution and refilling at the Base Pliocene (Fig. 3.11a-d). The following sections outline the expected facies configurations for each discrete phase of the crisis in line with the timeframe and three-step scenario outlined in CIESM (2008) and illustrated in Figure. 3.2. Further data underpinning these interpretations are referenced throughout this article and more specifically, within the individual seismic facies interpretations.

3.5.4.1 Stage 1: Pre-cursor to major drawdown (6.7 Ma - 5.6 Ma), Fig 3.11(a).

This initial stage represents the period of gradual restriction leading up to the main Messinian drawdown event at 5.6 Ma. There is evidence to suggest that this was a gradual process, which began well in advance of the main drawdown event at 5.6 Ma. Deposition of diatomites and black shales, as well as faunal and isotopic changes, began as early as 7.2 Ma in the deeper basins and has been attributed to uplift along the Rifian Corridor which led to initial constraints on Atlantic-Mediterranean marine exchange (Krijgsman et al., 1999; Kouwenhoven et al., 2003). A later study by Kouwenhoven et al., (2006) revealed a marked
transition to a more adverse environment occurred at c. 6.7 Ma, when microfossils, typical of low-oxygen conditions brought about by stagnation and hyper-salinity, were sampled in the Pissouri section in Cyprus. This progressive shift to monospecific assemblages within microfossil groups continued and it is estimated that severely stressed environments existed after c. 6.4 Ma. Deposition of this thin, oxygen depleted, shale layer commonly referred to as the Pre-Cursor unit (Roveri et al., 2008) is envisaged across the deep basins.

This unit, a prelude to the main phase of evaporite deposition, may have persisted until marine connections were closed completely at 5.6 Ma, though it is assumed to be absent or condensed over structural highs such as the Mediterranean Ridge. During stage 1 however, a partial marine connection at the Atlantic gateway is still likely and therefore, Mediterranean Sea Level fall would likely be minimal. However, some marginal and/or elevated thrust-top basins (e.g. The Caltanissetta Basin, Sicily and Pissouri Basin, Cyprus) experienced primary precipitation of evaporites. We liken this facies to lithological units such as the Permian Zechstein Kupferschiefer Formation; a thin, dark grey, sapropelic shale that formed under anoxic conditions below the influence of waves (Taylor, 1990).

3.5.4.2 Stage 2: Drawdown (5.6-? Ma) Fig 3.11(b).

During this stage a major basin-ward facies shift takes place as a dramatic drop in sea level occurs in response to closure of the marine gateway at the Gibraltar Straits. Erosion dominates the margins with coeval salt precipitation (mainly halite) in the deep basins. Carbonate rims become karstified and river systems deeply incise them, e.g. The Sahabi channel systems of the Libyan margin and the Nile’s Abu Madi and Baltim canyons (Dolson et al., 2005). Possible rejuvenation of Levantine (Afiq & El Arish) and Turkish canyon is also suggested (e.g. Bertoni & Cartwright, 2006). Products of this incision are predicted to occur as lowstand fans in the deep basin with a candidate for these existing in the Herodotus basin (SFVIII). Slumping, shelf collapse and their resultant mass transport complexes (MTC’s) are
likely basin-wide in extent due to the inevitable instability of margins following drawdown. Examples of these have been documented in our study (Fig. 3.7) and across the Mediterranean basins including offshore Libya and Sicily (e.g. CIESM, 2008). These MTCs are interpreted to be composed of a combination of the resedimented material of the PLG’s (known as the RLG’s), mixed clastics and carbonates. Arguably, such a deposit could be responsible for the variable reflectivity, mounded geometries and rafts of bedded material documented in SF I.

**3.5.4.3 Stage 3: Evaporite Cycles (5.6-5.33 Ma) Fig 3.11(c)**

This stage relates proposed changes in depositional lithology to fluctuations in brine salinity. The cyclical vertical changes in seismic facies observed in the Levantine Basin record a change from transparent units to distinctive high amplitude, bedded intercalations. These changes are inferred to have taken place across the basin as we have observed windows of analogous seismic facies in the Herodotus Basin and outside of our immediate seismic dataset (i.e. the Ionian Basin; Butler, 2013). These bedded units may be the result of periodic marine and/or freshwater incursions related to climate changes and/ or eustatic sea level fluctuations. During times of higher lake level, exchange of marine and hypersaline waters between the Mediterranean, Atlantic, Red Sea and Black Sea may have occurred (Clauzon et al., 2008). The two main sources of freshwater into the eastern Mediterranean basin are the Nile and Sahabi rivers, which were rejuvenated during these periods, allowing further dilution of the brines and an influx of clastics to take place.

We may expect to see halite remain the dominant precipitate in the deepest parts of the basins due to the sequestering of clastics along the basin margin and the lack of protrusion of river derived, freshwater wedges into the basin. This may explain why fewer layers are observed in the deeper Herodotus and Ionian Basins compared with the comparatively elevated Levantine Basin. However, it could also be due to poor seismic imaging and/or
disruption of layering by the post-depositional flow of salt flow in those areas. Because climate may vary between them, we cannot be sure of the synchronicity between the layers observed in the Levantine Basin and those of the Herodotus and Ionian Basins, nevertheless, their composition and the processes leading to their deposition are thought to be analogous.

3.5.4.4 Stage 4: Lago Mare (5.4-5.33 Ma) Fig 3.11(d)

This final depositional stage of the MSC is dominated by a brackish to freshwater environment, which represents the transition facies between hyper-saline conditions and the abrupt return to normal marine conditions at the Zanclean boundary at 5.33 Ma. In our dataset, this stage is represented by SF VIII and characterised by high amplitude, stratified reflections, deposited in isolated depressions in the more marginal parts of the basin. Lake level is likely to have risen incrementally throughout stage 3 and by this final stage, the accumulation of deep basin evaporite was almost complete. These deposits are thought to be equivalents to the so-called ‘Lago Mare’ units that are exposed in Sicily and Cyprus (Orszag-Sperber, 2006; Roveri and Manzi, 2008), and interpreted in well data from the offshore continuation of the Sirt Basin, offshore Libya. ‘Lake Sirt’ as it has been named, was described as a low energy lacustrine deposit associated with increasing freshwater input into the basin (Ceraldi et al., 2010; Bowman, 2012).

3.6. Conclusions

The high-resolution seismic facies analysis of the Messinian Evaporite Complex (MEC) reveals up to eight seismically distinct depositional facies that can be traced over regional distances. Seismic facies I-V are unique to the Levantine Basin and form 7 sequences, which show a progressive decrease in areal extent up stratigraphy, with only the deepest parts of the basin preserving all 7 sequences. Sequence 8 in the Levantine Basin is interpreted as a basin-floor fan that was deposited immediately after the cessation of salt deposition, and possibly as
a consequence of marginal uplift after the re-loading of the basin following the Pliocene reflooding. SF VI, VII and VIII are found across D1 and D2 but not encountered in D3 with SFVI showing high levels of internal strain and mobility, which is responsible for creating an array of salt-tectonic structures with related deformation in the overburden.

We interpret sequences in the Levantine basin as deposited over multiple depositional cycles, which is consistent with onshore drillings (e.g. Cohen, 1993; Gardosh et al., 2008) and propose that these cycles correspond to lithological variations (specifically halite-anhydrite couplets), linked to changing seawater salt concentrations. A key driver for these lithological variations is thought to be eastern Mediterranean climate oscillations between dry and humid periods, which impacts on freshwater input from the dominant North African fluvial systems (Nile and Sahabi Rivers). Humid periods correspond to an increase in freshwater into the basin, diluting brines and favouring the deposition of anhydrites, whereas, in drier periods, halite is the more dominant lithology.

It could be argued that climate oscillations are linked to the 100 Kyr component of orbital eccentricity. Indeed, our interpretation of up to 3-4 cycles of halite-anhydrite couplets fits the eccentricity periodicity of c.100 Kyrs, covering the time interval for the MSC in our study area of between 5.6 and 5.33 Ma. This contrasts with previous studies that infer that the Levantine Basin is the eastern equivalent to the mobile unit of the western Mediterranean trilogy, which is thought to have a depositional timeframe of just 50 kyrs. This does not seem plausible for the Levantine successions, suggesting that the western and eastern basins were separate depocentres during the MSC, separated by the Sicily Sill.

We also observe that layering of the Levantine evaporites may not be exclusive to this basin, but in fact, more widespread. A good correlation of thickness, reflection configuration and mechanical behaviour exists between several seismic facies observed in the Levant, with those interpreted in the Herodotus (our dataset) and Ionian Basins (VSA). The lack of such prominent layering outside of the Levantine Basin may result from simply, a more
homogeneous primary composition of the salt layer. However, we suggest that syn-and post salt deformation resulting from the flow of mobile salt may have destroyed the primary stratigraphic layering in these areas. These more isolated examples of the layering offer a valuable window into the evolution of the eastern Mediterranean’s relatively under-represented depocentres and could suggest the synchronous deposition of a single saline giant across these Eastern Mediterranean sub-basins further supporting our interpretation of a separate western and eastern Mediterranean saline giant.
3.7. References


Loget, N., Davy, P., and Van Den Driessche, J., 2006, Mesoscale fluvial erosion parameters deduced from modeling the Mediterranean sea level drop during the Messinian (late


Fig. 3.1 Study location and seismic database in its regional tectonic context. (compiled after McCluskey et al., 2000; Abdel Aal et al, 2000; Robertson & Mountrakis., 2006; Loncke et al, 2006; Bertoni & Cartwright, 2007 & Gardosh et al, 2008 ). Inset shows wider Mediterranean context of study area and the strait of Gibraltar; the closure of which is considered the key trigger for basinwide drawdown.
Fig. 3.2 (a) Correlation of Messinian events from margin to deep basin according to previously published stratigraphic scenarios (modified from Rouchy and Caruso, 2006). (b) An integrated scenario for Messinian stratigraphy where stages occur synchronously but lithological expression varies depending on marginal or deep basin setting. Model largely based on Sicilian outcrop studies (modified from CIESM, 2008).
Fig. 3.3 (a) Plio-Pleistocene overburden isochron and (b) Messinian salt isochron superimposed onto bathymetric image of the Eastern Mediterranean seafloor. Note the marked lateral thickness changes and considerable influence of the Nile Deep Sea Fan (outlined) on underlying salt distributions. Numbers 1-3 refer to structural domains described within the text.
Dipping sequence boundaries are truncated up-dip by relatively flat top salt.

Zone of poor imaging possibly related to buttressing against ESM leading to intense folding and thrusting.

(c) Regional composite seismic line (a-a’) shows the intimate inverse relationship between the thicknesses of the salt layer and the overburden. (d) Regional dip line (b-b’) across the Levantine Basin. The evaporite layer here is relatively tabular as a whole, but shows high levels of internal deformation along gentle basinward-dipping reflective units, which are truncated updip where the evaporite pinches out. Vertical black lines highlight joins in the composite section. (VE) denotes vertical exaggeration of section.
<table>
<thead>
<tr>
<th>Seismic Facies example</th>
<th>Thickness (TWT)</th>
<th>Internal configuration</th>
<th>Deformation</th>
<th>Reflection amplitude</th>
<th>Bounding relationship</th>
<th>Spatial distribution &amp; external geometry</th>
<th>Comments</th>
<th>Interpretations</th>
</tr>
</thead>
<tbody>
<tr>
<td>SF I</td>
<td>1-2 km</td>
<td>Specular, some bedding</td>
<td>minor</td>
<td>High</td>
<td>Unconformable; overlapped by SFII &amp; SFIII</td>
<td>Widespread across D3 with patchy occurrence elsewhere; largely isochronous</td>
<td>Intimately linked with SFII across the basin.</td>
<td>Anhydrites/marl/bioclastic arenites (Zičlak Fm).</td>
</tr>
<tr>
<td>SF II</td>
<td>1 km</td>
<td>Parallel, continuous,</td>
<td>mod frequency</td>
<td>Moderate - low</td>
<td>Unconformable; overlapped by SFII</td>
<td>Widespread across D3 with patchy occurrence elsewhere; largely isochronous</td>
<td>Intimately linked with SFII across the basin.</td>
<td>Basal &quot;dirty&quot; halite containing RLG’s calcarenites (Tibor,1992). Reef debris (e.g Gardosh, 2008).</td>
</tr>
<tr>
<td>SF III</td>
<td>1 km</td>
<td>Parallel &amp; mostly</td>
<td>discontinuous</td>
<td>High</td>
<td>M reflection truncates D3</td>
<td>Widespread across D3. High lateral thickness variations.</td>
<td>Up to three intervals which become progressively thinner and less extensive upwards. Possibly D3 counterpart to D1 SF VI but less clean.</td>
<td>Mobile halite dominant with subordinated rafted clastics and/or other salts (bitterns). Upwards thickness decrease related to freshwater dilution basin.</td>
</tr>
<tr>
<td>SF IV</td>
<td>1 km</td>
<td>Parallel</td>
<td>continuous</td>
<td>High</td>
<td>M reflection truncates D3</td>
<td>D3 - present in deepest parts of basin.</td>
<td>Separated from SFII due to higher reflection frequency but thought to be lithologically similar.</td>
<td>Anhydrite/gypsum dominated with sub-ordinate halite. Upwards thickness increase due to prolonged freshwater dilution phases.</td>
</tr>
<tr>
<td>SF V</td>
<td>1 km</td>
<td>Parallel</td>
<td>discontinuous</td>
<td>High</td>
<td>M reflection truncates D3</td>
<td>D3 - immediately above M reflection in proximal - intermediate slope setting. Lobe geometry - thins and laps out basinward.</td>
<td>Others interpret as base Pliocene clastic deposit - Yafa Formation. (e.g. Cohen, 1993). However, some evidence of sub-aerial boundary (M reflection).</td>
<td>Believed to be part of, or intimately related to the MSC. Sub-aerial surface, inconsistent with rapid deepening expected at zanclean boundary. (M reflection)</td>
</tr>
<tr>
<td>SF VI</td>
<td>1 km</td>
<td>Transparent to</td>
<td>semi-transparent,</td>
<td>High, high amplitude</td>
<td>Distant facies remaining in D2.</td>
<td>Widespread across D1 and D2. High lateral thickness variations created by diapirism and associated welds.</td>
<td>Linked with diapirism and other salt tectonic processes affecting salt layer and overburden. Seismic pull-ups common throughout.</td>
<td>Highly mobile halite with sheath folding (inset) indicating high internal strain. Cleaner version of SFIII.</td>
</tr>
<tr>
<td>SF VII</td>
<td>1 km</td>
<td>Parallel</td>
<td>continuous</td>
<td>High</td>
<td>Ponded in lows. Top surface is M reflection major U/C. Overlain by plocene Nile deltatics. Transitional lower boundary from underlying salts.</td>
<td>Ponded and patchy occurrence in marginal areas. When present is the uppermost Messinian facies in D1 &amp; 2.</td>
<td>analogues described from o/c and subsurface, e.g. Calabria (Gennari &amp; laccarino, 2004) &amp; Lake Sirt, (ceraldi et al, 2010) respectively.</td>
<td>&quot;Lago Mare&quot; freshwater dilution facies. Brackish, ponded lakes dominant during final stages of crisis.</td>
</tr>
<tr>
<td>SF VIII</td>
<td>1 km</td>
<td>Chaotic</td>
<td>with abrupt dip</td>
<td>High</td>
<td>Abrupt transition laterally and vertically into transparent (SF VI)</td>
<td>Distal D2 Isolated and lobate, eminates from base of slope. Thickens basin-ward-abrupt transition into transparent facies.</td>
<td>Lobate but not typical geometry of turbidite fan-halite interbeds may complicate.</td>
<td>Possible correlation to Complex unit (CU) of Loft atlas: interpreted as lowstand fans. This example may have become post depositionally mobile due to halite interbeds.</td>
</tr>
</tbody>
</table>

Table 3.1 Seismic facies atlas for the Messinian Evaporite Complex across the study area.
Fig. 3.4 Seismic-stratigraphic scheme for the Messinian evaporites of the Levantine basin. Cyclic alternations of transparent, mobile units with brittle, high amplitude units is observed regionally.
Fig. 3.5 3D representation of the vertical stacking pattern of the mapped intrasalt sequences 1-8 in the Levantine basin. The pseudo well highlights how the greatest degree of vertical variability would be encountered in the deepest part of the basin.
High frequency, post evaporitic (Plio-pleistocene) muds.

Fig. 3.6 Seismic sections comparing (a), the Messinian interval in the Herodotus basin (our data) and (b) the Ioanian basin (Virtual Seismic Atlas: Butler, 2013 Pers. coms). The seismic stratigraphic colour scheme developed in this study (see Fig. 4) is superimposed to show the correlation of layers beyond our immediate study area. The similarities suggest layering is widespread and the Eastern Mediterranean existed as a single saline giant. (b) Modified from Butler, 2013.
Fig. 3.7 Isochron maps of intra-Messinian sequences 1-5 of the Levantine Basin (displayed in ms TWT). These sequences were chosen for isochron generation due to their basinwide areal extent and thus, give the best representation of sequence thickness changes. Please note, the coarse nature of the seismic grid and high levels of intra-sequence faulting meant that picking anomalies feature heavily in these maps so the high peaks and troughs (i.e. reds and purples) should be ignored.
Fig. 3.8 (a) Map to show examples of localised seismic facies and key seismic features of interest. Coloured areas outline where the seismic facies has been mapped across our dataset. (b) Line a-a’ seismic example of SFVIII highlighting the internal deformation. Close up of deformation can be seen in (d). (c) Seismic line illustrating the ponded nature of SFVII in the marginal areas beneath the Nile cone. This example has been flattened along the top salt to remove later deformation. Note the sudden drop off in imaging beneath this unit close-up can be seen in (e).
Fig. 3.9 Geoseismic interpretation of salt diapirism in the Nile/Herodotus basin. (see fig. 3.3 for location).
Tilted onlap surfaces caused by salt evacuation.

Salt withdrawal synclines

Seabed

Velocity pull-ups indicate high velocity contrast expected

lack of pull-ups could mean turtles have a shale core.

Fig 3.10 Collapse of salt diapirs trigger subsidence in the overburden causing localised depocentres to form above areas where salt is withdrawn. These record the relative timing of salt removal by the growth strata preserved within them. (see Fig. 3.3 for location).
Fig. 3.11 Evaporite facies distributions for the Messinian Salinity Crisis (5.96-5.33 ma) Maps are compiled on the basis of observed facies patterns in this study combined with data and information from literature of both outcrop and sub-surface studies. Maps (b) and (c) represent a single phase of evaporite deposition and this is inferred to be repeated up to 4 times across the study area culminating with the final, ‘Lago Mare’ phase at approximately 5.4 m.a. lasting until the Zanclean flood event and the abrupt return to normal marine conditions at 5.33 ma. However, multiple ‘Lago Mare’ type facies were probably deposited between recharge events, but not preserved.
4. | CHAPTER FOUR| MANUSCRIPT II

GRAVITY–DRIVEN DEFORMATION OF A YOUTHFUL SALINE GIANT: SEISMIC EXAMPLES FROM THE MESSINIAN BASINS OF THE EASTERN MEDITERRANEAN

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Abstract

During the late Miocene (5.96-5.33 Ma), the Mediterranean basins became tectonically isolated, leading to the Messinian Salinity Crisis (MSC). The MSC involved a major evaporitic drawdown of the Mediterranean Basin, initiating the deposition of a vast salt deposit in the deep basins and widespread incision at the margins. The resulting saline giant, which we term the Messinian Evaporite Complex (MEC), is locally >3 km thick and has a total volume of c. 1 million km³.

The majority of previous studies have focused on structural style variability and evolution within individual sub-basins or domains of the Eastern Mediterranean. However, in this contribution, we aim to summarise the differing structural styles across the entire Eastern Mediterranean, before comparing and contrasting the driving forces behind their genesis at a regional scale. This study employs a more regional, subsurface-based approach and aims to improve our understanding of the structural development of the MEC in the deep basin domain. For this study, we use a combination of regional 2D seismic reflection surveys, a high-resolution 3D seismic reflection cube, and well and outcrop data from the basin margins to perform comprehensive analysis of intrasalt and suprasalt structural styles of the MEC across the eastern Mediterranean sub-basins, a study area of c. 230,000 km².

A series of structural domains are identified that are related to on-going, thick-skinned, basement-involved, plate collision-related tectonics, and thin-skinned, gravity-driven deformation driven by loading of the salt by the Nile Delta and tilting of the Levantine margin. This has led to the proposition of new models for the structural development of the region that identify both local and far-field tectonics as key drivers for the observed structural styles. The relative youth and shallow burial of this saline giant makes it an excellent natural laboratory and therefore offers a unique opportunity to study the early tectono-stratigraphic evolution of a giant salt basin.
4.1. Introduction

Salt-influenced tectonics along passive margins such as the Gulf of Mexico, offshore Brazil, and offshore Angola, often display higher levels of deformation than their salt-free counterparts (e.g. Jackson et al. 1994; Ge et al. 1997; Loncke et al. 2006; Hudec & Jackson 2007; Brun & Fort 2011; Rowan 2014). Salt movement is often initiated and sustained by gravity-driven processes that fall into two broad categories: (i) gravity spreading, in which deformation is driven by differential sedimentary loading, commonly associated with the basinward progradation of basin-margin sedimentary wedges; or (ii) gravity gliding, in which deformation is primarily driven by gravitational instabilities arising from basinward tilting of the salt and overburden (Schultz-Ela, 2001; Brun and Fort, 2011; Rowan, 2014) (Fig 4.1).

In reality, sustained salt flow is likely driven by a combination of gliding and spreading. Furthermore, irrespective of the mechanism driving salt flow and overburden deformation, both processes generally result in the formation of an updip, proximal domain of extension separated from a downdip, distal domain of shortening by a relatively low strain domain of translation (Letouzey et al., 1995; Schultz-Ela, 2001; Tari et al., 2002; Vendeville, 2005). However, the basin-scale partitioning of structural styles associated with spreading and gliding can be quite different. For example, if gliding dominates, in areas where regional subsidence is driven by thermal subsidence following continental extension and ocean crust emplacement, then the regional base salt dip and direction of gliding will be basinward along large tracts of the margin (Vendeville, 2005; Loncke et al., 2006). However, in locations where spreading dominates, considerable lateral changes in the thickness and progradation rate of basin-margin sedimentary wedges can occur, potentially resulting in the occurrence of more complex structural styles characterised by multiple sets of variably striking normal faults in the updip extensional domain (e.g. the Gulf of Mexico and Nile Deep Sea Fan; Rowan et al. (1999); Loncke et al. (2006). It is the interplay between these two triggers that ultimately determines
the structural style of a salt-influenced passive margin and, because the structural styles generated may be similar, they may not always be diagnostic of a specific trigger.

The structural styles observed on many salt-tectonic passive margins may therefore be complex, and deformation widespread. This reflects the mechanical and rheological properties of the salt itself as it is a relatively incompressible material that is often mechanically weaker than its adjacent rocks. Over extended timescales and when subjected to typical geological strain rates, it responds in a visco-elastic manner and begins to flow like a fluid, both in the subsurface and at the free-surface (i.e. seabed or land surface) (Hudec & Jackson, 2007).

For a tabular salt layer, the deformation arising from salt flow can occur by way of Poiseuille or Couette flow, or a combination of both (Weijermars et al., 1993; Rowan et al., 2004; Cartwright et al., 2012). Poiseuille flow corresponds to vertical thinning where the upper and lower boundary of a salt body experiences high shear strain but small horizontal displacement; whereas flow in the centre of the salt body experiences low shear strain but large horizontal displacement. This would result in a mirror image of vertical strain where the greatest shortening occurs in the mid-level evaporites (Cartwright et al., 2012) (e.g. Fig. 4.2a). Couette flow involves layer-parallel simple shear of the salt layer as one layer moves relative to the other, for example, as overlying sediments are translated seaward along a top-salt detachment (Rowan et al., 2004). This would result in the highest shortening at the top of the salt body (fig. 4.2b). However, if the main detachment were located at the base of salt, this strain profile would be reversed (Cartwright et al., 2012).

Salt is characteristically transparent on seismic reflection data; this may reflect the fact that the depositional salt is homogeneous and thus lacks internal acoustic impedance contrasts, or that the salt becomes highly strained during post-depositional flow. This makes the interpretation of intrasalt flow mechanics very difficult in many of the world’s more
mature salt provinces. However, in certain cases, salt bodies may be only mildly strained and contain sufficient lithological heterogeneity to produce regionally mapable, laterally continuous reflections on seismic data. Detailed mapping of these intrasalt reflections permit local and regional analysis of intrasalt deformation styles and the distribution of strain during the initial stages of salt flow (e.g. Cartwright et al., 2012; Reiche et al., 2014), and may offer an insight into the early growth history and kinematics of more mature diapiric salt bodies.

This study focuses on salt tectonics related to the Messinian (Late Miocene) evaporites of the Eastern Mediterranean. This is a rare example of an ancient saline giant where, in places, the exquisite preservation of intrasalt reflections permits spectacular imaging of the complex structural styles that have occurred as a result of salt flow, thus providing a rare opportunity to study the basin-scale early-stage development of a saline giant. Intrasalt reflectivity and structure have previously been studied in the Santos Basin, offshore Brazil (Cobbold et al., 1995; Fiduk & Rowan 2012; Jackson et al., 2014) and the Zechstein Basin, NW Europe (Van Gent et al., 2011; Strozyk et al. 2012). However, the examples presented by these authors have been limited to a relatively small area or number of structures in each basin. Furthermore, significant amounts of salt flow have resulted in the formation of large, extremely complex diapiric bodies, thus the early-stage evolution of the salt is hard to determine. Seismic reflection imaging of, at times, complex intrasalt structure across large areas of a sedimentary basin is rare and primarily due to a number of other factors unique to the Messinian saline giant, including its relative youth, short depositional timeframe and the lack of significant post-depositional tectonic overprinting.

4.1.1 Aims

The majority of previous studies have focused on structural style variability and evolution within individual sub-basins or domains of the Eastern Mediterranean (e.g. the Levantine margin: Gradmann et al. (2005); Bertoni & Cartwright (2006); Cartwright & Jackson
(2008); Gvirtzman et al. (2013); Reiche et al. (2014); The Nile Deep Sea Fan: Smith (1976); Chaumillon et al. (1996); Gaullier et al. (2000); Loncke et al. (2006). In this contribution, we aim to summarise the differing structural styles across the entire Eastern Mediterranean, before comparing and contrasting the driving forces behind their genesis at a regional scale. More specifically, we aim to address and examine; (i) the origin and evolution of the structural styles within and above the Messinian evaporite in the Nile/Herodotus Basin and the Levantine Basin; (ii) the driving mechanisms responsible for the generation of the observed salt-related structural styles; and (iii) what the structural complexity of the early-stage development of the Messinian saline giant can tell us about current approaches to the interpretation of saline giants globally.

4.2. Geological Setting

4.2.1. Tectonic configuration

The study area covers c. 180,000 km² of the offshore Eastern Mediterranean (Fig. 4.3a). For the purpose of this study, focus is directed to the post-Cretaceous collisional phase of Nile/Herodotus and Levantine basin evolution, however, for a full geological evolution of the eastern Mediterranean region, the reader is referred to Stride et al. (1977); Sestini (1984); Mart. (1993); Abdel-Aal et al. (2000); McClusky et al. (2000); Robertson & Mountrakis. (2006); Gardosh et al. (2008); Hawie et al. (2013).

The eastern Mediterranean region has been the site of the continental collision between Africa and Eurasia, which commenced in the Late Cretaceous. Continental collision has resulted in the progressive isolation of the Mediterranean Sea and subduction of remnant Tethyan oceanic crust along the Cyprus and Hellenic arcs at a rate of up to 10 cm/year in the Hellenic Trench (Robertson & Dixon 1984; Jackson & McKenzie, 1988; Mascle et al., 2000; McClusky et al., 2000; Robertson & Mountrakis, 2006). Areas of continental extension are also identified, most notably in the Suez Rift, which developed as the Arabian plate moved away
from the African plate during the late Oligocene to Present (Garfunkel & Bartov, 1977; Colletta et al., 1988). Further north, the subduction of the African plate beneath Eurasia induced Oligocene-to-Early Miocene back-arc extension, which eventually led to sea-floor spreading and the development of new Miocene-Pliocene oceanic crust beneath the Aegean Sea (Avigad et al., 1997). The regional seismic line and accompanying time-isopachs in Figure 4.4 allow comparison of the boundary conditions of the Nile/Herodotus and Levantine basins, whilst also showing the lateral variations in salt and overburden thickness.

4.2.1.1 The Nile Cone and Herodotus Basin

The Herodotus Basin is the deepest of the southeastern Mediterranean basins, forming an elongate NE-trending depression that is up to c. 3 km deep (Fig 4.3). It is generally agreed that this basin represents a relict slab of the Early Mesozoic Neotethys Ocean (Biju-Duval and Montadert, 1977; Mart, 1987; Sestini, 1989; Stampfli and Borel, 2002; Frizon de Lamotte et al., 2011). The basin is bounded to the north by an active accretionary complex (Mediterranean Ridge), which is associated with subduction of the African plate beneath Europe along the Hellenic Arc (Le Pichon et al., 1982).

The Eratosthenes Seamount (ESM), a static fragment of continental crust (Robertson, 1998), forms the easternmost limit and represents the boundary between the noticeably different structural and stratigraphic architectures that characterise the Nile/Herodotus Basin and adjacent Levantine Basin. Surrounding the seamount is a steep-sided, narrow (10 km), c. 400 m deep bathymetric trench, which has affected the top salt and overburden causing a down warping of reflections. This suggests that this trench is a post-depositional feature, perhaps related to salt withdrawal or dissolution around the seamount and that the overburden and top salt were originally flat-lying (Robertson et al., 1996; Major, 1998). However, some have suggested it corresponds to the seaward salt pinch out and likened it to the Sigsbee Scarp in the Gulf of Mexico (e.g. Loncke et al., 2006).
Mesozoic and Cenozoic sequences (over 7 km thick) characterise the deeper Herodotus basin fill (Voogd & Truffert, 1992; Garfunkel, 1998). These are overlain by up to 2 km of Messinian evaporites and up to 4 km Pliocene-to-Recent overburden, thinning to c. 1 km thickness in the deep basin (Garfunkel, 1998; Abdel-Aal et al., 2000; Loncke et al., 2006). The Plio-Pleistocene overburden is composed of relatively undeformed, broadly tabular packages of Nile Delta-derived clastic material, which, since the Pliocene has delivered approx. 188,000 km³ (compacted value) of sediment to the basin creating the c. 3 km thick Nile Deep Sea Fan (NDSF) covering some 100,000 km² (Loncke et al., 2006; Macgregor, 2012). As we will discuss below, Pleistocene progradation of the Nile Cone, folding and thrusting associated with growth of the Mediterranean Ridge accretionary prism, and pre-existing intra-basinal bathymetric highs have all contributed to the present distribution of the Messinian evaporites and the structural styles present within the Herodotus Basin.

4.2.1.2 Levantine Basin

The Levantine Basin forms an elongate NE-trending depression that is up to c. 1.5 km deep (Fig. 4.3). It formed in response to several rift phases during the Early Triassic to Late Cretaceous (Gradmann et al., 2005), and has since been affected by post-rift subsidence and, more latterly, on-going continental collision of the African-Arabian plate with the Eurasian plate. Northward motion of Afro-Arabia towards Eurasia is expressed through the pulsed, two-phase development of the Syrian Arc fold belt (Gardosh et al., 2008). Phase one, which occurred during the Late Cretaceous, is characterised by inversion of Early Mesozoic normal faults and the formation of asymmetric, relatively high-amplitude folds that are concentrated along the eastern Levantine Basin and onshore Israel. Phase two (Early Tertiary), is characterised by the formation of low-amplitude folds that are pervasive across the basin (Gardosh and Druckman, 2006). Strike-slip tectonics and transpression dominate along the
north-south trending Dead Sea Transform Zone (DSTZ) as a result of the Arabian plate’s oblique movement with respect to the northerly advancing African plate (Girdler, 1990).

More latterly, Pliocene basin subsidence occurred as a result of sediment loading of the Nile cone to the west, and uplift of the Judea and Samaria mountain range, located 20-50 km east of the basin (Gardosh and Druckman, 2006). Overall, the Levantine Basin is more structurally confined than the Herodotus; this difference will become important later when we compare the different ways in which the Messinian evaporite has deformed across the study area.

Despite this long and complex tectonic history, the configuration of the constituent sub-basins of the Eastern Mediterranean has remained broadly consistent over the last 5 Myrs, since the salt was deposited. This means that minimal tectonic overprinting has taken place compared with older saline giants. It is therefore likely that the intrasalt structural styles observed, specifically in the Levantine Basin, are a reflection of the deformation associated with the earliest stages in the evolution of a saline giant.

4.2.2 The Messinian Salinity Crisis

The Messinian saline giant is a product of the Messinian Salinity Crisis (MSC), a major sea-level drawdown event that occurred in the Late Miocene (5.9–5.33 Ma) in response to the temporary closure of the marine gateway between the Mediterranean Sea and Atlantic Ocean at the Gibraltar Straits (Hsü, Ryan & Cita, 1973; Ryan, 1973; Krijgsman, et al., 1999). This resulted in isolation of the Mediterranean basin and the largely synchronous basinal deposition of thick evaporite successions, which was coeval with extensive erosion and incision of the Mediterranean margins (Ryan, 1978; CIESM, 2008).

Following the two original Deep Sea Drilling Project (DSDP) legs that discovered Messinian salt in the Eastern Mediterranean (Leg 13 and 42; Hsü et al., 1973; 1978), numerous studies have attempted to address uncertainties surrounding its origin, spatial extent,
composition, and timeframe of deposition (e.g. Ryan and Cita, 1978; Rouchy, 1982; Krijgsman et al., 1999; Duggen et al., 2003; Manzi et al., 2007; Netzeband et al., 2006; Roveri et al., 2008; Manzi et al., 2010; Roveri et al., 2014). Generally, a tripartite division for the stratigraphy of the crisis is envisaged, with the constituent stratigraphic units referred to as the Lower, Mobile and Upper Evaporites (CIESM, 2008). The pre-drawdown Lower Evaporites are characterised by the primary precipitation of gypsum and non-reefal carbonates, which are commonly preserved in small, isolated, thrust-top basins (e.g. Butler et al., 1995) in marginal settings. Hydrological isolation of the deep basin at this time is recorded by a thin, anoxic shale layer that straddles the Tortonian/Messinian boundary (CIESM, 2008). Deposition of the Mobile Evaporites occurred during the main drawdown phase, marking the initiation of evaporite deposition in the deep basin and extensive erosion and resedimentation of the Lower Evaporites from the basin margins. The Upper Evaporites record the gradual freshwater dilution of the basin before the relatively abrupt return to normal marine seawater concentrations following the re-opening of the marine gateway at the Gibraltar straits at 5.33 Ma (Garcia-Castellanos et al., 2009). The top and base of the Messinian evaporites are defined by two regionally mapable reflections known as the ‘M’ and ‘N’ reflections respectively, which record the abrupt acoustic impedance contrast between the evaporites and their encasing clastic sediments (Ryan et al., 1973).

4.3. Dataset

4.3.1 Seismic

4.3.1.1 2D Data

This study utilizes a regional, multi-client, pre-stack, near zero-phased, time-migrated 2D seismic dataset supplied by BP Egypt (Fig. 4.3b). It covers an area of approximately 180,000 km² in the offshore Eastern Mediterranean and was acquired between 2000 and 2005. The seismic grid is irregular in terms of line spacing, which varies between 7 and 50 km, with an
average of c. 10 km. The data have a record length of between 8 seconds two way time (TWT) in the Herodotus Basin, distal Nile cone and Eratosthenes Seamount, increasing to 12 seconds TWT in the Levantine Basin. In addition, there are some ultra-deep lines over the proximal Nile cone; these have a record length of 14-20 seconds and image basement. The vertical seismic resolution is approx. 30 m, as indicated by wavelet extraction and data is displayed with normal polarity (SEG European convention; Brown 1999), where a downward increase in acoustic impedance is represented by a positive reflection (waveform deviates to the right). Despite some discrepancies in the acquisition and processing parameters across vintages, the seismic responses of the Messinian section are generally good throughout.

4.3.1.2 3D Data

A multi-client, pre-stack time-migrated 3D seismic cube, which is located in the deep-water, contractional domain of the Levantine margin, offshore Lebanon (Fig. 4.3b), was also utilised in this study. The survey was acquired in late-2006 by PGS and covers approximately 1350 km$^2$. The survey covers the northern part of the Levantine basin, the Latakia Ridge, and several other large Syrian Arc and Cyprus Arc-related fold belts. The cube has a high signal to noise-ratio and very good imaging at all structural levels.

4.3.2 Well Data

Although no exploration wells have yet penetrated the deep basin evaporite successions, valuable information on the time-depth and seismic character of the key sequence boundaries (i.e. top and base salt) can be extracted from four wells located along the Egyptian and Levantine margins (yellow dots, Fig. 4.3b). Data from these wells are limited to time/depth (checkshot) data and nanno-fossil zone boundaries but this is sufficient to allow the Messinian/Pliocene boundary (top salt), which is marked by the nanno-fossil zone boundary NN12, to be directly tied to the seismic data (e.g. Marakia-1 and North Sinai-1).
Additional data (e.g. wireline log suites and cuttings information) from four wells are accessible through previously published literature (e.g. DSDP legs 13 and 42A, Ryan et al., 1973; Hsu. et al., 1978a) and petroleum exploration drilling in the Nile Cone and Levantine Basin (e.g. Proceedings of the ODP Leg 160, Emeis et al., 1996; Gardosh et al., 2008) (Pink dots, Figure 4.3b). As stated above, all eight wells are located in marginal basin settings; however, these wells do provide one-dimensional information on the lithology of the Messinian evaporites in marginal locations, which have then been extrapolated into the deep-basin domain owing to the similarity of the seismic character in both settings.

4.4. Seismic-stratigraphic framework and composition of the Messinian Evaporite

The Messinian evaporite is immediately recognisable on seismic profiles because of the two high-amplitude, regionally developed seismic reflections that define its top and base (M and N reflections, respectively, of Ryan, 1978). However, a detailed, basin-wide study of the intrasalt seismic stratigraphy by Allen et al. (chapter three; this thesis) indicates that the internal seismic character varies markedly between the Nile/Herodotus Basin and the Levantine Basin. In this section we provide a brief overview of the main seismic facies, seismic-stratigraphic architecture and likely lithologies present in the Messinian evaporite across these two basins.

In the Nile/Herodotus Basin the evaporite is seismically transparent (Fig 4.4). We have no borehole data with which to directly calibrate the composition of the Messinian evaporite in the deep basin domains but reflection-free areas on seismic sections are commonly observed within igneous provinces or where homogenous sand, shale or salt bodies exist (Mitchum et al., 1977a). The presence of large diapirs and seismic artefacts (e.g. pull-up
Effect) in the Nile/Herodotus Basin (see below), suggests that this transparent facies most likely represents a highly strained salt body, predominantly comprised of high velocity halite.

In contrast, the Messinian evaporite in the Levantine Basin contains alternations of transparent and highly reflective material, allowing us to identify and regionally map up to seven intrasalt seismic-stratigraphic sequences (S1-S7), comprised of four distinct seismic facies (SF) (see section 5.2 for further discussion). Once again, we assume that the reflection-free intrasalt sequences are halite-dominated. The high-amplitude intrasalt reflections have previously been interpreted as interbedded clastics (Garfunkel and Almagor, 1984) and/or sulphate-rich deposits (e.g. Gradmann et al., 2005; Netzeband et al., 2006; Cartwright and Jackson, 2008; Allen et al., chapter three, this thesis), the latter being a typical component of an evaporitic cycle (Warren, 2010). However, based on: (i) their basin-wide distribution and relatively uniform thickness; (ii) their correlation to anhydrite-rich units penetrated by marginal wells (e.g. Hannah-1; Gardosh et al. (2008); and (iii) their distinctly different deformation style, i.e. brittle compared to the ductile properties of the inferred halite (see also Cartwright et al., 2012), we interpret that these sequences mainly represent interbedded sulphate-rich (anhydrite) deposits. We recognise that precise calibration of the Messinian evaporite in the deep basin will remain uncertain until it is drilled.

4.5. Salt-related structural styles

Regional variability in salt-related structural styles is illustrated on seismic reflection profiles that are taken either from the 2D or 3D seismic datasets. In this section, we will first revisit the regional salt-related structural styles of the Nile/Herodotus Basin, which have been the focus of studies by Gaullier et al. (2000) and Loncke et al. (2006), before focussing on the Levantine Basin. In addition, we will use 3D seismic data from the salt-related contractional domain, offshore Lebanon, to perform a more in-depth analysis of the structural styles
observed throughout the multi-layered Messinian evaporites that characterise this part of the basin.

4.5.1 Nile/Herodotus Basin

Structural analysis of the Nile/Herodotus Basin reveals dramatic lateral asymmetry in structural styles (e.g. Gaullier et al., 2000; Loncke et al., 2006). Loncke et al., (2006) divides the area laterally into three structural provinces (western, central and eastern), with the eastern province extending into the western Levantine basin.

The Nile/Herodotus Basin contains many of the classic features associated with a salt-involved passive margin. Dip-oriented (SE-NW trending) seismic profiles shown in Figure 4.5 depict the typical structural styles observed along this part of the margin. We identify four down-dip provinces; (i) stable shelf; (ii) proximal domain of extension; (iii) intermediate domain of translation; and (iv) distal domain of contraction. The boundaries between these provinces are oriented parallel to the present-day shelf edge. In the following sections we describe and interpret the intrasalt and suprasalt structural styles, and their lateral variability within each province from shelf to deep basin.

4.5.1.1 Post-Messinian Stable Shelf

Proximally, the NDSF is characterised by a wide (up to 200 km), relatively stable, flat-lying shelf up to 3 km thick with minimal deformation. Seismic reflectors are parallel and continuous, rhythmically alternating from high to low amplitude, typical of turbiditic systems. The Messinian evaporite is absent in this province, and, instead, laterally discontinuous, high-moderate amplitude concave reflections define a series of canyon-like incisions into presumed Eocene/Oligocene/Lower Miocene deposits. The dipping surfaces within these incision fills also appear truncated by the overlying horizontal beds. This unconformity that separates the Plio-Pleistocene NDSF deposits from the underlying Messinian/pre-Messinian strata is thought to represent the erosional surface known as the N reflection (sensu. Ryan, 1978), which
formed in response to the dramatic sea-level drawdown and sub aerial exposure of the shelfal areas during the early stages of the MSC, therefore, preventing salt deposition in this area.

4.5.1.2 Extensional Province

The shelf-slope transition is marked by a belt of seaward-dipping normal faults that coincide with the original up-dip depositional pinch out of the MEC. Fault strike is broadly parallel to the local strike of the convex-into-the-basin shelf edge, resulting in a broadly arcuate distribution of fault arrays (see Loncke et al., 2006). Throw on these faults can exceed 1 s TWT (c. 1000 m), and they commonly detach downwards onto a relatively thin underlying salt unit and contain small salt rollers flanked by welds in their footwalls. Some of the faults tip out within the Plio-Pleistocene succession, although many breach the seabed and are associated with bathymetric scarps that are up to c. 0.5 s TWT high.

The lower half to two-thirds of the Plio-Pleistocene succession is tabular and displays no significant change in thickness across the faults. In contrast, the upper part of the Plio-Pleistocene succession thickens dramatically towards and across the faults, defining a series of landward-dipping growth wedges. This bi-partite seismic-stratigraphic architecture indicates: (i) the salt was originally covered by a tabular slab of Plio-Pleistocene overburden; (ii) thin-skinned salt-related deformation, in the form of salt-detected growth faulting, commenced sometime during the Plio-Pleistocene; and (iii) many of these faults have ceased movement in the recent past as supported by ponded deposits in the hangingwall lows (Fig 4.5).

4.5.1.2.1 Diapir Sub-Province

The diapir provinces (see Fig. 4.3 for location) straddle the mid-base of slope region in front of the extensional province, which coincides with the present-day edge of the salt basin. They are defined by nucleated zones of diapirism that form in elongate belts up to 50 km wide along the west and east flanks of the NDSF, but are less well developed in the central area (Fig. 4.6). The height of the diapirs increases basinward, ranging from c. 250 ms TWT
proximally, to over 1 s TWT more distally. The line spacing in our data makes it difficult to determine whether these diapirs are single stocks or walls but Loncke et al., (2006) uses high-resolution seismic and bathymetry data to interpret a combination of circular diapirs and elongate salt ridges. The increase in height of the diapirs coincides with a basinward thinning of the overburden from c. 2.5 s to c. 0.75 s TWT, which remains largely constant across the basin centre.

Overburden deformation generally mimics the top-salt morphology. However, in areas of more intense diapirism, upturning of reflections adjacent to the diapirs is observed and often, these larger diapirs pierce the seabed as evidenced by collapse features above the diapir crest (Fig. 4.7). This indicates salt movement began post-depositionally and is still ongoing in places. Also present are paired anticlines and synclines overlying remnant diapirs or complete salt welds. These reflection geometries are consistent with the effects of diapir rise and fall (Vendeville and Jackson, 1992a; Vendeville and Jackson, 1992b) producing salt-withdrawal mini-basins flanked by turtleback anticlines (e.g. Fig. 4.8).

4.5.1.3 Translational Province

The salt gradually thickens to > 1 s TWT seaward of the extensional domain and creates an inflated central salt plateau with an overall convexity to the top surface of the salt. It is interesting to note that, within this domain, which separates the upslope extensional domain and the downdip contractual domain, evidence for high strains, for example, diapir growth, is absent. Furthermore, the Plio-Pleistocene overburden, which is 1.5 - 2 s TWT thick, is tabular and largely undeformed, again suggestive of limited diapiric growth of salt. The width of this province varies but is >120 km in the central Nile/Herodotus Basin (see Fig. 4.3).

This province is thin- to - absent in the easternmost Nile/Herodotus Basin and at our resolution of interpretation, the extensional and contractual domains appear to merge and the low-strain translational province is not apparent. However high-resolution analysis of
shaded bathymetry data by Loncke et al. (2006) and Loncke et al. (2010) revealed the complex deformation associated with the presence of the seamount. A narrow, NW-SE-trending deformed belt, more than 200 km long is characterised by structures which trend obliquely with respect to the NE directed extension of the NDSF as the salt and overburden are diverted around the seamount.

4.5.1.4 Contractional Province

More distally, the salt in the contractional province displays variable thicknesses from zero (in welds) to 2 s (TWT) in fold cores, but maintains average thicknesses of c. 1 s (TWT) over much of the province. The greatest degree of variability in salt thickness occurs in the north-northwest of the mapped area where the salt comes into contact with the Mediterranean Ridge deformation front. Here, the top and base salt horizons, which previously showed relatively smooth, well imaged, gentle north dipping surfaces off the Egyptian margin, abruptly develop increased rugosity that coincides with a degradation of seismic imaging that makes the base salt surface particularly difficult to map in this area (e.g. Fig 4.9a).

Contraction is transmitted through the largely tabular lower four fifths of the overburden (c. 1.5 s TWT thickness) as a series of upright salt-cored anticlines trending broadly NE-SW that form bathymetric ridges at the present-day seabed. Fold wavelength is locally changeable but generally decreases towards the Mediterranean Ridge from c. 4-8 km (SE) to c. 1-3 km (NW). Amplitude increase toward the ridge is more pronounced with a sharp boundary separating low amplitude structures (50-100 ms TWT) in the south of the domain from high amplitude (200-400 ms TWT) structures toward the north. At the boundary between the Herodotus basin and the thick-skinned, NE-SW trending deformation front of the Mediterranean Ridge, folding passes into a zone of contractional faulting (c. 50 km wide). Faults dip both north and south with the former becoming dominant with increased proximity.
to the Ridge. Some areas, particularly to the southwest of the mapped area, show more intense shortening as expressed through imbrication of sedimentary layers (e.g. Fig 4.9b).

The majority of the uppermost fifth of the overburden (0.1- 0.2 s TWT thickness) is characterised by parallel, undeformed reflections that infill the bathymetry created by earlier deformation. However, in places, reflections diverge toward the hanging-wall of thrusts, which indicates syn-depositional movement of the salt and/or faults (e.g. Fig 4.9c). This indicates the variable stages of growth on these faults and the relative timing of activity of salt tectonics in this basin.

The structural styles described are indicative of considerable shortening in both regional and counter-regional directions with respect to the Egyptian margin. This may result from a combination of the northerly encroachment of the Nile Cone and the south-easterly-directed accretion of the Mediterranean Ridge due to subduction along the Hellenic arc. These processes are progressively reducing the size of the Herodotus Basin over time (Reeder et al., 2000), with the Mediterranean Ridge serving to inhibit the northward flow of the mobile evaporites resulting in an over-thickened, highly deformed salt and overburden. The distal edge of this province is located along the northern edge of the study area but is not fully imaged on our data set. However, it is interpreted to be defined by the E-trending arm of the Mediterranean Ridge and, therefore, contain similar salt-related structural styles to those described above and observed at the northwestern end of Figure 4.9a & b.

4.5.2 Levantine Basin

Despite their close proximity, salt-related structural styles observed in the Levantine Basin and Nile/Herodotus Basin show significant differences. The Messinian evaporite has a broadly tabular external geometry across much of the Levantine Basin (Fig. 4.10). The unit is up to c.1.6 km thick in the basin centre, with high, up-dip marginal pinch outs. The base salt (Fig 4.10 b, (i)) dips gently (< 5°) north-westward away from the Levantine margin, and
intrasalt reflections are largely concordant with sub-salt strata. The top salt (M) reflection (Fig 4.10 b, (ii)) dips more gently north-westward than the base salt (N) reflection, thus defining a seaward thickening wedge of salt (4.10 b (iii)).

As described above, the Levantine Basin evaporite has a distinctive multi-layered seismic character (Fig 4.10 c), which we interpret as intercalations of halite- and sulphate-rich units that define the 7 seismic sequences. Using two relatively small but high-quality 3D seismic cubes from the southern and northern ends of the Levantine Basin, Cartwright et al. (2012) indicated that the proposed sulphate-rich units (our sequences 4 & 6) contained numerous shortening structures (e.g. salt-detached thrusts, upright and asymmetric folds). The orientation, dip and vergence of these structures will be examined over the following sections in relation to the structural elements that define the eastern, western, northern and southern boundaries of the Levantine Basin. Respectively, these are; the Levantine Margin, Eratosthenes Seamount, Latakia Ridge and NDSF.

4.5.2.1 Levantine Margin; Eastern Boundary

Along the eastern margin, shortening of intra-salt units is most commonly transmitted through sequences 4 & 6 and defined by numerous imbricated thrust faults that have an en echelon arrangement in cross section. Longitudinally, deformation generally increases basinward with proximal regions characterised by broad wavelength (i.e. 2-5 km), upright to westward verging anticlines and widely spaced faults showing reverse offsets of c. 40-80 ms (TWT). More distally, folding is replaced by more closely spaced (i.e. every 1 km) eastward-dipping, imbricated thrust stacks with offsets increasing to c.100-150 ms (TWT), before passing into the relatively undeformed basin centre. Vertically, thrusts show a progressive increase in the magnitude of deformation, with reserve basinward offsets increasing from sub 50 ms (TWT) in the lower third of the sequence, to c.50-75 ms (TWT) in the centre and over 100 ms (TWT) towards the top of the sequence (Fig. 4.11).
The geometry (if not the thickness) of the Plio-Pleistocene overburden along the eastern margin of the Levantine Basin is similar to that observed along the Egyptian margin. The overburden forms a seaward-dipping and thinning wedge that spans the length of the margin. The wedge is c. 2.5 s TWT thick at the basin margin and c. 0.75 s TWT in the basin centre. The stable part of the shelf is narrower (c. 30 km) and the slope is steeper and more irregular away from the influence of Nile-derived sediments to the south and southwest. Reflections at the base of this unit show localised onlap and downlap against the top salt horizon in the proximal part of the study area but are generally concordant across the basin.

Two well-defined structural provinces are observed along the Levantine Margin; an updip domain of predominantly extensional deformation in which the salt is relatively thin, and a downdip domain of predominantly contraction deformation in which the salt is relatively thick. In the up-dip domain, seaward-facing, salt-detached normal faults, which have up to 200 ms TWT of throw, are developed. Small (125 ms TWT high by 1 km wide) salt rollers are developed in their footwalls, which are separated from one another by primary welds (Ben-Avraham, 1978; Garfunkel and Almagor, 1984; Gradmann et al., 2005; Bertoni and Cartwright, 2006; Cartwright and Jackson, 2008) (Fig. 4.12).

The updip extensional province passes abruptly downdip into a domain of contraction, and the intermediate translational province, which is so well-developed (up to 120 km wide) in the Nile/Herodotus Basin, is only c. 8-10 km wide along the Levantine margin. The contractional domain contains upright to westward-verging buckle folds with average wavelength of c. 1 km and amplitude of up to 20-60 ms (TWT) and faults with reverse offsets that predominantly dip east but occasionally occur in dip opposed pairs that define pop-up structures.
4.5.2.2 Eratosthenes Seamount (ESM) Area; Western Boundary

The bathymetric high created by the static Eratosthenes Seamount (ESM) marks the western boundary of the Levantine basin. Intrasalt deformation is highly variable and imaging is often poor close to the seamount but primarily, the structures described previously in sequences 4 & 6 show opposing dips and/or vergences when compared to the eastern margin. Westward-dipping thrusts that form imbricate thrust fans pass eastward into upright to eastward verging buckle folding with wavelengths of c. 1 km and variable amplitudes of between 20-60 ms (TWT), west-dipping thrusts more distally (e.g. Fig. 4.10).

The overburden at this western edge is a relatively constant thickness (c. 0.5 s TWT) with no differential loading of the underlying salt. Once again, imaging is often poor in the areas close to the seamount. Where visible, the structural styles are characterised by upright to eastward-verging buckle folds with average wavelengths of c. 1 km and amplitudes of up to 20-60 ms (TWT). Faults appear to have reverse offsets that predominantly dip west in this province as opposed to east along the eastern margin but, once again, occasional antithetic structures are observed locally. Seabed deformation is present basinwide but is relatively subtle and typically characterised by small, bathymetric 'bumps' created by uplifted hanging-wall scarps and anticline crests. The fixed position of the ESM is likely to limit the westward spreading of the salt and overburden leading to buttressing and, in turn, complicated backflow of salt, which may explain the dominance of counter-regional (i.e. westward-dipping thrusts and east-verging folds) structures observed in this area.

4.5.2.3 Latakia Ridge and Nile Deep Sea Fan (NDSF); Northern and Southern Boundaries

A NNE-trending seismic profile (Figure 4.13) illustrates the variations in salt-related structural style between the northern and southern margins of the Levantine Basin and the reader is referred to this as an accompaniment for the following observations. The salt
interval itself shows strong similarities to that described in the east and west, with two, opposing transport directions away from the north and southern margins instead. At the north end of the section, the northern boundary of the Levantine basin is marked by the bathymetric high created by the Latakia Ridge. The salt interval is relatively tabular across the basin and does not significantly thin onto the ridge high. Immediately seaward of the ridge, the base salt and IM1 are tilted basinward on the southern flank of a prominent anticline with a wavelength of c. 5 km and amplitude of c. 400 ms TWT. To the south of this fold, spectacular sets of north-dipping intrasalt imbricated thrusts are developed along sequence 4. These thrusts have 50-80 ms TWT of reverse offset and detach onto the basal surface of sequence 4. Further south into the basin, thrusts pass into a domain of upright to apparent southward-verging salt-cored anticlines that have average wavelengths of 2 km and amplitudes of 200 ms (TWT).

The Plio-Pleistocene overburden in the northern part of the basin can be divided into two seismic packages; the lowermost package forms the bulk of the overburden. It is relatively tabular into the basin centre (c. 350-450 ms TWT thickness) despite being intensively folded (amplitudes: > 200 ms TWT; wavelengths: c. 2-5 km) and locally thrusted above the salt in proximal areas. These folds are expressed at the seabed and are related with c. 50 ms of bathymetric relief. The uppermost seismic package of the overburden shows pronounced local changes in thickness across the region but has a maximum thickness of c. 125 ms (TWT). In the north, the sediments infill the synclines created by the salt-cored buckle folds. However, in the basin centre, where deformation of the lowermost package is reduced, the uppermost package is characterised by more continuous reflections that subtly thicken towards the central basin trough.

The structural styles described indicate that deformation within the salt and overburden is likely to have occurred post-depositionally. The overburden structures are
largely harmonic with intra-salt structures, though intrasalt deformation appears more intense (Fig. 4.13d). This could be due to the relative mechanical weakness of these units compared to those in the overburden. Nevertheless, this coupled relationship points towards a more recent trigger for salt and overburden shortening such as the collisional tectonics along the Latakia ridge. Whilst this is a thick-skinned process, it is suggested as a trigger for the thin-skinned deformation observed (i.e. thick-skinned fault-related folding tilts the base salt creating an elevation head gradient; see Fig 4.1).

Furthermore, the absence of thinning onto the ridge may indicate this is not the original depositional edge of the salt basin, and that the original edge may have been incorporated into the fold and thrust belt post depositionally. Parallel, flat-lying reflections of the uppermost seismic package of the overburden suggests that there has been no recent movement on these structures.

At the southern end of the section, the eastern flank of the NDSF marks the south-south-western boundary of the Levantine Basin. In contrast to the northern part of the basin, the salt interval thins dramatically towards the NDSF, leaving only small salt rollers in the footwalls of overburden faults, which are flanked by primary welds. As the salt thickens towards the basin centre, the distinctive Levantine layering becomes visible, but deformation along the layers is initially low, with minor, low-amplitude folds visible along sequences 4 and 6. However, sequence 6 appears to be truncated by the (now landward-dipping) top salt surface. Deformation then abruptly increases away from the NDSF, and, in contrast to the northern edge of the basin, is characterised by south-dipping imbricated thrusts developed along sequence 4 and sequence 6. Sequence 4 thrusts have 50-80 ms TWT of reverse offset and detach from the basal surface of sequence 4. Sequence 6 thrusts have offsets of >100 ms (TWT) and are strongly truncated by the top salt surface (see Fig. 4.13b).
As aforementioned, the seaward thinning wedge of the NDSF dominates the overburden and the structural styles here are covered by those described previously (see section 5). These were interpreted as structural provinces related to gravity spreading of the overburden under a differential load (i.e. updip extension, midslope translation and distal contraction). Where the intrasalt deformation is greatest, the overburden thickness is relatively constant (c. 350 ms TWT); although, overburden deformation is characterised by lower-amplitude (c. 50 ms TWT) folds, which show no consistent relationship with intrasalt folding and thrusting (Fig. 4.13c).

This decoupling of the structural styles within the salt and overburden are interpreted to result from different phases of deformation relating to i) early salt movement due to loading of the basin centres by the accreting salt body, and ii); later seaward translation of the overburden creating the modest contractional deformation to sit above the highly strained salt interval. Furthermore, the truncation of intrasalt structures by the top salt supports the theory that they must have developed prior to the end of the MSC. It is also possible that later loading of the margin by the NDSF has driven further salt flow basinward but this deformation has remained contained within the salt interval. For further discussion on these interpretations, see section 6.1.

4.5.2.4 3D Intrasalt Structure

Regional, 2D seismic reflection profiles provide an excellent tool with which to constrain the regional variability of salt-related structural styles in the Eastern Mediterranean. However, these profiles are too widely spaced to allow confident mapping of individual intrasalt and suprasalt structures. More detailed structural mapping of intra-Messinian sequences is achieved using 3D seismic data covering part of the contractional domain offshore Lebanon (see Fig.4.14a) and yielded the following results.
The pre-Messinian section within the cube is defined by the presence of an array of closely spaced (c.1 km intervals) normal-faults informally referred to as the ‘piano-key faults’ (Kosi et al., 2012; Hawie et al., 2013; Reiche et al., 2014). These faults disturb the base salt and S1 surfaces with the time-structure map in Fig. 4.14b revealing the prominent NW-SE trend of these structures.

The dominant style of intrasalt deformation is once again characterised by numerous structures associated with longitudinal shortening along sequences 4 and 6 including fault propagation folds, salt-cored anticlines, imbricated thrust stacks and large recumbent folds, which leads to stratal repetition and over-thickening of the salt sequence (Fig 4.15). However, the denser seismic grid also reveals variations in the strike, geometry and dip direction of these structures with shortening being most intense in the SE part of the cube (Fig 4.16). The thrusts in this area have well-defined scarps in the top surface of sequence 4 (up to 250 ms TWT), which grade into smaller thrusts and salt-cored shorter-wavelength anticlines towards the deeper basin in the NW of the mapped area. In plan view they display seawardly convex traces striking N-S to NE-SW, defining a radial distribution pattern with dip-directions of the fault planes varying from E-SE-S (Fig 4.16). The northern part of the cube is dominated by E-SE dipping thrusts, which have a more linear trace in plan view, largely striking NNE-SSW. To the NW edge of the cube, the thrusts grade into NNE-SSW-NE-SW trending upright anticline-syncline pairs.

The timing of deformation appears varied with the largest structures in the SE appearing to have ceased movement. They have often undergone peneplanation by the top salt horizon and do not seem to show evidence for reactivation. However, in outboard areas, intra-salt deformation seems to be on-going, or very recently ended, as evidenced by the seabed deformation. Overburden deformation appears considerably less mature compared to what is observed within the salt itself. It is characterised by long wavelength (i.e. > 1 km),
open folds in the lower half. The upper half remains relatively undeformed with a gently sloping, undisturbed seabed with the exception of marginal channel cut features associated with present-day systems along the Levantine margin. Additionally, in the northwest of the cube, overburden deformation abruptly intensifies and folds increase in amplitude to c. 200 ms (TWT) and extend through the overburden to the present-day seabed. These structures show a coupled relationship with both the intrasalt and subsalt structures (e.g. Fig 4.13; 14), which could implicate recent movement along the subsalt ‘piano key’ structures as a trigger for remobilisation of salt, and therefore deformation of the overburden. The relationship between the Miocene sub-salt structures and intrasalt deformation was the subject of a recent study from Reiche et al. (2014). Using high-quality pre-stack depth-migrated seismic data from across the Levantine Basin, this study also documents the clear coupling of shortening structures within the evaporite sequence and the extensional faults within the sub-salt interval.

4.6. Discussion

Regional 2D and 3D seismic analysis of structural styles within the Messinian evaporites and their Plio-Pleistocene overburden reveal strong contrasts between the Nile/Herodotus and Levantine basins. This study recognises the variability in (i) the structural styles of the present-day Messinian evaporite and the Plio-Pleistocene overburden; (ii) the triggers and drivers for salt mobilisation; and (iii) the far-field tectonic controls on intra-salt structural styles in the Levantine Basin.

The majority of structural styles described and their distribution across the mapped area are consistent with models of salt tectonics triggered, and driven, by differential loading of a tabular salt body (e.g. Cobbold & Szatmari, 1991; Ge et al., 1997; Schultz-Ela, 2001; Vendeville, 2005; Loncke et al., 2006). This mechanism, known commonly as ‘gravity spreading’ is believed to control salt tectonic deformation both along the northern margin of
Egypt (by the Nile Delta) and along the Levantine margin (by unnamed deltaic systems, some Nile derived, in the SE; e.g. Mart & Ben-gai, 1982; Buchbinder et al., 1993; Ben-Gai et al., 2005).

In the Nile/ Herodotus basin, gravity spreading of the Nile Delta is expressed by the formation of an array of classical salt-tectonic structures such as diapirs, welds and salt withdrawal mini-basins. These occur in a relatively broad belt that mimics the lobate geometry of the delta. In particular, the overburden is characterised by spectacular thin-skinned deformation with concentric domains of proximal extension and distal contraction, the former being characterised by seaward-dipping, salt-detached growth faults, which are associated with salt rollers and welds, and the latter, by salt-cored anticlines and imbricated thrust fans. The low strain translational domain separates the proximal extension from the distal contraction and is characterised by a basin-centre inflated salt plateau and weakly strained overburden.

Gravity spreading also occurred along the Levantine margin, although the structural styles differ from the northern Egyptian margin in three principal ways: (i) the seaward-thinning wedge is linear, hence, spreading is unidirectional as opposed to radial along much of this margin; ii) the belt of extensional deformation is narrower (c.20 km compared to c.50 km); (iii) large diapirs and/or withdrawal structures (e.g. turtles and mini-basins) are absent. The combined effect of these factors is that deformation is contained within the salt interval and accommodated along the more brittle inter-beds via folding, imbricated thrust stacks and duplex structures.

Over the following sections we will discuss these observations in relation to current models of salt tectonics and gravity-driven deformation to determine what triggered and drove prolonged salt tectonics across the eastern Mediterranean and how different triggers can produce very similar structural styles with different temporal evolutions.
4.6.1 Triggers and Drivers for Deformation of the Messinian Evaporite and Plio-Pleistocene Overburden

There are numerous examples of spectacular salt tectonics in other passive margin saline giants such as the South Atlantic (Duval et al., 1992; Davison, 2007; Jackson et al., 2014); Gulf of Mexico (Diegel et al., 1995; Rowan et al., 2000) and offshore Angola (Lundin, 1992; Hudec and Jackson, 2004; Quirk et al., 2012). However, salt movement along these margins started early under a dominant ‘gravity gliding’ control in relation to tectonic and thermal subsidence inducing a seaward tilt of the basement. The Messinian evaporites show intense salt movement, despite the fact that they were deposited tens of millions of years after thermal subsidence ended (Vendeville, 2005). It could be argued that both the surface loading by the Messinian evaporites and the removal and replacement of up to 3 km of water load implicates isostatic/flexural adjustment of the lithosphere as a more relevant mechanism for basement tilting along the basin margins (Govers et al., 2009).

In the Nile/ Herodotus basin, evidence for early marginal tilt is not immediately obvious, as the shelfal succession remains tabular as opposed to seaward thickening (e.g. Fig. 4.5). However, structural restorations in the Levantine Basin by Cartwright and Jackson (2008) have demonstrated that salt flow can be initiated under modest angles of tilt (i.e. less than 1°) and therefore, evidence for such low angles may not be distinguishable on the seismic from the Nile/Herodotus basin.

Beneath the eastern flank of the Nile Cone where the Nile/Herodotus transitions into the Levantine Basin, the erosional truncation of basinal intrasalt contractional structures by the top salt surface indicates early salt movement. Additionally, the proximal truncation of intrasalt reflections by the now down-warped top salt surface further implicates modest marginal tilting as the most likely mechanism for early salt flow. The origin of the tilting could be related to subsidence induced by reloading of the basins by the salt layer itself, causing
mobile salt to drain from structurally higher zones into the subsiding basins (e.g. Santos Basin, offshore Brazil; Davison et al., 2012). Later differential loading of the evaporites by the Plio-Pleistocene Nile Deep Sea Fan drove further basinward salt flow through expulsion of the mobile substrate leading to a basinward migrating weld and the gradual back-tilting of the top salt to dip landward (e.g. Fig. 4.17).

Although this is our preferred model, other mechanisms for the observed reflection geometries (i.e. down-warping of top-salt and truncation of brittle inliers by this surface) must be considered. These could result from; (i) the natural salt pinch out due to being the depositional edge of the salt basin (ii) a pre-existing depression (i.e. canyon cut), against which intrasalt reflections abut. The former scenario is unlikely as we see evidence for the presence of salt inboard of this proximal truncation in the form of remnant diapirs, salt rollers and welds as well as associated overburden deformation. Furthermore, one may expect to see the brittle inliers mimic the down-warping of the top salt in a pinch-out situation, which is not apparent here. The idea of a large canyon cut also seems implausible in this instance, as the relatively symmetrical shape of the apparent incision would suggest it had a trend that ran parallel to the Nile margin. However, systems of the scale implied that are likely to be incising the Messinian shelf at this time would almost certainly have had a more oblique trend with respect to the margin and their source, the River Nile.

Our seismic interpretation of the Levantine Basin strongly suggests two distinct phases of salt deformation; i) early (syn-depositional), and ii) late (post-depositional) phase separated by a period of non-deformation. This is in support of many previous studies specifically focussed on this topic (e.g. Netzeband et al., 2006; Bertoni and Cartwright, 2007; Gvirtzman et al., 2013). Evidence for an early (syn-depositional) tilt-induced salt deformation phase is observed through the NW dip on the intrasalt units prior to the end-Messinian unconformity, which truncates these units up-dip (see Fig. 4.10). This discordance, as
suggested by Gradmann et al. (2005), could be related to a depositional unconformity (i.e. toplap surface of a prograding clinoformal system). However, the widespread parallelism of the intra-salt sequences, their abrupt up-dip truncation against the top salt, and no visible evidence for downlapping or basinward convergence onto the base salt horizon suggest the origin of this discordance is related to erosional truncation (Mitchum et al., 1977; Bertoni & Cartwright, 2007). This means an early phase of tilting of the evaporite series in the Levantine basin had to have occurred syn-depositionally. Additionally, the near-horizontal top salt and Early Pliocene reflections help to constrain the relative age of this tilting to have occurred sometime between the deposition of sequence 6 and sequence 7.

The mechanism for the syn-depositional tilting in the Levantine Basin is not formally identified but as aforementioned, it could result from isostatic readjustment due to the loading (evaporite deposition) and unloading (desiccation) of the basin during the MSC. Alternatively, Gvirtzman et al. (2013) raise the possibility that the intense salt deformation described expresses the uplift of the Carmel block, which has been recently constrained to have started uplifting in the Late Miocene (Fig.13 of Gvirtzman et al., 2011). The maximum thickness of the evaporite in the Levantine Basin (c.1.8 km) could cause over 1 km of subsidence (Bertoni and Cartwright, 2007). Although the present-day intra-salt horizons show a parallelism with one-another, their original geometry may have been different if sedimentation was keeping pace with subsidence. This has been suggested by Bertoni and Cartwright (2007), due to high estimates for the rate of evaporite deposition (1-100 m/kyr) and in this case we may expect to see landward convergence of reflections. However, as we have shown in the northern Levantine margin 3D cube, the magnitude of erosion along the top-salt surface was significant enough to decapitate large intrasalt thrusts and anticlines (see Fig. 4.14) so may have been sufficient to remove evidence for this convergence also.
Later loading of the margin during the Plio-Pleistocene is a likely driver for more recent gravitational collapse of the margin driving further intra and supra-salt deformation through a gravity spreading mechanism in much the same way as observed in the Nile/Herodotus basin. However, it has also been suggested that the middle-to-late Pliocene uplift (c. 3 ma) of the Judean Hills rift shoulder, which creates crustal hinge zones that separate regions of offshore subsidence from onshore uplift (Horowitz, 2001; Cartwright & Jackson, 2008), could also have triggered margin instability and seaward flow of evaporites. It is likely that both are influential to some extent and that the deformation observed involves a combination of the two mechanisms as suggested by Cartwright and Jackson. (2008).

4.6.2 Far-field tectonic controls on structural styles

4.6.2.1 Nile/Herodotus Basin

Over much of the Nile/Herodotus Basin, a radial pattern of spreading away from the NDSF is dominant. However, more distally, the Mediterranean Ridge (to the north and northwest) and Eratosthenes Seamount (to the northeast) act as buttresses that serve to inhibit, and, in the case of the static Eratosthenes Seamount, deflect the flow of the mobile evaporites. Around the ESM, this is expressed through a NW-SE-trending deformed belt, more than 200 km long, characterised by structures which trend obliquely with respect to the NE directed extension of the NDSF as the salt and overburden are diverted around the seamount (e.g. Loncke et al., 2006 and Loncke et al., 2010).

At the Mediterranean Ridge, over-thickened salt creates complex zones of salt backflow as recorded by the reversal of thrust dips and fold vergence in the overburden. It has been suggested that the intensity of surface deformation across the Mediterranean Ridge toe exceeds what is expected from the deep-seated tectonics (i.e. crustal accretion as the Africa and Eurasia continue their collision) currently active in this region (Chaumillon et al., 1996; Chaumillon and Mascle, 1997). This increased surface deformation is believed to be a result of
the interaction of the evaporites with the active southerly-directed deformation front of the ridge, which serves to disturb the salt interval, creating numerous decollement levels within the overlying evaporites. Consequently, much of the accreted outer wedge of the Mediterranean Ridge is attributed to the thrusting and imbrication of the MEC along these intrasalt detachment surfaces.

4.6.2.2 Levantine Basin

Many previous studies of intrasalt deformation across the Levantine Basin largely base their interpretations on dip-orientated sections off the Israeli and Lebanese margin (Almagor & Garfunkel, 1979; Garfunkel & Almagor, 1984; Gradmann et al., 2005; Bertoni & Cartwright, 2006). The Levantine Basin is more structurally enclosed than the adjacent Nile/Herodotus and therefore, the interfering boundary conditions that define the shape of this basin almost certainly contribute to the relationship between the Messinian and Plio-Pleistocene extensional and contractional provinces, potentially resulting in a more complicated situation than previously acknowledged.

Although alluded to briefly (e.g. Cartwright and Jackson, 2012), the structural styles influenced by far-field processes taking place at the north, west and southern basin boundaries are underrepresented in the literature, and we argue that the Levantine Basin salt tectonics are significantly influenced by these processes, thereby encouraging multidirectional salt flow towards the low-strain basin centre.

Whilst a large proportion of the shortening observed across the Levantine Basin is attributable to evaporite flow in response to marginal tilting and loading along the Levantine margin, the integrated 2D and 3D seismic structural mapping of regional and localised transport directions within the salt highlights the variability in the strike of the thrust structures and presents an inconsistency with what might be expected if gravity spreading and gliding along the Levantine Margin were the sole driving force. At the 2D seismic resolution,
the orientation of the intrasalt structures on a N–S section across the basin differ significantly from their orientation in an E–W section. However, through 3D seismic analysis in the northern Levantine Basin, a more intricate assemblage of structural trends are revealed that indicate a significant role being played by the tectonic lineaments that define the northern boundary of the basin (i.e. the ENE-WSW trending Latakia Ridge). This variability in the orientations of thrust and fold structures suggests i) a progressive rotation of the principal stress vectors through multiple phases of deformation; or, ii) influences from far-field compression, which may have served to skew principal stress orientations. We favour the latter explanation owing to the relative youth of this basin making it unlikely that regional stress field variations are responsible for multiple shortening directions observed.

4.6.3 Mechanics of Salt Flow

The relative mechanical weakness of salt means that it can flow over geological timescales under minimal shear stresses (Urai et al., 1986; Rowan et al., 2004; Hudec & Jackson, 2007). Salt typically flows by a combination of Poiseuille and Couette flow modes (Fig.4.2), which are likely to vary across the salt body and are dependent on the flow triggers and individual boundary conditions (Weijermars and Jackson, 2014). Where salt is more homogeneous and thus seismically transparent due to high magnitudes of post-depositional flow (e.g. the Nile/Herodotus basin), the internal mechanics of salt flow can be difficult to determine. However, in multi-layered salt that has been only weakly strained, such as that the Levantine, reflective intrasalt layers can record intrasalt strain (Van Gent et al., 2011; Cartwright et al., 2012; Jackson et al., 2014). Assuming areas of higher longitudinal strain would be more intensely deformed, these areas are symbolised by thrusting and buckle folding of the competent layers and can therefore, be used as a proxy for quantifying strain within the evaporite sequence.
The progressive upwards increase in intrasalt deformation between sequences 4 and 6 in the Levantine Basin is characteristic of Couette-type flow (see Fig. 4.11), perhaps driven by Plio-Pleistocene sediment loading (cf. Cartwright et al., 2012). However, we know some degree of salt flow is likely to have occurred prior to overburden deposition related to tilting of the base salt. The observation that the upper part of the salt (sequence 6) is, in some areas, gently dipping, truncated and overlain by sub-horizontal Plio-Pleistocene strata (e.g. Fig. 4.17) implies that intrasalt deformation initially occurred prior to deposition of the overburden and was perhaps later augmented by sediment loading and gravity spreading. We suggest open channel flow (see Weijermars and Jackson, 2014; their figure 2e), where salt on a slope with no overburden moves downslope like a salt glacier, may have dominated the early stage of deformation (e.g. Albertz et al., 2010; Davison et al., 2012). In this scenario a Couette-style flow regime is also anticipated, as the shear stress would be greatest and salt flow slowest at the base. However, analogue modeling of a multi-layered, mechanically stratified salt (e.g. Fig 4.18), much like that encountered along the Levantine margin, reveals the superimposition and gradual modification of smaller scale flow mechanics (2nd order) by larger scale flow mechanics (1st order) within the individual layers (Weijermars and Jackson, 2014).

As a consequence, we envisage superimposed intrasalt flow regimes occurring at different scales and driven by different processes. During the initial stages of deformation, one may expect early tilting and gravitational drainage of salt to produce a dominant Couette flow, with minor Poiseuille component (see Fig. 4.2) in the lowermost layers (relating to squeeze flow from the accreting salt sheet and/or early progradation). Later deformation was driven by gravity spreading which further intensified the original Couette component of salt flow.
4.6.4 Nile/Herodotus- Levantine Strain discrepancy

Despite the impressive internal deformation of the evaporite, it can be inferred that salt tectonics is generally less mature in the Levantine Basin as evidenced by the absence of structures that result from prolonged salt flow such as diapirs, welds and withdrawal synclines, which are common in the Nile/Herodotus Basin. A simple assumption that can be invoked to explain this is that Nile/Herodotus existed as a separate salt basin composed primarily of homogenous salt and therefore required less strain to initiate flow. However, we favour the interpretation of Allen et al. (Chapter 3) who envisaged a single salt basin that has undergone different syn-and post-depositional deformation histories dependant upon more localised influences, particularly basin geometry and differential marginal loading. Under this assumption, intense flow-related deformation may be inhibited by other factors if the resisting forces exceed the driving forces.

Numerical modelling of salt tectonics driven by differential loading (Last, 1988; Gemmer & Ings, 2004; Gemmer et al., 2005) predicts that the finite deformation pattern of a salt basin depends on its relative width and the length scale of the overburden thickness variation (w/l). A wide salt basin causes distributed domains of landward extension and seaward contraction whereas, in narrower salt basins, deformation is concentrated along narrower belts, resulting in higher strain rates leading to the system reaching gravitational equilibrium at an earlier stage (Gemmer & Ings, 2004).

The Levantine Basin is narrow with overburden spreading occurring over a width of c. 200 km compared with c. 500 km in the Nile/ Herodotus Basin and as noted earlier, the extensional domain along the Levantine margin is also narrower than its Nile/Herodotus counterpart. It is therefore suggested that the Levantine Basin represents a ‘lower strained’ gravitationally equilibrated version of the Nile/Herodotus Basin, which allows the exquisite
preservation of the primary stratigraphic layering that would otherwise be destroyed by more intense salt flow-related deformation such as that observed in the Nile/Herodotus Basin.

### 4.7. Conclusions

High quality regional 2D and localised 3D seismic datasets are used to investigate the variability in salt-tectonic structural styles and their triggers and drivers across the Nile/Herodotus and Levantine Basins. The results presented and discussed can be summarised as follows:

- Structural analysis of the Nile Herodotus Basin reveals dramatic lateral and down-dip asymmetry in structural styles that are consistent with characteristic, gravity induced, passive margin salt tectonics (i.e. updp extension, midslope translation and downdip contraction).

- The evaporite is largely seismically transparent across the Nile Herodotus Basin and the presence of large diapirs and seismic artefacts (e.g. pull-up effect) suggests that this transparent facies most likely represents a highly strained salt body, predominantly comprised of halite.

- In the Levantine Basin, regionally mapable alternations of transparent and highly reflective units (interpreted as halite and anhydrite couplets) define up to seven intrasalt seismic-stratigraphic sequences (S1-S7), comprised of four distinct seismic facies (SF).

- Reflective intrasalt layering in the Levantine Basin permits the recognition of numerous structurally complex areas dominated by shortening along sequences 4 & 6 defined by imbricated thrusting and upright-verging folds.

- These structures are consistent with down-dip transport directions with respect to the variably striking basin boundaries of the Levantine Margin, Latakia Ridge and Nile
Deep Sea Fan indicating multi-directional salt flow towards the low-strain basin centre.

- The timings and mechanisms of salt flow can vary both laterally and vertically through the Levantine Basin succession and we envisage superimposed intrasalt flow regimes occurring at different scales and driven by different processes.

- During the initial stages of deformation, one may expect early tilting and gravitational drainage of salt to produce a dominant Couette flow, with minor Poiseuille component in the lowermost layers (relating to squeeze flow from the accreting salt sheet and/or early progradation). Later deformation was driven by gravity spreading which further intensified the original Couette component of salt flow.

- The structural styles along the basin margins can be very similar (i.e. salt-cored anticlines and imbricated thrust fans) but the triggers and drivers for the salt flow that creates them can be very different and potentially, have different ages.

- Salt tectonics is generally less mature in the Levantine Basin compared to the Nile Herodotus Basin, which we interpret to be related to their development as part of a single saline giant that occupies at least the area of our study. However, due to more localised influences (particularly basin geometry and variable degrees and styles of marginal loading), the Nile Herodotus Basin and the Levantine Basin have undergone different syn- and post-depositional deformation histories although their depositional development is thought to be near synchronous.

- This has resulted in the exquisite preservation of the primary stratigraphic layering that would otherwise have been destroyed by more intense salt flow-related deformation such as that observed in the Nile Herodotus Basin.
4.8. References


Ryan, W., 1978, Messinian badlands on the southeastern margin of the Mediterranean Sea: Marine Geology, v. 27, no. 15.

Figure 4.1: Comparison of the two main triggers for initiating and driving prolonged salt flow. (a) A laterally varying overburden thickness above a horizontal, tabular salt layer. (i) Initial stage, assuming instantaneous overburden deposition, i.e. loading of a salt layer (black) by a sediment wedge (light grey) creates a pressure head gradient from left to right. (ii) Salt flows along pressure head gradient leading to expulsion and eventual welding coupled with collapse of the proximal overburden (1), and inflation of the distal salt and overburden (2) resulting in up-dip extension and down-dip compression-related structures; (b) Salt flow and overburden deformation assuming a uniform overburden thickness above an inclined, tabular salt layer. (i) Initial stage: prior to base-salt tilting, and with a tabular overburden, salt remains stable due to the lack of any pressure head gradient. (ii) Tilting creates an elevation head gradient from left to right and salt will flow along this gradient. Note the similarity between the resultant salt body geometries and structural styles despite the different triggers. Compiled and modified from: Schultz-Ela, 2001; Vendeville, 2005 and Hudic & Jackson, 2007. Schematic representations, not to scale.
Figure 4.2: Schematic cross-sections through a hypothetical multilayered evaporite sequence of alternating competent (white) and incompetent (black) units affected by (a) Poiseuille flow; (b) Couette flow. Shortening of competent unit symbolised by buckle folds. Longest arrows indicate faster flow and therefore, higher percentage of shortening. Note these are end-member models and both assume the presence of an overburden prior to initiation of salt flow.
Figure 4.3 (a) Base map illustrating the confining structural elements affecting the Messinian salt basins under investigation in this study (The Herodotus and Levantine specifically) and furthermore, how deformation is transmitted through the salt and overburden; areas with no colour indicate underformed strata - i.e. a translational province. (see inset for continental context of the study area). (b) Cropped map to illustrate: (i) 2D & 3D seismic coverage and well data available for this study; (ii) locations of key seismic lines displayed, and (iii) location of deformation corridor between the Nile/Herodotus and Levantine Basins. Base map generated using GeoMapApp. (2012). Structural trends compiled after McCluskey et al. (2000); Abdel Aal et al. (2000); Robertson & Mountrakis. (2006); Loncke et al. (2006) and Gardosh et al. (2008).
Fig 4.4 (a) Plio-Pleistocene overburden isochron highlights the thick sedimentary lobe of the Nile Deep Sea Fan (NDSF) extending out into the deep Nile/Herodotus basin (labelled). (b), Messinian salt isochron highlights the marked lateral thickness changes and considerable influence of the NDSF (outlined in black) on underlying salt distributions. (c) Regional composite seismic line (a-a’) shows the intimate inverse relationship between the thicknesses of the salt layer and the overburden.
The Messinian Unconformity ('N' reflection)

Pre-Messinian acoustic basement

Asymmetric, triangular salt rollers occupy footwalls of faults

Messinian/Pre-Messinian Drawdown Channels?

Hanging-wall growth packages record syn-tectonic sedimentation

Ponded deposits mark cessation of recent fault movement

Ponded deposits mark cessation of recent fault movement

Shelf is tabular and shows no signs of early margin tilting (e.g. seaward thickening)

Salt-cored buckle folding

Fig. 4.5 Regional composite dip line overview of the salt and overburden structural styles across the Nile/Herodotus basin. The section encompasses all the classic structural provinces associated with basin-ward salt expulsion; passing from up-dip extension to down-dip compression. The landward shelf area remains stable due to the absence of salt. Note the data gap which accounts for the apparent abrupt thickening of the salt, though this is interpreted to be more gradual (see Fig. 4.3 for location).
Fig. 4.6 Dip oriented seismic lines showing the structural styles of the diapiric domain across (a) the western flank of the Nile cone and (b) the eastern flank of the Nile cone (see base map for location). Note that diapirs tend to nucleate at the proximal edge of the present-day salt basin where the base salt flattens out. (see Fig. 4.3 for locations).
Fig. 4.7 Salt diapirism in the Nile/Herodotus basin. (a) Uninterpreted section; (b) geoseismic interpretation of section, and (c) close-up of salt-sediment interaction around the diapir. (see Fig. 4.4 for location).
Fig. 4.8 Uninterpreted seismic section (a) accompanied by geoseismic interpretation (b) showing the collapse of salt diapirs and the localised depocentres that form above them (see Fig. 4.4 for location).
Figure 4.9. Seismic examples of folding and faulting of the salt and overburden that define the contractual domain in the distal limit of the Nile/Herodotus salt basin which is believed to be closely linked to the buttressing effect of the Mediterranean ridge collision belt. (see Fig. 4.3 for

(a) sub-marine canyon systems

(b) shallowing of thrusts could indicate younging of structures away from ridge

(c) no growth in later ponded deposits

earlier growth strata

salt-cored anticlines

weld
Degradation of intra and sub-salt imaging possibly related to buttressing against ESM leading to intense folding and thrusting?

Intra Messinian sequences 1-6 show a gentle but fairly uniform basinward dip whereas the top salt is relatively flat-lying giving IM7 a basinward thickening wedge geometry. Updip truncation of internal layering by Top Salt seabed deformation related to activity of sub-surface structures salt backflow?

Fig 4.10: (a) Regional dip line across the Levantine Basin with respect to the NE-SW striking basin margin (VE=15) and located in Fig. 4.3. Box shows location of close up shown in Figure 4.12. (b) Time-structure maps along (i) base salt and (ii) top salt from the 2D survey coverage across the Basin, (iii) isochron map calculated for the interval between the top and base salt horizons. All maps have 200 m contour spacing. Dashed line indicates location of seismic profile displayed (b-b’). (c) Seismic-stratigraphic scheme for the Messinian evaporites of the Levantine basin. Cyclic alternations of transparent, mobile units with brittle, high amplitude units is observed and mapped regionally as shown in (a).
Fig. 4.11 Intrasalt structural styles along the Levantine margin showing the upwards increase in shortening intensity expressed through a change from undulating folds in sequence 4 to imbricated thrusting in sequence 6. (see Fig. 4.10 for location).
Figure 4.12. Inset close-up of welding and salt rollers along the Levantine Margin with associated collapse of the overburden accommodated along mostly seaward-dipping normal faults although buried keystone grabens create antithetic structures. (See Fig. 4.10 for inset location).
Fig. 4.13 (a) Regional N-S composite seismic line across the Levantine Basin incorporating the Nile Delta and Latakia Ridge basin margins (northern section of composite courtesy of PGS) (b) Line interpretation of (a). Fig 12 (c & d) Close-ups of intra-salt deformation along brittle inlier units sequences 4 & 6, to allow comparison of structural styles induced by different triggers. (c) salt movement basinward, triggered by thin-skinned processes related to 'gravity spreading' of the Nile deep sea fan. (d) Post-depositional thick-skinned deformation associated with the active Latakia ridge tilts the base salt leading to salt flow under a predominantly 'gravity gliding' mechanism. Note the striking similarity of the structural styles observed but also that they have clearly different timings and triggers.
Fig. 4.14 (a) N-S oriented 2D seismic line across the north and central Levantine basin showing the structural setting and basinal context of the 3D seismic cube (yellow bar). Note that it covers the basin centre where intrasalt facies variability is greatest. (b) Time-structure map of the base salt surface with interpretation of faults, which break the base-salt surface.
Fig. 4.15 Time structure map of the IM4 top surface across the 3D cube accompanied by examples of typical intra-salt deformation.
Fig. 4.16: Detailed structural analysis along the top surface of sequence 4 throughout the 3D cube in the Levantine basin. A clear radial pattern of fault strikes emanate from the SE of the mapped area, where a high-displacement, NE-SW striking thrust front can be observed, which propagates NW. (arrows on base map estimate direction of salt flow with respect to the boundary conditions).
Differential loading by NDSF causes basinward salt expulsion and driving prolonged intra-salt flow.

Fig. 17. Schematic model for the genesis of intrasalt truncation patterns observed in the southwestern Levantine Basin beneath the Nile Deep Sea Fan (NDSF); (a) early-stage salt deposition: following drawdown and isostatic rebound due to the removal of the water load, salt deposition gradually begins to infill the basin. (b) late-stage salt deposition: periodic recharge events lead to further salt accretion and re-loading of the crust. Consequently, basin centre subsidence coupled with marginal uplift tilts the base salt basinward creating an elevation head gradient from left to right along which, salt flow is directed. (c) post-salt marginal loading: Plio-pleistocene deposition of the NDSF loads the margin and drives further seaward flow of salt although where there is no truncation on intrasalt layering in the lower part of the salt succession, it can be difficult to distinguish between the two mechanisms.
**Fig. 4.18:** Detail of flowing physical model in a mechanically stratified salt interval (in this case, material substitutes for salt interbedded with sands were used). Differential flow to the right (gravitationally driven by gentle tilt of about 1°). First-order flow (across entire model thickness) shown by the passive marker is Couette. Second-order flow (within each black layer (salt) is almost pure Couette near the top where the load is negligible. With increasing depth, components of Poiseuille and squeezing flow increase due to an increase of load applied by the accreting salt layer. Note the superimposition of different flow mechanisms and different scales within the system. Model taken and modified from Weijermars and Jackson (2014), c/o Tim Dooley, Applied Geodynamics Laboratory, Bureau of Economic Geology.
5. | CHAPTER FIVE | MANUSCRIPT III

IMPACT OF MULTILAYERED EVAPORITES ON SUBSALT DEPTH CONVERSION:
TESTING A NEW APPROACH IN THE OFFSHORE MESSINIAN EVaporite
COMPLEX OF THE NORTHERN LEVANTINE BASIN.

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Abstract

Recent discoveries in the pre-Messinian of the Levant and offshore Cyprus areas have heightened industry interest in this hitherto underexplored region. Although the majority of reservoirs are located in the presalt succession, particular attention is now being paid to the seismic facies and structural styles present within the salt, principally due to the impact these may have on presalt seismic imaging, mapping and depth conversion.

Previous depth conversion attempts have adopted a somewhat simplistic approach, characterising the Messinian as a continuous, homogeneous, halite-dominated layer and applying a single velocity function (3900 m/s) to the interval. However, it is well known that the Messinian evaporite contains a range of seismic facies, is likely lithologically heterogeneous and is therefore characterized by highly variable seismic velocities both laterally and vertically. If these velocity variations are not taken into account, the depth, size and shape of possible presalt prospects may be uncertain and increase exploration risk. It is clear that a more sophisticated velocity model is thus required to better understanding the presalt prospectivity in the pre-Messinian succession of the Levant Margin.

In this study we construct a new intrasalt velocity model for the Messinian salt by undertaking a detailed seismic-stratigraphic analysis of this interval. Velocity data from an offset well (Hannah-1) provide a direct calibration of intrasalt velocity variations, and their link to lithology and seismic facies. Additional confidence in our velocity model is gained by comparing the studied Messinian succession with velocities encountered in analogous depositional settings.

Our multi-layered depth conversion approach predicts that the base Messinian surface is up to 400 m deeper than the one generated using a single velocity value. A more detailed facies sub-division and associated depth conversion method has therefore helped us to better understand the range of geometries of the base-salt and, potentially presalt
prospects, thereby reinforcing the importance of applying a multi-layered approach to depth conversion in salt-bearing sedimentary basins.

5.1. Introduction and Rationale

A key step in the analysis of sedimentary basins is the conversion of seismic horizons mapped in time (seconds two-way time) to depth (metres or feet); this process is known as depth conversion. Accurate depth conversion of seismic horizons requires knowledge of the subsurface acoustic velocity structure of the Earth, which is directly related to its composition. Because they directly (i.e. core) or indirectly (i.e. petrophysical analysis) sample the subsurface, boreholes can provide key information on the subsurface velocities. However, in areas with little or no well control, depth conversion can be problematic. No wells penetrate the basin centre of the Messinian salt thus detailed seismic facies analysis, paired with lithological data provided by basin-margin wells, provides one method to prognose the lithology and infer the velocity structure of basin-centre salt.

The Messinian evaporites of the Eastern Mediterranean are characterised by a thick (c. 1.6 km), multi-layered salt-rich succession, known as the Messinian Evaporite Complex (MEC). They were deposited during the Late Miocene (5.96-5.33Ma) largely in response to hydrodynamic isolation of the Mediterranean from the Atlantic which led to the Messinian Salinity Crisis or ‘MSC’ (Ruggieri, 1967; Krijgsman et al., 1999; Garcia-Castellanos et al., 2009). Major evaporitic drawdown of the entire Mediterranean at this time resulted in salt deposition in the deep basin and incision along the basin margins (Hsü et al., 1973; Hsü et al., 1977; Ryan and Cita, 1978).

Previous attempts to depth convert presalt seismic horizons in this area have adopted a somewhat simplistic approach, characterising the Messinian as a continuous, homogeneous, halite-dominated layer, and applying a single velocity function (3900 m/s) to
the interval. However, seismic reflection data indicate that a wide range of seismic facies, and likely lithologies and velocities, occur within the MEC (Mart and Ben-Gai, 1982; Gradmann et al., 2005; Bertoni and Cartwright, 2006; Netzeband et al., 2006; Hübscher et al., 2007; Cartwright et al., 2012; Gvirtzman et al., 2013; Reiche et al., 2014).

It is generally assumed that the instantaneous seismic velocity \( V_1 \) increases linearly with depth \( z \). In areas of uniform lithology that have not undergone severe structural deformation, depth conversion can often be performed according to a simple mathematical function:

\[
V_0 - k
\]

Where \( V_0 \) is a constant and \( K \) is the acceleration/compaction factor (Marsden, 1992). However, for areas where the lithology changes dramatically between layers but the layers are themselves laterally persistent (i.e. not strongly deformed), a single, constant velocity value, which is considered the mean value for the layer, is used (“layer cake” method; Marsden, 1989).

We focus on a small part (c. 50 x 50 km) of the northern Levantine Basin, offshore Cyprus, south of the Latakia Ridge and to the east of the Eratosthenes Seamount (Fig. 5.1). This region is considered a frontier exploration area, although discovery of a large (3-9 tcf) gas accumulation (Aphrodite) southeast of the Eratosthenes Seamount (Fig. 5.1) by Noble Energy in 2011, in addition to three other gas discoveries offshore Israel (Tamar, Dalit and Leviathan), has heightened interest in this area and support the presence of an extensive gas generation system that is expected to extend throughout the entire Levantine Basin into offshore Cyprus (Bowman, 2011). As a result, there is renewed industry interest in the Eastern Mediterranean as a whole, thus a detailed understanding of the stratigraphy of the
Messinian salt and the incorporation of this information into existing velocity models is both timely and essential. Improved velocity models will allow accurate conversion of presalt seismic horizons from time to depth, thus reducing uncertainties in the depth conversion of sub-salt prospects in addition to reducing the risk associated with drilling expensive exploration wells in these remote and underexplored basins.

The key aims of this study are to; i) determine the vertical and lateral variability of seismic facies and velocity of the MEC; ii) build a multi-layer velocity model to better represent the heterogeneity of the salt succession encountered in the basin centre; and iii) test the impact that a multi-layer velocity model has on depth conversion of a specified, single horizon, in this case, the base salt.

5.2. Dataset

Our dataset consists of 2D seismic reflection profiles with a total line length of 4685 km. These data cover an area of ca. 18000 km². The dataset includes profiles from three different surveys acquired in 2006 and 2008 by PGS and Spectrum in 2000. A total of 82 lines were used in this study (Fig. 5.1). The 2006 PGS survey was acquired offshore Cyprus with the Falcon Explorer vessel using an 8.1 km streamer. The streamer comprised 648 channels with a group length of 12.5 metres. During the 2008 survey PGS obtained new seismic profiles offshore Cyprus and Lebanon. Both profiles were recorded by a single 8.1 km long streamer. The streamer consisted of 1656 channels for the offshore Cyprus part of the survey and 1296 channels for offshore Lebanon, with group lengths of 12.5 metres for both surveys. Both surveys were recorded with a sampling rate of 2.0 milliseconds. All recordings were processed with full pre-stack time migration sequences that included noise attenuation, de-multiple and full Kirchoff 2D pre-stack time migration. Seismic reflection profiles from the 2006 survey were reprocessed in 2011 to optimize imaging. The Spectrum
seismic profiles were collected in 2000 with G.GUN sources and reprocessed in 2011. PGS seismic profiles image down to 9 seconds two-way time (s TWT), whereas seismic profiles acquired by Spectrum image down to 12 s TWT. Data in both surveys are un-interpretable below 8 seconds TWT due to poor imaging.

As a result of using different vintage seismic surveys, line spacing varies from ca. 10 km in the south to 5 km in the north (Fig. 5.1a). The closest available well that contained stratigraphic formation tops and a useable sonic log was Hannah-1, which is located offshore Israel, about 120 km south of the seismic dataset. Data from this well allowed us to at least partly calibrate lithology to seismic expression and velocity. The Hannah-1 well, which is located near the basin margin and the pinch-out of the salt, penetrates a mostly reflection free interval. According to Gardosh et al. (2008), the Messinian section is represented by carbonate reef debris at the base, a halite unit in the middle and an anhydrite at the top (Fig. 5.2).

5.3. Methodology

No wells are available in the area covered by seismic data. However, based on seismic facies analysis, changes in intrasalt structural style and comparisons with data elsewhere, a total of nine horizons were interpreted, these being; one horizon from the Pre-Messinian strata, Base Messinian, five intra-Messinian horizons, Top Messinian and Seabed (Fig. 5.3 a)

5.3.1. Construction of velocity model and depth conversion

Construction of a velocity model for depth conversion of a seismic horizon mapped on time-migrated data typically assumes that each mapped unit has a different but relatively constant internal velocity (layer-cake model; Marsden. 1989). Our approach is as follows: (1) extraction of intrasalt velocity values from the Hannah-1 well sonic log; (2) assignment of
intrasalt velocity values to intrasalt units mapped within the area of seismic data coverage; (3) depth conversion of the seabed horizon using a constant water velocity of 1500 m/s; (4) generation of isopachs for each intrasalt layer below the seabed by multiplying each isochron map by the constant velocity values derived from the Hannah-1 well; (5) addition of the first isopach (Plio-Pleistocene) to the seabed depth map in order to create a depth surface map of the top Messinian horizon; and (6) application of step (4) to the other horizons to obtain depth-converted surfaces (see Appendix A).

5.4. Results

5.4.1 Seismic Facies Mapping

The basal and upper bounding surfaces of MEC are correlated to Horizons N and M respectively; two regional, deep basin seismic events traditionally interpreted to mark the confines of the Messinian evaporites in the Mediterranean basin (Ryan et al., 1973). Offshore, these horizons are clearly recognised by their continuous, high amplitude character and the conspicuous change in seismic facies generated by, in the case of the N horizon, the transition from finely layered Middle-Upper Miocene strata to the overlying chaotic salt layer and for the M horizon, the change from chaotic salt to the overlying finely layered Plio-Pleistocene strata.

Overall, the MEC has a broadly tabular external geometry across much of the Levantine basin. The unit is up to 1.6 km thick in the basin centre, with high, up-dip marginal pinch outs. The base salt dips gently (< 5°) northwestward away from the Levantine margin, and intrasalt reflections are largely concordant with sub-salt strata. The top salt (M) reflection dips more gently northwestward than the base salt (N) reflection, thus defining a seaward thickening wedge of salt (Fig. 5.1b).
Internally, the salt has a distinctive multi-layered seismic character (Fig. 5.3a), defined by alternating transparent and highly reflective units. The more reflective units accommodate numerous shortening structures (e.g. salt-detached thrusts; upright, verging and isoclinal folds). Mapping of the intrasalt horizons across the Levantine Basin allowed us to define six intrasalt seismic sequences (Fig 5.3 b & c) that we interpret to be lithological and acoustically distinct and characterized by specific seismic velocities. The base Messinian horizon is the ‘target’ horizon for the depth conversion test we perform later in the chapter.

### 5.4.2 Layer-Cake Variable Velocity Approach

Seismic velocities derived from the sonic log data are plotted against depth in Figure 5.2. This indicates that carbonate reef debris has velocities of 2200-4000 m/s, that halite, which forms the bulk of the succession in this location, has an average velocity of 4450 m/s, and that the anhydrite at the top of the succession covers a range of velocities from 3800-5800 m/s. Using a combination of information from the Hannah-1 well and estimated lithology values for those units with no direct well calibration (according to average velocity values for given lithologies, Mavko. 2005, Appendix B), we propose a revised multi-layered ‘layer-cake’ velocity model based on the seismic facies scheme defined in Fig. 5.3b.

Using data from the Hannah-1 well (Appendix C) we assigned velocity values to the seismically defined layers identified in the area of interest (Fig. 5.4). The lowermost Messinian interval (S1) is interpreted to represent reef debris and has been assigned a velocity of 3250 m/s based on an average value derived from the Hannah-1 well for the analogous carbonate reef debris unit (i.e. 2200-4000 m/s). S2 and S4 and S6 are interpreted to be composed of halite and to be characterised by velocities of 4450 m/s (salt velocity in Hannah-1) (Fig.5.2). S3 and S5 were interpreted to be composed of limestone, anhydrite, shale and halite, and were assigned velocity values of 4250 m/s. Our inference of a halite vs.
non-halite system is partly based on structural styles within the salt being similar to those documented in studies of the Messinian salt from the southern Levant (e.g. Gradmann et al., 2005; Bertoni and Cartwright, 2006). The transparent sequences (S2, S4 and S6) show undulating deformation with folding but no obvious fracturing, suggesting they are rheologically more ductile; a common characteristic of halite. In contrast, the more reflective interbeds show evidence for intense buckle folding and faulting suggesting a more brittle deformation style and therefore, a rheological and likely lithological change between the sequences.

All nine seismic horizons were depth converted using the new velocity model for the Messinian (Appendix A). The uppermost Messinian sequence (S6) is only locally preserved in small depressions near the top of the salt. It was therefore merged with the Top Messinian horizon to give greater geological sense to the depth conversion method applied.

The base Messinian depth map was compared against the original depth map produced by Premier Oil using a single interval velocity for the Messinian evaporites (Fig. 5.5). The difference between these maps was up to 400 m, with the constant-velocity depth map being overall shallower than the variable-velocity depth map. This difference arises because the single velocity used previously is overall lower than that used in the multilayer model. More specifically, the depth structure shows marked differences between the two maps. The constant velocity model shows apparent 4-way dip closed structures, which could have been flagged as potential traps for migrating hydrocarbons. However, in the multi-layer approach, these structures largely disappear.

5.5. Model Applications and Limitations

The Messinian section in the northern Levantine Basin (offshore Cyprus) is characterized by a thick evaporitic succession represented by alternating transparent and
reflective seismic facies. The accuracy of depth conversion relies on the quality of the underlying velocity model; thus where salt displays considerable vertical facies variations, as seen in the Levant, a variable velocity, layer cake approach may be more geologically realistic. A variable velocity model was generated and tested on the base salt surface, to determine the differences encountered (if any) from previous models, which employ a single constant velocity function through the salt interval. This approach involves assigning each evaporite layer a velocity value based on its likely composition.

The area chosen for testing of the variable velocity method corresponds to where the greatest degree of vertical seismic facies variability occurs in the Levant (i.e. the deep basin centre). However, the model may not be optimal for other areas in the basin owing to the lateral pinch-out of certain layers and increased deformation of units back towards the basin margins. Structural thickening related to this deformation may lead to even more variability in the internal velocity and thus, depth conversion (e.g. Fiduk and Rowan, 2012: their figure 8; and Allen et al, 2014: this thesis, Figure 4.15).

Direct well control is the obvious crucial piece of information required to build the most accurate velocity model. The Hannah-1 well penetrates the Messinian in an up-dip, basin-margin location where the salt is transparent and seemingly not as heterogeneous as the basin centre succession. The composition of the intercalations, although well informed by other pieces of evidence (e.g. their geometry, rheology and information from marginal wells and analogous environments) remain speculative. It also must be recognised that not all multilayered salt bodies represent significant lithological changes. Some, such as the Ariri Formation in the Santos basin, (offshore Brazil) show strongly reflective intrasalt units, which display very similar structural styles to those observed in our study. However, borehole data reveal that these units are comprised of up to 86 % halite with subordinate anhydrite and carnalite (Fiduk and Rowan, 2012; Jackson et al., 2014). This highlights that it can be equally
misleading to assume multi-layered evaporites are comprised of significantly different lithologies, and thus layers of contrasting velocities.

This exploratory study, although simplified, suggests that the interpretation of internal facies within the Messinian salt is important in order to generate a more accurate velocity model for sub-salt seismic depth conversion of future prospects in the Levantine Basin and, perhaps one that can be implemented in other layered salt basins worldwide (e.g. Santos and Zechstein Basins).

Whilst we are aware that testing this model over a small area on a single surface does not give us grounds to propose the widespread utilisation of this method in all multi-layered salt scenarios. It does however; highlight the need to pay closer attention to salt with similar heterogeneities. These environments have been shown to be highly variable both in terms of lithology (and thus velocity) and internal deformation (thus strain) (e.g. Van-Gent et al., 2011; Strozyk et al., 2012; Cartwright et al., 2012; Jackson et al., 2014; Allen et al, 2014). It is therefore suggested that sophisticated depth conversion, with models built for specific and, perhaps, small areas, may be what is required in this type of setting.

5.6. Future Recommendations

We summarise this short study by making the following recommendations for future work:

• This model was only tested on one small area and on 1 surface so consider testing in multiple areas to compare, more specifically on sub-salt target horizons.

• More iterations are suggested using multiple lithologies (e.g. clastics/ carbonates shales/ high-concentration bittern salts) to see how this would affect the outcome bearing in mind that the Messinian is not drilled so we do not know for sure the
composition of the intrasalt layers and therefore, cannot say, unequivocally, that our interpretations of the lithology in the deeper basins are correct.

- To re-pick stacking velocities based on a multi-layered salt model and calibrate this with well data in order to generate an accurate velocity model for depth conversion of sub-salt prospects in other salt basins.

5.7. References


Fig. 5.1: (a). Location map of the study area showing 2D seismic coverage. Note purple dotted line represents the extent of available seismic-stacking velocities; red lines indicate seismic lines displayed in the study. Base map: GeoMapApp; 2012; Structural trends compiled after McCluskey et al., 2000; Abdel Aal et al, 2000; Robertson & Mountrakis, 2006; Loncke et al, 2006 and Gardosh et al, 2008. (b) seismic section showing the structural setting and trapping styles for the recent gas discoveries in the Levantine Basin (GeoExpro.com).
Fig. 5.2: Well-seismic tie through Hannah-1 with lithological interpretation of velocities derived from the sonic log. Note: The Hannah-1 well penetrates the Messinian in an up-dip, marginal location where the salt is more homogenous. Lithologies from Gardosh et al. (2008)
Fig. 5.3: (a) N-S trending regional line through the basin centre with accompanying line interpretation giving an overview of the intrasalt stratigraphic architecture and structural styles in the multi-layer velocity model test area (red box). Numbers 1-9 correspond to the nine mapped horizons. (b) Seismic sequence stratigraphic scheme for the Messinian evaporites of the central Levantine basin. Cyclic alternations of transparent, mobile units with brittle, high amplitude units are observed and mapped regionally, defining up to 6 depositional sequences in the basin centres. (c) 3D representation of the vertical stacking pattern of the mapped intrasalt sequences 1-6 in the Levantine basin. The pseudo well highlights how the greatest degree of vertical variability would be encountered in the deepest part of the basin.
Fig. 5.4 (a) The two approaches to depth conversion. Our model assumes that each interval has a different, but laterally and vertically consistent internal velocity. (b) Velocity model based on seismic facies model using a combination of average rock velocities (Mavko, 2005- Appendix B), literature and, where possible, the Hannah-1 well.
Pseudo dip-closed structures predicted from single velocity approach are largely eliminated by employing the multi-layered approach.

**Fig. 5.5:** Depth maps for the base Messinian surface with accompanying depth distribution plots for both the single and multi-layer depth conversion approaches. Allows for direct comparison between the two techniques.
6. | CHAPTER SIX | SYNTHESIS
6.1 Introduction

This thesis focuses upon both the regional and localised stratigraphic and structural evolution of the Messinian Evaporite Complex (MEC) across two main sub-basins of the offshore Eastern Mediterranean, combining regional 2D and localized 3D subsurface seismic interpretation supported by marginal well and outcrop data. To reiterate, the overarching aims of the thesis were to investigate i) the spatial and temporal distribution of Messinian seismic facies across the eastern Mediterranean sub-basins; ii) the local and regional controls in terms of tectonics and climate on the observed seismic facies distributions, and iii) the variability and controls of salt-related structural styles across the eastern Mediterranean sub-basins (i.e. Nile/Herodotus and Levantine Basins).

In order to further address these initial aims, this chapter will review and discuss the key findings from the preceding chapters, highlight the wider implications of our work and discuss any limitations. The key implications are structured around specific outcomes related to our understanding of i) Messinian Salinity Crisis; ii) salt tectonics and iii) the possible applications of our work to hydrocarbon exploration in the future. Although points ii) and iii) are separately discussed, they are closely linked. The reader should be aware that any contribution to our understanding of salt tectonic processes is important for hydrocarbon exploration due to its presence in many of the world’s largest hydrocarbon provinces.

6.2. Discussion of Key Themes

While the MSC is a widely studied event, the absence of fully recovered academic boreholes in the deep offshore areas render the nature of onset, duration, depositional environments and, perhaps most crucially, the lithological composition of the MEC highly speculative. Currently information can only be derived from indirect observations based on
seismic analysis of intrasalt seismic facies, stratigraphic architecture and structural styles. Well data from the marginal areas, although spatially limited, do provide confident, 1D information on lithology for the MEC in these more proximal settings, which can then be extrapolated into the deep-basin domain.

Overall, the findings from this work highlight the need for more regional-scale analysis of the MEC in order to determine whether the stratigraphy, composition and structural styles are controlled by factors local to an individual sub-basin, or whether they can be attributed to more far-field effects such as eustacy, tectonics and climate. Below I discuss some of the key findings in the context of their wider implications for the study of the MSC, salt tectonics and hydrocarbon exploration.

6.2.1 The Messinian Salinity Crisis

Although rare, previous attempts at Mediterranean scale (i.e. multi-site) analysis of the MSC (e.g. CIESM, 2008 and references therein; Lofi et al., 2011) have noted a clear disparity between the thickness and stratigraphic architecture of the deep basin MEC in the offshore western Mediterranean compared to that of the offshore eastern Mediterranean. In the west, the Messinian sequence largely adheres to a well-established trilogy commonly referred to as the Lower Unit (LU), Mobile Unit (MU) and Upper Unit (UU) (Montadert et al., 1970; Lofi et al., 2011), which are thought to represent aggrading facies, delineating an idealised, single cycle of evaporite deposition; i.e. the onset, acme, and cessation of the MSC respectively (Rehault et al., 1984). In the eastern Mediterranean, this tripartite division is not recognised. The LU and UU are presumed to be absent or post-depositionally removed, with the succession characterised by a thicker, multi-layered MU, of predominantly halite composition (Bertoni & Cartwright, 2006; Netzeband et al., 2006).

In this study, we recognise key differences that support the idea that the eastern and
western Mediterranean developed separately, forming two saline giants. The eastern unit is up to twice the time thickness (1 s) of the tripartite western succession and our work suggests up to seven seismically distinct depositional units, comprised of four discrete seismic facies constitute the MEC in the eastern basins. Furthermore, the top and base salt ages in the eastern basin are widely accepted to represent the M and N reflections, so we know that the Levantine evaporite complex spans the time interval of the salt deposition phase of the crisis (i.e. 5.6-5.33 Ma). This is considerably different to the timeframe for its proposed western basin counterpart, the MU (i.e. duration of 50-90 kyrs; CIESM, 2008).

I envisage a flaw in attempting to correlate between the eastern and western basin successions owing to the fact that, at the Mediterranean scale, they were likely subjected to different controls (e.g. basin geometry, climate, water depth, sediment supply, degrees of erosion, subsidence etc.). Combined, these controls would be expected to impact on the severity of drawdown and levels of salinity between the basins resulting in differing fill histories and evaporite lithologies.

For example, the western Mediterranean sediment input during the Messinian was largely delivered to the basin by southern European rivers (e.g. the Rhone and Ebro). However, the eastern basins were influenced by discharge from African systems (e.g. The Nile and Sahabi Rivers). Reconstructions of southern European climate before and during the crisis using pollen records reveals warm, humid conditions existed throughout this time period. The areas drained by the Ebro and/or Rhone Rivers had a mean annual temperature of c. 21°C and mean annual precipitation levels of up to 1300 mm/a\(^2\) (Fauquette et al., 2006). However, the North African Climate was less stable during this time, with marked oscillations between humid and arid conditions (Griffin, 1999; 2002) including over 100 climatic, and thus environmental cycles recorded during the Messinian and early Pliocene in the Sahabi basins (Griffin, 2006). This may explain the cyclicity in evaporite composition envisaged for the
offshore Eastern Mediterranean basins.

Furthermore, this disparity between the stratigraphy of the east and west basins leads us to agree with the numerical simulations of Meijer and Krijgsman, (2005) and Gargani and Rigollet, (2007), who showed that, from the time sea-level dropped below the Sicily Sill (c. 300 m), the two basins evolved individually, forming separate saline giants. The Sicily Sill acted as a barrier to hydrological exchange between the two, although, during eustatic highs, the sill may have breached and acted as a spillway. Similar scenarios could be envisaged for other sills around the Mediterranean including the Apennine and Suez spillways affecting satellite Messinian salt basins (Blanc, 2000; Ryan, 2009).

I propose that the halite-dominated succession of the eastern basin represents the depositional equivalent to the complete Messinian trilogy of the western Mediterranean, as opposed to representing just a thicker MU. In our scenario, I suggest the eastern and western Mediterranean evaporites constitute separate saline giants; disconnected for extended periods by the Sicily sill. As a result of the main Atlantic gateway being located in the westernmost Mediterranean, one may expect a slight diachronity between the onset of salt deposition; beginning first in the east, and slightly later in the west. The basin fills develop in different ways owing to the different hydrologic conditions expected to characterize the two depocentres during the acme of the crisis.

6.2.2 Salt Tectonics

This section is closely linked with section 6.2.3; as much of our ability to study salt tectonics comes from exploration efforts by the hydrocarbon industries. Salt has a significant influence on almost all aspects of a developing petroleum system. Its inherent mobility under relatively low strains rates means it can quickly compartmentalise a basin, becoming a strong controller of reservoir distribution and structural trap formation as well as providing an
effective seal to migrating hydrocarbons. An understanding of salt tectonics and the mechanics of salt flow is therefore crucial for reducing risk and increasing efficacy of hydrocarbon exploration in salt-containing basins.

6.2.2.1 Intrasalt Strain:

Understanding intrasalt strain regimes is important for understanding where likely pressure kicks may occur as these can form major drilling hazards. Indeed the presence of the Zechstein stringers (Strozyk et al., 2012) has, in the past, seriously hindered exploration efforts (Williamson et al., 1997). Where salt is more homogenized, like that of the Nile/Herodotus basin, the internal mechanics of salt flow can be difficult to determine. However, in a multi-layered salt body such as the Levantine, the more reflective, competent layers can act as key markers for intrasalt strain. The fact that minimal tectonic overprinting has taken place in the Levantine basin compared with older layered salt basins (e.g. Santos: Fiduk and Rowan, 2012; Jackson et al., 2014; Zechstein: Van-Gent et al., 2011; Strozyk et al., 2012) means that it is likely that the intra-salt structural styles observed are a reflection of the structural deformation associated with the earliest stages in the evolution of a saline giant.

Many previous studies of intrasalt deformation across the Levantine Basin largely base their interpretations on dip-orientated sections off the Israeli and Lebanese margin (Almagor & Garfunkel, 1979; Garfunkel & Almagor, 1984; Gradmann et al., 2005; Bertoni & Cartwright, 2006). Here, the salt deformation largely adheres to what may be expected under a gravity control (i.e. gliding or spreading), with salt flowing away from the relatively linear NNE-SSW striking Levantine margin. This forms well-developed NNE-SSW striking linear belts of updip extension balanced by down-dip compression. However, the basin is structurally enclosed by variably striking boundaries formed by the Latakia ridge, Eratosthenes Seamount and Nile Deep Sea Fan. Combined, these serve to isolate this basin in a largely compressive setting. We
suggest that these interfering boundary conditions strongly contribute to the structural styles documented in chapter four, specifically in the contractional domains.

The integrated 2D and 3D seismic structural mapping of regional and localised transport directions within the salt highlights the variability in the strike of the thrust structures and presents an inconsistency with what might be expected if gravity spreading and gliding along the Levantine Margin were indeed the sole driving force. At the 2D seismic resolution, the orientation of the intrasalt structures form apparent mirror images of one another on both N–S and E–W oriented sections indicating multi-directional flow towards the basin centre. Furthermore, at the 3D seismic resolution in the northern Levantine Basin, a more intricate assemblage of structural trends are revealed that I suggest reflect the far-field compressional tectonics taking place along the ENE-WSW trending Latakia Ridge.

Crucially, I observe very similar structural styles in the contractional domains related to each of these basin boundaries, despite the fact that the nature of the boundaries (i.e. Levantine Margin; ESM; NDSF and Latakia Ridge) are very different (e.g. passive margin; static buttress; prograding sediment wedge; and fold and thrust belt respectively). It has previously been suggested that the two key triggers for initiating salt flow (gravity gliding and gravity spreading) produce distinctive structural styles (Loncke et al., 2006). Although, as a rule this is generally true, our observations, specifically in the Levantine Basin suggest that structural styles can be essentially identical, albeit with variable transport directions, but the triggers and crucially, timings can be very different.

6.2.2.2 Salt Flow Mechanics:

The end-member models presented in Fig 4.2 depict the intrasalt deformation expected in a multilayer evaporite undergoing Poiseuille and Couette flow. However, both assume the presence of an overburden. Although the patterns of deformation we present in
chapter four initially look similar to the model representation of Couette flow, we know some degree of salt flow is likely to have occurred prior to overburden deposition related to tilting of the base salt. Consequently, the flow mechanics we observe across the Levantine basin do not match these common models of simple salt flow.

To account for the variances in intrasalt structural styles and strain across the Levantine basin, we envisage superimposed flow regimes occurring at different scales and driven by different processes. Prior to overburden deformation, early salt flow may be related to tilting and gravitational drainage of salt, producing a dominant Couette flow, with minor Poiseuille component in the lowermost layers (relating to squeeze flow from the accreting salt sheet and/or early progradation). Later deformation was driven by gravity spreading which further intensified the original Couette component of salt flow.

Alongside the contribution of this work to the study of salt tectonics, we also recognise the impact our work could have on reducing exploration risks in the Eastern Mediterranean and beyond. More specifically, we refer to the processes of drilling through salt and the complications that can arise such as pressure kicks and wellbore instability. A common assumption still made in many salt-wellbore stability analyses is that stresses within salt bodies are isotropic (Weijermars and Jackson, 2014). I suggest this is not the case, particularly in cases where lithological heterogeneities can cause complex strain partitioning throughout the salt body. I am therefore in agreement with Weijermars and Jackson (2014), who recommend that wellbore stability calculations for any borehole through geologically flowing salt should take this into account.

### 6.2.3 Hydrocarbon Exploration

The presence of salt is associated with many of the world’s largest and most productive hydrocarbon provinces (e.g. Gulf of Mexico, North Sea, Campos Basin, Lower
Congo Basin, Santos Basin and the Zagros). Recent discoveries in the pre-Messinian of the Levant and offshore Cyprus areas have heightened industry interest and brought the variable seismic facies and structural styles of the basinal Messinian into sharp focus, particularly with regards to their impact on depth conversion and seismic imaging.

Previous attempts at depth conversion have adopted a somewhat simplistic approach, characterising the Messinian as a continuous, homogeneous, halite-dominated layer. The detailed subdivision of the Messinian into its constituent depositional sequences provides a hitherto unachieved level of detail from which to build the velocity model. The velocities associated with the observed seismic facies have been calibrated where possible, by correlation with the offset Hannah-1 well and by reference to similar lithologies in analogous depositional settings.

This multi-layered, variable velocity depth conversion approach predicts that the base Messinian surface is up to 400 metres deeper than the one generated using a single velocity value. Therefore, our more detailed facies sub-division and associated depth conversion method has helped us understand the possible variations of interpreted depth, amplitude and wavelength of sub Messinian prospects and reinforced the importance of applying a multi-layered approach in analogous settings.

6.3. Limitations

This study has offered many interesting insights into our understanding of the events of the MSC within, and between sub-basins of the eastern Mediterranean region. However, our regional approach is both the advantage and disadvantage of this study. The multi-client 2D dataset that forms the bulk of our seismic coverage spans an area of c. 180,000 km², enabling the splicing together of seismic lines in order to create regional scale composite sections spanning the length and breadth of the eastern Mediterranean, linking sub-basins
and incorporating some of the more understudied areas of the offshore eastern Mediterranean. These sections have allowed us to systematically map and correlate seismic facies and structural styles of the MEC at a regional scale across the Eastern Mediterranean.

We have utilised and incorporated more specific information from localised outcrop and subsurface studies undertaken previously to underpin our interpretations and provide valuable fence posts from which to correlate between. As a result, we have proposed new models for the structural and stratigraphic development of the MEC in the Eastern Mediterranean.

However, whilst we gain a better understanding of the regional perspective using this approach, the resolution is compromised. Mapping complex structures from a grid of 2D data is a subjective process. For example, when following a fault, the interpreter has to make a decision on where that fault might join the next line, which could be kilometres apart. In our case, the seismic grid is irregular, with line spacing varying between 7 and 50 km and an average of c. 10 km so many of the more subtle changes in unit thickness, amplitude, external and internal geometry and/or structural styles are below the resolution of this dataset. Contrastingly, the 3D seismic data is arranged as a number of parallel straight lines very close together, negating the need to attempt interpolation between sparsely spaced 2D lines. As we have seen in chapter four, these dense grids of traces allow a much greater resolution to be achieved permitting more confident mapping of, in this case, intricate fault networks that led to the proposition of new ideas surrounding the triggers for Messinian salt flow.

As aforementioned, the lack of direct and/or complete subsurface calibration places an obvious restraint on making any unequivocal interpretations of the lithological composition of the evaporites. This is especially true for the deep basin intercalations seen in the Levantine Basin, which have been interpreted as many things from clastic intrusions to high salinity bitterns. Consequently, the stratigraphic evolution of the MEC proposed by us and all other
previous authors remain somewhat tentative. Therefore, broad, regional seismic studies coupled with the minimal, but crucial marginal well data available, offer the best opportunity to bridge the gap in knowledge between the marginal and deep basin characterisation of the MEC until such a time when the complete successions are drilled.

6.4 References:


7. | CHAPTER SEVEN | CONCLUSIONS

The key conclusions from each respective chapter within this thesis are summarised below:

7.1 Charting the Stratigraphic Evolution of a Youthful Saline Giant: New Insights from Regional 2D Seismic Facies Analysis of the Messinian Evaporite Complex in the Offshore Eastern Mediterranean.

- The high-resolution seismic facies analysis of the Messinian Evaporite Complex (MEC) reveals up to eight seismically distinct depositional facies that can be traced over regional distances. Seismic facies I-V are unique to the Levantine basin and form 7 sequences, which show a progressive decrease in aerial extent up stratigraphy, with only the deepest parts of the basin preserving all 7 sequences.

- SF VI, VII and VIII are found across D1 and D2 but not encountered in D3 with SFVI showing high levels of internal strain and mobility, which is responsible for creating an array of classic salt-tectonic structures with related deformation in the overburden.

- We interpret sequences in the Levantine Basin as deposited over multiple depositional cycles and propose that these cycles correspond to lithological variations (specifically halite-anhydrite couplets), linked to changing seawater salt concentrations.

- A key driver for these lithological variations is thought to be eastern Mediterranean climate oscillations between dry and humid periods, which impacts on freshwater input from the dominant North African fluvial systems (Nile and Sahabi Rivers).

- It could be argued that climate oscillations are linked to the 100 Kyr component of orbital eccentricity. Indeed, our interpretation of up to 3-4 cycles of halite-anhydrite couplets fits
the eccentricity periodicity of c.100 Kyrs, covering the time interval for the MSC in our study area of between 5.6 and 5.33 ma.

- We suggest that the western and eastern basins were separate depocentres during the MSC, separated by the Sicily Sill.

- We also observe that layering of the Levantine evaporites may not be exclusive to this basin, but in fact, more widespread.

- The lack of such good imaging of the layering outside of the Levantine Basin may relate to post salt deformation resulting from the flow of mobile salt may have destroyed the primary stratigraphic layering in these areas.

### 7.2 Gravity-driven deformation of a youthful Saline Giant: Seismic examples from the Messinian basins of the Eastern Mediterranean.

- Structural analysis of the Nile/Herodotus Basin (NHB) reveals dramatic lateral and down-dip asymmetry in structural styles that are consistent with classic, gravity induced, passive margin salt tectonics (i.e. updip extension, midslope translation and downdip contraction).

- The evaporite is largely seismically transparent across the NHB and the presence of large diapirs and seismic artefacts (e.g. pull-up effect) suggests that this transparent facies most likely represents a highly strained salt body, predominantly comprised of halite.

- In the Levantine Basin (LB), regionally mapable alternations of transparent and highly reflective units (interpreted as halite and anhydrite couplets) define up to seven intrasalt seismic-stratigraphic sequences (S1-S7), comprised of four distinct seismic facies (SF).
- Reflective intrasalt layering in the LB permits the recognition of numerous structurally complex areas dominated by shortening along sequences 4 & 6 defined by imbricated thrusting and upright-verging folds.

- These structures are consistent with down-dip transport directions with respect to the variably striking basin boundaries of the Levantine Margin, Latakia Ridge and NDSF indicating multi-directional salt flow towards the low-strain basin centre.

- The timings and mechanisms of salt flow can vary both laterally and vertically through the LB succession and we envisage superimposed intrasalt flow regimes occurring at different scales and driven by different processes.

- During the initial stages of deformation, it is expected that early tilting and gravitational drainage of salt produced a dominant Couette flow, with a minor Poiseuille component in the lowermost layers (relating to squeeze flow from the accreting salt sheet and/or early progradation). Later deformation was driven by gravity spreading which further intensified the original Couette component of salt flow.

- The structural styles along the basin margins can be very similar (i.e. salt-cored anticlines and imbricated thrust fans) but the triggers and drivers for the salt flow that creates them can be very different and potentially, have different ages.

- Salt tectonics is generally less mature in the LB compared to the NHB, which we interpret to be related to their development as part of a single saline giant that covered the Eastern Mediterranean sub-basins. However, due to more localised influences (particularly basin geometry and different levels and styles of marginal loading), the NHB and LB undergone different syn and post-depositional deformation histories although their depositional development is thought to be near synchronous.
7.3 Impact of Multi-layered Evaporites on Subsalt Depth Conversion: Testing a New Approach in the Offshore Messinian Evaporite Complex of the Northern Levantine Basin.

- Seismic facies analysis of the Messinian Evaporite Complex (MEC) of the Eastern Mediterranean reveals clear heterogeneities within the salt succession, indicating variable lithologies and thus, seismic velocities.

- Previous attempts to depth convert presalt seismic horizons in this area have adopted a somewhat simplistic approach, characterising the Messinian as a continuous, homogeneous, halite-dominated layer, and applying a single velocity function (3900 m/s) to the interval.

- In this study we construct a new intrasalt velocity model for the Messinian salt based on assigning each evaporite layer a velocity value based on its likely composition.

- The variable velocity approach reveals a marked shift in depth-converted values for the base of salt surface; a depth of the base Messinian surface 400 m deeper than the one that was generated using a single velocity value for the entire Messinian section.

- The constant velocity model shows apparent 4-way dip closed structures, which could have been flagged as potential traps for migrating hydrocarbons. However, in the variable velocity approach, these structures largely disappear.

- This study, although simplified, suggests that the interpretation of internal facies within the Messinian salt is important in order to generate a more accurate velocity model for sub-salt seismic depth conversion of future prospects in the Levantine Basin and, perhaps one that can be implemented in other layered salt basins worldwide (e.g. the Santos and Zechstein Basins).
THESIS APPENDICES
Appendix A.

Time-Structure, Isochron and Depth Structure maps of the intra-Messinian sequences using the variable-velocity model.

Figure A1: Time-structure map of the top IM1 horizon

Figure A2: Time-structure map of the IM2 horizon
Figure A3: Time-structure map of the IM3 horizon

Figure A4: Time-structure map of the IM4 horizon
Figure A5: Isopach of the SF1 sequence

Figure A6: Isopach map of the SF2 sequence
Figure A7: Isopach map of the SF3 sequence

Figure A8: Isopach map of the SF4 sequence
Figure A9: Isopach of the Overburden

Figure A10: Isopach of the section from base Messinian to pre-Messinian horizons
Figure A11: Depth converted seabed horizon

Figure A12: Depth converted map of the Top Messinian horizon
Figure A13: Depth converted map of the Base Messinian horizon

Figure A14: Depth converted map of the IM1 horizon
Figure A15: Depth converted map of the IM2 horizon

Figure A16: Depth converted map of the IM3 horizon
Figure A17: Depth converted map of the new IM4 (emerged version with the top Messinian) to take into account deposition of SF5 in the centre
## Appendix B

<table>
<thead>
<tr>
<th>Type of formation</th>
<th>P wave velocity (m/s)</th>
<th>S wave velocity (m/s)</th>
<th>Density (g/cm³)</th>
<th>Density of constituent crystal (g/cm³)</th>
</tr>
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<tr>
<td>Scree, vegetal soil</td>
<td>300-700</td>
<td>100-300</td>
<td>1.7-2.4</td>
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<tr>
<td>Dry sands</td>
<td>400-1200</td>
<td>100-500</td>
<td>1.5-1.7</td>
<td>2.65 quartz</td>
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<td>Wet sands</td>
<td>1500-2000</td>
<td>400-600</td>
<td>1.9-2.1</td>
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<tr>
<td>Saturated shales and clays</td>
<td>1100-2500</td>
<td>200-800</td>
<td>2.0-2.4</td>
<td>-</td>
</tr>
<tr>
<td>Marls</td>
<td>2000-3000</td>
<td>750-1500</td>
<td>2.1-2.6</td>
<td>-</td>
</tr>
<tr>
<td>Saturated shale and sand sections</td>
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<td>500-750</td>
<td>2.1-2.4</td>
<td>-</td>
</tr>
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<td>Porous and saturated sandstones</td>
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<td>1100-1300</td>
<td>1.8-3.1</td>
<td>2.71 calcite</td>
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<td>Salt</td>
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<td>2500-3100</td>
<td>2.1-2.3</td>
<td>2.1 halite</td>
</tr>
<tr>
<td>Anhydrite</td>
<td>4000-5500</td>
<td>2200-3100</td>
<td>2.9-3.0</td>
<td>-</td>
</tr>
<tr>
<td>Dolomite</td>
<td>3500-6500</td>
<td>1900-3600</td>
<td>2.5-2.9</td>
<td>(Ca, Mg) CO₂ 2.8-2.9</td>
</tr>
<tr>
<td>Granite</td>
<td>4500-6000</td>
<td>2500-3300</td>
<td>2.5-2.7</td>
<td>-</td>
</tr>
<tr>
<td>Basalt</td>
<td>5000-6000</td>
<td>2800-3400</td>
<td>2.7-3.1</td>
<td>-</td>
</tr>
<tr>
<td>Gneiss</td>
<td>4400-5200</td>
<td>2700-3200</td>
<td>2.5-2.7</td>
<td>-</td>
</tr>
<tr>
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<td>1000-1400</td>
<td>1.3-1.8</td>
<td>-</td>
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<td>-</td>
<td>1.0</td>
<td>-</td>
</tr>
<tr>
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<td>1700-1900</td>
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<tr>
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<td>1200-1250</td>
<td>-</td>
<td>0.6-0.9</td>
<td>-</td>
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</tbody>
</table>

Table B1: Rock velocities (after Mavko, 2005)
Appendix C

Figure C1: Time-migrated 2D seismic profile showing the Hannah-1 well section with formation tops (Gardosh et al., 2008).