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Probing connections between deep earth and surface processes in a land-locked ocean basin transformed into a giant saline basin: the Mediterranean GOLD project

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Abstract :

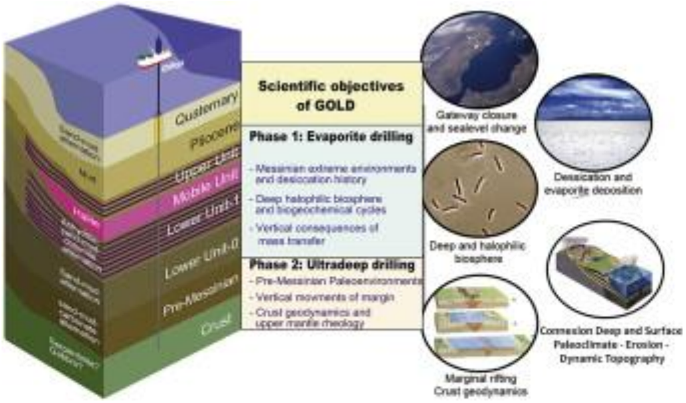
During the last decade, the interaction of deep processes in the lithosphere and mantle with surface processes (erosion, climate, sea-level, subsidence, glacio-isostatic readjustment) has been the subject of heated discussion. The use of a multidisciplinary approach linking geology, geophysics, geodesy, modelling, and geotechnology has led to the awareness of coupled deep and surface processes. Deep earth dynamics (topography, erosion, tectonics) are strongly connected to natural hazards such as earthquakes, landslides, and tsunamis; sedimentary mass transfers have important consequences on isostatic movements and on georesources, geothermal energy repartitions. The ability to read and understand the link between deep Earth dynamics and surface processes has therefore important societal impacts. Ground-truthing at carefully-selected sites of investigation are imperative to better understand these connections. Due to its youth (<30 Ma) and its subsidence history, the almost land-locked Gulf of Lion-Sardinia continental margins system provides a unique record of sedimentary deposition from the Miocene to present. Due to its high subsidence rate, palaeoclimatic variations, tectonic events and vertical evolution are all recorded here at very high resolution. The late Miocene isolation and desiccation of the Mediterranean, the youngest and most catastrophic event, the Messinian Salinity Crisis (MSC), induced drastic changes in marine environments: widespread deposition of evaporite (gypsum, anhydrite and halite) in the central basin, and intense subaerial erosion along its periphery. These extraordinary mass transfers from land to sea induced strong isostatic re-adjustments that are archived in the sedimentary record and represent a window to the lithospheric rheology and the deep processes. The GOLD (Gulf of Lion Drilling) project, proposes to explore this unique sedimentary record as well as the nature of the deep crustal structure, providing valuable information about the mechanisms underlying vertical motions in basins and their margins.

Keywords : Deep drilling, Geodynamics, Passive Margins, Paleoclimate, Messinian Erosional and Salinity Crisis, Deep Biosphere, Georessources

Highlights

► Characterization of the thermal, petrophysical and mechanical properties of the crust. ► Focus on the palaeoenvironment, palaeobathymetry, chronology of early Miocene sedimentation to lower Pliocene. ► Quantification of the consequences of the Messinian event with Thermo-mechanical models. ► History of water exchange between the Mediterranean Sea and the North Atlantic. ► Limits of life.

Graphical abstract



Acronyms

GOLD	Gulf of Lion Drilling
DREAM	Deep-sea REcord of mediterrAnean Messinian events
MSC	Messinian Salinity Crisis
IODP	Integrated Ocean Drilling Program
ICDP	International Continental Drilling Program
MDP	Multiple Drilling Program
EPOS	European Plate Observing System
CURVE	Coring a foreland basin: Upper Rhône Valley Events
AMED-1	Actions-Marges Mediteranee-1 cruise
GLWS	Gulf of Lion-West Sardinia Margin System
LWD	Logging while Drilling
BOP	Blow Out Preventer
JAMSTEC	Japan Agency for Marine-Earth Science and Technology
CDEX	Center For Deep Earth Exploration
GR or SGR	Total Gamma Ray
RHOB	density
NPHI	Neutron Porosity
Pef	Photoelectric Factor
NGS	Natural Gamma Ray
CGR	Compensated Gamma Ray
PCATS	Pressure Core Analysis and Transfer System
MDT	Modular Formation Dynamic Tester
QEMSCAN	Quantitative Evaluation Of Minerals By Scanning Electron Microscopy
VSP	Vertical Seismic Profile
S.W.T	Side Wall Cores

1. Introduction

One of the critical developments in Earth Science over the past decade has been the recognition of the importance of links between deep Earth dynamics and surface geologic processes (e.g. Cloetingh *et al.*, 2007). The field of dynamic topography has expanded as a consequence, but at the same time it has been demonstrated that the outcome of models depends critically on constraints regarding crustal structure and the thermo-mechanical properties of the lithosphere. Since the classical models of McKenzie (1978) and Wernicke (1985), understanding how passive continental margins form, i.e., the thinning of the continental lithosphere leading to vertical movements (subsidence) and its connection with the first oceanic crust, remains a major challenge in Earth Sciences (e.g. Lavier & Manatschal, 2006; Aslanian *et al.,* 2009; Cloetingh *et al.*, 2013). Deep earth dynamics (topography, erosion and tectonics) are also strongly connected to naturals hazards such as earthquakes, landslides, and tsunamis (e.g. Camerlenghi *et al.*, 2009, Lafuerza *et al.,* 2012). On the other hands, sedimentary mass transfers also have important consequences on isostatic movements (Allen & Allen, 1990; 2005) and represents a window to the lithospheric rheology and the deep processes (Leroux *et al.*, 2015). These sediment fluxes are the product of erosion and movement of material in and from sources (mountains), the transport by river systems to the plains, and deposition and storage in sink zones. They need to be quantified and modelled in a complete system in relation to the controlling parameters that link temporal and spatial scales across multiple orogen and basin systems (e.g., Matenco and Andriessen, 2013). Sediment deposition and mass transfers have also important obvious consequences on georesources (potential sources, reservoirs and cap rocks quality), geothermal energy (linked to the type of material at depth and burial depth reached) and migration of the fluids. Surely, these results would serve as an invaluable tool for also understanding petroleum systems in relation to the MSC.

Due to its youth and history of strong subsidence, this almost land-locked continental Gulf of Lions–West Sardinia margins system (GLWS) provides a unique record of sedimentary deposition from the Miocene to present that records palaeoclimatic variations and tectonic events (including subsidence history). The late Miocene isolation and desiccation of the Mediterranean, a major and extreme event in the Neogene, known as the Messinian Salinity Crisis (MSC), caused massive erosion of surrounding margins and widespread deposition of evaporites in the deep marine basins of Mediterranean Sea (see the consensus synthesis CIESM, 2008) that were only sampled for its uppermost part by IODP drillings during Leg 13 (Hsü *et al.,* 1973) (Fig. 1). These extraordinary mass transfers from land to sea, with up to 1.3 km of erosion on the shelf (Bache *et al.*, 2009) induced strong isostatic re-adjustments that are archived in the sedimentary record (Rabineau *et al.,* 2014).

Having the advantage of the multidisciplinary academic-industrial Action Marges Program (http://actionsmarges.fr/) and several European projects (e.g. Promess, Euromargins, TopoEurope), the Western Mediterranean Sea, and more specifically the Liguro-Provençal Basin, has been intensely studied from land to deep basin and from surface to deep crustal structure. Various numerical models have been developed to characterize and test « surface » observations (e.g. Dionisos : Rabineau et al., 2005; Rabineau et al., 2006; Leroux et al., 2014; Leroux et al., in press ; Braun et al., 2014); other models focused on modeling the coupling of surface and deep processes (e.g. Burov, E., Poliakov, A., 2001; Koptev et al, 2015, see also the review by Burov E., 2007 ; Cloetingh et al., 2013). The GOLD drilling project proposes a complementary process-oriented and ground-truthed approach, with the objective to better understand and quantify the mechanisms underlying the strong motions in the basin and on- and off-shore along the margins trough the sedimentary record, palaeo-environmental evolution and deep crustal structure with the overarching objective to answer the question**:** what are the mechanisms underlying vertical motions inside basins and their margins?

The GOLD drilling project (Pre-857A) is an integral part of the umbrella IODP project “Uncovering a salt giant” (MDP 857, Camerlenghi *et al.,* 2014), which proposes to carry out drilling transects using a set of IODP and ICDP platforms, extending from the basin margins to the deep ocean basins, and linking sediment source to sink (Fig. 2). These projects aim to settle the dispute about the desiccation history of the Western Mediterranean Sea by recovering a complete MSC sequence. In that view, the GOLD drilling project is end-member of the scientific drilling initiative 'Uncovering a Salt Giant' which encompasses scientific objectives focussed on the MSC (Deep-sea Record of Mediterranean Messinian Events (DREAM)) (Fig. 2). GOLD shares these objectives and others related to the deep crustal processes, deep biosphere, deformation and fluid flow.

2. The Gulf of Lion–Sardinia margins system: a Unique Natural laboratory

The Gulf of Lion–West Sardinia margins system (GLWS) corresponds to a pair of rifted margins formed by the rupture of the Corso–Sardinian micro-continent from the Ibero–European plate since Priabonian time (33.7Ma – Réhault *et al.*, 1984) in the context of collision between the African and European plates (Cloetingh and Kooi, 1992; Olivet, 1996). The opening took place at the southern end of the intra-European rift system, in a back-arc situation and in response to a SE rollback of the slab of the African plate subducting beneath the Maghrebides-Calabrian-Apenninic arc during an extensional phase (Kooi *et al.*, 1992; Réhault *et al.*, 1984; Jolivet & Facenna, 2000). The Corso–Sardinian microcontinent's counterclockwise rotation resulted in the emplacement of an oceanic crust starting in the late Aquitanian (23Ma to 19Ma) and lasting until the Langhian (around 15 Ma) (Olivet, 1996). Although the geodynamic evolution of rifting in back-arc basins is different when compared with cratonic rifting, the mechanics of thinning of the continental crust is rather similar (Aslanian *et al.*, 2012; Cloetingh *et al.*, 2013). The Sardinia Cruise (2006) surveyed both conjugate margins (Gailler *et al.*, 2009; Moulin *et al.*, in press; Afilhado *et al.*, in press), allowing precise palinspastic reconstruction of the Gulf of Lion – Sardinia margins system (GLWS) showing the same configuration as those of Atlantic margins and intracontinental basins (Aslanian *et al.*, 2013). Moreover, the puzzling similarity in the seismic velocity profiles of the intermediate domain and the atypical oceanic crust (Moulin *et al.*, 2015; Afilhado *et al.*, 2015) questions the role of the lower continental crust in the first oceanic crust fabric, as proposed Aslanian *et al.* (2009) and Sibuet *et al.* (2012) following the earlier proposition of Bott (1971). The Gulf of Lion–Sardinia margins system is expected to have a continuous and relatively complete sedimentary series, neither affected by basement tectonics nor by recent tectonic or gravity processes, and that can be divided in two second-order sequences: a late Aquitanian/Burdigalian transgressive sequence with a mixed silicoclastic-carbonate platform in a ramp-like configuration (Gorini, 1993), and a Langhian-Tortonian sequence characterised by prograding clinoforms on the platform and turbidites in the deep basin. During this last time-interval, major palaeogeographical change occurred with the initiation of the Rhône River and the creation of a platform-slope-basin morphology.

3. GOLD: Understanding the extreme Messinian Salinity Crisis (MSC) event and the deep response of the lithosphere.

The MSC is the youngest and most catastrophic event to occur during the Neogene period, inducing drastic changes in marine environments, widespread deposition of evaporite (gypsum, anhydrite, and halite) in the central Mediterranean basins (Hsü *et al.*, 1973), and intense subaerial erosion along its periphery (Clauzon, 1973). The closure of the Mediterranean is believed to be linked to uplifts of the Rifean Corridor and/or Betic internal basins due to slab detachment, with an uplift of more than 1mm/yr indicated over a period of at least 80 ka (Garcia-Castellanos and Villaseñor, 2011) but may also be connected to the major worldwide

Neogene kinematic change at the end of chron C3a (~5,9 My), clearly imprinted for instance on the Pitman FZ (Cande *et al.*, 1995) and in the Pacific-Antarctic ridge area (Géli *et al.*, 1997; Ondreas *et al.*, 2001). In the Western Mediterranean, this event has a well-preserved record. A variety of different interpretations have been proposed for MSC-related deposition and reflooding, each with their own strong palaeoenvironmental, tectonic, isostatic, and climatic implications, thus emphasizing the need to drill the entire sedimentary section in the deep basin:

(1) Interpreted thickness ranges from a "minimal" estimate with thin chaotic detritics (1 km) coeval with evaporite deposition and with additional turbiditic components embedded in the Lower Unit (Lofi *et al.*, 2011), to a "maximal" estimate with huge, thick, fan detritics deposited prior to the Lower Unit (Bache *et al.*, 2009), mixed with evaporites (Gorini *et al.*, 2015) for a total thickness of 3.5 km.

(2) The re-flooding is generally seen as a rapid flood along the strait of Gibraltar. It has been suggested that the re-connection itself was caused by subsidence to a threshold below the level of the Atlantic, by faulting, by erosion, or by a combination of these three mechanisms (Loget *et al.*, 2005; Garcia-Castellanos *et al.*, 2009). Geomorphological evidence from the strait suggests a large, catastrophic discharge (Blanc, 2002). Numerical modeling shows that the feedback between the rate of water inflow and the erosion it exerts on the gateway could run at a relative low water discharge for as much a few thousand years. Seismic stratigraphy shows a prominent flat wave-cut surface interpreted as erosional features carved during the refill, which argues for a slow initiation of the refill (Bache *et al.*, 2009). However, to explain the prominent erosional trough observed in the Alboran Sea (a feature that is revealed by seismic stratigraphy as deeper than 300 m, wider than 6 km in places, and at least 200 km long; Estrada et al., 2011), the flood's

> feedback should eventually lead to a water discharge close to 10^8 m^3/s, vanishing the level difference across the Gibraltar threshold in no more than a few years (Garcia-Castellanos *et al.,* 2009). If confirmed, this would consist of the largest documented flood event on Earth, exceeding by a factor of 10 the Missoula and the Altay outburst floods during the Pleistocene.

The large shelf and the low continental slope gradient in the Gulf of Lion offers the best potential for understanding the Messinian Mediterranean event as a whole. Here, we can measure subaerial erosion on the shelf, observe markers of marine transgression on the slope and toe of the slope, and map the succession of detritic units, their lateral seaward evolution, and their correlation with the evaporites. This area is unique in that it provides a full record of evaporite deposition in a deep basin. Its understanding requires an integrated approach quantifying the coupling of geodynamic, and surface processes, and linking IODP-ICDP drillings with transects from the basin margins to the deep ocean basins where the sediment source-to-sink budget is well constrained. A new ICDP project (CURVE) has been submitted in January 2015 in that view (Loget *et al.,* 2015). This will go hand-in-hand with multiscale seismic imaging of basin fill and the crustal and upper mantle structure through a combination of multichannel and wide-angle seismic profiling, and the deployment of novel seismic instrumentation (including the Mermaid system of floating seismometers (Jones, 2014) and the European Plate Observing System (EPOS)). Data will be interpreted with the aid of state-of-the-art coupled analogue and numerical facilities and experimental rock-deformation laboratories (e.g. Burov *et al.,* 2001; Burov, 2007; Watremez *et al.*, 2013; Burov and Gerya, 2014; Koptev *et al.,* 2015; Calignano *et al.,* 2015).

An exciting target for stable isotope investigations of the Messinian crisis that we will examine are evaporite minerals including sulfates (such as gypsum, jarosite, and hanksite), as well as halite and sulfohalites. Analysis of these minerals provides a means to determine fluid oxygen isotope ($^{18}O/^{16}O$) and hydrogen isotope (D/H) ratios (Yang et al. 1995; Khademi et al., 1997; Hodell et al, 2012). Therefore mineral fluid inclusions specifically may allow us to reconstruct paleohydrology. Although the composition of waters can be influenced by diagenesis, measurements of both sulfates and halites in co-occurring samples will allow for independent verification of fluid characteristics of co-precipitating mineral phases, to determine the possibility of isotopic signal degradation in a mineral of interest by re-equilibration with exogenous fluids.

Hydrographic conditions will also be constrained using more traditional paleoceanographic proxies, including widely-used carbonate-based proxies such as $\delta^{18}O$ and $\delta^{13}C$ in foraminifera (e.g., Rohling, 1999; Turco et al., 2001). Foraminiferal Mg/Ca records may help constrain paleotemperature and to disentangle temperature from water isotope (and salinity) changes, though previous studies have shown in the Mediterranean the presence of high-salinity waters (Ferguson et al., 2008) and carbonate overgrowths (Boussetta et al., 2011) may pose potential challenges in data interpretation. However, the application of methods such as flow-through time-resolved analysis (Hoogakker et al., 2009) and laser-ablation inductively-coupled plasma mass spectrometry (Fhlaithearta et al., 2010) can be used to separate out signatures of primary versus secondary phases in such successions. The recently-developed clumped isotope thermometer represents another potential temperature proxy that will be used (Tripati et al., 2010, 2014; Eagle et al., 2013; Tang et al., 2014).

In addition, reconstruction of the history of water exchange between the Mediterranean Sea and North Atlantic will be attempted based on the isotopic records of Sr, Nd and Pb in iron oxides and fish teeth (Flecker et al., 2002; Flecker and Ellam, 2006; Khelifi et al., 2009) Bromine concentrations and the stable isotopic compositions of sulphide, osmium, chlorine

(δ ^{37}Cl) and boron (δ ^{11}B) might also be used to further constrain the nature of the original water, evaporative and post-depositional processes (e.g. Vengosh et al., 1992; Eggenkamp et al., 2013), and evaporite crystal growth patterns that are controlled by the environment of their formation (Lugli et al., 2010; Van Den Driessche et al., 2011). These measurements will be performed from either core of in-situ fluid samples collected with the Modular Formation Tester (M.D.T.), from which formation pressure and pointwise permeability evaluations might be performed from small scale production tests (a few tens of cc each time). In sections where no core will be taken, miniplugs might be obtained from the SideWall Coring tool (S.W.T.).

4. GOLD as a key project for understanding connections between deep earth and surface processes

The almost land-locked Gulf-of Lions – Sardinia continental margins system is a unique natural laboratory to address such key questions on passive margin genesis, the nature of the intermediate crust and the first atypical oceanic crust, the timing of subsidence and its imprint in sedimentary systems, glacio-isostatic rebound, and the impact of the mass transport, in particular during the MSC.

Comprehending thinning of the continental lithosphere leading to vertical movements (subsidence), remains a major challenge in the Earth Sciences. Conservative models, which exclude exchanges between the lower continental crust and upper mantle, are usually proposed to explain the lithospheric stretching and consequential crustal thinning of passive continental margins. Major effort has been made to explore the conjugate Galician/Iberian and Newfoundland margins (ODP Legs 103, 149, 173, 210). Nevertheless, their results mainly concern an end-member of conjugate passive margins with strong continental lower crust (Huismans and Beaumont, 2011) and cannot be applied in general to other margins. Moreover, evidence of an emerged or shallow marine position of margins until the break-up (Aslanian *et al.*, 2009; Péron-Pindivic and Manatschal, 2009; Bache *et al.*, 2010), absence of extensional faults (Moulin *et al., 2005*; Bache *et al.*, 2010; Unternher *et al.*, 2010; Moulin *et al.*, in press) anomalous heat flow (Lucazeau *et al.*, 2010), the presence of a strong reflector in the lower crust (Pascal *et al.*, 1994; Moulin *et al.*, in press) and of exhumed mantle (Boillot *et al.*, 1989), have all modified our concepts of margin formation. The physical and numerical models proposed to explain some of these observations (Burov and Poliakov, 2001; Lavier and Manatschal, 2006; Kuznir and Karner, 2007; Reston, 2010; Huismans and Beaumont, 2011; Munteanu *et al.*, 2014) imply huge horizontal movements, which do not fit the geological and geophysical observations (Aslanian *et al.*, 2009; Aslanian and Moulin, 2012). Comparisons between different conjugate margin systems in different tectonic contexts around the world (Central Atlantic: Labails *et al.*, 2009; South Atlantic: Aslanian *et al.*, 2009; Liguro-Provencal Basin: Moulin *et al.*, in press; Afilhado *et al.*, in press; Black Sea: Munteanu *et al.*, 2011; Pannonian Basin: Matenco and Radivojeviić, 2012), intracontinental basins (Baikal lake: Thybo and Nielsen, 2010; Parentis Basin (Marillier *et al.*, 1988), and aborted rifts (Valencia Basin: Torné *et al.*, 1992) present a similar picture, with a ~200 km wide thinned basin in high position and missing lower continental crust (Aslanian *et al.*, 2013). The thinning process seems to be depth dependent and to mainly involve the lower/middle crust, which appears to be exhumed in the continent-ocean transition zone (Burov and Poliakov, 2001; Burov, 2007; Watremez *et al.*, 2013 Aslanian *et al.*, 2009; 2013). However, this exhumation does not explain the entire thinning of the system (Aslanian *et al.*, 2009; 2013). The thinning of the continental crust cannot be explained only by stretching, shears, faults or lower crust exhumation; some lower crust is still missing, and must have flowed elsewhere or mixed with the upper mantle (Aslanian and Moulin, 2012). This behaviour of the lower continental crust has strong implications for deep processes, vertical movements, and isostatic response to the mass transfer (e.g., Tesauro *et al.*, 2011) that should be readable in the sedimentary record. The nature and age of drilled sediments should provide major insight into palaeogeography, fluvial dynamics, palaeobathymetries, sea-level changes, sedimentary fluxes, erosion/sedimentation balance, and subsidence.

In addition, the MSC event was both a time of extreme erosion and major sea-level fall, huge mass transfer and important halite deposition implying major isostatic vertical movements, recently quantified on the outer shelf (Rabineau *et al.*, 2014). The amount of isostatic movement associated with the MSC still needs to be quantified in the deepest basin and related to the nature of the substratum that needs to be sampled and related to the rheology of the underlying material.

Finally, the post-rift subsidence was recently measured by the direct use of sedimentary geometries analysed in 3D and validated by numerical stratigraphic modelling (Leroux, 2012; Leroux *et al.*, 2015, in press). Three domains of subsidence were identified: on the platform and slope, the subsidence takes the form of seaward tilting with different amplitudes, whereas the deep basin subsides purely vertically. These domains agree with the deeper crustal domains highlighted by previous geophysical data (Moulin *et al.*, in press) and that the post-break-up subsidence continues to use the initial hinge lines of the rifting phase. This striking correlation between surface geologic processes and deep earth dynamic processes reveals the sedimentary record and sedimentary markers as a window into deep geodynamic processes, which may be used to decipher the laws of subsidence (Leroux *et al.*, 2015).

The sampling of post- and pre-salt sedimentary layers and crustal material in the key intermediate domain will allow us to test competing ideas about passive margin genesis and subsidence, to validate the interpretation of crustal velocity models, and to quantify the striking correlation between surface and deep earth dynamic processes.

The GOLD project is key for understanding the geodynamic evolution, structural settings and sedimentological deposition in a large number of analogue natural laboratories in the Mediterranean domain. Similar with the Liguro-Provencal Basin, a large number of other rapid roll-back systems associated with the formation of highly arcuated orogens (Jolivet and Faccenna, 2000; Faccenna *et al.*, 2004) have created similar contrasting extensional back-arc basins with hyper-extended margins floored by oceanic or continental lithosphere and locally inverted, such as the Alboran Domain, Pannonian Basin, Black Sea or Aegean Basin (e.g., Brun and Sokoutis, 2010; Cloetingh *et al.*, 2006; Crespo-Blanc & Frizon de Lamotte, 2006; Matenco and Radivojevic, 2012; Munteanu *et al.*, 2013). Many of these situations retain similar key elements that make the GOLD drilling site the best area to extrapolate the process-oriented understanding required to analyze features such as hyper-extended crust, rapid prograding environments or extra-ordinary sea-level variations. In particular, the comparison with the MSC events recorded with variable amplitudes along the systems of connected basins with variable paleobathymetries of the Paratethys (e.g., Krijgsman *et al.*, 2010; Leever *et al.*, 2010; Munteanu *et al.*, 2012; Popov *et al.*, 2006; ter Borgh *et al.*, in press), where no significant salt was deposited, is important for discriminating processes related with large sea-level variations from the ones specific to salt deposition.

5. GOLD and its link with heat and fluid flow processes and the Deep Biosphere

The heat flow at GOLD position has been measured recently during the AMED-1 cruise (Sept 2013) on a shallow core which revealed a surface heat flow value of 59 mW/m2 (pers. comm. J. Poort), taking into account the conductivity of the sampled clay sediments that induce a blanketing effect (Lucazeau and Le Douaran, 1985). This new measurement is similar although slightly lower than that reported earlier (62-64 mW/m² in Burrus and Foucher, 1986). However, the presence of a thick, heat-conductive salt layer stongly alter the local temperature distribution in the sediments. The geothermal gradient has an inverse relation with the conductivity for the same heat flux, therefore thick salt layers or domes cause higher geothermal gradient and temperatures above the salt and lower geothermal gradient and temperatures below the salt (Bjorlykke, 2010). The drilling will offer a unique opportunity to better estimate the effect of salt layers and anticlines on the thermal field. Moreover, signs of overpressure and fluid escape have been described further South of this area (Carmenlenghi *et al.*, 2009; 2012), which can be another important source of local thermal perturbations in sedimentary basins (e.g. Poort and Klerkx, 2004; Grevemeyer *et al.*, 2004). Particular care will be needed to monitor any overpressure at the GOLD site, and increase mud weight when appropriate in addition to the installation of the BOP. Hence, the drilling will also help to better understand the mechanisms of fluid migrations, including through the salt layer as recently reviewed by Bertoni & Cartwright, 2015. For this, geochemical analyses of pore water composition will be crucial to help determine the source depth and temperatures, and velocities of the fluids. To collect samples at depth and ensure in-situ conditions are retained at the surface during laboratory measurements, we want to propose deploying specialist tools like PCATS (Pressure Core Analysis and Transfer System : hydrostat pressure, MDT (Modular Formation Dynamic Tester : Pressure and permeability from High res gauges, fow line resistivity) for collecting in-situ fluid samples, mechanical sidewall tools for retrieving minicores / sidewall cores.

GOLD will also address questions concerning the microbial communities and associated environments in extremely deep marine sediments of the Mediterranean Sea. The site severe physico-chemical environment makes it ideally suited to address the habitability of environmental extremes, where high pressure, temperature, and salinity all may constrain the subsurface biosphere in this context. In this regard, GOLD is a unique opportunity to investigate the interacting effects of multiple extremes within and between diverse sedimentary strata. Potential microbial communities entombed in hypersaline deeply buried paleoenvironments will be compared to microbial communities that have been described in today's Mediterranean brines (Antunes *et al.*, 2011; Siam *et al.*, 2012; Maignien et al., 2012). These types of subsurface communities should be very distinct from lineages of subsurface sediments of normal salinity (eg. Fry *et al.*, 2008; Teske *et al.*, 2008). The GOLD project will therefore allow a detailed investigations of the effects of temperature, pressure and hypersalinity on: (i) microbial diversity/activity, (ii) life's physico-chemical limits, and (iii) the adaptation of subsurface life to environmental changes before, during, and after the Messinian Salinity Crisis.

6. Establishing the chronostratigraphy in GOLD project

The proposed site (N41°45.92', E05°00.10') is located at the toe of the continental slope at a water depth of 2420 m in the distal part of the Rhône deep-sea fan (Droz et al., 2006). A short 3 m core has recently been acquired at the drill site during the AMED-1 cruise and shows alternating clays and silts. At this site, we aim to drill down to the crust, through the 6230 m of sediments deposited during the last ~23 Ma. This drilling requires the use of a riser drill ship equipped with a Blow Out Preventer to go through the ~600 m thick Messinian halite sequence. This could be done by academia only with the Chikyu drillship from Japan, being the only vessel available within IODP that can satisfy this requirement (see plate 1). The succession of strata has never been drilled through before in the deep Western Mediterranean Sea, and the unexplored strata below the salt have never been sampled.

Wire line tools and measurements (Hearst and nelson, 1985; Ellis, 1987) will give us a continuous and high resolution picture of the complete depositional megasequence corresponding to the MSC (Gorini *et al.*, 2015). Increased knowledge of rocks petrophysical parameters and high quality log data (spectral gamma ray data for clay identification, acoustic velocities, electrical resistivity, density and capture cross sections for neutrons and electrons) will provide a complete calibration of the deep basin sedimentary sequence and seismic facies. In particular, the knowledge of depositional environments and petrophysical characteristics will provide a complete geologic insight, including relative changes in sea level, sequences and cyclo-stratigraphy within the deep western Mediterranean basin. These measurements are fundamental in analyzing the MSC deposits and their paleogeographic settings. Drilling a giant saline basin implies specific tools and measurements (Renoux *et al.*, 1991). Evaporitic rocks, carbonates, and clastics sediments are characterized in particular by various densities and capture cross sections data that can be discriminated by the use of nuclear tools (Ellis, 1987) such as the density tool (or LDT, for RHOB and the Pef) and so-called neutron porosity tool (for NPHI and SIGMA). For example, the photo-electric factor (Pef) allows the discrimination between sandstones (2 barns/el), dolomite (3 barns/el) and carbonates (5 barns/el). Similarly, large differences in Pef and capture cross section values (SIGMA) are obtained for different evaporitic minerals. While the former is directly available from the LDT, the latter is given by the Neutron (NPHI) tool, which allows the discrimination of water bearing minerals such as gypsum ($CaSO4,2H2O$)-(+50 p.u.) and carnallite ($KCl\ MgCl2\ ,6H2O$)-(+60 p.u.). Another important tool for minerals identification is the spectral gamma ray (N.G.T). It records selectively the Thorium (p.p.m.), Potassium (%) and Uranium (p.p.m.) natural radioactivity. Uranium content being characteristic of the pH (precipitation under euxinic conditions as for primary dolomites). The thorium log is the best indicator for clay identification. In particular, the thorium–potassium ratio provides a qualitative but clear identification of clay mineralogy. As a consequence and for example, the coupling between potassium and neutron logs leads to a direct determination of Carnallite (KCl, MgCl2, 6H2O). Finally the sonic tool allows the determination of P and S velocities at depth (m/s). This tool might also be a discriminative for some of the matrix components such as anhydrite (50µs/ft), and halite (67 µs/ft). In addition, the P and S velocities allows the computation of mechanical coefficients (such a the bulk and shear modulii, or the Poisson's ratio). Real time sonic-while-drilling acquisition could be essential to monitor to the existence of potential overpressured zones, but would require the use of LWD, which remains an alternative through the salt.

Detailed petrographical analysis performed with the QEMSCAN automated analytical system both on cuttings and core samples coupled with detailed clay mineralogy performed on selected samples at regular intervals throughout the drilled sequences, will allow the pin point key changes in composition of the sedimentary sequence and explain wireline log responses. These will provide indication on sediment provenance (heavy minerals), weathering processes and climate affecting the basin margin areas (smectite vs kaolinite vs illite) and diagenetic processes. The latter are important to ascertain the degree of preservation of biostratigraphic component and its significance.

The combination of high-resolution biostratigraphic studies based on Nanofossils, planktonic Foraminifers, and Dinoflagelates, together with magnetostratigraphy and wireline logging cyclo-stratigraphic patterns will provide an accurate chronostratigraphic framework for the pre- and post-evaporite strata (e.g. Gautier *et al.*, 1994; Krijgsman *et al.*, 1999; Sierro *et al.*, 2001; Flores *et al.*, 2005; Lirer & Iacarino, 2005; Di Stefano *et al.*, 2008…). Identification of Foraminifer microfosssils in marine Neogene series in the Mediterranean Sea has been successfully carried out in many industrial boreholes in the Valencia Basin, Gulf of Lions (down to more than 4000 mbsf), Cadix and DSDP boreholes despite of their diagenetic imprint (Cravatte *et al.*, 1974; Lanaja *et al.*, 1987; Sierro *et al.*, 2000; Ochoa *et al.*, submitted).

The final goal will be to tune the sediment cycles (if identified in the logs), with astronomical solutions as has been reported in many studies on rhythmic sections onland with an accuracy of a single precession cycle (+/- 20 ka) (e.g. Hilgen *et al.*, 1995; Suc *et al.*, 1995; Sierro *et al.*, 2001; Lirer *et al.*, 2005; …). The same approach has been sucessfully applied to offshore downhole logs with cyclic records (Sierro *et al.*, 2000; Williams *et al.*, 2002; Ochoa *et al.*, submitted). This approach would be very accurate with continuous downhole logs further calibrated using the cores (normal cores and/or lateral cores) but can also be performed with cuttings.

For the MSC interval, classical biostratigraphy will be limited because of the lack of typical open marine microfossils and no magnetic reversal expected within this time period. However, evidences from outcrops and onshore wells show cyclic sedimentation with alternations of gypsum and laminated marls with microfossil contents (benthic Foraminifers and Ostracods). These sedimentary sequences give a typical logging signal (Ochoa et al., submitted) that can be used to establish a robust chronology.

At the GOLD site, specific wireline logging tools will also be crucial to recognize patterns and alternating of lithological sequences (see above), to precise through direct pore fluid sampling the nature of in-situ fluids, to get information about hole stability at great depth, to study in particular the deformation of the salt under a steep geothermal gradient, or to determine ahead of time the top and the base of the salt from downhole seismic probing.

Cyclical changes in the logs in combination with microfossils, lithologic and geochemical properties (e.g. Strontium isotopes) of the sediment can be interpreted in terms of paleoenvironmental changes (e.g. Flecker *et al.*, 2006, Sprovieri *et al.*, 2003). Additional independent chronostratigraphic constraints can be provided by radiometric datings of tephras or microtephras, as volcanic activity is reported in nearby regions from the Mediterranean Sea during the messinian period in Murcia (Krijgsman *et al.*, 2006), and in the Tyrrhenian site 654 Leg 107 (Kastens *et al.*, 1987).

Moreover, borehole stability data will be essential to drill to more than 6 km, in particular through the thick salt layers. Data on borehole deformation might be obtained from the two orthogonal calipers of the Formation Micro Scanner (F.M.S.) borehole wall imaging tool (Pezard et al., 1990; 1992), or else with a full description of boreholes sections obtained from acoustic images of the borehole surface (Zemanek et al., 1970; Maury et al., 1999) with the Ultrasonic Borehole Imager (U.B.I.). In either cases, these cm-scale electrical or acoustic images of the borehole surface will provide essential high resolution data about sequence stratigraphy and sedimentological processes. Likewise, for borehole completion and the precise determination of adequate depth to set the different casing strings used to protect the upper part of the hole while drilling, Vertical Seismic Profiles (V.S.P.) might be conducted to determine either the top or the base of the salt, both well identified from sesimic profiles (e.g. Lofi et al., 2011).

In all, the GOLD project is divided in two parts (Plate 1): The first part targets more surficial processes and will provide the first chronological, lithological, palaeoenvironmental, palaeooceanographic, and palaeoclimatic constraints from samples in the deep basin through the entire MSC, and will also examine the deep biosphere. The GOLD deep site will provide the unique opportunity to determine how multiple extremes of high temperature, pressure, and salinity impact on life's frontier(s): When does the biosphere truly become the geosphere? The second part (Plate 1) will sample pre-MSC sediments to reconstruct the early history of the basin and its vertical evolution related to deeper processes. We will drill down to the substratum to reach, sample and ground-truth the petrographic nature of this unknown substratum.

As a summary, the main objective of GOLD (Plate 2) is therefore to sample for the first time the deep basin of the Mediterranean Sea in the Gulf of Lion while recovering strata from the base of Pliocene, through the Messinian Series (both detritic and evaporitic strata), the pre-MSC Series, and down to basement rocks in a key transitional zone of unknown petrographic nature, in order to:

1) Constrain the timing and quantify the consequences of MSC base-level change on river behaviour, the erosion, supply, and transport of sediment, karstification, evaporites

deposition and landscape-relief evolution, through the characterization and quantification of sediment fluxes.

2) Reconstruct a complete history of basin vertical evolution, with specific focus on the palaeoenvironment, palaeobathymetry, and chronology of early Miocene sedimentation, to address fundamental questions about rifting, passive margin genesis, and the nature of the first oceanic crust.

3) Characterize the thermal, petrophysical and mechanical properties of the lithospheric crust underlying the Western Mediterranean and establish the relationship between temporal and spatial variations in crustal structure and the mechanisms that generated the spectacular vertical motions of both the basin and its margins during the MSC.

Conclusion:

The GOLD project proposes to drill a complete sedimentary column without faults, major erosional hiatuses, or sedimentary time gaps down to the transitional crust in the Western Mediterranean Sea. The selected **GOLD site** is one of the very few deep target sites that can satisfy 1) technological and security constraints (linked with the use of IODP vessels and specially the R/V Chikyu operated by CDEX-Jamstec, such as: bathymetry <2500 m, bottom hole maximum depth <9 km), 2) scientific constraints, such as low geothermal gradient (for the deep biosphere), absence of salt diapirs (for the preservation of a complete stratigraphic record), and sampling of the transitional crust. The GOLD Project will gather a unique group of expertises. A Public-Private Consortium could be created with representatives from various international universities, public institutions, companies from the petroleum sector and any other industrial technical or environmental sectors.

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*********************NEW FIGURES and captions ***************

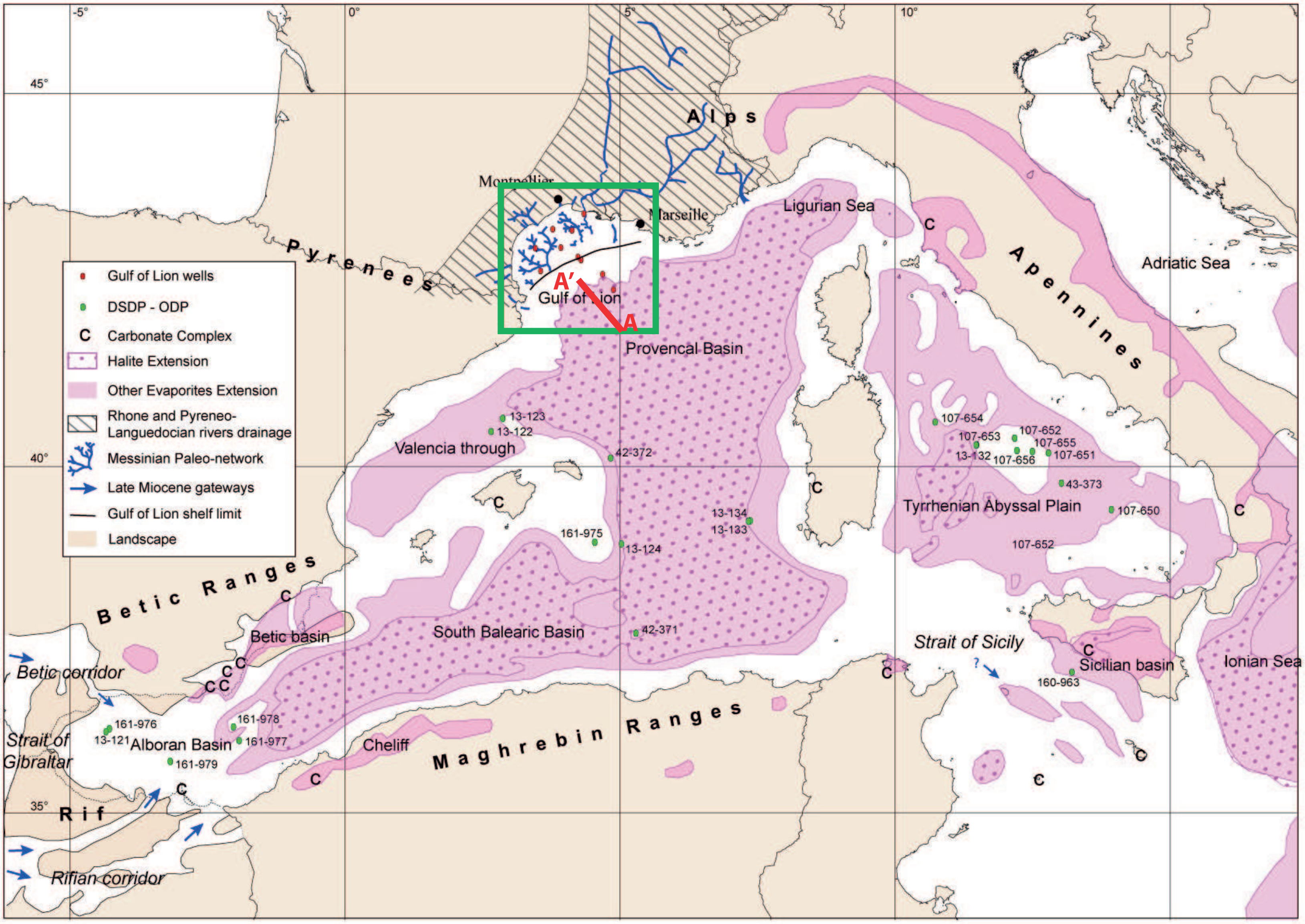
Figure Captions :

Figure 1 - Location map (modified from Bache et al., 2009). The Gulf of Lion is located in the green square. The location of the synthetic line A-A’ showed in Figure 2 is in red.

Figure 2 - Composite line drawing cross-section showing the markers of the MSC (modified from Lofi, et al., 2011; and the drilling strategy of the MDP "Uncovering a Salt Giant" (Camerlenghi et al., 2014). GOLD represents the Deep basin site (Target A). See approximate position of A-A' in Figure 1. The blue line represents present-day sea-level.

Plate 1 - Top: Location of the Sardinia profiles (red lines in the top figure) and the GOLD project in the Gulf of Lion. The NW-SE profile was extended onland (red and yellow circles). The grey lines represent the limits of the different crustal domains (see the text for more details). After Moulin et al., submitted. Bottom: GOLD drilling position on the two Sardinia seismic profiles. The multi-channel seismic reflection data was acquired using a 4.5 km long, 360 trace digital streamer and a tuned airgun array of 8260 in3. The blue line on seismic profile represents the sea-floor.

Plate 2 - Summary of addressed questions and sampling strategy of the GOLD project



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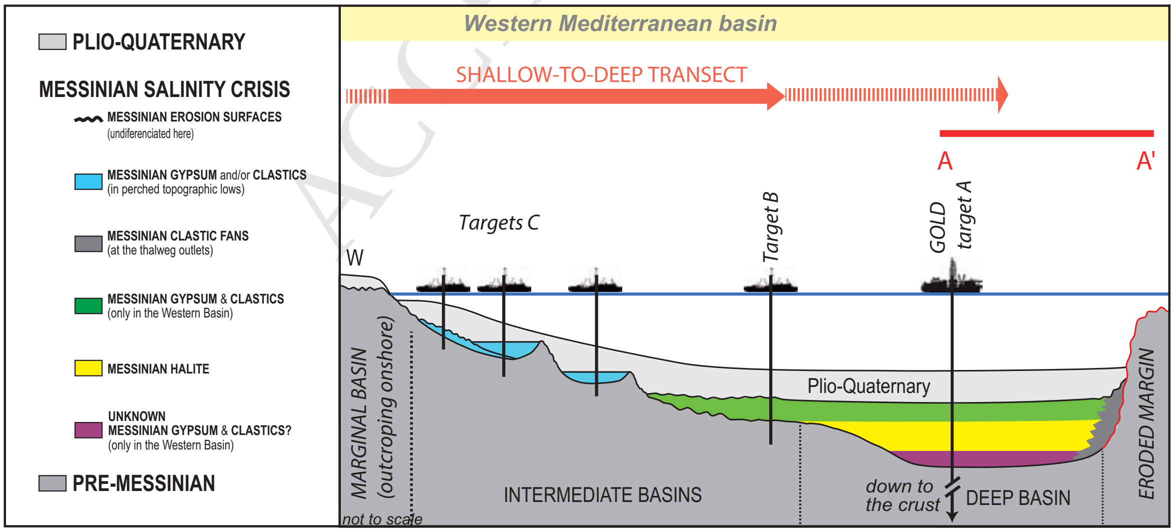

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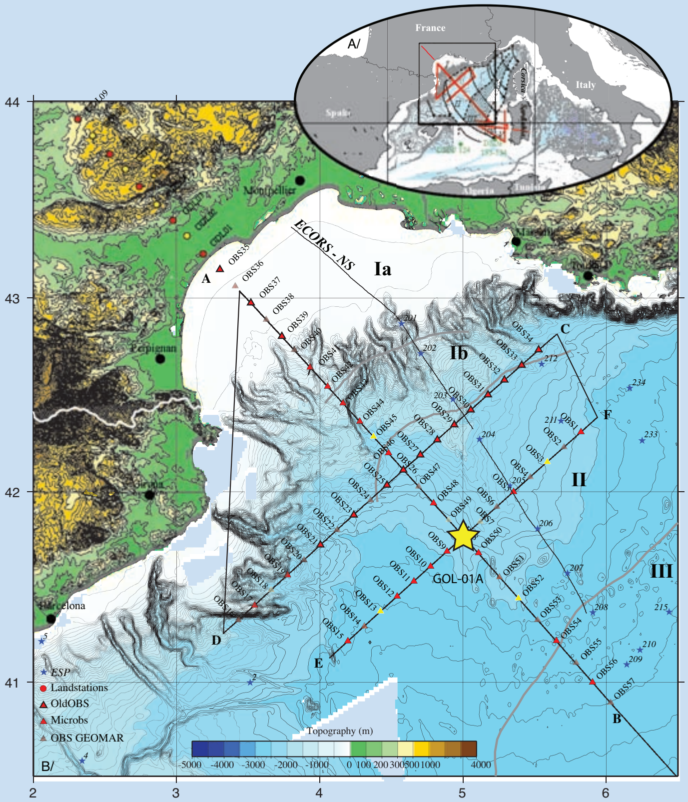


★ Location of the GOLD site shown on the figure below
The triangles represent the postion of the OBSs used
in the wide-angle seismic experiment Sardinia

GOLD SITE - Part 1:

Use suitable set of wire line tools and measurements throughout the drilling (Vshale, GR, density (rhob), neutron (Nphi), resistivity, Spectral GR NGT, PEF...)

Install casings when necessary (upper 800m, and through halite layer)

1) Drill through Quaternary without coring (800m). Keep cuttings every 10m.

2) Core through Pliocene strata (800-1645m) (siltstone-claystone-fine sand).

3) Core through Upper Unit (1645-2215m) (evaporites-sand-silt alternations).

4) Core in Upper part of Mobile Unit 2215-2235m (halite) (as deep as possible). For problems with core recovery: drill without coring but with LWD. Keep cuttings every 5m. Try spot-coring when heterogeneities are identified. Analyse logging measurements to position side-wall corings for biostratigraphic, geochemistry and microbiological investigations.

5) Core in Basal part of Mobile Unit (2785-2815m) (halite).

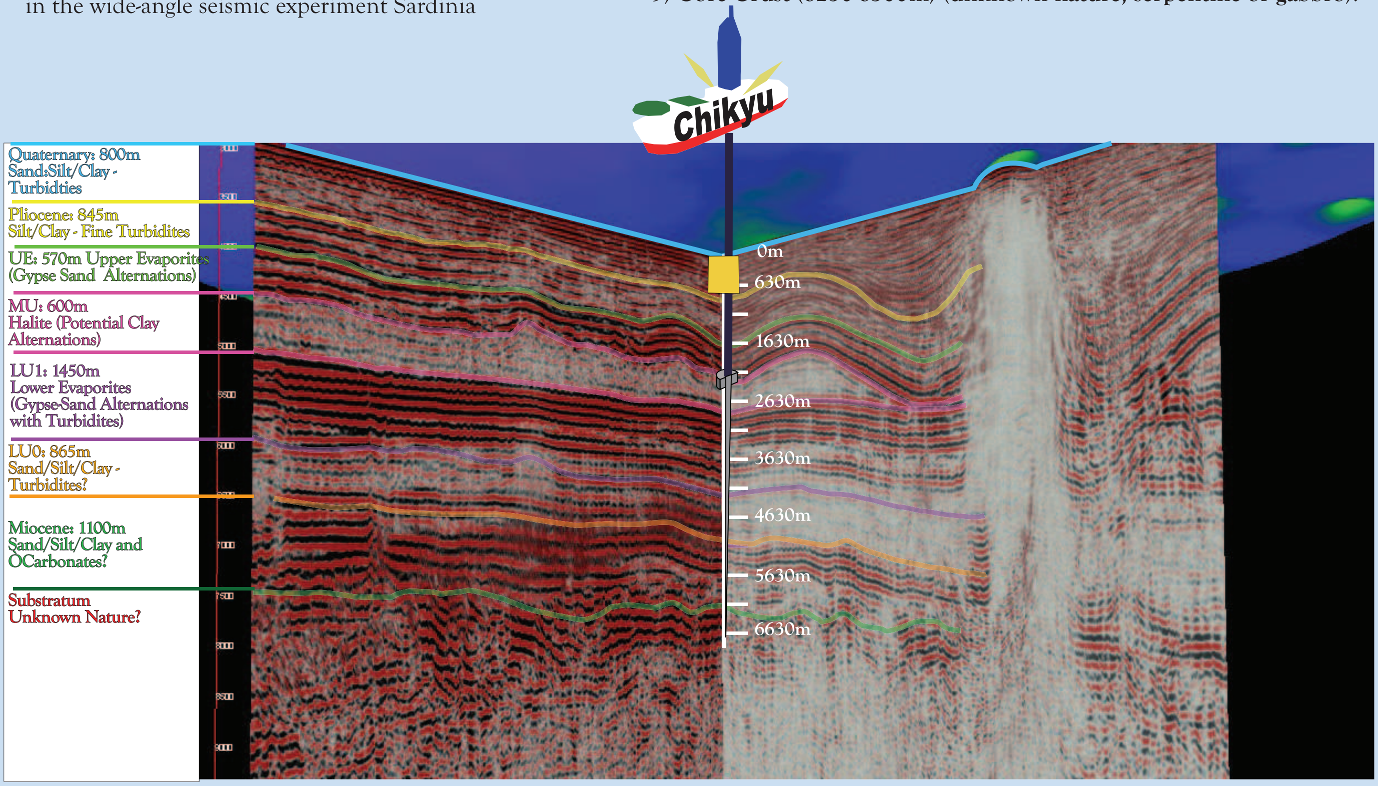
6) Core Lower Unit 1 (2815-4365m) (Evaporites-sand-clay alternations).

7) Core Lower Unit 0 (4365-5130m) (Sandstone-silstone-claystone).

- Part 2:

8) Core Pre-Messinian (5130-6230m) (Sand-silt-claystone and possible carbonates).

9) Core Crust (6230-6500m) (unknown nature, serpentine or gabbro).



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➢ Addressed questions

- ➢ *What is the nature, age, and paleobathymetry of sedimentary deposits*
- ➢ *When did the margin start to subside?*
- ➢ *What are the thermo-mechanical properties and spatio-temporal variations in crustal lithosphere structure?*
- ➢ *How did major rivers behave during the MSC? (erosion, karstification, supply, transport, landscape-relief evolution, mass transfer)*
- ➢ *What was the effect of the Messinian event on the subsidence history (water, salt, and sediment mass-transfers)? What are the consequences for thermo-mechanic models?*
- ➢ *What is the history of water exchange between the Mediterranean Sea and the North Atlantic?*

➢ Sampling strategy/data collection

Understanding connections between deep earth and surface processes

- ➢ multiscale seismic imaging of basin fill and crustal and upper mantle structure
- ➢ drilling monitoring and casing and set of wireline logging: geophysical and geochemical properties
- ➢ coring of the different MSC lithological units (Pliocene, UU, LU1, LU0) and potential spot-coring in halite (MU), coring of pre-Messinian units and crust material,
- ➢ exhaustive study of core material, taking into account diagenetic history and leveraging sedimentary biostratigraphic (foraminifera, nannofossils, dinoflagellates, ostracodes, diatoms), palynological, sedimentological, and geochemical analyses (including the chemical composition of pore waters), along with physical, paleomagnetic, petrological, and stable isotope study of the crustal cores.

Deep Biosphere & Deformation and fluid flow

- ➢ spot-coring of the different lithological units (every ~100m)
- ➢ wireline logging of a set of geophysical and geochemical in situ properties
- ➢ sampling of in situ formation fluids using wireline sampling tools
- ➢ extensive microbiological, genomic, biogeochemical, geological, palaeoceanographical and geophysical analyses of the core.

Plate 2: *Summary of addressed questions and sampling strategy of the GOLD project*