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Architecture and evolution of the Finale channel system, the Numidian Flysch Formation of Sicily; insights from a hierarchical approach

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Large scale channel systems are commonly imaged using seismic data and classified hierarchically. Where exposed at outcrop, similar scale ancient channel systems provide an opportunity to investigate subseismic scale architectures, produced for example through short duration autocyclic processes, and assess how they contribute to larger seismic scale architectures. In this study, a seismic scale slope-confined channel system from the Numidian Flysch Formation of northern Sicily is described using a hierarchical classification scheme. The channel system is 5.7 km wide and is organised within 3 hierarchical levels, comprising; 2 channel complex sets, 16 channel complexes, and >30 channel elements. channel complexes are mappable bodies and reach 500 m wide and 90 m thick.

Slope confined sinuous channel complexes contain stacked channel elements which show a progression of incision and bypass to fill with massive sandstones interspersed with graded turbidite deposits. Flows are interpreted to predominantly deposit during quasi-steady flow conditions although flow non-uniformity produced beds with complex grading patterns. Lateral expansion of channel elements produced terracing within the complex margin and had the capacity to alter flow rheology through incorporation of large mud volumes. Sinuosity of channel element thalwegs and offset stacking produced asymmetric channel complexes with heterogeneous internal architectures and lithofacies distributions.

Both channel complexes and channel elements thicken with younging indicating increased entrenchment through allocyclic forcing. The frequency distribution of channel-element thicknesses also shows a positive skew centred around 12 m as with published data global datasets. We question whether this distribution similarity may result from a fundamental process at the channel-element scale such as substrate armouring through coarse grained sedimentary deposits exceeding the capacity limits of transiting flows. The use of a hierarchical classification scheme therefore highlights the importance of subseismic scale processes on mappable architectures. The quantification of specific hierarchical elements also allows the role of allocyclic forcing to be investigated in an area of complex palaeogeography.

1. Introduction

Submarine channels represent sustained conduits on submarine slopes formed through a combination of erosion and deposition from transiting density flows. In recent years, submarine channel architectures and the facies that fill them have been intensively studied using both outcrop and high quality industry 3D seismic data. With notable exceptions including the Kirkgeçit Formation of Turkey (Cronin et al., 2005b), the Pab Formation of Pakistan (Eschard et al., 2003), the Gres du Champsaur of France (Brunt and McCaffrey, 2007) and the slope channel systems of the Lainsberg basin (Wild et al., 2005), studies of large-scale submarine channel systems are predominantly described using seismic data given the difficulties of sufficient outcrop exposure.

The manifestation of a channel system's evolution, both in terms of its architecture and the style of the deposits, are of major importance to hydrocarbon exploration whereby models can provide a degree of prediction in frontier provinces. Through outcrop and seismic studies, common evolutions associated with submarine channels have been recognised. At its most simple this may be described by an incisional phase in which excavation of slope sediment occurs, followed by an aggradational phase in which sediments fill the open channel form (McHargue et al., 2010). Through ancient outcrop and recent seismically imaged examples, this simple evolution has been recognised to repeatedly occur over a variety of time scales and magnitudes producing a complicated

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hierarchy of depositional elements (Abreu et al., 2003; Deptuck et al., 2007; Posamentier and Kolla, 2003; Fildani et al., 2013).

Erosional slope confined channel complexes (sensu Sprague et al., 2002) are a depositional element originally recognised within seismic data from the Gulf of Guinea (Cronin et al., 2005b) in which a well defined basal erosion surface confines smaller sandy channelised forms which commonly display a sinuous planform (Campion et al., 2000). Attempts to capture complexity such as this have resulted in several models based upon a variety of methods. Models by Campion et al. (2000), Mayall et al. (2010), McHargue et al. (2010), Navarre et al. (2002) and Sprague et al. (2002) are hierarchical and based upon recognition of major surfaces and architectural stacking patterns. These classifications are scale independent and, with the exception of Mayall et al. (2006) (their Fig. 6), are also time (duration) independent. In contrast, process based models such as Peakall et al. (2000) and Kneller (2003) link flow processes with changes in architectural style. Such models provide a way to characterise channel system architectures and infer channel processes based upon interpreted depositional elements (Pirmez and Imran, 2003). In particular, hierarchical models also allow for a methodical comparison between channel systems, although this approach is not yet commonplace within published studies.

This study presents a channel system from the Numidian Flysch Formation of Sicily. The system is similar in scale to large, seismically imaged examples from the Pleistocene Benin-major Canyon (Deptuck et al., 2007) and the Nile Delta (Catterall et al., 2010). This study aims to document the system using a hierarchical approach with the objective of answering the following questions. Are similar processes documented from different examples of the same depositional hierarchy within the Finale channel system? How do processes within smaller scale nested architectural elements (e.g. channel elements) contribute to the geometry of larger architectural elements (e.g. channel complexes)? Both of these questions are important when considering heterogeneity and reservoir connectivity within channel bodies on a scale commonly mapped within seismic data. We also discuss the effect of allocyclic controls upon depositional elements of different hierarchies.

2. Geological background

The Numidian Flysch Formation is an Oligocene to mid-Miocene deep-marine deposit found throughout the entire western Mediterranean, cropping out in Spain, Morocco, Algeria, Tunisia, Sicily and southern mainland Italy (Wezel, 1970) (Fig. 1A). It represents a linear series of roughly contemporaneous submarine fans on the North African passive margin, consisting of quartz rich sediment sourced from the African craton (Thomas et al., 2010). The Mahgrebian Flysch Basin (MFB) into which sediment was deposited (Fig. 2), was a foreland basin remnant of the Neo-Tethys ocean in which oceanic crust was subducted northwards beneath European crustal blocks termed the AlKaPeCa terrains (de Capoa et al., 2000; Guerrera et al., 2005; Thomas et al., 2010).

European AlKaPeCa terrains and their sedimentary cover formed an accretionary prism at the northern margin of the basin as they migrated southwards during the Oligocene and Miocene (de Capoa et al., 2004). Continental collision with the African margin occurred from the early to upper Miocene such that basin deposits were thrust upon the North African margin, resulting in the regional Alpine fold-and-thrust belt (Thomas et al., 2010 and references therein). Diachronous closure effectively split the basin into three sub-basins however, with the middle Tunisian/Algerian sector closing in the early Miocene and the western (Moroccan/Spanish sector) and eastern (Sicilide sector) sub-basins remaining open until the mid to late Miocene (Thomas et al., 2010). Numidian Flysch Formation deposits of the Sicilide basin, the subject of this study, were therefore deposited into a foreland basin embayment which opened north–eastwards towards the Italian Apennine Foreland Basin (Fig. 2) (Guerrera et al., 2005).

2.1. The Sicilide basin

Numidian Flysch Formation deposits of the Sicilide basin crop out throughout northern and central Sicily, southern Italy, and transgressing the basement of the Galite block in northern Tunisia (Belayouni et al., 2010; Wezel, 1970) (Fig. 1A). The North African passive margin was orientated approximately northeast–southwest and bordered by the Tunisian mainland and the Pelagian shelf to the south (Fig. 2). In northern Tunisia, the Fortuna Formation, a major fluvio-deltaic complex, fed sediment eastwards towards the Pelagian shelf (Vanhouten, 1980). Its role in providing sediment to the North African margin and henceforth to Numidian Flysch Formation submarine fans has been long debated with no obvious conclusion (Thomas et al., 2010) and references therein). Medium to Coarse grained shallow marine clastic deposits of the contemporaneous Bejaoua Group also crop out in northern Tunisia beneath nappes of the Numidian Flysch Formation (Riahi et al., 2010). A shallow marine shelf environment therefore separated the Numidian Flysch Formation slope from the Tunisian shoreline while there was a distally steepened ramp environment to the east around Malta and southern Sicily (e.g. Pedley et al., 1992) (Fig. 2).

Little detail is known regarding the slope architecture of this passive margin due to the thrusted nature. Wezel (1970) however interpreted a slope and continental rise environment for deposits in northern Sicily. Lobes have also been interpreted from western Sicily (Pescatore et al., 1987). In northern and central Sicily, a series of sandy channels have been described within a submarine slope environment (Johansson et al., 1998) (Fig. 1B). They range from 150 m to 3 km in width, and include some examples described within this study. Channels contain stacked beds of massive ungraded sandstones, and incise muddy slope deposits with no evidence for levee construction. Johansson et al. (1998) interprets this massive sandstone facies as the deposits of high-density turbidity currents and debris flows. Three types of erosive channel are documented, based upon grain size and channel dimensions (Johansson et al., 1998) although all are interpreted to be erosive and to contain nested channels bodies. Stow et al. (1999) elaborate on this interpretation and infer a correlation of some channels, providing a sinuous planform which is mapped for up to 10 km downslope. This study attempts to build upon this work.

3. Study area

In northern Sicily, several submarine channel examples crop out along a 19 km stretch of coastline. These include the Ponte Finale and Pollina channels previously documented by Johansson et al. (1998) (Fig. 1B). They form prominent headlands of thick sandstones which protrude tens of metres into the Tyrrhenian sea. Two major groupings occur with a separation of 13 km; 2 km west of Cefalu, and 11 km east of Cefalu (Fig. 1B). Here we focus on the eastern grouping centred upon the town of Finale and the Capo Raisigerbi headland (Fig. 1A, and B). Here, stratigraphy is exposed in an 8 km wide thrust sheet dipping 20° towards the northeast. 650 m of discontinuous section is accessible in a north to south transect from coastal cliff sections to the town of Pollina at 970 m elevation (Fig. 1B and C).

4. Methodology

Major sandstone bodies were mapped using traditional field mapping techniques, Differential Global Positioning System (DGPS)