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Research paper

Outcrop reservoir analogous and porosity changes in continental deposits from an extensional basin: The case study of the upper Oligocene Sardinia Graben System, Italy

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A B S T R A C T

Several recent hydrocarbon discoveries were detected in extensional areas located around fault-bounded tectonic highs. These tectonically-controlled mini-basins are diffusely characterised by terrestrial and shallow-marine successions with complex geometrical relationships. The degree of seismic resolution and the punctual well-log lithostratigraphic data do not allow suitable reconstructions of these plays and, thus, the use of good outcrop analogues is crucial in their reservoir characterisations.

In this paper, we present the results of a sedimentological study carried on continental deposits filling a segment of the Oligo-Miocene south-eastern basin margin of the Sardinia Graben System, in the central-western Mediterranean. This well-exposed terrestrial succession results from the erosion of Palaeozoic metamorphic and magmatic basement rocks exposed along the basin margin. Continental, coarse-grained eluvio-colluvial, alluvial and fluvial sediments exhibit changes both in thickness and lateral extensions due to the existence of several endorheic depocentres, which were aligned along major normal faults.

Based on the stratigraphic and sedimentological analysis of a number of exposed stratigraphic sections, the main depositional processes are identified for each specific facies association. Due to the grain-size of the dominant deposits, porosity is estimated by using an image analysis software on high-resolution digital photographs from a number of outcrop samples. The results show how porosity changes dramatically across the reconstructed sections due to the complexity of the reciprocal geometrical passages among all these lithofacies.

The dominance of colluvial/alluvial fans or river braidplain systems and the different nature of sediment occupying each depositional areas are interpreted as the response to the interplay between the capacity generated by the vertical tectonic displacement of major normal-faults and the interception of the base-level with the topography of these mini-basins. Our observations suggest six possible depositional scenarios that resume as many reservoir types in fault-controlled half-grabens with dominant continental lithofacies.

1. Introduction

The terrestrial realm represents a primary area for production of coarse-grained sediment accumulations (Collinson and Thompson, 1982). As observed in many modern continental settings, pebble-, cobble- and, more rarely, boulder-size clastic accumulations may

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form arrays of steep fans, often coalescing into aprons, developed along the slopes of valley sides and basin margins, or transported across plains for kilometric distances (Blair and McPherson, 1999). Sedimentary processes can vary greatly based on the role exerted by water in the sediment transport and deposition. The resulting deposits can thus be represented by: (i) eluvio-colluvial sediments, which are generally accumulated by avalanches related to the effect of gravity and in absence of relevant waters, such as *rockfalls* and *debrisfalls*; (ii) alluvial and fluvial sediments, which are instead generated by the dominant transport exerted by water flows, including *debrisflows* and *streamflows*. These sedimentary processes occur in continental depositional environments generating specific systems, such as colluvial and alluvial fans, often associated with braided or meandering rivers (Leeder and Gawthorpe, 1987).

Many recent hydrocarbon discoveries were found in extensional basins, filling depositional areas located on the flanks or partially over the margins of fault-bounded tectonic highs (e.g., the late Jurassic-lower Cretaceous in southwest Alabama, USA; the Miocene Mumbai High Field, western offshore India; the Triassic-Jurassic around the Utsira, Frøya and Mandal highs, Norwegian Sea; the late Jurassic in the Strathspey-Brent-Statfjord half graben, northern North Sea; Mink and Mancini, 1995; Davies et al., 2000; McLeod et al., 2002; Vasudevan et al., 2012). Most of these plays derive from sedimentary basins subjected to extensional tectonic regimes, where graben and half-graben petroleum systems exhibit syn-tectonic stratigraphic expansion of the seismic reflectors toward the bounding faults (e.g., Blair and Bilodeau, 1988; Gawthorpe et al., 1994). In many of these examples, coarse-grained continental deposits adjacent to the major fault zone (Trudgill, 2002) represent sedimentation associated with the initial stage of basin development. These deposits evolve laterally or vertically to sand-rich shallow-to deeper-marine sediments which, in a reservoir perspective, are usually retained more profitable respect to their fully continental counterparts. However, many recent case studies also revealed unexpected very-good oil and gas reservoirs entrapped in the continental basement-derived successions filling fault-controlled mini-basins (e.g., Jackson et al., 2010). These depressions usually consist of 100s-to-1,000s m long grabens and half-grabens located on top of tectonically-fragmented wide areas thought as tectonic ‘terraces’, which connect the marginal ‘platforms’ to the deeper basins (e.g., the middle-late Jurassic in the North Sea rift basin; Davies et al., 2000).

Although very common along the margins of many extensional basins (e.g., Steel and Wilson, 1975), fault-adjacent continental sediments are often difficult to differentiate from subsurface core datasets or they are often under a good seismic resolution to be properly assessed and evaluated. Moreover, coarse-grained deposits are commonly difficult to interpret from core data, because characterised by indistinct textural features or not well-defined sedimentary structures. Therefore, when exposed and preserved, ancient basement-derived continental facies represent useful outcrop analogues for similar subsurface oil-bearing successions.

The present study documents the sedimentological features and the depositional architectures of the upper Oligocene continental Ussana Formation (*Auct.*), which occupies the SE margin of the so-called Sardinia Graben System (Cherchi et al., 2008; Oggiano et al., 2009) (Fig. 1A and B). This basin boundary zone underwent an early phase of tectonic extension, resulting in the formation of isolated or interconnected grabens and half-grabens which were variously filled with the continental conglomerates and sandstones of the Ussana Fm (Fig. 1C) (Sowerbutts and Underhill, 1998; Casula et al., 2001).

During this initial tectonic fragmentation, different types of fault-related composite depositional systems formed, where colluvial, alluvial and fluvial sediments were adjacently accumulated with varying relative volume percentages and porosity vertical/lateral trends.

Our facies-based observations, allowed us to reconstruct: (i) the main depositional processes at the origin of the detected lithofacies; (ii) the lateral/vertical relationships between these types of sediments, and (iii) the main depositional systems and their reservoir potential.

All these elements can be jointly used as tool to successfully evaluate the best-productive sectors in similar hydrocarbon-bearing sedimentary rocks.

2. Geological setting of the Oligo-Miocene Sardinia Graben System

The Oligo-Miocene Sardinia Graben System (Cherchi and Montadert, 1982; Rehault et al., 1984; Cherchi et al., 2008) developed since the late Oligocene onwards in a N–S-elongated area presently comprised between the Gulf of Asinara to the North and the Gulf of Cagliari to the South (Fig. 1B). This basin resulted from the extensional regime that affected the Iberian-Europe Region at about 34 Ma, and was originated by the complex interplay of normal fault systems that dissected part of the so-called ‘Corsica-Sardinia microplate’ (Casula et al., 2001). Other authors consider this basin as the result of a multiphase extension and transtension in an intra- or back-arc setting, occurred as the Corsica-Sardinia microplate rotated from Eurasia in the Western Mediterranean from 21 to 15 Ma (Carmignani et al., 1994; Vigliotti and Langenheim, 1995; Vially and Trémoliéres, 1996; Faccenna et al., 2002).

The pre-Oligocene basement comprises intensely fractured and weathered metamorphic and magmatic rocks of Ercinian origin (Sowerbutts and Underhill, 1998; Casula et al., 2001; Oggiano et al., 2009), which are overlain by thin middle Eocene continental conglomerates and sandstones of the Cixerri Fm (Barca and Costamagna, 2010). The upper Oligocene continental deposits, known as the Ussana Fm (Cherchi and Montadert, 1984; Eschard, 1987), accumulated during the ‘syn-rift stage’ (Casula et al., 2001), and were transgressively buried by lower Miocene marine sediments (Simone et al., 2011, 2012). This succession was then exhumed and partially incised as consequence of the Plio-Quaternary regional uplift.

The present-day subsurface structure of the Sardinia Graben System consists of major normal faults, tilted blocks and transverse structures (Fig. 1C) (Casula et al., 2001). The basin shows large grabens whose margins are today well exposed (Fig. 1C), preserving sediments focused on the present study.

2.1. The upper Oligocene continental Ussana Fm

The Ussana Fm diffusely crops out in southern Sardinia, forming elongated deposits parallel to the main fault zones or occupying isolated sub-basins (Fig. 2A and B). In other sectors, their aerial distribution seems to have been controlled by transfer faults connecting two adjacent major normal faults (Fig. 2B).

The Ussana deposits are considered coeval with other shallow- and deeper-marine sediments, including the “Isili” and “Gesturi Sands” formations, whereas it is overlain by the lower Miocene shallow-marine sandstones of the “Marmilla Fm”. In this sector of Sardinia, transgressive conglomerates and fines of the “Gesturi Marls” Fm (Fig. 2C) represent the topmost Miocene stratigraphic intervals (Funedda et al., 2011).

Pecorini and Pomesano Chierchi (1969) firstly defined the “Ussana Formation” as a coarse-grained succession that recorded