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Late Miocene–Middle Pleistocene sequences in the Po Plain – Northern Adriatic Sea (Italy): The stratigraphic record of modification phases affecting a complex foreland basin

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ABSTRACT

During the Late Miocene–Pleistocene interval, a complex system of elongate foredeeps, the Po Plain-Adriatic Foredeep (PPAF), developed in the eastern sector of the Po Plain and in the northern Adriatic Sea, This system is the largest Late Miocene–Pleistocene complex of foredeep depocenters of the Peri-adriatic Basin with an overall length of 500 km and a width of 80–120 km.

In the last 15 years, several Eni-Agip multidisciplinary studies analyzed the buried Late Miocene–Pleistocene succession of the central-eastern Po Plain and northern Adriatic Sea. Detailed revisions of biostratigraphy, chronostratigraphy, sedimentology, seismic interpretation and sequence stratigraphy were performed using the very large Eni subsurface dataset including over 500 deep exploration and development wells and regional 2D and 3D seismic surveys. The large availability of subsurface data, the preservation and the relatively moderate structural deformation of the studied succession were essential factors for the generation of a detailed three-dimensional geological model for the foredeep basins and also for the related ramp/foreland and thrust-top basins areas. The model, which is presented in this paper, may be considered, for the large volume of qualitative and quantitative information, as a reference model for tectonically active foredeep basins dominated by basin-scale sand-rich turbidite systems.

During the Late Miocene, Pliocene and Early Pleistocene a severe tectonic activity affected the northern Apennine and the PPAF area. Due to the northern Apennine compressive tectonics, the PPAF underwent four regional phases of compressional deformation and depocenter migration towards the foreland (to the northeast). During these tectonic phases, four basin-scale tectonic unconformities were generated: the Latest Tortonian, the Intra-Messinian, the Intra-Zanclean and the Gelasian Unconformities.

The sequence-stratigraphic analysis of the basin was based on the recognition of allogroups, i.e. major stratigraphic units bounded at base and top by the four regional tectonically-induced unconformities, and of their component sequences, mainly of tectonic origin, ranked on the basis of their physical scale.

During the latest Miocene-to-Pleistocene time interval the foredeep shape was affected by a large variability in space through time, ranging from regular elongated shape to irregular shape, from simple foredeep to fragmented foredeep. A new evolutive model for the Apennine foredeep with two evolutive stages is proposed in this paper.

The PPAF was a deep-marine basin with water depths usually exceeding 1000 m. Its latest Miocene–Pleistocene succession mainly consists of thick sequences of turbidite deposits. Basin-scale, sand-rich, highly-efficient turbidite systems were largely predominant in the foredeep. Thick-bedded sand/sandstone lobes and thin-bedded fine-grained turbidite basin plain deposits represent the most common turbidite facies associations. Paleocurrents are predominantly directed to the southeast, parallel to the foredeep main axis.

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The thick PPAF succession consists of the turbidites of the Bagnolo (latest Tortonian–syn-evaporitic Messinian), Fusignano (post-evaporitic Messinian), Canopo (latest Messinian–Zanclean), Porto Corsini (Zanclean–Piacentian), Porto Garibaldi (Piacentian–Calabrian) and Carola (Calabrian–Late Pleistocene) Formations.

The fluvio-deltaic systems of the Paleo-Adda, Paleo-Mincio and Paleo-Adige Rivers, located along the Alps margins of Lombardia and Veneto foreland, provided the bulk of the PPAF siliciclastic sedimentary input. With the partial exception of the post-evaporitic Messinian, the clastic supply from the northern Apennine belt was subordinate.

The Messinian depositional systems underwent dramatic changes due to the combination of the salinity crisis and Intra-Messinian morphostructural reshaping. This behavior was not associated with a unique, dramatic lowering related to the Messinian Salinity Crisis (MSC) but was modulated by a combination of factors like climatic changes, deformation phases, isostatic rebound and sediment flux.

Stratigraphic relationships among decompacted coastal wedges suggest that the total lowering of the relative base-level did not exceed 900 m in the study area. This total drop was reached through three distinct base-level changes probably related to evaporation (ME2 Sequence), differential subsidence (ME3 Sequence) and regional uplift possibly associated to isostatic rebound (ME4 Sequence). The Zanclean (Early Pliocene) relative sea-level rise is estimated on the order of 800–900 m, with a shoreline landward shift in the foreland of at least 70 km. In the study area, the MSC was therefore recorded by an overall strongly asymmetric cycle where discrete events of various origin punctuated a relatively gradual base-level fall. During the entire MSC, the PPAF depocenters remained in relatively deep-water or deep-water conditions, associated with turbiditic sedimentation and locally to bottom currents.

1. Introduction

Over the last two decades, Eni geologists and geophysicists have performed several multidisciplinary studies of the buried Oligocene-to-Pleistocene depocenters of the Periadriatic Basin based on the modern principles of sequence stratigraphy.

Part of this activity was focused on the Late Miocene-to-Pleistocene succession of the central-eastern Po Plain and northern Adriatic Sea through several multidisciplinary studies based on the vast Eni subsurface database (Dalla, 1994; Bettazzoli and Visentin, 1997; Ghielmi et al., 1998; Amore et al., 2004; Nini and Visentin, 2004). Complete and detailed revisions of the biostratigraphy, chronostratigraphy, sedimentology, seismic interpretation and sequence stratigraphy were performed for this major depocenter of the Periadriatic Basin, hereafter referred to as the Po Plain-Adriatic Foredeep (PPAF). The main aim of these studies were: (1) to provide modern detailed geological models for the Eni (Agip at that time) Exploration and Development Departments to be used for their last phases of activity in this already mature area and (2) an improved characterization of the petroleum systems active in the area and of the related hydrocarbon trap types. Due to their corporate value, the results of these studies were released only partially (Ghielmi et al., 2008a, 2008b, 2010a; Bertello et al., 2009; Minervini et al., 2009). The different studies were eventually integrated in a single basin-scale model extended to both the onshore and offshore areas of the basin. A synthesis of the latest Miocene-to-Pleistocene tectono-sedimentary evolution of the central-eastern Po Plain and northern Adriatic Sea, based on the Eni model, is presented in this paper.

1.1. Dataset

The vast Eni subsurface database of the central-eastern Po Plain and northern Adriatic Sea includes both well and seismic data acquired over 40 years of activity in this area. It is comprised of: (1) a regional 2D seismic survey of the eastern Po Plain area; (2) a regional 3D seismic survey ("Adria 3D") of about 12,000 km^2 in the northern Adriatic Sea; and (3) several Eni 3D seismic surveys acquired for the development of onshore and offshore gas fields. I 500 explorative and development wells (with conventional and image logs, ditch cuttings, bottom and sidewall cores, etc.) were selected among all the available data.

1.2. Methodology

The Eni studies of PPAF are based on detailed well-log analysis and correlation strictly integrated with and calibrated by a dedicate seismic interpretation of the 2D and 3D seismic surveys. Twenty-two stratigraphic surfaces corresponding to unconformities and correlative conformities of different order and importance were correlated, at basin scale, on the well and seismic data applying seismic stratigraphy principles (Vail et al., 1977). The main result of this integrated analysis was a detailed physical stratigraphic model of the Late Miocene-to-Pleistocene sequence strictly based on the considerable well and seismic dataset. This model not only extends to the foredeep, but also to the ramp and part of the foreland, and to the piggy-back basins area, along the outer and inner foredeep margins respectively. The sequence stratigraphy of the succession (i.e. origin and areal extension of the unconformities, type of stratigraphic units, hierarchy, etc.) was defined on the basis of the evidences of the physical stratigraphic model.

The sedimentological interpretation of the succession was based on the description and interpretation of bottom cores and well logs of the studied wells. Fundamental information for the paleoenvironmental interpretation was also provided by the seismic facies of the deposits (amplitude, continuity, geometry, etc.). The facies models and turbidite systems classification of Mutti (1985), Mutti and Normark (1987), Mutti et al. (1992, 1999, 2003) were adopted as reference models in the sedimentological analysis and classification of the PPAF turbidites.

Paleontological analysis of foraminifera and nannoplancton assemblages were carried out on samples from bottom and sidewall cores, and on samples from ditch cuttings of selected stratigraphic intervals. On Messinian succession palynological analysis were also performed. The chronostratigraphic and paleoecological evidences were useful for the accurate datation of the unconformities corresponding to allogroup and sequence boundaries, and for supporting and verifying the well and seismic correlations as well as the environmental interpretations.

Notwithstanding the changes introduced in June 2009 by the Subcommission on Neogene Stratigraphy (SNS) of the International Commission on Stratigraphy (ICS) (Gibbard et al., 2010), which lowered the base of the Pleistocene to the base of the Gelasian stage (previously included into the Pliocene), the present work adopts the "old" chronostratigraphy (Gelasian as the last stage of Pliocene