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Research paper

Dating Pleistocene deltaic deposits using in-situ ^{26}Al and ^{10}Be cosmogenic nuclides

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ABSTRACT

The present study aims at testing the possibility of using the in-situ cosmogenic burial dating technique on deltaic deposits. The sequence analyzed is exposed along the Ligurian coast (north-west Italy) and is made of proximal marine and continental deposits previously considered Pliocene or Plio-Quaternary in age. In the study area two allostratigraphic units were recognized. The lower unit represents the evolution of a small coarse-grained delta developed in a fjord or embayment environment. The coarsening/shallowing upward trend observed within the sections, from bottom to top, suggests that the delta prograded rapidly in the landward portion of the canyon placed opposite to the paleo-river outlet. Within the deltaic sequence the transgressive and highstand system tracts were recognized. The unit 2 is composed by several alluvial fan systems deposited in small incised valleys developed within the previously, uplifted deltaic deposits and successively incised by a braided river system. In-situ produced cosmogenic nuclides were used in order to date the age of the deposition of the deltaic deposits. Results suggest that the studied deltaic sediments belonging to the unit 1 were deposited between 1,300,000 and 200,000 year ago thus during the Lower to Middle Pleistocene, whereas the unit 2 was deposited during the Middle Pleistocene as a consequence of a tectonically driven uplift phase. Furthermore samples collected within the prograding part of the delta show the higher denudation rates. The obtained results demonstrate that burial ages and related erosion rates inferred from cosmogenic nuclides concentrations can be considered as a very useful tool to reconstruct the sea level changes over the past 1 million year.

1. Introduction

The analysis of sedimentary basins is a fundamental tool in Earth Sciences, as their stratigraphic record preserve the climatic and tectonic history of their catchment area and depositional environment (e.g. Allen and Allen, 2005; Canuteanu, 2006). Deltas represent a particularly rich source of information as their internal structure is the result of the interplay between fluvial input, which in turn depends on the morphometric, tectonic and climate conditions of the source area, and basinal parameters such as eustatic sea-level changes, wave energy and storm regime (e.g. Allen and Allen, 2005). Constraints on the temporal evolution of the deltaic deposits offer, therefore, an invaluable opportunity to date changes in the tectonic and/or climate regime of the catchment areas and basins where the deltas were deposited (Backert et al., 2010; Breda et al., 2007; Longhitano, 2008; Ozel et al., 2007). Dating deltaic deposits usually relies on the presence of suitable biostratigraphic markers and on the application of techniques such as ^{14}C and optically stimulated luminescence (OSL), which can be applied to sediments not older than ~60,000 and ~250,000 years, respectively. The temporal limit of the ^{26}Al/^{10}Be cosmogenic nuclide burial dating is, however, up to 5 Ma (Granger et al., 1997; Granger and Muzikar, 2001) and it is therefore the only technique capable of dating Late Miocene to Pleistocene deposits, when fossils are not available.

In this work we use the ^{26}Al/^{10}Be burial dating technique to provide an age of deltaic deposits in the Ligurian Alps and constrain the catchment area-averaged erosion rates at the time of deposition. These data permit to identify the onset of the extensional tectonic regime in the area, responsible for the

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subsidence that created the basin in first place, and to quantify the effects of a change in tectonic processes on the landscape. We suggest that this technique applied to deltaic deposits provides unique insights to reconstruct the timing and rates of landscape response to tectonic and/or climatic perturbations in the Quaternary and beyond.

2. Geological setting

The study area is an SW–NE oriented, 7 km long and 3.5 km wide basin located in the Ligurian Alps, near the town of Vado Ligure and therefore named the 'Vado Ligure basin' (Fig. 1). It extends from the Rocca dei Corvi mountain (793 m elevation) to a depth of around 60 m on the continental platform, offshore. It is one of the many Ligurian extensional basins that were created from the Miocene as a result of a tectonic extensional phase, which still affects most of the western Mediterranean (Carminati et al., 2012) The Vado Ligure basin was deeply incised into a canyon, following the dramatic sea-level lowering during the Messinian salinity crisis (Ryan and Cita, 1978; Bache et al., 2009). At the beginning of the Pliocene the connection between the Atlantic Ocean and the Mediterranean Sea was reactivated (Gianmarino and Tedeschi, 1976; Breda et al., 2007), the canyon was flooded and partially filled with sediments. The remnant of the river system that excavated the Vado Ligure basin is now the 5.8 km long Segno River (Fig. 1) with its 21 km^2 catchment. The deltaic sequence is exposed between 16 and 70 m above sea level and about 300 m from the present coastline. The age of these deposits is unknown, but they have been attributed to either the lower to middle Pliocene, being stratigraphically placed between the Late Eocene – Messinian Piedmont Basin deposits, and the Holocene sediments (Carobene et al., 2008). Given the age attributed to the deltaic sequence, its exhumation is considered to have occurred in the Quaternary, suggesting that the area has been affected by a recent, relatively strong tectonic activity (Federici and Pappalardo, 2006; Carobene and Cevasco, 2011). An extensive sedimentological-stratigraphic study of the sequence has defined the overall structure of the delta (Ciampalini et al., 2009). The 40 m thick analyzed deltaic sequence is formed by an alternation of silty-sandy deposits and gravel layers rich in quartz clasts (Ciampalini et al., 2009). The stratigraphic and topographic highest part of the deltaic sequence is represented by a delta topset and channel facies association, which, in most cases, are incomplete because of erosion (Fig. 2). The foreset facies are the dominant feature of the deltaic sequence of Vado Ligure (Fig. 2); the association is around 20–25 m thick and, unlike the topset, is well preserved and exposed. The bottomset facies association represents the most distal area of the delta and it is exposed at the bottom of the analyzed sequence. The presence of quartz-clasts within the sequence, the small catchment area and the lack of temporary storage in the river banks make these deltaic deposits an ideal target to apply the $^{26}Al/^{10}Be$ burial dating technique (Granger and Muzikar, 2001).

3. Methodology and sampling strategy

This work presents the first attempt to use the $^{26}Al/^{10}Be$ burial dating technique to constrain time of sedimentation and catchment-specific palaeo-denudation rates from Plio-Pleistocene deltaic deposits. The terrestrial cosmogenic nuclide (TCN) method relies on the fact that rocks exposed on the surface of the Earth are constantly bombarded by cosmic rays from the space producing a cascade of particles and reactions in the Earth's atmosphere and on the Earth's surface (Lal, 1991; Gosse and Phillips, 2001). Interactions between these particles and the Earth's atmosphere create secondary cosmic rays, including neutrons and muons. Particles that manage to reach the Earth surface, penetrate for a few meters in rocks (depth of penetration is density-dependant), react with Si and O present in minerals, producing the ^{10}Be and ^{26}Al cosmogenic radio-nuclides (Lal, 1988; Nishizumi et al., 1991). In the upper few meters of the Earth's crust neutron production (spallation) is dominant, whereas muogenic interactions become of increasing relatively importance with depth (Gosse and Phillips, 2001). The rate at which these nuclides are produced depends on the flux of cosmic radiation, which itself varies through time, due to temporal variation in geomagnetic field strength; the thickness and composition of the atmosphere, which attenuate the flux; and the shape of the landscape that may shield areas from the bombardment (Gosse and Phillips, 2001). All these factors produce uncertainties in the determination of the cosmogenic nuclides production rates; however, these unknowns have no effect on the ratio of two cosmogenic nuclides from the same sample, as their production rates would be affected in the same way. In these terms, erosion rates calculated from the isotopic $^{26}Al/^{10}Be$ ratio are much more precise than those derived from the concentration of only one cosmogenic isotope, as the uncertainties associated with the production rate have no effects. The accuracy of the $^{26}Al/^{10}Be$ results data relies on a series of assumptions: (1) the quartz from which the cosmogenic isotopes are extracted needs to have been exposed at the land surface for a time necessary to accumulate a measurable cosmogenic radio-nuclides concentration, but much less than the half-lives of both nuclides (<<700,000 years); (2) transport time needs to have been negligible in comparison to the time of exposure to the cosmic rays during erosion, with no temporary storage within the catchment; (3) burial was rapid and deep (>10 m), to avoid cosmogenic nuclides production after deposition, although a correction that takes these factors into account can be used; (4) production rates need to have been constant during exposure to the cosmic rays; (5) the analyzed section has not been exposed to the cosmic ray during exhumation. Under these ideal conditions, the burial dating technique has been successfully applied, for instance to date cave deposits (Boaretto et al., 2000; Granger et al., 1997, 2001; Wagner et al., 2010; Balco et al., 2013), using equations (1) and (2), where only the production due to the spallation process (neutron production) is taken into account (Granger and Muzikar, 2001):

$$N_{Al}(t) = \frac{P_{Al}}{\lambda_{Al} + E/L} e^{-\lambda_{Al} t} \quad (1)$$

$$N_{Be}(t) = \frac{P_{Be}}{\lambda_{Be} + E/L} e^{-\lambda_{Be} t} \quad (2)$$

Where $N(t)$ is the measured concentration of ^{26}Al and ^{10}Be as a function of time t, t is the time of deposition, P is the production rate of the two radio-nuclides calculated considering the mean evelation of the catchment (360 m), λ_{Al} (0.980 ± 0.04) and λ_{Be} (0.459 ± 0.09) are the radioactive decay constants, E is the erosion rate and L is the attenuation length. Solving this set of two equations allows calculating the two unknowns, i.e. the burial age t and the denudation rate E at the time when the sediments now deposited were being eroded from the catchment area. The solutions of the equations can be presented using a plot, often called "banana plot", where the ratio $N_{Al}(t)/N_{Be}(t)$ is related to the $N_{Be}(t)$ (Granger and Muzikar, 2001).

The small-size of the catchment area of the Segno River and its torrential regime assure short transport of the sediments and rapid and deep deposition in the deltaic environment, but in the basin and, probably in most deltaic sequences, the sediments may have not been buried sufficiently fast and/or deeply enough to be