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Liquefaction features interpreted as seismites in the Pleistocene fluvio-lacustrine deposits of the Neuquén Basin (Northern Patagonia)

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ABSTRACT

Superbly exposed soft-sediment deformation structures in Pleistocene fluvio-lacustrine deposits along the southern border of the depression area called Bajo de Añelo (Departamento de Añelo, Neuquén Basin) have been analysed. In the study area, five stratigraphic sections were measured in detail: facies distributions and stacking patterns show that these sediments result from the interaction between fluvial and lacustrine systems, represented by cross-bedded and rippled strata, and varved deposits. The lateral extent of the deformation is some hundred metres and the deformed bed involves the lower-mid part of the 30-metre-thick succession. Deformation affects about 1.5 m of coarse-grained sand, fine-grained sand and rare gravel alternations. The base and top of the deformed layer are defined by planar surfaces: undeformed beds of similar thickness, lithology and facies to the deformed layer occur above and below.

Deformation is represented by a complex vertical succession of disturbed layers: each layer shows a general load-structure morphology. It can be described as a multilayered unstable density gradient system: in each bed a partial gravitational re-adjustment occurred after liquefaction. Unequal loading related to lateral variation of both bed thickness and grain packing and porosity is a probable additional driving force that can be described in the undeformed beds.

Trigger mechanism recognition for the observed liquefaction features can be based on the study of the geometry of deformed beds and on facies analysis results. Two key factors drive our interpretation: (1) the occurrence of undeformed beds below and above the deformed bed; (2) deformed and undeformed beds showing the same sedimentological features. These field data allow us to exclude the action of internal erosive and/or sedimentary processes (such as overloading, wave action, etc.) as possible trigger agents for liquefaction since deformation is totally absent in beds with similar sedimentary features. Furthermore, each internal erosive and/or sedimentary process can be discussed and easily excluded by analysing its specific signature in the geological record. Having excluded every possible internal trigger (autokinetic processes), the observed liquefaction effects can reasonably be interpreted as seismically induced (allokinetic trigger). From this point of view, this deformed bed is an important record of seismic activity in this sector of the Neuquén Basin during the Pleistocene.

1. Introduction

Soft-sediment deformation structures form in unconsolidated sediments with low to zero shear resistance as a result of tectonic and sedimentary processes. Loss of shear strength can be reached by means of liquefaction and/or fluidization in cohesionless sediments (Allen, 1982), or in cohesive muds as a consequence of the thixotropic behaviour of some clays (Grim and Güven, 1978). Liquidization processes (*sensu* Allen, 1977) can be induced by different trigger agents (earthquakes, overloading, storm waves, etc.); nevertheless, Owen (1987) showed that the final morphology of soft-sediment deformation is mainly induced by the nature of the driving force system (density contrast, unequal loading, tangential stress, etc.) acting on sediments after the loss of shear strength. In other words, the trigger agent is not directly recognisable by analysing the morphologies of deformation in soft sediment, since they simply record another process. For these main reasons, the interpretation of trigger mechanisms for deformation in soft sediment is a complex problem treated in many papers (*see* for example: Obermeier, 1996; Montenat et al., 2007).

In this paper we analyse superbly exposed soft-sediment deformation structures in Quaternary continental deposits cropping out in the central portion of the Neuquén Basin (Northern Patagonia, Argentina). The sedimentological analyses carried out on the entire sedimentary succession containing the soft-sediment deformation structures show the occurrence of undeformed beds with general

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features that are very similar to the deformed section. This fact allows us to deduce a reliable interpretation both of driving force system and trigger agent for deformation of the analysed continental deposits. Our purpose is to emphasize the importance of sedimentologic field data to the interpretation of soft-sediment deformation structures in similar sedimentary settings.

2. Geological and stratigraphic setting

The studied structures are located in the central part of the sub-Andean Neuquén Basin (32°–40°S latitude) which covers an area of over 120,000 km^2 in the central Andes (Fig. 1A). The basin has been long-recognised and is well studied (for a review and latest studies on specific stratigraphic intervals, *see* Veiga et al., 2005) and contains a near-continuous Late Triassic–Early Cenozoic succession deposited on the eastern side of the evolving Andean mountain chain. Its polyphase tectonic evolution has distinctive characteristics that result from the alternation of periods of generalized extension followed by periods of compression along the continental margin (Ramos, 1999; Ramos and Folguera, 2005). The record of tectonic changes within the 4000-m-thick Mesozoic to Quaternary mixed siliclastic-carbonate succession makes the basin a wonderful field laboratory for stratigraphy and basin evolution.

In the central portion of the Neuquén Basin, very thick Lower and Upper Cretaceous continental red-beds crop out pertaining to the Neuquén Group (e.g. Ramos, 1981; Cazau and Uliana, 1973; Leanza et al., 2004). These fluvial formations, previously named "Estratos con dinosaurios" (Wichmann, 1927), are some of the most fossiliferous with regard to Mesozoic vertebrates.

In the Añelo area, Quaternary deposits unconformably overlie different formations of late Early and Late Cretaceous age (Rayoso, Candeleros, Huincul-Lisandro, Portezuelo, Plottier, Bajo de la Carpa and Anacleto Formations), thanks to a protracted period of erosion. The first descriptions of the Plio-Pleistocene sedimentary deposition were by Wichmann (1922, 1924, 1927), but a formal subdivision can be ascribed to Padula (1951) and de Ferraríis (1966) (Fig. 2).

The clastic unit bearing the deformed beds that form the subject of the present study is named the Agua de la Caldera Formation (Ardolino et al., 1996), and crops out around the lower portion of the Neuquén River from Paso de Los Indios to Bajada Colorada (respectively about 50 and 180 km SW of the Añelo plateau). It is mainly composed of poorly cemented light blue-grey to brownish medium-fine sandstones, siltstones and mudstones. The type-section (53 m thick) was described by Uliana (1979) in the Agua de la Caldera locality. Outcrops of the Agua de la Caldera Formation occur also in the area of Cerros Colorados, north of the artificial lake of Los Barreales, and are represented by fine-grained grey conglomerates with sparse large cobbles made up of red Cretaceous sandstones of the Neuquén Group (Rodríguez et al., 2007). The Agua de la Caldera Formation is in turn covered by different coarse-grained fluvial terrace deposits of the Rio Neuquén (IV Nivel de Terrazas of Ardolino et al., 1996, corresponding to the Bajo Mesa Member of de Ferraríis, 1966), represented by medium-grained dark conglomerates.

Volcanic and tectonic processes were very active during the Quaternary in the central Andes sector (Muñoz and Stern, 1988). Coeval eruptions of the Quaternary shield volcano Auca Mahuida (whole-rock argon-argon dating recently produced ages of 0.88 to 1.7 Ma, except for the lowermost basalts which are latest Pliocene – Rossello et al., 2002) are reported just 30–40 km NNE of the study locality (see e.g. Ardolino et al., 1996, geological map of Departamento de Añelo at 1:200,000 scale and Rodríguez et al., 2007, geological Sheet 1:250.000 3969 II, Neuquén).

3. Facies analysis of Pleistocene deposits

In the study area, five stratigraphic sections were measured in detail. The most complete among these are the "Bajada de Añelo" (coordinates 38°15′40.29″S; 68°53′26.09″W) and "Añelo" (38°20′

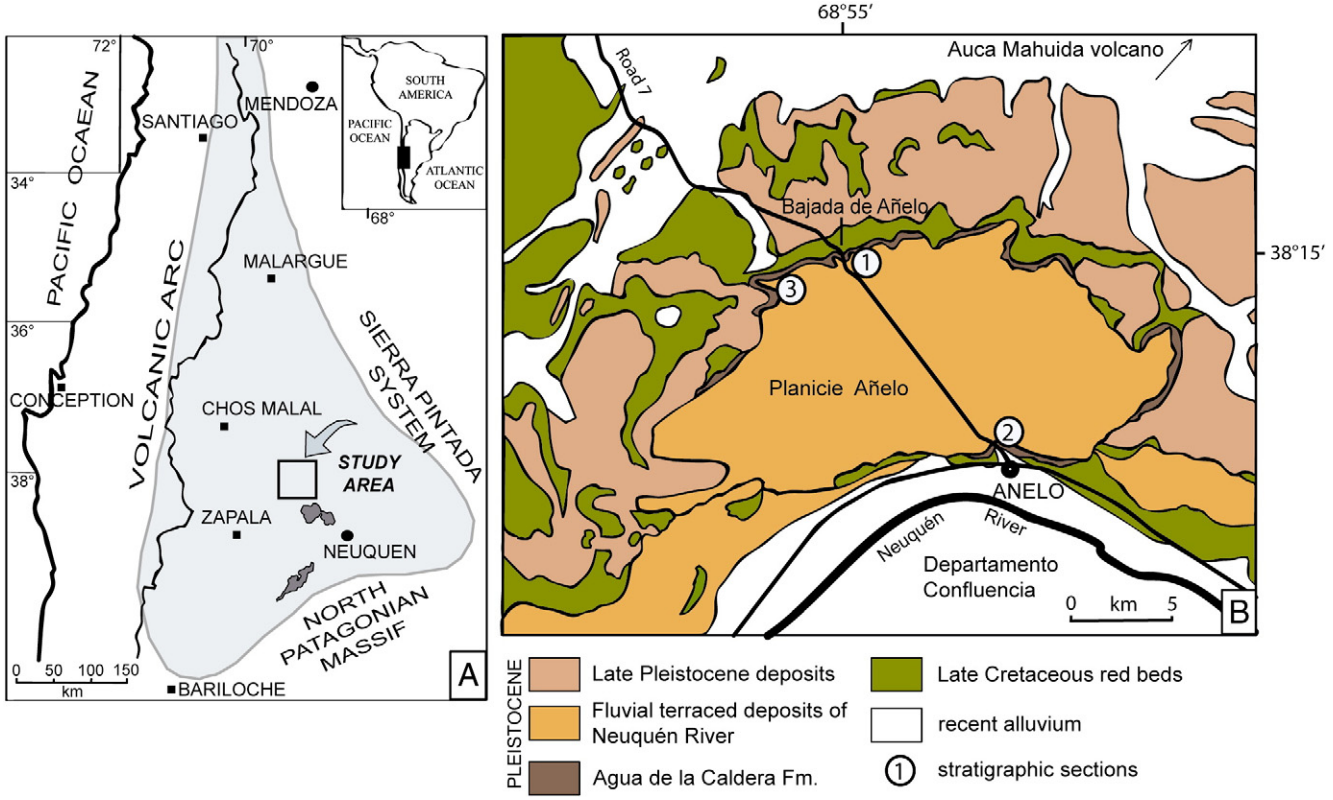

Fig. 1. A. Sketch map of Neuquén Basin and location of study area in the Departamento de Añelo (from Howell et al., 2005, modified). Grey area indicates the extent of the Basin. B. Geological map at scale 1.200,000 (*pars*) of the Departamento de Añelo (after Ardolino et al., 1996, part). 1. Bajo de Añelo sur Section; 2. Añelo Section; 3. Italians' Creek sections.