Sociedad Geológica de España

GEOGACETA, 79, 2026

Interaction between fluvial systems and alluvial fans over the Gorafe Unconformity (Granada Geopark): integration of digital outcrop model and facies analysis

Interacción entre sistemas fluviales y abanicos aluviales sobre la Discordancia de Gorafe (Geoparque de Granada): integración de modelado digital de afloramiento y análisis de facies

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ABSTRACT

The Gorafe Unconformity, located in the central sector of the Guadix-Baza Basin (Granada Geopark), represents a key outcrop to analyze the transition from compressive tectonics to Pliocene–Quaternary sedimentation in the central sector of the Betic Cordillera. This study presents the characterization of the sedimentary infill over this unconformity through the integration of classical field techniques with Digital Outcrop Modelling (DOM). Five main facies associations (FA1–FA5) have been identified, including floodplain deposits, fluvial channel and associated overbank deposits, palustrine environments and tufa barrier systems, and alluvial fan deposits. The interpretation of the DOM allowed the identification of vertical and lateral facies relationships, as well as recognition of progradation patterns and complex sedimentary geometries. The results highlight the interaction between a high-sinuosity meandering fluvial system and two transverse alluvial fan systems with opposite progradation directions. This interaction favored the obstruction of the axial fluvial system and the development of ephemeral ponding, which promoted the formation of tufa barrier systems. The study demonstrates the potential of digital outcrop models as a key tool for architectural analysis and, consequently, for paleoenvironmental reconstructions in complex settings.

Key-words: *Gorafe Unconformity, fluvial facies, alluvial fans, digital outcrop modelling, Guadix-Baza Basin.*

RESUMEN

La Discordancia de Gorafe, situada en el sector central de la Cuenca de Guadix-Baza (Geoparque de Granada), constituye un afloramiento clave para analizar la transición entre la tectónica compresiva y la sedimentación pliocuaternaria en el sector central de la Cordillera Bética. Este trabajo presenta la caracterización del relleno sedimentario sobre dicha discordancia, integrando técnicas clásicas de campo con modelización digital de afloramientos (DOM). Se han identificado cinco asociaciones de facies principales (AF1–AF5), que incluyen depósitos de llanura de inundación, de rellenos de canal fluvial y de sus desbordamientos asociados, de ambientes palustres y tobas de barrera y de sistemas de abanicos aluviales. La interpretación del DOM ha permitido establecer relaciones laterales y verticales entre facies, así como reconocer patrones de progradación y geometrías sedimentarias complejas. Se evidencia la interacción entre un sistema fluvial meandriforme de alta sinuosidad y dos sistemas de abanicos aluviales transversales, con direcciones de progradación opuestas. Esta interacción favoreció la obstrucción del sistema fluvial axial y el desarrollo de encharcamientos efímeros que propiciaron la formación de sistemas de barrera tobácea. El estudio demuestra el potencial de los modelos digitales de afloramiento como herramienta clave para el análisis arquitectural y, por consiguiente, reconstrucciones paleoambientales en entornos complejos.

Palabras clave: *Discordancia de Gorafe, facies fluviales, abanicos aluviales, modelado digital de afloramientos, Cuenca de Guadix-Baza.*

Geogaceta, 79 (2026), 59-62
https://doi.org/10.55407/geogaceta117196
ISSN (versión impresa): 0213-683X
ISSN (Internet): 2173-6545

Fecha de recepción: 11/07/2025
Fecha de revisión: 24/10/2025
Fecha de aceptación: 28/11/2025

Introduction

The Guadix-Baza Basin (Granada Geopark), located in the central sector of the Betic Cordillera, is one of the main Neogene–Quaternary intramontane basins in southern Spain. Its evolution is closely linked to the late orogenic phase of the central Betic Cordillera, characterized by a regional uplift and the beginning of continental sedimentation in previously marine basins (Viseras *et al.*, 2004). One of the most representative outcrops of this continental infill is the Gorafe Unconformity, where Pliocene–Quaternary sediments of the Gorafe-Huélago Formation unconformably overlie Mesozoic units of the External Zones (Vera, 1970).

The exceptional exposure of this unconformity allows for detailed analysis of the interaction between tectonic, sedimentary and paleogeographic processes that controlled the evolution of the continental infill. In this context, the application of Digital Outcrop Models (DOM), together with traditional sedimentological analysis, offers an effective tool for reconstructing stratigraphic architecture and spatial facies relationships.

The aim of this study is to characterize the sedimentary infill overlying the Gorafe Unconformity by identifying facies associations and analyzing their architectural relationships. The results highlight the coexistence and interaction of a high-sinuosity fluvial system with alluvial fan systems, providing new insights into the paleoenvironmental reconstruction of this region.

Geological settings

The Guadix-Baza Basin is located at the contact between the Internal and

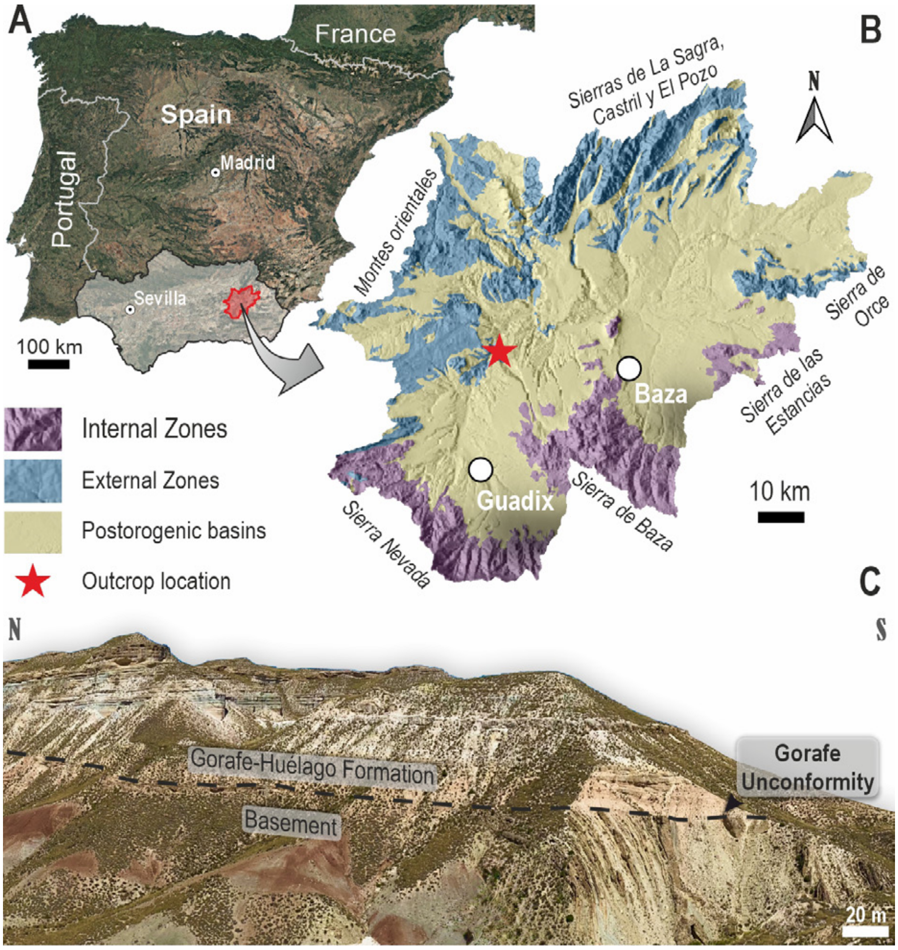

Fig. 1.- (A) Location of the Guadix-Baza Basin. (B) Geological map of the Guadix-Baza Basin, showing the studied outcrop (red star). (C) Panoramic outcrop view of the Gorafe Unconformity. See color figure in web.

Fig. 1.-(A) Localización de la Cuenca de Guadix-Baza. (B) Mapa geológico de la Cuenca de Guadix-Baza, indicando la ubicación del afloramiento estudiado (estrella roja). (C) Vista panorámica de afloramiento de la Discordancia de Gorafe. Ver figura a color en la web.

External Zones of the Betic Cordillera (Fig. 1A-B). The Internal Zones are mainly composed of Paleozoic to Cenozoic metamorphic rocks, whereas the External Zones consist of a thick succession dominated by Mesozoic carbonates deformed during the Alpine orogeny. The development of the basin occurred during the late Miocene, after the collision of the Internal Zones against the External Zones.

The sedimentary infill is divided into six main units (Fernández *et al.*, 1996; Viseras *et al.*, 2005): two marine units (I and II), a transitional unit (III), and three continental units (IV, V and VI). The latter, dated from Turolian to Late Pleistocene, record the final continental stages of basin evolution.

In the Gorafe sector, the deposits of the Gorafe-Huélago Formation (Unit V) unconformably overlie the Mesozoic carbonates of the External Zones, giving rise to the so-called Gorafe Unconformity (Fig. 1C). This area reflects the interaction of three sedimentary systems: a high-sinuosity axial fluvial system that flows longitudinally through the basin, and two transverse alluvial fan systems sourced from opposite directions, the Internal and External Zones, respectively (Viseras, 1991; Pla-Pueyo *et al.*, 2009; Pla-Pueyo, 2009).

Methodology and data

The study follows an integrated approach combining field techniques with Digital Outcrop Modelling (DOM). Field observations included the identification and description of sedimentary facies, along with the logging of a high-resolution sedimentological section.

The DOM was generated using aerial photogrammetry with a Mavic 3 Pro® drone, equipped with a 48 MP camera and RTK-GPS system. Flights were planned with DJI Flighthub 2® and conducted at a constant altitude of 50 m, capturing a total of 9,846 images. The final model reached a resolution of 1.66 cm/pixel. Ground Control Points (GCPs) were acquired using a high-precision GEOMAX Zenith 20 differential GPS.

Image processing was carried out in Agisoft Metashape®, resulting in a sparse point cloud, high-quality depth maps, and a textured mesh. Geological interpretation of the DOM was conducted using FaciesTool (Yeste *et al.*, 2026) a Python-based tool that enables direct assignment of facies associations onto the 3D model. This integration facilitated the correlation between field observations and the architectural analysis of sedimentary units on the DOM.

Results

Facies associations

Sedimentological analysis allowed the identification of five facies associations (FA1–FA5) in the succession overlying the Gorafe Unconformity (Fig. 2A).

FA1 consists of dark-colored clays and silts with carbonate nodules, root traces, charcoal fragments, and gastropod remains, interpreted as floodplain deposits (Fig. 2B).

FA2 includes alternating laminated silts and fine sands, along with channel-shaped sandy-gravel bodies with erosive bases and mixed clast composition. This facies is interpreted as fluvial channel fills and overbank deposits (Fig. 2C).

FA3 is composed of marls, limestones, and marly limestones with fenestral porosity, carbonate nodules, oncolids, dome-shaped geometries, and fossilized plant structures. These facies are associated with palustrine environments and tufa barrier systems formed in ephemeral ponds (Fig. 2D).

FA4 and FA5 correspond to alluvial fan deposits composed of clast-supported gravels, sands, and silts. They differ in clast composition: metamorphic clasts in FA4 (sourced from the Internal Zones; Fig. 2E) and clasts derived sedimentary rocks in FA5 (sourced from the External Zones; Fig. 2F).

Stratigraphic architecture

Integration of field logs with series extracted from the DOM enabled detailed characterization of the infill architecture (Fig. 3). Vertically, upward-thickening and upward-coarsening sequences were identified, where FA1 transitions to

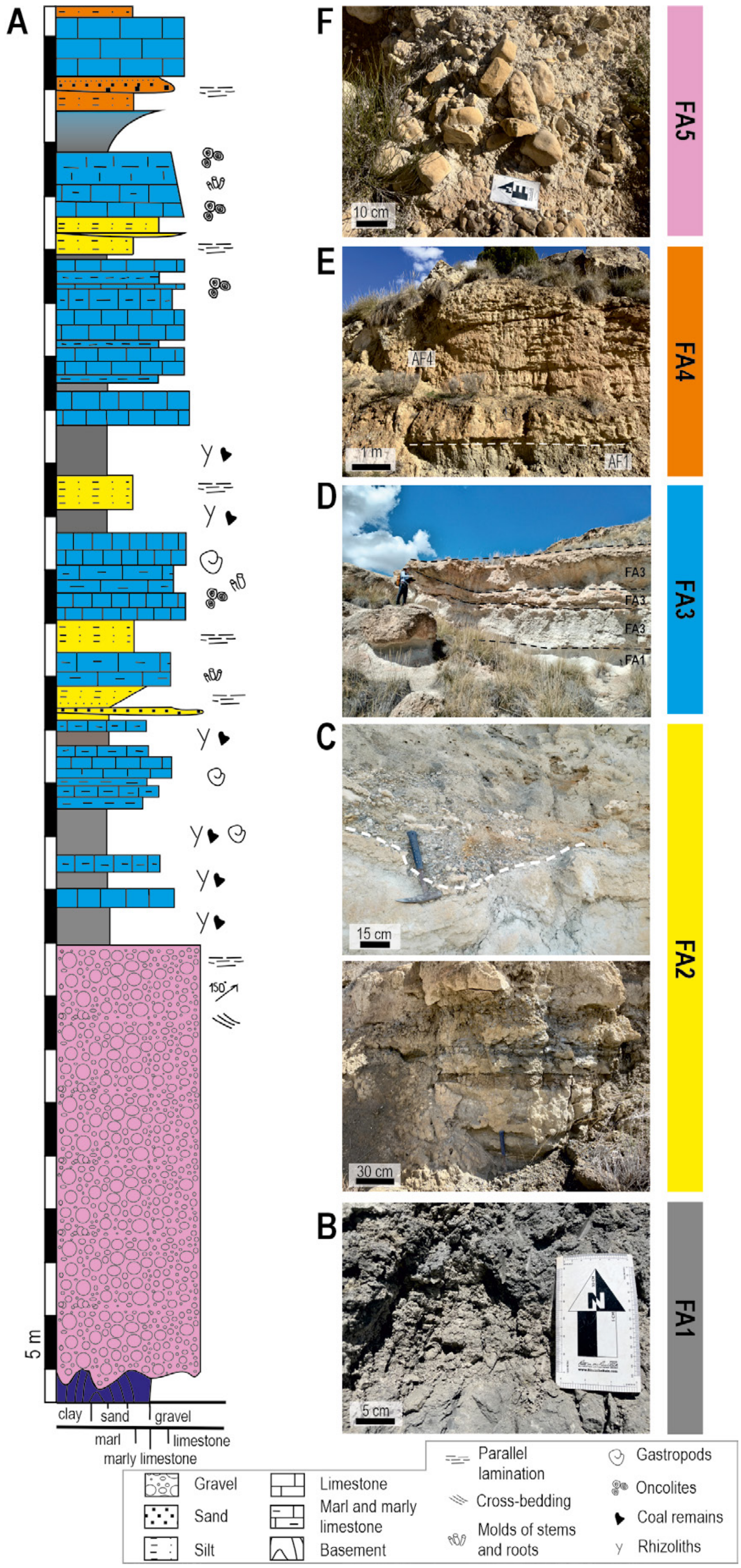

Fig. 2 (A) Sedimentary log measured in the outcrop (see Fig. 3A for its location in the outcrop). (B)–(C) Detail of the facies associations (FA1 to FA5, respectively) in the outcrop. See color figure in web.

Fig. 2.- (A) Registro sedimentario obtenido en afloramiento (véase Fig. 3A para su localización). (B)–(C) Detalle de las asociaciones de facies (FA1 a FA5, respectivamente) en el afloramiento. Ver figura a color en la web.

FA2 and culminates in FA3, or where FA5 shows internal fining-upward trends.

Spatially, FA5 dominates the base of the succession with southeastward progradation, while FA4 appears at the top, prograding northwestward. These facies laterally interdigitate with axial system deposits (FA1 and FA2), which show good lateral continuity. FA3 occurs interbedded, linked to ephemeral ponding associated with fluvial channel obstruction due to the convergence of alluvial fan systems.

This distribution reflects the interaction between a high-sinuosity meandering fluvial system and two transverse alluvial fan complexes with opposite progradation directions, responsible for the complex sedimentary architecture observed in the outcrop.

Discussion

The results allow interpreting the studied succession as part of a high-sinuosity fluvial system developed over a broad floodplain (FA1 and FA2), corresponding to the axial system described in the Guadix-Baza Basin (Viseras, 1991; Fernández *et al.*, 1996). This system is laterally interdigitated with two transverse alluvial fan complexes: one with metamorphic input from the south (FA4, Internal Transverse System) and another with carbonate clasts input from the north (FA5, External Transverse System).

The interaction between both systems generated temporary obstructions of the axial channel, promoting its lateral migration and the development of ephemeral ponding areas. In these zones, carbonate-rich stagnant waters favored the precipitation of carbonates over submerged vegetation, forming tufa barrier systems (FA3). The presence of fenestral textures, oncolites, and calcified root traces supports this interpretation.

Additionally, active fluvial channels could locally incise into these tufa deposits, partially reworking them, which explains the occurrence of tufa clasts and oncolites within some channel fills (FA2). This depositional model highlights the sensitivity of fluvio-lacustrine environments to variations in the balance between sediment supply and accommodation space, controlled by both autogenic processes, such as channel avulsion and sediment storage–release cycles (Shin *et al.*, 2024), and allogenic factors, such as regional tectonic and climatic interactions (Pla-Pueyo *et al.*, 2009).

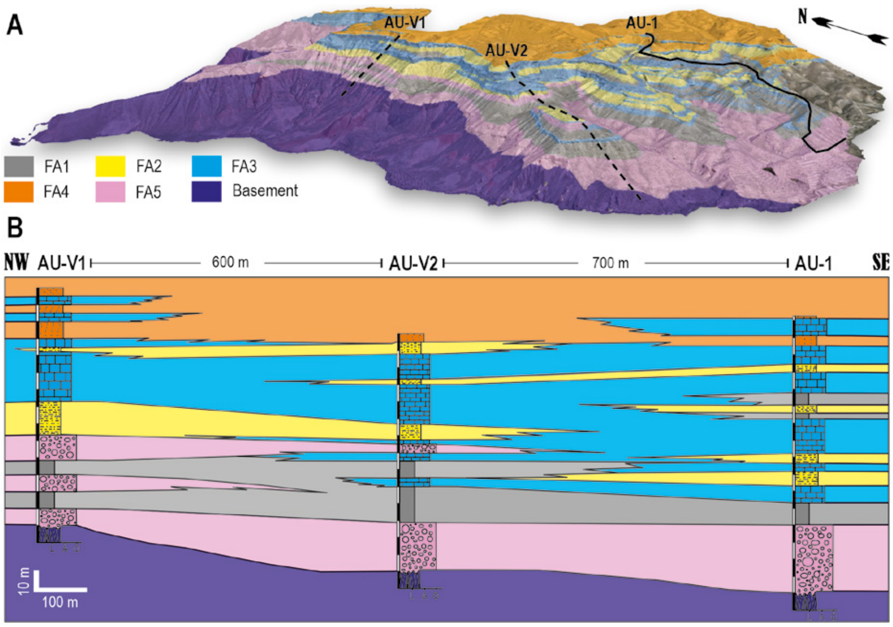

Fig. 3.- (A) Interpreted Digital Outcrop Model (DOM). Dashed black lines indicate the virtual sedimentary logs (AU-V1 and AU-V2) derived from the DOM. The solid black line represents the sedimentary log measured in the outcrop (AU-1). (B) Stratigraphic correlation cross-section of the facies associations between the sedimentary log obtained from the DOM (AU-V1 and AU-V2) and the sedimentary log measured in the outcrop (AU-1). See color figure in web.

Fig. 3.- (A) Modelo digital de afloramiento (DOM) interpretado. Las líneas negras discontinuas indican los perfiles sedimentarios virtuales (AU-V1 y AU-V2) obtenidos a partir del DOM. La línea negra continua representa el perfil sedimentario obtenido en afloramiento (AU-1). (B) Perfil de correlación estratigráfica de las asociaciones de facies entre los registros obtenidos en el DOM (AU-V1 y AU-V2) y el registro obtenido en afloramiento (AU-1). Ver figura a color en la web.

Conclusions

The sedimentological analysis identified five facies associations (FA1–FA5), corresponding to floodplain, fluvial, palustrine-tufa, and alluvial fan environments. Field data integrated with the Digital Outcrop Model (DOM) allowed detailed characterization of facies relationships and recognition of progradation patterns. The stratigraphy reflects the interaction between a high-sinuosity axial fluvial system and two transverse alluvial fans with opposite progradation directions (SE and NW), leading to complex depositional geometries. This interaction promoted channel obstruction, ephemeral ponding, and tufa barrier formation. The study highlights the potential of DOMs for architectural and paleoenvironmental analysis in complex sedimentary contexts.

Author contributions

Rodríguez-Fernández: work structure, methodology, data acquisition, editing, and figure preparation. Sánchez-Guerra: data acquisition and editing. Yeste methodology, manuscript revision, coordination, and supervision. Viseras: manuscript revision, coordination, and supervision.

Acknowledgements

This work was funded by projects PID2022-140850OB-C21 and PID2022-140850OB-C22, financed by MICIU/AEI/10.13039/501100011033 and ERDF/EU. Additional support was provided by the RNM-369 Research Group of the Andalusian Research and Innovation Plan (PAIDI). Juan Antonio Sánchez-Guerra acknowledges support from a technical contract (Ref. PTA2023-023493-I) funded by MICIU/AEI/10.13039/501100011033 and ERDF/EU. Luis Miguel Yeste acknowledges support from a postdoctoral contract (Ref. DGP_POST_2024_00896) funded by the Junta de Andalucía / CUII and the European Social Fund Plus (ESF+). We also thank REPSOL, CEPSA, ENAGAS and AGGEP for their support of this research project. We thank Geobit Consulting SL for providing an educational licence for Agisoft Metashape Professional. The authors are grateful to two anonymous reviewers and to the editor, Concha Jiménez de Cisneros, for their constructive comments, which significantly improved the manuscript.

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