Unlocking the correlation in fluvial outcrops by using a DOM-derived Virtual Datum: Method description and field tests in the Huesca Fluvial Fan, Ebro Basin (Spain)

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ABSTRACT

Adequate characterization of depositional architecture is of great importance when studying fluvial outcrops as reservoir analogs. The complex three-dimensional (3D) distribution and lateral/vertical relationships of sandstone bodies require a high degree of stratigraphic control in order to make a proper assessment of the distribution and connectivity of the reservoir facies. This demands the use of reliable correlation datums. Unfortunately, clear marker beds (e.g., ash/coal layers and paleosols) are not always available in fluvial outcrops, and when present they are often covered by vegetation or debris that prevents their tracking over long distances.

A new method to achieve highly accurate and semiautomatic correlations within fluvial DOMs (Digital Outcrop Model) is presented in response to the need for further correlation procedures, especially in the absence of suitable datums. The method is based on the hypothesis that the average depositional paleosurface of a sedimentary system can be represented by a plane at outcrop scale. If this assumption is valid, this plane can be used as a Virtual Datum to identify along the DOM the sediments that were deposited simultaneously.

The method was tested and applied successfully within two kilometer-scale outcrops of the Huesca Fluvial Fan (Early Miocene, N Spain), where the Virtual Datum provided

accurate correlations regardless of stratigraphic or topographical complexities. Moreover, the entire sedimentary successions were automatically subdivided into the desired stratigraphic intervals by only moving the Virtual Datum vertically. These intervals can be subsequently isolated to facilitate the detection of subtle variations and trends of their fluvial properties. Consequently, a Virtual Datum is the equivalent of having a marker bed crossing the stratigraphic succession of an outcrop at any desired position.

The advantages provided by a Virtual Datum proves to be especially useful in large and topographically complex outcrops that previously could not have been studied with such a high degree of 3D stratigraphic control.

INTRODUCTION

Fluvial sandstones represent some of the commonest reservoir rocks, and a great deal of the hydrocarbon production worldwide is extracted from sediments that were deposited by ancient river systems. However, because this type of reservoir has a very complex distribution in the subsurface, accurate field studies to characterize outcrops as analogs of buried fluvial systems are needed.

The three-dimensional (3D) architecture of sandstone bodies is not only the most complex and unpredictable but also the most important fluvial attribute that must be taken into account when characterizing reservoirs located within ancient fluvial sedimentary successions (North and Prosser, 1993). As noted by Miall (1996), these deposits are difficult to map in detail because of the high lateral heterogeneity of their facies and the poor definition of individual beds in successions consisting of repeated channel and overbank units. This author also argued that the restricted lateral and vertical dimensions of the paleochannels and their associated sandy deposits, together with the nonlinear evolution of facies belts through time and space, hamper our understanding of the 3D architecture and distribution of petrophysical properties within these sedimentary systems.

Methods employed to study hydrocarbon reservoirs are mainly seismic surveys, well logs and cores, which lack sufficient spatial resolution to properly characterize the geometries and sedimentological properties of the discrete elements composing fluvial reservoirs (Li et al., 2012). To this end, a number of studies have been focused on the detailed characterization and modeling of outcropping analogs as good approximations for understanding the behavior and spatial arrangement of fluvial reservoirs (Willis and White, 2000; Martinius and Næss, 2005; Miall, 2006; Pranter et al., 2009; Li et al., 2012). However, most of the available outcrops are composed of 2D sections, and geological expertise is needed to design accurate 3D reconstructions to determine parameters such as channel sinuosity, connectivity and continuity (Pringle et al., 2006).

Correlation uncertainty

Strong stratigraphic control is required when working in fluvial outcrops in order to perform accurate 3D characterizations of the geometries and stratigraphic architecture of sandstone bodies. The high lateral and vertical heterogeneity of facies in fluvial environments causes the uncertainty of the correlations to increase with the number of sandstone bodies and the distance between them.

Li et al. (2012) made an experiment to quantify the relationship between the density of data and the accuracy of correlations. First, these authors established a base case performing a high-resolution stratigraphic analysis based on 58 sections of a 30 Km-wide Cretaceous fluvio-deltaic outcrop. Subsequently, they designed three different datasets with progressively fewer sections than the base case in order to compare the interpretations made for each dataset. The results showed how, in extreme cases, overcorrelation led to the identification of only 40% of the existing fluvial bodies, whose widths and thicknesses were exaggerated by about 400% (Li et al., 2012). These results indicate how inaccurate correlations may result in very different stratigraphic frameworks, profoundly affecting the sizes, geometries and connectivities of the reservoir facies during subsequent modeling.

Geologists working in the characterization of large fluvial outcrops have used different methods to obtain a stratigraphic control over sedimentary successions, of which the use of marker horizons provides the most accurate and reliable correlations. Typical marker horizons are coal, paleosol or volcanoclastic levels, which are assumed to have been generated at a specific time and can extend tens of kilometers along the surface of fluvial systems (Miall, 1996). Similarly, the presence of major erosional surfaces (if flat) or of large tabular sandstone bodies can also be used as good datums. Unfortunately, in many outcrops the use of marker horizons is not possible because these either are absent or covered by debris or vegetation. In such cases, the correlation criteria will be largely based on the identification of similarities between the characteristics of the sandstone bodies (e.g., size, geometrical proportions, internal architecture and elevation) and/or on the recognition of distinctive sequential arrangements (e.g., amalgamated intervals, coarsening/thickening trends and prograding/retrograding sequences). However, given that these methods are strongly conditioned by subjective interpretations, the resulting correlations will continue to be uncertain. Moreover, the degree of uncertainty increases when correlating between nearby outcrops or between several outcrop faces that cannot be observed from the same location because of topographical constraints (e.g., if they are located in parallel valleys or on opposite slopes of the same hill), which rules out direct visual correlation or the use of photomosaics.

Background studies using TLS for characterizing geological outcrops

In recent years, improvements in digital data collection techniques and processing software have led to significant advances in the field of outcrop characterization (Pringle et al., 2004; Enge et al., 2007; Jones et al., 2011). This evolution is based on the premise that the greater the quantity, quality (accuracy) and speed of data collection, the better constrained the deterministic models derived from them (McCaffrey et al., 2005; Buckley et al., 2008; Jones et al., 2008; Faubel-Pérez et al., 2010). In this regard, Pringle et al. (2006) provide a review of the different digital data collection methods, highlighting Terrestrial Laser Scanning (TLS) as the preferred technique of geologists. TLS is based on lidar technology, which although developed in the early 1960s, has only recently been incorporated into the study of geological outcrops. Lidar typically uses the two-way travel time of a laser pulse to determine the distance to a target as sonar uses sound waves or as radar uses radio waves, but with a much higher resolution and accuracy. The word lidar has been commonly attributed to the acronym for *li*ght *d*etection *a*nd *r*anging in the literature. However, according to the Oxford English Dictionary and the first paper that refers to this technology (Ring, 1963), it is a portmanteau word for *li*ght + ra*dar*.

The main advantages of TLS over the rest of digital data collection techniques are the following: (1) very rapid collection of high amounts of 3D data (thousands of points per second); (2) high resolution (few centimeters) and accuracy; (3) acquisition of information about the scanned materials through the intensity of the returned pulse (Burton et al., 2011); and (4) photorealistic 3D data visualization obviating the need to create a mesh from the point cloud, avoiding thereby the generation of extra geometries (Kreylos et al., 2013).

In the last decade, TLS has been used to characterize geological outcrops with diverse purposes. Examples include the following: study of dinosaur footprints (Bates et al., 2008); characterization of folds, faults and fracture networks (Baker et al., 2008; Olariu et al., 2008; Jones et al., 2009; Wilson et al., 2009; García-Sellés et al., 2011; Pearce et al., 2011; Wilson et al., 2011); and geometrical depiction of carbonate platforms (Phelps and Kerans, 2007; Verwer et al., 2009).

Regarding the study of channelized bodies, several works have been focused on the detailed description, characterization and modeling of sandstone bodies (Labourdette and Jones, 2007; Pranter et al., 2007; Faubel-Pérez et al., 2009; van Lanen et al., 2009; Pyles et al., 2010; Olariu et al., 2011; Olariu et al., 2012; Rittersbacher et al., 2014; Sahoo and Gani, 2015); performing flow simulations (Klise et al., 2009; Nichols et al., 2011); the study of the alluvial architecture (Labourdette, 2011; Hajek and Heller, 2012); and building of geocellular and seismic 3D models (Enge et al., 2007; Janson et al., 2007; Buckley et al., 2010; Faubel-Pérez et al., 2010; Pringle et al., 2010; Tomasso et al., 2010). In these works, TLS data were mainly employed to characterize the internal/external geometries and spatial arrangements of sandstone bodies, whereas correlations were carried out by merely recognizing in the DOM the sedimentary features that have been traditionally used for correlation (e.g., marker beds, extensive sandstone bodies, major erosional surfaces or characteristic architectural arrangements). However, we consider that these correlation procedures do not exploit all the possibilities that an exhaustive analysis of TLS data can offer.

The main aim of the present paper is to provide a new TLS-based methodology leading to the creation of a Virtual Datum that furnish the degree of stratigraphic control needed to perform highly accurate correlations at outcrop scale and help solve some of the issues regarding the characterization of the fluvial reservoirs mentioned above.

OUTCROPS UNDER STUDY

Fluvial outcrops selected for testing the suitability of using a Virtual Datum as a correlation tool are located near Huesca, NE Spain (Fig. 1). Their sediments were deposited in the early Miocene by rivers that flowed through the Huesca Fluvial Fan (Hirst and Nichols, 1986; Hirst, 1991; Nichols and Hirst, 1998; Jones, 2004; Luzón, 2005; Fisher and Nichols, 2013). This fluvial system was developed adjacent to the northern boundary of the Ebro Foreland Basin under endorheic conditions (Puigdefàbregas and Souquet, 1986;

Puigdefàbregas et al., 1992; Barnolas and Gil-Peña, 2001), and have been classified as pertaining to the Sariñena Fm. (Quirantes, 1969).

The closure of the connection between the Ebro Foreland Basin and the Atlantic ocean during the Priabonian (Costa et al., 2010) marked the onset of a widespread deposition of thick continental sequences throughout the basin, resulting in the development of a series of large distributive fluvial systems (Hartley et al., 2010) spreading out from the surrounding mountain ranges, e.g., Montsant, Guadalope-Matarranya, Caspe, Luna and Huesca (Allen et al., 1983; Hirst, 1991; Puigdefábregas et al., 1991; Möhrig et al., 2000; Jones et al., 2001; Luzón and González, 2003; Luzón, 2005; Nichols, 2005; Cuevas et al., 2007; Barrier et al., 2010). The Huesca Fluvial Fan was the largest one, with a radius of about 60 Km, covering an area of around 4500 Km^2 and presenting thicknesses exceeding 1000 m (Hirst and Nichols, 1986; Hirst, 1991; Nichols and Hirst, 1998). This fluvial system evolved between the late Oligocene and the lower Miocene (Luzón and González, 2003) adjacent to the External Sierras, which were formed by the southward propagation of the South Pyrenean Frontal Thrust (SPTF in Figure 1). Its sediments were sourced from the Pyrenean axial zones and from the exhumed south Pyrenean piggy-back basins (Jupp et al., 1987; Vincent and Elliott, 1997; Vincent, 2001; Yuste et al., 2004), and were transferred towards a perennial lake located at the basin center (Cabrera and Sáez, 1987; Arenas and Pardo, 1999; Cabrera et al., 2002; Cabrera et al., 2011) (Fig. 1).

The Huesca Fluvial Fan developed after the main phases of deformation in the adjacent Pyrenees (Fisher and Nichols, 2013) in a context where the aggradation rates exceeded those of basin subsidence (Nichols, 2004, 2007). This suggests that tectonic controls did not play a significant role in the evolution of the system. Climatic controls can also be ruled out because of the lack of clear cyclical sequential arrangements in the vertical architecture of the available outcrops (Fisher and Nichols, 2013). Owing to the lack of significant allogenic forcings, the evolution of the Huesca fluvial Fan was largely controlled by autogenic processes, especially by the major avulsions triggered by cycles of channel backfilling and plugging (Nichols, 2007; Fisher and Nichols, 2013; Ventra et al., 2014). The resulting fluvial architecture largely consists of isolated to amalgamated sandstone lenses and sheets surrounded by fine-grained floodplain sediments, which is the characteristic facies arrangement of labyrinthine-type reservoirs (Webber and van Geuns, 1990).

Montearagón and Piracés outcrops (Fig. 1) are located approximately 45 Km away from the estimated apex of the Huesca Fluvial Fan (Jupp et al., 1987) and have been interpreted as belonging to the medial part of this fluvial system (Hirst, 1991). Despite being about 16 km apart, they are assumed to be located in similar stratigraphic positions like most of the outcrops of fluvial fan deposits in the zone (Cuenca et al., 1992). This is due to a slightly tilted sedimentary succession (typically $<1.5^{o}$) and to the relatively smooth structural relief (<100 m) existing across the whole fan area. In the absence of chronological data for the Montearagón and Piracés outcrops, biostratigraphic and geochronological datings in the proximity suggest a lower Miocene age (Álvarez-Sierra et al., 1990; Odin et al., 1997).

The Montearagón outcrop is located adjacent to the Flúmen river, 5 Km NE of Huesca (Fig. 1). It is composed of two parallel and unconnected slopes of kilometric length (Montearagón in the south and Barranco Hondo in the north, Fig. 2A) that present a fluvial succession about 80 m thick. The Piracés outcrop is located in the surroundings of the village of the same name (Fig. 1), and comprises more than 6 Km of steep and continuous slopes of about 100 m. This outcrop can be subdivided into two sectors (Fig. 2B): an amphitheater opened towards the SE (located to the N of Piracés), and a NW-SE trending cliff facing SW (located to the NW of the same village).

The two outcrops present several cliffs oriented towards the SW and/or NE (Fig. 2), which together with main paleocurrents towards the W-SW (Friend et al., 1986; Friend et al., 1989; Hirst, 1991) theoretically should provide numerous cross-sections of paleochannels. However, they differ in three-dimensionality and physiographic complexity as well as in the proportion and size of paleochannels (Hirst, 1991).

Sedimentary facies

Seven detailed stratigraphic logs (1:50 scale, more than 550 m in length, see location in Figure 2) were measured in the Montearagón outcrop to characterize the facies and verify the quality of the correlation results. Lithofacies described in Montearagón can be extrapolated to Piracés since both outcrops are located at similar radial positions of the same fluvial system (Fig. 1). Earlier studies carried out in the area (Friend et al., 1989; Hirst, 1991; Donselaar and Schmidt, 2005; Luzón, 2005) and observations made during the different TLS acquisition campaigns support this premise. Outcropping lithologies largely consist of fine to medium-grained sandstones embedded in siltstones and mudstones with scarce occurrences of centimeter-thick limestone levels (Fig. 3), and have been classified into channel-fill and overbank facies

Channel-fill facies are mostly medium grained, although coarse sandstone and/or pebbles are occasionally found forming basal lags, and typically exhibit a fining-upward granulometric trend to fine and very fine sandstone at the top. Most paleochannels show flat erosional basal surfaces that grade laterally to well-defined cut banks and are poorly incised into older deposits owing to the characteristic aggradational trend that prevails in endorheic basins (Nichols, 2004, 2007, 2012; Fisher and Nichols, 2013; Ventra et al., 2014). Trough cross-bedded sedimentary structures are commonly present in the lower parts of the paleochannels, whereas horizontally stratified and ripple cross-laminated fine sandstone dominate their upper parts. Clay plugs, which are also common, are the product of the passive infill of abandoned channels with sediments transported as suspended load during flooding events. Paleochannels in the medial zone of the Huesca Fluvial Fan have been interpreted as the deposits of braided, meandering and straight channels, which distally show a tendency to reduce their dimensions and increase their lateral stability as a result of a decrease in stream power (Hirst, 1991; Nichols and Fisher, 2007). In outcrop, sandstone beds stand out as steep rock faces owing to the lower erodibility of this lithology with respect to the surrounding fine-grained sediments. This contrast in erodibility is enhanced by a late-diagenetic calcite cementation of sandstones (Donselaar and Schmidt, 2005).

Overbank facies are composed of variable amounts of sand, silt and clay-rich sediments with an average content of carbonate of 30%, and were deposited from the suspended load during floods (Nichols and Hirst, 1998). The coarsest overbank sediments are found adjacent to the paleochannel margins in the form of levee deposits (Fig. 3, A). They consist of inclined beds of alternating sandstone/mudstone that extend from tens to hundreds of meters towards the floodplain, forming the characteristic channel "wings" (Fig. 3, B). Crevasse splays consist of extensive sheets of fine sandstone that typically show thicknesses exceeding one meter, non-erosive bases, coarsening-upwards sequences and a predominance of planar and ripple laminations. The feeder channels of these crevasse splays are constituted by small-scale ribbons (<1 m thick) of fine sandstone. The finest sediments, which were deposited by decantation in the waning stages of floods, constitute the bulk of the floodplain facies. Thin limestone levels occasionally occurring within the fine-grained intervals and the top of sandstones are attributed to the precipitation of carbonate from ponded waters.

Evidence of pedogenic processes associated with incipient paleosol development is found in the form of reddish decolorations, light yellow levels with versicolor mottlings (usually associated with rhyzoliths), gray levels with iron nodules and carbonate and gypsum concretions in the finest sediments. The development of these paleosol horizons has been associated with periods of non-deposition since their degree of maturity increases with distance from the active channels (Hamer et al., 2007a). Trace fossils are widely present in both overbank and channel fill facies as rhyzoliths, burrows and ant/termite nests. These traces do not always reach the top of the sandstone beds, which in the case of the channel fills suggests a discontinuous water regime since the fauna could not have colonized the bed of the channels had these been continuously active.

Friend et al. (1986) proposed a classification for the sandstone-bodies of the Huesca Fluvial Fan, which was later applied regionally by Hirst (1991). This classification is based on the cross-sectional external geometry and on the internal architecture of the paleochannels. Further descriptions and interpretations of paleochannel types and their internal architectures can be found in Nichols and Hirst (1998), Donselaar and Schmidt (2005) and Luzón (2005).

METHODOLOGY

DOM design

TLS is a remote sensing technology that uses the orientation angles of emitted laser pulses and their traveled distance, which is mainly extrapolated by using their time-of-flight, to determine the relative coordinates of a target with respect to the scanning location (García-Sellés et al., 2011). The device records each returned pulse as a point with relative coordinates, two-way travel time and signal intensity, and gathers thousands of points per second with a resolution of a few centimeters (at distances of hundreds of meters). During subsequent processing stages, the resulting point clouds are textured with high-resolution photographs, merged in a single point cloud, and later georeferenced by means of GPS (Global Positioning System) data. The result is a Digital Outcrop Model (DOM) that is ready for inspection and interpretation in order to measure and quantify any property of geometrical nature, e.g., bedding attitudes, fracture orientations, distances, thicknesses, areas and volumes.

Lidar data collection

This study was carried out with an Ilris-3D TLS device from Optech. According to the manufacturer, it is capable of registering more than 2000 points per second at a maximum distance of 1200 m (assuming optimal atmospheric conditions and target reflectivities of at least 80%), reaching maximum range and positional accuracies at 100 m of, respectively, 7 mm and 8 mm.

Lichti (2004) established that positional resolution of a laser scanner (defined as the level of identifiable detail within a scanned point cloud) is governed by the sampling interval and the laser beamwidth, which in turn are dependent on the scanning distance. Accordingly, he proposed a new parameter termed EIFOV (Effective Instantaneous Field Of View), which establishes the maximum resolution that can be achieved at different distances with a certain device. In the present study, scanning distances to the outcrop surface were mainly between 150 m and 550 m, which in the case of the Ilris-3D results in EIFOV resolutions ranging from 4 cm to 10 cm.

The Ilris-3D has a built-in CMOS sensor to acquire a digital image associated with each scan. However, the poor quality and resolution of this sensor demanded the use of an external camera to achieve a satisfactory photorealistic effect. For this purpose, a Canon EOS 40D camera was assembled over the TLS device and calibrated to ensure an adequate fit between each point of the DOM and its corresponding pixel in the photograph. The calibration process was carried out at the Geological Survey of Denmark and Greenland (GEUS) using a theodolite-surveyed steel grid with 110 targets and a calibration software developed by the Technical University of Denmark.

Accurate georeferencing of the scans is necessary to obtain well-oriented measurements from the DOM. To this end, positioning data in UTM coordinates were acquired using a Topcon GB-1000 GPS with post-processing. The GPS receiver gathered data between 15 and 25 minutes at each scanning location. These measurements were later derive-corrected using the GPS base station of the Escuela Politécnica Superior de Huesca. A final resolution of a few centimeters (of the same order as that of the TLS data) was reached in this way.

Data was acquired from 39 scanning stations, 18 in Montearagón and 21 in Piracés (depicted with red dots in Figure 2). At each scanning station, the entire surface of the outcrop located within the TLS detection range was captured by means of a series of consecutive scans, which were acquired with an overlap of about 25% in order to enable their correct alignment and merging during the subsequent processing stages. It should be noted that, before acquisition, a proper planning to obtain the maximum coverage by using the minimum number of scanning stations will optimize time and resources, especially in outcrops of such size and topographical complexity as Piracés.

The digital dataset obtained consists of more than 140 million of points distributed in 149 individual scans (56 from Montearagón and 93 from Piracés) and the high-resolution photographs and positioning data associated with each scan and scanning station, respectively.

Processing

Alignment of the individual scans was carried out with the IMAlign module of PolyWorks®, which uses the Iterative Closest Point method (Chen and Medioni, 1992) to obtain the best fit between the overlapped areas of two scans. First, the scans acquired from the same place were aligned, which resulted in as many individual point clouds as scanning stations. Subsequently, those point clouds with overlapped areas were aligned again, which should ideally provide a single point cloud of the entire outcrop if all the captured surfaces were interconnected. This was not the case, and some of the point clouds remained unconnected after alignment between the scanning stations. Under these circumstances, the assembly of the whole DOM is completed during the subsequent georeferencing phase.

Since the alignment process described above was performed in a 3D digital environment where the coordinates are relative to the TLS device, GPS coordinates measured at each scanning station were needed for georeferencing the DOM. To this end, PolyWorks® enables us to automatically extract the location of the scanning device for each scan and represents it as a point. If the process of alignment was correct, the location points of the scanning device for scans acquired from the same place should coincide. However, in practice they constituted narrow clusters of points, with the result that the UTM coordinates of each scanning location were finally assigned to the mass center of their corresponding cluster.

The result of this processing was a georeferenced DOM ready for interpretation and from which extraction of geographically oriented features is possible.

Extraction of a Virtual Datum

The sequence of steps and verifications that must be followed to obtain a proper Virtual Datum from the analysis of a DOM is depicted as a flow diagram in Figure 4. All the processes described in this flow diagram were carried out with the IMInspect module of PolyWorks®, which offers a series of tools enabling visualization, edition, interpretation and analysis of large lidar datasets.

The DOM was interpreted respecting the original point data instead of using a gridded mesh or a filtered point cloud. This ensures that no information is lost and prevents the creation of extra geometries or artifacts. Further arguments and discussions regarding the benefits of using raw point-based vs. gridded datasets can be found in Buckley et al. (2008) and Kreylos et al. (2013).

Prior considerations

The idea of using a planar surface as a Virtual Datum is based on the hypothesis that the depositional paleosurface of the fluvial fan can be represented by a plane at outcrop scale.

Thus, since the surface of a fluvial system constitutes an isochronous level, the plane that represents its overall geometry can be used to identify the materials that coexisted over the local fan surface (i.e., as a reference surface for correlations).

The DOM of an adequate fluvial outcrop can be used to indirectly derive the geometry of the original depositional surface. To this end, several stratigraphic horizons with its same geometry as that of the depositional paleosurface must be digitized to infer the orientation of the planar surfaces that best fit them. Paleosol levels are very suitable for this purpose for the same reason that they are used as datums to perform correlations, i.e. they develop in the surface of the fluvial system as continuous horizons with large lateral extensions. However, paleosols are not abundant or well developed in the studied outcrops, and when present they are not easy to track in the DOM since they are usually covered by debris or vegetation. Alternatively, the upper boundaries of the sandstone bodies (i.e., paleochannel fills) were selected for digitizing. These bodies are numerous in the outcrops and crop out forming laterally extensive exposures that are easily detected and may be traced in the DOM along hundreds of meters. As a result, they are the most suitable sedimentary bodies from which to calculate a Virtual Datum. Although they do not provide an approximation that is as accurate as paleosols or other marker beds, it may be assumed that the tops of the channel fills were deposited in the same way as the surrounding floodplain (Fig. 5). The reason for this is that under aggradational conditions (such as those that prevailed in the endorheic Ebro Basin), fluvial systems and hence fluvial courses tend to maintain stable slopes through time (Nichols, 2012; Fisher and Nichols, 2013; Ventra et al., 2014).

The outcrop should have a high degree of three-dimensionality to ensure satisfactory results. This is because the larger the roughness of the outcrop surface, the better constrained the geometrical reconstruction of a specific horizon from its intersection with the topography.

Otherwise, in a purely 2D outcrop like a vertical cliff or a road cut, digitization of a flat stratigraphic horizon will result in a straight line, which could be contained by several different planes.

However, the main limitation of the method is that it is only applicable to fluvial outcrops where the sedimentary succession is undeformed or homogeneously tilted. This excludes the outcrops where post-depositional tectonic processes (e.g., folding and faulting) have modified the original depositional surface in such a way that it can no longer be represented locally by a plane.

Digitization

Instead of following the exact shape of the tops of the sandstone bodies (red line in Figure 6), polylines must be digitized to depict their flat upper envelopes (i.e., a planar surface covering the external shape; green line in Figure 6). This is because digitization is focused on calculating the plane that best fits the top of the sandstone bodies at the scale of the entire paleochannel/paleochannel belt, which correspond to a $5^{th}/6^{th}$ order bounding surface of Miall (1988) (Table 1) or to 5a/6 bounding surface of DeCelles et al. (1991). Thus, the irregularities produced by sub-channel scale ($<5^{th}$ order) forms and processes (e.g., channel bars, levees, clay plugs and erosional events; Fig. 6) can be ignored, which leads to the calculation of planes with better adjustments to their parent polylines.

PolyWorks®, like most of the commercially available CAD software packages, offers two projection modes to display 3D data (reality) in 2D (screen): perspective and orthogonal. A perspective projection represents the objects in the same way that a human eye sees the scene in reality, with distant objects appearing smaller than closer ones. By contrast, orthogonal (or orthographic) projection ignores this effect, allowing the creation of scaled drawings where angles, sizes and heights remain unaffected by distance (Fig. 7). The use of an orthogonal projection for digitizing is highly recommended because it enables us to display the outcropping geobodies without perspective distortions. Its utility can be readily demonstrated when we consider the hypothetical case of working with a DOM composed of horizontal strata cropping out discontinuously across any topographical context. With an orthogonal projection, and if only the Z axis is used for rotations (untilted views), all the bedding surfaces will be displayed as straight lines regardless of the angle of view or the distance from the observer. However, with a perspective projection this only occurs when the surface is exactly at the same height as the observer (blue line in Figure 7A), while the rest of flat surfaces will be displayed as sinuous lines, hindering a proper digitization and the subsequent correlation process.

Once the tops of sandstone bodies are digitized, the next step involves the calculation of the planes that best fit the digitized polylines. This was accomplished in the present study by using an in-house developed macro that is based on analyzing the moment of inertia of a point set (Woodcock, 1977; Fernández, 2005; García-Sellés et al., 2011). Input data were obtained by selecting the closest points to the considered polyline (those located at a distance of less than 10 cm), after which the macro was able to calculate the orientation and position of the plane that best fits them, finally drawing it within the DOM (Fig. 8).

The quality of the adjusted plane is assessed by two parameters (Fernández, 2005): coplanarity (M) and collinearity (K). Coplanarity refers to the degree of fit between the plane and the points from which it was calculated with higher values indicating better adjustments. Collinearity is derived from the quantification of the 3D distribution degree of these points, providing information about the reliability of the plane, with $K=1$ indicating a linear distribution and progressively smaller values denoting better distributed point sets. Given these considerations, the higher the M and the lower the K, the better the quality and representativeness of a plane. Acceptable values of $M>4$ and $K<0.8$ were suggested by

Fernández (2005) when working with the intersection between geological surfaces and the topography.

After this first phase of interpretation, several tens to hundreds of lines together with their associated planes were obtained. The quality of these planes (acceptable M and K values) must be revised to ensure that the tops they represent were properly digitized. Should this not be the case, the original polylines must be improved in order to obtain better adjustments (Fig. 4).

Initial correlations

The next phase focuses on the identification and correlation of all the sandstone bodies that are located in the same stratigraphic horizon. This process is undertaken by a trial and error method that adopts a progressive approach towards a single plane of the upper boundaries of all the contemporary sedimentary units.

The preliminary correlations should be made by considering a large and laterally continuous sandstone body from which various exposures can be identified. The use of several distant polylines will enable us to calculate a plane from a better three-dimensionally distributed point set, thus ensuring low K values (high reliabilities). Subsequently, the geometrical relationships of this plane with respect to the remaining outcropping elements must be verified in order to establish whether it should be regarded as valid for further testing or discarded. The simplest way to do this is to expand the plane along the DOM (Fig. 4), but the fact that the data are concealed behind the plane hampers a proper evaluation of the plane-DOM intersection (Fig. 8B). This problem was solved by selecting the points located within a certain range from the plane, which resulted in a line of red points that enabled us to remove the plane (Fig. 8C).

Two variables must be considered to determine whether a plane is suitable for correlation: coincidence with other tops and its relationship with respect to the other stratigraphic horizons (parallel or oblique). Of these variables, the oblique cutting of any stratigraphic level (e.g., sandstone bodies, limestone levels, paleosols and ash layers) is the most obvious reason for rejecting a plane, and is therefore the key aspect that must be verified (Fig. 9). In other words, a plane will be taken into account only if it maintains a parallel relationship with all the stratigraphic horizons along the entire outcrop. Henceforth, all the planes regarded as valid must fulfill this requirement.

There are other indicators providing information about the degree of reliability of the calculated correlation planes. For instance, the situation in which a valid plane coincides both with the tops and the internal scours of other sandstone bodies (red line in Figure 10F) is the most favorable one since this strongly suggests that the plane denotes a significant stratigraphic level. However, if the opposite is the case (i.e., when it does not match any top or internal scour), the suitability of the plane will continue to be in doubt. In such cases, the performance of correlation tests in a sandstone-richest stratigraphic level will be the best option as this should provide more constrained and reliable results.

When a valid plane shows new coincidences with the upper boundaries of other sandstone bodies, it must be calculated again incorporating their polylines as additional input data. This will result in a new plane with an orientation very similar to the original one and a better K (reliability). Again, this plane could present new coincidences with other tops not previously considered, entailing a new recalculation. This process should be repeated successively until a final correlation plane is calculated taking into account all the possible interrelated sandstone bodies of the studied stratigraphic level.

Locating polylines that show small-scale deviations with respect to the plane they defined is frequent, especially if the latter shows a relatively low M (coplanarity). This does not always imply that these tops were miscorrelated since sandstone bodies usually lack a sharp and planar upper limit. As noted above, and shown in Figure 6, this may be attributed to irregularities due to bedforms, to subsequent erosive processes or to the presence of debris in the upper parts of the sandstone levels. One way to deal with this issue is to modify the trajectory of the polylines by adapting them to the plane-DOM intersection, which ensures better coplanarities during subsequent recalculations of the plane defined by them. However, this practice is only recommended when dealing with planes whose accuracy and reliability have been tested in various stratigraphic levels, and in circumstances were the modified polylines continue to represent the sandstone tops. Either way, care should be taken during early phases of correlation to avoid falling into a circular reasoning in which better adjustments are achieved because the polylines are adapted to the plane rather than the opposite.

Virtual datum establishment

The process described above must be repeated for several significant stratigraphic levels, preferably the ones that are more channel-prone, in order to determine whether the orientation of the correlation planes calculated from them is similar or not.

In the case of a sedimentary succession with no angular unconformities, which means that all their materials remain undeformed or have undergone post-depositional tilting (i.e., tilted to the same degree), the orientation of all the correlation planes should ideally be the same. Then, one Virtual Datum can be used for correlation within the entire outcrop. By contrast, if the outcrop presents angular unconformities (suggesting a synsedimentary tilting) the same plane will not be valid for correlation within the entire sedimentary succession and more than one Virtual Datum will be necessary, each one being applicable only within the stratigraphic interval from which it was calculated.

A Virtual Datum must be continuously supervised taking into account that it will continue to be applicable to the sedimentary succession as long as a parallel relationship with all the stratigraphic surfaces is maintained.

RESULTS AND PRACTICAL APPLICATIONS

A Virtual Datum was calculated for each of the two outcrops under study after applying the process described above. The Virtual Datum, and hence the bedding attitude presents a maximum dip of 1.22° towards 236° in the Montearagón outcrop, and a maximum dip of 1.54° towards 233° in the Piracés outcrop. In both cases, this digital tool for stratigraphic subdivision revealed its ability to correlate the sandstone exposures pertaining to the same paleochannel and their laterally associated overbank deposits (Figs. 9 and 10).

The accurate correlations provided by a Virtual Datum may be used as the base to design accurate 3D deterministic reconstructions of individual paleochannels/paleochannel belts and their associated overbank deposits in a way similar to that of Sahoo and Gani (2015). Increased certainty in the correlation of elements despite the fact that they are hundreds of meters apart or located in adjacent hills (Fig. 10) minimizes the number of cases where several exposures are erroneously regarded as the same sandstone body or vice versa. This avoids erroneous geometrical reconstructions of the paleochannels and incorrect assessments of the connectivity between sandstone bodies in subsequent stages of outcrop modeling. The same reasoning may be applied to the sandy overbank deposits, the miscorrelation of which will have an even greater impact on the model if laterally connected to the paleochannels.

In addition to being strictly a correlation tool between individual elements, the use of a Virtual Datum offers the possibility of identifying along an outcrop (or along various adjacent ones) the materials that coexisted on the fan surface. Thus, it can be used to isolate specific stratigraphic intervals from the remaining sedimentary succession, facilitating a rapid and accurate subdivision of the DOM into slices with a stratigraphic significance. This is shown with an example of each of the outcrops in Figure 11, where the stratigraphic slices were obtained by placing the Virtual Datum on the top of a large paleochannel and by selecting all the points located below the plane up to a distance equal to the maximum thickness observed for the sandstone body. Stratigraphic intervals can later be characterized separately in order to facilitate the detection of subtle spatial variations and vertical trends of several fluvial properties both within and between stratigraphic slices (e.g., sandstone proportion, channel size and typology, connectivity of reservoir facies, amalgamation index and geometry of the overbank deposits). This accurate 3D stratigraphic control can also be used as the base to perform a series of deterministic facies reconstructions of several intervals to evaluate the paleogeographic evolution in the zone.

There is also the possibility of digitizing the path of the stratigraphic logs in the DOM, which results in their automatic georeferencing and enables us to correct the thicknesses that were measured in the field by means of Jacob's staff (Fig. 3). The process of correction of the stratigraphic logs starts with the identification in the DOM of the sandstone bodies that are represented in them. Thereafter, the distance between their lower/upper limits and the point where the log started to be recorded is measured taking into account the dipping attitude of the sedimentary succession (provided by the Virtual Datum) to obtain true stratigraphic thicknesses. In the case of the studied outcrops, the regional dip is so close to horizontal that the measured vertical thicknesses are practically the same as the stratigraphic ones. The seven stratigraphic logs that were measured in Montearagón (Fig. 2A) were selected to test this method. After correction, differences ranging from 1.58% to 5.06% between the measured and real sedimentary thicknesses were found, with an average thickness underestimation of 2.95% (see Table 2). The possible reasons behind this general underestimation of the real thicknesses will be discussed below.

The availability of georeferenced and corrected stratigraphic logs together with the certainty in the correlation provided by the use of a Virtual Datum enabled us to design a highly accurate correlation panel (Fig. 12). To this end, the logs were placed in accordance with the real distance existing between them in a way similar to that of van Lanen et al. (2009) for the Wolfville Fm., and their relative vertical position was set using the Virtual Datum, which enabled us to restore the tilting of the series to horizontal. Furthermore, the geometries and thicknesses of the sandstone bodies between stratigraphic logs were drawn with the assistance of the continuous quantitative and qualitative information provided by the DOM. Consequently, the resulting correlation panel faithfully reflects the real dimensions, proportions and lateral/vertical relationships of the different facies, placing especial emphasis on the sandstone bodies.

The high degree of 3D stratigraphic control provided by a Virtual Datum proves to be very useful for extracting the accurate and realistic input data that are needed to perform a proper modeling as a reservoir analog from the DOM of fluvial outcrops, especially from the largest and most topographically complex ones. Furthermore, the advantages derived from its use can contribute to a better understanding of the driving mechanisms and processes that influence the evolution of fluvial systems.

DISCUSSION

Geologists have used several methods and approaches to achieve proper body-to-body correlations and stratigraphic subdivisions in fluvial outcrops. These methods include the use of marker horizons (e.g., coal beds, volcanic ash layers and distinctive paleosols), comparison between the characteristics of the sandstone bodies (e.g., height in the outcrop, location inside sequential arrangements and detection of internal/external architectural similarities) as well as line drawings on photomosaics. Of these methods, only those based on distinctive and laterally extensive marker horizons provide accurate correlations. Nevertheless, most outcrops lack such sedimentary features owing to their low preservation potential inside active fluvial environments. Even if these marker horizons are present they rarely crop out continuously and are seldom located in the desired position. The other methods are conditioned to a greater or lesser extent (depending on the quality, depositional architecture and structural setting of the outcrop) by the subjectivity associated with any interpretation. This means that different geologists studying the same area could end up establishing different correlations using these methods, with a level of uncertainty that will increase in proportion to the distance of correlation.

To overcome these difficulties, reliable correlations in outcrops of the Huesca Fluvial Fan were performed using a Virtual Datum obtained by an exhaustive geometrical analysis of their DOMs. The Virtual Datum consists of a plane that seeks to represent the average geometry of the local fan surface at the time of sedimentation, which implies that its use will be restricted to outcrops where the depositional paleosurface can be simplified with a plane. This requirement is met in the two studied outcrops since it was possible to calculate a Virtual Datum that fit all the stratigraphic levels without crosscutting relationships anywhere. Such a parallel relationship with all the horizons of an outcrop can only be achieved if the Virtual Datum represents the original depositional surface of the sedimentary system.

The upper boundaries of the sandstone bodies were used to calculate the Virtual Datum for two reasons: (1) since they protrude from the outcrop surface, they are the most easily recognizable sedimentary features that provide an approximation to the original depositional paleosurface; and (2), exposures of laterally extensive sandstone levels (several hundreds of meters wide) are very common, allowing the extraction of well-constrained planes. This approach is similar to that used by Pyles et al. (2010) for the DOM of a submarine channel complex, where these authors digitized the top of a clay plug of a paleochannel to establish a datum (“paleohorizontal surface”) in order to restore the displacement of a normal fault.

The same procedure could have been carried out by identifying and digitizing paleosol horizons, as they probably represent the best approximation to the paleosurface of the fluvial fan. Unfortunately, paleosols are not well developed in the studied outcrops (Nichols and Hirst, 1998; Hamer et al., 2007b), and when present they do not generate prominent features, often remaining buried under debris or covered by vegetation. Thus, the scarce paleosol exposures found in the outcrops are not laterally continuous enough to allow us to calculate well-constrained planes from them.

Alternatively, paleochannel exposures were used to calculate Virtual Datums given that the upper surfaces of the preserved sandstone bodies mimic the slope of the fan surface (Fig. 5). This is the case at least in aggradational settings, where a constant rise of the base level inhibits the development of major episodes of river incision (Nichols, 2012; Ventra et al., 2014), avoiding significant increases in the gradient of the river profiles with respect to the fluvial system surface. Furthermore, the progressive rise of the base level typical of endorheic basins not only determines a mainly constant topographic gradient of the depositional systems through time (which is also applicable to the profiles of the fluvial courses) but also a general layer-cake stratigraphic architecture (Nichols, 2012; Fisher and Nichols, 2013; Ventra et al., 2014). Climatically driven fluctuations in the level of the lake located in the basin center may cause modifications in the profiles of fluvial systems since the lake constitutes the base level of the basin. However, in such basins where the lake is very shallow and the gradient of the lake floor is very low, as in the Ebro Basin, the changes in the lake level have little impact on the fluvial systems (Nichols, 2012; Fisher and Nichols, 2013). Another result of the absence of major phases of fluvial incision in aggradational settings is that isochronous surfaces can be laterally extended through most of the considered lobe of the fluvial system because they are rarely truncated by younger deposits. This allows us to correlate across long distances using the geometry of the depositional surface. Therefore, the aggradational conditions expected within endorheic basins enable us to use the paleochannel deposits to infer the average orientation of the depositional paleosurface, facilitating the calculation of a Virtual Datum.

Like most of the geological surfaces, the sandstone tops are not strictly sharp and planar, and local-scale roughness is commonly observed (Figs. 6A and 6B). However, these irregularities are negligible when working at channel and channel belt scales so that the upper boundaries of significant sandstone bodies can be reduced to a flat upper envelope (Fig. 6C) that represents the overall attitude of the original depositional paleosurface (Fig. 5). Subsequent post-depositional deformations of the stratigraphic succession involve the modification of this primary surface, but in cases where the deformation is only related to a regional tilting, the plane-based correlations will still maintain their inherent stratigraphic significance.

As for the benefits arising from the use of a Virtual Datum, the ability to easily subdivide the entire sedimentary succession of an outcrop into stratigraphic slices simply by placing it at different altitudes provides an exceptional degree of control over the spatial distribution and temporal evolution of sedimentation. A comprehensive analysis of these stratigraphic intervals will facilitate the design of depositional models, offering greater insight into the evolution of the fluvial system and into its controlling mechanisms. Moreover, this high degree of stratigraphic control has deep implications for the modeling of outcrops as reservoir analogs. For example, the possibility of isolating a certain stratigraphic interval from the rest of the sedimentary succession facilitates the task of performing accurate deterministic reconstructions of the geometry and internal architecture of a given paleochannel and its related overbank deposits (Sahoo and Gani, 2015). Thereafter, these reconstructions will be used as input data to perform accurate object-based simulations. The availability of a precise stratigraphic subdivision also facilitates the detection of subtle spatial variations and trends concerning several properties (e.g., fluvial style, facies proportion, netto-gross ratio, grain size, porosity and distribution of lithofacies) within and between stratigraphic intervals. This is fundamental to obtaining the 3D variograms that are needed as input data to constrain the modeling.

A Virtual Datum will be applicable wherever a parallel relationship with the stratigraphic succession is maintained. This means that the use of a Virtual Datum calculated from one outcrop can be extended towards adjacent outcrops as long as no intersections with their stratigraphic horizons are found.

As for the quality of the sedimentological data acquired in the field with Jacob's staff, a DOM-based correction of the stratigraphic logs avoids biased estimations of facies proportions caused by their over/underestimation during the measurement process. This will improve subsequent reservoir models since stratigraphic logs are commonly used in the form of pseudowells as hard data to constrain modeling. After the correction of the stratigraphic logs that were measured in Montearagón, a general underestimation of the stratigraphic thicknesses was observed. As shown in Table 2, several factors that may have influenced the measurement process were considered, but no clear relationships were established. However, a comprehensive analysis of the distribution of errors within each stratigraphic log revealed that major measurement errors were mainly linked to moments when lateral displacements were required owing to the presence of thick sandstone bodies forming vertical cliffs of several meters. In order to facilitate lateral along-strike displacements, these were mainly performed on top of sandstone beds since they are thought to have a planar geometry and be isochronous along their extension. As pointed out above, this is not always the case, and the small-scale topography created by bedforms and erosional scours led to the errors of decimetric to metric order that have been found to be associated with the lateral displacements over sandstone tops (Fig. 6). Thus, stratigraphic logs that intersect a larger number of thick sandstone bodies are more prone to present measuring biases than those that do not require many lateral displacements.

The reasons behind the overall underestimation of the total thickness observed in all the logs are less significant given that they are always produced in the same direction (subtraction of total thickness in this case), suggesting that they are probably related to subjective and/or technical systematic biases. For example, faults in the construction of Jacob's staff, a geologist's tendency to add a few centimeters when performing visual projections or an imprecise calibration of the bedding attitude can explain these systematic errors. Anyway, here we note that the level of accuracy achieved by Jacob's staff measurements is surprisingly high given the simplicity of the measuring tool and method, and that it is suitable for most of the classic applications of the stratigraphic logs.

The use of the Virtual Datum can be extended to the DOM of any outcrop composed of materials that were deposited in aggradational settings by a sedimentary system whose original depositional surface is capable of being represented by a plane at outcrop scale. Another requirement is that the sedimentary succession remains undeformed or homogeneously tilted. As is well known from modern and ancient examples, the mechanisms and processes driving the evolution of fluvial systems generally tend to form relatively flat and continuous depositional surfaces. Therefore, outcrops whose materials were deposited by rivers within endorheic basins are regarded as suitable for using a Virtual Datum. Other sedimentary environments that tend to configure flat and extensive depositional surfaces include non-marginal zones of lacustrine systems, delta plains (topsets) of deltaic systems and submarine fans (turbidites). Nevertheless, further tests in such sedimentary outcrops are necessary to justify the use of a Virtual Datum in them, bearing in mind that the major incisions triggered by falls in the base level can disrupt the lateral continuity of the isochronous stratigraphic surfaces.

To date, outcrops belonging to the Huesca Fluvial Fan have been studied individually ignoring their relative stratigraphic positions despite the fact that some authors have assumed that they are located inside the same stratigraphic level (Hirst, 1991; Donselaar and Schmidt, 2005). However, such unconfirmed assumptions may lead to miscorrelations and, hence, to misleading reconstructions of the fan paleogeography and facies distribution. For this reason, future work will be focused on the development of a methodology using Virtual Datums to correlate distant outcrops and deduce their relative positions inside the entire fluvial sequence. Our intention is to proceed in a way similar to that of structural geologists when characterizing folds and faults by establishing several dip domains from dip data measured in the field (Wise, 1992; Fernández et al., 2004; Carrera et al., 2009), but using the dips provided by Virtual Datums. We trust that further methodological development starting from the bases established herein will help to shed light on this issue.

CONCLUDING REMARKS

A new TLS-based methodology to calculate a Virtual Datum that facilitates characterization of suitable sedimentary outcrops is presented. This tool consists in a plane that tries to mimic the geometry of the depositional paleosurface of the sedimentary system. It is obtained from the systematic reconstruction and analysis of the planes that best fit the upper boundaries of the sandstone bodies existing in a DOM. The procedure to calculate a proper Virtual Datum is described above and is schematized as a simple flow diagram in Figure 4.

The idea of using a planar surface as a correlation tool is based on the hypothesis that the original depositional surface of the sedimentary system can be represented by a plane at outcrop scale. This requirement was met in the two studied outcrops of the Huesca Fluvial Fan because a single Virtual Datum managed to subdivide their entire stratigraphic succession without crossing any stratigraphic horizon, which can be achieved only if the working hypothesis is valid.

Given the nature of this correlation tool, the applicability of a Virtual Datum will be restricted to DOMs of outcrops whose materials were deposited over a locally flat surface and in which the original depositional surface maintains its ability to be represented by a plane. This includes the outcrops showing sedimentary successions that remain undeformed or are homogeneously tilted, and excludes those presenting folds and/or faults.

The use of this digital tool provides a high degree of stratigraphic control inside the DOM of suitable outcrops regardless of topographical complexities or limitations, thereby facilitating extremely accurate correlations. The method is especially useful when dealing with large-scale outcrops (of kilometric order) made up of several faces that are unconnected or located on opposite sides of a hill, or when correlating through neighboring outcrops that are hundreds of meters apart (i.e., when the inspection of the entire outcrop at the same time is not possible). Under these circumstances, and especially in the absence of clear marker beds, the use of a Virtual Datum emerges as the most suitable way to build a proper stratigraphic framework taking into account all the available information.

Once a Virtual Datum is established for an outcrop, it can be placed on top of any particular sandstone body to achieve an immediate identification of all its available exposures even if separated by distances exceeding one kilometer. Thus, this tool allows us to identify the exposures that belong to the same paleochannel or paleochannel belt, considerably simplifying its subsequent 3D geometrical reconstruction and the analysis of its spatial relationships concerning the remaining outcropping elements. Moreover, since the TLS is a remote sensing technology the outcrop can be studied as a whole, the only limitations being the sensor range and the availability of scanning locations with proper perspectives towards the surfaces to be studied.

A Virtual Datum can also subdivide the entire outcrop into the desired stratigraphic slices without the need for additional criteria by only moving it vertically to a specific position and verifying its intersection with the DOM. Consequently, a Virtual Datum is the equivalent of having a marker bed crossing the entire stratigraphic succession in the desired position. Such a degree of stratigraphic control is very helpful to detect vertical variations and trends of properties (e.g., facies proportions, paleochannel size and type, depositional architecture).

In view of its numerous benefits, especially in large and topographically complex outcrops that lack suitable marker horizons, a Virtual Datum proves to be useful in building good models of reservoir analogs and in improving our understanding of the factors and mechanisms that influence the evolution of sedimentary systems.

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FIGURE CAPTIONS

Figure 1. Geological map of the North-Central Ebro Basin showing the location of the outcrops and the distribution of the Oligo-Miocene facies of the Huesca Fluvial Fan and the adjacent lacustrine system (modified from Nichols and Hirst, 1998). Location of the apex of the fluvial system was estimated by Jupp et al. (1987) based on a statistical analysis of the paleocurrents. Tectonic features: SPFT-South Pyrenean Frontal Thrust; BA-Barbasto Anticline. Cities: A-Ayerbe; B-Barbastro; F-Fraga; M-Monzón; S-Sariñena. Rivers: Al-Alcanadre; Ci-Cinca: Eb-Ebro; Fl-Flúmen; Gá-Gállego.

Figure 2. Topographical maps draped onto a shaded DEM of the Montearagón (A) and Piracés (B) outcrops. The extent of the scanned areas, the location of the scanning stations and the trajectories of the stratigraphic logs are indicated. Two panoramic views of the DOM, one with only an artificial lighting and the other with a color texture are provided for each of the numbered scanning stations (1 and 2 from Montearagón; 3 to 5 from Piracés).

Figure 3. Detail of the Montearagón DOM displayed with an orthogonal projection showing the trajectory of the stratigraphic log MA5. The log is presented on the right together with the depositional interpretation of several sandstone intervals. Application of the method explained in the section "Results and practical applications" sows how the heights and thicknesses of the sandstone bodies in the log match those observed in the DOM. Labeled boxes highlight the presence of a levee (A) and a channel "wing" (B).

Figure 4. Flow diagram depicting the series of steps and verifications that must be followed to obtain a suitable Virtual Datum.

Figure 5. Conceptual scheme of a sinuous (A) and straight (B) channel of the Huesca Fluvial Fan showing how the upper surface (red dashed line) of sandstone bodies (orange) can be used to infer the orientation of the depositional surface (green surface).

Figure 6. Detail of the Piracés DOM displayed in an orthogonal projection (A, see location in Figure 2). The upper boundaries of sandstone bodies were digitized in two ways: strictly following their tops (B), and depicting flat upper envelopes (C). Differences arising from these two methods of digitizing (D) are related to the depositional topography (e.g., clay plugs and levees), post-depositional erosive events, outcropping conditions (1) and concealment of part of the outcrop due to perspective issues during acquisition (2). Note how some large internal scours within the paleochannels are laterally related to the top of other sandstone bodies (black arrows), suggesting that they are interrelated.

Figure 7. Comparison between the DOM displayed with a perspective (A) or an orthogonal (B) projection. The two images show the same area of the Montearagón DOM (the SE boundary), and were captured from the same viewpoint. Colored lines represent the intersection with the DOM of several flat stratigraphic surfaces traced with a Virtual Datum. Using an orthogonal projection they are displayed as straight lines (B), whereas with a perspective projection this only occurs when the observer is at the same height as the surface (light blue line in A).

Figure 8. Detail of the Montearagón DOM displayed with an orthogonal projection (see location in Figure 2) where the plane calculated from a polyline together with the method to verify its intersection with the DOM are shown. After selecting the nearest points to the polyline (A), the macro (see text) calculates the plane that best fits them and includes it in the scene. As a result, the data located behind the plane are concealed (B). This is solved by selecting those points that are located within a narrow range from it, which results in a line that allows us to remove the plane and verify its geometrical relationship with respect to the stratigraphy (C).

Figure 9. Orthogonal views of the Montearagón DOM (A and B; see location in Figure 2) where two erroneous correlation planes that clearly intersect stratigraphic horizons are shown

(A’ and B’). By using a Virtual Datum (A’’ and B’’), the interpreted stratigraphic horizons are parallel to the remaining ones and connect the paleochannels with sandstone bodies that were previously interpreted as unrelated (pink boxes).

Figure 10. Panoramic views using an orthogonal projection of three areas of the Montearagón DOM: Montearagón E (A), Montearagón W (B) and Barranco Hondo W (C; see their exact location in D). The lines result from using the Virtual Datum to outline several stratigraphic intervals, which are shown with the same color in all the images. Note how the upper boundaries of some sandstone bodies are not represented by a single stratigraphic surface (E, F), suggesting a multi-stage depositional history.

Figure 11. Oblique views showing the full extent of the Montearagón (A to E) and Piracés (F to H) DOMs. Red intervals represent stratigraphic intervals that were obtained by placing the Virtual Datum over a large paleochannel and by selecting all the points located below the datum to a distance equal to the maximum thickness of the paleochannel (9 m for Montearagón and 21 m for Piracés). Stratigraphic intervals can be isolated (B and G), which facilitates their subsequent study and reconstruction. C, D and E are details of the stratigraphic interval isolated in B; and H is a view towards the west of the stratigraphic interval shown in G.

Figure 12. Correlation panel composed of the seven stratigraphic logs measured in the Montearagón outcrop (see its location in Figure 2), which were previously corrected using the method described. Body-to-body correlations were performed with the Virtual Datum, and tilting of the series was restored to horizontal. The classification of sandstone levels was carried out according to the geometrical and architectural criteria established by Friend et al. (1986). There is no information about the zone below the Montearagón Castle because it was not captured during the acquisition campaign.

Figure 1
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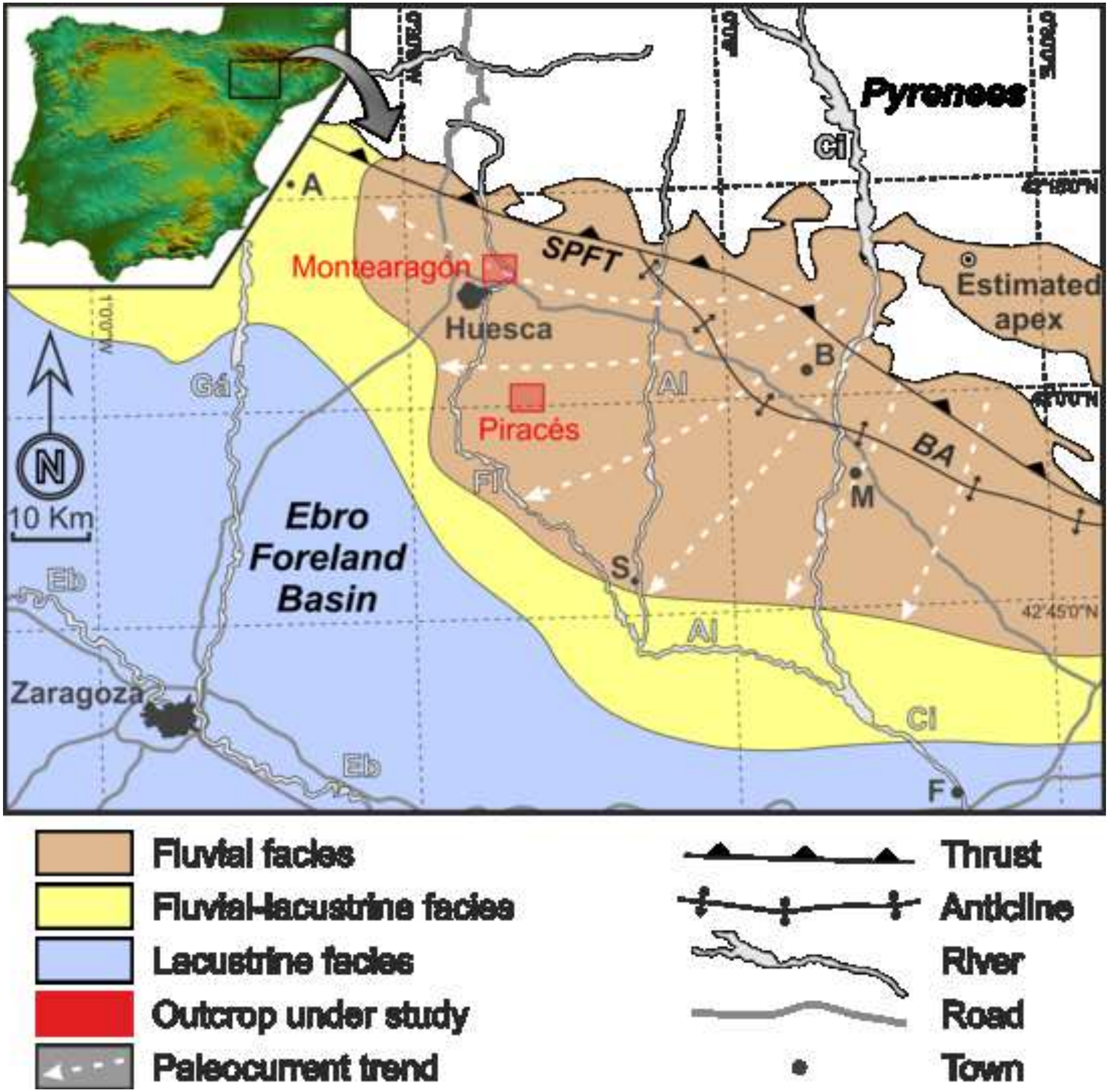

Figure 2
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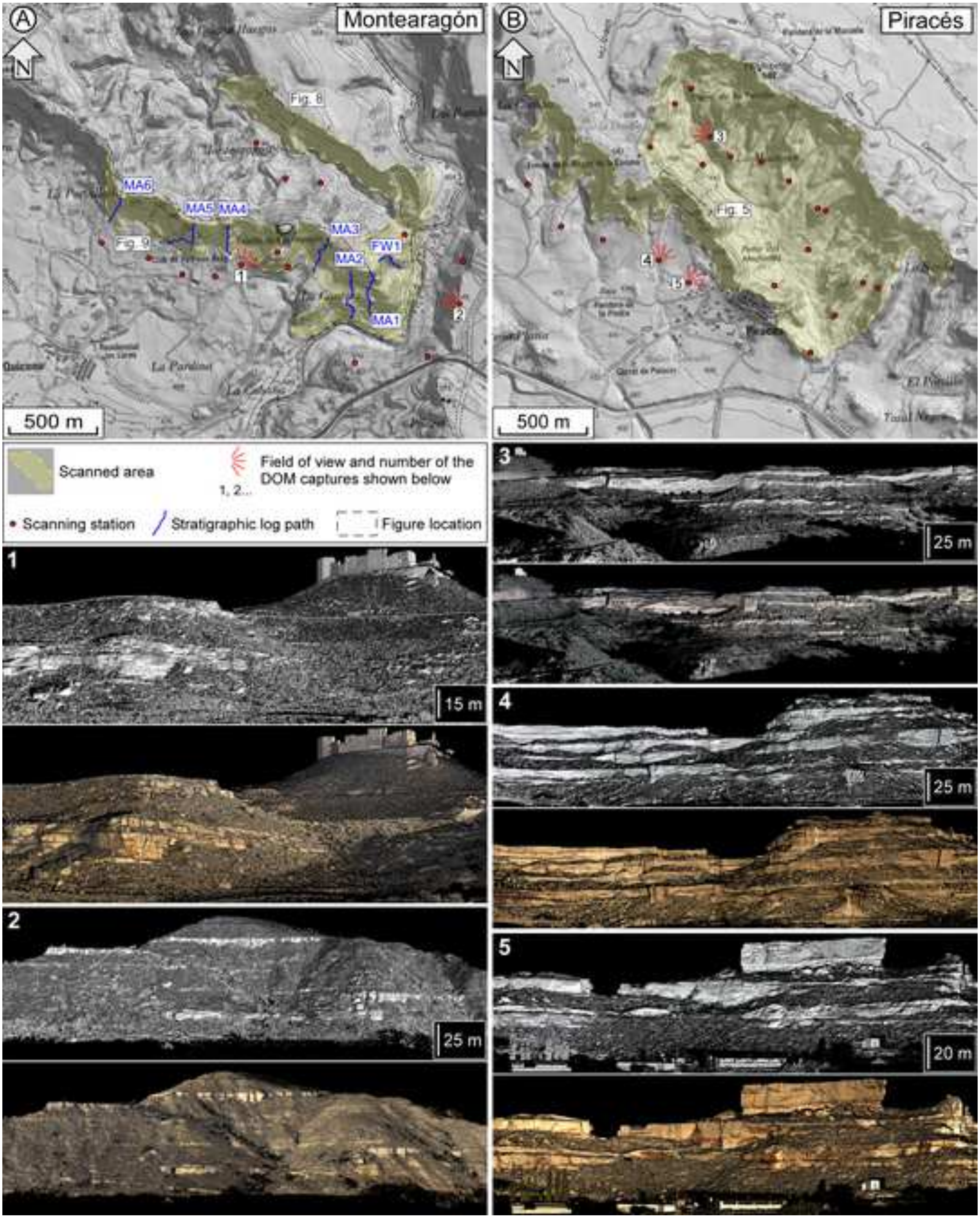

Figure 3
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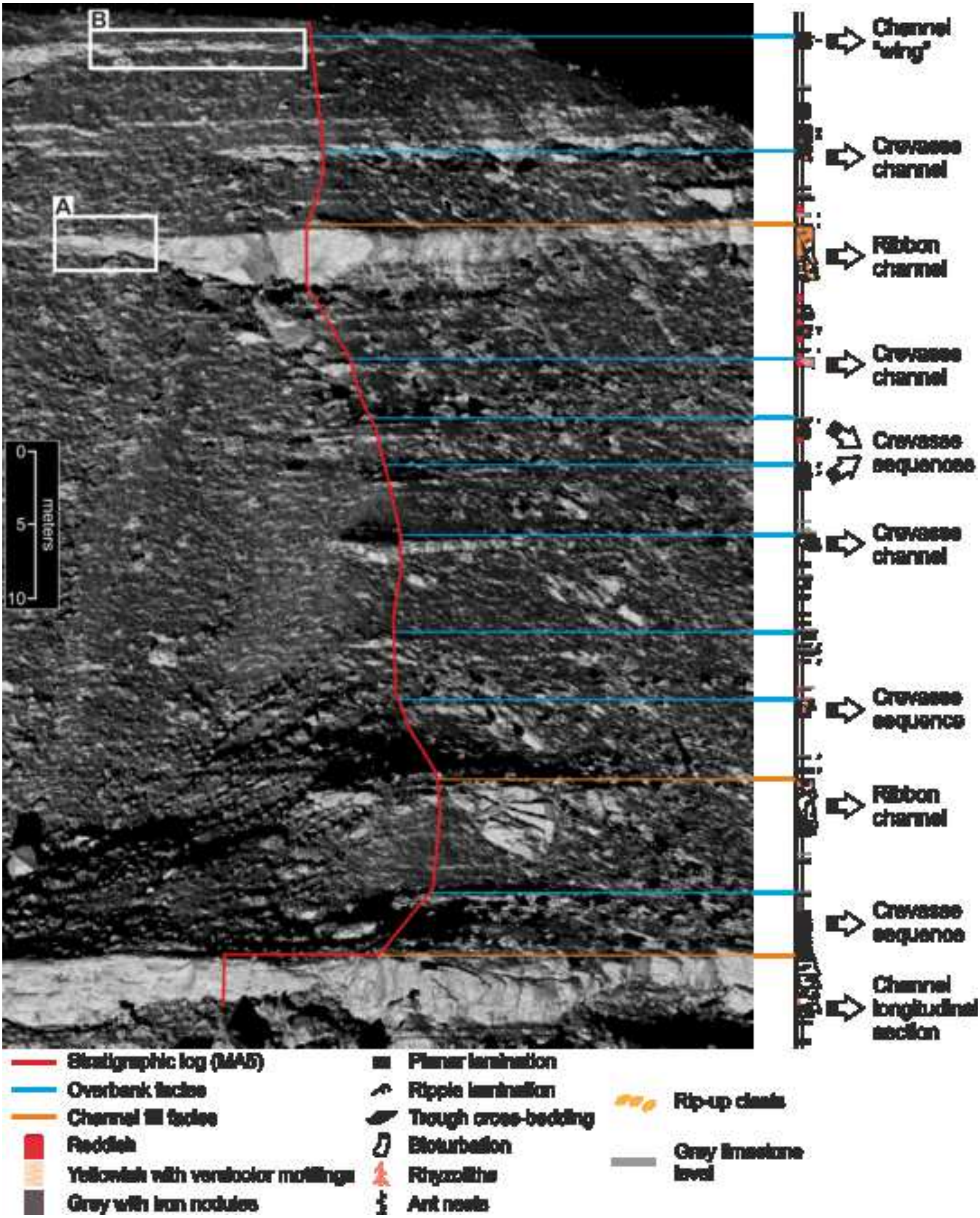

Figure 4
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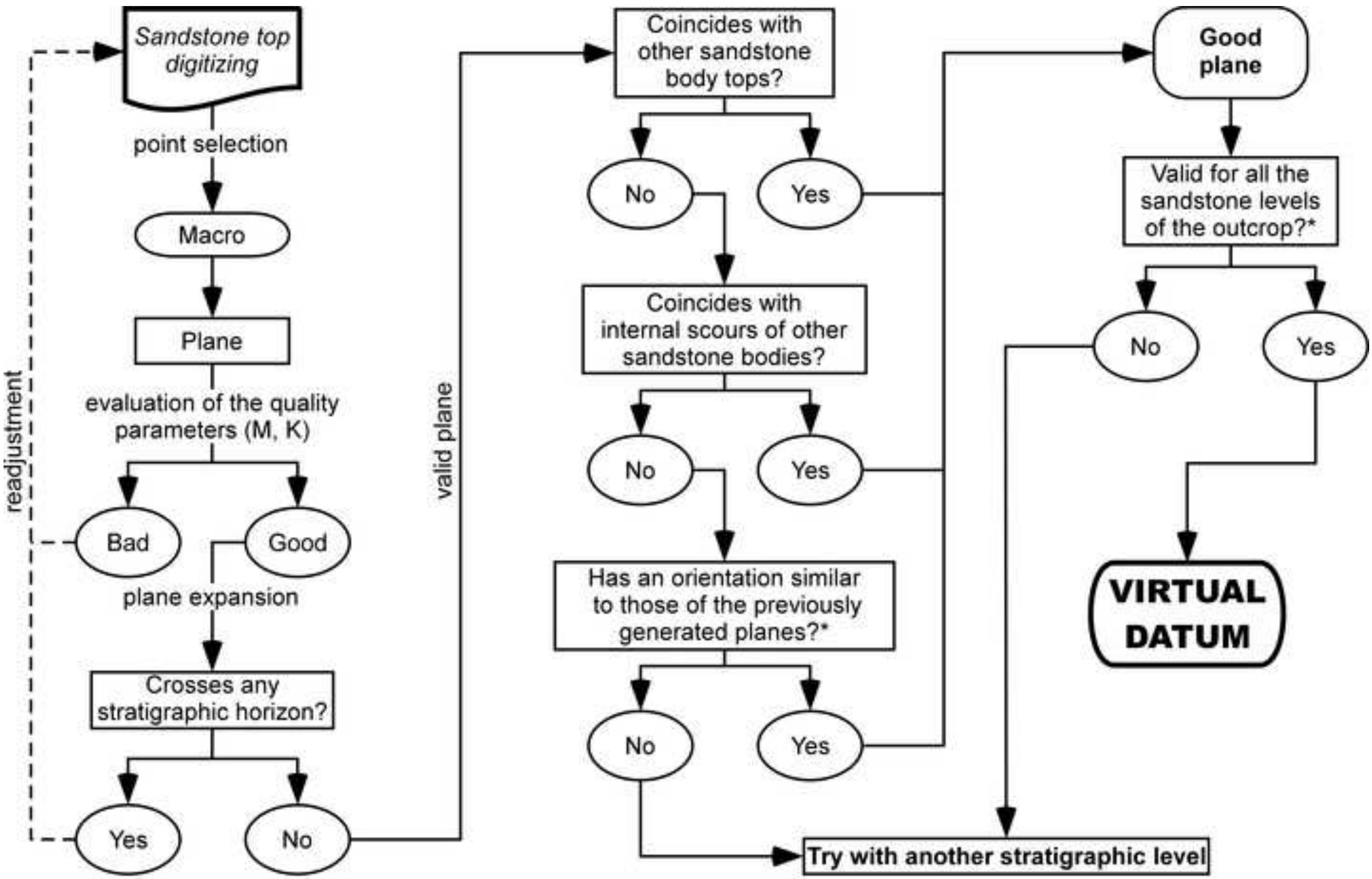

*Assuming that the outcrop lacks angular unconformities. Otherwise the question will refer only to the stratigraphic interval from which the plane was calculated.

Figure 5

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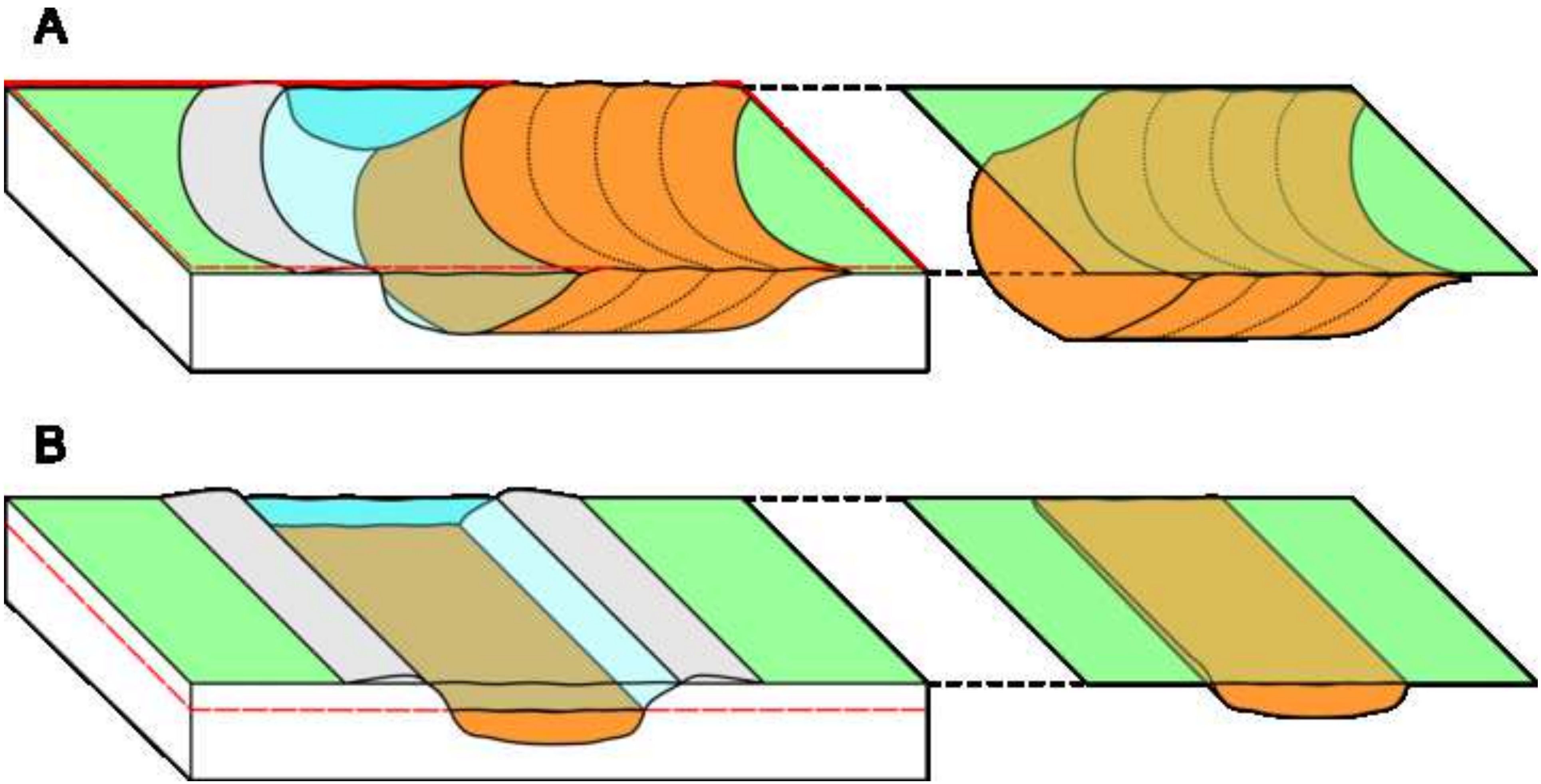

Figure 6
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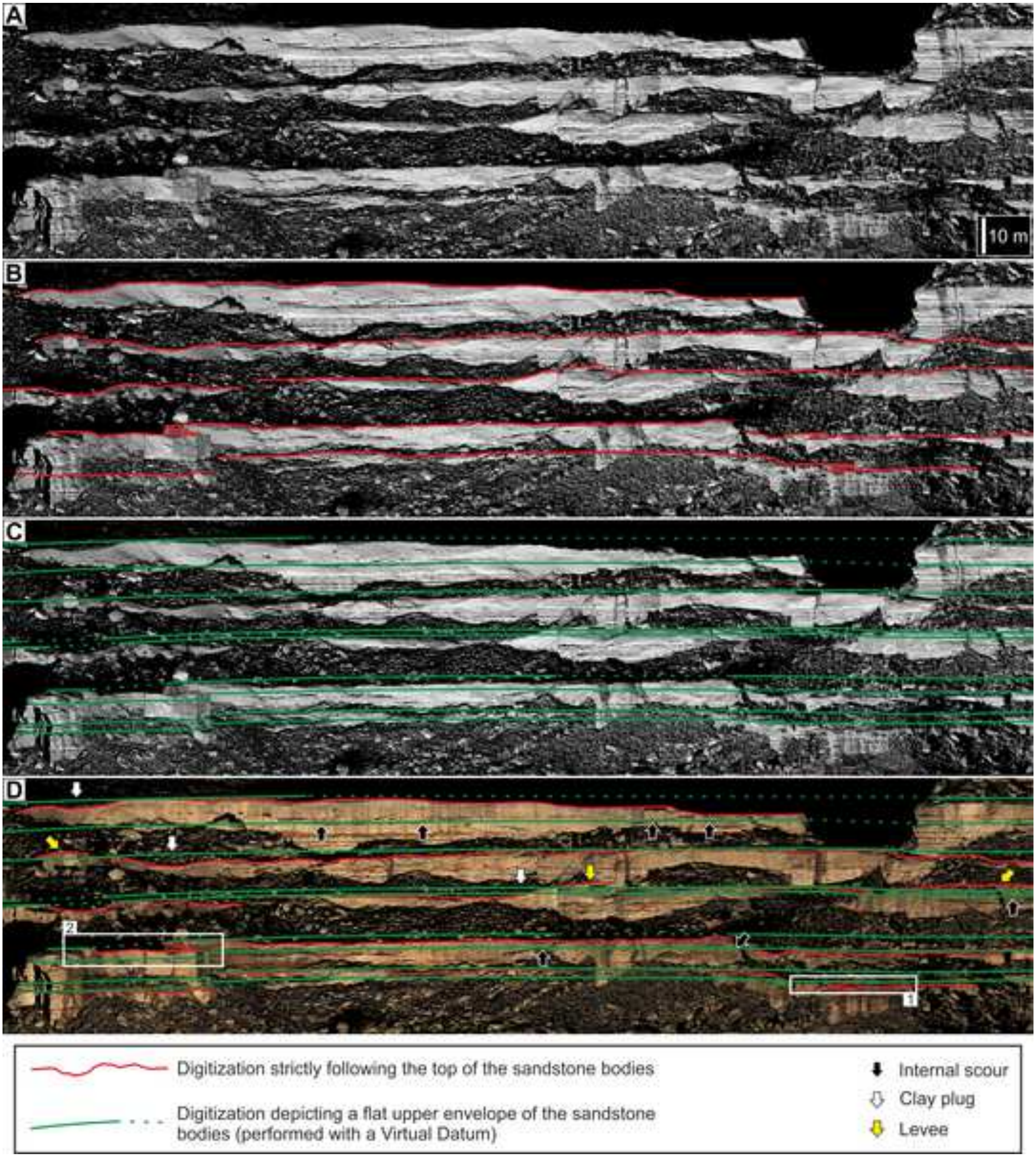

Figure 7
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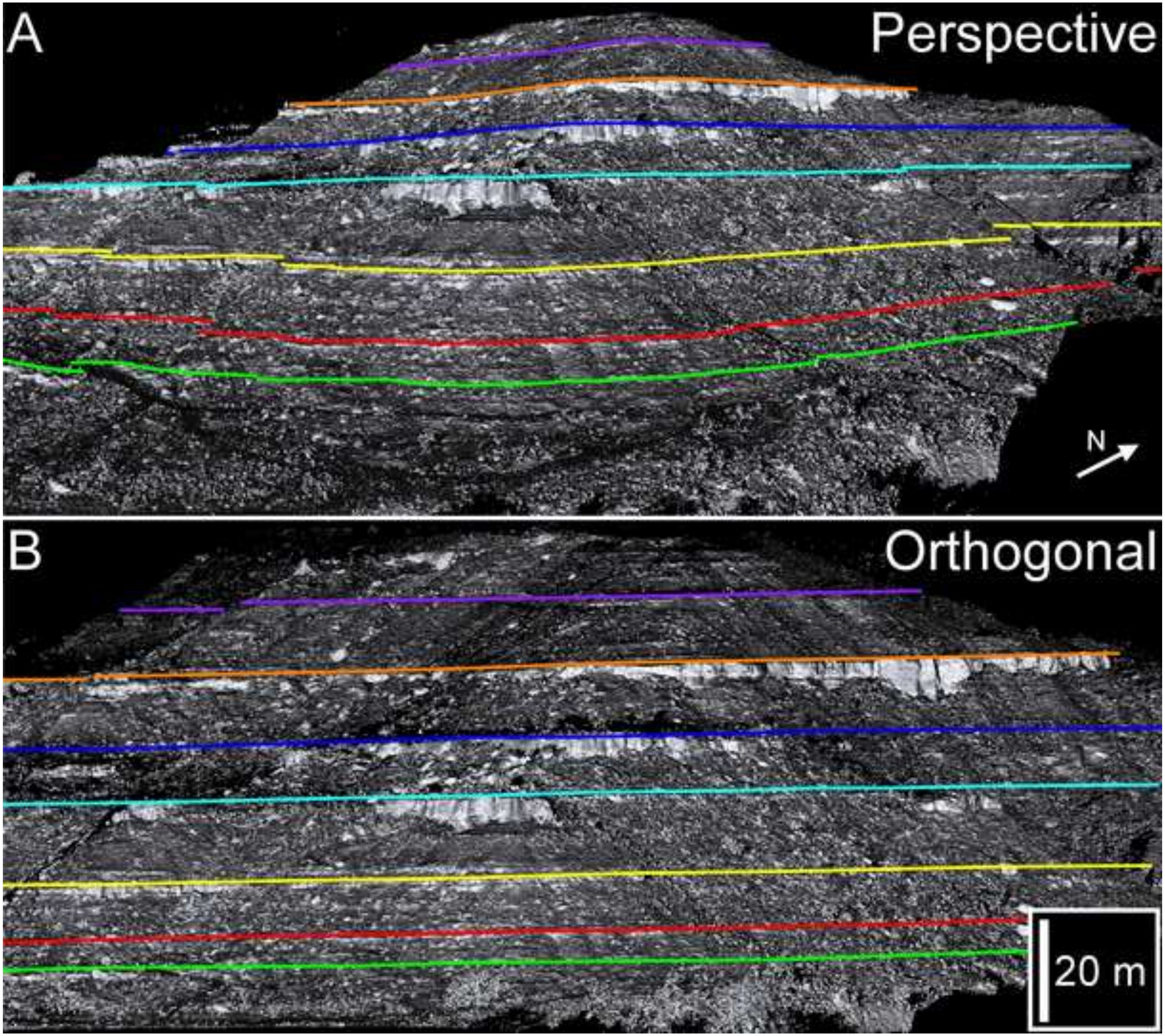

Figure 8

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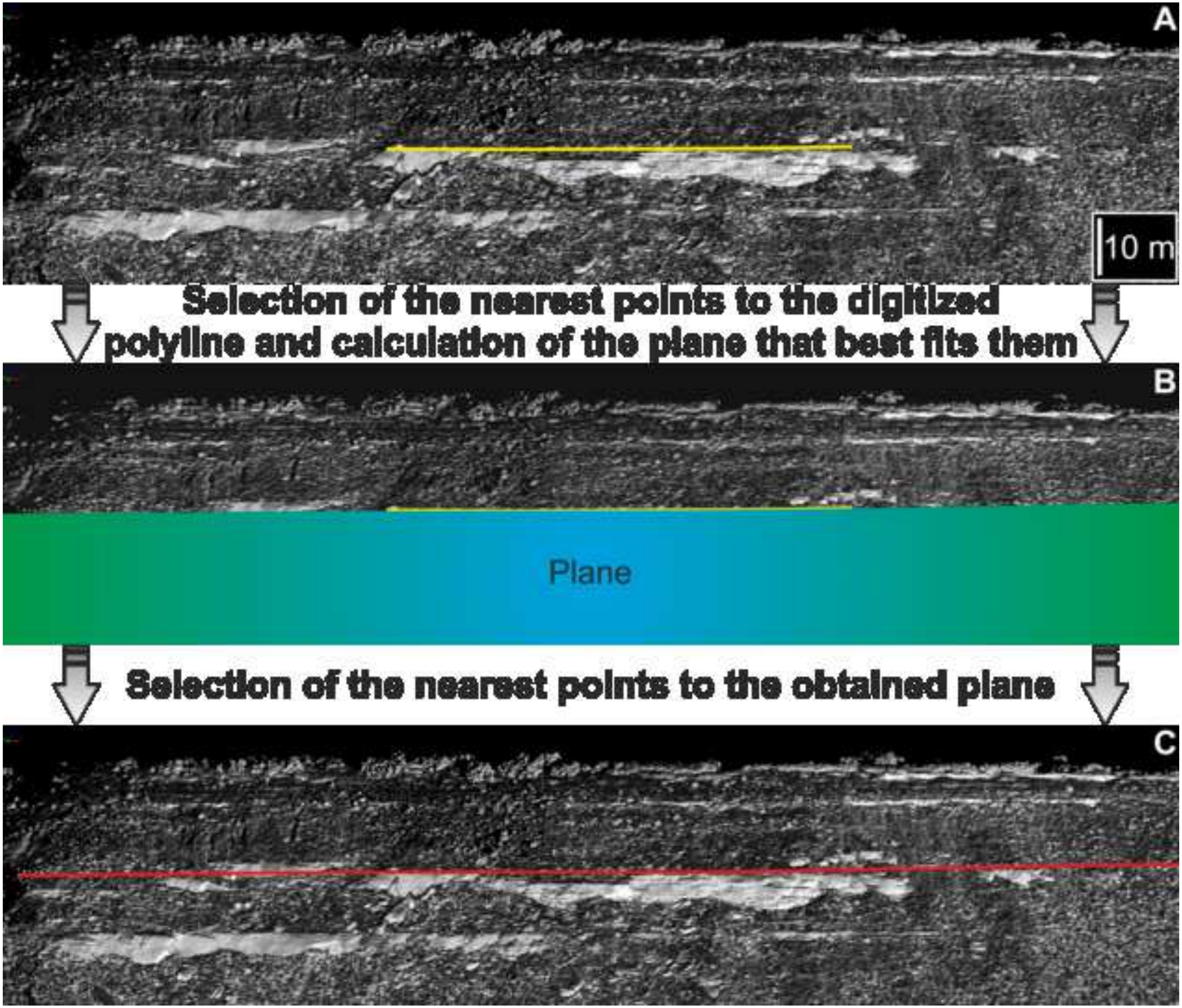

Figure 9
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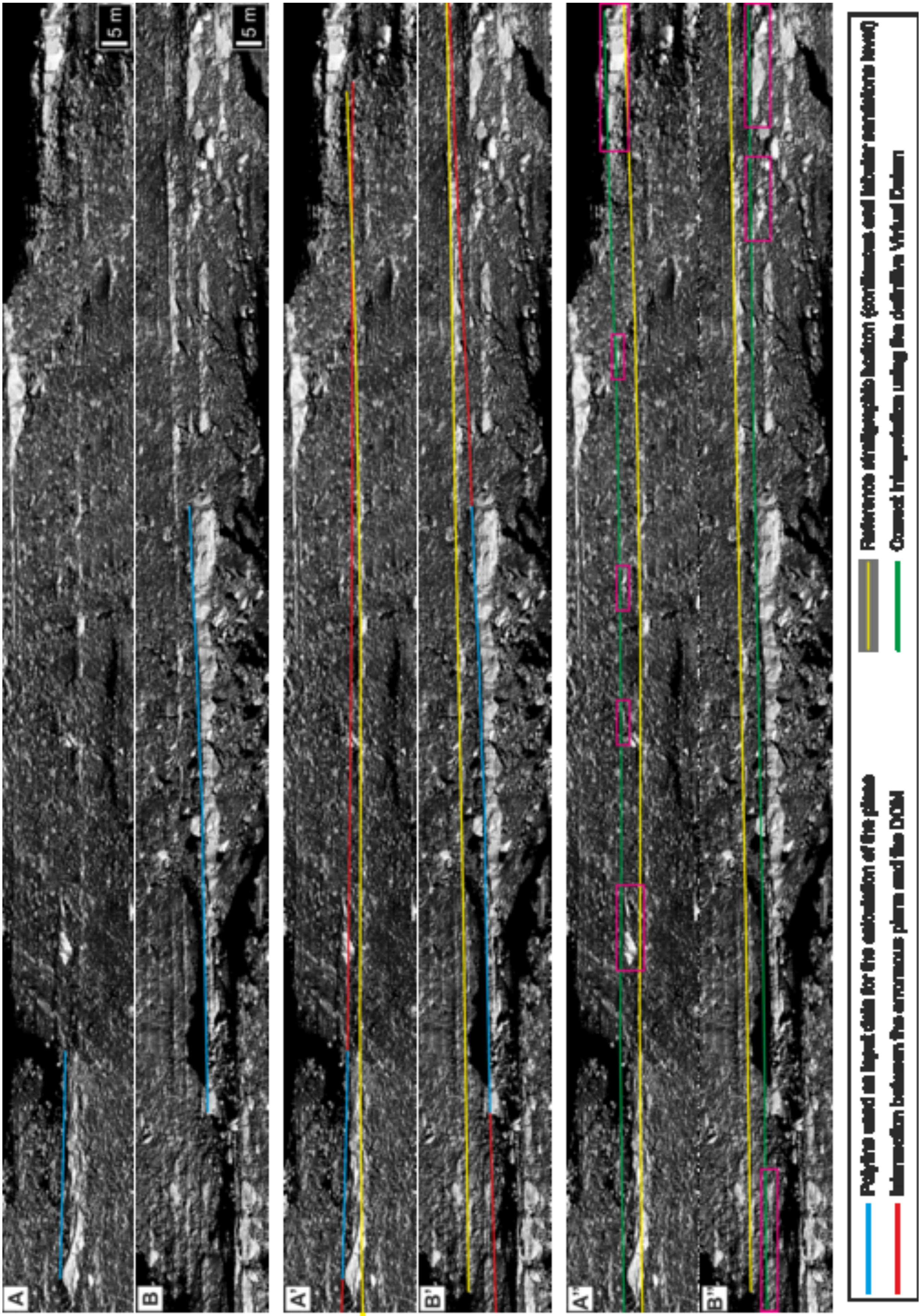

Figure 10
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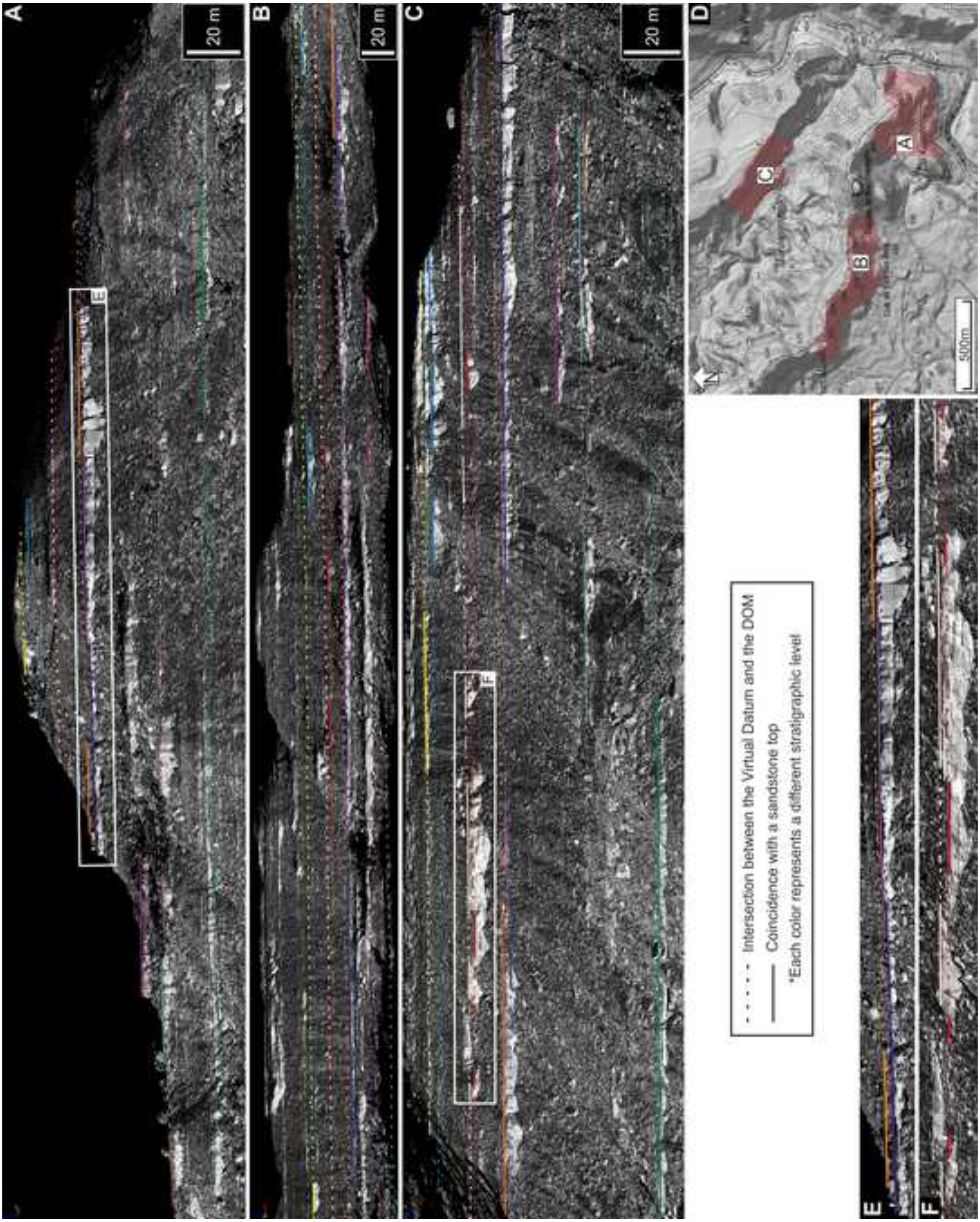

Figure 11_1

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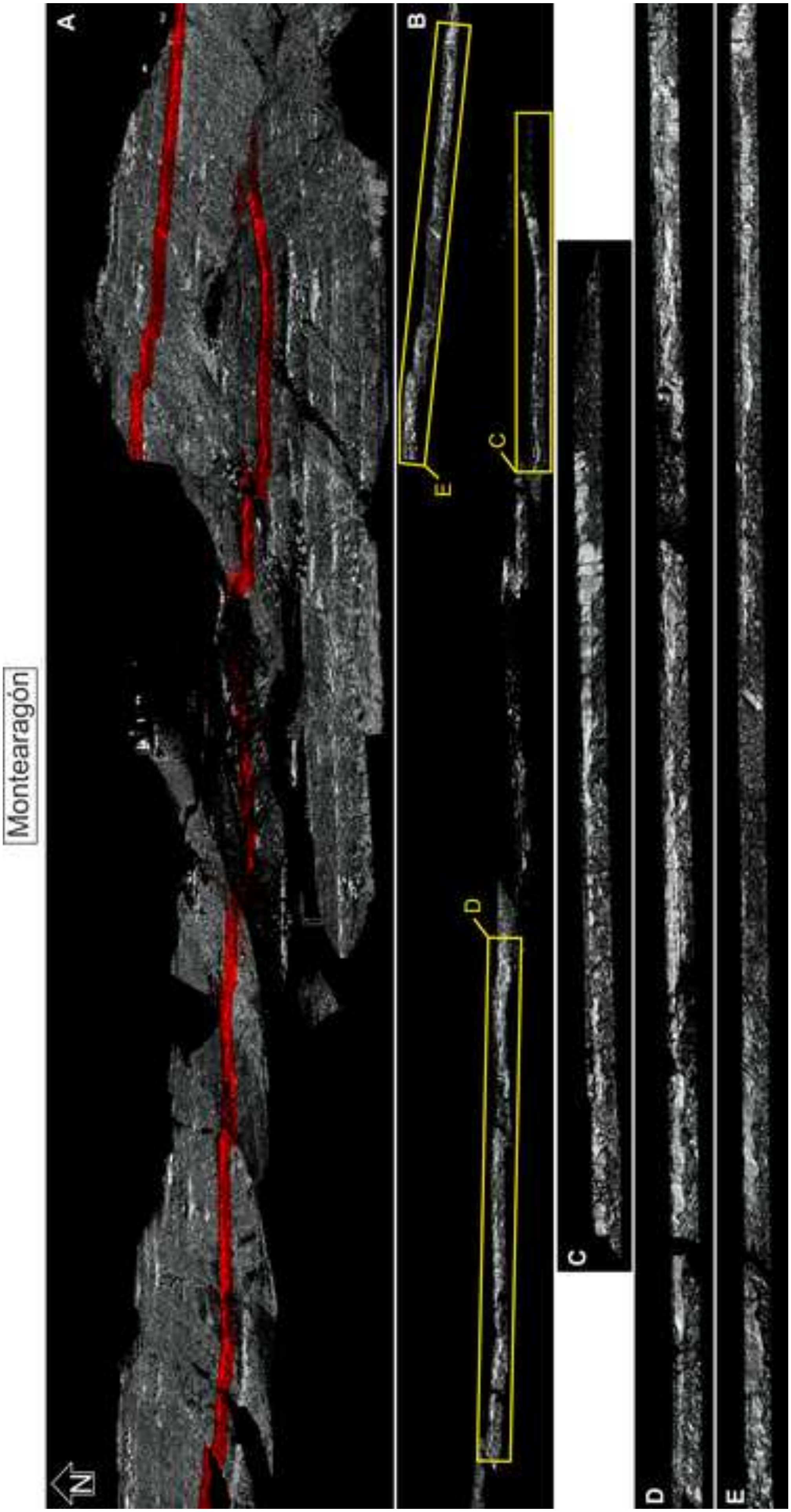

Figure 11_2

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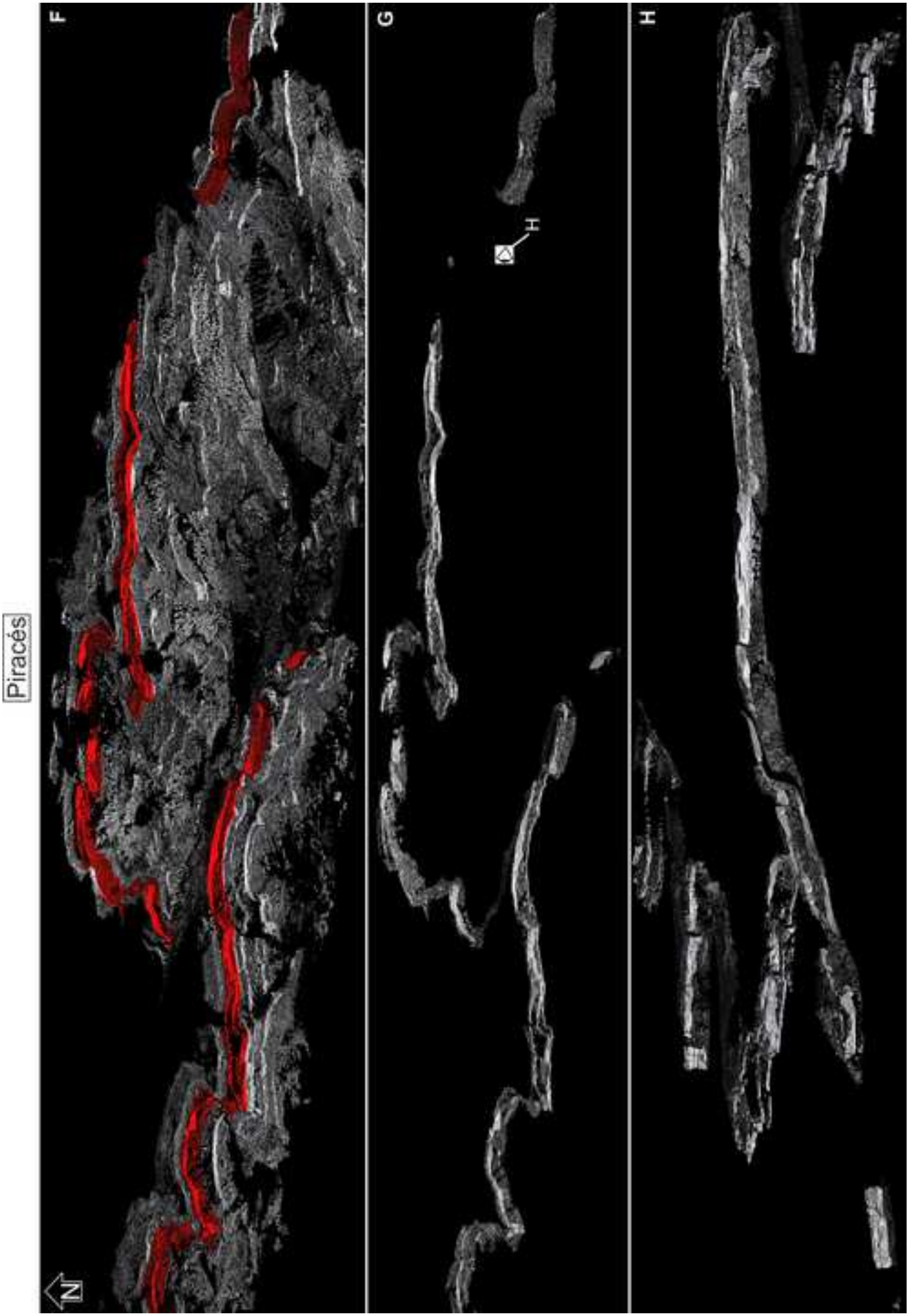

Figure 12
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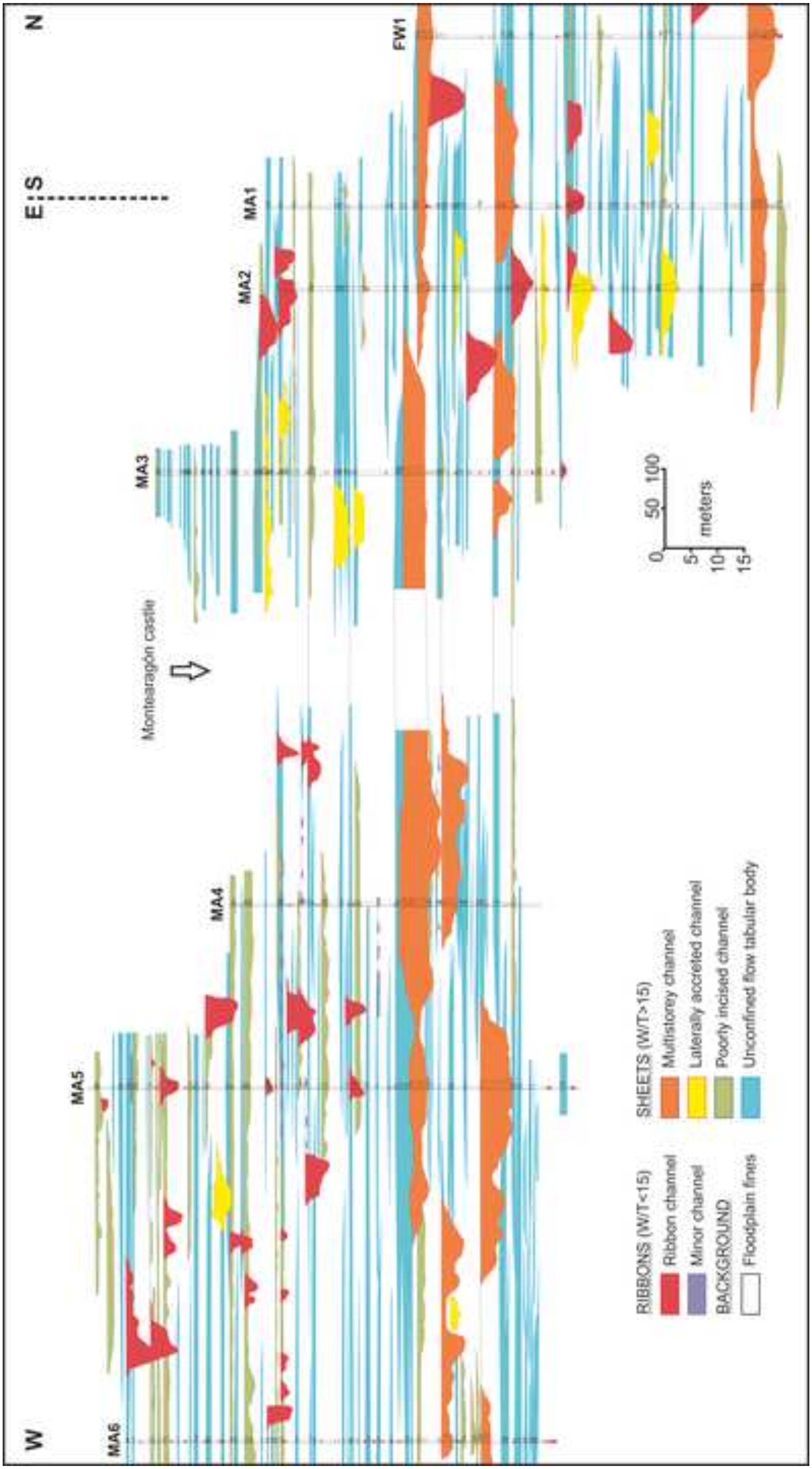

Table 1

TABLE 1. HIERARCHY AND CHARACTERISTICS OF THE BOUNDING SURFACES FOR FLUVIAL DEPOSITS

Surface order	Time scale of process (years)	Characteristics and nature of bounding surfaces	Fluvial depositional units	Significance and example of processes
1st	10^{-6}-10^{-3}	Lamination/set bounding surface	Lamina, ripple	Migration of dune bedforms under steady flow conditions.
2nd	10^{-2}-10^{-1}	Coset bounding surface	Mesoform (dune)	Change in hydrodynamic conditions through time, related to short-term unsteady flow or local non-uniformity
3rd	10^{0}-10^{1}	Inclined erosion surfaces within coset or group of cosets, dipping 5-20º in direction of accretion	Macroform growth increment	Medium-term change in hydrodynamic conditions related to stage fluctuation or major shifting of flow across/around a bar form (e.g. seasonal events, 10-year floods)
4th	10^{2}-10^{3}	Separates units with discrete accretionary integrity (e.g. convex-up macroform top, minor channel scour, flat surface bounding floodplain elements)	Macroform (point bar, levee, splay, inmature paleosol)	Shift of bar/subchannel pattern related to inherent channel-floor instability or to reorganization during a major flood (e.g. 100-year floods, channel and bar migration)
5th	10^{3}-10^{4}	Laterally extensive and with a marked shift in grain size, bedform scale, etc. (e.g. flat to concave-up channel base)	Channel, delta lobe, mature paleosol	Long-term geomorphic processes (e.g. shifting and erosion of a channel floor, isolated channels with relief reflecting channel avulsion or extensive surfaces within larger sandbodies recording channel migration)
6th	10^{4}-10^{5}	Regionally extensive and separating major channel sandbodies from contrasting facies (fine-grained sediment or contrasting channel facies)	Channel belt, alluvial fan, minor sequence	Major change of fluvial regime, recording shifts of base level, climatic changes (5th-order, Milankovitch cycles) or fault pulses
7th	10^{5}-10^{6}	Sequence boundary; flat, regionally extensive, or base of incised valley	Major depositional system, fan tract, sequence	4th-order (Milankovitch) cycles or response to fault pulses
8th	10^{6}-10^{7}	Regional disconformity	Basin-fill complex	3th-order cycles by response to tectonic and eustatic processes

Note: Designed by combining information from Miall (1996) and Reading (1996).

Table 2

TABLE 2. DIFFERENCES BETWEEN THE THICKNESSES MEASURED IN THE FIELD AND IN THE DOM FOR EACH STRATIGRAPHIC LOG, ALONG WITH OTHER FACTORS THAT MAY INFLUENCE ON THE MEASUREMENTS

Log name	Measured thickness* (m)	Real thickness† (m)	Absolute error (m)	Relative error (%)	Orientation § (°)	Mean slope† (%)	Channel proportion# (%)	Sst. proportion# (%)
FW1	67.10	68.18	-1.08	-1.58	48.43	0.48	13.59	28.05
MA1	93.10	95.87	-2.77	-2.89	56.23	0.36	13.80	33.68
MA2	96.00	97.62	-1.62	-1.66	57.08	0.34	22.79	41.22
MA3	73.60	75.29	-1.69	-2.24	37.08	0.34	9.75	35.54
MA4	54.00	56.88	-2.88	-5.06	64.03	0.33	16.32	41.41
MA5	87.40	90.36	-2.96	-3.28	6.18	0.48	22.44	44.69
MA6	75.70	78.80	-3.10	-3.93	30.54	0.49	8.48	31.61
Mean	*78.13*	*80.43*	*-2.30*	*-2.95*	*42.80*	*0.40*	*15.31*	*36.60*

*Measured assuming horizontal stratification.

†Calculated from the DOM.

§Regarding the stratigraphic maximum dip direction provided by the Virtual Datum (236.51°).

#Calculated from the logs.