Pitfalls in the geological characterization of alluvial deposits: site investigation for reactive barrier installation at Aznalcóllar, Spain

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Abstract

The alluvial deposits of the Agrio River in SW Spain have been studied using terrace mapping, boreholes, trenching and vertical electrical sounding to select an adequate place for a Permeable Reactive Barrier. Geological and hydrogeological data available prior to the barrier construction suggested a simple geological model based on three terraces, the most modern being deeper than the oldest. The barrier was accordingly trenched through the youngest terrace. However, excavation of the barrier and subsequent subsoil data demonstrated that the internal structure of the Agrio alluvial deposits does not follow such a simple model. A revised model, less favourable to the existing barrier design, revealed the oldest terrace to be deeper than the youngest, and to form a palaeochannel oblique to the surface terraces and river trends. The study methods used are standard, but proved to have insufficient resolution to detect key features of the alluvial geology. It is concluded that such characterization methods, though widely used, are not appropriate where alluvial terraces may display complex internal structures not reflected in the modern surface geomorphology. In hindsight, the study area should have been larger, so as to encompass at least the width of the alluvial plain and to extend for a hundred metres or so up and downstream from the proposed barrier location. Lithological logs of the boreholes should have been carefully described from both cuttings and downhole geophysical logs, which would have allowed more accurate delineation of the stratigraphy of the alluvial deposit. Subsequent geophysical methods should have been calibrated to this stratigraphy to characterize the internal structure and basal contact of the alluvial deposit.

Keywords: alluvial deposits, boreholes, geomorphology, hydrogeology, permeable reactive barrier, trenching

The Aznalcóllar tailings dam was constructed over an old alluvial terrace of the Agrio River, a tributary of the Guadiamar River (Fig. 1) near Sevilla (Spain). The dam failed on April 25th 1998. Nearly 6 million m^3 of acidic water and pyritic mud were spilled, flooding the Agrio/Guadiamar valley system, reaching the Guadalquivir marshlands and the boundary of the well-known Doñana National Park, 40 km downstream. Tailings were deposited over an area of 4630 ha, along a 62 km river reach.

The spill caused important socio-economic and ecological damage, mainly to the agricultural activities of the Agrio and Guadiamar valleys and the fauna around the Doñana National Park, south of the site. The accident attracted worldwide coverage, both at the scientific and general public levels. A large number of scientific studies and technical actions were undertaken to assess the degree of contamination and to mitigate its effects (e.g. Manzano *et al.* 2000; Ayora *et al.* 2001). As a result, most of the tailings were removed from the valley and riverbed, thus preventing further extension of the contamination. Residual pollution included tailings dispersed in the soil and acidic groundwater in the alluvial aquifer of the Agrio River. To restore the latter and reduce acidic water influx to the river, an experimental Permeable Reactive Barrier (PRB) was designed and built in the Agrio alluvial deposits, 2 km downstream from the failed dam (Figs. 1 & 2).

The objective of this paper is to describe the geological characterization performed to locate and design the barrier. Efforts ranged from regional geological studies to detailed site investigations. The former were largely based on previous work (Salvany & Custodio 1995; Salvany *et al.* 2000a, b; Salvany 2004) and were aimed at identifying potentially contaminated aquifers and their hydrogeological modelling (Castro *et al.* 1999; Jaén *et al.* 1999; Bernet 1999). A detailed site characterization was carried out at the Agrio River. As suggested by most authors (e.g. Driscoll 1986), this consisted of surface mapping and geophysical exploration, followed by borehole drilling, hydraulic testing and water sampling. All these data converged on a simple geological model based on three terraces, each one made up of relatively uniform sandy gravel deposits, the most modern being deeper than the oldest. Based on this, the PRB was built across the youngest and deepest terrace, so as to intercept most of the polluted groundwater. Barrier construction and further studies demonstrated that the structure and stratigraphy of the alluvial deposits were more complex than expected. The subsequent geological model revealed that the initial model was based on methods which, though widely used, were inadequate to detect the relevant geological features.

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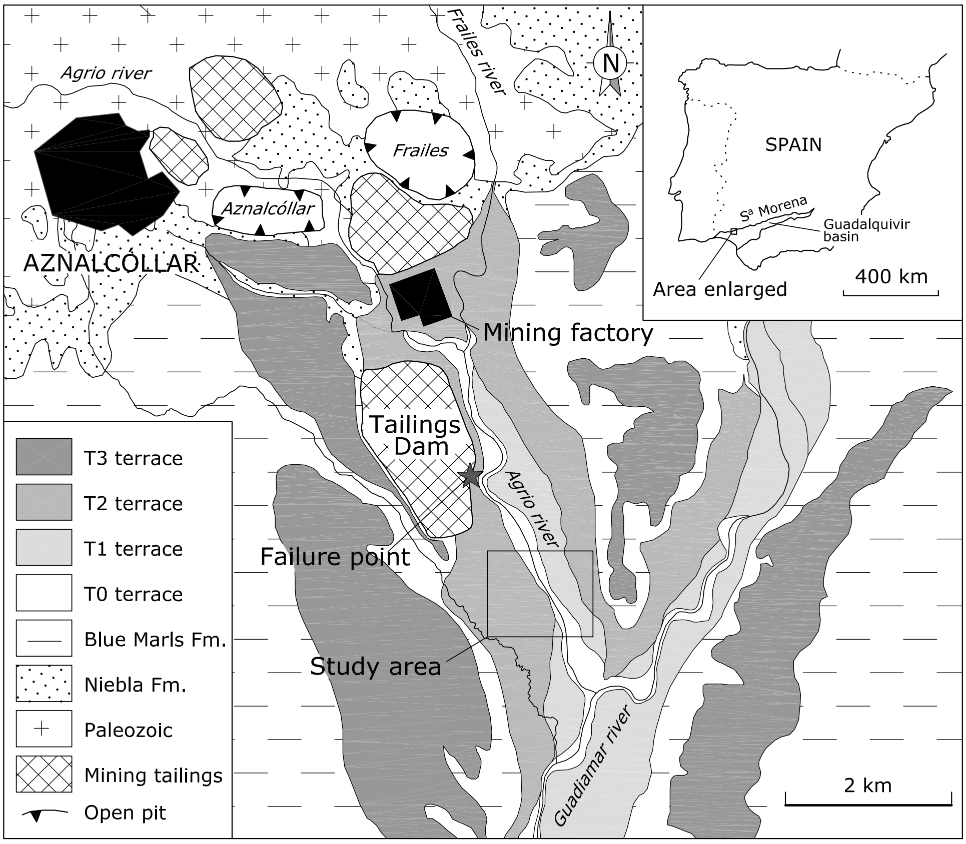

Fig. 1. Geological map of the Aznalcóllar mining area, including the location of the study area in the Agrio River valley.

From this experience, the paper objective is extended so as to discuss the apparent contradiction between terrace morphology and internal structure, and the limitations of conventional characterization methods (mapping, electrical soundings and drilling). To this end, the paper starts by providing some background information on the geological setting and the PRB design. Actual characterization methods and the resulting model are then described. Finally, methods and data obtained after the PRB construction are presented. The paper ends with a section devoted to discussing differences between pre-conception and reality, from which several lessons are then drawn.

Background

Geological setting

The Agrio River flows through the Aznalcóllar mining district, where massive sulphide (44 million tonnes of evaluated reserves, IGME 1978) and cupriferous pyroclastic deposits (34 million tonnes) of Lower Carboniferous age have been exploited extensively since the mid-nineteenth century (minor mining works go back to prehistoric times). The workings produced Cu, Pb, Zn and Ag by processing minerals including pyrite, chalcopyrite, galena and blende (IGME 1978). At first, various mining companies intermittently operated underground mines. Mining switched to open-pit methods in 1975 and two large pits were excavated: first Aznalcóllar and later (from 1996) Los Frailes (Fig. 1). Excavation of both pits and mineral processing operation produced a large amount of waste that was dumped around the Agrio valley, as well as over its alluvial deposits, significantly altering drainage patterns. The mine is closed at present.

The upper part of the Agrio River flows over Palaeozoic igneous and metamorphic rocks of the Sierra Morena, which contain the ore deposits exploited by the Aznalcóllar mines (IGME 1978). The lower part of the Agrio River flows over the Tertiary deposits of the Guadalquivir basin. These include two upper Miocene units: the Niebla Formation and the Blue Marls Formation, both of which dip a few degrees toward the south. The Niebla Formation is a layer of mixed carbonate-siliciclastic composition that unconformably covers the Palaeozoic rocks, with a maximum thickness of 15 m. The Blue Marls consist of a monotonous marly unit that reaches several tens of metres thick, and overlies the Niebla Formation.

In the part of the valley underlain by Tertiary strata, the Agrio River alluvial deposits consist of four terraces (Salvany *et al.* 2000b). The upper terrace (T3) is located on top of the hills surrounding the valley (Fig. 1). It is developed along both margins of the river and is always separated from the other terraces by the Blue Marls,

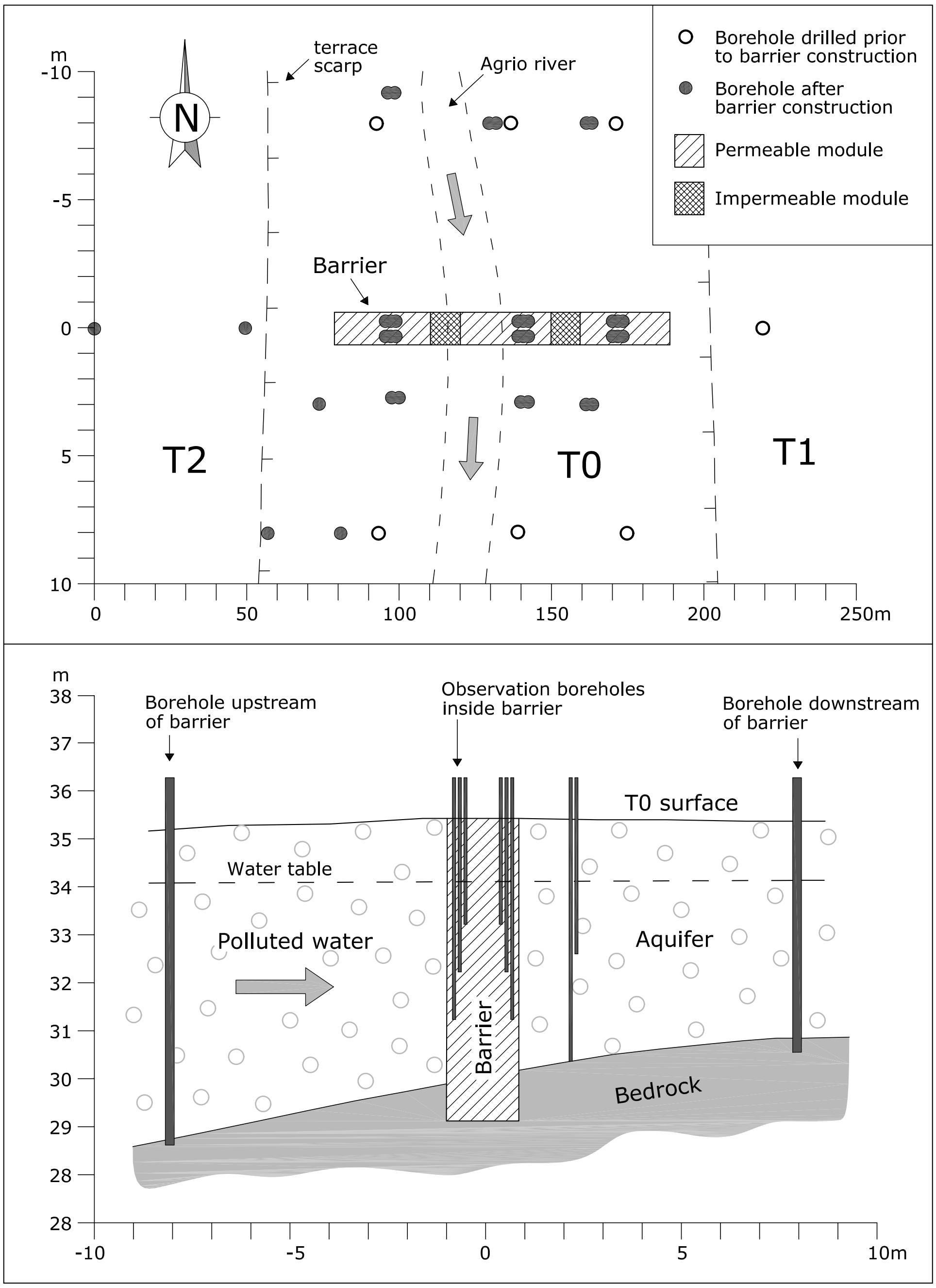

Fig. 2. Plan view (above) and longitudinal section (below) of the Permeable Reactive Barrier built in the Agrio River.

which outcrop on the hill slopes. The intermediate terrace (T2) forms a wide flat area below the hills, also on both margins of the river. The edge of this terrace forms a continuous scarp up to 5 m high. The lower terrace (T1) is mainly developed along the left margin of the river, forming a flat area, a few metres lower than the intermediate terrace. Both terraces are in contact, except at the river outlet, where the Blue Marls separate them. The modern floodplain (T0) is a 50 to 200 m wide erosive terrace that cuts through T1, and is bounded by a continuous scarp up to 1.5 m high. It represents a river channel and a floodplain that have been significantly modified by mining activities and especially by the clean up after the 1998 dam failure.

All of these terraces are made up of gravels and sands coming from the Sierra Morena source area. Polymictic graded gravels of up to 20 cm are the dominant lithology, with abundant sand and silt matrices, while sands form subordinate layers mainly in the upper part of each terrace.

Salvany *et al.* (2000b) used radiocarbon ages from five organic matter samples to date the T1 deposit as Holocene, with ages ranging from 5000 to 300 years BP They considered T2 to be an early Holocene deposit, as indicated by the age of a sample dated at 6285 years BP in its upper level. However, a second radiocarbon age obtained during this study for a deeper deposit revealed an age of more than 46440 years BP (outside the

Fig. 3. Permeable Reactive Barrier construction. Left: installing steel sheet piles to hold the alluvial walls. Right: backhoe excavation prior to filling with the reactive material.

radiocarbon range), thus implying that this terrace belongs to a Pleistocene age and spans a much wider age interval than T1. The T3 terrace is also assigned to the Pleistocene.

Permeable Reactive Barriers

Permeable Reactive Barriers (PRBs) are deep trenches excavated into an aquifer and filled with a permeable material that causes pollutants to either degrade or precipitate. PRB technology is relatively new (Blowes & Ptacek 1992; Gillham & O'Hannesin 1992; Naftz *et al.* 2002). Only a few are based on the use of organic substrates and limestone for the treatment of Acid Mine Drainage (AMD) (Benner *et al.* 1997; Ludwig *et al.* 2002; Younger 2002). Therefore, the Aznalcóllar PRB was considered to be an experimental site. Its objective was two-fold: to reduce pollution in the alluvial aquifer and to gain experience with this type of technology. A wide range of laboratory and field experiments were performed (Alcolea *et al.* 2001). Design of the reactive barrier material was aided by yearlong laboratory column experiments. These were qualitatively reproduced by means of a reactive transport numerical model, using RETRASO (Saaltink *et al.* 1998) that allowed simulation of the long-term behaviour of the barrier, and also supported design of the width of the PRB.

The PRB should be as shallow and narrow as possible to reduce costs, yet intersect as much of the polluted flux as possible. At the time of design groundwater was believed to flow perpendicular to the river in terrace T2, entering terrace T1, in where it was believed to flow parallel to the river. Therefore, the barrier was located within T0 at the narrowest point of terrace T1, and to span the whole thickness of T0. In this way, groundwater was to be constrained to flow through the barrier. It was designed to total 110 m in length and consisted of three modules each 30 m long, 1.4 m wide and 4 to 8 m deep, separated by 10 m wide inert clay modules (Fig. 2). It was built during September 2000 in submodules of 10 m length by first installing sheet piles to hold the walls and then excavating the inside with a backhoe (Fig. 3). After excavation, each module was filled with different ratios of reactive material (limestone chips, iron cuttings and organic compost), so as to produce conditions for sulphate reduction and metal sulphide

Fig. 4. Drilling method used to study the alluvial deposits of the Agrio River: Left: Tripod and hanging steel bailer. Right-above: detail of the valve in the lower end of the bailer that facilitates retention of cuttings within the cylinder. Right-below: bailer emptying. Deposited material is a mixture of water and broken alluvium, sometimes with fragments of unaltered soil.

precipitation (Fryar & Schwartz 1998; Waybrant *et al.* 1998). Observation boreholes at different depths were left inside the PRB to monitor its performance.

Study methods

The study focused on the T0, T1 and T2 terraces. The T3 terrace does not seem to be relevant to the hydrogeology of the area and was not studied. Following previous work on the structure and stratigraphy of alluvial deposits (McGown & Miller 1984; Hagedorn & Rother 1992; Taylor & Lewin 1996; Chen *et al.* 1996, amongst others), the following study methods were used.

Terrace mapping

A detailed geomorphological map (1:10 000) was produced after interpretation of aerial photographs and fieldwork, not only for the Agrio River but also for all the alluvial area of the Guadiamar drainage basin. This allowed confirmation of the four terraces described above (Salvany *et al.* 2000b). Fieldwork included a study of the alluvial deposits exposed in the scarp fronts, as well as the bedrock outcrops within the terraces and through the river channel, which was useful for identifying the structure of the alluvial deposits.

Boreholes

The lithological logs (drilling cuttings) of 43 boreholes were analysed, 35 of them drilled for the PRB purpose (20 after PRB construction), and 8 drilled during earlier studies. Almost all of them reached the Miocene Blue Marls. They were drilled using the cable tool percussion method (Cruse 1979) (Fig. 4). The choice of drilling method is often controversial. In this case, the assumed presence of cobbles and boulders hindered alternative methods. With the exception of the direct rotary method, all others are rated as not recommended, slow or impossible (Driscoll 1986; Custodio & Llamas 1987). Hence, it is not surprising that cable tool percussion was the method of choice for this area, so that a number of experienced drillers were available for drilling inexpensive holes. A field geologist produced a drilling log for each borehole.

The cable tool percussion method often involves chiselling followed by bailing to remove the cuttings. In this case, however, the loose nature of the material led drillers to use a steel valve bailer 4 m long and 200 mm

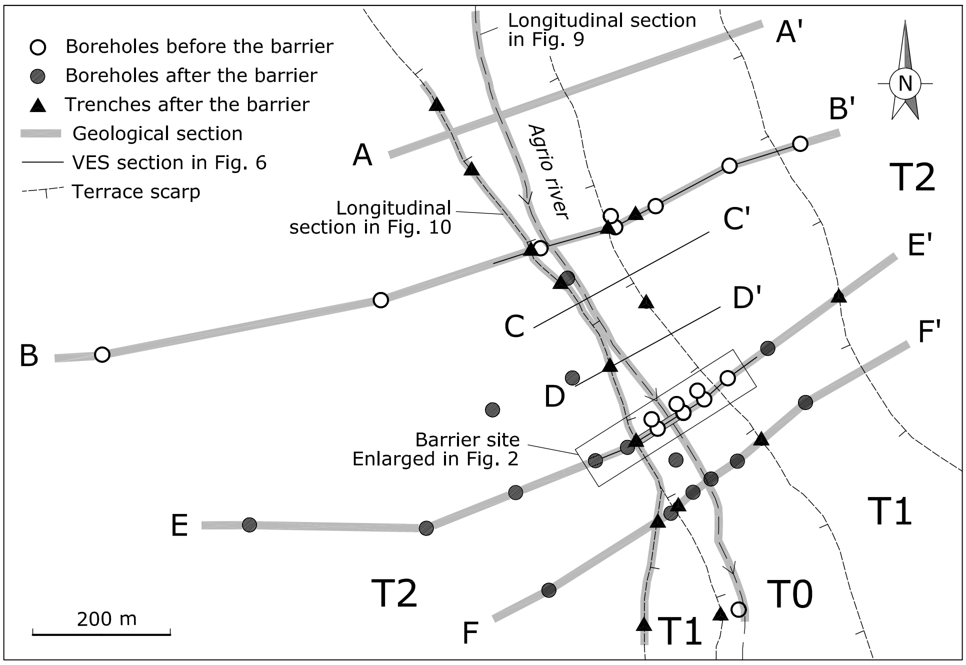

Fig. 5. Map of the barrier site showing location of all the data capture points (boreholes, trenches, geological sections and VES sections) illustrated in subsequent figures. See Figure 1 for location of this map.

of diameter provided with a plain cutting shoe to break up the largest boulders (Fig. 4). The bailer was emptied every half-metre, which was expected to provide a good albeit disturbed sample, sufficient to identify the type of material. It must be stressed that the expected (and reported!) presence of gravel throughout the aquifer thickness prevented undisturbed sampling using a U100 tube, which would have been feasible in less cobbly deposits.

Trenching

Fourteen trenches aligned to T1 and T2 scarps on both sides of the Agrio River were excavated with the aid of a backhoe after the PRB construction. They were useful for identifying the connection between terrace deposits and to clarify their stratigraphy, as well as for taking unaltered samples.

Trenches proved an excellent method for studying the terraces. They allowed rapid investigations of shallow sectors, several metres long, where the depositional structure of the alluvial deposits could be observed in detail. However, this method is restricted to the unsaturated zone and to the length of the shovel arm. When trenches encounter the water table they are rapidly flooded and the walls collapse, thus preventing observation.

Vertical Electrical Sounding

An area 2 km downstream of the failed dam was characterized by means of Vertical Electrical Soundings (VES) to contribute to the selection of an appropriate site to locate the PRB. The aim of this work was to estimate the thickness and basal contact relief of the alluvial deposits, relying on the assumed high lithological contrast of resistivity found between the marls of the bedrock and the alluvial gravels. Three prospecting campaigns were carried out.

The first and principal campaign was undertaken prior to construction of the PRB (CGS 1999). Four transverse cross-sections were made, mainly on the T0 and T1 terraces (Figs. 5 & 6). The longest cross-section comprised 22 VES's, each 20 to 25 m wide, and followed a line of boreholes drilled for groundwater control. The other three sections were placed parallel to the first one, at 100 m intervals downstream, and comprised 9, 11 and 12 VES's, respectively. The second campaign was undertaken during the PRB construction to complete the network around the PRB and in a section 100 m downstream of the PRB location. A third campaign was undertaken after the barrier construction.

RESIST software (Vander-Velpen *et al.* 1993) was used for the interpretation of the VES data. Models with 2 or 3 layers were needed to fit field data. Resistivities over 20–30 ohm/m were considered representatives of alluvial material, while values below were taken as representative of the Blue Marls. A reasonably good correlation with reported borehole lithological profiles was obtained for the T0 and T1 terraces.

Hydrogeology data

The hydrogeology of the alluvial aquifer of the Agrio River and its connection with the Guadiamar aquifer

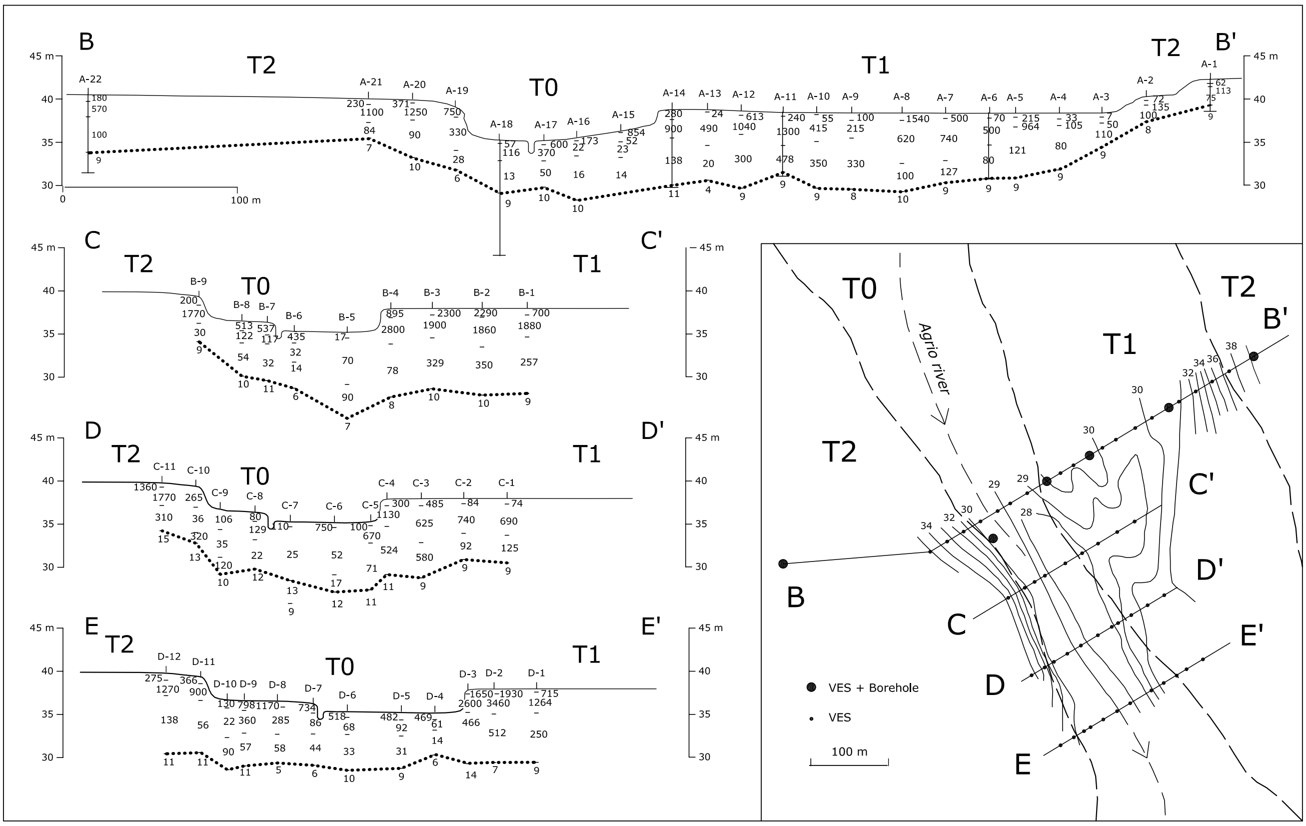

Fig. 6. Vertical Electric Sounding (VES) profiles across the Agrio River terraces (adapted from CGS 1999). The dotted line indicates the bottom of the alluvial deposits interpreted from VES. Units are ohm/m. Contour lines on the map are the isobaths expressed in metres calculated from VES.

has been studied by Bernet (1999). He suggested a two-layer hydrogeological model (Fig. 7): a lower layer, which corresponds to a narrow paleochannel below the T0 or T1 terraces following the inner alluvial plain, where groundwater flows downstream; and a wider upper layer, which includes the T2 terrace, where groundwater flows obliquely from the margins toward the inner area of the alluvial valley. Thus, the T0–T1 terraces were deduced to drain the adjacent T2 terrace and are in turn drained by the river.

A very good river-aquifer hydraulic connection is believed to occur along the valley of the Agrio River. Therefore, the mean longitudinal hydraulic gradient in the aquifer is approximately equal to the river gradient, about 0.1%.

Several long-term cross-hole pumping tests were performed. Conventional interpretation of these tests yielded transmissivity (T) values around 2000 m^2/d (or hydraulic conductivity of 500 m/d for a saturated thickness of 4 m) and a storativity of around 0.20.

Three of these tests, including drawdown curves at 6 observations well each, were interpreted jointly, using the geostatistical inversion methodology presented by Meier *et al.* (2001) based on the code TRANSIN II (Medina & Carrera 1996). Geostatistical inversion yields

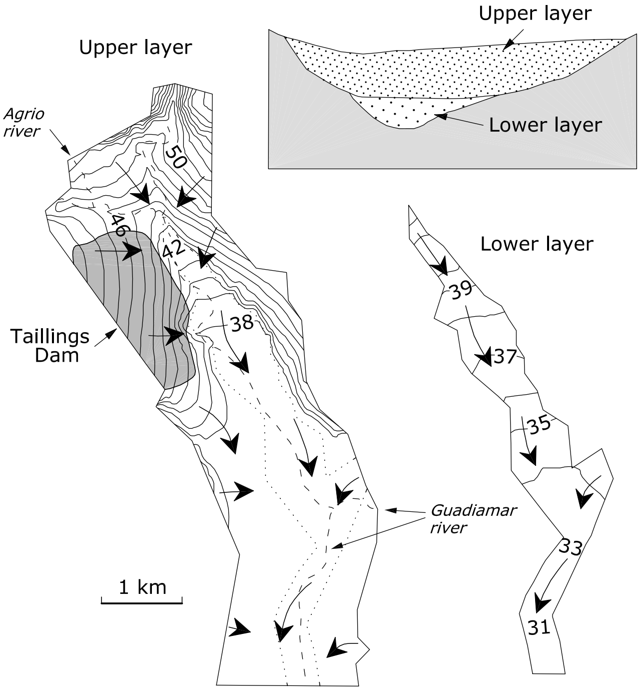

Fig. 7. Understanding of the hydrogeology of the Agrio River aquifer before the barrier construction (Bernet 1999). Contours represent hydraulic head. The dotted line indicates the location of the lower layer below the upper layer. The dashed line is the line of the modern river.

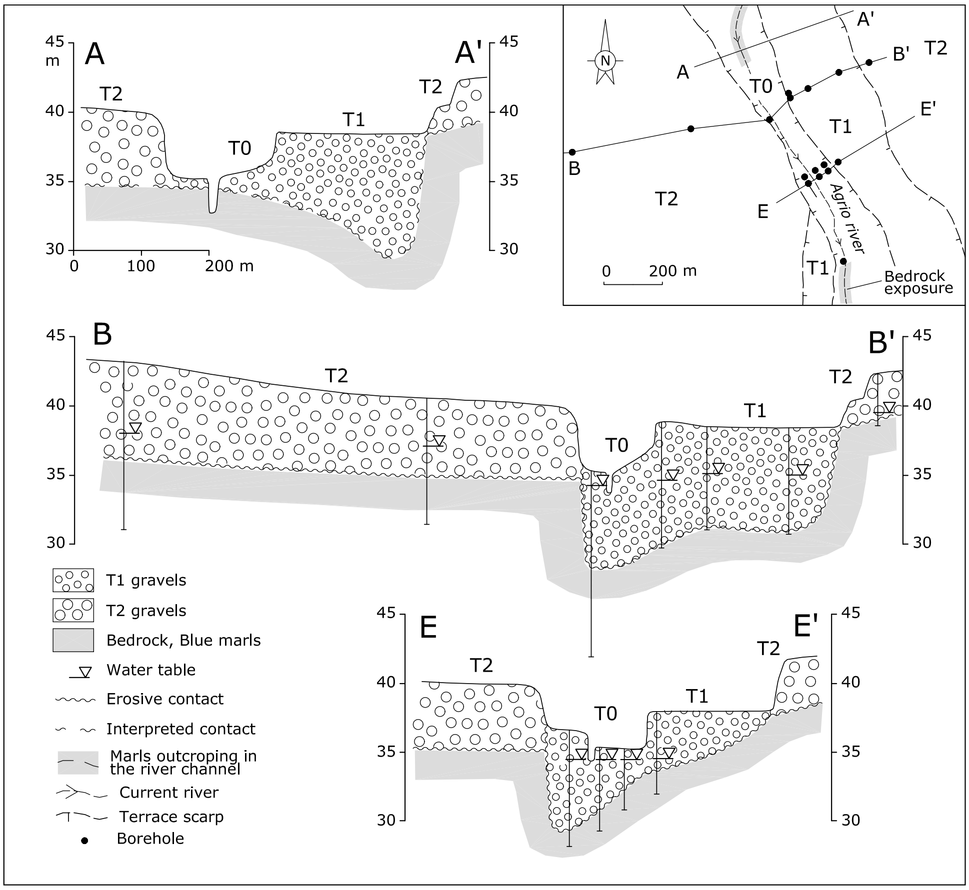

Fig. 8. Conceptual geological model assumed for the Agrio alluvial deposits before the barrier construction. Cross-sections B and C are based on borehole data. Cross-section A is interpreted from the surface data. Boreholes and cross-sections location are indicated in the small map. See Figure 5 for location.

a spatially variable transmissivity field that fits all drawdown curves optimally. In this case, inversion produced high T pathways at both sides, but especially at the western side. These were interpreted as palaeochannels. It also led to a reduction in T downstream, but with high uncertainty. At the time, these trends were interpreted as natural. In hindsight, it is clear that the high T region at the western side can be attributed to the fact that the aquifer extends beyond the model boundary. The reduction in T downstream can be attributed to the disappearance of T2 deposits.

Tracer tests were performed with a series of tracers. The low pH of the water affected the detectability of some tracers. The best results were obtained with ionic tracers (iodide and bromide). They yielded an "equivalent open space" (porosity times thickness) of 0.45 m. This would imply 0.11 porosity for a thickness of 4 m. Obviously, such porosity is much smaller than the 0.3 expected for this type of materials (and suggested by the storativity value of 0.2), but was deemed reasonable as a "point" mesurement in fining-upward alluvial deposits, where most of the flux often concentrates in the lowest portion of the saturated thickness.

First conceptual geological model

The geomorphologic map and data from fifteen boreholes which followed two transverse cross-sections through the Agrio River (sections B and E in Fig. 8) and four VES profiles were available prior to the PRB construction (Fig. 6). Boreholes indicated that alluvial deposits below the T1–T0 terraces were always deeper than those of the T2 terrace. The VES also showed this tendency. These data suggested a conceptual geological model consisting of two alluvial deposits: an upper deposit associated with the T2 terrace and a deeper deposit associated with the T1 terrace; the latter has been partially eroded by the current river, forming the T0 terrace. The T2 deposit shows a flat bottom and a relatively uniform thickness ranging between 5 and 7 m, while the T1 deposit (up to 9 m thick) revealed the filling of a sinuous palaeochannel. This sinuosity was deduced from the asymmetrical shape of the palaeochannel, which is sometimes located close to the western side of the T1 deposit (Sections B and E in Fig. 8) and elsewhere is just at the opposite margin (Section A).

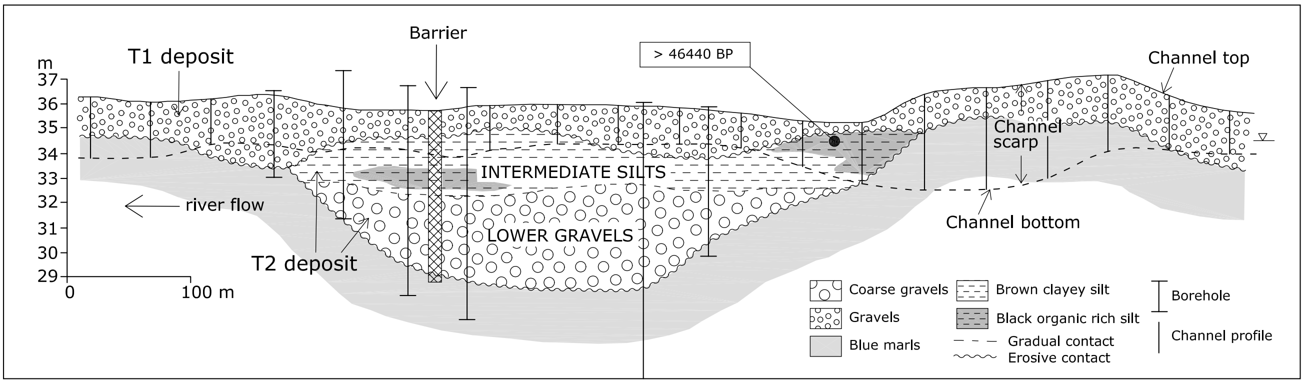

Fig. 9. Longitudinal section through T0 terrace following the current channel of the Agrio River. It has been drawn from lithologic profiles exposed in the channel scarp and data from some boreholes drilled near the channel boundary. An oblique cross-section of the palaeochannel is shown just where the reactive barrier was build. Note that bedrock (Blue Marls) is outcropping in both margins of the palaeochannel, and that the organic silt layer is also outcropping in some lengths of the channel bottom. See Figure 5 for location.

Following this geological model, the PRB was placed in the T0 terrace along the cross-section E of Figure 8. There, the palaeochannel in the T1 deposit, carrying most of the pollution, just crosses below the T0 terrace. In this location, the palaeochannel is at its narrowest and shallowest, thus minimizing PRB costs.

A heterogeneous alluvial deposit was exhumed during construction. It displayed an unexpected three-layer structure (Fig. 9): (1) a *lower layer*, with a maximum thickness of 5 m, made up of coarse gravels up to 30 cm thick and medium-coarse sands, with a massive and clean appearance and lacking fine sediments; (2) an *intermediate layer*, 1 to 3 m thick, formed by a mixture of clay, silt and sand, which can show two different lithofacies: a brown deposit with abundant vegetal root marks of green colour, containing lenses of fine gravels as well as frequent scattered organic remains, and a black organic-rich deposit of massive aspect; and (3) an *upper layer*, made up of gravels and sands, up to 3 m thick.

Organic silty materials like those in the intermediate layer had been observed earlier outcropping at some points on the river channel (Fig. 9), but were interpreted as minor silt lenses scattered within the gravels, with no relevant significance in the structure of the deposit, because they appeared to be absent in the surrounding boreholes. The apparent contradiction between the barrier stratigraphy and that shown by the boreholes will be discussed below.

Second conceptual geological model

As the observations made during PRB construction were reported, the initial conceptual model was immediately questioned. This led to the excavation of trenches along the western T2 scarp. These trenches demonstrated that the intermediate silt layer extended below the T2 terrace (Fig. 10), implying that this layer (and consequently the underlying gravels) do not correspond to the T1 deposit but belong to T2. This agrees with the pre-Holocene age obtained from a sample of organic matter from this layer (Fig. 9) because, as mentioned above, the T1 deposit is clearly of Holocene age. Thus, the T2 deposit must consist of three layers (lower part of Fig. 10): the lower and intermediate layers described at the PRB site (Fig. 9), and a third upper layer of gravels outcropping along the T2 scarp. Trenches on the other side of the river showed that a relatively well sorted gravels forms the T1 deposit.

These new data invalidated the initial conceptual geological model and suggested a second model consisting of two palaeochannels (Fig. 11): a lower palaeochannel filled by T2 deposits (mainly by the coarse gravels of the lower layer) and a higher palaeochannel filled by gravels belonging to the T1 deposit. The two palaeochannels overlap upstream (Section B, in Fig. 11), forming an apparent single deposit due to their similar composition. The palaeochannels also overlap in the barrier site (Section E) giving a structure in which the T1 palaeochannel in part cuts the bedrock (below the T1 terrace to the East) and partially cuts the silt layer of the T2 deposit (below the T0 terrace). Thus, at the PRB site the upper layer really corresponds to the T1 deposit, while other subjacent layers belong to the T2 deposit (Fig. 9). Downstream (Section F), the two palaeochannels are completely separate, the lowest below the T2 terrace and the highest below the T1–T0 terraces, with a bedrock rise between them.

This second conceptual model was confirmed by new boreholes drilled on the western T2 terrace. They clearly illustrated that a palaeochannel which flowed to the SW is found below the T2 terrace, and crosses obliquely the three terraces (Fig. 11, upper part).

Although this study did not include a detailed sedimentological analysis, the available data indicate the following sequential evolution (Fig. 12):

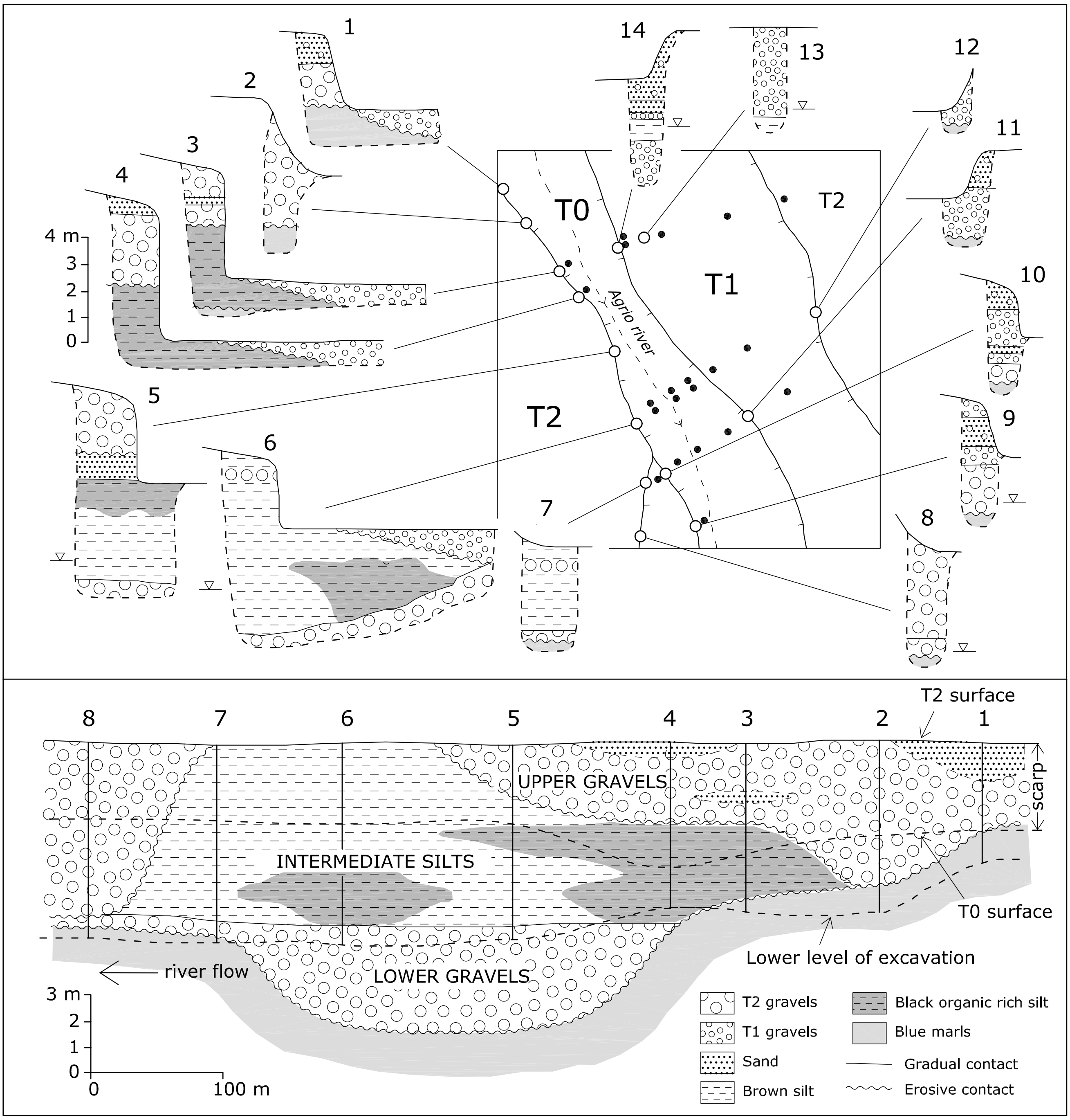

Fig. 10. Upper part: trenches excavated in the terrace scarps of the Agrio River. Lower part: Longitudinal section through T2 scarp in the western margin of the Agrio River interpreted from trenches. See Figure 5 for location.

First sequence (B and C in Fig. 12): This started with the deposition of the T2 lower gravels, filling a previously excavated channel (T2 paleochannel of the model) cut into the bedrock. This sequence represents a first alluvial episode of high energy, as demonstrated by the deposition of coarse gravels and the lack of fine sediments. Without a sedimentary break, a second episode of lower energy takes place, grading over the first and giving way to an expansive organic-rich flood plain (Nanson & Croke 1992), where organic mud and sand, as well as fine gravels coming from small fluvial channels, were deposited. This is a Pleistocene sequence as indicated by the age of the organic silts. Similar alluvial sequences have been described by Brown & Keough (1992) and Prosser *et al.* (1994).

Second sequence (D): This is represented by the upper gravels of the T2 terrace, which again represent an energetic alluvial episode following an erosive phase that incised the top of the organic-silt layer. This sequence developed during the early Holocene and finished with the formation of the T2 terrace.

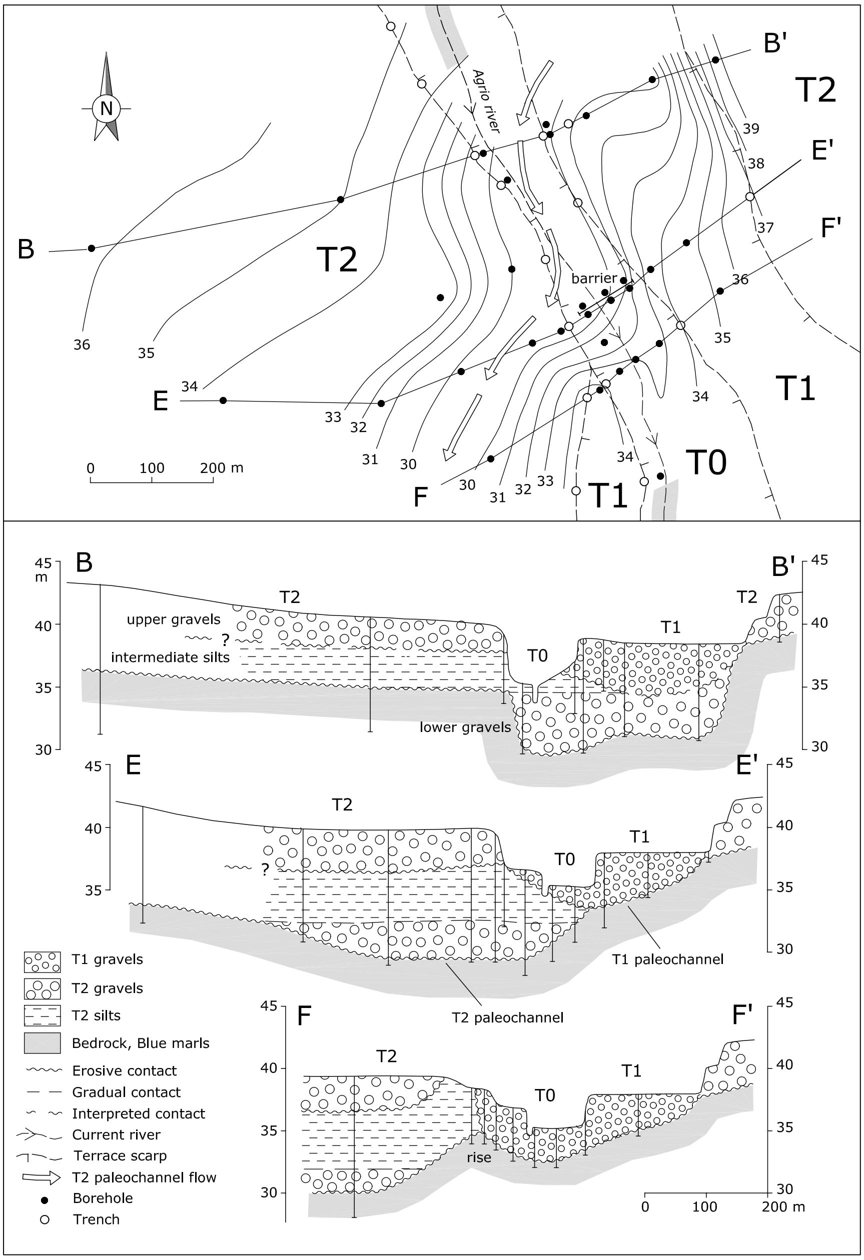

Fig. 11. Conceptual geological model assumed for the Agrio alluvial deposits after the barrier building. Upper part: map of the studied area with location of boreholes and trenches, and the terrace scarps. Contour lines are the isobaths of the alluvial bottom expressed in metres, calculated from the boreholes and trenches. Lower part: cross-sections through the Agrio terraces. Note that both map and cross-sections delineate two palaeochannel; a lower T2 palaeochannel crossing obliquely all terraces, and a highest T1 palaeochannel below T1-T0 terraces. The barrier was built across the T0 terrace following section E, intersecting the western limb of T2 palaeochannel as well as the eastern limb of T1 palaeochannel. See Figure 5 for location.

Third sequence (E): This started to develop around 5000 years BP after an erosive phase which removed the previous alluvial deposits as well as the Blue Marls, and formed the basal surface of the T1 paleochannel. It is an alluvial deposit of progressively waning energy that starts with coarse gravels and fines upwards to sands. This sequence formed the T1 terrace, which was then eroded by the modern river channel, forming the T0 terrace. This last erosion occurred after the age calculated for the upper sands of the T1 terrace (300 years BP).

Discussion and conclusions

The case study demonstrates that the structure and composition of alluvial deposits can be much more complex than suggested by simple analysis of terrace

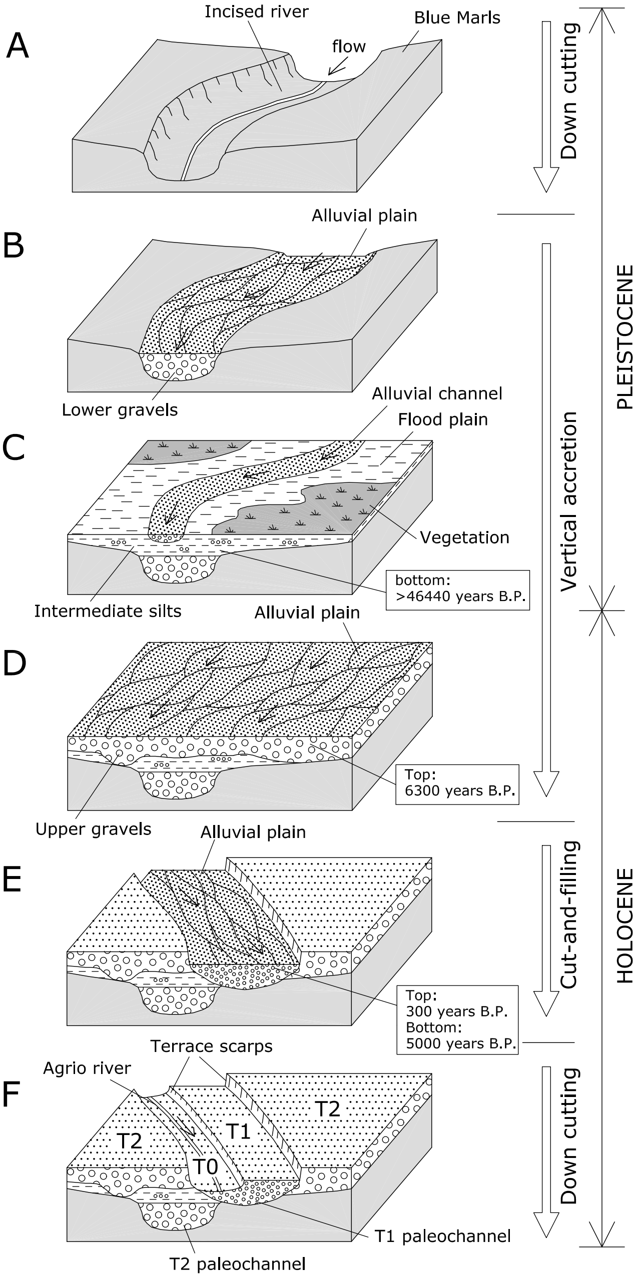

Fig. 12. Diagram blocks summarizing the main sedimentary events interpreted for the Agrio alluvial deposits of T2 and T1 terraces. Ages correspond to the Guadiamar alluvial deposits, from Salvany *et al.* (2000b).

geomorphology. The initial model failed to properly identify the geometry of the deposits. As a result, the PRB may not have been located in the best place because it failed to intercept the whole saturated thickness as planned, leaving untreated a wide zone of groundwater flow to the west. As it turned out, the central and eastern modules worked properly (Fig. 2). However, the western module, which happened to be the least permeable, was bypassed laterally. The second model implies that the barrier should have been located 300 m upstream (near cross-section B-B' in Fig. 11). Several causes contributed to the error: data may not have been sufficient and, ironically, both percussion-drilled boreholes and geophysics lacked sufficient resolution. More importantly, all data appeared to be consistent with a preliminary model derived from field mapping, which may have generated a bias in subsequent data gathering and interpretation.

The study indicates that percussion drilling samples in gravels (in which U100 sampling is infeasible) may not adequately show the lithologies encountered, especially when traversing horizons of fine material. The valve percussion method disperses the sample because some material may fall off the borehole walls and some may be pushed into the fine layers during the percussion phase. Moreover, the excess water washes out fine sediments when the valve is open at the surface and the sample is poured. This explains why the silt layer went unnoticed during the first boreholes surrounding the barrier, even though it was clearly observed during its excavation. Samples corresponding to this layer were recorded as sands containing some gravel.

It could be argued that these problems were caused by the lack of experience of the field geologist. In fact, problems were corrected in later boreholes by lowering the casing immediately after each bailing operation and by hitting the bottom of the hole with the minimum possible energy. This caused the borehole to become nearly dry when reaching the silt layer, which could then be adequately sampled. However, this procedure is exceptional and costly, as it slows down the drilling rate, which explains why even experienced geologists tend not to recommend it. In hindsight, it would have been much more fruitfull to check boreholes with other logging methods (like resistivity or gamma-ray logs), which are helpful to detect lithologic changes, especially between coarse and fine detrital deposits.

Geophysical methods were applied over an assumed relatively uniform alluvial deposit of sandy gravels. Results did not show great differences from the available borehole data and contributed to define the contact between alluvial material and Blue Marls, but did not detect the silt layer. A few VES's were performed on the T2 terrace, but appear to have mis-identified the intermediate silt layer as Blue Marls. This emphasizes the need to calibrate a priori well-logged boreholes to verify VES.

Hydrogeological data lacked resolution and could be fitted to both models. Joint geostatistical inversion of multiple cross-hole hydraulic tests using the boundaries of the first model led to identification of a high transmissivity strip on the western side of the alluvial deposits, which can be caused by the need for a wider flow domain. It also identified a reduction in transmissivity downstream which may reflect the model response to the downstream disappearance of terrace T2. Lack of experience with geostatistical inversion led us to believe that these trends reflected natural variability. This case suggests that such results deserve closer attention.

Trenching was a good method to study the structure and lithology of the terrace deposits. It was especially useful in showing the linkages between terraces along the scarps. Despite its limitations below the water table, and its depth restrictions, this is a cheap and fast method for a preliminary investigation of the degree of heterogeneity of the alluvial deposits under study and allows unaltered sampling.

These experiences lead to the conclusion that the barrier location should have been based on study of a large area of ground, at least equivalent to the width of the alluvial plain and extending some hundreds of metres up and downstream from the previously selected site. This would have allowed identification of large-scale trends. There was no need to greatly increase the number of measurements of anyone type, but rather for a complete set of data obtained simultaneously using different geophysical and mechanical methods which can then be compared and contrasted. Specifically, down-hole geophysical logs (especially electromagnetic and gamma ray) would have been helpful. Also, extreme care should be taken during percussion drilling, especially during sampling, to avoid loss of the fine sediments and dispersion of the coarse portion.

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