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Aquifer Analogues
Gli analoghi di acquifero

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ABSTRACT - The reconstruction and interpretation of the architecture of subsurface reservoirs is currently assisted by the use of comparisons and correspondences with analogues, both in petroleum geology and in aquifer studies. This is due to the fact that in both cases, the reservoir/aquifer models rely on strongly incomplete bases of hard data, which are mostly point-like and widely spaced. In the last decades, different kinds and concepts of analogues have been used; among them the *present-day environments, processes, sediments and depositional units*, the *outcrop analogues*, the c*onceptual (hydro)-facies models* and the s*imulations and mathematical models*. In this paper, some of the major outcomes and pitfalls in the use of these analogue concepts are summarized and discussed, then some bearings on aquifer characterization and modelling are presented. The use of the different analogue concepts proved to be applicable mostly at the scale of the facies and depositional elements, the "local scale" of hydrogeologists, with applications in the field of the study of transport of contaminants. In this case, the volume and connectedness of the most permeable facies (in general open framework gravels) has been demonstrated to be the most effective element of heterogeneity to be recognized, mapped and modelled. At the scale of the depositional systems to basin fills, the "regional scale" of hydrogeologists, the application of knowledge collected from analogues to aquifer complex modelling, is still a problematic matter, due to the difficulty of comparing analogues with the poor image of the subsurface which is obtained by borehole data and geophysical surveys. At this scale, permeability and its geostatistical representation are always non-stationary. If the different-scale heterogeneities are considered in their hierarchic arrangement, non-stationarity must be assumed also at the scale of facies and depositional elements. The hierarchic approach to characterization of heterogeneity, based on analogue studies, will allow to account for non-stationarity through rank of the depositional units, providing a key to link the different physical scales, i.e. from local studies to regional studies.

KEY WORDS: Alluvial Sediments, Aquifer Analogues, Aquifer Characterization, Hydrostratigraphy, Groundwater.

RIASSUNTO - La ricostruzione e l'interpretazione dell'architettura dei complessi acquiferi sono frequentemente assistite dall'uso di paragoni e dalla ricerca di corrispondenze tra le successioni di sottosuolo e "analoghi" di diversa natura. Questa procedura è presa in prestito dalle metodologie sviluppate ed utilizzate per decenni nel campo della geologia del petrolio. La necessità di utilizzare analoghi fisici o concettuali per interpretare e modellare le successioni di sottosuolo, deriva dal fatto che queste ricostruzioni vengono eseguite utilizzando basi molto incomplete di dati quantitativi, normalmente puntiformi e molto spaziati, come sono i dati di pozzo, o scarsamente dettagliati, come i dati geofisici. Negli ultimi decenni sono stati sviluppati e studiati differenti tipi di "analogo di acquifero". Tra questi i più popolari sono 1) *le unità deposizionali degli ambienti attuali, con i relativi processi,* 2) *gli analoghi di affioramento,* 3) *i modelli concettuali di (idro)facies* e 4) *i modelli matematici sintetici e le simulazioni.* Il lavoro presenta succintamente i metodi, i risultati ed i limiti, nell'utilizzo di queste tipologie di analogo. Successivamente vengono prese in esame alcune ricadute di questi metodi sulla caratterizzazione di acquiferi ed acquitardi e sulla relativa modellazione. L'uso dei differenti concetti di analogo si è dimostrato utile principalmente alla scala delle facies e degli elementi deposizionali, indicata dagli idrogeologi come "scala locale". In questo caso l'applicazione è rivolta principalmente allo studio dei processi di trasporto dei contaminanti. Quasi tutti i lavori presentati concordano nel dimostrare che la connettività dei corpi caratterizzati dalla massima permeabilità (in genere facies ghiaiose a trama aperta) controlla in modo primario la ripartizione e/o concentrazione degli inquinanti. Il volume delle stesse unità è assai meno influente, quando la connettività è bassa. Lo studio degli analoghi consente di analizzare, mappare e modellare la distribuzione ed il comportamento di queste facies, alla scala locale. L'applicazione dei risultati degli studi basati sugli analoghi è molto più difficile alla "scala regionale" degli idrogeologi, cioè in merito ad ordini gerarchici compresi tra quello dei sistemi deposizionali ed il riempimento dei bacini sedimentari (sistemi e complessi acquiferi). I problemi risiedono principalmente nella scarsa possibilità di includere le proprietà idrodispersive ricavate dallo studio degli analoghi nelle ricostruzioni del sottosuolo, a causa delle difficoltà nell'eseguire confronti con queste ultime, che risultano

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generalmente poco dettagliate e molto incerte. Nel caso della geologia degli acquiferi, rispetto agli studi petroliferi, manca inoltre uno strumento geofisico sufficientemente efficace, al fine di tridimensionalizzare le ricostruzioni basate sui dati puntiformi di pozzo. Infatti gli strumenti quali georadar o tomografia elettrica, per quanto dotati di elevata risoluzione, non consentono di penetrare la tavola d'acqua, e non risultano quindi utilizzabili per studi regionali. A questa scala, la permeabilità, e la sua rappresentazione stocastica, sono non-stazionarie. Qualora i differenti tipi di eterogeneità alle diverse scale fisiche, venissero analizzati nella loro organizzazione gerarchica, potrebbe venire affrontato anche il problema, sostanzialmente rimosso fino ad ora, della non-stazionarietà alla scala locale, corrispondente all'ordine gerarchico delle facies e degli elementi deposizionali. L'approccio gerarchico alla caratterizzazione dell'eterogeneità, basato sullo studio degli analoghi, potrà permettere di studiare la non-stazionarietà delle proprietà idrauliche in relazione alla gerarchia delle unità deposizionali, più che in relazione alle loro dimensioni fisiche. Un approccio di questo tipo permetterebbe di ricongiungere le analisi sviluppate alle differenti scale fisiche (locale e regionale), e di introdurre ulteriori vincoli nelle ricostruzioni del sottosuolo, sulla base della conoscenza dei fattori che controllano lo sviluppo dei sistemi deposizionali (e delle unità idrostratigrafiche che ne derivano), e sulla stima di parametri utili a condizionare e/o convalidare le simulazioni ottenute.

PAROLE CHIAVE: Acque sotterranee, Analoghi di acquifero, Caratterizzazione degli acquiferi, Idrostratigrafia, Sedimenti alluvionali.

1. - INTRODUCTION

Progress towards a better characterization and modelling of porous groundwater reservoirs, requires the integration of several different methods and involve the use of multiple data-sets, consisting of both descriptive "soft" geological data and "hard" hydrological parameters. Since the last decades, a wide number of authors agreed that if the problem of the *influence of geological heterogeneity on groundwater flow and transport processes* is addressed, emphasis should be moved from the dominantly hydrological approach, which replaces the heterogeneous porous aquifers with homogeneous equivalent media, to the study of the architecture of the aquifer itself, at different scales (MIALL, 1996; ANDERSON, 1997; HUGGENBERGER & AIGNER, 1999; BRIDGE & HYNDMAN, 2004). In this latter perspective, the problem is almost the same as for the study and characterization of oil fields and reservoirs, and therefore the approach and the problems are in many ways similar. The general question is how to forecast the distribution of permeability of the subsurface rocks and sediments, within the highly complex and heterogeneous architecture of the continental and coastal depositional systems (which host most of the groundwater resources in porous media around the world). Similarly to petroleum geology, the study of the subsurface is mostly based on point-data, obtained from boreholes. A major difference, on the contrary, is given by the fact that geophysical data (both well logs and surface investigations) have been by far less commonly available for aquifer studies than for oil industry, until the last decade. This is not only because of shortage of investment in the field of groundwater, but it is also due to limitations of the most common reflection seismic tool, which gives satisfactory results at the widest basin scale only.

Since the very beginning of the modern geological studies for hydrocarbon exploitation, the subsurface investigation has been accompanied by analysis of the outcropping sediments, either those which were considered correlative to the buried reservoir formations, or those which were supposed to represent feasible *analogues* of the same (ALEXANDER, 1993). A similar approach to the study of aquifer analogues, to assist groundwater reservoir characterization, was introduced much later in hydrogeology, and became widespread since the last twenty years only. The increasing popularity of this approach arises some questions, that are summarized as follows:

1) what is an aquifer analogue, what kind of analogues have been used so far, what kind of information do analogue provide and which is the reliability of the outcomes of analogue studies with respect to knowledge of the subsurface geology and hydrostratigraphy?

2) do analogue help to address the problem of scale-dependence of hydrological parameters, when developing groundwater flow models?

The following chapters aim to address these two groups of questions, based on some literature and own experience; the purpose is to discuss these topics, without any presumption of presenting a thorough review of literature or suggesting any solution.

2. - THE AQUIFER ANALOGUE CONCEPT AND THE TYPOLOGY OF ANALOGUES

The concept of aquifer analogue has been borrowed from petroleum geology. It is generally considered as a tool to assist characterization of buried hydrostratigraphic units, both to determine typology and scale of heterogeneity which control the permeability distribution at the scale of the individual depositional units, and as a forecasting tool at the wide scale of basin stratigraphy; in this latter case the use of analogues must be coupled with detailed investigation of the subsurface, to allow for comparisons between the analogue and its buried equivalents (cf. GALLOWAY & HOBDAY, 1983; ANDERSON, 1989; MIALL, 1996; BRIDGE, 2003). The concept has thus become a part of the routine methodology for aquifer characterization (Huggenberger & Aigner, 1999).

In the recent literature some different kinds of analogues to aquifer architecture have been proposed (tab. 1).

2.1. - PRESENT-DAY ENVIRONMENTS, PROCESSES, SEDIMENTS AND DEPOSITIONAL UNITS

The study of sediments forming in their depositional settings has been developed mostly in the alluvial environments. The former qualitative process-oriented studies and models (e.g. Cant & Walker, 1978; Bluck, 1979, 1982; Schumm, 1981; Crowley, 1983; Miall, 1985; Orton & Reading, 1993), have been replaced by studies oriented to quantitative modelling of depositional units, which incorporate in a hierarchic frame, geometry of the elementary units, compositional, textural and structural properties, allowing to map porosity and permeability, generally at the scale ranging from facies to depositional elements (Miall, 1996, with references therein). For instance, Brayshaw *et alii* (1996), reviewed the effectiveness of texture and fabric on porosity and permeability distribution in laminated sands and gravels, from the study of present-day alluvial deposits. In the case of cross-sets, they concluded that the distribution of open-framework gravel is the most influent variable and that porosity and permeability are greatest in the upper part of the foresets and lowest in the bottomset, due to grain-size segregation. Hydraulic conductivity of Holocene cross-bedded alluvial gravel sand units had been already shown to be anisotropic, with the maximum component parallel to cross strata in tabular sets, and parallel to the trough axis in trough cross-bedded sets (Weber *et alii*, 1972; Pryor, 1973). The study of the 3-D architecture of large, mid-channel sand braid bars, from the Jamuna River (one of the largest, low sinuosity, moderately braided, sand-bed rivers of the world, in Bangladesh), allowed Best *et alii* (2003), to present a model of bar architecture and evolution, which can be considered of general validity, and applies to similar and smaller river-channel settings. This study clearly depicted the internal architecture of this kind of fluvial element, presenting an integrated data-set which links large-scale depositional processes and subsurface alluvial architecture. Relevant, as an analogue to aquifer heterogeneity, is the distribution and preservation potential of mud drapes, i.e. of dm-thick and tens of metres wide units, which have been shown to deposit at the bar lee and, during falling-stage, on the sheltered flanks of the bar itself, interfingering with dune cross-laminated sands. This work relied on integration of data obtained from the study of trenches, cores and ground penetrating radar (GPR) surveys, to characterize heterogeneity of such a depositional body. A very simple scheme of 4 radar facies, including mud drapes, is presented. Any scheme like that is potentially of help for interpretation of radar images of the non-saturated sediments in aquifer complexes. At last this study provides also an example of a process-oriented study, because the Authors were able to monitor bar evolution (on site and by

Tab. 1 - *Type and scale of aquifer analogues, with references to selected examples from recent literature.*
- Tipo e scala degli analoghi di acquifero, con riferimento ad esempi selezionati dalla bibliografia recente.

Analogue type	Information	Scale/ Hierarchy	Examples
Present-day environments, sediments and depositional units	Processes controlling poro-perm properties; textures, structures and architecture of elementary depositional bodies; hierarchy of depositional units and boundaries; 3-D models	Facies to depositional element	Weber *et alii*, 1972; Pryor, 1973; Cant & Walker, 1978; Bluck, 1979, 1982; Schumm, 1981; Crowley, 1983; Miall, 1985; Orton & Reading, 1993 Brayshaw *et alii*,1996; Best *et alii*, 2003; Lunt & Bridge, 2004; Lunt *et alii* 2004a, 2004 b;
Outcrop analogues	Geometry of sedimentary units; internal architecture; facies assemblage; hierarchy of depositional units and boundaries; porosity and permeability distribution	Facies to depositional system	Siegentahler & Huggenberger, 1992; Huggenberger, 1993; Diaz Molina *et alii*, 1995; Lanz *et alii*, 1996; Miall, 1996; Egglestone *et alii*, 1996; Webb & Anderson, 1996; Smith & Jol, 1997; Webb & Davis, 1998; Aigner *et alii*, 1999; Anderson *et alii* ,1999; Asprion & Aigner, 1999; Beres *et alii*, 1999; Bersezio *et alii*, 1999a; Klingbeil *et alii*, 1999; Hornung & Aigner, 1999; Heinz & Aigner, 2003a, 2003b; Heinz *et alii*, 2003; La Penna & Rizzo, 2003; Felletti *et alii*, 2004; Zappa *et alii*, 2004; Bersezio *et alii*, this volume
Conceptual (hydro)-facies models	Vertical facies associations and trends; conceptual distribution of pervious to non pervious units	Facies to depositional systems	Walker, 1984; Anderson, 1989; Phillips & Wilson, 1989; Poeter & Gaylord, 1991; Miall, 1996.
Simulations and mathematical models	Probabilistic distribution of elementary facies, porosity and permeability; estimates of flow properties	Facies to depositional element	Bierkens & Weerts, 1994; Jussel *et alii*, 1994a, 1994b; Webb, 1994; Koltermann & Gorelick, 1996; Whittaker & Teutsch, 1996; Carle *et alii*, 1998; Webb & Davis, 1998; Anderson *et alii*, 1999; Felletti *et alii*, 2004.

recurrently shot aerial views), identifying the formative process of different packages of braid-bar sedimentation. The resulting classification of different depositional styles (including upstream, downstream and lateral accretion of bar, bar-margin slipface, bar-top accretion, channel vertical accretion and low-stage mud drapes) provides a valuable analogue for characterization of sandy alluvial aquifers.

At present, a lot of interest has moved also to the study of the coarse-grained, alluvial aquifer analogues. Among many others, quantitative 3-D models of channel belt deposits of gravelly braided rivers, have been presented by LUNT & BRIDGE (2004) and LUNT *et alii* (2004a, 2004b), based on the study of Sagavanirktok River (Alaska). The methodology is very similar to that shown before (sediment description based on cores, natural exposures and trenches, GPR surveys and study of frequently repeated aerial photos to unravel evolution of channels and bars). The results seem to provide a general model, which may be applied to the analysis of different-scale braided river deposits, because the Authors demonstrated the relationship between the dimensions of stratasets, bedforms and channels and the scale of the river setting. The model represents in 3-D the shape of the deposits, which show a hierarchy of different-scale strata-sets, formed by different scale bedforms. In this framework, the distribution of the grain-size, and the consequent estimates of porosity and permeability, have been correlated with the different-scale strata-sets. The highest permeabilities (open framework gravels) revealed to be common in the lowest part of the simple, large-scale sets of the unit bars, but also at the base of the compound sets of large-scale strata which form as a consequence of migration of compound bars. On the other hand, intermediate permeability (sandy gravel and gravelly sand) characterize the major part of the compound sets of large-scale strata formed on compound bars, which show variable grain-size trends, as well as of the large-scale simple sets of unit bars and channel-fills, which are frequently characterized by fining upward trends. The low rank units, such as the medium-scale packages of cross laminae resulting from dune migration and the lowest-scale cross-sets formed by ripples, show low permeability (at least one order of magnitude lower than the previous ones), being formed by sand and sand/silt textures. The sandy-silt units, eventually with soil profile, may also form dm-thick caps above the largest-scale channel-belt deposits, but their preservation potential is generally low.

The few examples here reviewed, among the many others, indicate that this kind of aquifer analogue is potentially worth for quantitative characterization of heterogeneity of real aquifers. For example, the eventual link between some morphological-textural parameters and the river depositional processes, would provide a tool for improvement of the still problematic process-oriented mathematical models (KOLTERMANN & GORELICK, 1996; ANDERSON, 1997 with references therein; BRIDGE, 2003 for discussion of pitfalls). On the other hand, any quantitative 3-D model which is capable to describe the spatial variation of textural properties of sedimentary units within their hierarchic framework, provides additional constraints to geostatistical simulations of aquifer structure. In this perspective it is very important to determine the relationship between textures (as a proxy for porosity and permeability) and thickness of different scales of stratasets, because this could guide the geostatistical modelling and the eventual choice of the location of borehole placements (LUNT *et alii*, 2004b).

2.2. - OUTCROP ANALOGUES

This is the most widely used type of analogue, both in oil industry and in hydrogeological applications. In the latter case, the 2-D or 3-D exposures of Quaternary unconsolidated sediments are more frequently studied than the ancient analogues from the rock record. This is quite obviously due to the necessity of obtaining estimates and/or measurements of grain-size, porosity and permeability which are comparable to those of the real aquifers. In fact these are mostly hosted in the Plio-Quaternary basin fills, and thus are characterized by a poor diagenetic overprint, because they underwent a less complicated history of burial-exhumation than the rocks that are exposed in the mountain chains. At present the study of outcrop analogues is oriented to 3-D exposures, which should allow the development of models which account for the complex 3-D path of groundwater flow, including tortuosity at the scale of granules and connectivity of the most (and least) permeable sediment packages. Unfortunately this kind of exposure is rare in the Quaternary unconsolidated sequences of the wide plains of Europe, because natural cuts are relatively uncommon, and can be looked for only at the terrace scarps of the fluvial plains or in some uplifted successions (spectacular cases involve Quaternary successions along the Italian coastlines, at the Apennine fronts and within intermountain basins). Artificial 3-D exposures at gravel and sand pits are in some cases excellent, but they are ephemeral through time and usually show a limited thickness of sediments, because of emergence of the water table into the excavations. Despite these limitations, a lot of outcrop analogue studies have been proposed so far.

The information which can be obtained by these studies is very differentiated and encompasses potentially a wide range of physical scales and stratigraphic hierarchies (respectively from cm to Km and from laminasets to depositional systems and even depositional sequences, in the case of large or composite outcrops). In any case, due to physical limitation in width and height of exposures, the most proper scale of application of outcrop analogue studies, is that ranging from facies to stacks of depositional elements (MIALL, 1996; AIGNER *et alii*, 1999; HEINZ & AIGNER, 2003a). This kind of studies aims to describe and model the facies units at some specific site (EGGLESTONE *et alii*, 1996; ANDERSON *et alii*, 1999; KLINGBEIL *et alii*, 1999; HORNUNG & AIGNER, 1999; ZAPPA *et alii*, 2004 among many others), or to characterize facies units and depositional elements at several different sites, in order to collect statistically manageable data-sets (HEINZ & AIGNER, 2003b; HEINZ *et alii*, 2003) or to characterize the depositional architecture at the intermediate to wide scale of the individual depositional elements and of their associations (SIEGENTAHLER & HUGGENBERGER, 1992; DIAZ-MOLINA *et alii*, 1995; HORNUNG & AIGNER, 1999; BERSEZIO *et alii*, 1999a; FELLETTI *et alii*, 2004 among a vast amount of other works). All these studies provide at first the description of the distribution of porosity and permeability through the different-scale units, within their hierarchic association and for different depositional settings. This is the most important contribution of sedimentary geology to aquifer characterization, as it has been recommended for example by WEBB & DAVIS (1998). In fact, at the operative scale of studies based on outcrop analogues, the most direct application is to the analysis of transport of contaminants at the local scale, more than to the study of regional flow problems.

The measurements of permeability are obtained by 1) the use of field minipermeameters, which show many problems of reproducibility of outcomes in rocks, are hardly used in unconsolidated sediments and require a large number of measurements to yield a statistical representation of the permeability distribution across the outcrop (HORNUNG & AIGNER, 1999), 2) laboratory permeability analyses on undisturbed samples, that are very difficult to collect, or 3) estimates based on empirical formulas, like Kozeny-Karman or Hazen equations (references in BEAR, 1979), which use textural parameters like D_{10} or D_e, obtained by the grain-size curves. In the case of gravels and sandy gravels, an important pitfall in the use of the grain-size proxy in formulas for permeability estimation is represented by the need for very large volumes of sediments to be analysed in order to obtain significant curves. Most Authors use permeability data from literature in this case. Some attempts to obtain estimates of grain-size and permeability by the use of image analysis of very detailed photos have been proposed, but the results were not considered satisfactory (BERSEZIO *et alii*, 1999b). Moreover, the estimates of permeability based on grain-size determinations yield values which are average values on the volume of the samples, and do not account for grain-size segregation within a sediment packet or a facies, for instance due to lamination, grading, clustering or changes in packing (BRAYSHAW *et alii*, 1996). For these reasons the permeability estimates that are generally attributed to the individual facies should be managed carefully because they represent only a crude approximation to the order of magnitude of this physical property. Therefore, the qualitative description and localization of the most permeable sediment packets (usually open framework gravels which are avenues for transport of contaminants, mostly in the case of light immiscible fluids floating above water; BRAYSHAW *et alii*, 1996), is at present the principal outcome of outcrop analogue studies. Differently, how to quantify and model the same properties, from this starting point, are still open questions, which pose several problems. The most widespread approach is the multidisciplinary combination of sedimentological, geophysical and hydrogeological description of analogues with the geostatistical methods to simulate the distribution of permeability of some individual units through the analogue volume and with the numerical upscaling of the conductivity and numerical modelling of flow, to trace the movement of imaginary particles through the representation of the aquifer analogue (see for instance WEBB & ANDERSON, 1996; WEBB & DAVIS, 1998; ANDERSON *et alii*, 1999; HEINZ *et alii*, 2003; FELLETTI *et alii*, 2004 with the many references quoted by the Authors). ANDERSON *et alii* (1999), mapped 11 lithofacies, which were clustered into 6 hydrofacies by permeability estimates based on empirical formulas, into a 50 by 60 by 3.3 m thick outcrop analogue of gravelly braided deposits. As many other Authors, they combined sedimentological analysis of the exposures, with sedimentography of photomosaics and GPR profiles, to derive a 3-D geostatistical simulation of the volume, in which geometry of architectural elements and distribution of hydrofacies were reconstructed. An hydrogeological model was developed, including particle tracking through the simulated volume. The model showed that the high hydraulic conductivity of the most permeable hydrofacies (open-work gravel) has a significant impact on the effective hydraulic conductivity of the flow field, despite the low abundance of these deposits (4%). A comparable result has been obtained by ZAPPA *et alii* (2004), in the study of some smaller volumes, representative of individual sand-gravel, alluvial mesoforms consisting of sand dunes, gravel sheets and gravelly-sand elementary bars. In the latter case the open-work gravel represented less than 2% of the investigated volume, but due to good interconnectedness was able to generate preferential flow paths, raising also the hydraulic conductivity of the entire model block. Particle tracking experiments allowed ANDERSON *et alii* (1999) to show that preferential transport occurs within some connected open-work gravel units, but the geostatistical simulation of the volume was also affected by a notable degree of uncertainty in the shape and extent of these connected packages. Differently, in the case of larger volumes of comparable sediments, JUSSEL *et alii* (1994a) could argue that the same most permeable hydrofacies would not have a primary effect on the conductivity of the flow field. Presumably these differences can be ascribed either to the real different connectedness of the hydrofacies in the various analogues, or to variable capability of the different-scale simulations to capture connections between hydrofacies. This depends on the different detail of the studies and on the different simulation methods. It is apparent that in the less detailed models of large volumes of sediments, the estimated connectivity is higher and the effects of specific sedimentary packets are smoothed or averaged. One could conclude that: 1) the description of volume, distribution and connectedness of the most permeable hydrofacies is a goal of the outcrop analogue studies, of primary interest to hydrogeologists; 2) taking into account the scale dependence of these properties and also of their representation by different models, it seems still important the development of proper procedures for upscaling the conductivity through the physical scales and the hierarchy of sedimentary units.

As the aforementioned examples show, the study of outcrop analogues is often integrated by the employment of geophysical tools. The most detailed results, in the non-saturated zone, are yielded by the GPR, which is currently used to add 3-D information at the available exposures (HUGGENBERGER, 1993; SMITH & JOL, 1997; ASPRION & AIGNER, 1999; BERES *et alii*, 1999; HEINZ & AIGNER, 2003b). Other tools can be used, with different detail, like the geo-electrical tomography (LA PENNA & RIZZO, 2003) or the shallow, high resolution 2-D and 3-D seismic reflection surveys (LANZ *et alii*, 1996). In turn, outcrop studies allow for calibration of the geophysical outcomes, providing improvements for these techniques and for their applications to aquifer characterization and hydrostratigraphy. From the scale of the depositional elements to the basin-fill, well calibrated geophysical data, combined with borehole and well data, represent the unique medium to compare the outcrop analogues with their buried counterparts. Much effort has to be done on this topic, in order to be able to obtain a satisfactory integration of surface and subsurface data, at the proper scales. For instance in the Quaternary Agri basin, BERSEZIO *et alii* (this volume), compared outcrop analogue analysis of large exposures with the electrical tomography image of the equivalent buried aquifer structure. The attempt revealed satisfactory only at the scale of the large aquifer units, but no heterogeneity data could be imported from the outcrop model into the subsurface model, due to lack of resolution of the subsurface reconstruction. At present, either the investigation depth of the high resolution methods (GPR, electrical tomography) is too low for regional correlations with analogues, or the resolution is too low for the deep-penetrating methods (vertical electrical soundings for instance) at the same purpose.

2.3. - CONCEPTUAL (HYDRO)-FACIES MODELS

In a very broad sense, also some of the popular conceptual facies models (WALKER, 1984) can be considered as aquifer analogues, because they provide archetypal examples for interpretations and comparisons (ALEXANDER, 1993). At the scale of a hydrogeological site investigation, a hydrofacies has been defined by POETER & GAYLORD (1991), as a unit with relatively homogeneous hydraulic properties and with specific connectedness of the materials, controlling funnelling of contaminants. ANDERSON (1989), defined a hydrofacies as a homogeneous but anisotropic unit, that is hydrogeologically meaningful for field experiments and modelling. It is also expected to have an horizontal correlation length that is larger than the vertical correlation length. It should help to interpret and quantify heterogeneity of depositional elements and larger sediment units. In this way, the architectural element analysis (MIALL, 1996, with references therein), can be translated and scaled-up into a qualitative and/or quantitative hydrofacies or hydrostratigraphic model. PHILLIPS & WILSON (1989), considered a hydrofacies model like a model of the permeability architecture of the investigated sediment volume. It would incorporate the spatial dimensions of the architectural elements, the spatial statistics of the permeabilities of the component elemental units (hydrofacies) and their relative frequencies, and the nature of the permeability transitions between the elements. These concepts are now of widespread use for description and qualitative use in the study of aquifers, but the quantitative use of hydrofacies models is still very difficult at present, and probably is not so efficient as it could be thought (see discussion in ANDERSON, 1997).

2.4. - SIMULATIONS AND MATHEMATICAL MODELS

The simulation of aquifer heterogeneity, using geostatistical techniques, provides mathematical models aimed to approximate the real aquifer architectures, either by conditional simulation constrained to some outcrop analogue or to a field of wells, or by imitation of processes or depositional structures (review by KOLTERMANN & GORELICK, 1996; WEBB & DAVIS, 1998). In some way these analogue models can be compared with the physical models, which are realized by flume experiments, providing 3-D virtual images of the sedimentary bodies, which respond to the rules and parameters chosen by the operator. The imitation of structures can be directly derived from the study of outcrops, as it has been partly discussed above, or from borehole data, or can be linked to the formative processes of sediments. Examples are provided by BIERKENS & WEERTS (1994), JUSSEL *et alii* (1994a, 1994b), WHITTAKER & TEUTSCH (1996), ANDERSON *et alii* (1999), FELLETTI *et alii* (2004). ANDERSON *et alii* (1999) simulated a synthetic braided stream deposit, based on the data-set obtained from two river systems, using the algorithm for braided stream facies imitation which was provided by WEBB (1994). Then the Authors developed a hydrogeological model by assigning estimates of hydraulic conductivity to the hydrofacies. The comparison between the outcomes of a flow model and a particle tracking model relative to the synthetic deposit and the results of similar models obtained with the geostatistical simulation of a real braided stream deposit, allowed to show that the scale of the simulation affects the outcomes, presumably enhancing the connectedness of the most permeable units in the less detailed synthetic model. Another kind of model uses the Markovian approach to conditional simulation of hydrofacies architecture, based on transition probability, i.e. predicting the spatial change of discrete variables (for example determining the probability of transition from the discrete variable "sand facies" to the "mud facies") and has been applied to alluvial aquifers (CARLE *et alii*, 1998, with references therein). This method has the advantage of capturing heterogeneity at fine scales, provided that the input data are adequate and that a sufficient knowledge of the 3-D architecture is already available, for instance from an outcrop or a flume experiment or a presently evolving depositional unit. All these methods produce multiple realizations, that are simulations of real or synthetic sedimentary bodies, but are difficultly compared with the observed data. Therefore they are affected by uncertainty that, however, can be quantified. Some outcomes are considered unrealistic (see discussion in BRIDGE, 2003), but insights on the behaviour of simplified geological architectures are in general of help to understand the real aquifers. Anyway, when using geostatistical models and running computer models, the sedimentary geologists and hydrogeologists should remember that the simulation and the real sediments are not interchangeable, and that the hydrogeological behaviour of the model cannot be directly attributed to any real case in study. This statement leads again to the general problem of how to connect knowledge collected from the analogues with the geological and hydraulic properties of the buried aquifers. The most important point is how to match the different scale and detail of the available observations and measurements, and how to account for dependence of hydraulic properties from various orders of scales and sedimentary hierarchies.

3. - AQUIFER ANALOGUES, SCALE OF DATA AND SCALE DEPENDENCE OF HYDRAULIC PROPERTIES

It is well known that permeability is a scale-dependent property. Within an individual cluster of grains, permeability depends primarily on the physical and chemical interactions between the mineral and the fluid phases, involving the size, shape and mineralogy of grains and fluid composition. Looking at a little larger volume than pores, permeability is a property of the assemblage, in which textural and structural properties determine the tortuosity of the flow paths, for example through an individual facies. In a large-volume represented by a facies assemblage (a depositional element, for instance), the connectedness between most and least permeable sediment packages (or facies) determines the effectiveness of preferential flow paths (or barriers) and also the average behaviour of the aquifer unit as a whole. From this scale, up to the basin-fill scale (which is the regional scale of aquifer complexes), permeability varies through space as a consequence of the different types of assemblage of different-scale sediment units. This behaviour can be also described in other terms, stating that permeability varies as a consequence of the hierarchic assemblage of the depositional units, that determines the volume and interconnectedness of high-permeable units, the continuity of permeability barriers and also the average hydraulic behaviour of an aquifer. Several examples of the hierarchical assemblage of different-rank permeability units have been described in analogues, as it has been summarized in the previous chapter. Therefore, the study of analogues demonstrates this statement and could allow to develop quantitative models of aquifer heterogeneity, which locate permeability changes (behaviour of a continuous variable) within the hierarchy of the assemblage of facies (which represent a discrete variable) into sedimentary units of increasing rank. This would have some impact on

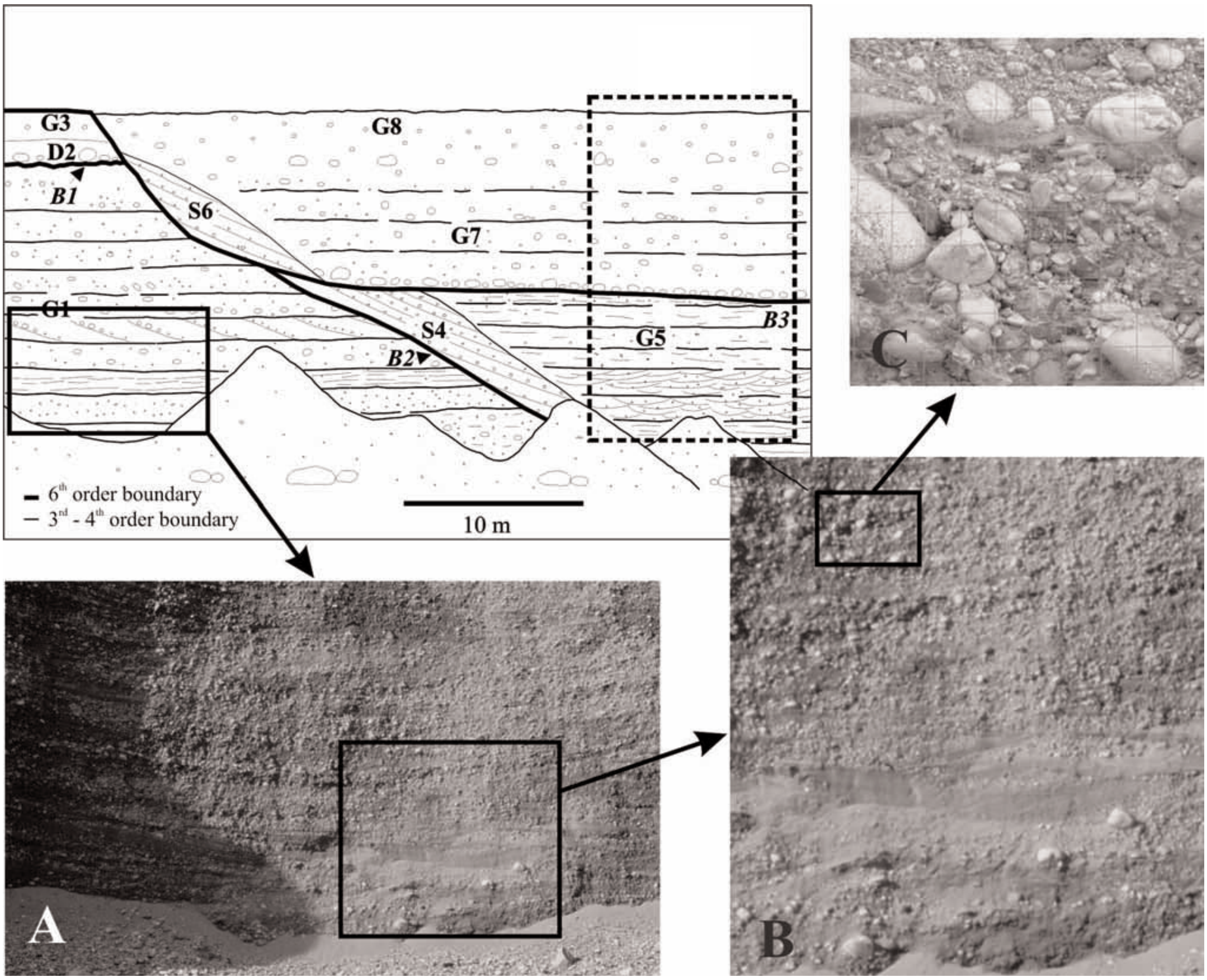

Fig. 1 - Example of aquifer analogue in the Pleistocene glacio-fluvial sediments of the Ticino Valley. The hierarchic internal architecture and assemblage of the stratigraphic units (G1 - G8, S4 - S5, D2) and bounding surfaces (B1 - B3), control the non-steadiness of permeability distribution at the physical scale of the outcrop analogue. The different rank units represented in pictures A - C are characterized by variations of hydraulic conductivity, from the rank of the depositional elements (A) to the grain assemblage within a facies (C).

- Esempio di analogo di acquifero tratto dalla successione fluvio-glaciale pleistocenica della Valle del Ticino. La gerarchia dell'organizzazione architetturale e l'associazione delle unità stratigrafiche (G1, G8, S4, S5, D2) e delle superfici-limite (B1 - B3) controllano la non-stazionarietà della distribuzione delle permeabilità, alla scala fisica dell'analogo. Le unità di ordine gerarchico differente, rappresentate nei riquadri, sono caratterizzate da variazioni di conduttività idraulica, dall'ordine degli elementi deposizionali (A) a quello dell'assemblaggio dei granuli in una facies (C).

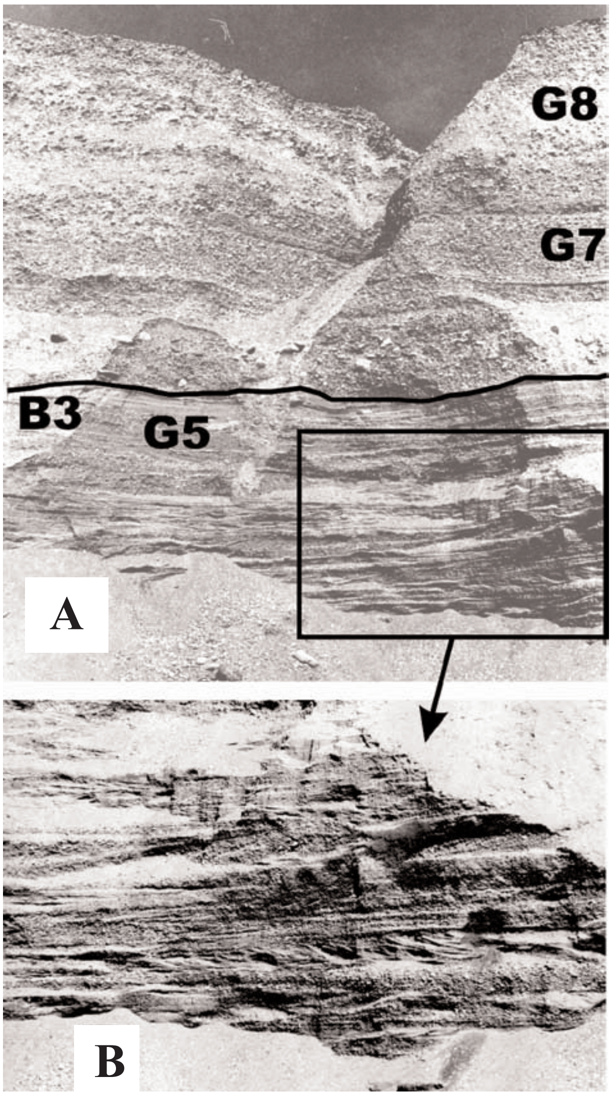

Fig. 2 - Aquifer analogue in the Pleistocene glacio-fluvial sediments of the Ticino Valley; picture A is framed in fig. 1.
A) The stacking pattern of cross-laminated sandy-gravel, planar to horizontal laminated gravels, and trough cross-laminated sands (unit G5), massive sandy gravels and planar to horizontal laminated gravels (unit G7), massive sandy gravels (unit G8), determines the heterogeneity of the aquifer analogue, controlling permeability distribution at the rank of the depositional system. The vertical and horizontal assemblage of these units (fig. 1) determines the non-stationary behaviour of permeability at this physical scale and rank.
B) The repetitive stacking of facies with different permeability within unit G5, suggests non-steadiness also at this scale. Therefore, the hierarchic assemblage of different-scale sediment units ultimately controls the permeability distribution and determines the non-stationary behaviour of the ensemble.
- *Analogo di acquifero nella successione fluvio-glaciale pleistocenica della Valle del Ticino. L'ubicazione dell'immagine A è riportata in fig.1.*
A) L'appilamento di diverse facies (ghiaie sabbiose a laminazione incrociata, ghiaie a laminazione planare ed orizzontale, sabbie a laminazione obliqua concava a grande scala - unità G5 - ghiaie sabbiose massive e ghiaie a laminazione orizzontale - unità G7 - ghiaie sabbiose massive - unità G8) determina l'eterogeneità dell'analogo di acquifero e controlla la distribuzione della permeabilità alla scala del sistema deposizionale. L'associazione verticale ed orizzontale di queste unità (fig.1) determina il comportamento non stazionario della permeabilità a questa scala fisica ed a questo ordine gerarchico.
B) L'appilamento ripetitivo di facies con differenti permeabilità, all'nterno dell'unità G5 suggerisce non stazionarietà anche a questa scala. Perciò l'associazione gerarchica di unità deposizionali a scale diverse esercita il controllo principale sulla distribuzione delle permeabilità e determina il comportamento non stazionario dell'insieme.

the geostatistical approach to aquifer simulation and hydrogeological reconstruction, helping to replace the common approach to a randomly distributed property with the representation of a hierarchically ordered distribution of permeability, which is typical of ordered architectures, if the proper scales are considered. In theory, such an approach would also lead to include the qualitative information about geological controls on deposition and stratigraphic evolution into the stochastic models, in order to add constraints to forecasting of aquifer architecture. Some attempts towards the development of a similar kind of methodology have been already presented, following the hierarchy concept of Miall (1991), by Aigner *et alii* (1999) and Heinz & Aigner (2003a), who called this approach "hierarchical dynamic stratigraphy". In figure 1 and figure 2, an example from an outcrop analogue of Pleistocene glacio-fluvial sediments in the Ticino Valley is presented. Both pictures show how in this alluvial aquifer analogue, the hierarchic assemblage of different rank depositional units determines the repetitive assemblage of high and low permeable gravel, gravelly sand and sand units, controlling their volume and the number and extent of their connections.

Another important point concerns the scale of analysis, which is critical for the development of stochastic models of aquifer heterogeneity, based on aquifer analogues (mostly of the outcrop type). Most of the stochastic representations of aquifer heterogeneity assume that these systems are stationary at the local scale, like the outcrop scale, and non-stationary at the regional scale (aquifer systems and complexes). Anderson (1997, with references) discussed this point, presenting several literature examples which demonstrate that the assumption of stationarity may be appropriate at the local scale (i.e. smaller than that of the contaminant plumes to be modelled) only in the cases of relatively homogeneous sediment units, but even then, heterogeneities can affect transport processes. The example in fig. 1 and fig. 2 shows that multiple-scale heterogeneities, which are hierarchically ordered, affect the local-scale portion of an aquifer analogue that is exposed at one outcrop. Therefore, a general stochastic model for a natural heterogeneous medium must be non-stationary in space, at any scale, since accounting for the spatial distribution of hydrogeologic properties requires location-dependent probabilities and statistics. This statement links the physical scale of the real heterogeneity of the aquifer to its stochastic representation (for instance, a geostatistical simulation). The next step could be that of relating nonstationarity to the hierarchy, or rank, of the depositional units, which is not necessarily represented by their physical scale, allowing to incorporate the causal (genetic) link between different orders of heterogeneity within the aquifer analogue, into the models. A proper upscaling procedure would then be able to capture the hierarchic arrangement of the most effective heterogeneities (ZAPPA *et alii*, 2004), in order to determine the extent and location of the most permeable hydrofacies, but also to evaluate the average groundwater flow properties through the real aquifers at the regional scale.

4. - CONCLUSION

The development of a hierarchical approach to aquifer characterization, based on different types of analogues, seems a promising field for future research. The identification of the architectural elements and of their bounding surfaces in outcrops should provide a key for comparisons with the buried aquifers and for the upscaling procedures.

At the scale and rank of individual facies or elementary facies associations (i.e. alluvial bars, minor channel fills, delta foresets etc.) the textural and geometrical components of heterogeneity can be quantified and modelled by sedimentography, statistical analysis and 3D geostatistical simulations, based on *outcrop analogues* and *present-day environments, processes, sediments and depositional units.* This would allow to assess which are the most influent properties in determining hydraulic conductivity at this scale. Then, 2D and 3D flow models can be obtained using the geostatistical models of peculiar sediment volumes, which allow to quantify incertitude on the realizations. At this purpose a major problem working with Quaternary analogues is that of measurement of permeability, which is hardly done by minipermeameters in unconsolidated sediments, while the use of laboratory permeametry on oriented and “undisturbed” samples provides only a proxy for permeability magnitude in the 3 directions of space. The “grain assemblage-scale” measurements can be therefore scaled-up numerically, to obtain the components of the equivalent conductivity tensor (K_{eq}) and the anisotropy ratio at the facies scale. Validation of the geostatistical sediment model can be obtained by direct comparison with different sections cut into the real sediment volumes of the outcrop analogue, by the analyses of trenches in present-day sediments and by comparison with GPR images. Validation of the outcomes of the K_{eq} computations can be obtained by comparisons with results of *in situ* infiltration tests. The quantification of sediment properties at the facies to facies-assemblage rank is therefore inclusive of hard data and soft data, whose uncertainty could be assessed. These can be used as input data for a similar analysis and modelling procedure, that can be repeated at the immediately higher hierarchic order of an architectural or depositional element, from the same outcrop analogue, or within a comparable buried unit. The influence on hydraulic conductivity of facies assemblage and connectivity can thus be estimated, and the study of anisotropy will allow to recognize the preferential water flow paths, vs. the averaging effect due to the different styles of stacking patterns. The quantification of incertitude at this scale is based on statistical and probabilistic analysis (probability of facies transitions vs. estimates of facies abundances and their corresponding K values). The use of these analogue models to scale-up or to distribute the computed properties at the rank of depositional systems (aquifer systems) to basin fills (aquifer complexes) is a difficult matter, because it requires comparisons with geophysical, borehole and well-data, which offer a relatively poor proxy of the real aquifer complexes. This step will require a new approach to improve the geological prediction of sediment geometries and facies variations in the subsurface. Calibration of the geophysical tools with analogue data will probably provide also some improvement of their efficiency.

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