Dealing with spatial heterogeneity

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Abstract Heterogeneity can be dealt with by defining homogeneous equivalent properties, known as averaging, or by trying to describe the spatial variability of the rock properties from geologic observations and local measurements. The techniques available for these descriptions are mostly continuous Geostatistical models, or discontinuous facies models such as the Boolean, Indicator or Gaussian-Threshold models and the Markov chain model. These facies models are better suited to treating issues of rock strata connectivity, e.g. buried high permeability channels or low permeability barriers, which greatly affect flow and, above all, transport in aquifers. Genetic models provide new ways to incorporate more geology into the facies description, an approach that has been well developed in the oil industry, but not enough in hydrogeology. The conclusion is that future work should be focused on improving the facies models, comparing them, and designing new in situ testing procedures (including geophysics) that would help identify the facies geometry and properties. A world-wide catalog of aquifer facies geometry and properties, which could combine site genesis and description with methods used to assess the system, would be of great value for practical applications.

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Résumé On peut aborder le problème de l'hétérogénéité en s'efforçant de définir une perméabilité équivalente homogène, par prise de moyenne, ou au contraire en décrivant la variation dans l'espace des propriétés des roches à partir des observations géologiques et des mesures locales. Les techniques disponibles pour une telle description sont soit continues, comme l'approche Géostatistique, soit discontinues, comme les modèles de faciès, Booléens, ou bien par Indicatrices ou Gaussiennes Seuillées, ou enfin Markoviens. Ces modèles de faciès sont mieux capables de prendre en compte la connectivité des strates géologiques, telles que les chenaux enfouis à forte perméabilité, ou au contraire les faciès fins de barrières de perméabilité, qui ont une influence importante sur les écoulement, et, plus encore, sur le transport. Les modèles génétiques récemment apparus ont la capacité de mieux incorporer dans les modèles de faciès les observations géologiques, chose courante dans l'industrie pétrolière, mais insuffisamment développée en hydrogéologie. On conclut que les travaux de recherche ultérieurs devraient s'attacher à développer les modèles de faciès, à les comparer entre eux, et à mettre au point de nouvelles méthodes d'essais in situ, comprenant les méthodes géophysiques, capables de reconnaître la géométrie et les propriétés des faciès. La constitution d'un catalogue mondial de la géométrie et des propriétés des faciès aquifères, ainsi que des méthodes de reconnaissance utilisées pour arriver à la détermination de ces systèmes, serait d'une grande importance pratique pour les applications.

Resumen La heterogeneidad se puede manejar por medio de la definición de características homogéneas equivalentes, conocidas como promediar o tratando de describir la variabilidad espacial de las características de las rocas a partir de observaciones geológicas y medidas locales. Las técnicas disponibles para estas descripciones son generalmente modelos geoestadísticos continuos o modelos de facies discontinuos como los modelos Boolean, de Indicador o de umbral de Gaussian y el modelo de cadena de Markow. Estos modelos de facies son mas adecuados para tratar la conectvidad de estratos geológicos (por ejemplo canales de alta permeabilidad enterrados o barreras de baja permeabilidad que tienen efectos importantes sobre el flujo y especialmente sobre el transporte en los acuíferos. Los modelos genéticos ofrecen

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nuevas formas de incorporar más geología en las descripciones de facies, un enfoque que está bien desarollado en la industria petrolera, pero insuficientemente en la hidrogeología. Se concluye que los trabajos futuros deberían estar más enfocados en mejorar los modelos de facies, en establecer comparaciones y en diseñar nuevos procedimientos para pruebas in-situ (incuyendo la geofísica) que pueden ayudar a identificar la geometría de las facies y sus propiedades. Un catálogo global de la geometría de las facies de los acuíferos y sus características, que podría combinar la génesis de los sitios y descripciones de los métodos utilizados para evaluar el sistema, sería de gran valor para las aplicaciones prácticas.

Introduction

The word "Hydrogeology" can be understood as a combination of "hydraulics" and "geology." Hydraulics is a relatively simple science; we know, at least in principle, the governing hydraulic equations and can solve them, analytically or numerically, given the geometry of the system, boundary conditions, etc. Geology is more complex: it refers not only to the description of what the system looks like today, its properties in space, etc., but also to the history of its formation, because geologists have been trained to accept that one needs to understand the succession of complex processes involved in the creation and modification through time of the natural objects that one is trying to describe. To understand this complexity, geologists have a limited number of clues or data, whose interpretation requires several assumptions and may lead to alternative solutions. Geology also includes a set of disciplines whose contribution is needed to study or describe the system: sedimentology, tectonics, geophysics, geochemistry, age dating, etc. "Hydrogeology" is thus the science where the two are combined: finding the solution of the flow (and transport) equations in a complex, only partly identified, geologic system.

If the world were homogeneous, i.e. if the rock properties were constant in space, and/or easy to determine, hydrogeology would be a rather boring job: solving well-known equations in a perfectly identified medium. Fortunately, the world is heterogeneous, with highly non-constant properties in space, and "dealing with heterogeneity" is what makes the work fascinating. Everybody has heard of in situ experiments conducted in the field by experimentalists trained to work in the lab.: the first thing they do is to physically "homogenize" the site, by mechanically mixing the superficial horizons. "Otherwise it is too complex and one cannot understand what is going on," they say, referring to Occams'razor. The first thought that comes to mind is that they miss part of the fun by ignoring spatial heterogeneity, the second one is that their results are mostly useless, because the world is heterogeneous, and to understand "hydrogeology," one has to acknowledge this and deal with it.

Hydrogeology has been too much inclined towards "hydraulics" and the solving of the flow equations, and not enough towards "geology" and understanding/describing the rock structure, facies and properties in a geologically realistic manner, thus proposing "exact" solutions, but to poorly posed problems.

This article first provides a brief history of how hydrogeologists have dealt with heterogeneity so far, and then an attempt is made to give a personal view of how hydrogeologists may be dealing with it in the future. Making predictions is quite difficult, and a French saying adds "especially for the future"! These predictions are very likely to be wrong, but it is hoped that these suggestions may trigger additional work, foster discussions, generate controversy, and that, in the long term, better methods will be developed to deal with heterogeneity.

Four important issues are not addressed here: (i) the transition from Navier-Stokes' equations to Darcy's law, which, at the pore scale, is the first scale of heterogeneity of the velocity vector in natural media; (ii) the multiplicity of scales of heterogeneity, discussed in Carrera (this issue), and also Noetinger (this issue); and (iii) the multiple processes involved in flow and transport in natural media (flow, transport, diffusion, biogeochemical reactions, etc.). The focus will rather be on the methods used to account for heterogeneity for any of these processes, to represent it and to model it. Finally, (iv) the reasons why the Earth is heterogeneous will not be examined either, i.e.: sedimentation processes, the formation of crystalline rock, tectonics, diagenesis, etc, because it is assumed that all geologists are familiar with this.

Brief history of the methods used to deal with heterogeneity

The early approach

The first practical field hydrogeologists dealt with heterogeneity by trying to locate "anomalies" and make use of them. Water is not present everywhere in the ground; only those who can locate the highly porous and permeable strata in the ground are able to decide on well locations or discover springs. For instance, Brunetto Latini (1220–1295) wrote: "The earth is hollow inside, and full of veins and caverns through which water, escaping from the sea, comes and goes through the ground, seeping inside and outside, depending on where the veins lead it, like the blood in man which spreads through his veins, in order to irrigate the whole body upstream and downstream" (in Poirée 1979). Famous hydrogeologists, like Paramelle (1856), used their geologic knowledge to detect heterogeneities and discover springs. Others use divining rods... Darcy (1856) however, who was probably the first to attempt to quantify flow, developed his theory for artificial homogeneous sand filters and did not have to deal with heterogeneity. He produced however cross sections of an "aquifer," tapped by an artesian well, therefore implicitly differentiating between an aquifer and an "impervious layer." It was Dupuit (1857, 1863) who first tried to apply Darcy's law to natural media, which were of course heterogeneous. It is not clear if Dupuit was con-

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scious of the magnitude of heterogeneity. To extend Darcy's law to natural media, his approach was intuitive: assume the existence of a "homogeneous" layer and use Darcy's law. He did not discuss in detail how he would define the permeability of this homogeneous layer, but since Darcy had developed an apparatus to measure the permeability, he would most likely have taken samples on which to measure it. Had he taken several samples, and measured different values, nothing is there to give a clue on how he would have averaged them, in order to define an "equivalent" homogeneous layer. In fact, Dupuit was a mathematician, he developed the steady-state flow equation, and proceeded to find analytical solutions in various settings (like the classical Dupuit–Forscheimer solution around a well, Dupuit 1863). Had he been aware of heterogeneities, his analytical tools would not have allowed him to take them into account, and he would have ignored them altogether. Theis (1935) was the first to produce a simple tool to directly "estimate" the equivalent homogeneous property of an aquifer; this was the new well test that automatically "averages" the local (variable) properties, such as permeability and storativity. Before Theis, it was already possible to derive in situ values for permeability, by means of the steady-state solutions around a well (Thiem 1906), or local injection tests (Lefranc, Lugeon, etc) and the local values were in general averaged without any consideration for the type of average to use. This quotation is by Morris Muskat (1949), speaking of oil reservoirs: "it appears extremely unlikely that actual underground strata will be of strictly uniform permeability over distances or areas associated with oil-producing reservoirs. However, as such random lateral variations as undoubtedly occur are literally impossible of exact determination, they must be considered as averaged to give an equivalent uniform-permeability stratum. Moreover, even if the nature of these variations were known, the difficulties of exact analytical treatment would still force the use of averaging procedure and reduction to an equivalent permeability system." He then goes on to mention the Cardwell and Parsons (1945) bounds for averaging, and treats some special cases where simple geometric trends in permeability are known.

The simple distinction between an aquifer and a substratum or confining layers seems to have emerged relatively early. It is a first recognition of heterogeneity, but with a very simple "layered cake" conceptual model, which can be traced back to many early earth scientists, like the British geologist Whitehurst in 1778, or the French chemist Lavoisier in 1789 (who was interested in geology). This conceptual model is deeply inscribed in our discipline, and hard to abandon. It has been the cause of the use of transmissivity rather than permeability. The classification of the confining layers into aquitards and aquicludes came much later, when leakage was studied, and is probably due to Paul Witherspoon in the 1960s, see e.g. Neuman and Witherspoon (1968).

The rules for averaging permeability in hydrogeology were discussed in detail by Matheron (1967), although the issue of averaging had already been addressed earlier in other fields of physics, e.g. by Landau and Lifschitz (1960), or by Cardwell and Parsons (1945). Matheron dealt with the issue by considering permeability as a magnitude varying randomly in space according to a specified distribution. He showed that for two-dimensional parallel flow, in steady state, for a spatial distribution that is statistically invariant by a rotation of 90° and identical for the permeability $k/E(k)$ and the resistivity $k^{-1}/E(k^{-1})$, the correct average is the geometric mean. An invariance of the spatial distribution implies that not only the univariate (pdf) and bivariate (covariance) statistics are identical, but the complete spatial distribution function must remain the same for k and k^{-1}. In particular, this applies to the multi-Gaussian log-normal distribution, which is often mentioned as correctly representing the distribution of permeabilities in natural media. Note that the physical reason why permeabilities are distributed log-normally has never been explicitly stated, and, on the contrary, examples are found where this assumption is not correct. One has to remember, however, that the flow equation is a diffusion equation which can be written, for heterogeneous media:

$$\partial[\ln(\mathrm{K})]/\partial x\, \partial h/\partial x + \partial^2 h/\partial x^2 = \ldots$$

Assuming that the parameter $\ln(K)$ has a Gaussian distribution is quite frequent for the same equation in other fields of physics. Matheron also recalls the arithmetic and harmonic bounds for averaging, which apply to all media, already published by Cardwell and Parsons in 1945. Surprisingly, he also states (without complete demonstration) that there is no averaging in radial flow in steady-state, which is against the standard practice of steady-state well testing; he argues that the average permeability can vary anywhere between the arithmetic and harmonic means, depending on the value at the well, and on the boundary conditions. It has however been shown empirically that, in transient state at least, the geometric mean is the long-term average that a well test produces (see e.g. Meier et al. 1999). This issue of averaging will be discussed again below, and its role and some of its properties will be specified. It must be emphasized that pumping tests are still a key research topic, since they remain the most useful way to investigate the properties of the underground. In other words, hydraulic tests in boreholes still have a long life ahead; for instance, new analytical solutions such as those by Barker (1988) or Chang and Yortsos (1990), Acuna and Yortsos (1995), for non-integer or fractal spatial dimensions, which do not apply only to fractured rocks, show that new pumping test analyses can help to better characterize heterogeneity, even if the fractal dimension itself is not a predictive parameter that can yet be linked with the geometry, spatial permeability distribution or observable connectivity of the medium. But other techniques, as suggested below, may be developed.

Did this simple equivalent homogeneous medium approach work, with the tools available at the time (analytical solutions, the image theory, conformal mapping, etc...)? Yes, somehow it did, since early hydrogeologists

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were able to develop well fields, to adapt the exploitation to the resources and to solve local engineering problems without major catastrophes.

Heterogeneity and numerical modeling

The breakthrough in quantitative hydrogeology came in the early sixties with numerical modeling. It is hard to pinpoint who built the first digital model of an aquifer, it came after several attempts (started in the oil industry) to use electric analogs, the digital models being initially numerical versions of the analog, see e.g. Walton and Prickett (1963), Prickett (1968). The names that come to mind are Tyson and Weber (1964) in Los Angeles, Zaoui (1961) at Sogréah and the Chott-el-Chergui in Algeria, Prickett (1975) for a review, and others.

The analogs and, better still, the digital models, offered the possibility of making the aquifer properties variable in space while adapting the model to the geometry of the domain and changing the boundary conditions, the recharge, etc. Heterogeneity and the way in which it was accounted for in models will be the focus here. Assuming that there are a few pumping test values for the aquifer permeability, they are nevertheless much fewer than the number of cells in the model: the model offers a possibility of "dealing" with heterogeneity in a much more precise way than the well test data alone would permit. The initial approach was to assume that a permeability (or transmissivity) given by a pumping test was a "local average" of the true local value, over an area equivalent to that of the mesh of the model. In other words, the issue of "support" in Geostatistics, which concerns the size of the domain on which a measurement is made, was not yet clearly understood, but the idea was firmly established that the permeability measured by a well test was to be assigned to the mesh where that well was located. Between wells, the value assigned to each mesh was to be interpolated from the adjacent wells. This could be done by zoning (e.g. Voronoï, or Thiessen, polygons surrounding each well), or by polynomial trend fitting, or by hand contouring, etc. Heterogeneity was thus defined by a set of "measured" averaged values at local wells, interpolated in space. This did not work very well: since the model could calculate heads and flow rates, these values could be compared with observations, and the model could be "verified." Model calibration was the answer, initially through trial-and-error and soon to be followed by automatic inverse procedures (see Carrera, this issue). The important point here is that heterogeneity is represented (at a certain scale) in the models, but heterogeneity is neither defined nor prescribed: the heterogeneity description is based on the local (averaged) measurements, and its distribution in space is inferred by the inverse procedure. As the modelers soon realized that the inverses have an infinite number of solutions, they tried to restrict the range of "inferred heterogeneities" by assigning constraints to the inverse: regularity, zoning, algorithmic unicity, etc, see Carrera (this issue).

Did that work? Yes, it did, and it is still often used today, a calibrated model is a reasonable tool for aquifer management and decision making, see e.g. a discussion with Konikow and Bredehoeft (1992a, 1992b) in Marsily et al. (1992). Where the approach started to fail or at least to show its limitations was first in the oil industry, where the predictions of oil recovery and water-cut (i.e. water-to-oil ratio in a producing well) made by calibrated models proved very unreliable. Had such models been used to predict groundwater contamination problems, their limitations would also have become apparent, but such problems were still new in hydrogeology at that time (seventies–eighties). The reason is that oil production and water-cut, as well as contaminant transport, are very sensitive to conductive features such as high-permeability channels, faults or, on the contrary, low permeability barriers that are by definition intrinsically "averaged" in the well-testing method and in the inverse inference approach. In a comparison of seven inverse methods, Zimmerman et al. (1998) tried to "embed" in artificially generated media such highly conductive channels, and asked the seven inverses to identify them, based on calibration on head measurements. The results showed that most missed such heterogeneous features.

In fact, the head variations due to heterogeneity are small, whereas those of velocities and travel time are large, as can be seen intuitively when considering a layered aquifer with flow parallel to the bedding: the vertical heterogeneity does not produce any variation in the head distribution over the vertical, while velocities can vary tremendously from layer to layer. Trying to infer the heterogeneity from the head data alone was a quasi-impossible task. At present, head and concentration data (e.g. environmental tracers or contaminants) are more often available and used jointly in the inversion.

In the oil industry, to overcome these limitations, important efforts were devoted to "reservoir characterization" in the 1980s, following the introduction of "sequential stratigraphy," see e.g. Vail et al. (1991). This involved advanced geologic analysis of depositional environments, combined geophysics and well logging, detailed characterization of modern outcropping depositional analogs of deep buried reservoirs, in order to learn how to describe and represent them. This advanced geological analysis of reservoirs and of organics-rich source-rocks, to characterize their heterogeneity, was at the base of the development of new tools, such as Geostatistics and Boolean methods, which will now be described. Unfortunately, these "reservoir characterization" efforts did not really catch on in hydrogeology, which was (and still is) lagging behind reservoir engineering in this matter.

Stochastic methods and geostatistics

Considering an aquifer property as a random variable was discussed, e.g. by Matheron already in 1967, but for the purpose of averaging, not to describe heterogeneity. In the oil industry, Warren and Price used a stochastic approach as early as 1961 to assign permeability values to a 3-D reservoir model, also with the problem of averaging in mind, but this did not evolve into significant changes in the treatment of heterogeneity. The origin of stochastic hydrogeology can be traced to two schools: Geostatistics, developed by Matheron (1963, 1965), for mining estimates, and first applied to hydrogeology by Delhomme (1976, 1978, 1979), and to Freeze (1975), Gelhar (1976) and Smith and Freeze (1979). In 1975, Freeze assigned random values of permeability to cells of a 1-D model, drawn from a log-normal distribution, without considering any spatial covariance between the random values, as Warren and Price (1961) had done. Delhomme (1976, 1978, 1979) and Smith and Freeze (1979) included such a covariance. At the same time, Gelhar (1976, 1993) was pioneering stochastic hydrogeology, taking the covariance into account; his work was more theoretical and used analytical methods, as did the subsequent works by Dagan (1985, 1989).

Geostatistics, and in particular the definition of the covariance (or the variogram) of the permeability distribution, is the first appearance of the new concept that heterogeneity can be described by a "structure," i.e., that the geological processes that created the medium have imposed a pattern on the spatial distribution of the inhomogeneous values. It is no longer possible to produce a "plausible" map of the heterogeneity of a medium without having some underlying "structure" in mind. This structure is, in Geostatistics, defined by a new function, the spatial covariance (or variogram) which is a tool to characterize the heterogeneity. The inference of this structure from the data is the compulsory first step of a Geostatistical analysis, with the tacit assumption that all relevant heterogeneities and "structures" can be captured or represented by the covariance, which will be challenged later. See e.g. Chiles and Delfiner (1999), or Marsily (1986).

The Geostatistical approaches to dealing with heterogeneity were initially considered as continuous processes. These can produce three results:

1. The first is a better estimate of the spatial distribution of the parameter values in the cells of a model, based on a set of "measured" values. Kriging provides an "optimal" (in the sense of minimum variance of the estimation error, not necessarily "best approach") method for assigning permeability (or transmissivity) values to the meshes of a model, significantly superior to zoning, or to arbitrary interpolation (see e.g., Marsily 1986; Chiles and Delfiner 1999). However, when highly correlated structures such as buried channels or fractures are present, it is not possible to directly represent them with a single variogram, and, if they have been identified, geologically informed zoning is preferable. Furthermore, an extension of Kriging, co-Kriging, can be used to estimate permeability based on both well-test results and additional measurements (e.g. specific capacity, electrical resistivity, etc.). See e.g. Aboufirassi and Marino (1984), Ahmed and Marsily (1987, 1988, 1993). Lastly, Kriging provides a rigorous framework to address the "support" issue, i.e. to consider data that are representative of different averages over space, e.g., slug-test data that are only local values and well test data, which are averages over areas depending on the duration of the test. Kriging can incorporate these different data and produce estimates that are representative of averages over the precise area of a mesh, that can vary in size inside the domain, see e.g., Chiles and Delfiner (1999), Roth et al. (1998), Rivoirard (2000). In several instances, it has been shown that a Kriged distribution of the permeability or transmissivity will produce a model that is almost calibrated and need not be adjusted, see e.g. Raoult (1999), or to some extent, in basin modeling, Gonçalvès et al. (2004b). It is clear however that Kriging does not always perform well, as will be seen later. One also needs to apply Kriging with some rigor on the log-transformed transmissivity values, in order to estimate geometric mean values and not arithmetic means. Back-transforming the Kriged ln$T$ into T values must also be done correctly, i.e. simply as $T=\exp[\ln T]$ without any additional term using the variance of the estimation error to supposedly correct an assumed estimation of the median rather than of the mean, as is sometimes erroneously done: see e.g. Marsily (1986).
2. The second is that Geostatistics provides a clear concept to constrain an inverse calibration procedure, to infer the spatial distribution of the parameter value. This is discussed at length in Carrera (this issue) and was the basis for the "Pilot Point" inverse approach (see e.g. Marsily 1978; Certes and Marsily 1991; Ramarao et al. 1995; Lavenue et al. 1995; Marsily et al. 2000; Lavenue and Marsily 2001).
3. Monte-Carlo simulations of aquifer models where the parameters are conditional realizations of the (unknown) spatial distribution of the parameters is one method to assess the consequences on flow and transport of the uncertainty on the heterogeneity of the system, as represented by the Geostatistical approach. Assuming that the conditional realizations display the full range of uncertainty on the heterogeneity of the aquifer, and assuming that the covariance is actually capable of capturing all of the relevant heterogeneity, the Monte-Carlo flow simulations provide an estimate of the resulting uncertainty on the flow and transport (head, flow rate, concentration, etc); see e.g., Delhomme (1979), Ramarao et al. (1995), Lavenue et al. (1995), Zimmerman et al. (1998).

Geostatistics has helped greatly, and the method is widely used to deal with heterogeneity. It is conceptually simple, the additional degree of freedom is very small (a variance, a range and a type of covariance model), the tools are available and the data requirements are standard ones: to build a groundwater model, well tests are necessary, and Geostatistics make better use of the data without asking for more. Additional data such as specific capacity, electric resistivity, etc., can also be used jointly. To the question: "how do we know, in a very practical sense, that the generated statistics are correct?," the answer is that this description of reality is a model, not an exact de-

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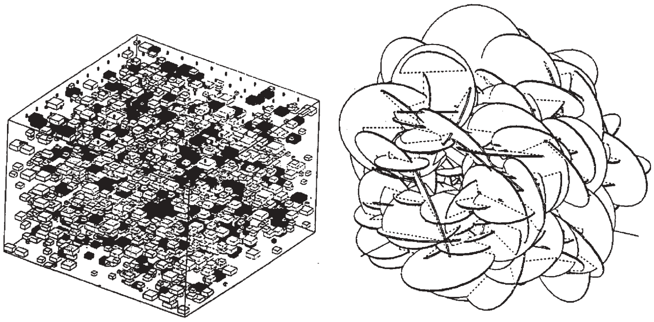

Fig. 1 Examples of Boolean models: (*left*) sand lenses, from Haldorsen and Damsleth (1990), and (*right*) circular discrete fractures, from Billaux (1990)

scription; natural heterogeneity is much more complex than any model can account for. The only value of using such a model is if it provides a better description (closer to the unattainable reality) than previous models, and thus gives better predictions than its competitors. Through the examples outlined above, simple geostastistics has shown that it provides better descriptions of continuous parameter fields than any alternative method. This is not to say that it is correct, only that it is useful.

Stochastic shales

Geostatistics represented a first attempt at describing the structure (in a statistical sense) of heterogeneities. The tool used for that, the variogram (or the covariance), has two major components: the range, which is proportional to the average size of heterogeneous bodies, and the sill, which is a measure of the magnitude of the changes (e.g., in permeability) from one heterogeneous body to another. These "bodies" were thought of as "hills" and "holes," circular or ellipsoidal (in the case of an anisotropic variogram), distributed randomly in space. On a Kriged map, or better on a conditionally simulated one, it is easy to see the range of the structure, which is close to half the average distance between two "hills" or two "holes" in the map. The sill is close to half the average squared difference between the values measured on the top of the hills and those measured at the bottom of the holes. The map was representing a continuous function. It is clear however that this description of reality is only a model.

In 1986, Haldorsen and Chang initiated a breakthrough in the oil industry with their "stochastic shales" approach, where the "objects" are discontinuous. Their concept of heterogeneous bodies is also statistical, but founded on geometrical concepts, not covariances. They consider heterogeneous sand bodies as "objects," whose shape is perfectly known (e.g., shoe boxes, see Fig. 1) but the size of the box and the position of its center are drawn randomly from a prescribed distribution. These objects are embedded in a continuous matrix, which for Haldorsen and Chang, was a shale, the "objects" being sand lenses. This type of model is called Boolean. The shape of the object is extremely flexible and left to the decision of the modeler, see many examples in e.g. Haldorsen and Damsleth (1990). The required statistics concerning the shapes and positions of the objects are estimated from available data, such as borehole logs, outcrop mapping, seismic surveys, etc. Several sets of objects with different shapes and properties can be used together (e.g. sand lenses and limestone bodies inside a shale matrix, or different types of sand structures). Once the distribution in space of the objects is drawn, they are sometimes called facies, or "flow units"; it is still necessary to discretize the domain into cells and to assign properties to each facies: permeability, porosity, etc. This can be done by a direct relation (each facies is described by one set of parameters), or by a random sampling of parameter values, defined by a distribution function and sometimes by a covariance, for each facies. The model is by definition stochastic, and many realizations can be produced.

This approach allowed abrupt changes in facies and permeability when Geostatistics was generating continuous fields. This is a fundamental step toward modeling actual geological media, where discontinuities and abrupt changes are widely present (e.g. sand bars vs. matrix, channels vs. floodplain, turbidites vs. continental margin deposits, etc). Note that the concept of roughness defined here for a surface could be defined for a 3-D medium as a "texture" parameter. This parameter has not been considered so far, since it is not relevant for the flow problem, but it might be interesting to investigate it when dealing with dispersion.

Did this approach work? It was indeed a breakthrough, essentially in the oil industry, as it empirically popularized the underlying concept of connectivity. If two sand lenses are not hydraulically connected, fluids will not readily flow from one to the other. This lack of connectivity happens in nature, and so far the models had been inept at dealing with this concept, Geostatistics introduced quite smooth transitions in space, not abrupt changes, whereas in reality nature does not vary smoothly. So the stochastic shales concept was very useful, although Boolean models addressing the connectivity issue had been developed much earlier, e.g. by Matheron (1967); Marsily (1985) and Fogg (1986) also emphasized the connectivity issue. In hydrogeology, the "stochastic shale" concept has not been widely used (see however e.g. Desbarats 1987; Pozdniakov and Tsang 2004) except that the same type of Boolean model was captured by the fractured rock community, where the "objects" were discrete fractures (Fig. 1). The concept of fracture connectivity (sometimes named percolation threshold, in the framework of the percolation theory) makes a lot of sense. Many versions of the discrete fracture model are available and have been tested, validated and compared, see e.g., Marsily (1985), Long and Billaux (1987), Cacas et al. (1990a, b), Long et al. (1991). They also completely renovated the vision of how fractured systems behave by introducing this concept of connectivity, which will be discussed later together with the upscaling issue. These Boolean tools are available and used, but require a new type of data on the geometry of the "objects" which they represent. Some of these data are

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available (well logs) and were in fact ignored in earlier approaches. But some are not easily accessible, e.g., the fracture shapes and sizes, and have to be "guessed" or assumed constant in space, so that what is seen on an outcrop can be taken as representative of what lies kilometers below the surface, in the real aquifer. One additional drawback of the Boolean models is that they are extremely difficult to condition to observed data. In other words, it is very hard to make the stochastically generated "objects" occupy the exact positions of the observed ones, e.g., along a borehole (sand lenses, fractures, etc.). Some attempts at conditioning have been made (see e.g. Andersson 1984; Chiles and Marsily 1993; Lantuéjoul 1997a, b, 2002, for fractured rocks and facies). Conditioning to objects without a volume (i.e. a fracture) is easier than to an object with a volume (i.e. a facies of a given thickness). Conditioning may be iterative, and is a priori only possible for a finite number of conditioning points. For facies, it is therefore necessary to discretize the facies, e.g. along a borehole. More fundamentally, some scientists question the utility of these models and claim that continuous Geostatistical models can manage just as well as discontinuous Boolean ones (e.g. Anda et al. 2003), but the authors of the present paper strongly disagree. Boolean models have made an extremely valuable contribution in dealing with heterogeneity by introducing the facies concept and addressing the connectivity issue.

Geostatistics fights back: discontinuous facies models

With their stochastic shales concept, Haldorsen and Chang (1986) in fact started a controversy with the continuous Geostatistical approach. The tenants of Geostatistics immediately fought back, and introduced discontinuous Geostatistical models. The concept of disjunctive Kriging was introduced by Matheron as early as 1973 (Matheron 1973, 1976), but not commonly used; Journel (1983), Journel and Isaaks (1984), Journel and Alabert (1990) and Journel and Gomez-Hernandez (1993) developed the Indicator Kriging approach, where an indicator can take (at any given point in space) the value zero or one, depending on whether the point is inside or outside a given facies. Matheron and the Heresim Group at the French Institute of Petroleum developed the Gaussian Threshold model, where a continuous Gaussian random function in space generates a given facies if the function value at a point in space falls between two successive prescribed thresholds (Matheron et al. 1987, 1988; see also Rivoirard 1994; Chiles and Delfiner 1999; Armstrong et al. 2003, or Marsily et al. 1998, for a review of such stochastic models). With the new method, "objects" are also produced as in the Boolean one, but these objects are defined by applying a threshold value to the result of a continuous Geostatistical simulation. This description of the various methods is a drastic simplification of the complexity of these models and ignores the significant differences between them. But the final outcome of the simulations is a series of "facies" in 3-D space, the shapes of which are indirectly defined by the covariance function of the underlying continuous Geostatistical function (indicator or Gaussian).

An alternative is the multiple-point Geostatistical approach developed by Journel, see Strebelle (2002). The approach allows simulations of facies maps using conditional probabilities that describe the exact geometry of the surrounding data. In practice, the conditional probabilities are calculated from a training image that can be derived either from outcrop observation, expert knowledge or geophysics (see an example in Caers et al. 2003). The method makes it possible to simulate complex geometries such as channels, meanders or lenses and can preserve the relations between the facies.

An infinite number of simulations of a given aquifer can be generated with these methods. Both the Gaussian threshold and the multiple-point methods are very powerful, and the 3-D facies structures that they generate are consistent with what geologists have observed on outcrops or inferred from imaging the subsurface, as illustrated by Fig. 2 (Beucher personal communication 2004). They look realistic, much more so than the Boolean ones and have many features of real geologic structures. Contrary to the Boolean ones, these models can easily be conditioned to observations and thus provide the correct generated facies at the location where the true facies has been observed, e.g., along a borehole. When a series of facies distributions in 3-D space has been defined, it is still necessary to assign properties to each facies (permeability, porosity, etc). As in the Boolean models, this can be done deterministically or by sampling from a prescribed distribution. The fitting of such models is discussed below.

Datawise, this approach offers the hydrogeologist who carries out the study the opportunity to use the geologic information that is, in general, available, or that could be collected at little additional cost by examining the geology (adequate description of the boreholes, better interpretation of the geophysics, comparison of the site with existing well-known sites, etc...). By contrast, these data are more appreciated and used in the oil industry, where a good geological description is made of each borehole, sometimes with cores taken from the formations, and always including well logging. In that respect, hydrogeologists are clearly lagging way behind the reservoir engineers in terms of use of geologic data. The fitting of the facies covariance function for the truncated Gaussian model is thus possible, and this approach is increasingly being used. Seismic data can also be used, either to define seismic facies that are correlated with "real" facies, or as indicators of the proportion of each facies in a vertical profile (Beucher et al. 1999; Fournier et al. 2002), or as a training image for the multiple-point approach. Making use of additional data is certainly a better way to deal with heterogeneity than trying to extract new results from the same old data.

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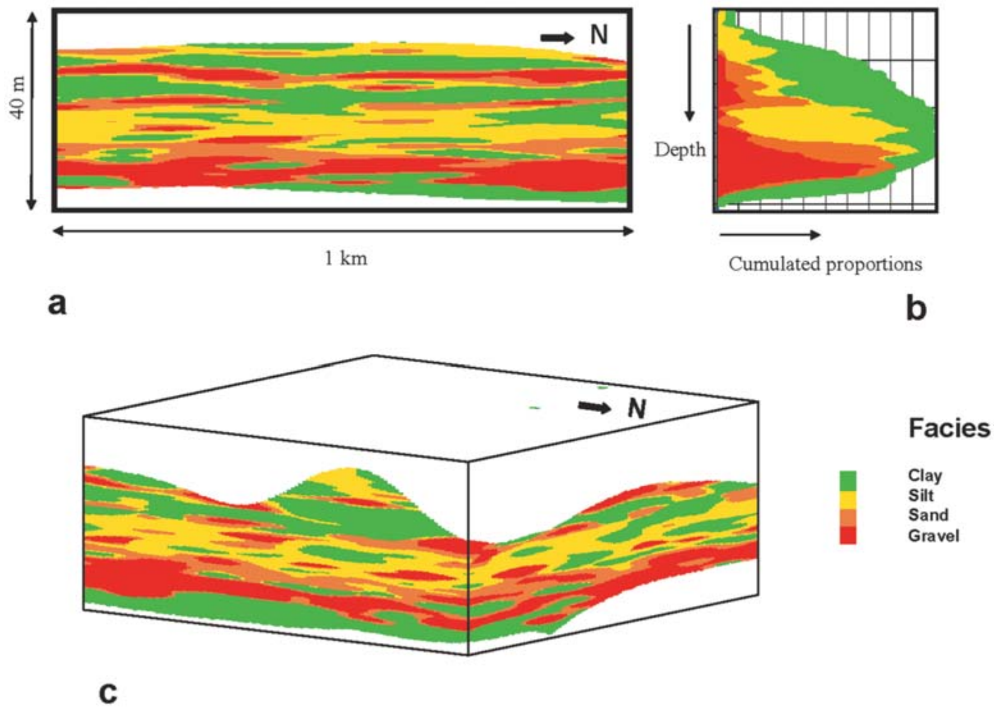
Fig. 2 Example of a four-facies Gaussian Threshold model using the HERESIM code (Matheron et al. 1987, 1988). **a** Cross-section; **b** proportion of each facies over the vertical; **c** 3-D representation. From (Beucher, personal communication, 2004)



Markov chain models

In the same vein as the Indicator facies models, a third approach was developed in the 1990s to address the same problem of building facies distributions from the geologic information, to describe the heterogeneity. It is based on the use of transition probability and Markov chains, to describe facies discontinuous in space. Following Carle et al. (1998), the transition probability from a facies k to a facies j is defined as:

$$t_{jk}(\mathbf{h}) = \text{Probability that } k \text{ occurs at } \mathbf{x} + \mathbf{h} \text{ given that } j \text{ occurs at } \mathbf{x}$$

where $\mathbf{x}$ is a point in space and $\mathbf{h}$ a lag vector. It can be shown that the transition probability can be related to the indicator cross-variograms $\gamma_{jk}(\mathbf{h})$ of facies j and k through the relation:

$$2\gamma_{jk}(\mathbf{h}) = p_j\left[2t_{jk}(0) - t_{jk}(\mathbf{h}) - t_{jk}(-\mathbf{h})\right]$$

where $p_j = E[I_j(\mathbf{x})]$ is the volumetric proportion of facies j, assuming stationarity in space, and $I_j(\mathbf{x})$ is the indicator variable of facies j, i.e. I_j=1 if point $\mathbf{x}$ is inside facies j, and zero otherwise. Note that the transition probability is not symmetric in $\mathbf{h}$ and $-\mathbf{h}$, whereas the cross-variogram is. Defining such a transition probability is, by definition, a Markovian approach: the probability of k occurring at location $\mathbf{x+h}$ is only dependent of what happens at location $\mathbf{x}$, and nothing else; by contrast, a non-Markovian approach would say that the transition probability may also depend on what happens at other points in the vicinity of $\mathbf{x}$. For those more familiar with Markovian processes in time, the assumption is that the probability of what happens at time $\mathbf{t}+\Delta\mathbf{t}$ is entirely defined by the initial condition, i.e. what happens at $\mathbf{t}$.

Given this definition, the continuous-lag Markov chain model simply defines the function which relates the transition probability $t_{jk}(\mathbf{h})$ to the lag $\mathbf{h}$. This function is assumed exponential with distance in the example given by Carle et al. (1998), which can be seen as choosing a given functional form for a set of variograms and cross-variograms in the Indicator approach: $t_{jk}(h) = \exp\left[\mathrm{r_{jk}}\,\mathrm{h}\right]$. The coefficients of the exponential, r_{jk}, are the unknowns to be calibrated, called the conditional rates of change from category j to category k per unit length of the lag distance h. Furthermore, this rate of change can be made a function of the direction of the lag vector $\mathbf{h}$. The exact Markov chain is in fact written in matrix form, since there are n^2 transition probabilities if there are n facies; these n^2 rates are however not independent, and only $(n-1)^2$ coefficients have to be calibrated on the available data. In practice, these coefficients can be directly related to fundamental interpretable properties of a geologic medium, such as proportions of each facies, mean length, asymmetry and juxtapositional tendencies. The first step of the Markov model is thus a calibration of the parameters on the data, just as the first step in Geostatistics is to calibrate the variogram models on the data. Then, conditional simulations can be generated, as in the indicator or Gaussian threshold approach.

Despite its simplicity, the Markov model seems to be quite flexible and to better account for spatial cross-correlation, such as juxtapositional relationships, e.g. fining-upward tendencies of different facies, than the indicator approach. The approach seems also internally consistent, as is the Gaussian threshold method, since the full matrix of the transition probabilities between all facies is consistently calibrated simultaneously from the data, whereas with the Indicator method, the direct and cross-vari-

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ograms are generally calibrated one by one and may not always be consistent. Their authors claim that it is easier to fit to the data than the Indicator variograms, and that it can produce simulations by the sequential simulation method and simulated annealing. It seems that the major advantage of the Markov transition probability approach may be to better insure that a given facies is found close to another one, as occurs in nature, due to sedimentological principles.

Additional presentations of the Markov chain model, and its comparison with the Indicator approach, can be found in Chiles and Delfiner (1999). Additional development and applications to real facies systems in hydrogeology can be found in Carle and Fogg (1996, 1997), Carle et al. (1998), Fogg et al. (1998, 2000), Weissmann and Fogg (1999), Weissmann et al. (1999, 2002), LaBolle and Fogg (2001).

Upscaling

Both the Boolean models and the facies models require upscaling. Upscaling is in fact the new terminology for averaging, a concept already discussed and initially used to find an equivalent property for an entire aquifer, when analytical methods made it necessary to have one single parameter for an entire system. But here the issue is different. The Boolean and facies models are pixel or vauxel models, i.e. they represent reality as a series of small cells or volumes. Typically, several tens or hundreds of millions of cells are generated by the models, still far too many to use them directly as calculation cells for the flow models, even if parallel computing and the continuous increase in computing power have today raised the number of cells acceptable in a model to millions. Furthermore, uncertainty evaluation requires that many stochastic realizations of the same problem are run, thus prohibiting the treatment of very large problems with the flow models.

Upscaling is the grouping of these elementary cells, to which a permeability has been assigned, as discussed above, into larger blocks that define the upscaled grid of a flow model. There are numerous methods of upscaling, generally with the objective that the flow and transport calculations made at the upscaled level, with the upscaled parameters, provide a calculated solution as close as possible to the one which could have been calculated, if the small scale meshes had been kept, with their original parameter values. Upscaling is not a problem for porosity (except if the upscaled volume includes aquitards in which solute can diffuse), as porosities add up arithmetically, but the real issue is the permeability, see e.g. a review in Renard and Marsily (1997). For infinite media, averaging has been resolved at least theoretically, as shown above (e.g. the geometric mean in 2-D, Matheron 1967, or a power mean in 3-D, e.g. Noetinger 1994, 2000; Abramovich and Indelman 1995; Indelman and Rubin 1996). But these theoretical results are only valid if rigorous assumptions are satisfied, on the distribution function of the permeability (in general, log-normal), on the type of flow (in general, parallel), etc. One particularly striking example of how wrong such generally unquestioned assumptions can be is given by Zinn and Harvey (2003), who compare three random permeability fields in 2-D, all with nearly identical log-normal distributions and isotropic covariance functions. The fields differ in the pattern by which the high- or low-conductivity regions are connected: the first one has connected high-conductivity structures; the second is multivariate log-Gaussian and, hence, has connected structures of intermediate value; and the third has connected regions of low conductivity. The authors find substantially different flow and transport behaviors in the three different fields, where only the log-Gaussian case behaves as predicted by the stochastic theory. This example stresses again the importance of connectivity in dealing with heterogeneity, as pointed out by e.g. Fogg (1986), or Western et al. (2001). Given these results, one must consider that upscaling is still a very important research subject, where the detailed properties of the elementary cells must be taken into account in a much more precise way than just by their average values. However, the need to upscale may diminish with the constant increase in computing power of modern equipment. On the other hand, an important issue is the increasing use of unstructured grids within the numerical models while Geostatistics requires a regular grid (support effect). To preserve the coherence of the Geostatistical model, it will still be necessary to transfer the heterogeneity model onto the unstructured grid using both upscaling techniques, when the mesh of the numerical grid is larger than the Geostatistical one (He et al. 2002); downscaling techniques will also be needed when the opposite situation occurs e.g. around flow singularities. Upscaling of geochemical parameters, such as distribution coefficients, kinetic constants, etc, is an almost virgin issue, see e.g. some preliminary work by Pelletier (1997), Glassley et al. (2002) or discussion in Delay and Porel (2003), Carrayrou et al. (2004).

Fitting a facies model

When a facies model has been built, either with a Boolean or a Geostatistical approach, and when permeability values have been assigned to each small-scale cell, and upscaled to the flow model cells, the ideal situation would be that the model is (by chance) perfectly calibrated. Unfortunately, this almost never occurs, and the model has to be calibrated. There are two possible ways of doing this: keep the geometry of the facies, and change the values of the permeabilities within the facies. Or alternatively, keep the values of the permeabilities, and change the geometry of the facies. The first option is standard: the facies geometry can be seen as zoning in a classical inverse (see Carrera, this issue) and the permeabilities can be adjusted within each facies. However, some recent work on the adjustment of the geometry has been published, called the "gradual deformation" (Hu 2000, 2002; Hu et al. 2001a, b). This offers the possibility of gradually and continuously changing the shape of both Boolean objects (e.g. the position of a discrete fracture, its size, etc, or the shape of a sand lens) and Geostatistical

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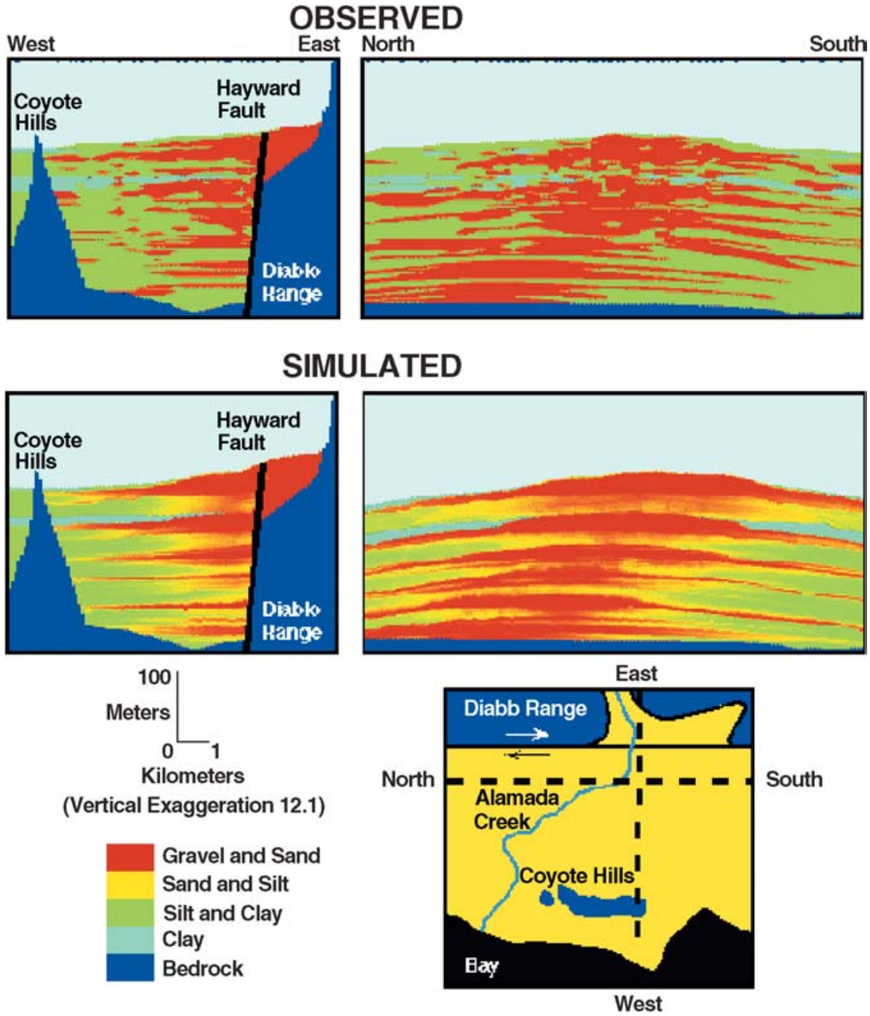

Fig. 3 Observed and simulated cross-section of the San Francisco Bay, using the genetic approach. From Kolterman and Gorelick (1992)

facies. This is a breakthrough in the calibration of facies models that could be combined with a more classical inverse on the parameter values.

Genetic/genesis models

The next breakthrough in dealing with heterogeneity came in 1992 with Kolterman and Gorelick. Despite some early attempts at recreating the spatial distribution of rock properties by modeling the rock formation processes (e.g. by basin modeling, which will be discussed later), this paper was the first real attempt at generating sediment facies not by Boolean or Geostatistical methods, but by using a sedimentation model, that of Tetzlaff and Harbaugh (1989), and simulating river flow and sediment transport, deposition and erosion over a period of 600,000 years, for the San Francisco Bay. This required considerable computing power and CPU time, as well as the reconstruction of the climate history of the region over the same period of time, day by day, and of the evolution of the streams, the bay and the movement of the Hayward Fault, which crossed the area. Fig. 3 is a cross-section of the outcome of this effort, taken from the authors, and compared with observations.

The authors of this paper believe this is a breakthrough because, for the first time, the major effort is put into building a model whose sole purpose is to represent the actual geologic processes that created the sediments; from the outcome of this model, the properties of these sediments are derived, in particular their heterogeneity. Of course this is a very challenging task, with immense difficulties: which process is represented, how to reconstruct the necessary data (e.g. climate records), how can the embedded uncertainty be quantified, are there random components in the modeling (there are some random decisions made by the model through time in Kolterman's and Gorelick's 1992 approach). But the power of the genetic approach is that the modeling of processes can in principle represent features that statistical methods would never have captured. For instance, a meandering depositional environment would never be amenable to a simple bivariate Geostatistical approach, only multiple-point Geostatistics (still under development, see e.g. Strebelle 2002; Krishan and Journel 2003) could approach that, or bivariate Geostatistics where the correlation structure itself is a correlated random field function of the meander properties, see e.g. Carle et al. (1998). Although a first attempt at comparing a genetic and a Geostatistical ap-

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proach on the same site has been published recently (Teles et al. 2004, see below), there is still much work to be done to compare the various genetic and Geostatistical models; this is a very important area of new research. Another striking example can be seen in Fig. 3: Kolterman and Gorelick introduced the movement of the Hayward fault in their model; the result is that the mouth of the sediment outlet in the bay (where the coarse sediments accumulate) moves from North to South during the simulation, as can be seen on the North–South cross-section. This would never have been found in a statistical approach.

It is worth noting that very early attempts at developing genetic models had been launched by Matheron in the late 1960s, he called them at the time "the Ambarzoumian processes," see e.g. Matheron (1969) or Jacod and Joathon (1971, 1972). But they had not been used in hydrogeology. A number of genetic models have been developed since, mostly for the oil industry, where sediment transport and deposition are approximated by a diffusion equation, which can be shown to approximately represent sediment transport, in a marine or deltaic environment; see e.g. Paola et al. (1992), Heller and Paola (1992), or Grandjeon (1996), Grandjeon et al. (1998), Grandjeon and Joseph (1999), Doliguez et al. (1999), Euzen et al. (2004), or Quiquerez et al. (2000). Webb (1995), Webb and Anderson (1996), have developed a sediment model, partly empirical, partly genetic, to represent fluvial deposits. Kolterman and Gorelick (1996) present a review of such models. Teles et al. (2001) have built a genetic/genesis model of fluvial sedimentation, representing both meandering and braiding patterns, which uses empirical rules to represent sediment transport and erosion. The model does not represent water flow and sediment transport per se, but rather the result of the alluvial processes by using geometric rules. It is considered that these geometric empirical rules embed the fluvial processes that create the structures. Some of these geometric rules can be seen as in part Boolean. A series of different facies are thus assembled, see e.g. Fig. 4.

As for Boolean or Geostatistical facies models, each facies is then assigned a property value, e.g. a permeability, to be introduced, after upscaling, into a flow model. Teles et al. (2004) showed that the genetic model is able to represent the connectivity of buried channels in the alluvium (or the role of barriers of such channels, when they are filled with clay), whereas the bivariate Geostatistical approach ignores such features, with significant influence on the prediction of solute transport. So far, these genetic models have not been conditioned to hard data. They cannot generate a facies at the location where it has been observed or, at best, with great difficulty. It is conceivable to combine multiple-point Geostatistics and genetic models where the outcome of the latter would be used as training images for the former; other ideas have also been suggested, e.g. to prevent a non-observed facies from being deposited at a given location; this approach has been used to generate conditional Boolean fracture sets by not keeping random fractures which do not appear at the conditioning points, see e.g. Andersson (1984), Chiles and Marsily (1993).

At a different scale, basin models can also be considered as genetic models: Betheke (1985), Ge and Garven (1992), Garven (1995), Burrus (1997), Person et al. (1996, 2000). Indeed, they represent the succession of sediment deposition, they can include high resolution sediment types for a given facies and they explicitly model compaction and porosity–permeability reduction as a function of the effective stress. They also represent thermal evolution, organic matter maturation and sometimes, some temperature-dependent diagenetic processes (porosity clogging). The 3-D Paris basin model is perhaps one of the more detailed examples of this type. It is based on more than 1,100 litho-stratigraphic well data (Gonçalvès et al. 2004a), see Fig. 5.

Some genetic models try to produce faults as a result of tectonic stresses, see e.g. Quiblier et al. (1980), Renshaw and Pollard (1994, 1995), Taylor et al. (1999), Bai and Pollard (2000), Wu and Pollard (2002), Person et al. (2000), Revil and Cathles (2002). Karstic systems can also be studied with a genetic approach, by trying to model the carbonate dissolution mechanism; a number of attempts have been made in this area, see Bakalowicz (this issue). So far, the genetic approach has been focused on detrital or alluvial sediments rather than on calcareous deposits, although some attempts have been made to represent the evolution of limestone (Grandjeon and Joseph 1999). But much work remains to be done on various types of rocks.

Does this approach work? The answer is yes, and it is developing rapidly. In terms of data, it requires a solid scrutiny and interpretation of the litho-stratigraphic record. Sedimentologists have to study, in detail, the available sediment samples, sometimes to date them (with ^{14}C on organic debris for recent alluvial sediments, or with micropaleontology, isotopic geochronology...), to investigate the depositional environment, and interpolate the information in space keeping a genetic concept in mind. For the Aube valley, as described in Teles et al. (2004), for instance, a series of 44 auger holes was sufficient to build a reasonable genetic model of the plain, bearing in mind the existence of studies of the succession of climate periods during the Holocene, where each period is characterized by a type of sediment, a deposition pattern (braided or meandering), which is valid for a large area, not only for a given alluvial plain. Generic or regional geologic knowledge is thus available, and vastly increases the value of the collected data. An example of the value of such knowledge can be found in Herweijer (1997, 2004). He studied the famous MADE experimental site in the Mississippi valley, where very well characterized tracer tests had been made (see e.g. Harvey and Gorelick 2000). His approach was to construct a conceptual model of the stratigraphy of the site, based on the available geologic observations and the results of the pumping tests. Previous authors had tried to use the Geostatistical approach at MADE, and to infer the spatial covariance structure of the alluvial sediments in order to describe its heterogeneity, without paying much attention

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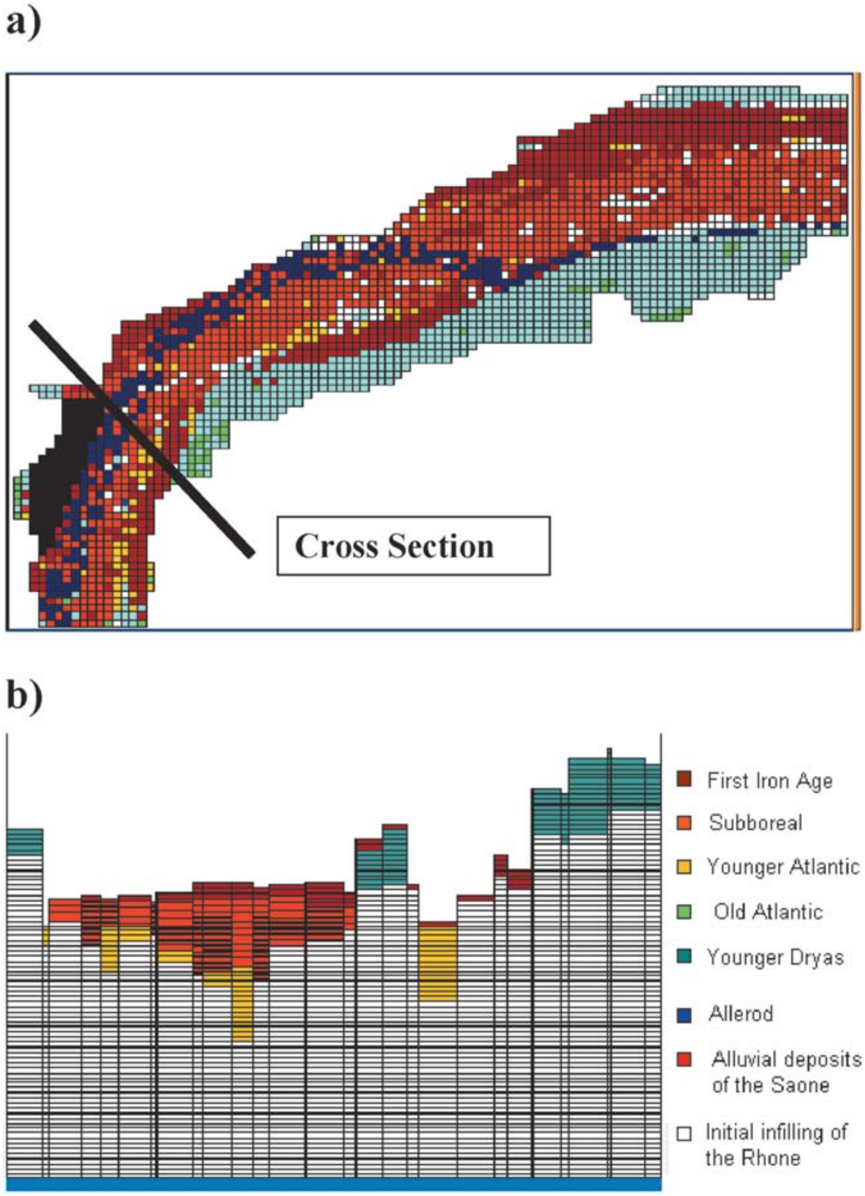

Fig. 4 An example of sediment pattern in the Rhône Valley in France, as created by a genetic model (Teles et al. 2001). **a** Plan view of the sediments in the plain. Meshes are 200×200 m, the alluvial domain is 20 km long. **b** Cross section (North-West–South-East at Villeurbanne, as marked on **a**. The *colors* show the sediment units ages from 15,000 years to present, as given in **b**. The lithology of each sediment is associated with each episode. From Teles et al. (2001)

to the geology ("all this is alluvial material"). What Herweijer (1977, 2004) observed is that within the alluvium, two successive sedimentation structures existed; one from a braided stream, one from a meandering stream. Geostatistics cannot easily incorporate such information. Calibrating a unique covariance structure for the entire thickness of the alluvial aquifer was just like trying to find a compromise between apples and oranges, whereas incorporating some genetic knowledge would definitely have improved the "dealing with heterogeneity," even with the Geostatistical approach and without a genetic model. An alternative approach could have been to use "variogram maps" (or covariances) which can incorporate anisotropy and statistical non homogeneity. Much more complex structures than those achievable with a simple variogram can be obtained in this way, see e.g. Anguy et al. (2001, 2003).

Very recently, ANDRA, the French Nuclear Waste Disposal Agency, presented some on-going work on the construction of a flow and transport model for two carbonate aquifers, in the Dogger and Oxfordian of the Paris basin, where these two aquifers surround a clay layer whose feasibility as a repository is being studied. The model is to be used to represent the transport to the outlets of radionuclides that would eventually leak out of the clay formation. To calibrate the flow model, ANDRA and its contractor, the French Institute of Petroleum, used the genetic model DIONISOS (Grandjeon 1996; Euzen et al. 2004), which solves the diffusion equation to represent transport and deposition of sediments, to define the properties of the two aquifers. This work will be published in 2005 (Houel et al. 2005). Genetic models are no longer only theoretical research tools for academics!

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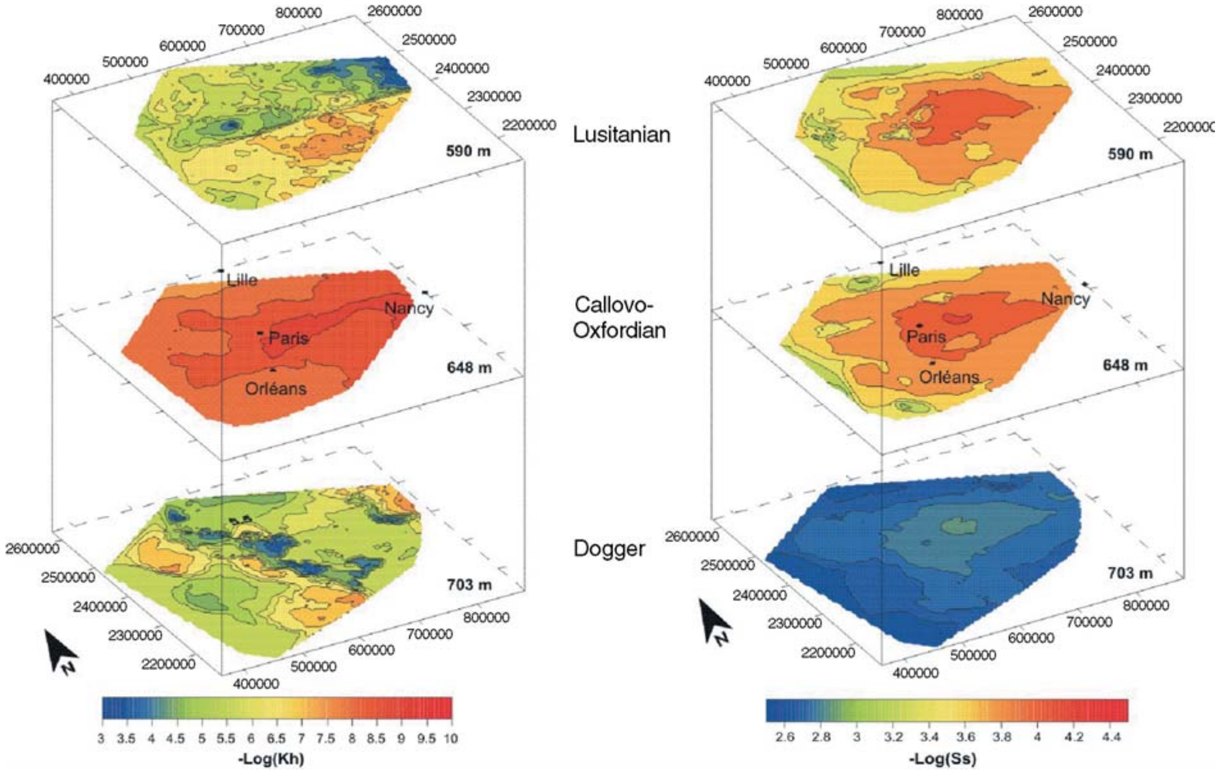

Fig. 5 Basin modeling of the Paris basin: calculated horizontal permeability and storativity distributions of three aquifer layers at present. The heterogeneity is the result of the sediment facies description, kriged from the borehole lithostratigraphic data, defined by the percentage of three poles: *1.* clay; *2.* limestone; *3.* sand. The maps include the effect of the compaction history with different compaction rules for each pole, and different porosity–permeability relations. The calculated permeability in each cell is the geometric weighted average of the permeability of each pole. The depth of the center of each layer is given on the right. From Gonçalvès et al. (2004b)

Different genetic models may be more appropriate for different scales. Those representing small-scale processes, such as Webb (1995) or Teles et al. (2001, 2004) are better suited to account for stratigraphic details that are not generally recorded in classical hydrogeologic studies, e.g. an alluvial meandering plain over a small distance. On the contrary, the genetic models based on the diffusion equation to represent transport and deposition are better suited for large scale problems, like marine sedimentation, alluvial fans, even marine carbonates. The Kolterman and Gorelick (1992) approach may lie in between.

The future

When does heterogeneity matter?

The first question is: "when does heterogeneity matter?" As has been shown earlier, methods to deal with heterogeneity exist and will certainly be improved in the future, but they generally need additional data, on top of the usual ones, or at the very least, increased scrutiny of the geologic data; they also need a good deal of thinking...! An attempt to list the areas where "dealing with heterogeneity" is obligatory, and those where ignoring it will do just as well is given below.

Ignoring heterogeneity

It is impossible to completely ignore heterogeneity, but one can use methods that "deal" with heterogeneity automatically and allow the user to ignore it. A simple example is permeability measurements. Any hydrogeologist knows that if he/she needs to know the permeability of an aquifer, making measurements on core samples will not be a good solution. One should rather perform a pumping test, of a reasonable duration, and extract from it the average permeability of the aquifer, which can then be used to make predictions, or build a model. It is the "tool" (the pumping test) that "deals" with the heterogeneity, and automatically produces a reasonable and useful value for practical purposes.

Again and again, it has been found that if a watershed model is built, to represent surface and subsurface flow, making local measurements of the soil permeability, on cores or even with double-ring infiltrometers, produces a permeability value much too low to represent the observed behavior of the watershed (flow, water levels,... see e.g. Carluer and Marsily 2004). The same observation has been made e.g. on a deep sandstone aquifer, the Pierre Shale, see Neuzil (1994). Is this due to an insufficient number of measurements? To an inappropriate measurement system? To unidentified processes acting at a different scale than that of the measurements? If the flow in

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the aquifer is to be modeled accurately, and the only available information is a set of local values measured on cores, then it is indeed necessary to "deal with heterogeneity" and derive a method that can construct the spatial pattern of the local permeabilities, and identify the connectivity of special features and channels that govern the flow, which are, it is believed, not accessible at the local measurements scale.

But, in general, when the appropriate measurements are available at the appropriate scale, then it is indeed possible to ignore, to some extent, heterogeneity and use the global measurements directly to make predictions. This would apply first to flow, not to transport. The conclusion is thus that where regional aquifer management is concerned, for optimization of well discharge, estimates of available resources, then a large-scale view of the heterogeneity is sufficient, and aquifer property estimates can be derived by means of the usual tools: pumping tests and aquifer model calibration by trial-and-error or inverse procedures. Of course, as emphasized earlier, selecting an inverse which adopts a given parameterization of the permeability field already amounts to making some assumption on the nature of the heterogeneity (e.g. zoning, Pilot Points based on Kriging, etc), but again, the tool (inverse) will "deal" with heterogeneity, and most likely two different inverses will, in the end, provide predictions that are not vastly different, even if the permeability fields are far from identical. Just to give an example, Besbes et al. (2003), see also OSS (2003), recently built a flow model of the multilayer aquifer system of northern Sahara, extending over three countries (Algeria, Libya, Tunisia) and an area of more than 1 million km^2, probably the largest flow model ever built. The objective was to agree on a multinational policy of exploiting this huge aquifer, which receives little recharge and is currently being mined by increasing withdrawal. How long can the situation last, are there risks linked with over-exploitation, is pumping in one country affecting its neighbors? The distance between "adjacent" wells is sometimes several hundred kilometers; even if the geology is well-known in terms of horizons, local heterogeneity is obviously not a concern. Average transmissivity, vertical permeability of aquitards, local discharge into the sea and into playas, present level of withdrawal, present recharge, and finally values of the specific yield in the unconfined sections of the aquifers are the most important parameters that will govern the long-term response. The precise nature of the boundary conditions, present and future recharge (with climate changes) are also very important issues to be resolved in such large aquifers (see e.g. Jost et al. 2004). Where should the money be spent? Most likely on large scale reconnaissance: geology, pumping tests when available or feasible, collection of seismic surveys (made for oil exploration) that give the thickness of each layer, use of Geostatistics (Kriging) to interpolate the scarce data in space, and then model calibration using the 50 years of existing records. Depending on which lithologies are present, large-scale sedimentation models or basin models could be used to determine the general trend in the properties of the system, after a state-of-the-art hydrostratigraphic conceptual model has been built. This would be the recommendation. There is a small incentive to bracket the uncertainty in this example. If a withdrawal limit is given to a particular country, not to jeopardize another country's resources, is this known with a 5%, or 50% bracket? To address that issue, it is necessary to recognize that the basic parameters of the model are uncertain, and to do one of the following:

- i Simple sensitivity study. Arbitrarily assume that the calibrated parameters have a given estimated range of uncertainty (e.g. 20%, 100%...) everywhere and run the model with different sets of parameters, and see if the consequences are different.
- ii Post-optimal residual sensitivity study. This can be done if a stochastic inverse has been run, which gives, after calibration and linearization, the residual uncertainty on the parameters, which can be different in each area of the aquifer. This defines the range of parameter uncertainty, which was "guessed" and assumed uniform in approach (i). See e.g. Cooley (1997).
- iii Full-scale post-optimal uncertainty analysis using a stochastic inverse and Monte-Carlo simulations, see e.g. Ramarao et al. (1995), Lavenue et al. (1995).

In this huge aquifer, there may be some local problems, however, where local heterogeneity can be important. One is the exact situation around playas. At present, the playas are outlets for the aquifers. In the future, it has been shown by the huge model that the lowering of the piezometric surface will dry up this flux: the playas, containing salt brines, may start salt water infiltration into the aquifers, when they receive storm flow, or return flow from irrigation. Predicting the rate of salinity increase in the aquifers, the time needed for near-by wells to become brackish, or possibly engineering measures to prevent this from occurring, will require a better understanding of the flow and transport at a small scale around the playas, thus taking local heterogeneity into account. Another instance is the vertical upward leakage from deep brackish aquifers into superficial freshwater aquifers. Assigning a single permeability to one aquitard is likely to be much too simplistic, and a detailed study of the aquitard heterogeneity would be necessary. But this is unlikely to happen in practice today, as (i) it would be quite expensive; (ii) there is no well established method so far to deal with aquitard heterogeneity, and (iii) the bad consequences would be felt in tens of years, thus reducing the incentive to assemble funds. However, this problem of aquitard heterogeneity should be considered as an area for future work, see below.

Taking heterogeneity explicitly into account

One opposite example when "dealing with heterogeneity" is obligatory is in transport. Consider a remediation case, where surfactants have to be injected to dissolve and re-

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cover DNAPL's in a superficial aquifer. A large amount of money will be spent on injecting, recovering and treating the water. Having an optimally functioning system is economical, and spending money to decipher the heterogeneity will pay off, as this will make it possible to optimally locate the wells, adjust the pumping rates, and insure that the system is hydraulically closed and that no surfactant coupled with DNAPL's will leak out of it. The scale of the problem is meters, at most hundreds of meters. What can be done? It would be useless to apply the "ensemble stochastic approach," and try to characterize the heterogeneity by a covariance function: in order to apply the stochastic theories, some averaging must be done. The pollution plume becomes "ergodic" when the travel distance is several times (on the order of 10) the correlation length. One is not interested in an average or ensemble behavior, but in a detailed local description of the real system. One needs imaging of the underground. Any geophysical imaging technique (radar, electric panels, electromagnetic surveys, NMR, etc, see Guérin, this issue) will be the starting point. An initial borehole survey will then describe the lithology, and provide clues to understand the structure of the aquifer, together with the geophysics. The technique needed here to describe the heterogeneity is definitely a facies model, one needs a lithological description (nature and shapes of facies), as precise as possible, on the basis of which properties will be assigned. This is not just permeability, but porosity, clay content, sorption parameters, etc, all properties that are estimated facies by facies, and extrapolated in space to represent the site. Modeling must be very detailed, and upscaling may not be needed, what is still a challenge is to determine the number of samples that are needed per facies, their size, measurement method (on samples or in situ) and the grid size that can represent them. A first cut of the facies model would be obtained from a genetic model. A state-of-the-art geologic characterization of the site must first be completed, as commonly made in petroleum work but less often in hydrogeology. Then, a genetic model (such as Kolterman and Gorelick 1992; Webb 1995; or Teles 2001, 2004) should be built. It will describe which different stratigraphic units are present at the site, the likelihood of erosion processes, the type of sedimentation pattern (meandering or braided stream, if in an alluvial deposit, etc). Since these models are presently not conditioned to the data, it will be necessary to go to a Geostatistical facies model, not a Boolean one which is difficult to condition. How to "fit" the Geostatistical facies model to the genetic one is still unclear (this discussion is about the future!), but the basic idea would be to select the covariances (in case of bivariate Geostatistics) or the multiple-point pattern by fitting them on the images produced by the genetic model. Another approach to fitting a facies model on the data is the transition probability and Markov chain method, as briefly described above, see e.g. Carle and Fogg (1997), Carle et al. (1998), Weissmann and Fogg (1999), Weissmann et al. (1999). The final facies model would then be conditioned on all the observation points, and the geophysics. The fine-tuning of the model would be made by calibration on experiments made on the site (pumping tests, see e.g. an example of 3-D interpretation of a pumping test with an inverse in Lavenue and Marsily 2001). Preliminary tracer tests would also be used to calibrate the model. Multiple realization models may be necessary to provide an estimate of the uncertainty of the answers, e.g. the duration of the remediation period.

The grey areas when dealing with heterogeneity

In the two above examples, one real (Sahara) and one semi-real (DNAPL), the answer to the question "does one need to address the heterogeneity issue?" is a clear-cut "no" and a "yes," the difference is, in part, related to the difference in scale of the two problems. But there are grey areas, where the answer is not that simple. There is indeed no universal answer to the method of treatment of heterogeneity. The transport problems will in general require that more attention be paid to heterogeneities than the flow problems since for transport, connectivity is most important. The scale of the problem must also be considered: a small-scale problem requires detailed understanding of the heterogeneous pathways, whereas for a large-scale problem, flow and transport will be averaged by the crossing of several heterogeneous structures, and an "ensemble" average will emerge (the behavior becomes ergodic, in the stochastic language), averages can be used, or averaging tools, such as the covariance function.

Finally, the situation is also influenced by the medium in which the study is performed. There is a plethoric amount of work in the recent literature that concludes on the non-ergodic behavior of fractured rocks regarding both flow and transport. This would mean that heterogeneity (in this case mostly its influence on connectivity) should be carefully accounted for. On the other hand, densely fractured aquifers have been managed successfully for a long time, assuming the continuity of flow and, to some extent, a pseudo-homogenization scale. For such media, there is no clear answer except for theoretical cases or synthetic cases. Further work is needed to classify the behavior of fractured rocks with respect to topologic parameters such as connectivity, fracture length distribution, mass density of the network, etc. See initial attempts in e.g. Aupepin et al. (2001), Rivard and Delay (2004).

The type of answer to be provided is also a criterion. Suppose that a leachate plume from a landfill is to be studied. If the objective is to determine the flux to a river, the detailed pathway that the plume follows to reach that river is not important, it is the rate of mass transfer that matters. Average properties can be used. If, on the contrary, the question is the maximum concentration that can be attained in a downstream well, the pathways, the dilution and dispersion along that pathway, etc, require a more detailed analysis of the heterogeneity at the site. Finally, the cost of data collection must also be considered: deciding to launch a more sophisticated study and collect the necessary data requires that a realistic budget is available.

This question pertains to an on-going controversy in hydrogeology, the parsimony issue, which is related to this article through the selection of the method to deal with heterogeneity: should simple and robust models (e.g. equivalent homogeneous media, continuous Geostatistics, zoning...) be preferred, as much as possible, or should one rather try to represent heterogeneity with the more complex methods? The authors of this paper think that using simple models has been taken too far in hydrogeology and is no longer justified, powerful models exist and computer time is no longer an issue. Making simplifying assumptions such as averaging ignores the connectivity issue; treating a problem in 2-D may not be justified if the flow and transport processes include a 3-D component (e.g. vertical heterogeneity of the aquifer, density effects, etc). Even if the 3-D structure of the system is poorly known, making "educated guesses" on this 3-D structure may be less erroneous than ignoring the 3-D structure, and using averages. Problems like scale-dependent dispersion, extreme tailings, etc, are in fact the results of homogenization rules that do not apply at the scale of interest, and thus do not allow the use of the classical governing equations, which assume ergodic behavior. Many ineffective "pump and treat" operations are due to this misguided approach. This is however not to say that simple models do not have a role to play, in many instances: see e.g. a discussion on this issue in Voss (1998). But to determine if a simple model is a satisfactory answer to a given problem, there is no alternative than to compare its output with that of a more complex one!

Areas for future work

In the following, attempts are made to indicate where future research efforts should be concentrated in order better to handle heterogeneity.

1. Transport problems generally require a better understanding of heterogeneity than flow problems. Average properties as given by a well test include the heterogeneities, for flow calculations, but do not describe adequately the transport. And, in most cases, the time required for a tracer test to provide representative answers is prohibitive. The type of tracer experiments carried out at Borden in Canada, Cape Cod in Massachusetts or MADE in the Mississippi valley is scientifically of great interest for testing assumptions, models and methods, but too costly to be used regularly for transport problems. Something else is needed.
2. Even for transport problems, the approaches may differ if the source term is diffused or at one point. For diffuse sources, e.g. nitrate or pesticide contamination, an average description of the medium may be enough; what is of interest here is the mass conservation, possible decay by biological processes (linked to the average velocity and transfer time), and general flow direction. The major problem is rather the source term, the amount used by the farmers, and the modeling of the consumption/release/decay of the products in the plant root zone. The exact concentration in a given well downstream need not be precise, it is the order of magnitude with respect to the norms that matters. This would apply to relatively well-defined aquifers with simple structures, like the Chalk aquifer in northern France and Great Britain. Aquifers with complex multilayered structures or with interbedded aquitard lenses may require more refined treatment, if breakthrough concentrations at different horizons need to be predicted, see e.g. Weissmann et al. (2002).
3. Two-phase flow is probably more demanding than solute transport, in terms of describing heterogeneity (see Noetinger, this issue). This is why many methods summarized above were developed by the oil industry, for predicting oil recovery and water-cut. This would also apply, in hydrogeology, for NAPL and DNAPL studies, and for the unsaturated zone. Many more parameters than just permeability and porosity are required (relative permeabilities, wetability, capillary pressure, sorption, etc). All these must be treated simultaneously, since they are correlated. One of the facies approaches seems the best option. In soil science, genetic models should be developed to better describe the structure, in terms of facies or horizons, of the unsaturated zone. For sea water intrusion, or for soil salinization by capillary rise, although transport is not multiphase, the problem is similar with strong dependence on heterogeneity. Heterogeneity is also a fundamental issue for superficial hydrological processes occurring in the vadose zone (infiltration, saturation, overland run-off) and their description. It has long been recognized that the simple Horton model does not fit all observations, but it is still widely used for lack of other simple models. Heterogeneity is an important aspect to consider since it can explain some of the observations such as "saturation from below." This phenomenon might be due to local heterogeneities that lead to local perched saturated zones and, in the end, to overland flow.
4. Dealing with heterogeneity is a three-part issue: the problem to solve/the methods to use and models to build/the data to collect, in that order, and the relevant scales of each of these. But very often the problem is ill-posed: the difficulty is there, the data are there, and the hydrogeologist is asked to select and use the best method to treat the data and solve the problem! In general, however, there is some flexibility in designing an additional data collection phase, which provides a measure of freedom.
5. Many research programs have, at times, collected large amounts of data without any model in mind, or else an inappropriate one. In general, these data are useless, even leading to the wrong type of model. A way to remedy that is to develop experimental sites where measurements and experiments are set up and interpreted by joint research groups involved with both experimental and modeling work. This was the

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case for the famous experiments in e.g. Borden, Cape Cod, MADE, Mirror Lake in North America, the Neckar alluvial site in Germany, or the fractured rock site of Fanay-Augères in France. One may expect a better bridging because experiments are built to feed models and models evolve to account for new measurements.

6. Subsurface imaging is obviously an asset, as it can help describe the geometry of the heterogeneous system. Geophysics could be used more systematically; so far, good examples of a successful use of geophysical images in the treatment of practical problems where the heterogeneity plays a role are lacking. Additional geological reasoning, as required by the genetic approach, has the merit of putting the problem into a broader context, and to bring in sources of information relevant to a site, but generic in nature: e.g. succession of climate states, from which the morphology and nature of the sediments can be derived. On the North American continent, fluvio-glacial sediments are probably the first target where genetic studies would be of interest, see e.g. Anderson (1989).
7. Except for geophysical imaging, the range of exploration methods to display heterogeneity is poor. Most of the standard tests are integrating tests, not exploratory tests (pumping tests, tracer tests, etc). New methods must be developed. In the detailed field studies for transport (e.g. Borden, Cape Cod, MADE, etc), one interesting tool was the borehole flow meter used, to assess the local permeability variations of the formation. But this tool was applied in a Geostatistical framework, to assess the spatial variability (covariance) over the vertical and the horizontal of the aquifer, treated as a continuous stochastic field. It may be possible to use the same tool in a facies-type of approach, to identify the local properties of each facies. Tsang and Doughty (2003) used temperature or salinity changes by logging boreholes which they had flushed and filled with freshwater to detect flowing fractures. A related example of assigning facies permeability from the results of in situ tests is given in Reis et al. (2000). They built a Geostatistical facies model of a petroleum reservoir. They used this model at the finest scale grid (without upscaling) to represent radial flow around a well and thus interpret well tests in four different wells. Rather than interpreting each well test independently with a standard Theis approach, which would provide four different integrated transmissivities, they decided to identify the individual permeability of each facies, assumed to have identical properties at each well location, so that the four tests could be simulated with the same permeability values assigned to each facies. Of course, at each well, the facies distribution was different, but one nice feature of the Geostatistical facies model is that it can easily be conditioned at the wells, therefore at each tested well, the exact vertical distribution of the observed facies was represented in the radial flow model. One needs to rethink the interpretation of the "classical" data in terms of describing the heterogeneity. To quote C.V. Theis (1967): "I consider it certain that we need a new conceptual model, containing the known heterogeneities of natural aquifers, to explain the phenomenon of transport in ground water." New tests may have to be invented, that emphasize the role of heterogeneity rather than averaging it (e.g. injection tests in packed sections of a well rather than a full well pumping test, over the whole thickness of the aquifer). Today, such tests are not thought to be very useful because there is no way to exploit their results. But if one thinks in terms of a facies model, which has been built for the site, and needs parameters for each facies, then there are tens of tests that could be designed and interpreted with the facies model, just as Reis et al. (2000) did. The experimental sites whose interest was emphasized in Section 4 above should be used for that kind of development. Major breakthrough in experimental work has already been achieved in many areas in nuclear waste Underground Research Laboratories, such as Lac du Bonnet, Canada, Yucca Mountain, US, Grimsel and Mont Terri, Switzerland, Stripa and Äspö, Sweden, Mol, Belgium, Asse and Gorleben in Germany, Tournemire in France, etc, thanks to available funding, creative ideas, and the need to characterize in detail the formations, even if the design of new measurement methods was not the primary objective.
8. There is a need to create a catalog of aquifer and aquitard properties and descriptions, with a summary of the methods used in the reconnaissance, and the modeling of the site (as well as the purpose of the study). For one thing, there is a great similarity (even if there are differences) in geologic objects. In tectonics, the study of the Himalayas has a lot to learn from the results of the study of the Alps or Rocky Mountains, and vice versa, as the processes at work are the same. It should be the same for hydrogeology. The structure of the sediments in a river along the coast of Peru has probably a lot of features in common with a similar river in the Pyrenees. This becomes particularly true when considered in genetic terms, the processes are the same everywhere, it is only the local conditions (climate, geometry, geology...) that make the two aquifers different. But that difference is secondary to describing the shapes, the texture, and mostly the methods used for studying the "objects." Furthermore, one study in Texas may provide "default" values for a parameter in France that was not measured. Take the case for instance of a local dispersivity value in a given facies. If a good description of that facies is available (grain size analysis, type of sediment, etc), and if there is a similar facies at a different site, one may start by assuming that the Texan value is a first guess for the new case. This "default" value would be all the more credible if, by assembling the catalog, similar facies are found to

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have similar properties at different locations. The link between grain size and hydraulic properties needs to be re-evaluated and used (note that German hydrogeologists make much more use of grain size data than any others). The creation of a catalog has already been advocated (e.g. Voss, personal communication 1988; Dagan 2002), but never put into practice. One reason may be the cost, and the exact focus of the catalog, which should be clear: if integrated values are to be transposed from site to site, this will never work (e.g. a transmissivity measured in an aquifer in Texas will be of little use for a case study in France). But if facies are considered, sedimentary structures, rock history, methods used to characterize sites, then the need for the catalog may be more evident. One would need an International Organization like UNESCO to develop such a project on a world-wide basis.

9. The upscaling problem may need additional work, see Noetinger (this issue). The problem that Zinn and Harvey (2003) emphasized is a major one. When one does upscaling, the small-scale boxes that need to be "averaged" into a big box may have internal structures that do not permit them to be treated as a "homogeneous" small-scale medium defined by one single value (of permeability, even with anisotropy), as shown by these authors. The small-scale boxes have themselves complex internal structures, with different connectivity properties. In other words, there is a nested scale problem to consider. The upscaling in the vertical direction also needs more attention, the scale of variability is finer and the measurements may not always provide an adequate description of the true structure in the vertical direction (there is no easy method to measure vertical permeability in boreholes). There is a need to look again at upscaling. Until the large-scale permeability of an aquifer can be reconstructed from small-scale measurements, there will be a credibility problem for hydrogeology.
10. The connectivity issue is of utmost importance, not just for upscaling, but for correct flow and transport predictions. Just to give an example, the Rhine Valley aquifer in France has been heavily polluted by salt brines in the area upstream from Mulhouse by leaching from potash mine tailings. This started in the early 1900s, and in the 1980s, the salt plume had moved several kilometers downstream, and was getting closer to the water supply wells of the city of Mulhouse. Detailed surveys had been made of the position of the plume, its spreading and its progression, until it was decided to move the wells laterally to a non-polluted area. Alas! When the new wells were drilled, it was discovered that a second plume, totally undetected, and connected to the first one only in the source area, was also present, and that the selected "non-polluted" location was no better than the initial one! In this case, the distribution and connectivity of high-permeability facies should have been studied; in other cases, it is the low-permeability barriers connectivity that would matter. Is the facies approach the best one to tackle this issue? Or is percolation theory the right tool? Or the fractal approach? Again, there is a scale problem; percolation thresholds are valid for ensemble averages, i.e. large-scale problems, and detailed facies description is perhaps better suited for the small scale. This is a very important research topic. The multiple-point geostatistical approach may be able to respect the connectivity pattern of a training image; the definition of a connectivity function which can be imposed on a simulation by simulated annealing may be another, see e.g. Allard (1994) or Western et al. (2001).
11. Heterogeneity of low-permeability layers and aquitards is almost an untouched subject, although very relevant for waste storage or brine or pollutant leakage through aquitards to aquifers. Heterogeneity can be linked to sedimentological processes, such as those studied e.g. by Ritzi et al. (1995) on till and lacustrine clays of glacio-fluvial aquifers; it can also be linked with tectonic processes in the underlying or overlying aquifers. It has indeed frequently been observed, when a multilayered aquifer model is calibrated, that the leakage factor needs to be increased in the vicinity of faults, see e.g. Castro et al. (1998). Other factors should also be considered.
12. In a genetic approach, rock properties evolution through time due to geomorphological and mechanical processes, to weathering at the surface, or to dissolutions/precipitation by geochemical processes at depth are still almost virgin topics, where predictive modeling is concerned.
13. It has been emphasized here that hydrogeology has so far failed to adequately apply fundamental geologic methods and principles to aquifer characterization. In the future, this will be an important field of activity. Rather than bringing in merely "static" geological characterization, it seems appealing to consider modeling approaches used in other Earth sciences fields such as geomorphology, marine or continental sedimentology to generate particular landforms and features. One interesting approach was developed by Niemann et al. (2003) to simulate topographies from sparse elevation data. Their model embeds the effects of evolutionary processes (tectonic uplift, fluvial incision and hillslope erosion). The simulated surface is iteratively adapted to observation points by spatially changing the erodability field. This leads to surfaces that are consistent with the heterogeneity, roughness and drainage properties of fluvially-eroded landscapes as well as being in exact agreement with observation points. Following this approach, one could consider embedding empirical laws describing the 3-D structure of sediments or features in Geostatistical methods or interpolators.

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Conclusion

In conclusion, the authors of this paper believe that the future of "dealing with heterogeneity" in hydrogeology depends largely on a conscious decision to better characterize, describe and model the geology of the sites of interest, similar to what has been done for the last 25 years in the oil industry. In many instances, the homogenization or averaging approach that has been commonly used so far in hydrogeology has shown its limits. Detailed studies are needed of outcropping analogs, catalogs of well-characterized study sites, improved geophysical imaging at the depth of interest with dedicated methods, as the seismic methods used in the petroleum industry are poorly suited to superficial aquifers. There are already a series of facies models that seem adequate to model the observed structures, they should combine genetic approaches and Geostatistical, Boolean or Markovian methods. There is certainly room for improvement in these methods, but what is most needed at this time is a thorough inter-comparison of these facies modeling approaches (and of simpler models too) on a set of well-characterized study sites, where the geologic description is properly done, and where transport experiments are run, like in the old Borden, Cape Cod, MADE sites. When a systematic comparison of methods is done, as for the inverse in the 1990s (Zimmerman et al. 1998), the outcome can really show the possibilities and limits of each approach, whereas, at present, most authors have shown how good their own method is, on theoretical or real examples, but have not convincingly shown how it compares with others.

A second area of development is to derive methods to identify the material properties at the scale of the facies structures. All the facies need to be identified, from the highly permeable to the low, including the intermediate mixed texture facies such as sandy mud, silty clay, etc, that are presently often ignored. The methods to identify the facies properties can go from newly designed in-situ tests at the proper scale, to correlating these properties with indirect data like grain size, geophysical properties (electric, mechanic, magnetic, etc) or a combination of all these (joint geophysical inversion). On that aspect, the geophysicists need to start thinking about defining the underground by complex facies models, with which they would try to identify by inversion the physical properties, and stop offering "layered cake" structures where they have identified equivalent properties that are no longer wanted.

A third area of development is to derive techniques to assess the connectivity of facies. The geometric properties of the facies are the key ingredients, which can result from geometric assumptions (directional transition probabilities, length distribution, etc). But they can also result from field testing, by interference tests, environmental tracer studies, temperature measurements, etc. As was shown here, the upscaling issue, which often remains a necessity, is very much dependent on the correct assessment of the connectivity of facies.

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