

# ***Oilfield Anisotropy: Its Origins and Electrical Characteristics***

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**Getting a grip on anisotropy of the earth can mean the difference between success and failure in reservoir evaluation and development. Accounting for the effects of anisotropy in measurements of the earth begins with understanding the geologic foundations of anisotropy—how sediments are laid down, converted to rock and deformed. Here is a summary of some geologic mechanisms for anisotropy, and some recent progress on anisotropy of electrical properties of rock formations.**

Across the many disciplines of the oil field, a nearly universal phenomenon is anisotropy—the variation of a property with the direction in which it is measured. Where anisotropy arises, convenient assumptions fall. Seismic reflectors appear at the wrong depth. Seismic lines don't tie. Waterflood programs fail. Induction logs are misinterpreted and mistake water for pay.

As producers seek a finer comb to draw through measurements of the earth, they are changing the status of anisotropy from unwelcome guest to hard-working collaborator. Advances in theory and computing

power now allow anisotropy to be factored into field development decisions. A full mathematical description of anisotropy remains difficult—for example, representing flow in three dimensions requires six variables.<sup>1</sup> But accounting for the simplest effects of anisotropy is coming within reach.

What is meant by anisotropy depends on who is talking. Geophysicists generally focus on variation of seismic wavefront velocity or on the polarization of shear waves. Petrophysicists may measure resistivity anisotropy. Drillers and geologists may think first of anisotropy in rock strength or stiffness produced by earth stresses. Stratigraphers may concentrate on anisotropy of magnetic properties. And reservoir engineers need go to great lengths to characterize permeability anisotropy to plan an optimal production strategy (see "Case Study: Anisotropy for Steering Horizontal Wells," page 50).

In all geoscience disciplines, however, there are two difficulties in dealing with anisotropy. One is that the conceptual underpinnings of anisotropy originate from the laboratory study of crystals—pure, homogeneous materials under pristine, controlled conditions. Today's physical models of the earth draw much from this work, even though the earth is a composite, heterogeneous material sampled under anything but pristine, controlled conditions. Applying the physics of pure materials to the earth is like putting an economics professor to work on the floor of the Tokyo

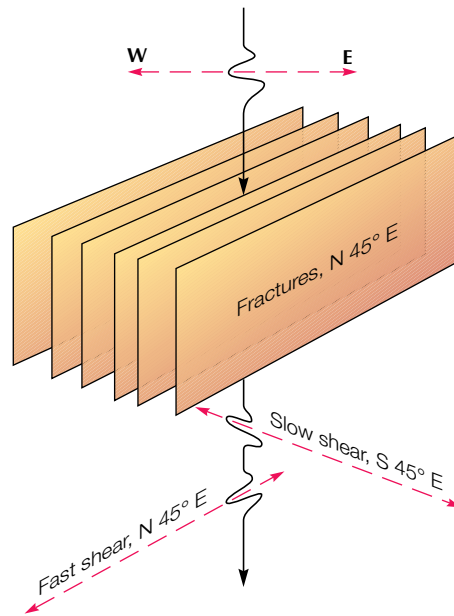
stock exchange. A smart one will figure out how to survive, but not without a struggle.

Physicists first met this challenge early in this century when they left the laboratory to make measurements of the earth's subsurface. They brought with them the mathematics of materials assumed to be isotropic—having properties with the same value in all directions—and homogeneous. For the most part, the convenient assumptions held remarkably well. Where the assumptions began to fail, there arose the second difficulty with anisotropy—if you don't have the tools to deal with anisotropy, the temptation is to ignore it or sweep it under the rug.

Assumptions about isotropy began to crack as early as the 1930s, when measurements made with electrodes laid in different directions on the earth's surface were seen to give different results when strata were dipping than when strata were flat.<sup>2</sup> In geophysics, the introduction of shear wave sources in mid-1970s showed that shear wave anisotropy was often significant and could be analyzed quantitatively (*next page*).<sup>3</sup> A leap, however, took place in the mid-1980s, when sensors again reclined with the expansion of horizontal drilling. In vertical wells, electrical anisotropy was often

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In this article, CDR (Compensated Dual Resistivity) and RST (Reservoir Saturation Tool) are marks of Schlumberger.



observed to be negligible and could be ignored. With horizontal boreholes, acoustic and electrical anisotropy became obvious and demanded consideration.<sup>4</sup> For many, the simple, isotropic days were ending and a new way of thinking was required.

This article gives an overview of the geologic basis of anisotropy as it is understood today in the oil field. It begins with a review of basic concepts and geologic mechanisms that produce various types of anisotropy and then focuses on recent advances in the measurement and interpretation of electrical anisotropies. Two crucial and well-characterized anisotropies—acoustic/seismic and permeability—are detailed in other articles in this issue (see pages 24 and 36).

### What is Anisotropy?

A material is anisotropic if the value of a vector measurement of a rock property varies with direction. Anisotropy is typically used to describe physical properties, which, for the purposes of geoscience, can be thought of as parameters intrinsic to the body of the rock at a given state. The notable exception is that anisotropy is often used to describe a state of stress, which is not a property but a condition that results in anisotropy of intrinsic physical properties.

In the simplest form of earth anisotropy, a vector measurement has constant magnitude in any horizontal direction that is different from the magnitude of the vector in

#### □ How fractures split shear waves.

**A notable feature of acoustic anisotropy is shear wave splitting, or polarization, typically caused by fractures. If a shear wave of a polarization is not parallel to the strike of a fracture set, the wave will be split into two components as it passes through the fractures. The first, faster component will have particle motion aligned parallel to the fracture strike. A second, slower component will have a wavefront aligned perpendicular to the fracture strike.**

[From Lynn HB: "Seismic Detection of Oriented Fractures," *Oil & Gas Journal* 84, no. 31 (August 4, 1986): 54-55. See also Crampin S: "Evaluation of Anisotropy by Shear-Wave Splitting," *Geophysics* 50 (January 1985): 142-152; Crampin S: "Anisotropy and Transverse Isotropy," *Geophysical Prospecting* 34 (February 1986): 94-99.]

the vertical direction. This is called *transverse isotropy* in the vertical direction and derives from the early days of logging, when anisotropy was observed in vertical wells at 90° (transverse) to uniform (isotropic) flat-lying beds.<sup>5</sup> Resistivity, for example, would appear to be the same for any wellbore azimuth, but be different from the value in the vertical direction.

A growing usage today, especially among geophysicists, is to qualify isotropy with respect to an axis of symmetry. Transverse isotropy in a vertical well that crosses horizontal beds would be transverse isotropy with a vertical axis of symmetry, abbreviated TIV. Properties measured in a horizontal well that crosses a series of vertical fractures

1. Each variable here is a scalar, a quantity that has magnitude but no direction. For an introduction to the analysis of anisotropy: Lake LW: "The Origins of Anisotropy," paper SPE 17652, *Journal of Petroleum Technology* 40 (April 1988): 395-396.
2. Maillat R and Doll HG: "Sur un Théorème Relatif aux Milieux Electriquement Anisotropes et ses Applications à la Prospection Electrique en Courant Continu," *Ergänzungshefte für angewandte Geophysik* 3 (1932): 109-124.  
For a review of resistivity anisotropy: "Formation Anisotropy: Reckoning With its Effects," *Oilfield Review* 2, no. 1 (January 1990): 16-23.
3. Crampin S, Evans R, Uçer B, Doyle M, Davis JP, Yegorkina GV and Miller A: "Observations of Dilatancy-induced Polarization Anomalies and Earthquake Prediction," *Nature* 286 (August 1980): 874-877.

A shear wave is like the wave that travels down a jump rope that is attached to a tree at one end and at the loose end, given a shake either side to side or up and down. Particle motion in a shear wave is perpendicular to the direction of wave propagation.

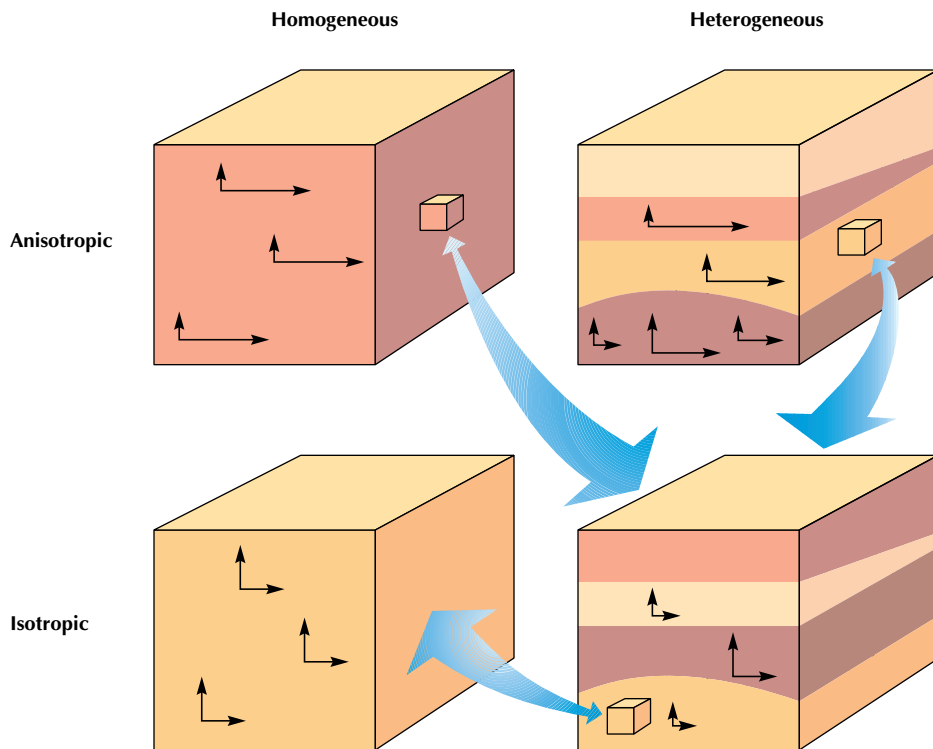
4. Crampin S, Bush I, Naville C and Taylor DB: "Estimating the Internal Structure of Reservoirs with Shear-Wave VSPs," *Geophysics: The Leading Edge* 5, no. 11 (1986): 35-39.

Alford RM: "Shear Data in the Presence of Azimuthal Anisotropy," *Expanded Abstracts*, 56th SEG Annual International Meeting and Exposition, Dallas, Texas, USA (November 2-6, 1986): 476-479.

5. For acoustic anisotropy due to layering in deviated and horizontal wells: White J: "Recent North Sea Experience in Formation Evaluation of Horizontal Wells," paper SPE 23114, presented at the SPE Offshore Europe Conference, Aberdeen, Scotland, September 3-6, 1991.

For a discussion of electrical anisotropy, see references 27-36.

5. Maillat and Doll, reference 2.



□ Four possible conditions for isotropy/anisotropy and homogeneity/heterogeneity. Note that what is apparent at one scale may not be apparent at another. For example, when viewed at a large scale, a sample may appear homogeneous and isotropic (lower left), yet at a small scale may be heterogeneous and anisotropic (lower right). Here, heterogeneity is expressed as bed boundaries. They may represent differences in composition, such as sands and shales, or differences in grain size and packing.

might have transverse isotropy with a horizontal axis of symmetry, called TIH (see page 37). The nomenclature clings to isotropy as the frame of reference, since it remains far easier to model than anisotropy. Transverse isotropy is often assumed for simplicity of calculation. Increasingly, some workers are considering anisotropy with different values along all three axes.<sup>6</sup>

Anisotropy is sometimes confused with heterogeneity. There are two important distinctions. Foremost, anisotropy is variation in a vectorial value with direction **at one point**, whereas heterogeneity is variation in vectorial or scalar values **between two or more points** (next page, top). The second distinction between anisotropy and heterogeneity is that anisotropy tends to describe mainly **physical** properties, whereas heterogeneity is typically used to describe point-to-point variations in compositions, geometries or physical properties.

Anisotropy and heterogeneity may coexist. There are four possible conditions: isotropic and homogeneous, isotropic and heterogeneous, anisotropic and homogeneous, and isotropic and heterogeneous (left). Fairly common is the third case, anisotropic and homogeneous. An example would be a bed with an acoustic velocity varying in direction at any given point (anisotropy) but the same variation with

## Case Study: Anisotropy for Steering Horizontal Wells

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Lake Maracaibo, in western Venezuela, having produced for more than 35 years, presents the challenges of a typical mature oil field. Maraven S.A., the operator of Block IV of the Bachaquero field, is planning to use horizontal drilling to produce bypassed oil and thereby increase recovery.

Part of the interval of interest is composed of elongated sands with laterally discontinuous shale layers. The lateral extent of these bodies is usually less than well spacing, so they cannot be described confidently using well data alone. Instead, scientists from Maraven and Schlumberger-Doll Research used a geostatistical method to derive a model of permeability anisotropy in the

sands and shales. This provided a means to more accurately locate horizontal drainholes.

One example of the modeling uses clay weight percent, determined from gamma ray, geochemical logging, RST Reservoir Saturation Tool measurements and infrared determination of mineralogy from cores. Clay weight percent is inversely related to permeability. If clay weight percent is assumed to be isotropic, the geological model comprises bull's-eye patterns, in which red is high clay volume and blue is low (next page, bottom). Bull's-eyes result because the model assumes clay is evenly (isotropically) distributed around the wells.

Geostatistical analysis from 31 wells in the area indicated that the clay weight percent, and

direction observed at all points (homogeneity). If different variations were observed at different points, the bed would be both anisotropic and heterogeneous.

Fundamental to both anisotropy and heterogeneity is the concept of scale. Whether anisotropy and heterogeneity are perceived depends on sample size and sampling resolution. In fact, to say “this rock is anisotropic” is almost meaningless unless scale is also defined—that is, both the size of the sample and the resolution of the sampling method. Anisotropy, for example, can be detected only when the observing wavelength is larger than the ordering of elements creating the anisotropy.<sup>7</sup> A crystal, for example, may be homogeneous above the molecular scale but highly anisotropic to larger wavelength electromagnetic and sound propagation. Many crystals together may form a homogeneous rock that is anisotropic if the crystals are aligned, or isotropic if they are ran-

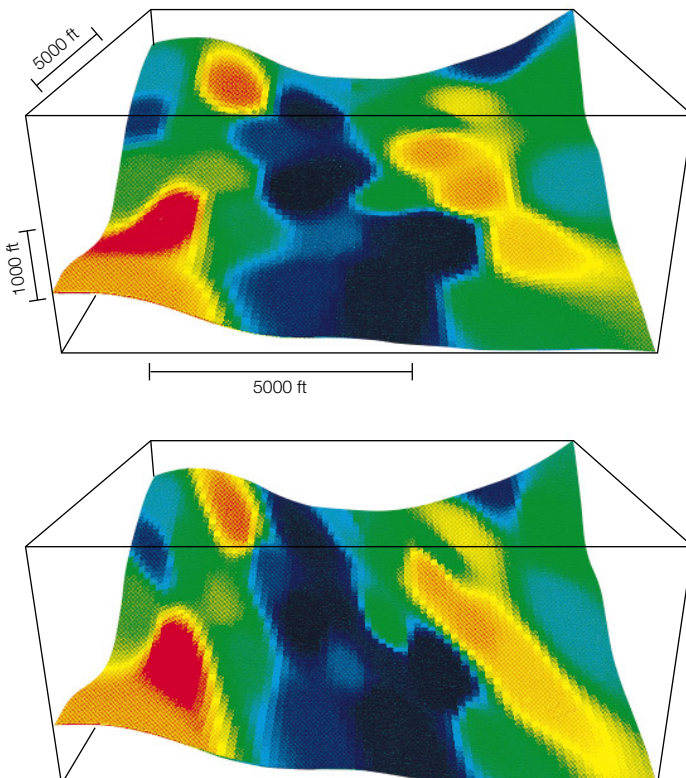
6. Chemali R, Gianzero S and Su SM: “The Effect of Shale Anisotropy on Focused Resistivity Devices,” *Transactions of the SPWLA 28th Annual Logging Symposium*, London, England, June 29-July 2, 1987, paper H.

For a review that deals with electrical biaxial anisotropy: Nekut AG: “Anisotropy Induction Logging,” *Geophysics* 59 (March 1994): 345-350.

7. Helbig K: *Foundations of Anisotropy for Exploration Seismics*, *Handbook of Geophysical Exploration Section 1 Seismic Exploration*, Volume 22. Oxford, England: Elsevier Science Ltd, 1994.

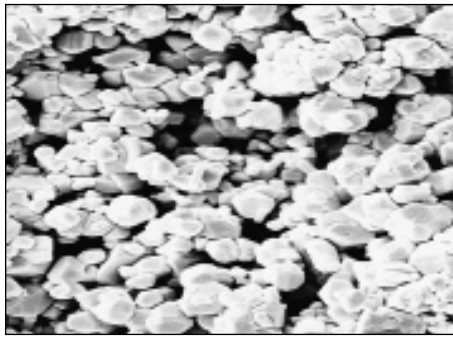
Anisotropy Vector	Heterogeneity Vector or scalar
Variation in a vectorial value with direction at one point	Variation in vectorial or scalar values between two or more points
Physical properties	Physical properties
<b>Dielectric constant, magnetic properties, permeability, resistivity, rock strength, thermal conductivity, wave velocity</b>	Density, <b>dielectric constant, magnetic properties</b> , natural gamma ray activity, neutron-capture cross section, <b>permeability</b> , porosity, <b>resistivity, rock strength</b> , saturation, <b>wave velocity, wettability</b>
	Composition
	Mineralogy
	Geometry
	Grain size, grain shape, sorting, packing, bedding, foliation, folding, jointing, faulting

□ **A scheme for classifying anisotropy and heterogeneity in the oil field. All parameters listed as physical properties can be thought of as intrinsic to the fluid-saturated rock, and varying, to one degree or another, with composition, geometry and state (pressure, temperature, saturating fluid composition and stress). Physical properties listed in bold can be both anisotropic and heterogeneous. Whether a parameter is a physical property or a state can depend on the time frame in which it is considered. Wettability may have an imposed direction, so when viewed at the microscale, it could be anisotropic. For example, a flat, solid surface with unidirectional scratches has an apparent contact angle (quantification of wettability) dependent on direction. A small drop will be elongated, like a rugby ball, instead of spherical.**

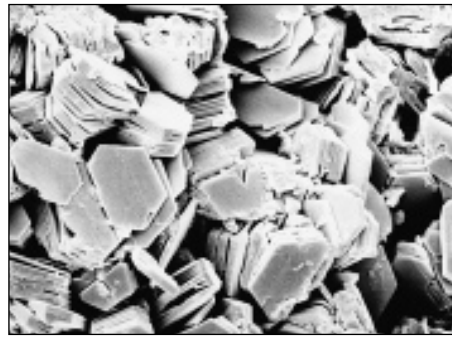


□ A three-dimensional representation of clay weight percent, which is closely related to permeability, for Block IV of the Bachaquero field, Lake Maracaibo. Red is high clay volume and blue is low. The isotropic model (*top*) assumes clay is evenly distributed around the well, and results in the bull's-eye pattern. With anisotropic interpolation of the same data (*bottom*), the bull's-eyes are converted into more realistic ellipses, following the trend of the elongated sands.

therefore the horizontal permeability, have a horizontal anisotropy of 3:1—value in the x plane is three times that of the y plane. Analysis of azimuthal variations in permeability indicated the principal axis of the anisotropy is at 340°. Factoring these data into the reservoir model converted the bull's-eyes into ellipses, with the main axis at 340°. The results of this model were transferred to a fluid flow simulator and indicated favorable locations for horizontal drainholes along the axes of these elongated sands. Orientation of these sand bars derived from this geostatistical method agrees with that derived from regional well data. The proof will come from the drilling program, scheduled to begin in early 1995.



20  $\mu\text{m}$



20  $\mu\text{m}$

□ Scanning electron photomicrographs showing aligned (left) and randomly oriented grains. In the left image, the alignment is apparent because the solution effect has dissolved intergranular cement. In the right image, layers are aligned within each kaolinite booklet, but booklets are randomly oriented. These are samples of Bassien limestone from the Mukta field, offshore Bombay, India.

domly packed (above). A series of different kinds of rock layers, each of which is homogeneous and isotropic, can be heterogeneous and anisotropic when viewed as a unit. This is typically the case for laminated sand-shale formations, in which each layer has a thickness of 1 cm [0.4 in] or less. A more recent insight is that resistivity anisotropy can also come from changes in grain size that affect saturation distribution, as well as from shaliness. This will be discussed later.

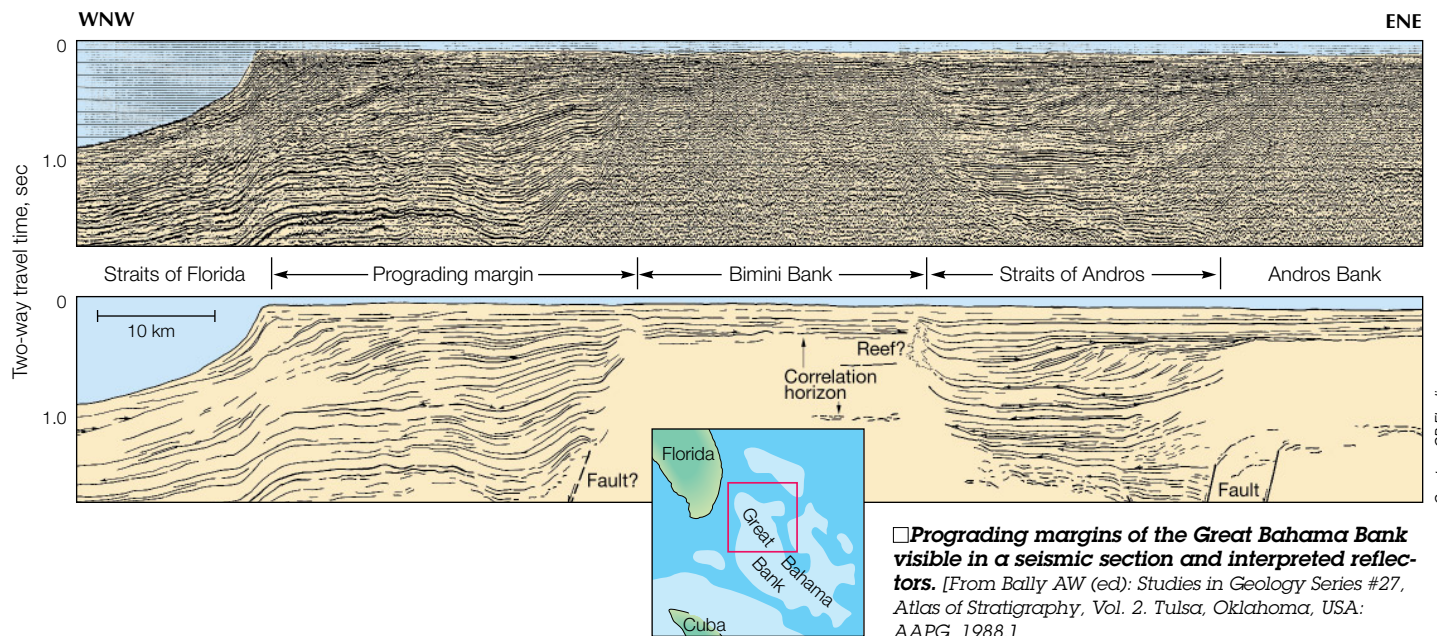
Thus, anisotropy on the scale of meters may escape detection in core measure-

ments. On the other hand, anisotropy on the scale of centimeters may escape detection by wireline-conveyed formation testing, which has such a large wavelength—several meters—that it averages out any observable anisotropy. From all measurements, reservoir engineers are usually after something much bigger—not the permeability of a core or of a single layer in a well test, but of a reservoir compartment, which can be on the scale of square miles. The ultimate goal is to quantify anisotropy at any scale as accurately as possible.

### Where Does Anisotropy Come From?

Anisotropy in the earth develops during deposition and during processes that take place after deposition. In clastic sediments, anisotropy can arise during and after deposition.<sup>8</sup> In carbonates, anisotropy is controlled mostly by fractures and diagenetic processes, and so tends to arise after deposition.<sup>9</sup> Anisotropy in carbonates may be predetermined during deposition, as evidenced by layering on seismic sections of slope deposits (*below*). Layering is thought to be induced by subtle changes in carbonate mineralogy, produced by variation in carbonate balance in the atmosphere and water. Changes in carbonate mineralogy result in changes in both texture and diagenetic potential, and consequently porosity and permeability.

For anisotropy to develop during deposition of clastics, there needs to be an ordering of sediments—in essence, some degree of homogeneity, or uniformity from point to point. If a rock were heterogeneous in the five fundamental properties of its grains—composition, size, shape, orientation and packing—anisotropy could not develop because there would be no directionality to the material.<sup>10</sup> Anisotropy at the bedding scale that arises during deposition therefore may have two causes. One is periodic layering, usually attributed to changes in sediment type, typically producing beds



Courtesy GP Eberli

of varying material or grain size. Another results from the ordering of grains induced by the directionality of the transporting medium.<sup>11</sup> The cause of this ordering and the ultimate architect of this deposition-related anisotropy is gravity.

Deposition of clastics always begins with movement of grains under the influence of gravity. Whether carried by water or by wind, grains tend to align in the direction of least resistance to the movement of air or water. At a gravel beach face, for example, repeated washing by waves may form oblong pebbles, and orient them with their long axes parallel to the wavefront. This kind of grain alignment can set up a preferential rock stiffness in one direction and a weakness 90° to that direction.<sup>12</sup> Eolian sands, for example, may have a greater grain-to-grain strength in the downwind direction.<sup>13</sup> There is also evidence that postdepositional tectonic deformation can result in shortening in one direction, changing the azimuthal distribution of grain assemblages.<sup>14</sup>

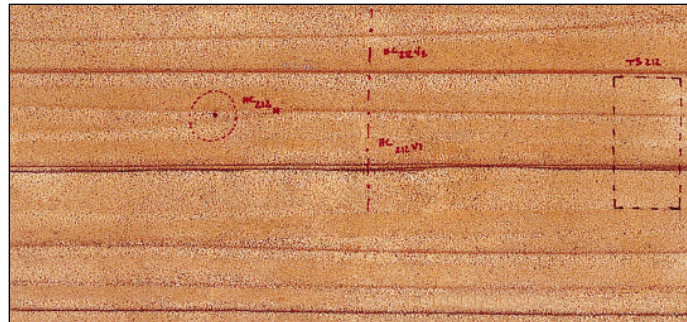
Under the action of gravity and transport, grains will also undergo sorting—separation by shape, weight or size. On riverbeds, the heaviest minerals concentrate where current velocity slows, typically in the troughs of riverbed dunes. In eolian deposits, different parts of a migrating dune are associated with distinct types of grain alignment and packing, each giving rise to different permeability anisotropies.<sup>15</sup> Pryor, at the University of Cincinnati, Ohio, USA, observed that in dunes and beaches, permeability increases with increasing grain size and decreasing sorting, but in river bars, permeability increases with increases in both grain size and sorting.<sup>16</sup> This is thought to be due to greater irregularity in packing in river bars compared to dunes and beaches. Anisotropy is therefore governed not only by variation in the type of material but also by variation in its arrangement and grain size (right).

In all depositional settings, variation in transport energy produces variation in the degrees of grain orientation, packing and sorting. Because topography varies laterally,

Mesaverde 255



Navajo 212



Cutbank 192



□ **Three faces of permeability anisotropy, with three different causes. The Mesaverde sandstone has a ratio of horizontal-to-vertical permeability ( $K_v/K_h$ ) of 170, caused mainly by laminations of shale (light-colored layers) in a sandstone matrix. The Navajo sample is a clean sandstone with a remarkably high permeability anisotropy of 276 caused by variation not in composition but in grain size and packing. Dark bands are tightly packed fine grains stained by ferric oxide. Light red intervals are more loosely packed larger grains. The Cutbank sample has a permeability anisotropy of only 2.7. Here, alternating dark and light layers are the result of changes in abundances of chert and other silicates. Anisotropy is caused by small but sudden changes in grain size and therefore sudden changes in porosity.** (From Auzeais et al, reference 17.)

8. Clastics are rocks composed of broken fragments of other rocks that have been transported some distance.

9. Diagenesis is all the physical, chemical and biological changes undergone by a sediment after deposition.

10. There are many schemes for classification of sediments. This one is from Griffith JC: *Scientific Method in Analysis of Sediments*. New York, New York, USA: McGraw-Hill, 1967.

11. Rajan VSV: "Discussion of the Origins of Anisotropy," paper SPE 18394, *Journal of Petroleum Technology* 40 (July 1988): 905.

12. Lynn HB: "Field Measurements of Azimuthal Anisotropy: First 60 Meters, San Francisco Bay Area, CA, and Estimation of the Horizontal Stresses' Ratio from  $V_{s1}/V_{s2}$ ," *Geophysics* 56 (June 1991): 822-832.

13. Nelson R: "Distribution and Character of Fractures in Sedimentary Basins and Their Importance for Hydrocarbon Reservoirs," *Expanded Abstracts*, 57th SEG Annual International Meeting and Exposition, Tulsa, Oklahoma, USA (1987): 854.

14. Giesel W: "Elastische Anisotropie in Tektonisch Verformten Sedimentgesteinen," *Geophysical Prospecting* 11 (1963): 423-458.

15. Goggin DJ, Chandler MA, Kocurek G and Lake LW: "Patterns of Permeability in Eolian Deposits: Page Sandstone (Jurassic), Northeastern Arizona," *SPE Formation Evaluation* 3 (June 1988): 297-306.

16. Pryor WA: "Permeability-Porosity Patterns and Variation in Some Holocene Sand Bodies," *AAPG Bulletin* 57, no. 1 (January 1973): 162-189.

so does transport energy. This produces lateral gradients in sediment texture, composition and geometry. Over time, stacking of lateral gradients produces a vertical gradient.<sup>17</sup>

Many causes of anisotropy induced after deposition are lumped under the heading of diagenesis—the physical, chemical or biological alteration of sediment after deposition and during and after lithification.<sup>18</sup> Compaction by overburden pressure can cause rotation of grain axes into the horizontal plane.<sup>19</sup> Compaction and dewatering of muds cause clay platelet alignment that gives rise to the pronounced anisotropy of shales (*page 40, bottom*). Realignment of grains may also result from their fracturing or plastic deformation. Grains can also undergo significant alteration from pressure solution—dissolution of grains at their contact points, causing flattening of formerly pointy contacts. This rearrangement of grain material results in reduction of pore space and welding of grains.<sup>20</sup> Pressure solution in carbonates can develop stylolites—tight, usually horizontal sawtooth surfaces that consist of the insoluble residue of dissolved material. Stylolites can act as laterally extensive flow barriers and appear as highly conductive (dark) layers on resistivity imaging logs. In sandstones, pressure solution features are not usually confined to narrow bands, but are dispersed over a larger volume, typically increasing with depth.

The third type of diagenesis, induced by burrowing animals, can take place in either carbonates or sandstones, and either enhance or undo depositional anisotropy. For example, burrows can perforate a clay layer, making a former flow barrier permeable. Burrows may also be confined to an already permeable sand, increasing its permeability and thereby amplifying the permeability contrast between a sand and a shale.

In the evaluation of anisotropy, diagenetic changes can't be ignored because they may significantly alter anisotropies established during deposition. For example, the control of grain orientation and packing over pore geometry, and thereby over permeability, may be destroyed by quartz overgrowth and clays that develop in place (*right*). This means that a model of permeability anisotropy may be flawed if it is based only on the depositional environment. The

exception, however, may be laminated beds. Here, diagenetic plugging of pores and pore throats may reduce permeability, but may not alter permeability anisotropy.<sup>21</sup>

Moving up from the grain-pore scale, the next level of feature is bedding. A bed is a typically defined as layer thicker than 1 cm that is distinguishable from layers above and below by a break in lithology, a sharp physical break, or both. Of significant interest to the reservoir engineer is the effect of bedding scale geometry, namely, a common phenomenon called crossbedding (*next page*).

A crossbed is a single layer or a single sedimentation unit consisting of internal laminae inclined to the principal surface of sedimentation.<sup>22</sup> Crossbedding is caused by migration of wave ripples on a sediment surface. Settings in which crossbeds develop include lateral shifting of tidal channels on intertidal flats, channel fill, beach and bar migration and eolian dune migration.

Crossbedding is of interest chiefly because when all crossbeds in a formation have one orientation, they have a much greater influence on fluid flow anisotropy than effects at the pore scale. Permeability is significantly lower across crossbed boundaries than along them. This permeability anisotropy does not arise from variation in material, since crossbedded formations are fairly uniform lithologically. Instead, it arises from large variation in grain size and therefore layering of high and low permeability.

The next scale up from bedding is folding and fracturing. Folding can reorient directional permeability established during deposition and initial diagenesis.<sup>23</sup> At the reser-

voir scale, however, the influence of folding on anisotropy may be a second-order effect. The first-order effect on anisotropy is fracturing, which can be associated with folding. Fractures tend to concentrate near the apex of folds, although they may concentrate elsewhere, since their distribution is governed by the strain distribution in the fold.<sup>24</sup> Fractures are distributed somewhat by the mechanical properties of the rock, tending to concentrate in low-porosity formations, which are more brittle.

Fracturing is a leading contributor to anisotropy induced postdepositionally, especially in carbonates. Either open or filled with porous breccia, fractures form zones with physical properties sharply different from those of the surrounding rock. Fractures by definition also have a well-defined directionality. These two features together—contrasting properties and directionality—make them potent generators of anisotropy at a scale as large as whole reservoirs, or as small as a core plug.

Healed, or mineralized, fractures have the same well-defined directionality as open fractures, but may not contrast as sharply with properties of the surrounding rock, and so may not generate anisotropy that is as pronounced or as detectable. For example, if the mineralizing material has an acoustic impedance or resistivity close to that of the surrounding rock, the fracture may not produce detectable anisotropy of acoustic wave velocity or resistivity. Most of the interest in anisotropy induced by open fractures centers on their effect on seismic energy and on fluid flow.<sup>25</sup>

### A Closer Look at Electrical Anisotropy

Of all the investigations into anisotropy in the oil field, some of the most intriguing recent work has been in the oldest arena of anisotropy—resistivity measurements. The earliest observations of anisotropy were noted by discrepancy between surface measurements in different directions. Later, discrepancies were noted between surface and borehole measurements, and between induction and laterolog measurements.<sup>26</sup> Several papers have reviewed advances in interpreting anisotropy from wireline resistivity measurements.<sup>27</sup> Now, much attention is focused on harnessing anisotropy interpreted from logging-while-drilling (LWD) measurements. Here is a brief description of electrical anisotropy and a historical perspective on some recent developments.

In electrical anisotropy, resistivity depends on the direction of current flow in the rock.



Courtesy, Julian Singer

□ **How diagenesis can affect permeability anisotropy. Pore-filling clay, such as this kaolinite, can destroy the permeability of this Bassien limestone.**

The effect of anisotropy on resistivity logs depends on the angle between the borehole and formation. In a vertical well crossing flat-lying beds, an induction tool measures horizontal resistivity, the current flowing parallel to bedding. Vertical resistivity, the current flowing normal to bedding, is always at least as much as, if not more than, horizontal resistivity.<sup>28</sup> Therefore the notion of a single number for true resistivity,  $R_t$ , becomes less useful as electrical anisotropy increases. A more descriptive approach is to think of two resistivities— $R_t$ , vertical and  $R_t$ , horizontal. With increasing well deviation, the contribution from the vertical component becomes stronger.

In a horizontal well through flat-lying beds, resistivity logs read higher because the contribution of vertical resistivity reaches a maximum. This, combined with polarization horns, results in correlation difficulties and overestimation of hydrocarbon saturation.<sup>29</sup> As long as the resistivity anisotropy remains incompletely quantified, the log analyst is working with a resistivity somewhere between the horizontal and vertical values, so hydrocarbon saturation cannot be precisely determined. The goal of accounting for resistivity anisotropy is to obtain a correct estimate of hydrocarbon saturation.

In one of the earliest papers on LWD resistivity measurements, in 1990, Anderson et al at Schlumberger compared the log response of wireline induction and 2-MHz resistivity LWD tools in dipping formations.<sup>30</sup> The work focused on development of a modeling code to calculate the degree of LWD signal distortion in thin, dipping beds. The code modeled the likely CDR Compensated Dual Resistivity response for any dip angle. The modeling code provided a good first approximation, and worked for



□ Crossbedding in a Devonian fluvial sandstone bar, from the Catskill delta, New York, USA.

Stefan Luthi photo

TIV isotropic resistivity. The authors showed that in anisotropic beds logged at dips above 30°, the shallow and deep resistivity measurements become a combination of vertical and horizontal resistivities. At this point, LWD resistivities behave differently from wireline induction resistivity in dipping

laminated or shaly formations: the deep and shallow LWD resistivity measurements each respond differently to anisotropy and therefore separate.

This year, a new method was published that derives both a vertical and horizontal resistivity from the two LWD resistivities and

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28. To avoid the ambiguity of using the horizon as a frame of reference, vertical resistivity is sometimes called transverse resistivity and horizontal resistivity is called longitudinal resistivity.

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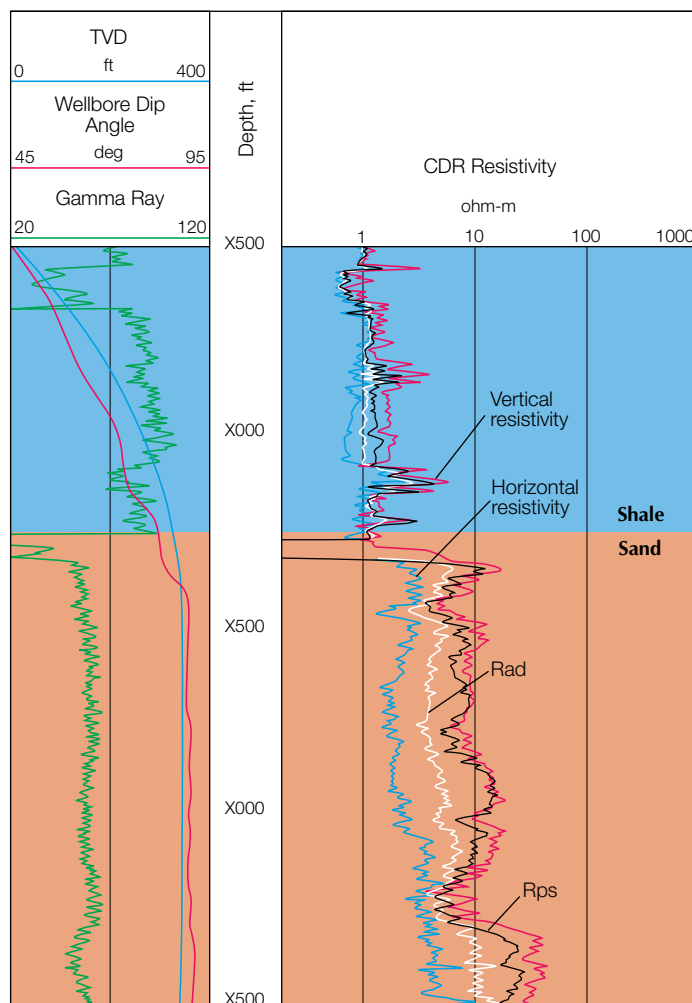
the known dip angle, iteratively using the solution from Moran and Gianzero, then both at Schlumberger.<sup>31</sup> This gives analysts their first opportunity to actually calculate the horizontal and vertical resistivities directly from log measurements—sometimes with surprising results (*right*). Large anisotropies (10:1 or greater) have been observed, and not just in shales and laminated sand-shale sequences. Some of the largest anisotropies are showing up in what have in the past been taken to be clean, homogeneous sands. In these formations, the anisotropy is thought to be due to variation in grain size and the close cousin of grain size, irreducible water saturation.

Without this processing, the original LWD resistivities are higher than the vertical well induction resistivity. The derived horizontal LWD resistivity, however, reconciles the directional well log with the vertical well log. Because it is the horizontal resistivity that corresponds to “ $R_t$ ” in offset vertical wells, this horizontal resistivity is used for correlation and to keep the borehole trajectory in anisotropic pay zones.<sup>32</sup> A similar approach to correct for resistivity anisotropy has been developed.<sup>33</sup>

Considering the case of laminated sand-shale resistivity, Hagiwara, now at Halliburton, has proposed another similar method using the horizontal and vertical resistivities of laminated sand-shale sequences to determine sand resistivity and net-to-gross ratio, making the simplifying assumption that the shale laminations are electrically anisotropic.<sup>34</sup>

In a parallel development, James Klein at ARCO Exploration and Production Technology has been studying the petrophysics underlying electrically anisotropic reservoirs. Building on work by Chemali and colleagues at Halliburton, he proposed a method to disentangle the resistivity of sand laminates (taken as being isotropic) from the anisotropic contribution of shales in a laminated sand-shale sequence. Input parameters are the volume of shale laminations, dip angle, and both the horizontal and vertical resistivity of the shale laminations.<sup>35</sup>

Klein’s on-going work, however, extends the understanding of electrical anisotropy beyond shales and sand-shale sequences.<sup>36</sup> He has been investigating the origin of electrical anisotropy in clean, seemingly homogeneous sandstones as observed by Leake,



□ **Electrical anisotropy in a horizontal Gulf of Mexico well. The horizontal and vertical resistivities, derived from CDR measurements, show a more pronounced anisotropy in the gas sand than in the shale. At most, shale anisotropy reaches 2.5, whereas sand resistivity, ranging from 2 to 10 ohm-m, has an anisotropy of about 5. The cause of resistivity anisotropy is suspected to be variation in grain size, and therefore in irreducible water saturation.**

formerly of Oxy USA, and Shray and Lüling, both of Schlumberger. The key insight concerns what appears to be homogeneous sandstone consisting of layers with more or less constant porosity but varying grain sizes and capillarity.<sup>37</sup> While this sandstone is isotropic when 100% water saturated, it becomes anisotropic when desaturated to reservoir conditions.

Klein and collaborator David Allen of Schlumberger Wireline & Testing in Sugar Land, Texas, USA are investigating this theory and its implications. Preliminary work suggests that resistivity anisotropy may be related to grain-size variation and therefore to permeability anisotropy. Less dramatic, but equally illuminating, is that resistivity anisotropy in the water leg will usually be different from that in the oil leg, as well as different in the invaded zone and uninvaded formation. These linkages between resistivity and permeability anisotropies are the fuel for exciting work. Resistivity anisotropy, once a bothersome headache, may one day provide clues to deeper understanding of permeability.

—JMK

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37. Capillarity is the action by which surface tension draws fluid into the interstices of a material.