How can anisotropy be used for reservoir characterization?

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Introduction

Interest in reservoir characterization continues to grow as emphasis within the petroleum industry shifts from exploration to improved recovery of existing fields with complicated heterogeneity. to contact mobile oil unrecovered or bypassed by previous injection procedures. The optimization of production using advanced secondary recovery programmes is critically dependent upon the detection of reservoir bodies, together with the distribution. alignment and density of heterogeneities on a variety of scales. Seismic measurements are of value in inferring spatial variability, using various assorted attributes derived from the wavefield, such as impedance, instantaneous phase and instantaneous frequency. These are widely used to delineate the structure of the reservoir and in many cases detect changes in the nature of the internal architecture. Indeed. many impressive images have been obtained with 3D seismics and this technique looks likely to continue its status in the popularity rankings. However, seismic measurements can lack sufficient detail to adequately resolve some important heterogeneities, and higher resolution is almost always desired for a greater definition of small-scale features. This requires a denser spatial sampling and sources with higher frequency and broader bandwidth, for which one must also contend with the problems associated with absorption in the near surface. Is there an alternative to this type of imaging, and if so, what?

During the last decade, a new brand of data analysis has evolved which has changed our perspective on seismic resolution, and may provide a suitable alternative strategy in usual surveying. This type of analysis may be used for traditional scalar (compressional) data. but more frequently' for the detailed information in elastic wave (multicomponent) data which is acquired by recording polarized sources (vertical and horizontal motions) with receivers aligned along the three mutually orthogonal directions. This takes advantage of scattering of long-wavelengths waves from heterogeneities which. although individually much smaller than a wavelength, produce sufficient forward scattering to alter the transmitted wavefield and carry an imprint of the common ensemble characteristics. The seismic effects of the scattering interference are simulated by an *equivalent homogeneous medium* which could replace the heterogeneous medium and produce the same wave behaviour. If the heterogeneities possess a degree or class of aggregate alignment, then this equivalent medium is anisotropic. The seismic effects of the scattering are then replaced by a homogeneous medium with up to 21 elastic constants in the elasticity tensor of the generalized Hooke's law (Hudson 1991). Using this concept we may gain insight into the geometry and density of the internal structure of the rock. facies units. sand channels, cross-bedding, or other reservoir components, but sacrifice some detail on their exact spatial distribution and their individual seismic expression within the group due to the averaging process. This powerful concept allows complicated geology to be analysed using processing tools for a homogeneous structure, whilst retaining the impact of the complexity and the level of description.

But what specific reservoir features can we usefully image using this new approach that cannot be imaged with traditional 3D seismic, and are these new images useful? The answers to these questions depend upon our understanding of *reservoir heterogeneity* and its influence on the seismic response. To define this more fully we must address:

1 the particular scalelength distribution of the reservoir features relative to the seismic wavelength;
2 factors which define and classify the various types of scattering behaviour; and finally;
3 the way in which these consort to form the composite seismic response.

Scalelength of heterogeneity

Although the term heterogeneity is generally accepted to refer to a lack of spatial uniformity for different types of reservoir complexity (whether structural, lithological. thermal or related to flow) manifest as various scalelengths, it is clear that different disciplines still view these scalelengths from the basis of the type of data they use and their historical objectives. The exploration seismologist may have the visual impression from reflection images of several effectively homogeneous units of a kilometre or so in size containing embedded faults

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or fractures, the reservoir geologist may refer to individual facies units within the reservoir facies units within the reservoir on the physical scale of 10 m to 1 km with the lower limit just resolvable by 3D seismic, whilst rock physicists tend to visualize the microstructure of the individual rock units. Clearly each viewpoint has a role to play in production monitoring and reservoir surveillance. and none is incorrect, but there is a need to unite these in a common framework for interpretation of the reservoir processes. To place equivalent medium theory in its proper context. the various features of reservoir architecture must be displayed together with the range of wavelengths (λ = 1 cm to 1 km) used in most seismics (Fig. 1). Scalelengths for heterogeneities in a reservoir setting can vary from large basin description (defined here as *megascale)* relating to the field wide variability across depositional systems. to the *macro-scale,* where distributions of lithofacies on the well-to-well scale and the geometric distribution of reservoir compartments is important, the cross-bed mesoscale with features such as ripple laminations. to the smallest *microscale* which includes grains. pores. crystals. minerals or even pore throats (McDonald and Tyler. personal communication).

Traditional seismic image those heterogeneities with scalelengths (a) obeying the inequality $a/\lambda > 1/4$. this being a rough rule-of-thumb for the separation between two features before their individual identity us lost-the exact value of this limit is still hotly debated. Here we use a/λ instead of the more correct and formal mathe-

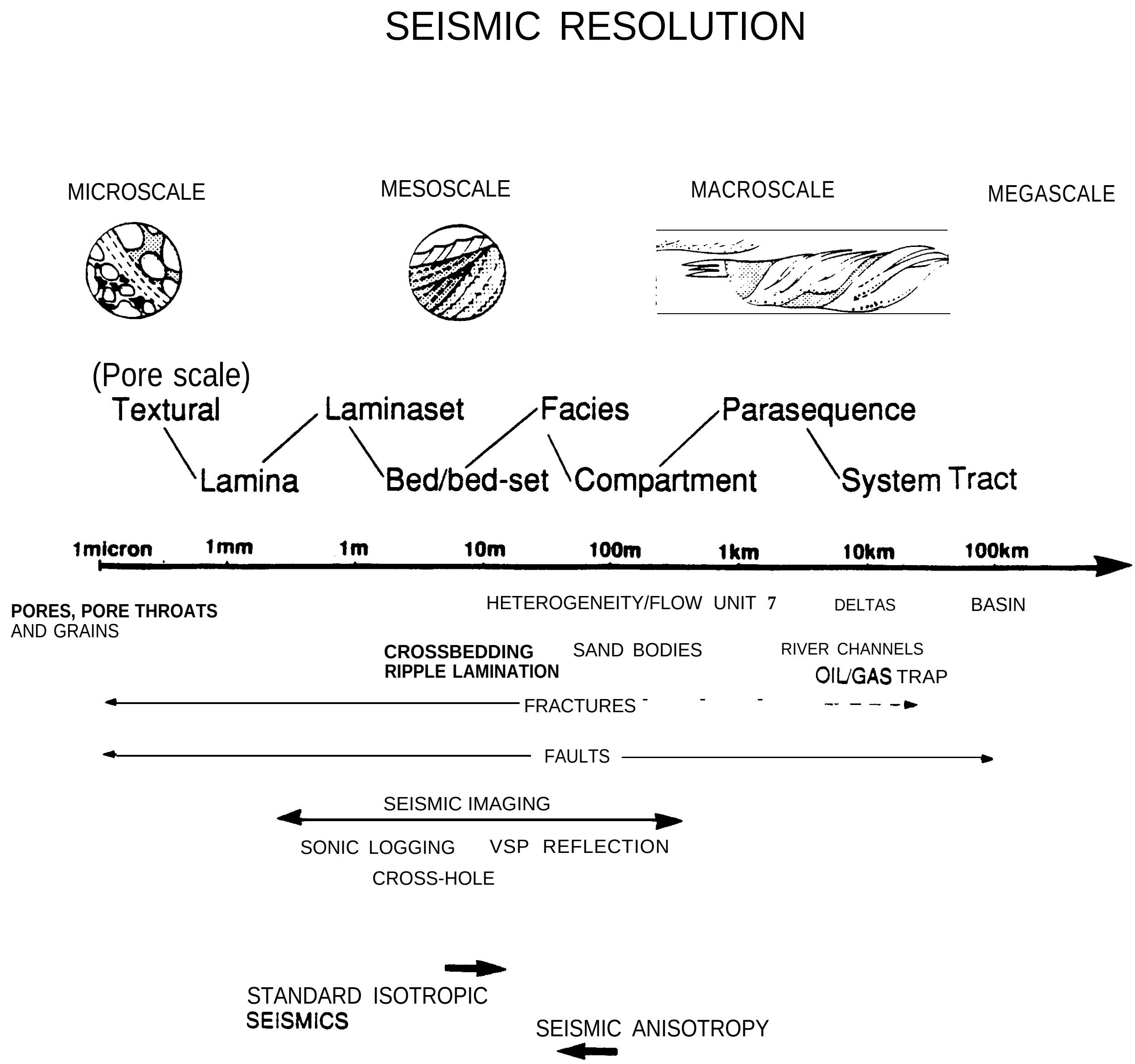

Fig. 1. Scalelengths of various heterogeneities affecting reservoir processes compared to seismic wavelengths. Standard seismics image structures at large scalelengths ($a/\lambda > 1/4$). whereas the phenomenon of seismic anisotropy helps to image smaller scale features ($a/\lambda < 1/8$). The terms *microscafe, mesoscale. macroscale* and *megascale* refer to generic scalelength ranges, with the more geologically specific terminology also being given.

matical product *ka*. which appears in most fundamental theory. as this ratio is easier to visualize. Data interpretation in the high-frequency range utilizes ray theory to obtain structural and lithological information from seismic boundaries assumed to lie in a piecewise homogeneous medium. with each discrete event being the result of high frequency constructive backscattering. Equivalent medium theory has a range of validity to the left of the operative seismic wavelength (current laboratory work suggests the limit is a λ < 1 8). so that features with scalelengths smaller than the seismic wavelength are 'resolved'. In principle. it seems that the role of equivalent medium theory could be to fill the lower scalelength portion of the seismic resolution (apart from a small gap), and so provide information on a complete spectrum of reservoir features which includes the characteristic dimensions of many fundamental flow units. Unfortunately nature is not that simple. and there are other competing phenomena which may make this interpretation difficult; these are discussed below.

Boundaries of scattering behaviour

Not all scattering behaviour fits neatly into either of these two categories, and the contrasting scattering theories actually represent two end members of a variety of regimes. The limitations of the long-wavelength approximation are governed by the boundaries of these different regimes, which are controlled to some extent by *a* ii. the pathlength *L* travelled by the waves through the scattering region (here we use the parameter L/λ), but also by the heterogeneity strength (magnitude of departure from the background model), geometry, and nature (physical manifestation as a change in velocity. density. impedance or some complicated boundary condition involving, for example, a fluid flow process).

Dependence upon scalelength and pathlength

This dependence can be understood by constructing a scattering classification similar to Aki and Richards (1980) (Fig. 2), with which we may begin to appreciate other scattering phenomena. For example, moving along the solid vertical line AB in Fig. 2 from A to B takes us through a regime where ray theory is applicable towards the equivalent medium regime (B) at a fixed pathlength (L/λ). We reach a regime where diffraction theory becomes important when the seismic wavelength begins to interact with obstacles which limit the wavefront and migration is required to reposition the images from the diffraction patterns to the edges of these reservoir features. For even smaller scalelengths, between a fraction of a wavelength and several wavelengths, we encounter an intermediate regime where there is strong multiple scattering. This area relates to the phenomenon of localization, where there is significant multiple scattering of transmitted waves and trapping of elastic wave energy in certain parts of the

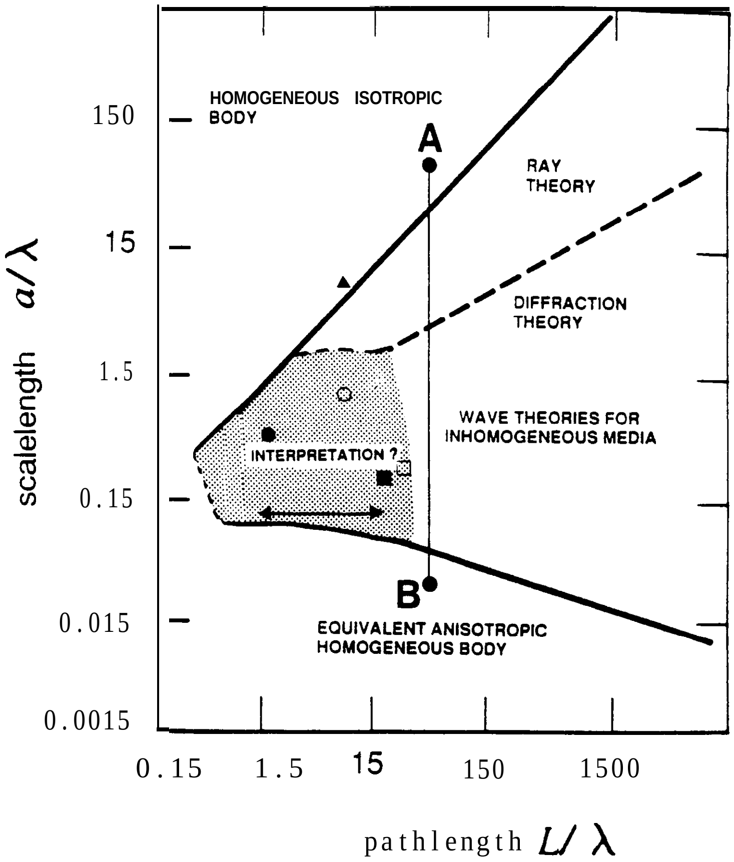

Fig. 2. Broad classification of various scattering regimes. adapted from Aki and Richards (1980). using wavelength-normalized scalelength (a λ) and pathlength (L λ). Vertical reference line AB is drawn between ray theory and equivalent medium regimes. Results in the shaded are particularly difficult to interpret or predict. and in principle present the biggest challenge to seismic interpretation, yet include many of the current observations. Symbols correspond to approximate positions of laboratory and numerical measurements: Rathore et *al.* (199 l)-solid circle; Ebrom er *al.* (1990)—arrowed line; Ikelle *et* al. (1993)—open square; Kerner (1992)—solid square; Liu *et al.* (1993b)—open circle: Mueller (1992)—solid triangle.

medium. This is characterized by rapid dispersion and high attenuation in the seismic data, and a wave behaviour strongly dependent upon the pathlength. A great deal of theoretical efforts has been expended to understand this zone, and predictions are now possible for the larger pathlengths (the familiar O'Doherty–Anstey formula applies for small fluctuations in this zone: Shapiro *et al.* 1993). This is also where coda waves generated by large contrast changes along propagation paths from local earthquakes have been modelled successfully using statistical methods based on backscattering or diffusion models (Herraiz and Espinosa 1987). However, for small pathlengths the physical processes become more chaotic and less predictable, and it may be difficult to interpret the data (shaded area in Fig. 2). Here, it is usual to model the waves using finite difference or finite element procedures. This regime is particularly important as pathlengths (L/λ) for a typical surface seismic survey with λ = 100 m are around 1 to 20

(L = 100-2000 m). and the scalelengths (a λ) for the heterogeneities which we believe control fluid flow pathways and access to unrecovered mobile oil are between 0.01 and 10 (a = 1-1000 m).

Dependence upon heterogeneity strength

The positions of the boundaries of this classification. defining our ability to predict the scattering behaviour using exact mathematical solutions. depend markedly upon the strength of the scatterer. For example, with weak heterogeneities the zone of localization is quite small and predictions may be made at both the high and low frequency ends using a suitable pertubation approach such as the popular Born approximation (which violates energy conservation). As the contrast in the heterogeneity diminishes further, the effect of localization decreases and the distinction between geometric ray theory. diffraction, localization and an equivalent medium theory becomes less obvious. A third axis of scattering strength must therefore be imagined in Fig. 2, with the shaded region becoming a conical shape. the tip directed towards progressively weaker scattering strength.

Given the classification in Fig. 2. we see that interpretation using the concept of an equivalent medium now rests upon the positions of the upper and lower boundaries relative to the subsurface heterogeneity imaged at the seismic wavelengths in a particular dataset. and our major concern is the extent and effect of the central zone of localization where the wave behaviour is unpredictable. Another concern, is that our perception of heterogeneity based upon Fig. 1 suggests that all scattering processes may be present simultaneously in a typical seismic dataset generated by a source with a finite bandwidth intersecting these regimes. What apparently looked like an extremely useful concept appears to be wavetype and data specific. Further investigation is required to consider how far the concept may be pushed in actual data before our analysis and interpretation breaks down.

Numerical and empirical boundaries for scattering behaviour

It is interesting to note that some observations have already been made for heterogeneity distributions known to be classified within the localization regime. For example, the laboratory experiment of Rathore *et al.* (1991). whose principal aim was to test different equivalent medium theories, was performed using synthetic sandstones in which were embedded dry disc-shaped voids of similar size to the source wavelength. Although significant diffraction and dispersion effects were observed. the phase velocities agreed with predictions from equivalent medium theory, with an observed shear-wave birefringence of 11%. The scalelengths, pathlengths, and wavelengths used place this experiment in the shaded are of Fig. 2 (solid circle). Kerner (1992) also concluded that an equivalent anisotropic medium can still fit first break velocities for 1 D media exhibiting cyclic and transitional layering, with pathlengths L λ of 20–40. and scalelengths a λ of 1 6 (open square in Fig. 2). There was a strong velocity variation of 23-33%. Ikelle *et al.* (1993) show a similar agreement for 2D randomized media with an a λ of 0.2 in the smallest dimension and L λ of 30 (solid square in Fig. 2). These contrast with the controlled laboratory experiment of Ebrom *et al.* (1990) using laminated and fractured synthetic materials. where a threshold scalelength (mean normalized layer thickness) of around λ 8 is obtained across pathlengths L λ between 2 and 20 (arrowed line in Fig. 2) for phase velocities. This experiment is close to our predicted boundary between strong scattering and equivalent medium regimes. The onset of the limiting conditions in these experiments could be observed as a noticeable increase in the dispersion and associated attenuation, although it must be noted that this behaviour is also highly dependent upon the constituent materials.

Further evidence has come from observational studies from VSP and surface seismics. Velocity and polarization variations of the leading shear-waves in field observations from a shallow reverse VSP (Liu *et al.* 1993a) with an L/λ of 10 have shown remarkable agreement with equivalent medium theory, in spite of evidence of an intermediate-scale fracture system (a, λ = 1) (open circle in Fig. 2). Dimming of reflected shear-wave amplitudes in shear-wave sections (L/λ = 10) from large fractures in the Austin Chalk (a/h = 10) have been successfully interpreted by Mueller (1992) using equivalent medium theory (solid triangle in Fig. 2). There also appears to be an ever increasing body of observational evidence from exploration and earthquake seismology to support polarization alignments for the leading shear-wave (and partial support for time delays between split shear-waves) which may be interpreted by a simple anisotropic equivalent medium. This appears to occur for a wide variety of geological scenarios and geographical locations (Crampin and Love11 1991), even though there are a vast range of different scalelengths and types of heterogeneity.

All of the above results suggest that even when the long-wavelength limit has quite clearly been violated, there are some circumstances where the dynamic and kinematic parameters of the wavefield may still relate to some equivalent medium, except perhaps for obvious pathological cases. This does not necessarily imply that the different measurements from the wavefield such as velocities, polarizations, and time delays, which are dependent on different properties of the wavefield and take different averages of the medium, relate to the *same* equivalent anisotropic models, and this may not be the case in complicated structures. The relationship may bear some similarity to what is presently being uncovered regarding resolution using standard seismic interpretation (Jannane et *al.* 1989). The above observations highlight a dependence on the *nature* of the heterogeneity, and a requirement to model more exactly the seismic interaction with realistic geological and petrophysical conditions. The effect of the nature of the heterogeneities on the boundaries of Fig. 2 has not yet been fully explored and remains an area for future research development. However. given the above observations on face value it does seem potentially possible to use equivalent medium theory to resolve some of the reservoir features we initially thought unresolvable with seismic data. Before we can be fully prepared to address this finding in the context of this paper. we must also consider another pressing problem: out of the spectrum of possible candidates in Fig. 1. what set of heterogeneities do the seismics image. and consequently will these images be of ultimate value?

Composite seismic response

For a typical seismic dataset with a source generating a range of wavelengths, the wavefield will interact with the various reservoir-dependent heterogeneity distributions in Fig. 1, and the data will represent a mixture of the scattering regimes. As heterogeneities from smaller scales are larger in number they may contribute as much to the data as a smaller number of large-scale features. and so with a large number of potential candidates. what feature, if any. dominates the effective medium response? Clearly. two influential parameters are the scattering strength of the individual scatterers and the particular wavetype analysed. For example, with compressional waves, dry open fractures dominate over those with a water, oil or cement fill, or for shear-waves the directional scattering is more distinctive for thin fracture asperities than those with a larger effective aspect ratio. The multicomponent seismic response of each geometric group of heterogeneities may thus be different. This. and other results, are particularly important in interpreting the multicomponent seismic response. as not all reservoir features can be satisfactorily correlated to productivity. For example. in a fracture-controlled reservoir some fractures may be sealed by diagenetic mineralisation, and others may divert a flood from its planned course or provide channels for early breakthrough. The composite seismic response must also depend upon the way each class of heterogeneity such as pores. fractures. and facies units are organized within the medium. There is growing evidence of a fractal distribution for some aspects of the fault system (Yielding et *al.* 1992). However. as the spatial distribution of small-scale features must be constrained to some extent by the distribution of larger scale features. the reservoir could be organized into groups of entities determined by the largest physical scalelength downwards. There is some evidence to support a subdivision into a number of isolated fractal families (D. Schwartz. personal communication) or geological subunits with a progressive sequence of characteristic scalelengths (Brodov and Mushin 1985). With a large number of different candidates. we are left wondering how the various scattering processes combine. and what do seismics really tell us'?

The work of Liu et *al.* (1993b) gives some indication of how we should visualize combinations of different heterogeneity sets. They conclude that for observations of the shear-wave transmission response along raypaths inside a cone of angles within 36° of the vertical. a biplanar microcrack ($a/\lambda << 1$) model is similar to a monoplanar microcrack system. except when the two strike directions are orthogonal. The composite monoplanar microcrack system possesses a crack density weighted-mean of the individual crack strikes. and an additive crack density. So. with only a finite range of ray directions sampling the anisotropic behaviour. one may actually fail to observe the added behavioural complexity of other model combinations or attribute the fluctuations to noise. It follows that the seismic response of arbitrarily aligned heterogeneities may be seismically difficult to distinguish from a single aligned distribution for many of our standard seismic acquisition configurations, and may be satisfactorily fit by a monoplanar crack model. This may explain, in part. why considering the vast numbers and variety of heterogeneities which are potential candidates for dominating the scattering. it is surprising that the effective seismic response appears to fit, in general, by a single effective medium with a hexagonally symmetric anisotropy. This observation does not imply or exclude a physical model of this simplicity, but simply that an effective anisotropy of this form is suitably close to the measured characteristics of the seismic wavefield so that the distinction cannot be made. The concept of a simple anisotropic system as a fundamental building block for the effective seismic response of a medium containing many different heterogeneities is of considerable value to data processing and interpretation, but does not help address the pressing issue of how best to image those reservoir features which determine fluid-flow behaviour and establish links to productivity. So how can we use the equivalent medium concept to our advantage and what generic rules are available to help us during interpretation?

At present. we can achieve results through a judicious selection of appropriate data, where particular subsurface features are known to clearly dominate. One recent success of this strategy, mentioned above, is the detection of fracture swarms known to exist in the Austin Chalk in Texas. using the dimming of relative shear-wave amplitudes (Mueller 1992). Here. a direct correlation can be made between the anisotropic shear-wave behaviour and natural fracture distributions which control fluid storage and mobility. This approach has been successful in targeting horizontal wells. Another approach is to use anisotropic analyses in combination with standard 3D reservoir seismics (Davis *et al.* 1993) to provide an integrated and structurally constrained multicomponent interpretation. Other successes from VSP experiments have been noted by Crampin and Love11 (1991). However. if the anisotropic equivalent medium concept is to be of more general value, it may be necessary to design suitable experiments to properly 'tune in' to the distributions of interest using appropriate raypath directions. pathlengths. and frequencies. to image a desired group of heterogeneities. If such designs are to be successful. it is essential that the detailed statistical character of the heterogeneity population be calibrated. This must be achieved using geophysical and engineering measurements in the borehole, and surveillance for temporal variations of the anisotropic behaviour in cross-well experiments, necessitating a stronger cooperation between geophysicists. geologists and reservoir engineers. To design surveys for enhanced resolution of reservoir features, there is still a requirement for pushing the limits of downhole source and receiver technology to higher and higher frequencies for better definition, but the equivalent medium concept demonstrates that there is now also an argument in favour of lower frequency seismic measurement to corroborate structural information from robust images interpreted by ray theory. Such integrated experiments may help to achieve an answer to the open question regarding which wavefield characteristic is most indicative of the reservoir properties which govern the fluid flow structure, and how can we make best use of seismic anisotropy for reservoir characterization.

Conclusions

How can anisotropy help?

The concept of an equivalent medium for the seismic scattering process acts as a seismic pseudofunction for reservoir complexity. It is a valuable concept for maintaining a high level of description for the internal geological structure on a wide variety of scales of interest to the reservoir engineer and is of immediate value in providing:

1 a powerful image of heterogeneity distributions with some degree of alignment, which are known to dominate the seismic data, through inversion of the appropriate seismic wave properties for an anisotropic equivalent medium: and

2 a suitable mathematical framework for the modelling, processing and analysis of the seismic wavefield in complicated heterogeneous reservoirs.

Whilst it is generally true that not all heterogeneity scalelengths are suitable for treatment by equivalent medium theory (strictly long wavelengths) and seismic measurements may be complicated by intermediate-scale features close to a wavelength, particularly small pathlengths, the range of applicability for this approach may not be as restrictive as we initially described. A number of laboratory, field and numerical studies performed over the past few years indicate that this concept may be pushed beyond its mathematical upper limit as perceived by interpretation of basic velocity and polarization measurements along specific propagation directions. These observations do give hope that. as with many areas of seismology, a simple theory can make useful predictions. even though the underlying mathematical assumptions are not rigorously satisfied. They further suggest that it may be possible to simulate the scattering processes over all scales by overlapping fundamental combinational units. with different weightings for wave characteristics such as first break. velocity. polarization. attenuation and dispersion. perhaps by a group theory such as that of Schoenberg and Muir (1989).

Future directions

Although geological. geophysical. and engineering measurement technologies span much of the production scale, from 1 cm resolution in well logs to 10 m lateral and vertical resolution in 3D seismic surveys. predictions away from the borehole must be made using surface seismic data with limited resolution. One major problem is in relating scales from these various measurements and what is required is a consistent theory to unite these scales, providing a more effective extrapolation of borehole measurements. The anisotropic equivalent medium may help to relate the measurements from one scale to another if the relationship between the scalelength distribution (and hence anisotropic elastic constants), operative seismic frequency and the fundamental wavefield measurements can be properly defined. Significant progress has already been made in this direction, with the development of an analytic framework suitable for all scalelengths and large pathlengths in 1D media (e.g. Shapiro et *al.* 1993). Future simulations of realistic geological expressions by an equivalent medium are no doubt possible as the introduction of complex and frequency-dependent elastic constants make the anisotropic model very versatile. Until then. anisotropy remains an invaluable aid for estimating fracture details, processing seismic waves propagating through heterogeneous media, and a useful tool for simplifying complexity whilst not missing out on all the information. It has considerable untapped potential. and is still under-exploited in reservoir characterization.

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