TIGHT-GAS PRODUCTION: A GUIDE FOR GEOTHERMAL FIELD EXPLORATION & DEVELOPMENT?

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SUMMARY - Mainstream oil and gas exploration and production is typically dominated by finding and developing localised *in situ* structures capable of ponding buoyant hydrocarbons that at distant times migrated from distant source formations. The mechanics of past oil and gas displacement are not typically regarded as of interest. Indifference to the mechanics of *in situ* fluid movement is, however, not true of production from "tight-gas" (low permeability) formations in western Colorado, USA or the Cooper Basin, South Australia. The source of tight gas is generally known to be coal measures lying directly below the reservoir formations, and gas production is widely understood to be dominated by the erratic and unpredictable vagaries of *in situ* fracture permeability at both whole-field and interwell scales.

Tight-gas production has important parallels with geothermal energy production:

- The basal energy source is local and known in advance;
- Fluid movement is largely by buoyancy drive;
- Cap-rock formations are important for ponding the basal fluids;
- Multi-km-scale *in situ* fracture systems connecting the basal source to reservoir depths determine local field prospectivity;
- Km-scale fracture structures are key to individual well performance;
- Fracture system flow heterogeneity is poorly understood and rarely if ever integrated into a comprehensive field production plan.
- There is no good reason why *in situ* fracture-borne flow heterogeneity continues to be ignored.

In an important respect, however, tight-gas fields differ from geothermal fields: the former are moderately rich in well-log and well-core data, while the latter are poor in both. Experience with tight-gas well-log and well-core suggests that future geothermal exploration and development make provision to acquire and interpret well-log and well-core data for both regional and local understanding of *in situ* fluid flow in fracture-networks. The moderate tight-gas well-log and well-core data resources are closely related to the vast well-log and well-core resources of main-stream oil and gas field exploration and production. These vast resources make a very clear statement of the nature of *in situ* fracture heterogeneity in crustal reservoirs. Application of the perspective on fractures derived from mainstream oil and gas field data to tight-gas flow heterogeneity indicates that geothermal field exploration and development can materially benefit both conceptually and practically by systematically coring and logging wells.

- Conceptually: fracture-related *in situ* crustal heterogeneity obeys a universal form of scale-independent spatial fluctuation at scales from grain-size to reservoir-size; as such, the spatial details of fracture heterogeneity cannot be inferred from small-scale sampling; reliable reservoir structure knowledge requires interwell-to-reservoir-scale observation in both exploration and production phases of energy delivery.
- Practically: the physical basis of *in situ* crustal fracture heterogeneity is known and can be incorporated into exploration and production scenarios; it is possible to simulate electromagnetic and seismic investigations and/or time-lapse imaging/monitoring of prospect flow structures, while fluid/heat flow numerical simulations can be conducted with current technology to provide larger scales and higher efficiencies in geothermal energy delivery.

1. DISCUSSION

1.1 Conceptual View of Fracture and Flow Heterogeneity in Crustal Rock

Crustal rock is subject to two pervasive features related to fractures and fluid flow. The first feature is that Fourier power spectra of most geophysical well-logs scale inversely with spatial frequency k,

$$S(k) \propto 1/k^{\beta}, \beta \approx 1 \pm 0.2.$$

The scaling law for *in situ* geophysical fluctuations holds variously for sonic, resistivity, gamma activity, mass density, neutron scattering, and chemical abundances over 5 decades of scale length (~cm to ~km) in sedimentary and crystalline rock for both horizontal and vertical wells. The power-law nature of *in situ* geophysical property fluctuations recorded in well-logs is most easily understood in terms of long-range spatial-correlation of essentially random fluctuations in grain-scale percolation-fracture density. The spatial correlation of grain-scale fracture density fluctuations occurs at all scale lengths from mm (grain dimensions) to km (reservoir dimensions).

The second feature of crustal rock is that well-core sequences of porosity $\varphi(i)$ and permeability $\kappa(i)$, i=1,2,3…n, are observed to fluctuate in space in close association. If well-core poroperm sequence fluctuations $\delta\varphi$ and $\delta\log(\kappa)$ are reduced to zero-mean-unit-variance form, then the association can be simply expressed as

$$\delta\varphi \approx \delta\log(\kappa).$$

This relation is valid at the level of 85% ± 8% cross-correlation over a sample of many thousands of well-core data. The observed physical relation is equivalent to a simple mathematical statement $\delta n \approx \delta\log(n!)$ if n represents the number of grain-scale fractures per unit volume and the factorial $n!$ captures the combinatorial nature of fracture-connectivity for percolation flow in spatially-correlated grain-scale fracture populations.

These two well-log/well-core derived empirical expressions for *in situ* spatial fluctuations in crustal rock given an explicit means of estimating fluid flow heterogeneity expected for crustal reservoirs. In particular, the two expressions imply that well productivity will vary greatly in space and time, and that the ability to infer the location of high productivity wells is extremely limited without extensive and systematic large-scale observation of the reservoir over space and time.

The distribution of production wells in the Ohaaki geothermal field (Fig 1) illustrates the spatial variability characteristic of crustal reservoirs. Wells designated as producers are marked by red dots, with a similar range of wells not regarded as producers shown as black dots (wells regarded as monitor wells are shown as 'X's). In the two sectors of the Ohaaki geothermal field, production wells are clearly commingled with non-production wells. What controls the observed spatial distribution of well productivity?

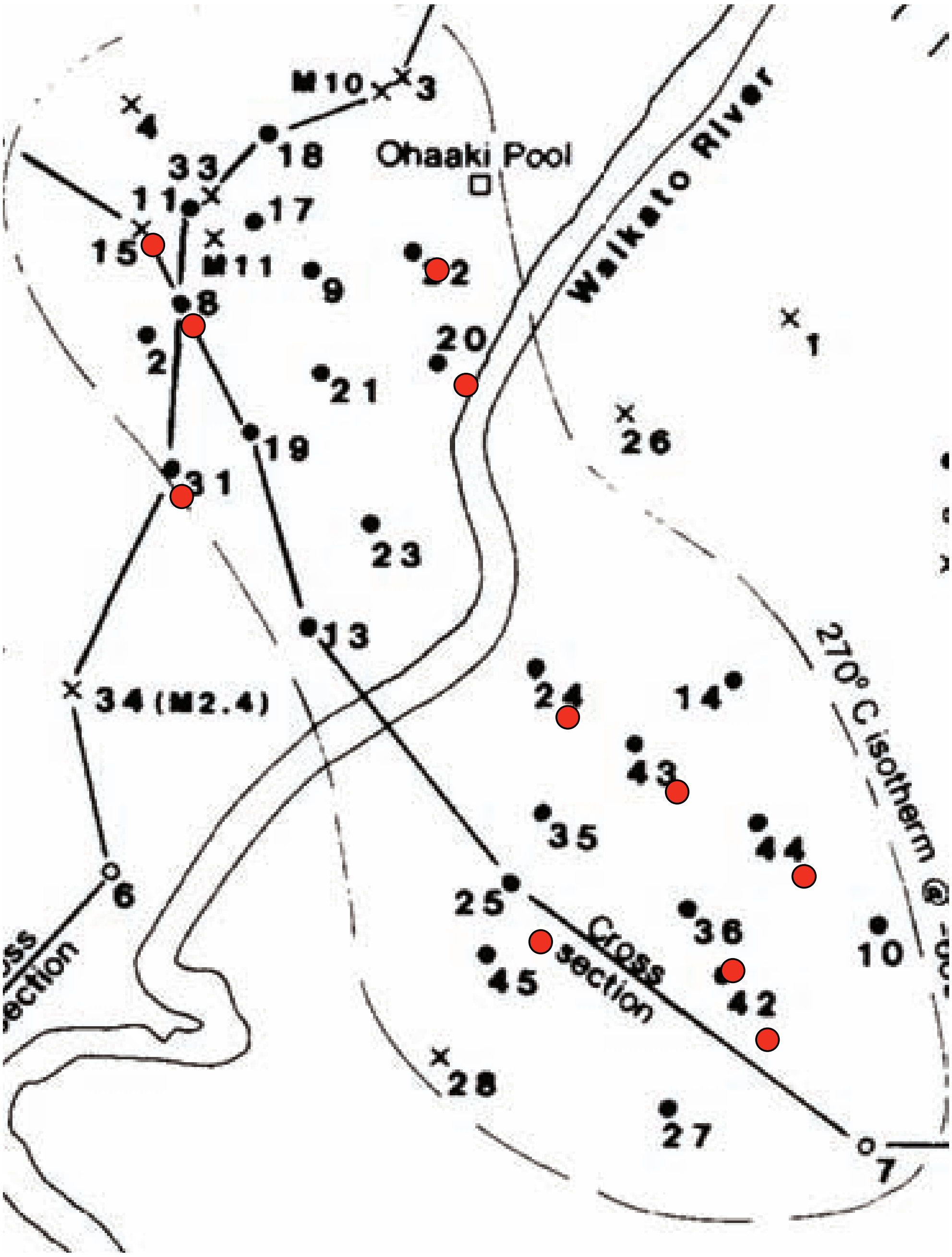

Figure 1 – Location diagram of Ohaaki geothermal field wells. Wells denoted as producers are shown as red dots; similar wells not regarded as producers are shown as black dots. Monitor wells are shown as 'X's

Figs 2 and 3 illustrate how the power-law scaling fracture-density heterogeneity characteristic of crustal rock can create spatial regions of high well productivity intimately commingled with spatial regions of low well productivity. Production wells (asterisks) are associated with warm colours denoting high fracture-density with high degrees of percolation-fracture connectivity, while non-production wells (circles) are associated with cool colours denoting low fracture-density with low degrees of percolation-fracture connectivity. The spatial fluctuations in Figs 2-3 are constrained only by well-log power-law scaling law $S(k) \propto 1/k$ and fracture-control of permeability $\delta\varphi \approx \delta\log(\kappa)$ derived from well-core data.

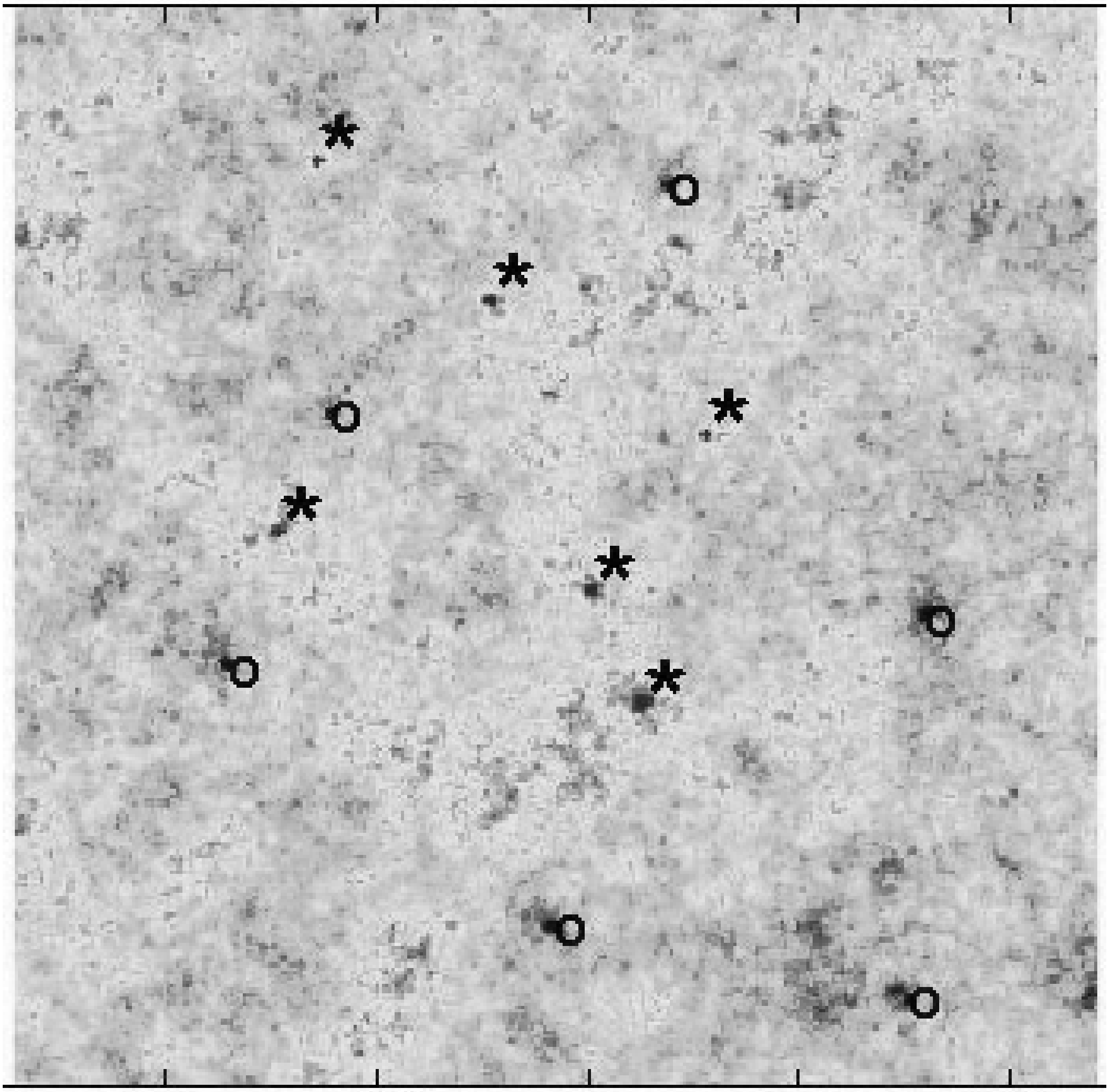

Figure 2 -- Ohaaki East production (asterisks) and non-production (circles) well distributions embedded in a stochastic fluctuation environment of power-law-scaling spatial fracture heterogeneity and percolation fracture-control of permeability.

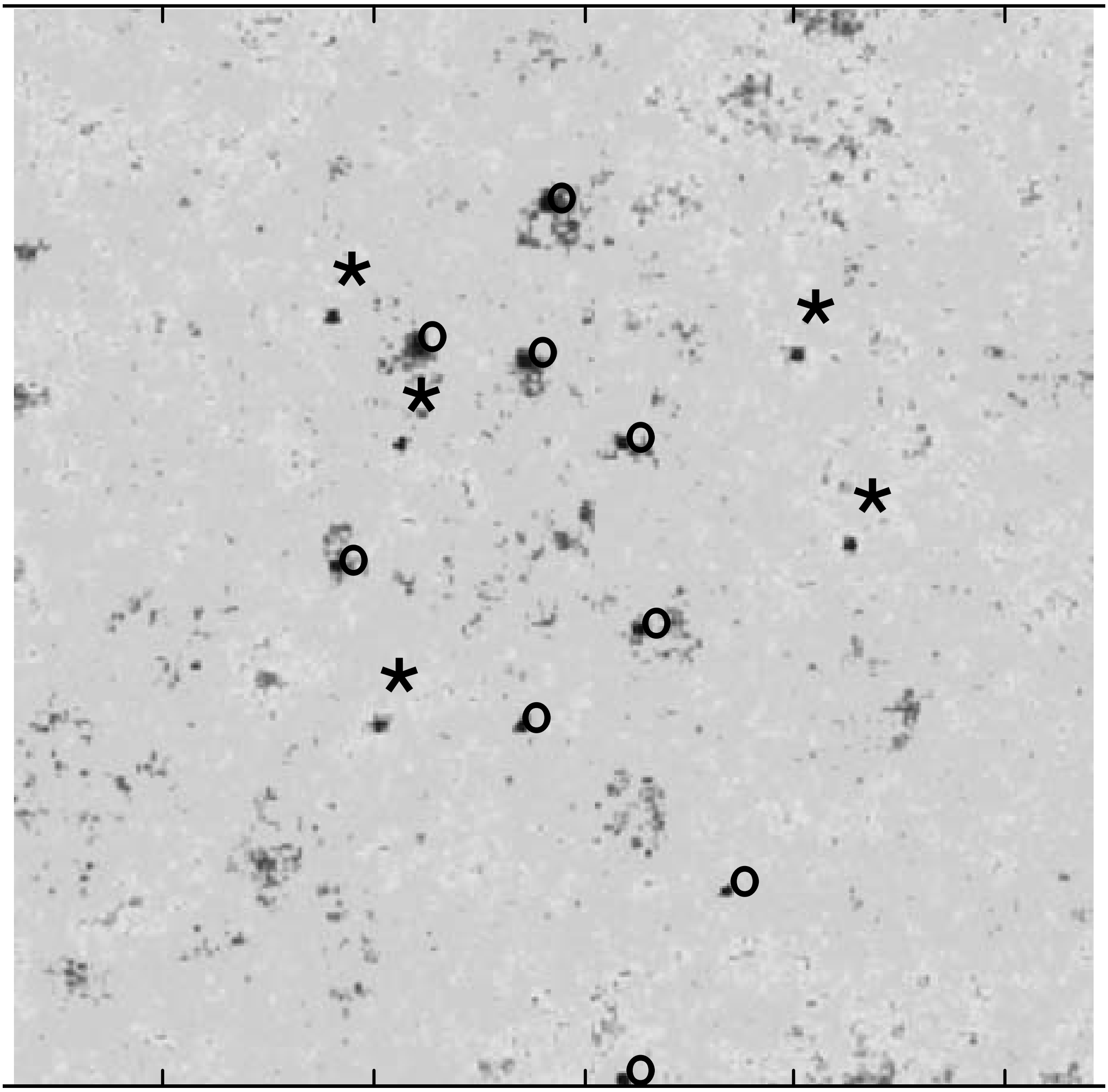

Figure 3 -- Ohaaki West production (asterisks) and non-production (circles) well distributions embedded in a stochastic fluctuation environment of power-law-scaling spatial fracture heterogeneity and percolation-fracture control of permeability.

It is essential to understand that the spatial distributions of high- and low-fracture-density fluctuations shown in Figs 2-3 have no inherent predictive power. The particular stochastic realizations of power-law-scaling fracture density fluctuations merely show that Ohaaki East and Ohaaki West producer well distributions are broadly consistent with the observed heterogeneity properties of crustal rock as mandated by well-log power-law scaling law $S(k) \propto 1/k$ and well-core data on fracture-control of permeability $\delta\varphi \approx \delta\log(\kappa)$. A more realistic model of an individual reservoir that can be used to organise and guide additional drilling to generate additional geothermal power requires systematic observation of large-scale *in situ* reservoir structure. With such data in hand, stochastic reservoir models can be generated that more and more closely conform to actual *in situ* reservoir structure, and hence reservoir flow simulations will become increasingly accurate predictors of reservoir conditions in time and space.

1.2 Fracture-Density Fluctuations as Practical Basis for Reservoir Heterogeneity Modeling

The power-law nature of *in situ* geophysical property fluctuations $S(k) \propto 1/k^{\beta}$, $\beta \approx 1\pm0.2$, can be understood to arise from long-range spatial-correlation of grain-scale percolation-fracture density fluctuations in analogy with critical-state phenomena such as the organization of mm-scale domains by Angstrom-scale iron atom magnetic dipoles. In this analogy, grain-scale fracture density plays the role of thermodynamic energy usually associated with temperature; at a critical density n_0 of grain-scale fractures, percolation pathways become effectively infinite in extent, the spatial correlation length goes critical, $\xi \propto 1/\sqrt{|n-n_0|} \rightarrow \infty$, and the spatial correlation function becomes power-law, $\chi(r) \propto 1/r^{p} \exp(-r/\xi) \rightarrow 1/r^{p}$.

The analogy between power-law-scaling phenomenology observed in well-logs for crustal rock and power-law-scaling phenomena in critical-state thermodynamic systems centers on rock as generic binary population of two forms of grain-grain contact. The first population of grain-grain contacts comprises well-cemented bonds that afford little opportunity for inter-granular percolation flow. The second population of grain-grain contacts comprises fractured bonds with disrupted cements affording ready percolation flow through the fractured cement bonds.

The two populations of grain-grain contacts in crustal rock can change in time. With little tectonic deformation, disrupted grain-grain contacts re-cement over time. Conversely, with steady tectonic deformation, the density of disrupted grain-grain contacts increases over time. However, the pervasive existence of well-log power-law-scaling fluctuation spectra $S(k) \propto 1/k$, and the equally pervasive existence of micro-earthquake activity with minimal induced crustal strain, indicate that crustal rock exists almost everywhere in a critical state of grain-scale percolation fracture density. The association of grain-scale percolation with grain-scale density mandated by well-core fluctuation relation $\delta\varphi \approx \delta\log(\kappa)$ further indicates that grain-scale fracture density tends to control the geophysical and reservoir properties of critical-state crustal rock.

This perspective on spatial fluctuations in the reservoir properties of crustal rock allows comprehensive physically-based approach to reservoir modeling. Each geological unit in a reservoir model will have characteristic mean reservoir properties. Some geological units will be naturally permeable, others will be naturally impermeable, etc. Within each geological unit, however, spatial fluctuations in both vertically and laterally will create uncertainty and heterogeneity in the formation reservoir properties on all scale lengths. Further, tectonic deformation of the reservoir crustal block will introduce large-scale percolation pathways transcending the dimensions of any or all geological units. Such transcending fracture pathways can appear as major fracture systems and even grade into faults with strong localized fracture density. Faults can thus be regarded as effectively localization centers for large-scale fracture-density clustering.

These geological and geophysical features of reservoir structure can be numerically modeled with considerable degree of physical accuracy by associating each point in model-space with a grain-scale fracture density. For impermeable geological formations, local fracture-densities tend to be low and fracture-connectivity is reduced. For permeable geological formations, local fracture-densities tend to be higher and fracture-connectivity correspondingly enhanced. There is, however, an ever-present chance that some local fluctuations in fracture density will connect to larger and larger fracture-density structures that can transcend the dimensions of geological formations. The location and configuration of transcending fracture-density features cannot be predicted in advance. If observed *in situ*, however, macroscopic fracture-density features can be seeded within the numerical model to create a stochastic realization of the particular macroscopic feature within a given formation at a given locale. Thus practical numerical models of reservoir flow structure can be logically built from systematic observation of *in situ* reservoir structure.

1.3 Observing the Reservoir to Build Practical Reservoir Heterogeneity Models

The essential perspective on reservoir heterogeneity is that fluctuations in reservoir properties occur at all scale lengths. While small-scale fluctuations will not in and of themselves greatly affect reservoir performance, small-scale fluctuations can in fact be an integral part of large-scale fluctuations that do affect reservoir performance. It is not possible, however, to distinguish between small-scale fluctuations that do and do not contribute to large-scale fluctuations. Only dedicated observation of the reservoir can provide the needed spatial information.

Well-log and well-core data provide earth samples at scale-lengths from mm to km and therefore need to be systematically acquired to register the broadband fluctuation nature of each specific reservoir locale. But these data must be incorporated into an observation program that identifies the large-scale reservoir structures manifested between well-log and well-core sample sites. *In situ* fracture density thus provides the logical unifying basis for observing reservoir structure in time and space. A number of observations related to *in situ* fracture density can be made using standard geophysical tools:

- Precision crosswell seismic velocity tomography;
- Locating natural micro-earthquake locations and event properties;
- Locating induced micro-earthquake locations and event properties;
- Natural/controlled source shear-wave splitting surveys;
- Natural/controlled source electromagnetic wave polarization surveys.
- Well-log neutron porosity and thermal gradient systematics potentially detecting lateral variations in flow structure away from a wellbore.

Each of these fracture-observation methods either requires or benefits from systematic access to and use of wells. Crosswell seismic velocity tomography can be made almost arbitrarily sensitive to time-lapse reservoir phenomena by use of downhole sources and sensors. Natural and induced seismic events in an active reservoir are generally slight in magnitude but the number and distribution of events increases greatly with increased sensitivity that only comes from downhole sensors. Downhole sensors generally record cleaner waveforms and thus allow more sensitivity and accuracy in assessing the orientation and temporal delay for shear-wave-splitting. Natural and controlled electromagnetic survey data have not heretofore commonly used downhole sensors but there seems to be no overriding reasons why EM sensors cannot be usefully deployed downhole to escape the extreme surface noise conditions and hence to provide more sensitive and more easily interpreted fracture-related polarizations.

In each of these *in situ* fracture-observation methods aimed at determining active reservoir structure, the unified numerical model of fracture density heterogeneity can:

- Model/interpret seismic and/or electromagnetic wavefields generating the reservoir observation data;
- Incorporate the entire suite of well-log and well-core geological formation data for both volcanic and basement formations;
- Model fracture-borne percolation-network flow of reservoir fluids directly connected to reservoir observation.

2. CONCLUSIONS

Abundant well-log and well-core data indicate that reservoir heterogeneity has at once a simple and a complex nature. The simple nature is that many physical properties of reservoir flow are closely related to a single physical parameter, grain-scale fracture-density. The complex nature is that grain-scale fracture-density spatially fluctuates on all scale lengths from mm to km and as such generates spatially erratic and unpredictable *in situ* flow structures. In light of the spatially erratic and unpredictable nature of *in situ* flow structures, accurate understanding of reservoir flow can only be obtained through systematic geophysical reservoir observation. In compensation for the need to explicitly observe the large-scale reservoir flow structure, the fracture-density fluctuation basis of reservoir flow heterogeneity can be simply realized in numerical models.

3. REFERENCES

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