**INTRODUCTION**

The ever-increasing energy demand requires recovery from existing fields to be maximized, a process mostly dependent on accurate reservoir models. Borehole imaging is one of the fastest and most precise methods for collecting subsurface data (Figure 1). Borehole imaging can feed even millimeter-scale information into these models (Paillet et al., 1990). Increasingly, borehole images can be transmitted and integrated into reservoir models while drilling, which is an important step toward real-time field optimization (Sparkman, 2003). Recent advances in modeling software allow the fully integrated use of image data in reservoir models for the first time. As a result, the status of borehole image technology is shifting from being a niche application to being a key component of both static and dynamic reservoir models. Technological advances in borehole imaging during the past 5 yr have facilitated these developments. One important area of progress is the introduction of high-resolution oil-base imagers (Pavlovic, 2002). The quality of recent images in oil-base mud systems comes close to wireline image resolution. Even more significant is the development of high-resolution logging-while-drilling (LWD) tools (Ritter et al., 2004) that now rival traditional wireline images. The latest generation of LWD imaging tools can detect high-permeability streaks only a few decimeters thick and can track them for long distances using advanced, image-based geosteering technology (Prosser et al., 2006).

Borehole imaging is now on its way to becoming a mature technology, and it is used in increasingly advanced applications (Prensky, 1999; Inaba et al., 2003). Good examples of this include the integration of dipmeter and borehole image data with nuclear magnetic resonance logging (Mathis et al., 2004; Daoud et al., 2006), and three-dimensional (3-D) resistivity profiles derived from image data to improve the identification of high-permeability intervals that standard wireline tools do not recognize (Aplin et al., 2003). When image log data are coupled with sophisticated interpretation techniques, complex reservoir connectivity problems can be solved (Bal et al., 2002).
Nowadays, crisp images are increasingly being generated in all borehole environments (Figure 2). This fosters rapid advances in geomechanical imaging applications (Zoback, 2007). Geomechanical analyses of image log data can greatly improve fluid-flow predictions in fractured reservoirs (Barton et al., 1997) and can also help optimize wellbore trajectories (Finkbeiner et al., 2000). Because they can delineate geobody orientation, image logs can also provide a critical wellbore calibration of 3-D seismic features (Hesthammer and Fossen, 2003). Although the value of widespread application of imaging technology is widely acknowledged, still, too few geoscientists are sufficiently familiar with this type of data. This volume aims to provide some guidance in borehole image principles and workflows and to illustrate the value of image data for managing and modeling the subsurface.

DIPMETER AND BOREHOLE IMAGE LOGS IN THE EXPLORATION AND PRODUCTION LIFE CYCLE

The organization of this volume reflects the stages of field development in the exploration and production (EP) life cycle (Figure 3). Thus, dipmeter and image log applications are discussed from job planning to complex field development projects.

Planning, Acquisition, Quality Control, and Management of Dipmeter and Borehole Image Data

Borehole image acquisition includes the planning of logging jobs and the deployment of appropriate data management systems and quality control guidelines (Serra, 1989). Such procedures help improve the quality of both image acquisition and image interpretation throughout the exploration, appraisal, development, and production stages; this is important because an interpretation can only be as good as image quality and resolution permit. To acquire dipmeter and borehole image logs of optimum quality, it is essential to have the operator work closely with the service company to select the appropriate imaging tool, considering the required geological resolution, mud type and weight, and expected formation characteristics. Lagraba, Hansen, Spalburg, and Helmy (Lagraba et al., 2010) discuss these preparatory considerations in Chapter 2, including the value of information analysis.

Management of dipmeter and borehole image data is another significant challenge faced by operating and service companies. All the major oil companies have corporate databases that, together, contain thousands of dipmeter and borehole image logs, with legacy data commonly of unknown quality. The dipmeter and image data sets are constantly being upgraded as new tool types are introduced or existing data sets are (re)processed and (re)interpreted (Aplin et al., 2002). This places a permanent pressure on data management requirements. However, having a fit-for-purpose system to manage image data can add tremendous value to the logs that are acquired. The accessibility of quality-controlled logs is fundamental for real-time operations as well as reservoir management. Optimized data flow and storage systems are outlined by García-Carballido, Boon, and Tso, who present a structured approach to the quality control of image data in Chapter 3. Consistent quality control checkpoints and templates as discussed in this chapter is recommended for general use. They are prerequisites
for assuring data integrity during subsequent reservoir modeling stages. A practical addition to this process is the use of a consistent but flexible corporate naming convention. This convention supports data transparency and assures that interpretations are easy to share among the geoscience community.

Chapter 4 outlines data processing and interpretation principles for dipmeter and borehole image logs. Hansen and Buczak provide a step-by-step guide through this process, with numerous illustrations (Figure 4). The expression “one person’s information is the other’s noise” has been coined to highlight the importance of having a genetic, rock-calibrated processing and interpretation workflow (Adams et al., 1990).

The oil industry can make use of neatly quality-controlled, processed, and interpreted dipmeter and borehole image logs.
borehole image data in new ways for static reservoir modeling applications. The ease of the seamless integration of image data with any other data set, as well as of data management, is shown in Chapter 5, and it is a key driver for the current upsurge in image log utilization. Pöppelreiter, Crookbain, Sapru, and Lawrence present an overview of current applications of dipmeter and borehole image interpretations in reservoir models (Figure 5).

**Exploration**

Borehole image logs now have an established place in most exploration wells. For hazardous boreholes that cannot be cored, they are considered a must-have. Arguably, one of the largest advances that dipmeter and borehole image technology has experienced in the last 15 yr is its application to geomechanics (Figure 6). Barton and Moos provide a comprehensive summary of geomechanical applications in Chapter 6. As shown in this chapter, the prediction of maximum hydrocarbon column height in fault block structures is an important application of geomechanics during the exploration stage. Such analyses can potentially reduce the risk of encountering breached fault seals with uneconomic hydrocarbon volumes (Wiprut and Zoback, 2002). Additional confidence in such analysis is provided when imaging is combined with hydrocarbon indicators from seismic data. However, the full use of geomechanical principles in reservoir modeling is not yet a reality, partly because a software package suitable for widespread use is not available. Nevertheless, some promising studies have looked at developing geomechanical algorithms within standard modeling packages (Wynn et al., 2005; Pöppelreiter et al., 2009).

The exploration portfolio of many oil companies increasingly contains structures that are poorly imaged on seismic data. A significant contribution of dipmeter and borehole image logs when dealing with such structurally risky trap configurations is in the delineation of the dip and azimuth of the top of the reservoir. Chapter 7 presents a case study of a salt flank structure by García-Carballido, Styles, and Pöppelreiter, which is a good example of this. The workflow proposed can generally be applied to areas with poor seismic quality to reduce top structure uncertainty. This workflow also emphasizes the value of using dipmeter data that were acquired during the exploration stage to help well planning during the appraisal or development stage. Moreover, dipmeter and borehole image data are also used to determine paleocurrent direction and fairway reservoir trends to reduce reservoir risk. This technique of sand fairway mapping tends to increase exploration success, particularly within mature hydrocarbon provinces where calibration points are at hand (Heine, 1993).

Chapter 8 outlines reservoir characterization by EARTH Imager (Baker Hughes/Baker Atlas) data from a wildcat well. Maddock and Ravnas describe image acquisition under high-temperature, high-pressure conditions in a well that was drilled with oil-base mud.
The images acquired are superb examples not only of the value of dipmeter and borehole images acquired in exploration wells, but also of the limitations.

For such interpretations to work, however, rock calibration is essential (Figure 7). The nonuniqueness of dipmeter and borehole image data prevents a direct conversion of image patterns into reservoir models. Rock calibration based on cuttings, core, or outcrops is indispensable. Conceptual models, like the ones by Donselaar and Schmidt that are shown in Chapter 9, are a prerequisite for making meaningful use of image data for this kind of application. Chapter 7 and Chapter 19 both show examples of the limitations of using uncalibrated dipmeter and borehole image interpretations with fluvial deposits.

**APPRAISAL**

One of the prime objectives of acquiring dipmeter and borehole image logs during the appraisal stage is to estimate the structural and stratigraphic complexity of a field (Adams et al., 1990; Hurley, 1996; Bal et al., 2002). An example of how outcrop-calibrated borehole image data can be turned into a geological model is shown by Slatt and Davis in Chapter 10. The examination of calibrated images from behind outcrop logging revealed groups of diagnostic features in deep-water depositional systems identifiable on image logs. Genetic elements interpreted from borehole images have specific geometries, internal architecture, and properties that can be used to constrain conceptual reservoir models. However, limitations in resolution are also highlighted by the authors. This methodology can be applied to the substantial core sections that are commonly acquired during the appraisal stage. They provide critical calibration regarding depositional environment, diagenesis, and reservoir architecture (Prosser et al., 1999).

However, structural features, like fractures, are commonly less well calibrated at the appraisal stage. Fractures tend to be undersampled in vertical wells. Optimizing well design and placement, selection of appropriate mud systems that reduce rig down time, and improved well completion efforts depend on image-based geomechanical models (Barton and Zoback, 1998; Rahim et al., 2005). Geomechanical models are particularly useful during the appraisal stage when the drilling experience is still limited, and these models can achieve substantial cost savings.
DEVELOPMENT

At the development stage, image log interpretations are applied to determine the net-to-gross ratio in sand-shale intercalations (Hackbarth and Tepper, 1988), analyze reservoir connectivity, and characterize faults, and for a large variety of other applications besides those mentioned here. Reservoir architecture and connectivity are of particular interest because they can impact the number and type of wells in a development (see Figure 8). Barton, O’Byrne, Pirmez, Prather, van der Vlugt, Alpak and Sylvester (Barton et al., 2010) present an integrated workflow for heterogeneous deep-water depositional systems in Chapter 11. This workflow covers all aspects from outcrop analysis of key flow barriers, i.e., channel-base drapes in a deep-water depositional system, to flow barrier reservoir modeling and simulation. Identification of these baffles, which are just a few centimeters thick, is only possible with a combination of core, logs, and dipmeter or borehole image logs. The chapter demonstrates the major impact of these volumetrically insignificant shales on fluid flow and on the development of a reservoir.

Vertical wells, which are commonly preferred during appraisal, tend to undersample structural features. Carbonate reservoirs are particularly sensitive to this, because it is commonly only after the interpretation of image logs and dynamic data that these reservoirs are identified as fracture plays (Bell et al., 1992). Mattioni, Chauveau, Fonta, Ryabchenko, Sokolov, Mukhametzyanov, Shlionkin, Zereninov, and Bobb demonstrate the value of image logs for fracture characterization in Chapter 12. The authors apply the concept of mechanical stratigraphy to a single, slightly deviated well in a dolomite reservoir. They translate a careful investigation of lithology, bed architecture, and stratigraphy into a conceptual fracture model and quantitative fracture relationships. Their systematic, iterative workflow is complemented by the construction of a discrete fracture network model (Trice, 1999).

PRODUCTION

Field and well optimization, and reservoir management, are key processes for maximizing production while limiting expenditure. A robust surveillance plan for the production stage commonly includes dipmeter and borehole image logs. The number of these data sets depends on the actual reservoir complexity (Figure 9). In matrix-dominated reservoirs, it may only be necessary to acquire image logs in key wells. Also, conversely, fractured reservoirs can only be described adequately after horizontal development wells have been drilled and a representative number of borehole image logs have been acquired (Adams et al., 1999).

An intelligent well design that connects additional permeable reservoir facies can enhance production in some reservoirs. In Chapter 13, Lofts and Morris describe a sophisticated geosteering method to maximize the penetration length of a reservoir using the latest LWD imaging tools. Modern LWD tools provide an operating company with real-time information of a quality that rivals wireline tools. Lofts and Morris discuss how to plan and implement advanced geosteering, combined with real-time reservoir model updates, in detail in this chapter. The image quality they
Figure 7. Calibration of image logs with rock (e.g., cuttings, core, and outcrop) is essential to convert images into meaningful geological interpretations (courtesy of Xu et al., 2009).

Figure 8. Application of dipmeter and image log data interpretation results for facies identification and well correlation (courtesy of Barton et al., 2005, permission to reprint from Shell EP).
present suggests that imaging in LWD mode is set to change the way complex reservoirs are developed.

At the production stage, powerful visualization technology can be used to delineate structural trends in fractured reservoirs. In Chapter 14, Richard and de Pieri demonstrate the power of visualization and data integration as a platform for discrete fracture models.

Davatzes and Hickman outline fracture distribution in a geothermal field in fractured basement, using detailed observations and data integration, in Chapter 15. Such models are used as inputs to simulations that allow a better understanding of fluid flow; i.e., they clarify the extent of high-permeability layers, thief zones, baffles, and barriers (Moeck et al., 2007).

Borehole image data sets can be combined with data from a variety of other sources to model and manage the reservoir and, possibly, influence the field development strategy.

Image logs are also indispensable in reservoirs with complex pore structure, such as carbonate reservoirs. The characteristic (very) high resistivity that these reservoirs commonly display has a detrimental effect on image quality (see Figure 10). In Chapter 16, Chitale, Johnson, Entzminger, and Canter describe a recently introduced tool that can image the diagenetically altered zones in carbonates that can act as flow barriers or high-permeability zones, where subtle resistivity contrasts have commonly made imaging difficult in the past. Moreover, the improved interpretation

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**Figure 9.** Fracture characterization using Schlumberger’s Fullbore Formation MicroImager (FMI) data in conjunction with open-hole logs to establish an e-facies scheme tuned to detect at least some structural features. APLC = log measure porosity; SGR = standard gamma ray; THOR = thorium; MDT_F = modular formation dynamics tester.
software that is also described in this chapter shows how to convert images into Lucia-type permeability classes.

Another aspect of image-based carbonate reservoir characterization is pore-type partitioning (Akbar et al., 1995). The separation of touching and non-touching vug systems with their very different permeabilities (Newberry et al., 1996), which is particularly important in this regard, is described by Xu in Chapter 17 (Xu, 2010). The methodology can lead to a much improved permeability prediction with very high resolution, so it can enhance the predictability of reservoir models (Lovell et al., 1997).

The complexity of fractured reservoirs and the importance of dynamic calibration of features interpreted from image logs are presented in Chapter 18 by Follows, Beck, Farmer, Al Salmi, de Bruijn, De Pieri, and Welling. The authors highlight the importance and power of having an integrated reservoir surveillance strategy. This chapter also emphasizes the complex flow behavior of fracture systems and demonstrates that the dynamic properties of fractures cannot always be derived from image logs alone (Nicholls et al., 1999). This chapter also shows that the overall dynamic behavior of a fracture class can be estimated by its static properties. The flow in individual fractures,
however, can vary widely. Integration of image logs (see Figure 11) and production logs leads to an appropriate dynamic characterization of the reservoir.

Samantray, Kraaijveld, Bulushi, and Spring present the fully integrated use of dipmeter or borehole image data for field development planning in a cluster of fluvial reservoirs in Chapter 19. They describe a methodology that can be applied generally to brown field developments and mature assets. Their study is also an important example of how the value of legacy data sets, accumulated in their thousands by national and international oil companies, can be realized using them as inputs for reservoir models.

**PERSPECTIVES**

This volume combines a presentation of the fundamentals of dipmeter and borehole image technology with descriptions of state-of-the-art applications. The need to (iteratively) integrate image data with other data sources is a recurring theme. Integration requires better software, and several tools are nearly ready to be put on the market. The next generation of modeling software is expected to bridge the gap between stand-alone specialist borehole image processing and interpretation tools and plug-ins for mainstream subsurface interpretation software. This may put borehole imaging on the desktop of large numbers of geoscience and petroleum engineering professionals, including seismologists, geologists, petrophysicists, reservoir engineers, production technologists, and well engineers.

The next generation of image interpretation software is also expected to provide standard mechanical modules that again will be a significant factor in future generations of reservoir models. Tool development is likely to move toward improved vertical resolution, larger borehole coverage, and imaging.

Figure 11. Visualization of borehole images with seismic and other data as a powerful way to establish structural trends, geometries, and flow properties. Such relationships can be used to build fracture realizations as part of static or dynamic reservoir models (courtesy of Richard and de Pieri, 2010).
in all possible mud systems. Soon multisensor and multiarray imaging tools will facilitate data integration during data acquisition in the subsurface, using different data acquisition methods (Badir, 2007). This will break the present dominance of resistivity and acoustic devices. New technology, such as the recently introduced intelligent drill pipe (Reeves et al., 2005), is likely to further enhance data transmission to the surface.

All of these developments will pave the way for imaging to shift from qualitative to quantitative petrophysical interpretations (Kraaijveld and Epping, 2001), opening up a completely new range of petrophysical interpretation methodologies.

We hope that this volume sparks enthusiasm for dipmeter and image log technology and provides a useful reference both for the novice and for the experienced subsurface professional.

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