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Research paper

The geology of offshore drilling through basalt sequences: Understanding operational complications to improve efficiency

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A B S T R A C T

Offshore drilling in basins with a significant basaltic component poses a number of complications to drilling operations. These include slow and variable rates of penetration (ROP), drilling fluid losses, drill bit or string sticking, overpressured formations, wellbore spalling and collapse. In this contribution we investigate features of large igneous province (LIP) volcanic facies that may directly contribute to drilling complications. Combining borehole and field based examples we identify highly vesicular brecciated lava flow tops and hydro-volcanic facies as a major potential cause of catastrophic drilling fluid losses. The risk for drilling losses is generally higher in the upper parts of thick volcanic successions where hydrothermal secondary mineralization and alteration may be less pervasive. We demonstrate how these facies may be identified early by integrating real time mud logging data with characteristic drill cuttings and LWD (logging while drilling) wireline data as it becomes available. We highlight the potential of basaltic formations to maintain porosity and permeability to greater depths than is typical for sediments due to the high compressive strength of crystalline basalt frameworks. The heterogeneous sub surface distribution of key volcanic facies commonly includes intimate mixing and layering of hard and dense with soft and weak volcanic rock which may promote complex in-situ stresses to develop during burial compaction. Where this occurs, wellbore stability predictions such as the fracture and wellbore collapse gradients for volcanic sequences may deviate from those expected in basin equivalent sedimentary sequences. Examples of swelling volcanic clay horizons, unstable volcaniclastic sequences, and intrusion related ledge effects are used to characterize the main causes of drill bit and string sticking. A greater understanding of drilling complications encountered within prospective areas containing volcanic sequences is needed if better pre-drilling risk assessment, cost prediction, real-time identification and mitigation is to be achieved.

1. Introduction

Commercial drilling through basaltic formations has been undertaken for over a century, (Luzier and Burt, 1974; Burns et al., 2012). Drilling through basalt is already common in many areas of the world to access water aquifers (Buckley and Oliver, 1990; Tolan et al., 2009), geothermal energy (Fridleifsson and Elders, 2005) and hydrocarbons both beneath (Smallwood and Harding, 2009; Davison et al., 2010) and also within lava packages (Stanistreet and Stollhofen, 1999; Schofield and Jolley, 2013). A number of recent studies have also positively appraised the potential of thick basaltic successions for natural gas storage (Reidel et al., 2002) and carbon dioxide sequestration (McGrail et al., 2006; Goldberg et al., 2008; Zakharova et al., 2012). Safe and cost effective drilling through basalt is therefore likely to continue to be

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important in many aspects of the future management of our natural resources and environment.

Perhaps the most comprehensive studies into both Large Igneous Province (LIP) emplacement and associated drilling comes from the thousands of well penetrations (Luzier and Burt, 1974; Burns et al., 2012) and many decades of study (Long and Wood, 1986; Self et al., 1996; Ebinghaus et al., 2014) within the Columbia River Basalt Province (CRBP), Washington State, USA. Within the CRBP, inter-basaltic aquifers produce enough water to support a multi-billion dollar per year agricultural industry (Burns et al., 2012) testifying to the ability of basaltic formations to both hold and flow huge volumes of fluid (Tolan et al., 2009). In many offshore basaltic sequences, well data is sparse and integration between onshore analogues and well data (Nelson et al., 2009; Millett et al., 2014) are required to better constrain and predict the distribution of volcanic facies in offshore seismic data (Jerram et al., 2009). The types and styles of drilling projects through basalts are also varied. Drilling for irrigation (e.g. within the CRBP, Luzier and Burt, 1974) and hydrothermal energy (e.g. in Iceland, Gudmundsson, 2005) in basaltic terrains is commonly undertaken onshore using open circulation systems (limited control of the drilling fluid and cuttings coming back up the hole) with water as the drilling fluid. Other methods such as reverse circulation drilling using water, drilling mud or air-lift techniques have also been employed in the CRBG to avoid some of the problems discussed in this study during deep onshore drilling (Reidel et al., 2002).

Many wells have also been drilled into offshore volcanic sequences, commonly the oceanic crust, by the different scientific drilling programs e.g. ODP, IODP, IDDP (Detrick et al., 1988; Teagle et al., 2012). These scientific investigations have generally undertaken full-core drilling to relatively shallow depths of penetration due to drilling without a riser (e.g. Joides Resolution drill ship). In riserless drilling, drilling fluid and cuttings flow straight into the ocean without the use of a blow-out protector (BOPs are required to shut in a wellbore if an uncontrollable pressure ramp or ‘kick’ is encountered) and therefore drilling without a riser and BOP restricts drilling to relatively shallow depths for safety.

Significantly fewer studies into offshore commercial drilling through basalt are available where a closed circulation drilling fluid system is used with a riser and BOP. This along with expensive drilling muds used in order to aid cuttings removal, cool the drill bit, prevent formation fluid influx and to maintain wellbore stability at greater depths of penetration adds significant possible complications to any drilling operation (Cook et al., 2012). An important related problem for companies involved in offshore drilling is the significantly increased costs of rig hire and operation whereby any drilling down time has serious financial implications, in the worst cases potentially holding back the exploration of prospective regions.

In this contribution we investigate possible linkages between volcanic related drilling problems and the geology of basaltic facies and stratigraphy. In this regard we aim to develop integration between drilling engineering, volcanic geology and mud engineering. In all drilling operations prevention is better than remediation but where drilling related complications do occur, the correct and timely identification of the cause of the problem is paramount. The ability to better predict problematic well conditions and associated well costs during the well planning stage is also an important theme where optimisation is desirable in commercial offshore drilling programs through basalt.

2. Drilling problems in basalt

In this section we investigate the key drilling difficulties associated with basaltic sequences. We identify four main categories including rate of penetration (ROP), drilling fluid losses, swelling volcanic clays and unstable volcanic formations prone to caving or wash-outs (Fig. 1). Each potential problem area is discussed in terms of known volcanic facies using field and borehole examples to highlight important causal links. Prevention of problems is always the primary goal for drilling operations and therefore prespud research, planning and prediction are the primary defence (Cook et al., 2012). Problems are, however, inevitably encountered in some wells due to the complexities of geology and in-situ stresses within the shallow crust. In such cases the timely identification of the causes of drilling problems are paramount to effectively remedying the problem in the safest and most efficient manner. A wide range of solutions to drilling problems exist each with differing effectiveness depending on the nature of the problem.

2.1. Rate of penetration (ROP)

Rock type exerts a primary control on ROP, however, it is also affected by a host of other variables including hole condition, mud circulation, bottom-hole pressure, bit type and condition, weight on bit and rotary speed. Average ROP through basaltic sequences has been historically very low relating largely to the hardness and high abrasivity of basalt (Käsling and Thuro, 2010). ROP values of <3 m/h are relatively common for conventional rock roller bits in basalt sequences (Grindhaug 2012; Rickard et al., 2014). Drill bit technology has improved significantly in recent years with the introduction of hybrid drill bits recording ROP increases up to >10 m/h, an increase of almost three times that of conventional rock roller bits drilled through similar undifferentiated basaltic sequences on Iceland (Rickard et al., 2014). Even with these improving results, ROP through basalt remains substantially slower than in sedimentary strata (Grindhaug 2012), where ROP > 20 m/h at similar depths is common.

The ROP through different volcanic facies can also be significantly different as a function of their wide range in physical properties. Average ROP through hyaloclastite sequences may for instance be significantly faster than in lava dominated sequences. This is demonstrated by examples from the Chevron operated 217/15-1 ‘Lagavulin well’ which penetrated a ~2.6 km volcanic section of the NAIP in the NE Faroe Shetland Basin of the UKCS (Fig. 2a). For the example in Fig. 2a the facies related ROP variation extrapolates to almost 2 days drilling time difference for a ~500 m basaltic sequence excluding other complications. In financial terms this time period may easily exceed $2 m in operational costs (depending on the drilling campaign/location). The effect of alteration on basaltic facies physical properties is also significant and increases with increasing temperature (Franzon et al., 2001; Frolova, 2010); therefore, both the amount of surface weathering and the geothermal gradient will also significantly affect ROP.

Long interval averaged ROP through basaltic sequences also hides significant internal variations observed within different volcanic facies e.g. stacked lavas, which can be used to aid interpretation (Fig. 2b after Archer et al., 2005). At the well planning stage an assessment of the volcanic facies from integrated seismic interpretation and available well data analysis can be made to better constrain drilling time predictions. Treating basaltic sequences as homogenous is acknowledged to be outdated in the geosciences and drilling rate prediction should reflect this modern realisation.

Increasing ROP or drilling breaks are commonly used as an early indicator of overpressure in conventional drilling (Ablard et al., 2012). Overpressured formations may, however, be more difficult to identify in volcanic sequences especially if they underlie a lava flow sequence. This is due to the very slow ROP within lava flow