Fault reactivation, leakage potential, and hydrocarbon column heights in the northern North Sea

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To investigate the question of how faults affect the migration of fluids in petroleum reservoirs, we evaluated the state of stress and pore pressure acting on the major faults in four oil and gas fields in the northern North Sea. Many of the faults bound hydrocarbon reservoirs. Our goal was to test the hypothesis that faults that are being reactivated in the current stress field are permeable and thus tend to leak, whereas those that are not (i.e. faults that are inactive in the current stress field) are likely to seal. To address this question, we utilize a detailed analysis of the magnitude and orientation of all three principal stresses in a number of wells in each field. These data, along with information on pore pressure, allowed us to resolve the shear and effective normal stress acting on distinct ~100 m × 100 m elements of individual fault planes. By comparing the stress state resolved on each fault element to expected stress at failure (using a Coulomb failure criterion) we created color-shaded maps showing the proximity to fault slip (and hence leakage) along each fault. Fault reactivation and hydrocarbon leakage in this area appears to be caused by three factors: (1) locally elevated pore pressure due to buoyant hydrocarbons in reservoirs abutting the faults, (2) fault orientations that are nearly optimally oriented for frictional slip in the present-day stress field, and (3) a relatively recent perturbation of the compressional stress caused by postglacial rebound. We demonstrate that the combination of these three factors may have recently induced fault slippage and gas leakage along sections of previously sealing reservoir-bounding faults in some fields, whereas in others, the stress and pore pressure are not sufficient to cause fault reactivation. We show that only in cases where reservoir-bounding faults are not potentially active, the pore-pressure difference across faults can become quite high. Hence, the leakage potential of reservoir-bounding faults appears to exert an important influence on potential hydrocarbon column heights.

Introduction

The question of how faults affect the migration of fluid in petroleum reservoirs is complicated, as some faults contribute dramatically to formation permeability (Dholakia et al., 1998) and allow hydrocarbon migration between different reservoir units (Finkbeiner et al., 2001), yet others provide effective barriers separating distinct reservoir compartments (Hunt, 1990). The sealing potential of a fault can be related to the juxtaposed lithologies across the fault and the presence or absence of seals resulting from the structure and content of the fault zone (Weber et al., 1978; Downey, 1984; Allan, 1989; Nybakken, 1991; Knipe, 1992; Berg and Avery, 1995; Fristad et al., 1997). However, the process by which a previously sealing fault begins to leak is unclear.

In this paper we consider the effect of fault reactivation on fault seal and fluid flow in the context of in-situ stress and pore pressure. We test the hypothesis that faults that are critically stressed in the current stress field (i.e. capable of slipping) are permeable, whereas those that are not critically stressed are not permeable. A number of permeability studies in fractured and faulted crystalline rock appear to confirm this hypothesis (Barton et al., 1995, 1998; Hickman et al., 1998; Townend and Zoback, 2000). Studies in hydrocarbon reservoirs in sedimentary basins in the Santa Maria Basin (Finkbeiner et al., 1997), the Gulf of Mexico (Finkbeiner et al., 2001), the Timor Sea (Castillo et al., 2000), and on a single partially leaking fault in the northern North Sea (Wiprut and Zoback, 2000b) appear to confirm that critically stressed faults are responsible for promoting hydrocarbon leakage and migration.

In this study we expand upon the work presented by Wiprut and Zoback (2000b) in the Visund field. The point of departure from our previous work is that we evaluate here the leakage potential of seismically mapped faults throughout the Visund field as well as three other fields in the northern North Sea (Fig. 1). We also address the effect of critically stressed faults and water-phase pore pressure on the potential height of hydrocarbon columns.

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