Fault reactivation and fluid flow along a previously dormant normal fault in the northern North Sea

David Wiprut
Mark D. Zoback
Department of Geophysics, Stanford University, Stanford, California 94305-2215, USA

ABSTRACT

Detailed seismic imaging and in situ stress and pore-pressure measurements are used to analyze reverse-fault reactivation of a long-dormant normal fault in the northern North Sea. Fault reactivation is caused by three factors: (1) a recent increase in the compressional stress in the area associated with postglacial rebound, (2) locally elevated pore pressure due to the presence of natural gas in a hydrocarbon reservoir on the footwall side of the fault, and (3) a fault orientation that is nearly optimally oriented for frictional slip in the present-day stress field. We demonstrate that the combination of these three factors induces fault slippage and gas leakage along sections of the previously sealing reservoir-bounding fault. We argue that similar pore-pressure triggering of fault slip in the crust may occur because of the accumulation of gas columns of, e.g., CO_2 and He in the vicinity of tectonic faults.

Keywords: stress, pore pressure, Norway, faults, faulting, leakage.

INTRODUCTION

In this study we consider fault reactivation and fluid flow in the Visund oil and gas field in the context of in situ stress and locally high pore pressures due to gas accumulation in a reservoir abutting a long-dormant normal fault. The mechanical role of fluids has long been of interest to scientists studying earthquakes and faulting (see review by Hickman et al., 1992). There are several well-studied cases in which seismicity was induced by high pore pressures resulting from fluid injection at depth (Healy et al., 1968; Raleigh et al., 1976; Zoback and Harjes, 1997). Sahagian and Proussevitch (1992) suggested that high pore pressure due to a buoyant column of gas at the top of magma chambers may be responsible for triggering volcanic eruptions, and Linde et al. (1994) and Sturtevant et al. (1996) suggested that gas dissolution from magma during the passage of seismic waves may trigger further seismicity in geothermal areas.

VISUND OIL AND GAS FIELD

The Visund field is located offshore Norway in the easternmost major fault block of the Tampen spur (Færseth et al., 1995) along the western edge of the Viking graben (Fig. 1, inset). The reservoir is divided into several oil and gas compartments, some of which are separated by the A-Central fault. As shown in Figure 1, low seismic reflectivity along the southern part of the A-Central fault is interpreted to be the result of gas leakage from the reservoir. The data in this region are very high quality and there are no changes in lithology that might account for the change in seismic reflectivity. The question of how faults affect the migration of fluid in petroleum reservoirs is complicated, because faults are known to act as both barriers and conduits. Some faults contribute dramatically to formation permeability (Finkbeiner et al., 1998), yet others provide effective barriers separating distinct reservoir compartments (Hunt, 1990).

Figure 1 also shows the orientation of the maximum horizontal stress determined in five wells in and near the Visund field from observations of drilling-induced tensile wall fractures (Moos and Zoback, 1990; Brudy and Zoback, 1993, 1999). Drilling-induced tensile wall fractures have been shown to be reliable indicators of the direction of the maximum horizontal stress (Brudy et al., 1997). Five rose diagrams in the lower part of Figure 1 show the consistency of maximum horizontal stress orientations in each well. Each rose diagram shows the mean orientation of the maximum horizontal stress, the $\pm 2\,\sigma$ error in this orientation, and the number of times the tensile fractures in each well could be subdivided into 0.2-m-long intervals. The final rose diagram shows a compilation of the entire data set. The depths over which the data were observed in each well are shown by vertical black lines in the plot to the right of the rose diagrams. The orientation of the maximum horizontal stress is remarkably consistent, both laterally across the field and with depth.

Figure 2A shows a summary of in situ stress and pore-pressure data for the Visund field over the depth range of principal interest. The pore-pressure data are direct measurements conducted with the Schlumberger Repeat Formation Tester. The vertical stress shown in Figure 2A was derived by using the average overburden gradient for the entire field. We calculated the overburden in each well by integrating density logs. The data for the minimum horizontal stress were derived from analysis of carefully conducted leak-off tests in wells throughout the field. The magnitude of the maximum horizontal principal stress was determined from analysis of the drilling-induced tensile fractures (following Brudy et al., 1997). Determinations of stress magnitude and orientation are described in detail by Wiprut and Zoback (2000). Note that we are able to fit lines quite well to the principal stresses and that the maximum horizontal stress is distinctly larger than the vertical stress, and the minimum horizontal stress is nearly equal to the vertical stress. This result is consistent with the strike-slip and reverse-slip stress field indicated by earthquake focal-plane mechanisms in this part of the North Sea (Lindholm et al., 1995). The inset of Figure 2A shows a detailed view of the pore-pressure measurements in the three wells closest to the A-Central fault. Well D was deviated to penetrate the A-Central fault at 2933 m true vertical depth (indicated by the horizontal dashed line), whereas wells B and C were drilled vertically. The pore-pressure data in well D are discussed subsequently.

Figure 3 shows two views of the A-Central fault as determined from three-dimensional seismic reflection data. In the upper part of Figure 3, a map view of the fault is shown along with the orientation of the maximum horizontal stress in the three wells closest to the fault. The shaded area shows the lateral extent of gas leakage (simplified from Fig. 1). In this area, the A-Central fault juxtaposes reservoir sandstones on the footwall side with cap-rock shales on the hanging-wall side. In the lower part of Figure 3, a perspective view of the approximately east-dipping fault surface is shown. The A-Central fault developed during the Jurassic as a normal fault with an ~60° dip (Færseth et al., 1995) and as much as

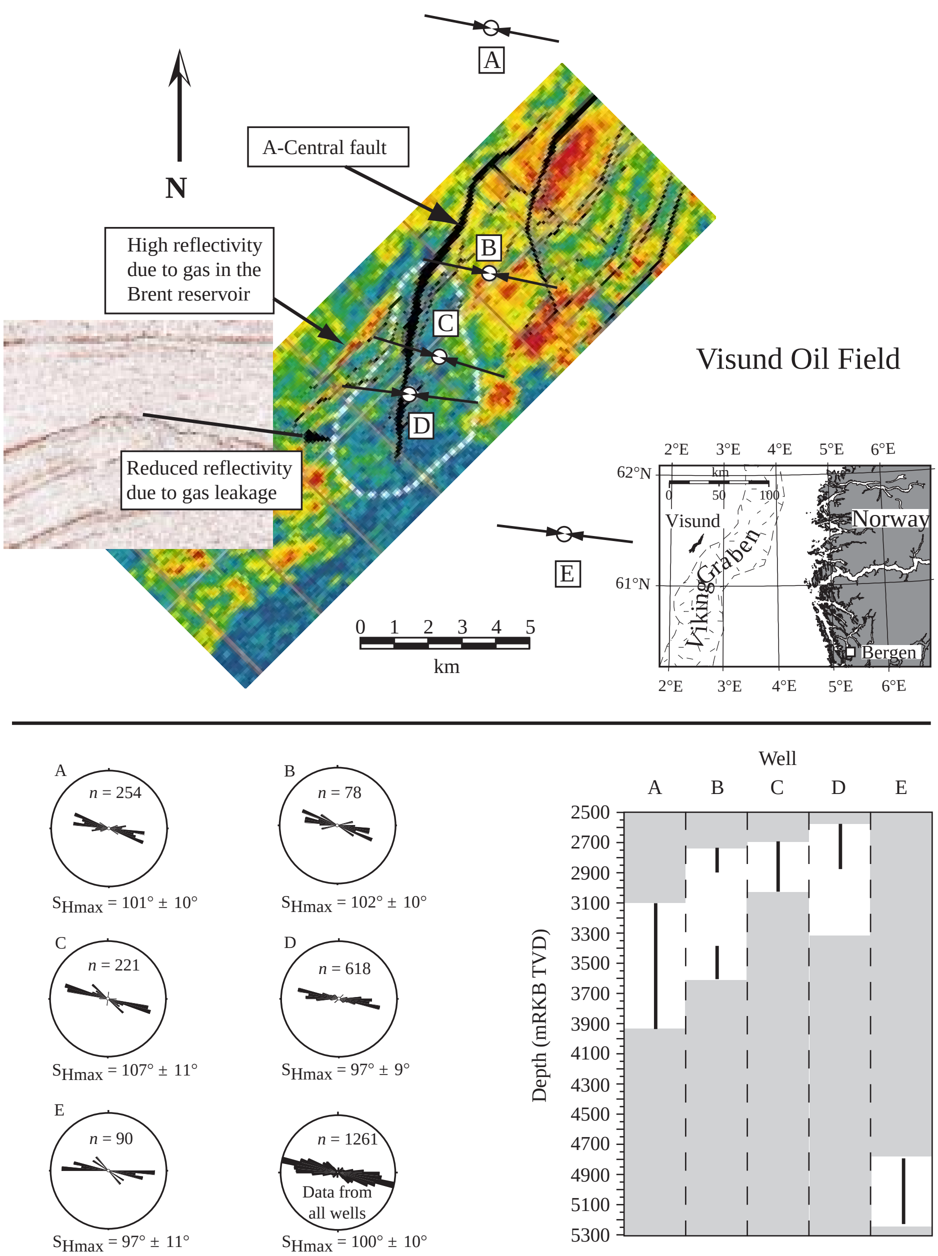

Figure 1. Map view of Visund field showing seismic reflectivity of reservoir horizon as well as mean orientation of maximum horizontal stress in five wells (A–E). Inset shows location of Visund field with respect to coast of Norway and Viking graben. Rose diagrams show range of orientations seen in each well. To right of rose diagrams, depths (meters relative to kelly bushing, true vertical depth, mRKB, TVD) over which data could be seen in each well are shown by black lines. Gray regions indicate parts of well that were not logged.

300 m of normal throw (Linn Arnesen, Norsk Hydro, 1998, personal commun.). Since that time, the fault appears to have rotated and now dips between 30° and 45°. Both the focal-plane mechanisms of earthquakes occurring in the vicinity of the Visund oil field (at 5–30 km depth) and the in situ stress measurements shown in Figure 2A indicate that the current state of stress in this area is highly compressional. As earthquakes along passive continental margins such as Norway's are quite rare, a number of investigators have suggested that the compressional stress observed in this region may be related to lithospheric flexure associated with Pleistocene deglaciation (Stephansson, 1988; Klemann and Wolf, 1998; Grollimund et al., 1998). If this interpretation is correct, the existence of the current compressional stress in this area is a geologically recent (ca. 10–15 ka) phenomenon.

FAULT SLIP AND HYDROCARBON LEAKAGE

The evidence for gas leakage in the immediate vicinity of the A-Central fault points to the fault as the possible conduit by which the hydrocarbons are escaping from the reservoir. To investigate this possibility further, we evaluated the state of stress and pore pressure acting on the fault plane in the context of 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 rock masses appear to confirm this hypothesis (Barton et al., 1995, 1998; Hickman et al., 1998). Figure 2B shows how we apply this hypothesis conceptually to the A-Central fault. As gas accumulates in a permeable reservoir bounded by a sealing fault, the pore pressure at the fault-reservoir interface increases because the pore-pressure gradient in the gas is considerably less than the hydrostatic gradient owing to the extremely low density of gas. As the height of the gas column increases, at some point the pore pressure will be sufficient to induce fault slip, providing a mechanism to increase fault permeability and allow leakage from the reservoir.

To evaluate the hypothesis that parts of critically stressed faults are permeable and are the cause of localized leakage, we resolve the stress orientations and stress magnitudes shown in Figures 1 and 2A into distinct ~100 m × 100 m elements on the fault plane to determine the shear and normal stress on each part of the A-Central fault. It is then straightforward to compute the pore pressure at which the fault element is expected to slip, if Mohr-Coulomb frictional failure is assumed. We refer to this pore pressure as the critical pore pressure. The color shading on the fault plane shown in Figure 3 indicates the difference between the critical pore pressure and the reference pore-pressure line shown in Figure 2A. This difference is called the critical pressure perturbation. Red colors indicate that a small increase in pore pressure (<~7 MPa) is enough to bring the fault to failure. Blue colors indicate that the pore pressure must rise significantly (>20 MPa) before those parts of the fault will begin to slip in the current stress field.

Note that the largest parts of the A-Central fault that are most likely to slip (i.e., shaded in red) are located along the same part of the fault where leakage seems to be occurring. Thus, there appears to be a good qualitative correlation between the critically stressed fault criterion and the places along the fault where flow appears to be occurring. Because well D penetrates the fault in this area, we can evaluate this correlation more quantitatively. As shown in the inset of Figure 2A, the pressure below the fault (indicated by the position of the dashed horizontal line) is within ~1 MPa of the theoretical critical pore pressure for fault slippage (the thick dashed line). This value is several megapascals above the background pore pressure, just as predicted in Figure 3. Above the fault, pore pressures are significantly reduced, indicating that there is poor pressure communication across the fault. Geochemical analysis of gas from both sides of the fault indicates that the hydrocarbons are derived from different sources (i.e., no fluid flow across the fault) (Arnd Wilhelms, Norsk Hydro, 1998, personal commun.). Because leakage appears to be localized to the region where the fault is most likely to slip, fault slip rather than capillary-pressure effects seem to be responsible for the gas leakage. Thus, in this case, as with cases reported by Barton et al. (1995), Hickman et al. (1998), and Finkbeiner et al. (1998), fault slip appears to have principally promoted fault-parallel flow.

It is not clear at this time whether leakage along the A-Central fault is an episodic or steady-state condition. It is possible that once sufficient gas leaks out of the reservoir to reduce the pore pressure, the fault may seal again. The reservoir could subsequently be recharged by hydrocarbons migrating in from neighboring regions, as chemical analysis of the hydrocarbons in the Visund field and the surrounding areas indicates. This could be the mechanism by which the pore pressure increases to the critical value where the fault fails. It may also be the case that once the fault has been reactivated, it remains permeable, and the hydrocarbons would leak continuously from the reservoir.

The relationship between pressure and fluid flow along reservoir-bounding faults such as the A-Central fault is reminiscent of a pressure-regulated valve. Pore pressure acting against an initially sealing fault can rise only to a certain value before fault slippage occurs and hydrocarbons leak upward along the fault through the cap rock. Sibson (1992) speculated that some tectonic faults act as valves that (while closed) allow near-lithostatic pore pressures to accumulate. After a pressure-induced earthquake occurs, fracturing of the crust in the region surrounding the earthquake increases permeability and dissipates the high pore pressure.

Pore-pressure–induced faulting and leakage may be a dynamic mechanism that acts to control the hydrocarbon capacity of reservoirs bounded by faults. This process was observed in the Gulf of Mexico (Finkbeiner et al., 1998) where only small amounts of hydrocarbon could be trapped against reservoir-bounding faults near frictional failure, whereas larger columns could be trapped against faults of different orientation initially further from failure. Because columns of naturally occurring nonhydrocarbon gases in the crust (e.g., CO_2 and He) can get trapped against locked sections of active tectonic faults, it is perhaps reasonable to speculate that the excess pressure associated with the buoyancy of these gas columns may be capable of nucleating fault slippage. This possibility is especially interesting because increased fluxes of mantle-derived He and CO_2 have been documented in the vicinity of the San Andreas fault (Kennedy et al., 1997).

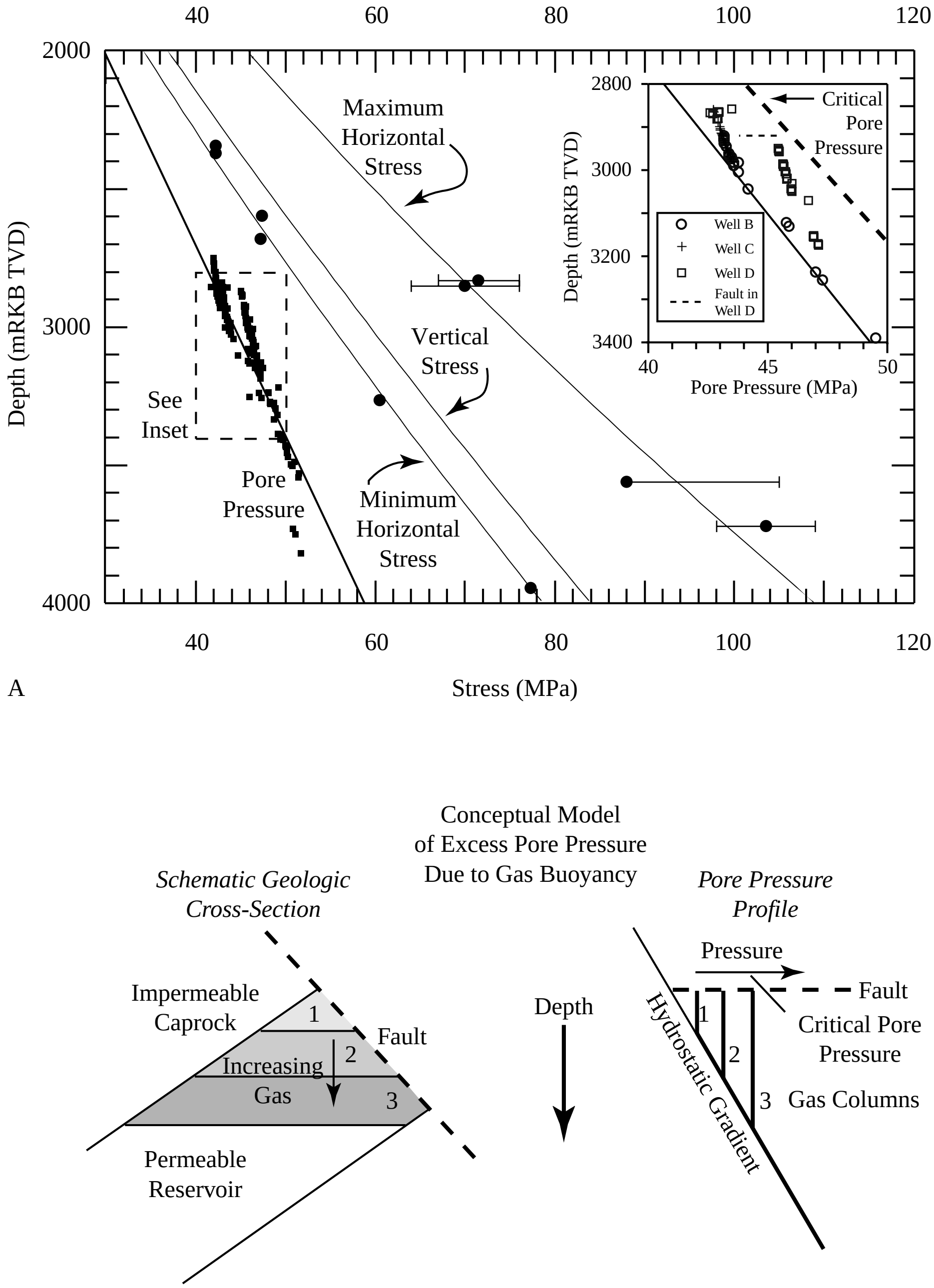

Figure 2. A: In situ stress and pore-pressure data obtained from wells throughout Visund field (Wiprut and Zoback, 2000). Best-fit lines to data are shown. Inset shows pore-pressure measurements in three wells drilled close to A-Central fault. Depths, abbreviations are as in Figure 1. B: Conceptual model showing increase in pore pressure at reservoir-bounding fault as result of increasing gas column in reservoir.

ACKNOWLEDGMENTS

We thank Norsk Hydro for generously providing the data used in this study and financial support for D. Wiprut. We especially thank Linn Arnesen for providing data that allowed us to calculate the orientation of the A-Central fault.

REFERENCES CITED

Barton, C.A., Zoback, M.D., and Moos, D., 1995, Fluid flow along potentially active faults in crystalline rock: Geology, v. 23, p. 683–686.

Barton, C.A., Hickman, S.H., Morin, R., Zoback, M.D., and Benoit, D., 1998, Reservoir-scale fracture permeability in the Dixie Valley, Nevada, geothermal field, *in* Proceedings of Society of Petroleum Engineers/International Society of Rock Mechanics and Mining Sciences Rock Mechanics in Petroleum Engineering, Volume 2: Trondheim, Norway, Society of Petroleum Engineers, p. 315–322.

Brudy, M., and Zoback, M.D., 1993, Compressive and tensile failure of boreholes arbitrarily inclined to principal stress axes: Application to the KTB boreholes, Germany: International Journal of Rock Mechanics and Mining Sciences and Geomechanics Abstracts, v. 30, p. 1035–1038.

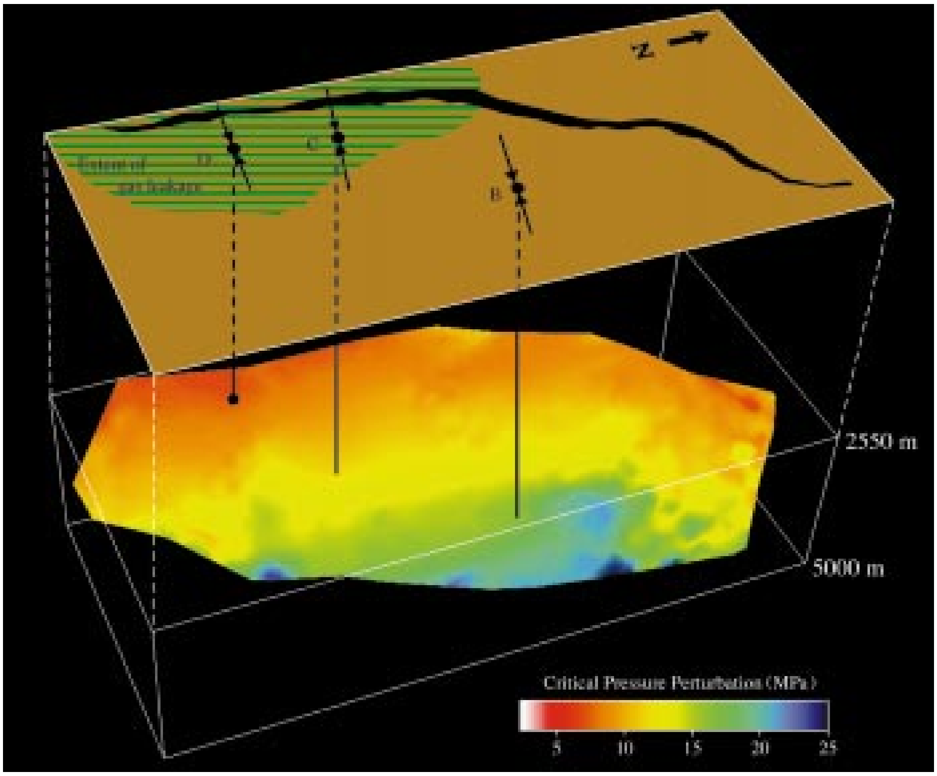

Figure 3. Map view and perspective view of A-Central fault as determined from three-dimensional seismic reflection survey. Map view shows region of gas leakage as inferred from reduced seismic reflectivity (see Fig. 1). Perspective view is colored to show excess pore pressure needed to induce fault slip in current stress field (see text). Part of fault most likely to slip corresponds to that which appears to be leaking.

Brudy, M., and Zoback, M.D., 1999, Drilling-induced tensile wall-fractures: Implications for determination of in-situ stress orientation and magnitude: International Journal of Rock Mechanics and Mining Sciences, v. 36, p. 191–215.

Brudy, M., Zoback, M.D., Fuchs, K., Rummel, F., and Baumgaertner, J., 1997, Estimation of the complete stress tensor to 8 km depth in the KTB scientific drill holes: Implications for crustal strength: Journal of Geophysical Research, v. 102, p. 18,453–18,475.

Færseth, R.B., Sjøblom, T.S., Steel, R.J., Liljedahl, T., Sauar, B.E., and Tjelland, T., 1995, Tectonic controls on Bathonian-Volgian syn-rift successions on the Visund fault block, northern North Sea, *in* Steel, R.J., et al., eds., Sequence stratigraphy on the northwest European margin: Amsterdam, Elsevier, p. 325–346.

Finkbeiner, T., Zoback, M.D., Stump, B., and Flemings, P., 1998, In situ stress, pore pressure, and hydrocarbon migration in the South Eugene Island Field, Gulf of Mexico, *in* Mitchell, A., and Grauls, D., eds., Overpressures in petroleum exploration, workshop proceedings: Pau, France, Elf Aquitaine Memoir 72, p. 103–110.

Grollimund, B., Zoback, M.D., and Arnesen, L., 1998, Flexurally-induced stresses in the northern North Sea: Preliminary comparison of observation and theory, *in* Proceedings of Society of Petroleum Engineers/International Society of Rock Mechanics and Mining Sciences Rock Mechanics in Petroleum Engineering, Volume 1: Trondheim, Norway, Society of Petroleum Engineers, p. 189–198.

Healy, J.H., Rubey, W.W., Griggs, D.T., and Raleigh, C.B., 1968, The Denver earthquakes: Disposal of waste fluids by injection into a deep well has triggered earthquakes near Denver, Colorado: Science, v. 161, p. 1301–1310.

Hickman, S., Sibson, R., and Bruhn, R., 1992, Introduction to special section: Mechanical interaction of fluids in faulting: Journal of Geophysical Research, v. 100, p. 8749–8764.

Hickman, S.H., Zoback, M.D., and Benoit, R., 1998, Tectonic controls on fault-zone permeability in a geothermal reservoir at Dixie Valley, Nevada, *in* Proceedings of Society of Petroleum Engineers/International Society of Rock Mechanics and Mining Sciences Rock Mechanics in Petroleum Engineering, Volume 1: Trondheim, Norway, Society of Petroleum Engineers, p. 79–86.

Hunt, J.M., 1990, Generation and migration of petroleum from abnormally pressured fluid compartments: American Association of Petroleum Geologists Bulletin, v. 74, p. 1–12.

Kennedy, B.M., Kharaka, Y.K., Evans, W.C., Ellwood, A., DePaolo, D.J., Thordsen, J., Ambats, G., and Mariner, R.H., 1997, Mantle fluids in the San Andreas fault system, California: Science, v. 278, p. 1278–1281.

Klemann, V., and Wolf, D., 1998, Modeling of stresses in the Fennoscandian lithosphere induced by Pleistocene glaciations: Tectonophysics, v. 294, p. 291–303.

Linde, A.T., Sacks, I.S., Johnston, M.J.S., Hill, D.P., and Bilham, R.G., 1994, Increased pressure from rising bubbles as a mechanism for remotely triggered seismicity: Nature, v. 371, p. 408–410.

Lindholm, C.D., Bungum, H., Villagran, M., and Hicks, E., 1995, Crustal stress and tectonics in Norwegian regions determined from earthquake focal mechanisms, *in* Proceedings of the Workshop on Rock Stresses in the North Sea, Feb 13–14, 1995: Trondheim, Norway, Foundation of Scientific and Industrial Research at the Norwegian Institute of Technology, Rock and Mineral Engineering, p. 77–91.

Moos, D., and Zoback, M.D., 1990, Utilization of observations of well bore failure to constrain the orientation and magnitude of crustal stresses: Application to continental, Deep Sea Drilling Project, and Ocean Drilling Program boreholes: Journal of Geophysical Research, v. 95, p. 9305–9325.

Raleigh, C.B., Healy, J.H., and Bredehoeft, J.D., 1976, An experiment in earthquake control at Rangeley, Colorado: Science, v. 191, p. 1230–1237.

Sahagian, D.L., and Proussevitch, A.A., 1992, Bubbles in volcanic systems: Nature, v. 359, p. 485.

Sibson, R.H., 1992, Implications of fault-valve behaviour for rupture nucleation and recurrence, *in* Mikumo, T., et al., eds., Earthquake source physics and earthquake precursors: Tectonophysics, v. 211, p. 283–293.

Stephansson, O., 1988, Ridge push and glacial rebound as rock stress generators in Fennoscandia: Bulletin of the Geological Institutions of the University of Uppsala, new ser., v. 14, p. 39–48.

Sturtevant, B., Kanamori, H., and Brodsky, E.E., 1996, Seismic triggering by rectified diffusion in geothermal systems: Journal of Geophysical Research, v. 101, p. 25,269–25,282.

Wiprut, D.J., and Zoback, M.D., 2000, Constraining the full stress tensor in the Visund field, Norwegian North Sea: Application to wellbore stability and sand production: International Journal of Rock Mechanics and Mining Sciences (in press).

Zoback, M.D., and Harjes, H.P., 1997, Injection-induced earthquakes and crustal stress at 9 km depth at the KTB deep drilling site, Germany: Journal of Geophysical Research, v. 102, p. 18,477–18,491.

Manuscript received December 10, 1999
Revised manuscript received April 6, 2000
Manuscript accepted April 13, 2000