

A fault caught in the act of burping

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ABSTRACT

We report on the first direct observation of a migrating fluid pulse inside a fault zone that, based on previous evidence, is suspected to be a conduit for fluids ascending from depth. We find that areas of high fault-plane reflectivity from a fault at the South Eugene Island Block 330 field, offshore Louisiana, systematically moved up the fault 1 km between 1985 and 1992. The updip movement can be explained by the presence of a high pressure fluid pulse ascending a vertically permeable fault zone. These fault burps play a central role in hydrocarbon migration.

Key words: hydrocarbon migration, fault zones, seismic reflectivity

INTRODUCTION

Faults display a split-personality as both impediments to fluid flow and, at times, preferential pathways for flow. Both behaviors are invoked in the petroleum industry to explain how hydrocarbons move (Hooper, 1991) from the location at which they are generated (e.g., by flowing along faults) into fault-bounded reservoirs (Holland *et al.*, 1990) where they are trapped (e.g., by a lack of flow across faults). In the Gulf of Mexico, growth faults cutting through low permeability sediments provide a means for hydrocarbons generated in deep, pressurized source rocks to migrate into shallow reservoirs.

Despite the fact that fault-hosted fluid flow is still poorly understood, several studies, both theoretical and observational, have put our understanding of the interaction of fluids and faults on firmer footing. One popular model, introduced by Rice (1992) and discussed by Reil and Cathles (2002), maintains that fluids may intermittently propagate as shock waves along faults at geologically fast rates (from m/yr to km/yr). The shock waves are excited in the subsurface when the rock permeability is a strongly nonlinear function of fluid pressure - a characteristic of highly fractured zones, such as fault zones. Nur and Walder (1992) refer to intermittent times of intense fault-hosted fluid flow as “fault burps”, a descriptive term that we adopt for this paper. As with Nur and Walder (1992), Finkbeiner *et al.* (2001) choose to view these episodic flow events in terms

of pore pressure buildup followed by release when the Coulomb failure criterion is exceeded. Such behavior is reminiscent of the fault-valve model of Sibson (1990), in which fluid flow along faults is episodic and initiated by an increase in fault zone permeability in response to fault slip. Recently, Miller *et al.* (2004) have shown how a combination of Rice’s shock wave model and Sibson’s fault-valve model explains the upward movement of aftershock epicenters along a fault in the deep crust beneath Italy.

Several lines of evidence taken at the South Eugene Island Block 330 field, offshore Louisiana, indicate that faults there have hosted significant vertical fluid flow over the last 250,000 years, continuing to the present day. The evidence includes (a) oil seeps from the fault scarps along the ocean floor (Anderson *et al.*, 1995), (b) thermal anomalies associated with the spatial patterns of the fault scarps (Anderson *et al.*, 1991), (c) reports from drilling of anomalously high pore pressure confined to one of the fault planes (Losh *et al.*, 1999), (d) a year-to-year variation in the fluid chemistry of hydrocarbons produced from the same reservoir (Whelan *et al.*, 2001), and (e) geochemical anomalies seen in core samples taken from fault zones (Losh *et al.*, 1999). We present an additional set of data - seismic reflection images - that indicate fast (> 100 m/yr) fluid movement along growth faults. Previously, we have demonstrated that reflections from the fault-planes that appear in seismic data from South Eugene Island Block

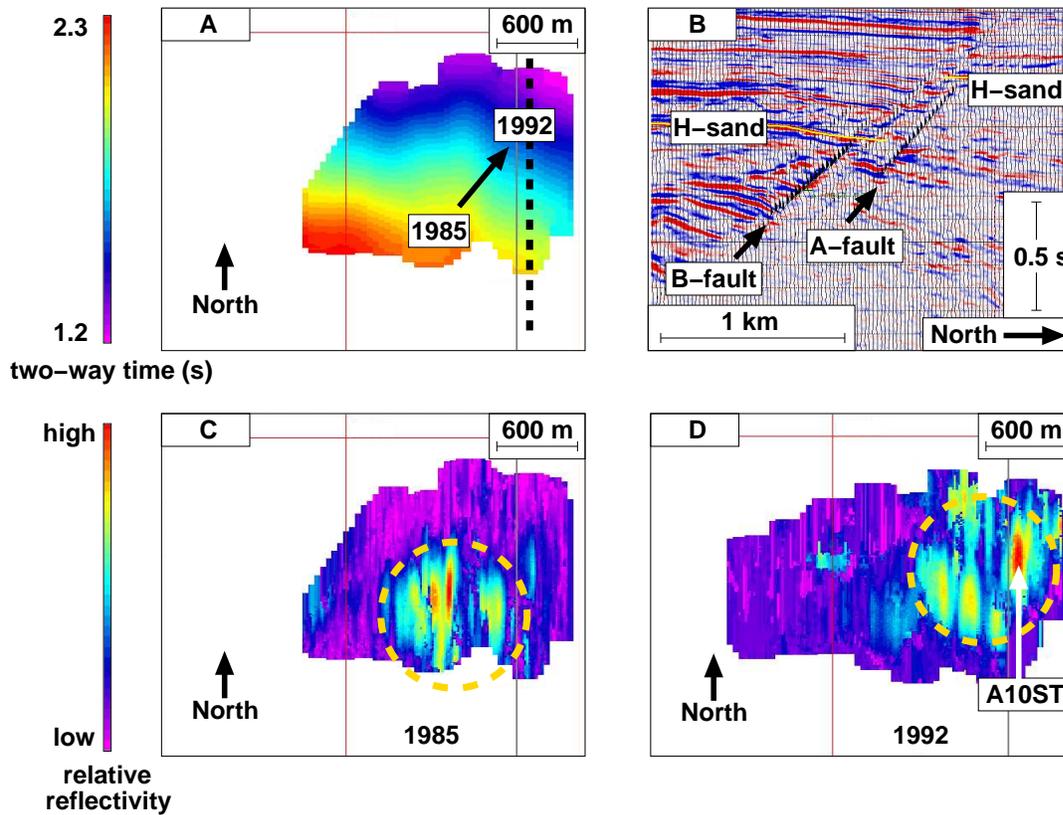


Figure 1. (A) Map of the two-way reflection time (TWT) to the B-fault plane. Using the approximation 100 m depth ~ 0.1 s TWT (Losh *et al.*, 1999), this map shows the structure of the B-fault, most notably the down-to-the-SW dip. (B) Overlay of the dip-filtered seismic reflection image (black & white wiggle plot) on top of the original image (red & blue variable density plot) along the dashed line in (A). The dip-filtering highlights the fault-plane reflections from the B-fault and a nearby fault known as the A-fault. The H-sand is shown to indicate throw. (C) Map of the B-fault, as in (A), but with reflectivity from the fault-plane in 1985 plotted instead of TWT. The area of highest reflectivity is circled in gold. (D) Map of the B-fault reflectivity, as in (C), but from 1992. The data extend over a slightly larger area than in (C); however, the spatial perspective is identical. The area of highest reflectivity, circled in gold, is shifted roughly 1 km NE in the updip direction relative to its location in 1985, as is expected for a fluid pulse ascending the B-fault. This movement is depicted by the arrow in (A). Also shown is the location of the A10ST well intersection, where exceptionally high fluid pressures were encountered while drilling into the B-fault zone in 1993 (Losh *et al.*, 1999).

330 contain information about the distribution of fluid pressures across faults (Haney *et al.*, 2004).

FLUID MIGRATION AS SEEN IN TIME LAPSE SEISMIC DATA

The South Eugene Island field is an ideal location for this study. Multiple vintages of seismic reflection surveys can be interpreted in the context of abundant fluid pressure, geochemical, and other data. Much of the

available data is due to a multifaceted drilling project conducted by the Global Basins Research Network (GBRN) in the 1990s (Anderson *et al.*, 1995). During late 1993, GBRN intentionally drilled into and successfully cored some of the growth faults at South Eugene Island. Normal faults that transect the field separate upthrown sediments saturated by highly-pressurized fluids from normally-pressurized dowthrown sediments; the faults are typically at the same pressure as the upthrown sediments (Losh *et al.*, 1999). However, exceptionally pressurized fluid was encountered in one penetration of

a growth fault, the B-fault, in the A10ST well (Anderson *et al.*, 1995; Losh *et al.*, 1999). Losh *et al.* (1999) stated that “the isolated pocket of anomalously high fluid pressure in the A10ST well may represent a spatially limited pulse of anomalously pressured fluid.”

To test the hypothesis of a moving fluid pulse, or fault burp, we isolate the fault-plane reflections from the B-fault in images derived from seismic surveys taken in 1985 and 1992 and look for indications of movement. First, we pick the fault plane in the 3D seismic reflection images (Figure 1A). We then proceed by dip-filtering the seismic reflection images in the direction of the B-fault (Figure 1B). This dip-filtering step serves to accentuate the fault-plane reflections while simultaneously attenuating the reflections from the sedimentary layers. The final step is to extract the amplitude of the fault-plane reflection along the B-fault in a small time-window around the picked fault-plane. In Figures 1C and 1D, we show reflectivity as a function of position on the fault-plane for both datasets. Patches of high reflectivity, or “bright spots”, are known to be associated with the presence of fluids (Dobrin, 1976).

The most striking pattern in the fault reflectivity maps of Figures 1C and 1D is the northeast movement of the highest reflectivity areas between 1985 and 1992. This movement, in the up-dip direction, is to be expected for a fluid pulse ascending the B-fault. From the reflectivity maps at the B-fault, we estimate the movement of the fluid pulse to be on the order of 1 km between 1985 and 1992, for an average velocity of ~ 140 m/yr. In the next section, we describe how we estimated this velocity for the pulse. Such fast fluid flow up a growth fault at South Eugene Island is in line with the study by Finkbeiner *et al.* (2001). In their study, Finkbeiner *et al.* (2001) analyzed in situ stress data and pressure measurements and showed that overpressure in some of the deep reservoirs abutting the B-fault could induce frictional failure on the fault plane. The fast movement of fluids up a permeable fault also agrees with a nonlinear permeability model first discussed by Rice (Rice, 1992). In this model, the fluid pulse is a shock wave that moves with velocity v given by

$$v = \frac{k_o(1 - \phi_o)g(\rho_g - \rho_f) \sin \alpha}{\eta_f \beta \phi_o} \times \left[\frac{\exp(-\sigma_f/\sigma^*) - \exp(-\sigma_i/\sigma^*)}{\sigma_i - \sigma_f} \right], \quad (1)$$

where k_o is the permeability at zero effective stress, ϕ_o is the porosity at zero effective stress, g is gravitational acceleration, ρ_g is the density of the rock grain, ρ_f is the density of the fluid, α is the dip of the fault, η_f is the dynamic viscosity of the fluid, β is a parameter describing the linear dependence of porosity on effective stress (Elliott, 1999), σ_i is the initial effective stress state ahead of the pulse, σ_f is the final effective stress state behind the pulse, and σ^* is a parameter describing the exponential dependence of permeability on effective stress (Rice,

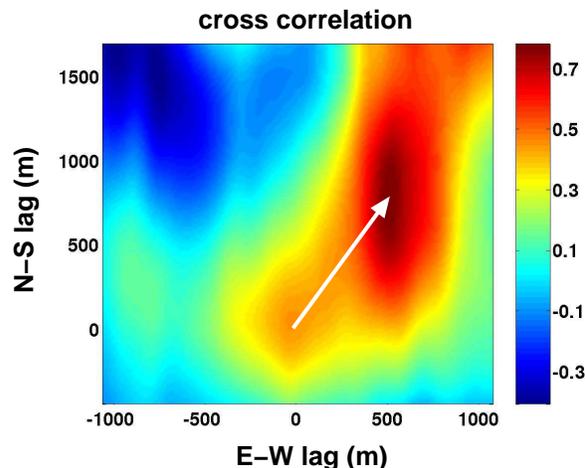


Figure 2. Spatial cross correlation of the 1985 and 1992 B-fault amplitude maps shown in Figures 1C and 1D. There is a maximum in the cross correlation when the spatial lag is 1 km to the NE (the up-dip direction of the A-fault). At the maximum, the correlation coefficient is 0.78, which is close to the value 0.80 for a horizontal reflector known as the O-sand at zero spatial lag (see Figure 3). The correlation shown here can be seen visually in Figures 1C and 1D.

1992; Revil & Cathles, 2002). We note that models by Finkbeiner *et al.* (2001) and Rice (1992) are not the only ones of relevance to the behavior we observe along the B-fault at South Eugene Island. Currently, a “vug-wave” model is being developed (Losh *et al.*, 2005) that describes a fluid pulse which is mechanically coupled with the shear strain in the fault. This model has the potential to bridge the link between what we have observed at South Eugene Island and the phenomenon of “slow” or “silent” earthquakes that show sudden aseismic slip (Cervelli *et al.*, 2002).

QUANTIFYING THE PULSE MOVEMENT

In Figure 2, we plot the spatial cross correlation of the amplitude maps from the B-fault. There is a local maximum at 1 km spatial lag in the NE direction. This corresponds to what is seen visually in Figures 1C and 1D. The value of the correlation at the maximum is 0.78, which is close to the correlation value of 0.80 computed for a horizontal reflector known as the O-sand at zero-lag (see Figure 3). The zero-lag correlation for the B-fault amplitude maps, as shown in Figure 2, is 0.45. The fact that the correlation is as high as 0.80 for the O-sand in its zero-lag position supports the similarity of the two surveys and their processing schemes. In another study (Haney *et al.*, 2005), we tested how the presence of noise, a lack of DMO processing, and application of AGC degraded migrated amplitudes. The application of AGC most severely altered the relative amplitudes. Though an AGC appears to have been applied to the

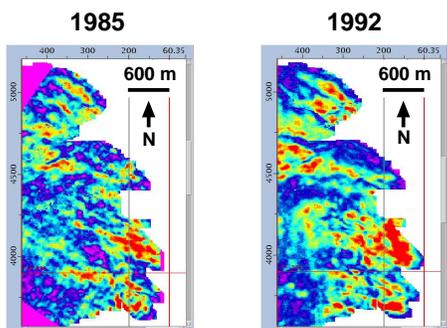


Figure 3. A comparison of the O-sand amplitude in the 1985 and 1992 surveys. The O-sand is a gently dipping sedimentary layer boundary at ~ 2.3 s TWT. Hence, the O-sand abuts the B-fault in the lower part of the B-fault plane displayed in Figure 1A. The consistency of the amplitudes in these two images, compared to the changing amplitudes along the B-fault shown in Figures 1C and 1D, supports the interpretation of relative amplitude changes in the two surveys. Though we only show the O-sand here, this consistency holds for the other sedimentary layer boundaries as well.

1985 data, it obviously did not damage the amplitudes from the O-sand enough to bring its correlation below 0.80. We have also checked the K-sand and found good amplitude agreement in its zero-lag position. Both the O- and K-sands are in the same depth interval as the B-fault plane.

The similarity of the amplitudes in the 1985 and 1992 surveys at the O-sand support the hypothesis that the 1 km of movement seen at the B-fault is an actual change in reflectivity; however, we need to show that the 1 km of movement in the seismic image is not the result of over- or under-migration, given typical errors in migration velocities. Note that the 1 km of movement up the B-fault, which dips at 45° , is equivalent to 700 m of lateral movement. To explore the issue of over- or under-migration, we first make the approximation that the shooting lines in the 1985 and 1992 seismic surveys were in the dip direction. This means the action of 3D migration on the reflection from the B-fault is purely a vertical and lateral movement in a single vertical plane. We then use the expression for the lateral movement applied to a time sample in a stacked section by a constant-velocity 2D migration, denoted Δx_m (Yilmaz, 1987)

$$\Delta x_m = \frac{pt_{in}v_m^2}{4}. \quad (2)$$

In equation (2), t_{in} is the two-way time of the input point, v_m is the migration velocity, and p is the time

dip of the fault-plane reflection. The time dip is given by

$$p = \frac{2\sin\theta}{v}, \quad (3)$$

where θ is the dip of the fault-plane and v is the true subsurface velocity, not necessarily equal to the migration velocity v_m . Given the true subsurface velocity, the amount of lateral movement applied by migration should be

$$\Delta x = \frac{pt_{in}v^2}{4}. \quad (4)$$

The difference in the amount of lateral movement applied by migration, Δx_m , and the amount of lateral movement that should be applied, Δx , is the error in the lateral placement of the input point Δx_e due to an incorrect migration velocity

$$\Delta x_e = \Delta x_m - \Delta x = \frac{pt_{in}(v_m^2 - v^2)}{4}. \quad (5)$$

Denoting the depth of the time sample in the stacked section as z , t_{in} is given by

$$t_{in} = \frac{2z}{v\cos\theta}. \quad (6)$$

Therefore, using equation (3) and (6), equation (5) may be written as

$$\Delta x_e = z\tan\theta \left[\left(\frac{v_m}{v} \right)^2 - 1 \right]. \quad (7)$$

To estimate the amount of error in lateral positioning due to over- or under-migration at the B-fault, we use the approximate depth z and dip θ of the fault given by 2 km and 45° , respectively. From equation (7), a $\pm 5\%$ error in migration velocity results in a lateral positioning error of ~ 200 m, less than the 700 m of lateral movement we observe at the B-fault in the 1985 and 1992 seismic surveys. Given that the geology above the B-fault is essentially a vertically-varying, compacting stack of sediments and that a considerable number of wells with wireline data passed through this section, we feel that a $\pm 5\%$ error in migration velocity is a conservative estimate of the error. In fact, a 700 m error in lateral positioning requires a $\pm 17.5\%$ error in migration velocity, much too large for a target in a 1D geologic setting above salt. Furthermore, the movement of the pulse observed in the 1985 and 1992 data, if an artifact of incorrect migration velocities, would require that the errors in the two data sets be negatively correlated. For example, if the 1985 data had a -5% error in migration velocity (under-migration) and the 1992 data had a $+5\%$ error in migration velocity (over-migration), the residual mis-positioning between the two surveys would still only be 400 m. If both surveys had a $+5\%$ error in migration velocity, there would be no apparent lateral movement. We therefore conclude that 1 km of movement up the B-fault is significant enough to stand out in the presence of typical positioning errors due to incorrect migration velocities.

CONCLUSION

At a location on the B-fault plane at the South Eugene Island Block 330 field, where anomalously high pore pressures have been reported in the fault zone (Anderson *et al.*, 1995; Losh *et al.*, 1999), areas of high reflectivity appear to move up the fault-plane, as would be expected for an ascending, pressure-driven fluid pulse. The seismic waves are able to sense these different pressure domains due to the effective stress controlling the elastic properties of the soft Plio-Pleistocene sediments (Haney *et al.*, 2005). This observation gives additional credence to the dynamic fluid injection hypothesis (Whelan *et al.*, 2001) and points to natural flow processes in sedimentary basins that occur on production time scales.

The movement seen in the 1985 and 1992 seismic data warrants more extensive study of the faults at South Eugene Island. One possibility in the future is to go to the fault scarps on the ocean floor with a small submersible and take samples of the fluids coming directly out of the fault scarps, since Anderson *et al.* (1994) report oil seeps that correlate with their location. The shallow water depth at South Eugene Island (< 100 m) makes such an investigation using a submersible possible. Submersibles have proven to be useful in sub-sea geological studies, as shown by Chaytor *et al.* (2004) in the Pacific ocean and Roberts (2001) in the Gulf of Mexico. Other data sets to incorporate into future fault studies are prestack data, especially for doing AVO analysis on a fault-plane reflection, and microseismicity data. Without question, future studies on faults should incorporate time-lapse measurements to capture the essence of faults as dynamic and quickly-changing zones.

ACKNOWLEDGMENTS

Supported by a research grant from Shell International Exploration and Production, whom also provided the 1992 seismic data. The 1985 data, originally acquired by Pennzoil, is currently in the public domain. We thank R. Anderson, W. He, S. Naruk, J. Busch, and S. Wilkins for help and discussions.

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