EXPLORER

Intra-Basement Intrusions in the STACK Area of Oklahoma

May 2018 | Satinder Chopra , Lennon Infante Paez , Kurt Marfurt

Although fractured basement rocks can sometimes form hydrocarbon reservoirs, such as found in Vietnam and Venezuela, in general they are considered to have insufficient porosity to contain significant amounts of hydrocarbons. The top of basement also often represents a major unconformity. While a given seismic acquisition and processing program might accurately image the overlying moderately dipping sedimentary section, more steeply dipping features in the basement might be poorly imaged, resulting in a low frequency, "wormy" character. For these two reasons, relatively little has been published on the appearance of basement features in 3-D seismic data volumes.

In many parts of the world, basement faults control shallower faulting in the overlying sedimentary cover. Such faults can enable fluid migration up and down.

Hot fluids from below can diagenetically alter fault zones in the shallow section. Wastewater injection from above can find its way into the basement, potentially "lubricating" previously "locked" faults. In addition to fluids, magma can also flow within the basement and depending on the age of magmatism, into the sedimentary column. These magmatic flows may follow previous zones of weakness.

The revitalization of old basins by technological advances in producing unconventional reservoirs has justified the acquisition of modern, high-density 3-D seismic surveys of areas that were thought to be well understood. In Oklahoma, these surveys provide new images of the basement that was previously thought to be relatively homogeneous granite and rhyolite.

While extrusive and intrusive igneous rocks sometimes form good hydrocarbon reservoirs, more often they pose an interpretation hazard. In the absence of well control and a clear understanding of the seismic polarity, volcanic mounds can be misinterpreted as carbonate buildups, lava-filled incised valleys as turbidites and sills as bright spots. Although mafic dikes and sills are well-documented in the sedimentary column of the North Sea, Australia and offshore Brazil, and andesitic features in the sedimentary section of Mexico and Argentina, their appearance internal to the basement is less well documented. Fortuitously, a suite of papers in the August 2017 issue of Interpretation on volcanics provided new insights into the seismic geomorphology of intrusive and extrusive igneous features. Using concepts of seismic geomorphology, coupled with an understanding of the Midcontinent Rift from gravity and magnetic surveys, these analogues provide insight into the character of these previously unseen features in recently acquired 3-D seismic data.

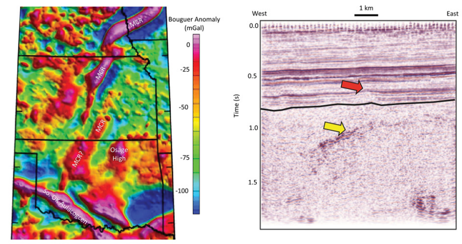

Figure 1: (a) The residual Bouguer anomaly map showing the extent of the Midcontinent Rift extending from Lake Superior, through Kansas, and thought to continue into north central Oklahoma. (b) An image from a legacy survey acquired over the Osage High showing a hypothesized intrusion dipping up the east. The black horizon indicates top of basement, while the red horizon indicates the top Mississippi Limestone. (After Elebiju et al., 2011.)

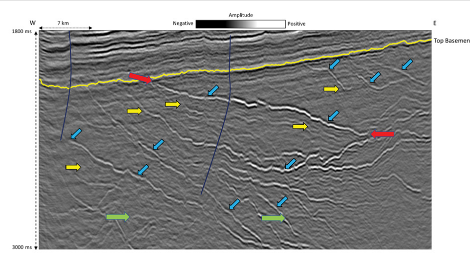

Figure 2: A vertical slice through a modern, high density, wide-azimuth survey acquired to image the Stack play of northern Oklahoma. This survey also images the deeper basement and the hypothesized southern extension of the Midcontinent Rift (indicated by the symbol "MCR?" in figure 1. We interpret the steeply dipping strong reflectors indicated by the cyan

The Midcontinent Rift and the Osage High

From gravity and magnetic surveys, the North American Midcontinent Rift appears to continue southward into Oklahoma (indicated by the "?" in figure 1a). Shallow basement (about 3,000 feet) also occurs over the Osage High, where legacy surveys suggest the presence of igneous sills stepping up to the east. The Wah-Zha-Zhi well reported on in the December 2012 AAPG Explorer drilled 7,000 feet into basement in this area encountered rhyolite, granite and gabbro. A recent August 2017 special section on the subsurface expression of igneous features published in the AAPG-SEG journal Interpretation provides additional insight on seismic geomorphology, reflection strength compared with that of the host rocks, cross-cutting relationships and "stepping" of the reflectors.

In 2016, TGS acquired and processed a 3-D wide-azimuth seismic survey over Kingfisher, Canadian and Blaine counties of Oklahoma in order to image the Meramec, Woodford, Osage and other targets that form the Sooner Trend Anadarko Canadian and Kingfisher, or "STACK" play. The quality of these images is vastly superior to older seismic images in the same area, where the suite of stepping-up-to-the-west sills seen in figure 2 are significantly better focused than similar features seen on legacy surveys such as in figure 1a. The overlying sedimentary structure in figure 2 is gently dipping to the left of this image, such that we can discount these steeply dipping events as being multiples. Yellow arrows indicate the "stepping up" features seen in sedimentary column of the North Sea, Brazil and New Zealand. These "steps" are sometimes misinterpreted to be faults, although some of these offsets are due to faults observed as lineaments in the curvature attribute extracted on the basement map. Flatter

arrows to be sills that potentially follow earlier zones of weakness. Yellow arrows indicate vertical steps in these sills where we can image the sill. Other offsets might be faults that offset them, some of which continue into the sedimentary section (blue curves). While events that gently dip to the west (paralleling the top basement) may be multiples, flatter events are reflectors in the basement that either existed before the sill emplacement or are additional flat-lying sills. Red arrows indicate the sill mapped in figure 3. Data courtesy of TGS in Houston.

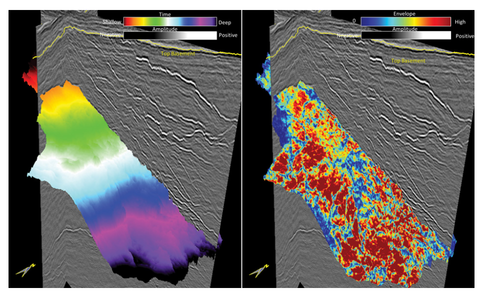

Figure 3: (a) Time-structure map of the picked intrusive event indicated by the red arrow in figure 2 with representative vertical slices section through the seismic amplitude volume. Abrupt changes in this time-structure map correlate to "step-up" features. (b) The corresponding horizon slice through the instantaneous envelope (also called reflection strength) along the same horizon, which we interpret to

events indicated by the green arrows are either flat-lying, potentially volcanoclastic sediments, or flat-lying intrusive sills. Some of the discontinuities correspond to faults (in green) that continue into the sedimentary cover (black curves).

represent the heterogeneity of the sill thickness. Data courtesy of TGS in Houston.

Figure 3a shows a time-structure map of the sill indicated by the red arrows in figure 2. Discontinuities in this map correspond to “step-up” features in the sill. If we assume that the host rock is relatively homogeneous granite or rhyolite, the lateral changes in reflection strength shown in figure 3b correlate to lateral changes in sill thickness. Figure 4 is a photograph of an outcrop analogue, intruding through a sedimentary section. Note how the sill climbs using a series of step-ups through the relatively flat-lying strata. Smaller sills extend from the main intrusion, sub parallel to the relatively flat-lying sedimentary layers.

Our Interpretation

Magma typically forms during break up of continents as a result of decompression and partial melting of the asthenosphere. It can intrude laterally or vertically through the rock layers above depending on the rock types, the localized structures prevalent there, and more importantly the state of stress in the areas. Our current hypothesis is that these intrusions were fed by the magmatism that created the Mid-Continent Rift System when the North American craton began to split during the Precambrian about 1.1 billion years ago by thinning of the lithosphere due to convection of the hot but solid asthenosphere. None of these intrusions cut through the overlying Cambrian sediments that lie above the top basement.

This igneous bodies appear to be inclined sheets flowing from a deep source point (maybe from a series of sub vertical dikes that cannot be imaged in the seismic data) that also extents outwards like many of the studies we have seen before from the European side of the North Atlantic margin. In this part of Oklahoma, the few wells that tag basement find it to be felsic in composition (granite or rhyolite) although there is a lack of information about its nature and extension. Using this assumption, the high reflectivity between the felsic basement and the igneous intrusions indicate a change in magma composition. Therefore, we interpret the composition of these inclined sheets to be mafic (having more magnesium and iron rich minerals such as pyroxene and olivine) which have higher impedance (ρ≈3.0 g/cm3, vP≈ 7 km/s) compared to their felsic counterpart (ρ≈2.7 g/ cm3, vP≈6 km/s). This difference in magma composition is consistent with a continental rift setting in which continental crust that is melted by conduction of the hot Asthenosphere would create felsic magma, whereas magma that intruded near the upper crust through discontinuities such zones of weakness have retained their original mafic composition.

Summary

Surface seismic studies have dramatically changed our perception of igneous systems due to the possibility of studying igneous bodies in 3-D. Such high-quality data promise to provide a much deeper understanding of the Midcontinent Rift. Such studies help understand the occurrence of sills or intrusive bodies in sedimentary rocks. The transport or flow pathway mechanisms include the intrusion of magma along faults or compliant lithologies. Three-dimensional surface seismic data help us understand the shapes of such intrusive bodies, interpret or understand rock deformation mechanisms and map flow pathways that magma might have followed. As these bodies offer high acoustic impedance contrast than the different sedimentary rock layer interfaces, they are conspicuous by their higher amplitudes.

Explorer Geophysical Corner (Click to View Column Archives)

The Geophysical Corner is a regular column in the EXPLORER that features geophysical case studies, techniques and application to the petroleum industry. **R. Randy Ray,** consulting geophysicist/geologist in Lakewood, Colo., served as editor of Geophysical Corner from January 2001 until January 2006. **Bob A. Hardage**, senior research scientist at the Bureau of Economic Geology, the University of Texas at Austin was editor of Geophysical Corner from January 2006 until 2012. **Satinder Chopra**, award-winning chief geophysicist (reservoir) at Arcis Seismic Solutions, Calgary, Canada, and a past AAPG-SEG Joint Distinguished Lecturer began serving as the editor of the Geophysical Corner column in 2012.

Satinder Chopra

Satinder Chopra, award-winning chief geophysicist (reservoir), at Arcis Seismic Solutions, Calgary, Canada, and a past AAPG-SEG Joint Distinguished Lecturer began serving as the editor of the Geophysical Corner column in 2012.

Lennon Infante Paez

Student Member of AAPG and Doctoral Student at University of Oklahoma

Kurt Marfurt

Kurt currently serves as the Frank and Henrietta Schultz Professor of Geophysics within the ConocoPhillips School of Geology and Geophysics. Marfurt also served as the EAGE/SEG Distinguished Short Course Instructor for 2006 (on seismic attributes).

Share this article:

Figure 4: A photo showing igneous sills rising through a sedimentary section in Greenland, showing a morphology similar to the hypothesized sills seen in the basement features shown in figures 2 and 3. Note how the sills "step up" into the shallower section. Photo courtesy of John Howell (pesgb.org.uk/events/event-240).

Extended reading