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Seismic Expressions of Igneous Flows - Hydrocarbon Prospectivity: Kerala-Konkan Basin, India

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Summary

We present a series of observations denoting various features commonly found in volcanic passive margin set-up. Analysis of such seismic features, both in the deep and shallow section and inferred geology from such an analysis can have deep impact on prospect delineation in volcanic basins. Sill intrusion can generate subtle anticlinal traps that might be valid prospects because thermal effect of sills is relatively limited. Thus, there is less chance of generating an over-mature prospect, unless the sills occur in high numbers. Apart form seismic, filtered gravity and magnetic data may be used to define areas with high amount of large intrusives. Flood basalt regions in volcanic basins which simply blanket sedimentary basins without intrusives in the subsurface are most prospective regions. In this case, basalt thickness estimation and associated burial depth become an important parameter to estimate prospectivity. Clustering of small gas – related amplitude anomalies stacked vertically in footwall or hanging – wall traps along single faults is direct observational evidence that links fault planes to significant fluid flux. Pockmark craters and mounds identified on the sea bottom and within the seismic section, formed due to igneous intrusion and hydrothermal pipes are also discussed for analysis of seal integrity.

Introduction

Volcanic basins are defined as sedimentary basins significantly affected by flood basalt volcanism. The presence of shallow basalt covering the underlying sediments significantly inhibits imaging of the subsurface. Additionally, the sub-basalt sediments are commonly intruded by sill and dike complexes (e.g., Bell and Butcher, 2002; Smallwood and Maresh, 2002), creating additional seismic imaging problems. Other nonseismic problems include uncertainties in the temperature history of the basin and associated digenetic effects generated by igneous rocks. On the other hand, forced folds formed above saucer-shaped sills may form potential hydrocarbon traps (Figure 1). Seismic evidence of small gas-related amplitude anomalies along single faults connecting deeper seismic with shallow is indicative of hydrocarbon potential that a basin holds despite poor seismic imaging (Figure 2). Volcanic intrusives, expressing itself as discordant amplitude anomalies, help in hydrocarbon maturation and fluid migration. In this article, we briefly review the main igneous rock types encountered in volcanic basins and their seismic expressions as well as explain how to interpret seismic images in volcanic basins from an explorer's point of view.

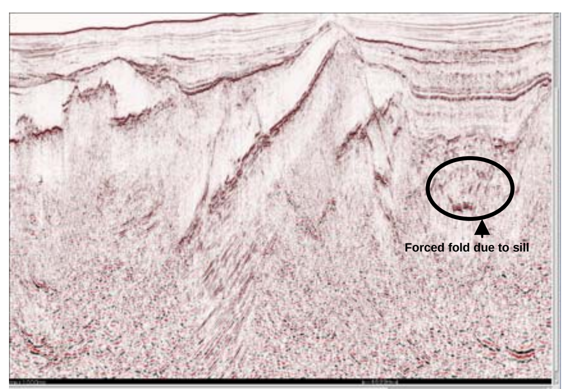

Figure 1: Jack-up overburden due to sill intrusion

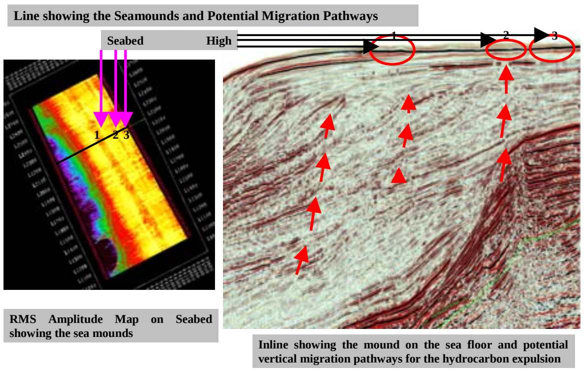

Figure 2: Amplitude anomalies along single faults

Flood basalts

Flood basalts are fed from feeder dikes and volcanoes over a short period of time, with high effusive rates. Generally basalts behave similarly to sedimentary deposits and are controlled by the relationship between supply, subsidence, and topography, causing accumulation of volcanic flows in basins and a relative thinning over highs. Important differences between sediments and volcanic extrusives are that the former are more dependent on interplay between sea level fluctuations and tectonics, whereas the latter are governed by the periodicity of volcanic eruptions. Most flood basalts generally propagate through inflation and can therefore be classified as pahoehoe sheet flows (Self et al., 1997). Flow thickness in flood basalt (Figure 3) provinces is upto hundred of meters compared to several meters in present-day flows (Jerram, 2002).

Basalt flows consist of a solid inner part and a more porous part at the top of a flow caused by weathering as evidenced in several Ocean Drilling Program boreholes (Planke et al., 1999). The base of the flow is commonly rubbly where the flow chilled against underlying soil and rock. When basalt erosion products interact with water, thick hyaloclastites form, consisting of a mix of basalt-derived sediments and breccias generating prograding foresets (Kiørboe, 1999; Pedersen et al., 2002).

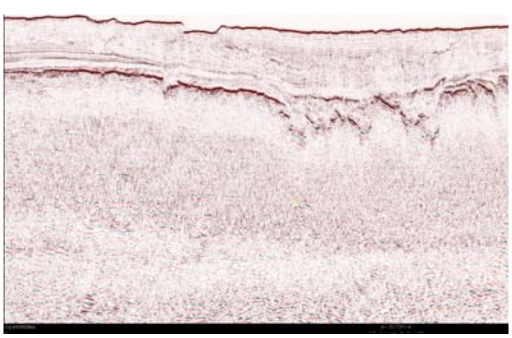

Figure 3: Seismic section showing Flood basalt and difficulty of sub-basalt seismic imaging

Other extrusive rocks associated with flood basalt provinces include acidic flows and air-fall tuff layers emanating from nearby volcanoes, as well as hydrothermal vents (Planke et al., 2005). The latter are generated by the interaction of sill intrusions and sediment pore fluids, causing fluidization and vertical transport of sediments. This occurs at shallow depths or regions where permeability is low (Jamtveit et al., 2004). The result is an explosive eruption of gas and sediments at the seabed and the formation of a mound structure. These mounds are easily recognizable on seismic sections, commonly showing conical and eye-or onion-shaped geometries. Mounds are very useful in constraining timing of sill intrusion because mounds are commonly found at the paleoseabed (Figure 4).

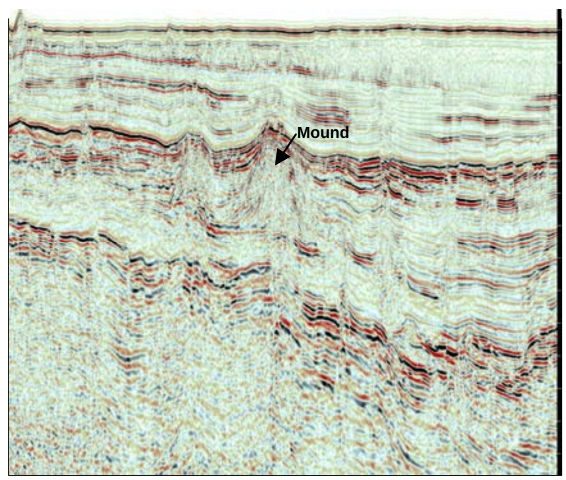

Figure 4: Seismic expression of a mound and underlying pipe

Most of the flood basalts are fairly subhorizontal and well layered. Their internal physical heterogeneity creates a tendency to generate strong multiple reflections. Below this basalt layer, no coherent energy is recorded mainly because of a low signal-to-noise ratio and multiples as scattering and attenuation caused by heterogeneity of basalt stack. To improve existing high-frequency seismic data in basalt-covered areas, simple band-pass filtering using a high-cut filter might yield better imaging quality apart from better demultiple analysis, and improved velocity picking (Figure 5).

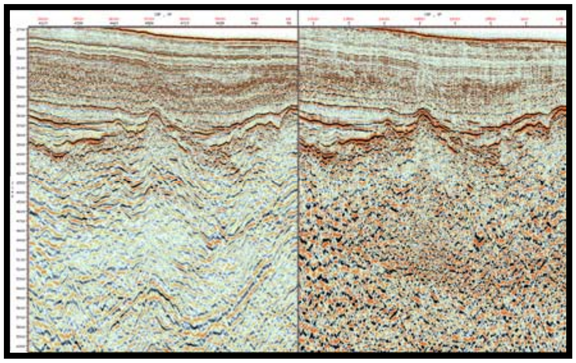

Figure 5: Comparison of seismic showing better imaging quality with proper filtering, demultiple analysis and velocity picking

Sills and Dikes

Although the seismic method is good in imaging sub-horizontal volcanic features, such as basalt flows, tuffs, and sills, it performs less well when dealing with steeply dipping events such as dikes and igneous complexes (e.g., plutonic intrusions). Most of the intrusives imaged on seismic data are therefore doleritic sills, characterized by their high acoustic impedance (e.g., Gibband Kanaris Sotoriou, 1988; Planke et al., 1999; Hansen, 2004). Various mechanisms have been described for the emplacement of sills and dikes (e.g., Bradley, 1965; Pollard and Johnson, 1973; Francis, 1982). Emplacement of sills and dikes in sedimentary basins is dependent on vertical stress and magma pressure. Generally, this means that fairly competent host lithologies (i.e. sand or limestone dominated) mainly display dikes, whereas softer lithologies, like shales, claystone, marls, and salt, display sills. Moreover, zones of weakness, such as subhorizontal unconformities and subvertical faults, are also prone to sill and dike intrusion, respectively (Price and Whitham, 1997). Additionally, sill intrusion is dependent on the depth of burial of the host lithologies, commonly intruding within 3–4 km from the paleosurface (e.g., Bellienietal.,1984; Kontorovich et al., 1997; Smallwood and Maresh, 2002). On seismic data, sills are commonly seen to climb near rheologically stronger, more competent highs (Planke et al., 2000). In all flood basalt provinces, sills and dikes are directly related to the flood basalts and have similar chemical composition (doleritic). Sills and dikes can generate contact metamorphic aureoles on intrusion in sediments, with higher velocities in the aureoles than in unaffected sediments. On seismic data, when sills intrude relatively close to the seabed, the interaction between magma and unconsolidated fluid-rich sediment generates peperites (e.g., Einsele et al., 1980).

Igneous processes can produce jack-up structures generated by intruded igneous bodies as documented by various authors (Pollard and Johnson, 1973; Hansen, 2004) (Figure 6). These jack-up structures have been described in the field and from seismic data showing forced fold structures generated by sills with sediment fill onlapping the jacked-up horizon (Trude et al., 2003). Jack-up structures could potentially be hydrocarbon traps (Figure 1).

Igneous processes can also help in hydrocarbon maturity by increasing temperature during magma emplacement as depicted in Figure 7. Several factors play a role in assessing the maturity window, the important being, time scales associated with igneous maturation compared with burial maturation, thermal conductivities and advective / convective dissipation of heat.

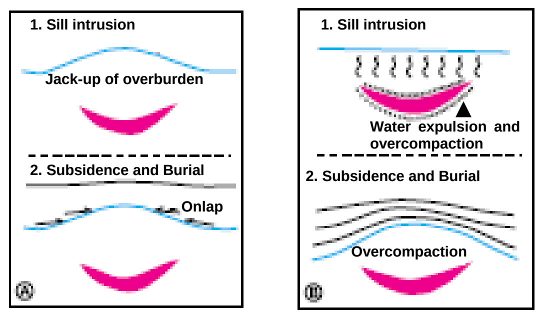

Figure 6: (A) Cross section model of trap generated by sill jack-up. (B) Cross section model of trap generated by differential compaction (After Rohrmann, M., 2007)

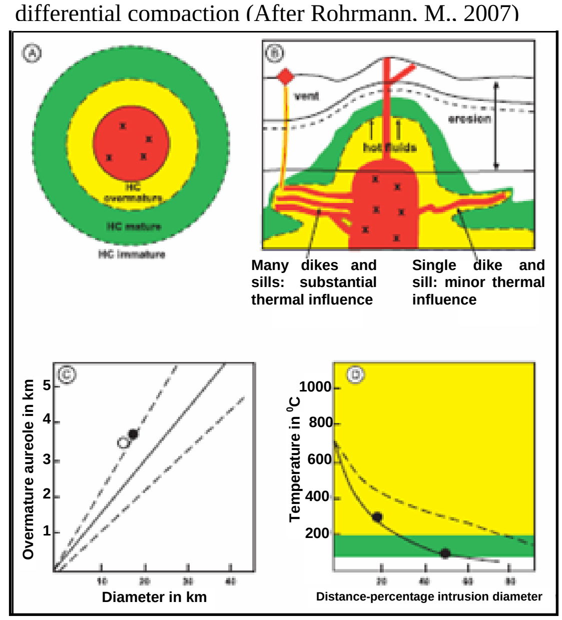

Figure 7: (A) Image of hydrocarbon (HC) maturity around hypothetical stock intrusion in map view. Hydrocarbon maturity includes both oil and gas windows. (B) Image cross section of stock intrusion and hydrocarbon maturity aureole; Multiple sills are assumed to be intruded simultaneously. (C) Estimates of the over-mature aureole around large intrusions. (D) Temperature versus distance (After Rohrmann, M., 2007)

Igneous intrusions have generally much lower permeability than the host medium facies. However, the intrusion of hot magma at greater than 1000 ^{0}C into cold and wet sediments results in major changes in host rock properties for tens of meters away from the immediate contact zone (Einseleetal.,1980). In addition to fracturing associated with forceful intrusion, fracture sets also form during prograded metamorphism in the contact aureole, during hydrothermally driven fluid loss from surrounding sediments (Einsele et al., 1980) and also in the thermal contraction fracturing during longer term cooling of the intrusive body itself. These different fracture sets thus provide a fracture permeability network at various scales surrounding the intrusion and occasionally within the body of the intrusion itself. The fractures that develop during initial intrusion will significantly modify fluid-flow behavior around the intrusion during and immediately after the intrusion event. Fractures within the metamorphic contact aureoles can provide potentially longer term flow conduits, but hydrothermal fluids are highly mineralizing, and the fracture sets have a high probability of closing quickly because of cementation.

The scale and distribution of the fractured country rock associated with any given intrusion depends mainly on intrusion size, geometry, and mechanism. In many petroliferous sedimentary basins, the most important types of intrusion likely to feature in any assessment of seal bypass are mafic dikes and sills, which are widely developed, for example, on many volcanic continental margins (Planke et al., 2000). These range in size from a few meters to many kilometers in dimension and, in the case of dikes, can cross many kilometers of sealing sequences (Figure 8) (Rubin, 1995).

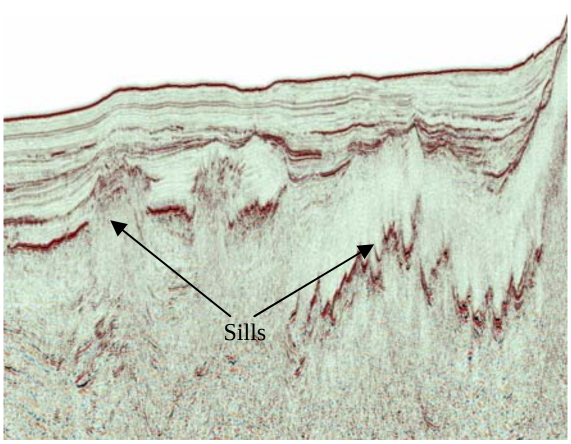

Figure 8: Exhibiting number of sills

The dimensions and typical context of these types of intrusions mean that they may be important in providing secondary migration routes in addition to having a negative impact on seal integrity.

There are important parallels with the preservation of fluid inclusions, including hydrocarbon inclusions, in terrestrial settings where petroleum systems have encountered temperatures and pressures higher than normally encountered in sedimentary basins. Inclusions containing higher hydrocarbons are preserved in sites where microthermometry indicates temperatures of up to 200^{0}C or higher. Hydrocarbons survive the intrusion of magmatic bodies into organic-rich sedimentary rocks (Figure 9). The stability of hydrocarbons at these high temperatures is commonly regarded as anomalous, which it would be at the surface, but under elevated pressures in the sub-surface, stability fields are extended to high temperatures.

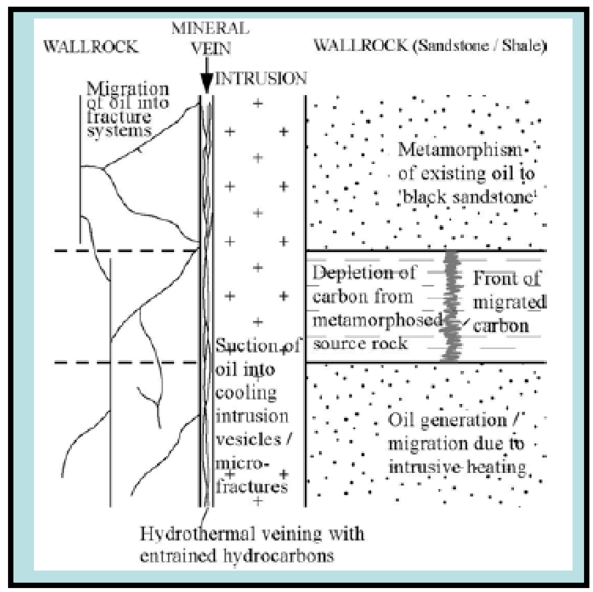

Figure 9: Range of relationships between hydrocarbon generation and deposition around an igneous intrusion (After Wycherley, et.al., 2004)

Pipes

They can best be defined seismically as columnar zones of disturbed reflections that may or may not be associated with subvertically stacked amplitude anomalies. Pipes are commonly ignored on seismic data because they tend to exhibit a vertical to subvertical geometry (Figure 10) and can therefore be confused with seismic artifacts such as migration anomalies, scattering artifacts, lateral velocity anomalies, and attenuation artifacts related to shallow diffractors (Løseth et al., 2001, 2003; Davies, 2003). Care is therefore needed in differentiating true pipes from seismic artifacts, which is best done by considering the structural and stratigraphic context of any candidate pipe. They are commonly seen to emanate from crestal regions, e.g., tilted fault block crests, fold crests, or crests of sand bodies with positive topography, but many pipes are also documented from flat-lying units or synclinal regions, albeit with some focusing element at depth. Pipes are commonly circular or subcircular in planform, and they are therefore easiest to identify in 3-D seismic volumes using slice-based or horizon-based attributes.

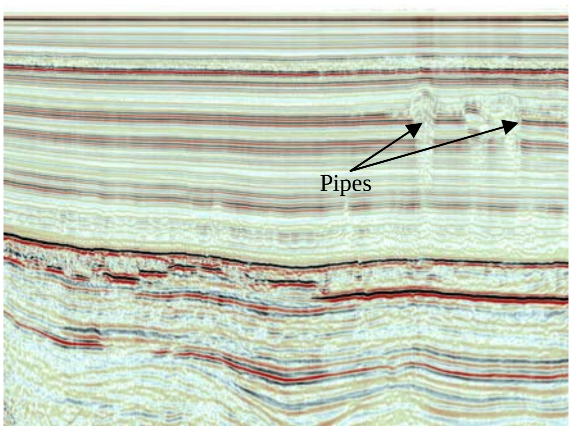

Figure 10: Seismic expressions of pipes. The pipe is seen to emanate from a small fold structure deeper in the profile, which is inferred to be the fluid source unit for the genesis of the pipe

Hydrothermal pipes form by the release of a high flux of hydrothermal fluids associated with certain kinds of igneous intrusions, particularly mafic sills or laccoliths (Svensen et al., 2004), and can therefore be expected to affect sealing sequences when they are breached by igneous intrusions. The hydrothermal fluids are derived from the magma by devolatilization and from the host sediments by localized heating, metamorphism, or simply thermal pumping of pore fluids (Delaney, 1987; Einsele, 1992). The volumes of fluids involved depend primarily on magma composition, temperature, and intrusive volume (Delaney, 1987).

From studies of ore petrogenesis, breccia pipes are known to act as fluid-flow conduits for many millions of years after the initial intrusion-related phase of hydrothermal activity (Barrington and Kerr, 1961). Much complementary evidence of this is seen on seismic data for hydrothermal pipes acting as fluid conduits after a gap of many millions of years after their initial formation (Svensen et al., 2004; Hansen et al. 2005). This propensity for durability as flow conduits means that these types of pipes have important implications for seal integrity and also for secondary hydrocarbon migration.

Conclusions

1. Flood basalts express themselves as bright amplitudes in volcanic margin set-up. They are fed from feeder dikes and volcanoes over a short period of time with high effusive rates. Any sub-basalt play is mainly a structural play. Most prospective regions of volcanic basins are where flood basalts simply blanket sedimentary basins without intrusives in the direct subsurface. In this case, basalt thickness estimation and associated burial depth become an important parameter to estimate propectivity.

2. Sills and dikes express themselves as discordant amplitude anomalies characterized by their high acoustic impedance, localized forced folding and hydrothermal pipes in volcanic margin basins and other magmatically active settings. Sill intrusion can generate subtle anticlinal traps that might be valid prospects because the thermal effect of sills is relatively limited. Organic matter may be preserved within fluid inclusions in rocks around intrusions and has a better chance of survival compared to organic matter that is not sealed within inclusions.

3. Pipes are characterized by cylindrical or steeply conical zones of intense disruption of stratal reflections typically developed directly above igneous intrusions and commonly linked to sea-floor mounds. Much complementary evidence of this is seen on seismic data for hydrothermal pipes acting as fluid conduits after a gap of many millions of years after their initial formation.

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