BACH HO FIELD, A FRACTURED GRANITIC BASEMENT RESERVOIR, CUU LONG BASIN, OFFSHORE SE VIETNAM: A “BURIED-HILL” PLAY

Trinh Xuan Cuong* and J. K. Warren**

A combination of seismic, wireline, FMI and core data shows that Bach Ho field in the Cuu Long Basin, offshore SE Vietnam, is an unusual “buried hill” reservoir. There is little or no production from associated siliciclastic “grus” or granite wash, and the fractured reservoir matrix is largely made up of unaltered acid igneous lithologies (mostly granites and granodiorites). A major NE-SW late Oligocene reverse fault system cross-cuts the field, with about 2000 m of lateral displacement in the highly productive Central Block. The associated fracture meshwork greatly enhances reservoir quality. Transpressional wrench faulting in the late Oligocene in this part of the field emplaced a block of brittle granitic rock on top of organic-rich Eocene – Oligocene mudstones, and facilitated the early migration of hydrocarbons into the fracture network.

Structure, not erosion, set up the 1000 m column of liquids in the fractured granodiorites which form the reservoir at Bach Ho. Faulted intervals with associated damage zones create an enhanced secondary porosity system in the granodiorite; effective porosities range from 3-5% and occasionally up to 20%. Some associated fractures are partially blocked by authigenic calcite and kaolinite.

Features that degrade reservoir quality at Bach Ho include: (i) a thin, low-permeability clay-plugged “rind” created by surface-related (meteoric) Eocene – Oligocene weathering — this rind variably overprints the uppermost 10-40 m of exposed basement throughout the Cuu Long Basin; and (ii) widespread hydrothermal cements which largely predate late Oligocene wrench faulting; cementation mostly took place during post-magmatic cooling and precipitated zeolites, carbonates and silica in fractures which cut across both the igneous and the country rocks.

Porosity-occluding hydrothermal and authigenic precipitates developed in pre-existing fractures in the Bach Ho granodiorite. These pre– late Oligocene mineral-filled fractures acted as zones of structural weakness during and after subsequent late Oligocene structural deformation. Together with new fractures formed during thrusting, the older fractures may have reopened during thrust emplacement, and subsequent gravitational settling of the Central Block.

INTRODUCTION

Vietnam has produced almost 1 billion brls of crude oil and 300 billion cu. ft of natural gas. The country’s estimated resources, both on- and offshore, total some 6.5-8.5 billion brls of oil and 75-100 trillion cu. ft of gas (AAPG Explorer, February 2005). Most of the production in the Cuu Long Basin, offshore SE Vietnam, has come from fractured and weathered granitic basement reservoirs at fields including Bach Ho (White Tiger) (the largest field), Rang Dong (Aurora), Rong Tay (Dragon West) and Hong Ngoc (Ruby). Use of the term “basement” in this paper

Key words: Bach Ho, Cuu Long Basin, Vietnam, fractured basement, buried hill, basement high, Vung Tau, granite.
follows that of Landes (1960) who defined it as any combination of metamorphic or igneous rocks (regardless of age), which are unconformably overlain by a sedimentary sequence. North (1990; p. 216) gave a broader definition of “basement” that includes rocks with a sedimentary origin, providing they have essentially little or no matrix porosity.

The discovery well for Bach Ho was drilled in 1975 by Mobil Oil Co. but the company left Vietnam in the same year. The Bach Ho “buried-hill” was not developed until the mid-1980s by Vietsovpetro. Today, the field’s average daily production (about 140,000 b/d) is declining; in 2008 it was about 25,000 b/d less than in the previous year (www.upstreamonline.com/live/article169696.ece). This rate of decline is somewhat higher than that predicted by Vietsovpetro, which envisaged an annual decline of about 20,000 b/d for the period 2010-2014, but it can perhaps be expected in a field producing from an open fracture system with little matrix storage.

At Bach Ho, matrix between hydrocarbon-filled fractures is largely composed of unaltered igneous and metamorphic rocks. Some production wells in fractured granodiorite in the Central Block of the field produce as much as 15,000 b/d, although rates of 2000-5000 b/d are more typical (Cuong, 2000; Dien et al., 1998). Matrix storage in the reservoir is low to non-existent, yet near-constant production rates have been maintained for more than five years, implying significant recharge to the fracture network. To date, the fine-grained Tertiary fluvio-deltaic sedimentary rocks which encase the productive basement block have not produced sufficient volumes of hydrocarbons to make them a target.

Not all basement highs in the Cuu Long Basin have such outstanding reservoir and production characteristics. A contrast to the success of Bach Ho is given by the development and production history of Dai Hung (Big Bear) field, where hydrocarbons are hosted in a similar granite/granodiorite matrix. In 1993, BHP led a consortium that won the bid to develop Dai Hung and predicted that the field could produce up to 250,000 b/d. By the mid-1990s, some 25,000 b/d were being produced but then output declined rapidly and BHP left the consortium in 1997 announcing that the field was not profitable. Petronas
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then took over as operator but failed to raise output beyond 10,000-15,000 b/d and left in 1999. In 2000, Vietsovpetro (the operator of Bach Ho and Rong fields) took over Dai Hung but was only able to produce some 5400 b/d.

There is therefore a need to investigate the geology of Bach Ho field and to understand why successful economic production comes from this unusual reservoir. Previous studies of the granitic basement reservoirs in the Cuu Long Basin include papers by Areshev et al. (1992), Dmitriyevskiy et al. (1993), Tran et al. (1994), Koen (1995), Tuan et al. (1996), Dong (1996), Dong et al. (1996, 1997, 1999), Dong and Kireev (1998), Quy et al. (1997), Tandom et al. (1997), Tjiia et al. (1998), and Vinh (1999). However, these studies are based on relatively old data or focused on particular areas of research. In this paper, we attempt to integrate available data in order to compile a predictive exploration model for the Bach Ho type of “buried-hill” play. We attempt to evaluate fracture distribution in the basement reservoir and to assess factors influencing reservoir quality.

REGIONAL STRUCTURE AND STRATIGRAPHY OF BACH HO FIELD

The Cuu Long Basin is filled with 6 to 8 km of sedimentary rocks which overlie pre-Tertiary basement. The sedimentary fill rests on an undulating basement surface which divides the basin into a series of sub-basins trending parallel to the main basin axis (Fig. 2) (Hall and Morley, 2004; Lee et al., 2001). The pre-Tertiary basement is mostly composed of Upper Triassic – Cretaceous plutonic rocks whose
The shallowest part of the highly fractured “buried-hill” at Bach Ho lies at a depth of 3050 m (Fig. 2), while the effective base for liquids production in the field is typically shallower than 4650 m. However, the deepest producing interval in the field is a fractured basement block with a flow rate around 100 b/d at a temperature of 162°C. Productive intervals in Bach Ho wells are invariably fractured zones.

Production data indicates that Bach Ho field is made up of a number of separate basement blocks with differing hydrodynamic properties. For production purposes, the field is divided into the Northern, Central and Southern regions. Communication between fractured basement and onlapping sandstones is not seen in current production and pressure data.

The current geothermal gradient at Bach Ho field increases with formation age. It is 2.2-2.5°C/100m in Quaternary – middle Miocene sediments; 3.4°C/100m in the lower Miocene and Oligocene; and 3.9°C/100m in the basement. Temperatures in the basement at depths of 3-4 km range from 120 to 165°C. It has been observed that 90°C formation waters from Bach Ho contain thermophilic sulphate-reducing archaea/bacteria (Rozanova et al., 2001). Geothermal gradients were locally higher in the Mesozoic and early Tertiary during magmatism.

**Tectonic evolution**

The structural evolution of the extensional Cuu Long Basin can be explained in terms of (Figs 1, 2): (i) the propagation of the South China (East Vietnam) Sea rift around 17-32 Ma (Taylor and Hayes, 1983; Hutchison, 2004), and (ii) the collision of India and Eurasia beginning in the Palaeogene, which drove the extrusion of Indochina along the Mae Ping and Red River Faults (Tapponier et al., 1982, 1986), although more recent studies have shown that collision-driven strike-slip extrusion, and its influence on basement tectonics throughout Indochina (including offshore Vietnam) has probably been over-emphasized (Morley, 2004; Hall and Morley, 2004; Searle, 2006). Local variations in tectonic activity have had a significant influence on basement structure in the Cuu Long and Nam Con Son Basins, resulting in subsidence and uplift with different intensities and styles at various times since the Cretaceous. Hall and Morley (2204.) concluded that the basement “grain” in northern Sundaland (including offshore Vietnam) is not related to the Himalayan collision but is due to localised collisional

**Fig. 3. Cuu Long Basin stratigraphy (after Dien et al., 1998).**

<table>
<thead>
<tr>
<th>Geologic Age</th>
<th>Palaeobathymetric Change</th>
<th>Lithology</th>
<th>Thickness (m)</th>
<th>Source rock</th>
<th>Reservoir</th>
<th>Seal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quaternary</td>
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<tr>
<td>1.64</td>
<td>Bien Dong</td>
<td>Fine-grained marine sands interbedded with siltstones</td>
<td>400 - 700</td>
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<tr>
<td>1.52</td>
<td>Dong Hai</td>
<td>Coastal environment to the west, river-mouth and shallow marine sedimentation in the basin center and to the east. Mostly fine to medium-grained sandstones, intercalated with grey siltstones and mudstones.</td>
<td>600 - 900</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>1.24</td>
<td>Con Son</td>
<td>Coastal setting with fluvial dominance. Mostly medium and medium-grained sandstones alternate with grey mudstones and several interbeds of siltite.</td>
<td>500 - 600</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.04</td>
<td>Bach Ho</td>
<td>Mainly shallow marine with a strong fluvial influence in its lower part. Mostly sandstones, interbedded with grey, green or brown mudstones. It is absent in the west of the basin. Its upper part (the Rotala Bed) is composed of green mudstones.</td>
<td>800 - 1400</td>
<td></td>
<td></td>
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<tr>
<td>1.23</td>
<td>Tran Tuan</td>
<td>Predominantly lacustrine sediments, mostly in the centre and east of the basin. Sediments are mostly black mudstones intercalated with grey-brown, fine to medium-grained sandstones. In the west, lacustrine sediments show a higher percentage of sand and coarser grain sizes. Volcanoclastics are also common in this unit.</td>
<td>200 - 2700</td>
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</tr>
<tr>
<td>0.92</td>
<td>Quoc Lang</td>
<td>Only in the western part dominated by interbedded conglomerates and medium-grained sandstones, minor mudstones.</td>
<td>100 - 300</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.05</td>
<td>Late Miocene</td>
<td>Mostly hydrothermally-altered Late Cretaceous granites, lesser Late Triassic &amp; Late Jurassic intrusives (basic and weakly acidic). Together with the generation of the Late Cretaceous granite, some andesitic and dacitic dykes were emplaced with patterns controlled by conjugate faults and fractures. Country rocks were metamorphosed by both mechanical and thermal processes especially during Late Cretaceous.</td>
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**Composition ranges form basic (diorite) to acidic (granite) (Table 1; Dong and Kireev, 1998).**
events which preceded the main India–Asia collision. These smaller-scale events included left-lateral movements on the Mae Ping and Three Pagodas Faults. Initial movement on some of the major faults which are still active at the present day therefore took place in the Cretaceous, and not all movements were driven by the mid- to late Tertiary uplift of the Tibetan Plateau.

The Cuu Long Basin is located along-strike from the youngest spreading centre in the South China (East Vietnam) Sea. Since spreading began at around 32 Ma, its dominantly SW propagation has influenced structural grain in the Cuu Long Basin basement (Fig. 2; Hutchison 2004). The regional structural grain is NW–SE to north-south (Hall and Morley, 2004; Morley, 2004). Extension-derived stresses from this spreading centre may still result in fault movements in the Cuu Long Basin (Shi et al., 2003).

**Stratigraphic evolution of the Bach Ho cover**
The sedimentary succession at Bach Ho comprises Eocene, Oligocene and lower Miocene deposits (Fig. 3). Sands in the mud-dominated Eocene and lower Oligocene succession are mostly immature arkoses, with lesser lithic-arkoses and some feldspathic litharenites deposited in alluvial/fluvial and lacustrine environments. Upper Oligocene sediments are fine-grained lacustrine muds, while the overlying lower Miocene succession passes from muddy delta-front deposits up into marine shales (Que, 1994). Sandstones in the lower Oligocene and lower Miocene successions are possible secondary reservoir targets at Bach Ho. Late Oligocene lacustrine and lower Miocene marine shales constitute regional seals. Oils throughout the Cuu Long Basin are sourced from lacustrine muds (ten Haven, 1996; Reid, 1997). Source rocks in Bach Ho are present in the Eocene and Oligocene intervals (Canh et al., 1994; Areshev et al., 1992), with the upper Oligocene being the most prolific (Hung et al., 2003). None of the hydrocarbons offshore Vietnam are derived from a deep mantle source, contrary to a suggestion which was made during early field development studies (Dmitriyevskiy et al., 1993).
Igneous and hydrothermal evolution
Widespread Mesozoic plutonism on- and offshore SE Vietnam was dominated by Jurassic – Late Cretaceous granites and granodiorites (Hall and Morley, 2004). At a regional scale, plutonism was driven by the NWward subduction of the Proto-Pacific Plate beneath East Asia. Lateral forces associated with the northward movement of India gave rise to stress changes within Indo-china which resulted in crustal thickening and pluton emplacement in Vietnam and Thailand (Morley, 2004; Hutchinson, 2004).

At Bach Ho, three phases of igneous intrusion are recognised (Late Triassic, Late Jurassic and Late Cretaceous) and correspond to the Hon Khoai, Dinh Quan and Ca Na complexes, respectively (Table 1) (Areshev et al. 1992; Dong and Kireev, 1998; Morley, 2004). Late Triassic and Late Jurassic intrusives consist of basic and weakly acidic rocks. These are a minor component of the Bach Ho basement and occur mainly in the northern part of the field. Elsewhere, the basement is composed of Late Cretaceous acidic rocks (mostly granitic) which are characterised by their brittle behaviour under stress (Fig. 4a). Andesitic and dacitic dykes were emplaced with orientations controlled by conjugate faults and fractures. Thermal haloes associated with each phase of magma emplacement altered country rocks into greenschist meta-sediments. Cements precipitated during associated hydrothermal circulation tended to occlude any porosity in the granites and adjacent Mesozoic sediments (Fig. 4b). During subsequent episodes of tectonism, regions of hydrothermally-cemented and fractured zones tended to be weaker than adjacent zones dominated by unaltered and unfractured granites.

Bach Ho Basement – seismic character
Seismic responses can be used to divide the Bach Ho basement into three depth-related seismic zones (Fig. 5, line positions shown in Fig. 6; see also the schematic diagram in Fig. 16). Interval velocities in the upper, middle and lower zones typically range from 3500 to 3800 m/s, 3900 to 5200 m/s and 5000 to 5500m/s, respectively.

The upper zone is characterized by high continuity of the basement-top reflector immediately below the purple reflector in all three lines in Fig. 5. Its character is created by the sharp acoustic impedance contrast between the weathered top of the basement, the overlying fine-grained sediments and the underlying fractured igneous basement. This upper zone signature is best developed at the highest parts of the Bach Ho structure and loses thickness and definition away from the crest.

Below is a zone characterized by groups of lower frequency, higher amplitude and lower continuity signatures within a chaotic reflection background (the approximate vertical extent of this zone is indicated by the yellow arrows in Fig. 5a-c). Its presence in all the Bach Ho seismic lines implies that there are laterally-developed velocity contrasts between the relatively brecciated and altered zones (or dykes) in the upper part of the basement high and the

<table>
<thead>
<tr>
<th>Table 1. Primary minerals, composition and K-Ar age ranges in igneous rocks that constitute the reservoir in Bach Ho field, offshore Vietnam (After Dong and Kireev, 1998). See Fig. 6 for the location of the Central and Northern blocks.</th>
<th>Central Block</th>
<th>Centre of Northern Block</th>
<th>Eastern part of the Northern Block</th>
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</thead>
<tbody>
<tr>
<td>Ca-Na complex (108-115 Ma)</td>
<td>Dinh Quan complex (135-154 Ma)</td>
<td>Hon Khoai complex (194-281 Ma)</td>
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<tr>
<td>Plagioclase</td>
<td>25-40</td>
<td>40-54</td>
<td>47-58</td>
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<tr>
<td>Quartz</td>
<td>25-35</td>
<td>18-24</td>
<td>Dec-17</td>
</tr>
<tr>
<td>Biotite</td>
<td>02-Oct</td>
<td>05-Oct</td>
<td>05-Oct</td>
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<tr>
<td>Muscovite</td>
<td>0-3</td>
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<td>Hornblende</td>
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<td>0-3</td>
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<td>Hastingsite</td>
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<tr>
<td>Dominant type of plagioclase</td>
<td>Oligoclase</td>
<td>Oligoclase</td>
<td>Oligoclase</td>
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<tr>
<td>Plagioclase</td>
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<tr>
<td>Granite</td>
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<td>14-28</td>
<td>17-28</td>
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<td>Granodiorite</td>
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<td>18-24</td>
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<td>Biotite quartz monzonite</td>
<td>02-Oct</td>
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<td>Biotite</td>
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<td>18-24</td>
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Fig. 5. Seismic profiles across Bach Ho field (see Fig. 6 for line locations). Top of basement shows high continuity and amplitude in all three lines, this interval is referred to as Seismic Zone 1. Below this, Seismic Zone 2 (yellow arrows) is made up of low frequency, high and low amplitude reflections with a background of chaotic reflectors. Seismic Zone 3 is a zone of free reflection. Note the low-angle reverse fault and its associated alteration zone present in all three lines, which continues to both north and south (see Fig. 6). Some high-angle basement faults are also visible. Variations in reflection intensity within the basement block indicate, in part, variations in acoustic impedance related to variations in the intensity of alteration. A schematic interpretation based on lines 1 and 2 is shown in Fig. 16.
Bach Ho field, offshore SE Vietnam: A fractured basement reservoir

surrounding granitic rocks. There is a suggestion of pervasive faulting in this interval (indicated by the red lines in Fig. 5), but individual faults cannot be located accurately due to the relatively low resolution of the seismic data.

Seismic attribute contrasts in lines 1 and 2, and comparison with outcrop analogues at Vung Tau (see below), imply that the upper part of the Bach Ho high is more altered and brecciated compared to the underlying zones. Cores and sidewall cores show the lower part of the high are more weakly altered and, although fractures and breccias are still common, they are typically occluded and cemented by hydrothermal minerals (Fig. 4b). An underlying third zone (beneath the yellow arrows in Fig. 5a-c) is characterized by chaotic reflections and is thought to possess few open fractures; it is not considered to be economic.

Seismic, image logs and core data can be used to divide the Bach Ho basement into three blocks (North, Central, and South), each bounded NE-SW fault segments (Fig. 6). The reverse fault to NW of the Central Block locally has a lateral displacement of up to 2000 m (Dong, 1996). The “chaotic” seismic zone, described above as indicating a high degree of fracturing and deformation, is particularly associated with this reverse fault (see Figs 5a, b). The reverse fault dies out along strike and passes into a linked normal fault to both NE and SW (Fig. 6). This relationship implies that the reverse-faulted margin of the Central Block is an inverted portion of a pre-
existing normal fault. FMI analyses (see below) show that fracture intensity is greatest in the Central Block. Production wells in the Central Block consistently show production rates as high as 4000-6000 b/d.

By contrast, the seismic profiles indicate the presence of normal faults along the SE flank of the field, dipping to the south and SE. Seismic character of the basement in this part of the field is characterized by lower amplitudes, and reservoir quality is lower compared to the NW margin of the Central Block.

Most fault sets at Bach Ho, as interpreted from seismic profiles, are confined to the basement and do not appear to continue into the overlying sedimentary cover; nor can they be resolved in deeper parts of the basement. NW displacement of up to 2000 m on this fault emplaced a block of igneous basement on top of Tertiary mudstones. Subsequent gravitational collapse of the block and stress relaxation served to open uncemented fractures within the block and to reopen pre-existing zeolite- and kaolinite-filled fractures. Intense fracturing of basement rocks in the Central Block and enhanced reservoir characteristics are reflected in the high well outputs.

THE VUNG TAU GRANITES: ANALOGUES FOR BACH HO BASEMENT

Triassic-Cretaceous granites and granodiorites outcrop on the coast near Vung Tau, about 100 km SE of Ho Chi Minh City (Fig. 1). Weathered outliers can be found up 0.5-1 km away from the outcrop which extend for several km along the coast. A number of granite quarries and road cuts were visited, mapped and photographed in order to better understand fracture style, timing and host lithologies. The outcrop studies defined a number of fracture styles and exposure-related features which are discussed in the following paragraphs.

Contractions and surface-related fractures
Stress-release sheet fractures (exfoliation fractures) in granodiorites at the Big Mountain location, Vung Tau, are sub-parallel to the topography of the basement block. Dip angles tend to be low – sub-horizontal to 10-15° (Fig. 7a). Near the present-day land surface, the spacing between stress-release sheet fractures ranges from several centimetres to 3 m and increases progressively with depth.

Exfoliation fractures form in the shallow subsurface as a result of stress release as a pluton exhumes and associated overburden stresses first decrease then disappear (e.g. Younes et al., 1998). The fractures are formed due to changes in thermal stress during annual or daily ambient temperature cycles in combination with meteoric-driven weakening of matrix strength due to mineral transformations (Holzhausen, 1989). The lateral extent of individual sheet fractures could not be measured at the Vung Tau exposures. Nermat-Nasser and Horri (1992) noted that open sheet fractures in granites can reach widths of 200 m. Tandom et al. (1997) showed that at depths of up to 200-250 m, exfoliation sheet fractures in an igneous host can be 25-30 m or more apart. By analogy, sub-horizontal exfoliation fractures may therefore be present at Bach Ho in the top 50-100 m of basement rocks.

At the Vung Tau outcrops, exfoliation fractures were observed to become blocked at depths of 10-30 m below the surface with fine clay soils and other weathering products including kaolin and Fe-oxides. The contribution of these types of fracture to reservoir porosity at Bach Ho will therefore probably be low.

Sub-horizontal features (“temperature reduction fractures”) can also form as a magma body cools and contracts. The intensity of this type of fracturing varies with the relative proportions of quartz, K-feldspar and plagioclase minerals. Contractional fractures are more likely to occur in acidic rocks with elevated proportions of quartz (Osipov, 1974). Rocks with minor quartz but more feldspar (quartz-monzonites or diorites) show less volume shrinkage and hence fewer contractional fractures. The acidic lithologies which dominate the Central Block at Bach Ho will be susceptible to contractional fracturing. However, the contribution of early thermal reduction fractures to effective primary porosity will probably be low. At the Vung Tau outcrops, these fracture types were observed to be filled by hydrothermal mineral cements such as zeolites or coarse calcite spar.

Tectonic fractures
Tectonic fractures in the Vung Tau outcrops dip at angles of 50-90° and are typically composed of cross-cutting conjugate sets (Fig. 7a, b). Dominant orientations are NE-SW and north-south; the NE-SW trend is aligned with the trends of the regional Dong Nai and Mae Ping faults, and parallels the regional structural “grain” associated with opening of the South China Sea (Morley, 2004; Hall and Morley, 2004; Tjiia et al., 1998; Dong et al., 1999).

At a quarry at Round Mountain near Vung Tau, tectonically-induced fracture apertures are mostly mm-
Fig. 7. Field photographs of basement outcrops at Vung Tau (see Fig. 1 for location)
(A) A weathered zone, 2-5 m thick, overlies the top of basement rocks at Small Mountain, Vung Tau. Sub-vertical (red) and sub-horizontal (green) fractures with varying densities occur beneath the weathered zone. Sub-horizontal fractures are a combination of sheet and exfoliation fractures with fracture spacing varying from 0.05-0.50m (yellow arrows) and 0.5-3.0m (light blue arrows).
(B) Basement rock (at Small Mountain, Vung Tau) is deformed by tectonic fractures showing high dip angles (red). A narrow igneous dyke (ca.0.8m wide) cuts across the basement. The dyke runs along a fault and separates hanging- and foot-walls. Near the dyke, fractures are mostly parallel to the dyke margin and there are vugs or aperture fractures at the contact with the country rocks. Rocks to the left of the dyke are more highly fractured than those to the right.
(C) Plan view of basement (at Small Mountain, Vung Tau) showing conjugate, relatively steeply-inclined fractures.
(D) A weathered zone (0.5 to 2.0 m thick) caps the basement rocks which are cross-cut by conjugate, steeply dipping fractures and faults (Small Mountain, Vung Tau).
(E) Close-up of Fig. 7d showing deformation and brecciation in the fault damage zone, especially at the intersection of two faults where a cave has formed (indicated by white arrow). Numerous steeply inclined fractures are associated with the breccia. There are two fracture sets: a tectonic (sub-vertical) set and a release (sub-horizontal) set.
(F) Close-up of breccia in Fig. 7e, showing composition of broken basement fragments (0.3 to 3.0 cm across) in a matrix dominated by the products of weathering and diagenesis. There are two sets of fractures: a steeply inclined tectonic set and a set of sub-horizontal release fractures.
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scale but range up to 1-2 cm wide, with rare apertures up to tens of cm across. About 30% of measured fracture apertures were between 0.2 cm and 1.0 cm. Most fractures were filled, or partially filled, by varying combinations of modified magma and hydrothermal precipitates and clays. They are interpreted as outcrop analogues of the mineral-filled fractures illustrated in Fig. 4b.

Fault damage zone widths ranged from tens of decimetres to several metres, depending on the associated fault displacement (Fig. 7b, f). The intensity of fault-related fracturing varies from very high near to major faults (100-150 fractures/metre), and decreases at greater distances (e.g. 35-50 fractures/metre at a distance of 1.5 m from the fault in Fig. 8). Major shear zones with high associated fracture intensities are up to 35 m or more wide at Vung Tau (Tjiia et al., 1998).

Igneous dykes
Andesitic and rhyolitic dykes cut across the granites and granodiorites exposed along the Vung Tau coast (Fig. 7b). The dykes are in general oriented parallel to nearby faults and fractures, with widths varying from 0.5m to several metres. The dykes are characterized by higher densities of fractures (about 5-10 cm spacing) than the surrounding granites (10-50 cm spacing). Fracturing in the dykes is typically oriented parallel to the dyke axis. Mineral-filled (clay and zeolite) mm-cm scale vugs and contractional fractures occurred at contacts between dykes and adjacent granitic rocks. Analogous features in the Bach Ho subsurface contained zeolites and other hydrothermal products. Oil staining in such fractures indicated later re-opening. The mineral-filled fracture constituted zones of relative structural weakness compared to the adjacent granodiorite (Fig. 4b).

Weathered zones
A weathered and lateritized soil profile blankets the Vung Tau outcrops, and soil-related muds infiltrate exfoliation, tectonic and contractional fractures (Fig. 7a, d). Soil penetrations into open fractures, and associated weathering haloes, constitute a zone up to 40-50 m thick on the flanks of Vung Tau outcrop blocks; the zone is 10-20 m thick over the crests of the blocks. Inland from the coast, in areas where soils are less well developed, weathered and bleached granite domes up to tens of metres across are exposed subaerially. Basement blocks are Bach Ho were likewise subaerially exposed. By analogy with the Vung Tau outcrops, weathering and the infiltration of clay-sized fines will have occluded open fractures in the subsurface (Vinh, 1999).

FRACTURE CHARACTER IN BACH HO BASED ON IMAGE LOGS

Image log analysis at Bach Ho detected several fracture types and their interpretation was aided by calibration against outcrop analogues (Fig. 7) and core. An interpreted image suite from well BH-12 is
shown in Fig. 9 (fracture identification follows the classification scheme of Schlumberger, 1992, 1997a, b). This interval illustrates the utility of running a combination of imaging tools (DSI, FMI, UBI, ARI) when defining the nature of fractures intersecting a borehole.

The FMI (Fullbore Formation MicroImager) tool produces a high-resolution microresistivity image of the borehole wall, covering 80% of the wall in an 8.5-inch borehole. Each microconductivity button can read up to 1 cm into the formation and in combination with adjacent buttons is capable of distinguishing conductivity anomalies smaller than the tool’s effective resolution of 0.2 cm. Of currently available imaging tools, the FMI tool provides the most detail for analysis of the Bach Ho reservoir. It sees most natural and induced open fractures intersecting the borehole wall together with matrix variations in bulk formation textures, but is has problems seeing finer open fractures and in separating open from closed mineral-lined fractures at the sub-millimetre scale.

The DSI (Dipole Shear Sonic Imager or Stoneley wave) tool, in contrast to the FMI tool, has a 15 cm (6-inch) depth of investigation and a vertical resolution of 1 m. The presence of open fractures strongly affects the waveform, so this tool is better suited to locating broader-scale intervals (m-scale) characterized by numerous open fractures.

The ARI (Azimuthal Resistivity Imager) tool records lateral resistivity up to 60 cm (24 inches) into the formation. The increased depth of investigation attained when using a combination of DSI and ARI images allows for intervals with numerous open fractures to be distinguished from intervals with numerous but perhaps smaller, probably cemented and unproductive fractures. As with the FMI images, it is possible to orient fractures picked from ARI images (Fig. 10).

The UBI (Ultrasound Borehole Imager) tool is an acoustic imaging log providing a 360° scan of the borehole wall. Although it has a lower resolution than the FMI tool, the full-bore coverage of the UBI tool provides a detailed caliper of the borehole, and can separate larger mineral-lined and closed from open fractures. This is invaluable in confirming fractured intervals seen in FMI, and is also useful for stress analysis and in confirming good hole conditions for setting MDT packers.

The following discussion, together with the results shown in Fig. 10 and the individual well fracture roses illustrated in Fig. 6, are based on the application of these imaging tools to the Bach Ho reservoir. Much of the image-to-rock calibration was based on a detailed core study of well BH-12 (Fig. 11), this was also the well where a complete multi-image log suite was run across the reservoir (Fig. 9).

Natural fractures
Continuous fractures
These fractures show a continuous conductive response in the electrical image (e.g. 3705 m in well BH-12: Fig. 9). They also have a strong corresponding Stoneley wave reflection coefficient. The amount of energy lost in the fracture is thought to correspond to how open the fracture is (Horby and Luthi, 1992). However, zones with extremely rugose or washed-out profiles can generate similar acoustic loss anomalies (above 3590 m).

Discontinuous fractures
Partly-filled mineralized fractures generate discontinuities which in the image log appear as only partly conductive intervals (e.g. 3715 m in Fig. 9). This style of fracture development is not laterally extensive and does not drain as effectively as a grouping of continuous fractures intersecting the well bore.

Boundary fractures
These fractures are normally associated with changes in the lithology and/or texture of the rock (e.g. 3696 m, 3719.5 m, 3722 m in Fig. 9).

Brecciated fractures
These are commonly associated with major faults, creating brecciated zones with polygonal textures on the electrical image and more conductive signatures in the deep resistivity log (e.g. 3690-3696 m in Fig. 9). The thickness of the brecciated zones can vary from several decimetres to tens of metres. In the Stoneley waveform image, these zones show obvious intersections of downgoing and upgoing wave fields (e.g. 3719.5-3722 m in Fig. 9). Ties to resistivity logs and production data show that these brecciated zones within the basement reservoir act as significant hydrocarbon storage systems and have high permeability. In well BH-12, major breccia intervals occur at 3597-3604 m, 3617-3625 m and 3704-3723 m.

Vuggy fractures
Strong Stoneley wave and corresponding low resistivity responses can be used to indicate the likely presence of vugs in the reservoir. They can occur in unaltered granite but are more common within fractured and altered zones (e.g. 3705 m in Fig. 9). Typically they form the large cm-scale “cavities,” as seen in the FMI and UBI, but these logs indicate resistivity or acoustic contrast and so are indirect indicators of fracture style. The logs may be responding to mineral fills, not fluid content. Even if the vugs are fluid-filled, they may be isolated and such a vuggy zone may not be capable of generating substantial fluid interconnection to the well bore.
Faults
Faults are often indicated by associated rapid increases in fracture intensity, truncation features or brecciated zones on the image log, as can be expected by analogy with observations from Vung Tau (Fig. 7).

Drilling induced fractures:
Borehole enlargements are a common feature along the axis in well BH-12 and other wells at Bach Ho and are obvious in the caliper response. They are related to stress release failure, and FMI shows they are typically parallel to the least principal horizontal stress. Long, straight drill-induced fractures are usually perpendicular to the direction of borehole enlargement, as seen in the image logs (e.g. 3725-3730m in Fig. 9). Recognizing induced fractures and borehole breakout is invaluable in determining the current orientation of the principal stress field. Sudden rotations of the image tool travelling across basement sections indicates that principal stress directions vary with reservoir depth and reflect the complex tectonic history of the basement.
Bach Ho field, offshore SE Vietnam: A fractured basement reservoir

Fig. 10. Fracture pattern and distribution from FMI/FMS interpretations of wells in Bach Ho field. Dip angles vary from 20 to 45° in Group 1 fractures (release and exfoliation) and 45 to 75° in Group 2 fractures (tectonic). Dominant strike angles vary from block to block across the field (see Fig. 6 for fracture roses for this data).

Enhanced fractures
In addition to natural fractures, pre-existing fractures which are extended or reopened in the borehole by drilling are classified as “enhanced fractures” (Standen, 1991). It is difficult to differentiate enhanced from other fractures using image and conventional logs. For example, possible enhanced fractures may occur below a depth of 3750m in FMI images in well BH-12, but production test data shows they do not affect the volume or rate of hydrocarbon production in this interval.

Fracture identification using conventional logs
Fracture identification using conventional logs is important in Bach Ho wells where there are no image logs. Many authors have discussed the use of conventional logs for fracture detection (e.g. Stearns and Friedman, 1972; Aguilera, 1993; Ershaghi, 1995; Schlumberger, 1997b). In well BH-12, image logs could be used for fracture calibration and verification of the interpretations arising on conventional log approaches (Figs 11, 12, 13). The vertical resolution of conventional logs is typically lower than that of
Fig. 11. Core descriptions of cores 1 and 2 from well BH-12. Core 1 sampled a strongly altered rock (SAR electrofacies), while core 2 sampled the unaltered granite (FR electrofacies) from 3830-3830.8m and the moderately altered rock (MAR electrofacies) from 3830.8-3832m. Inset at lower right shows standard core-plug derived permeability, porosity and grain density. The listed plug permeabilities are maximum (plug drilled parallel to mineral-filled microfracture), at 90° to microfracture and vertical (with respect to core axis). Definitions of the various electrofacies were given by Cuong (2000).
Fig. 12. Composite log of well BH-12 summarizing reservoir zones based on wireline logs, oil flow rates and core analysis data. Wireline logs indicate lithological properties in each zone. Note the rotation of the FMI tool in fractured intervals, this is a zone of prominent secondary porosity. Flow rates indicate Zones III and perhaps IV are effective reservoir. Pores in Zones I and II are poorly connected and are sub-economic. Within the Bach Ho reservoir interval, the caliper log is one of the best direct indicators of reservoir quality. Definitions of the various electrofacies are given by Cuong (2000).
image logs and the depth of investigations is broader, so that conventional logs define fractured intervals rather than individual fractures.

A higher gamma signal is typical of fractured intervals in *Bach Ho* and reflects precipitation of radiogenic hydrothermal minerals along fractures (although these fractures only contribute to reservoir porosity when re-opened as a result of later deformation) Electric logs, especially the microlaterlog and the proximal log, can indicate fractures in *Bach Ho* basement. However, conductive minerals, such as pyrite and other metal sulphides, and drilling-induced fractures, reduce the accuracy of natural fracture determination using these logs.

Porosity-logging tools, neutron, density and sonic, are the most useful conventional logs when defining fractured zones. Our studies show the sonic log is the most useful porosity log in *Bach Ho* field as it not only indicates fractures by elevated values on shear and compressional responses, but also differentiates secondary and primary porosity. Caliper logs reliably define fractured intervals by enlargements of the wellbore (e.g. 3600m, 3626m, 3705m, 3720m, and 3723m in well BH-12: Fig. 12), while associated hole rugosity tends to create anomalous values in most conventional logs, especially pad-mounted porosity logs. This is an important factor in deriving reliable core-to-wireline transforms (see below).

In general, individual wireline logs do not provide reliable definitions of fractured intervals at *Bach Ho*. Logs in combination, such as cross-plots, give more reliable results but still show variable quality outputs that are subject to error. Based on conventional log and cross-plot approaches, we attempted to define fractured zones in well BH-12. We then compared these outputs to image-log based fracture interpretations (compare Figs 12 and 13). The results were variable and only the M-N, M-PEF and DT4S-DT4P cross-plots could be considered partially reliable fracture indicators. The M-N, M-PEF cross-plots detect fracture zones through the presence of hydrothermal minerals in the fractures. They do not clearly distinguish between zones with open versus closed fracture networks. Comparison of the fractured zones defined by the three cross-plots is shown in Fig. 13. These zones are generally coincident and given the resolution problems of conventional logs to image logs, the outputs are considered to reasonably indicate the intensity of fracturing in *Bach Ho* basement.

Fracture presence or absence can be estimated from the wireline determined compressional and shear velocities (Sibbit, 1996), but again the result is not quantifiable in *Bach Ho* due to washout in almost all the fracture zones. This also strongly influences the reliability of sonic readings (e.g. 3617-3628m, 3704-3723m in well BH-12).

**PROBLEMS WITH OBTAINING REPRESENTATIVE POROSITY MEASUREMENTS IN CORES**

During core-based petrophysical studies, it was not possible to quantify porosity distribution in the fractured basement at *Bach Ho*, even using whole core determinations. Core and plugs of suitable quality for core analysis tended to come from relatively unfractured intervals, while fractured zones tended to be recovered as rubble without little coherency. Studies showed that neither water saturation nor permeability could reliably be estimated from either logs or core (Fig. 14). This reflects both the inherent limits of conventional wireline log interpretation in the high resistivity environment of the *Bach Ho* igneous and metamorphic basement, and also the limited and biased core recovery.

Total porosities in *Bach Ho* basement rocks are low, typically between 0 and 3%, this is less than the standard deviation or error range of tool-based porosity estimates (e.g. inset in Fig. 11). Therefore, calculated values of porosity from conventional wireline logs, even in fractured intervals, are at best semi-quantitative at *Bach Ho*. Simple equations of wireline porosity calculation were applied and appeared to give consistent results, but are influenced by poorly controlled variations in matrix mineralogy and fracture intensity. An assumption was made that unaltered rocks have zero effective porosity. Therefore porosities calculated by different logging tools had to be corrected to zero for intervals of unaltered matrix, even where apparent porosity is listed in log outputs due to lithology effects within these intervals. Multiple mineral models can remove some of these lithological effects, but are only accurate when volumetric inputs for each mineral are known. Wireline porosities illustrated in Fig. 12 were calculated as best-estimates based on combinations of neutron, density and sonic logs, and verified against core data and image logs.

In many fractured reservoirs, especially in carbonates, the difference between porosities obtained from neutron/density logs (i.e. total porosity) and sonic porosity can be used to indicate intervals of secondary porosity. But such wireline-determined intervals of secondary porosity in *Bach Ho* basement typically did not correspond to open fractures or vugs. The intervals also encompassed zones of non-effective porosity due to hydrogenation by authigenic minerals (read as porosity by the neutron log) or microporosity in authigenic clays and zeolites. These features were created during hydrothermal alteration and episodes of pore occlusion, and were not tied to effective porosity in the reservoir.

The matrix in *Bach Ho* has extremely high resistivities as it is composed of non-porous igneous
rock. This means a formation factor exponent “m” could not be measured accurately in the laboratory, making water saturation calculations (via Archies Equation) tentative.

FRACTURE DISTRIBUTION AT BACH HO

Fracture analysis shows that there is no consistent field-wide relationship between the faults and fractures mapped by seismic methods and the natural fracture orientation defined by image logs (Figs 6 and 15). In the Southern Block (well BH8), the strike of the FMI-defined fractures are sub-perpendicular or at a high angle to strikes of seismically-mapped faults (Fig. 6). FMI-defined fractures in the Central Block (wells BH2, BH3, BH4) show a less consistent set of strike orientations. In wells to the north of the Central Block (wells BH1, BH5 and BH6), and wells to the east but downdip of the Central Block (well BH9), the strike of the FMI-defined fractures is less well oriented than in wells in the Southern Block, but again is sub-perpendicular to the general NNE-SSW orientation of the seismically-defined faults (Fig. 6).

The lack of a general trend in fracture strike is most marked in wells in the Central Block compared with the surrounding regions (Fig. 6). Regions to the north, south and east of the central high show a reasonably consistent tie between seismic and image-log data, whereby FMI fracture strikes are oriented sub-perpendicular to seismically-defined fault trends. This signature is consistent with the regional-scale early-mid Tertiary extension tied to the opening of the proto-South China Sea (see Hall and Morley, 2004). The region with the poorest tie between FMI- and seismically-defined fault orientation is the Central Block. This is the structurally highest block in the field and unlike the adjacent blocks, was affected by late Oligocene thrusting. Blocks to the north, south and east of the Central Block show evidence of extensional block faulting but no reverse faulting (Fig. 6). As discussed above, seismic analysis shows the Central Block was translated by late Oligocene reverse faulting, which laterally displaced it by up to 2 km to the WNW.
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intersects an open fracture system tied to a deeper-seated; as study of the Vung Tau outcrops showed, fracture density and porosity increase significantly in the damage zone (Figs 7, 15b).

In summary, open fractures tend to be most significant in the Central Block of Bach Ho, where thrust faulting emplaced a brittle basement block on top of Eocene-Oligocene mudstones. Thrusting, together with subsequent gravity-driven extension, served to open or re-open tectonic fracture networks. Cross-linkage of such fractures was probably aided by the formation of exfoliation fractures.

RESERVOIR ZONATION TIED TO GEOLOGIC HISTORY

Combining all the available geological, petrophysical and seismic data, the Bach Ho basement can be divided into three reservoir zones, A-C (Fig. 16). Zone boundaries are not horizontal, but are probably irregular and fracture-controlled.

Zone A is strongly altered and fractured due to a combination of tectonism and fluid flushing. It is capped by a relatively thin, intensely weathered and clay-plugged interval, similar to that observed at outcrop at Vung Tau, which varies in thickness and can be unconsolidated, even at depths of 4000 m. This interval can be considered as a regional-scale seal capping the underlying basement reservoirs.

The remainder of Zone A is characterized by the presence of open to partially-open conjugate fractures and brecciated zones, and has good but variable
Fig. 15. Fracture distribution variations with depth and faulting at Bach Ho field. (A) Fracture density in Bach Ho wells changes with depth below top-basement. Fractures tend to be most common in the upper part of the basement block (Zone A) but also increase in the vicinity of faults in deep wells. Layering (1-10) is based on FMI. For reasons of confidentiality the well locations are not given, but all wells are located in the region shown in Fig. 6. (B) Fracture density and porosity distribution increases in the cored damage zone near a fault. There was no core recovery in the fault zone itself. The figure is based on core in well BH-420 but for reasons of confidentiality the location of this well is not given. This trend of fracture increasing toward a brecciated zone is similar to the trend seen in outcrop near Vung Tau (see Fig. 7).
reservoir qualities. Zone A forms the principal reservoir interval at Bach Ho. Pores and fractures may have been locally enlarged by meteoric dissolution. However, most of the effective porosity is associated with fractures of tectonic origin. New fractures were formed, and pre-existing zeolite-filled fractures were re-opened, during late Oligocene thrust-related emplacement of the Central Block. This combination of fracture origins explains the wide spread of fracture orientations seen in FMI data (Fig. 6).

Regionally, the base of the fractured interval in Zone A at Bach Ho is at a depth of around 3800-3900 m. This depth is approximately equivalent to the top of the Eocene sedimentary interval where it onlaps the basement block. The top-Eocene also corresponds regionally to the base of the upper part of the second seismic zone (roughly at the level of the blue reflector in Fig. 5 and part way into the zone defined by yellow arrows). In well BH-12, the boundary between Zones A and B is coincident with the wireline-defined boundary separating Zones II and III.

Zone B is less intensely fractured and altered than Zone A, and many fractures are closed or filled by authigenic or hydrothermal precipitates. The base of the zone lies at a depth of around 4000-4600m and probably coincides with the lowermost extent of effective production. Zone B reservoir quality is variable and patchy. The zone corresponds to the wireline-defined Zone II in well BH-12, and the lower part of the second seismic zone in Fig. 5.

Zone C is weakly altered and fractured, and almost all pores and fractures are filled by zeolites and other hydrothermal minerals. Reservoir quality is very poor and the zone is not therefore considered an exploration target. Zone C is equivalent to wireline-defined Zone I in well BH-12 and to the third seismic zone located below the yellow arrows in Fig. 5.

DISCUSSION: BACH HO AND OTHER “BURIED HILL” PLAYS

In the oil industry the term “buried hill” is widely used to describe a reservoir associated with a palaeotopographic high, where onlap by subsequent sedimentary layers indicate that the feature was once exposed at the landsurface (e.g. Luo et al., 2005). Reservoirs are in general located in the uppermost (fractured and weathered) parts of the “hill” or in the immediately surrounding sediment apron. Table 2 and Fig. 17 summarise how the reservoir characteristics of the Bach Ho structure compare with those at other “buried-hill” type traps. Table 2 does not list discovery...
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Fig. 17. “Buried-hill” plays (see text and Table 2 for detail):

(A) Cross-section through the Amarillo-Kansas Arch, USA, which hosts giant oilfields (Panhandle-Hugoton) in reefal carbonates which developed on the basement high and which are sealed by subsequent platform evaporites. “Granite wash” derived from the eroded basement block (see inset) hosts local accumulations.

(B) Cross-sections through two “buried-hill” fields, Clair and Xinlungtai. At Clair, the reservoir is dominated by sediments reworked from the exposed granite high; at Xinlungtai, the reservoir is a combination of a fractured basement block, a weathered sediment “halo” and an apron of reworked grus.

(C) Cross section through La Paz Field, Venezuela, where the reservoir is hosted in a fractured thrust-block. Hydrocarbons are sourced from the underlying La Luna Formation.

wells in fractured basement which did not pass into production (e.g. the Lago Mercedes No. 1 well in Chile: Wilson et al., 1993; see also wells listed by Schutter 2003a, b); nor does it list wells and fields producing from fractured volcaniclastics or shallow gabbroic and serpentinite intrusives which were synchronous with nearby sedimentation (e.g. Kalan et al., 1994; Harrelson, 1989).

In most “buried-hill” type reservoirs within igneous or metamorphic matrix, two main processes contribute to effective porosity: (a) weathering and mechanical reworking, which can produces a “granite wash”; and (b) open fracture and joint networks (Powers, 1932). A classic “granite wash” play occurs at Elk City field, Oklahoma (Sneider et al., 1977). Fracture-associated porosity tends to be tied to structurally-induced permeability fairways, e.g at La Paz field, Venezuela, where production comes from a combination of fractured Mesozoic carbonates and granitic basement (Nelson et al., 2000).

A common characteristic of all the fractured basement fields listed in Table 2 is that the original reservoir matrix was tight and had high resistivities, as in Bach Ho. Effective porosity in such a reservoir is secondary, and is related to tectonic deformation or fluid flow. Tectonically-produced porosity is related to stress release during faulting and uplift/unroofing, and comprises open faults, fractures, microfractures...
and joints produced at a variety of scales ranging from kilometres to millimetres, and with variable degrees of matrix damage ranging across the same scales. Secondary porosity produced by fluid circulation includes dissolution via meteoric waters in weathering zones, and deeper-seated alteration and leaching produced by hydrothermal circulation. The two types of secondary porosity development can be interrelated, where, for example, pre-existing tectonic fractures act as conduits for meteoric waters or hydrothermal fluids.

A combination of deeply-circulating meteoric waters moving along tectonic fractures, and a reworked sedimentary “halo”, characterizes rift-associated basement plays in China and the Gulf of Suez, as well as at the Clair field, offshore Shetlands (Fig. 17b). However, weathering or “granite wash” associations do not occur in the Cuu Long Basin. The limited dataset in Table 2 suggest that meteoric-enhanced basement plays tend to occur at depths of less than 3000 m, suggesting that diagenesis associated with deeper burial causes a reduction in porosity. This may reflect the dominance of immature first-cycle arkoses and litharenites which weather from uplifted basement blocks in rift settings.

An uplifted basement block in a rift setting will subsequently undergo thermally-induced subsidence, and can commonly be overlain by rapidly-deposited lacustrine or marine mudstones, which can be overpressured. The mudstones may however include source rock intervals, and a build-up of overpressure will cause hydrocarbons, once generated, to migrate into the sediment “halo” or into the fractured basement (e.g. Fig. 17a).

A third group of “fractured basement” plays, including that at Bach Ho, is characterized by a dominance of tectonically-induced fractures with little or no overprint by meteoric dissolution, and an absence of sediment “haloes” associated with surface-driven weathering. These plays tend to occur in systems characterized by active (Neogene) tectonics in thrust-wrench fault settings, and include the La Paz/Mara fields of Venezuela and perhaps the Sarkadkeresztrő field, Hungary (Fig. 17c; Table 2).

At La Paz, thrusting emplaced a block of fractured granitic basement and associated limestone cover on top of the prolific La Luna source rock (Nelson et al., 2000). These plays may have effective porosity at depths below 3000 m, related to brittle fracturing of the recently deformed basement matrix.

Many basement highs have been drilled in the Cuu Long Basin; none, however, have the production capacity of Bach Ho. Historically, geologists working in the Cuu Long Basin have used the weathered “buried hill” plays of China as appropriate analogues. However, the weathered crust at Bach Ho is less than 30 m thick. Also, sediment “haloes” are absent from Bach Ho, and there is little evidence that surface-driven meteoric alteration was responsible for generation of secondary porosity. Nor can the hydrothermal circulation, as inferred by Areshev et al. (1992), explain the porosity. Both meteoric leaching and hydrothermal alteration tend to degrade effective porosity at Bach Ho, not enhance it. Rather, porosity at Bach Ho is largely tied to zones of brittle fracturing associated with late Oligocene thrusting and subsequent gravity-driven extension. A more appropriate structural analogy for Bach Ho would therefore be the La Paz field.

CONCLUSIONS

Compared to many other “buried hill” plays worldwide, Bach Ho field is unusual in that the fractured reservoir matrix is largely made up of unaltered acid igneous lithologies (mostly granites and granodiorites). Unlike classic “buried-hill” plays, a “halo” or “granite wash” of reworked basement material is absent. A large-scale NE-SW trending, late Oligocene reverse fault system cross-cuts the field, with approximately 2000m of lateral displacement in the Central Block, where a block of basement rock was emplaced on top of organic-rich Eocene-Oligocene mudstones.

Using a combination of core-calibrated wireline and seismic data, the igneous matrix at Bach Ho can be divided vertically into three zones (A-C): the two lower zones (below 3800-3900m) are relatively weakly deformed and are in general sub-economic; the upper zone, which constitutes the main reservoir in the Central Block, is strongly fractured. Fractures have a variety of origins, and include pre-existing structures reopened during late Oligocene deformation and more recent syntectonic fractures.

Future exploration offshore Vietnam should not just define “buried hills”, but should attempt to identify basement highs where fractured basement blocks have been thrust onto mudstone successions.

Postscript

This study, based on the results of more than 30 years of exploration and development by Vietnamese and other earth scientists, underlines a number of applied geological principles known to explorationists for many years.

1) You will not fully understand a complex reservoir before you must produce from it.

2) Seismic collected across possible fractured basement reservoirs gives a reliable indicator of structural culminations in a basin and so defines the first-order drilling targets. Subsequent higher seismic resolution obtained from a 3D survey may better define additional targets, and have regional
Table 2. Summary of oil- and gasfields known to have produced economic volumes of hydrocarbons from fractured and variably weathered igneous and metamorphic basement highs, where the unaltered host rock had little or no permeability.

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<td>Utikuma &amp; Red Earth fields, Peace River Arch, Alberta, Canada</td>
<td>Middle to Upper Devonian clastics 1500-2500 m</td>
<td>Granite wash is organized into two systems of partially superimposed clastic wedges (alluvial fan deltas &amp; estuaries) that interface with, and are overlapped by, the evaporitic Keg River and Muskog Formation. Lower and upper Granite Wash clastic wedges reach a combined maximum thickness of 70 m. In the Devonian the Peace River Arch (Precambrian granitic/cratonic core) formed an active series of parallel horsts (with exposed crests) and graben depressions (basins).</td>
<td>Devonian Muskeg Fm (marine-fed basinswide evaporite)</td>
<td>Cant, 1988; Dec et al., 1996</td>
</tr>
<tr>
<td>Elk City, Hall-Gurney, Gorham, Panhandle and the Amarillo Arch, USA</td>
<td>Precambrian basement, Pennsylvanian clastics (wash) and Permian carbonates (regional reservoir) 1000 - 2700 m</td>
<td>Minor, deeper reservoir in fractured, variably weathered pink granites and quartzites in some fields, but clastic production is mostly within a drape made up of a mechanically reworked Paleozoic grus and arkose &quot;halo&quot; and in syn-high reeal build-ups. The high/arc formed in a pre-Pennsylvanian collision event. There is some 120 m of fault displacement at the top of the Precambrian granite on the SW flank on the regional (10 km long) Gorham anticline.</td>
<td>Permian salts and mudstones, (marine-fed platform saltmarsh and mudflat)</td>
<td>Landes, 1960; Snieder et al., 1977; Walters, 1991; Sorenson, 2005</td>
</tr>
<tr>
<td>Clairfield, offshore Shetlands, UK</td>
<td>Precambrian (Lewisian) basement 1850 m</td>
<td>Reservoir is elongate NE-SW trending, normally faulted horst made up of a combination of fractured Devonian-Carboniferous redbeds and Lewisian granites. Most storage is in clastics but basement fractures are higher permeability conduits</td>
<td>Cretaceous mudstone (marine)</td>
<td>Coney et al., 1993</td>
</tr>
<tr>
<td>Xinglongtai field, Western depression of the Liaohé Basin, China</td>
<td>Precambrian ~ 2700 m</td>
<td>Highly fractured and weathered Archean granites and Mesozic volcanics with a clastic halo in and about a horst block bound by normal faults. Relief on the Archaen-cored &quot;hill&quot; is 1000 m and the oil column in the field is 700 m high.</td>
<td>Tertiary mudstone (lacustrine)</td>
<td>Luo et al., 2005; P’An, 1982</td>
</tr>
<tr>
<td>Dongshennpu field, Da Ming Tun Depression, China</td>
<td>Precambrian ~ 2800 m</td>
<td>Produces from fractured and weathered Archean metamgranites and Proterozoic metasediments. Structure is the higher part of normally faulted set of basement blocks (edge of half graben) and is overlapped by Tertiary sediments (source and seal).</td>
<td>Tertiary mudstone (lacustrine)</td>
<td>Xiaoguang &amp; Zuan, 1991</td>
</tr>
<tr>
<td>Yannxia field, Western part of the Liuxi Basin, China</td>
<td>Silurian (Caledonian) basement ~ 2200 metres</td>
<td>Highly fractured and weathered Palaeozoic metamorphic host making up the crestal zone the normal-faulted (wrench-faulted?) Yannxia horst block. Situated along trend from the thrust asymmetrical antilone of Laxijuniuno field, which is broken up by imbricated minor thrust faults on forelimb. Intense thrusting during Miocene.</td>
<td>Tertiary mudstone (lacustrine)</td>
<td>Guangming &amp; Jianguo, 1992; P’An, 1982</td>
</tr>
<tr>
<td>Zeit Bay &amp; Geisum fields, Gulf of Suez, Egypt</td>
<td>Precambrian basement ~ 1200 metres</td>
<td>Highly fractured and weathered basement granitic horst forming a fault-defined high within Gulf of Suez rift. The 250 m thick oil column in Zeit Bay field extends from Mesozoic sandstones and granite wash down into the fractured and weathered basement, which contains one-third of oil in the field.</td>
<td>Miocene evaporites (basinside salt &amp; evaporite mudstone)</td>
<td>Salah &amp; Ali-sharhan, 1998 Yones et al., 1998</td>
</tr>
</tbody>
</table>
significance for future exploration (e.g. the importance of the cantilevered blocks in controlling reservoir quality at Bach Ho), but still may not be capable of reliably defining variation in quality in the known reservoir blocks within the survey area.

(3) Often it is the simplest wireline tools, which make direct physical measurements through a complex reservoir, which are the most reliable in terms of indicating variations in reservoir quality. Thus caliper logs are the most reliable indicators of fracture density and reservoir quality in wells at Bach Ho.

"Experience is a hard teacher because she gives the test first, the lesson afterwards"

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