GEOLOGY AND PETROLEUM POTENTIAL OF THE KHORAT PLATEAU BASIN IN THE VIENTIANE AREA OF LAO P.D.R.

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The Vientiane area of southern-central Lao Peoples' Democratic Republic (Laos) includes an extension of the Khorat Plateau Basin, which covers most of neighbouring NE Thailand. This basin contains one producing gasfield and several other gas discoveries. The Vientiane area is in the initial stages of petroleum exploration, and no drilling has yet occurred.

With the aid of new seismic data, the structure and stratigraphy of the Vientiane area are described in relation to the region's tectonic history. Some aspects of this history are still poorly understood. We suggest that the age of the regional base-Khorat unconformity is Late Jurassic instead of Late Triassic as most previous studies have assumed. Recent studies have also shown that the structural inversion of the Khorat Group began in the mid-Cretaceous and not in the Tertiary.

With reference to published information from petroleum exploration in NE Thailand, new data from Laos are interpreted as showing that the Vientiane area has encouraging petroleum potential. Exploration risk, which is associated with the presence and reservoir quality of the Permian carbonates which form the primary target, is judged to be lowest in traps containing Permian palaeo-highs.

INTRODUCTION

Laos is a landlocked, hilly and forested country located mainly between Thailand to the SW and Vietnam to the NE (Fig. 1). Its land area is roughly equivalent to that of the UK or the State of Oregon. The population is approximately four million, and gross domestic product per caput is amongst the lowest in the world. Laos has no indigenous petroleum production, importing refined products via neighbouring countries.

The Khorat Plateau Basin is defined by the large area of Mesozoic (mainly Cretaceous) continental sedimentary rocks of the Khorat Group, which covers approximately 200,000 square km in parts of Thailand, Laos and Cambodia (Fig. 2). The Sayabouri Basin (referred to as the Nakhon Thai Basin in Thailand) has a similar stratigraphy to the Khorat.

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Plateau Basin, and extends from Thailand into China through western Laos. The Khorat Plateau Basin is a focus for hydrocarbon exploration, partly because the sedimentary rocks contained in the lower part of the Khorat Group provide the regional top seal for some of the hydrocarbon "plays", and partly because the Basin's burial history has led to the generation of hydrocarbons from underlying Palaeozoic and Triassic source rocks.

Petroleum exploration in the Khorat Plateau Basin began in Thailand in 1962, and has so far resulted in the drilling of 21 exploration and appraisal wells and the acquisition of over 30,000 km of 2-D seismic data. There have been three significant gas discoveries (Nam Phong-I, Phu Horm-I and Dong Mun-I: Fig. 2), of which Nam Phong is currently on production with published reserves of between 300 and 500 BCF. Significant gas shows were encountered in seven other wells (Assavaritiprom et al., 1995). Despite unsuccessful results from recent drilling, exploration of the area is continuing following the 1996 Thai licensing round.

In Laos, petroleum exploration began in 1990 with the award of licences to foreign companies. No wells have yet been drilled, although both the Monument Group and Hunt Oil have contracted to drill one exploration well each.

The Vientiane Contract Area was awarded in 1991 and is licensed to a group consisting of Monument Resources (Overseas) Ltd (operator), Shlapak Development Co. (USA) and Novus Petroleum (Australia). Proprietary data from this group's exploration programme is used herein.

GEOLOGY

Regional Tectonic Elements

The Khorat Plateau Basin (Fig. 1) is situated on the SE margin of Eurasia. This margin consists of an assemblage of allochthonous continental terranes which originated from rifting of the margin of Gondwana.

Indochina is sutured to South China in the NE at the Song Ma and Song Da sutures, and to Sibamasu (Shan Thai) in the west at the Nan-Uttaradit suture. The terrane probably extends northwards as the Qamdo-Simao or Simao block of southern China (Metcalfe, 1996). The Precambrian granulite core outcrops in the Kontum Massif of the Annamitic Foldbelt of Vietnam (Fig. 2).

The sutures shown in Fig. 1 have been interpreted mainly from outcrop geology. Their location is indicated by ophiolites, metamorphic belts, imbricate thrust zones, major wrench faults, volcanic arcs and intrusive granites. The timing of suturing is constrained by the ages of pre-collision ophiolites, by isotopic dating of collision-related metamorphic and igneous minerals, and by biostratigraphic dating of post-collision, unconformably-overlying sedimentary rocks. In some areas, data of this kind are sparse, leading to uncertainties in the ages and locations of the sutures. On the basis of similar suturing ages (Metcalfe, 1996) and the trend of the Sayabouri Basin, we have joined the Nan-Uttaradit and Changning-Menglian sutures, following the interpretation of Barr and MacDonald (1987).

The SE margin of Indochina is a passive margin connected to the South China Sea by extended continental crust. In the south, wrench-related Tertiary rift basins cover the assumed boundary between Indochina and East Malaya. These basins contain large hydrocarbon reserves.

In the Khorat Plateau area there are two dominant structural trends parallel to, and associated with, margins now represented by suture zones. An approximately north-south trend, associated with the Nan-Uttaradit suture zone in the west, is indicated by surface structures such as the Phetchabun Foldbelt and the Sayabouri Basin (Fig. 2). A second approximately NW-SE trend, associated with the Song Ma and Song Da sutures, is represented by surface structures such as the Annamitic foldbelt, Nam Theun Basin and Khammouan, Nam Leuk and Phu Phan Uplifts (Fig. 2). These two trends converge in the
area to the east of the Khorat Monocline in a zone which extends N-S into the Vientiane area (Fig. 3).

A subsidiary east-west trend is also present in some areas (e.g. the east-west reverse fault on Fig. 3) which may represent a more ancient structural grain.

**Regional Tectonic History**

Basin development in the region has been controlled by the rift, drift, collision and post-collision history of the Gondwana continental fragments as they became sutured to
the Eurasia margin. The northwards movement of terranes involved the opening and closing of successive Tethyan oceans. In the Vientiane area the current interpretation of tectonic history and its relation with the stratigraphy is summarised in Fig. 4.

The region's complex tectonic history has only partly been deduced. Current evidence and interpretations of the major tectonic events affecting the Khorat area can be summarised as follows:

(i) **Rifting from the northern margin of Gondwana**

Palaeomagnetic and faunal assemblage data (Metcalfe, 1996) indicate that this occurred in the Late Devonian, when five fragments, including Indochina and South China, became separated from Gondwana.

(ii) **Extension and drift phase**

Block-faulted crustal extension in a continental margin setting occurred from the Devonian to the Late Permian. The closure of the Song Ma suture is thought to have occurred in the Early Carboniferous (Metcalfe, 1996). This may represent the full collision of Indochina with South China (Hutchinson, 1989; Metcalfe, 1996), or a minor collision with the Song Da arc fragment (Mouret, 1994). Continued extension and deposition in the Khorat area following this event (Kozar et al., 1992) suggest the latter.

(iii) **Collision and suturing**

In the Middle Triassic, there was major compressional uplift and erosion. Intense deformation of this age has been interpreted from seismic data in the Phu Phra area of NE Thailand (Mouret et al., 1994). The term "Indosinian" is applied to this orogeny but care should be taken since some researchers also apply it to a later event associated with the base-Khorat unconformity. The Middle Triassic was a time of significant continental amalgamation and suturing in the region, with the closure of the Song Da suture (Metcalfe, 1996) and the more remote suturing between N. China (Sino Korea) and South China (Metcalfe, 1996, Mouret, 1994). The Nan-Uttaradit suture between the west of Indochina and Sibumasu is also postulated by many authors to have closed at this time (e.g. Bunopas and Vella, 1983, Cooper et al., 1989, Metcalfe, 1996), although ages of Early Carboniferous to Late Jurassic have been proposed by others. As discussed below, we favour a Late Jurassic age for the closure.

(iv) **Extension**

Late Triassic crustal extension caused the development of a number of localised, intermontane basins within the Khorat area (Cooper et al., 1989, Sattayarak et al., 1989). Extension has been explained by Cooper et al. (1989) as being due to the collapse of over-thickened crust following closure of the Nan-Uttaradit suture. However, if the final closure of this suture did not occur until the Late Jurassic, then an alternative explanation is that the basins were created by transtension caused by oblique convergence between Indochina and Sibumasu. On the basis of their morphology, a transtensional origin for the basins was proposed by Sattayarak et al. (1989).

(v) **Suturing**

Prior to the deposition of the Late Jurassic Khorat Group, there was a significant compressional episode, which led to fault reactivation, folding and regional peneplanation. New biostratigraphic data (see next section) are interpreted to show that the age of the base-Khorat unconformity is Late Jurassic, and not Late Triassic as has previously been assumed. This correlates with the Late Jurassic age of closure proposed for the Nan-Uttaradit suture by Stokes et al. (1996) from recent data in the west of Laos. A Jurassic age of suturing is also supported by isotopic age data from metamorphic zircons sampled from
across the suture in Thailand, which indicate a maximum age of Early Jurassic for the last amphibolite facies overprint (Ahrendt et al., 1993).

(vi) **Thermal subsidence**

The Khorat Plateau and Sayabouri Basins formed during the Late Jurassic to mid-Cretaceous when regional, uniform subsidence took place over much of northern Indochina. The basins exhibit classic "sag" architecture with an almost complete absence of syn-depositional faulting. The Khorat Plateau Basin reaches a maximum thickness of 4,200 m in the area of the now-inverted Phu Phan Uplift (Canham et al., 1996). An origin
due to thermal subsidence following suturing and crustal loading was proposed by Cooper et al. (1989).

(vii) First inversion

The long-wavelength structures which dominate the surface of the Khorat Plateau Basin have resulted from a combination of mid-Cretaceous and Tertiary episodes of thick-skinned inversion. The regional evidence for mid-Cretaceous inversion is sparse due to lack of studies and Tertiary erosion of the Late Cretaceous section. However, data from Laos (Lovatt Smith et al., 1996) and NE Thailand (Sattayarak and Polachan, 1990) demonstrate that significant inversion structuring occurred during the Aptian to Cenomanian. The inversion is attributed to the suturing of West Burma with Shan Thai at the Shan Boundary suture. This closed during the Early Cretaceous (Metcalfe, 1996) and would have placed the whole area in compression. The style of inversion is thick-skinned, with detachment depths calculated at 15 km (Cooper et al., 1989), which supports a distant collision as the mechanism for compression.

(viii) Thermal subsidence

Deposition of the Late Cretaceous Phon Hong Group began in restricted basins (Sakhon Nakhon, Khorat Basin and Sayabouri Basin) during mid-Cretaceous inversion. In the Vientiane area, seismic data shows true depositional inversion following the mid-Cretaceous event, so that Late Cretaceous depocentres formed over pre-existing stable platforms (Lovatt Smith et al., 1996). Isopach maps and sections of the Cretaceous over the Thai part of the Khorat Plateau Basin (Sattayarak and Polachan, 1990) suggest a similar relationship in NE Thailand. The similarity of basin architecture to the Early Cretaceous basin indicates that thermal processes were the mechanism of subsidence.

(ix) Regional uplift and second inversion

Fission-track analysis of Khorat Group detrital minerals indicates that the most recent phase of uplift began at around 60 to 65 MM (million) yrs ago (Mouret et al., 1993; Lovatt Smith et al., 1996). The evidence for regional uplift and erosion during the Tertiary is demonstrated in Late Cretaceous depocentres. In the Vientiane Plain, halokinetic modelling of the Thangon Formation showed that around 1,000 m of section has been eroded (Lovatt Smith et al., 1996). In the Phu Phra area of NE Thailand, this figure was put at 1,500 m (Mouret et al., 1993). In both of these areas, the Late Cretaceous section is tectonically undeformed, showing that this uplift has been regional. The Khorat Plateau Basin is currently at regional elevation (Cooper et al., 1989) of around 150 m AMSL, showing that regional uplift is still continuing.

Further inversion structuring also occurred during the Tertiary (Sattayarak and Polachan, 1990), although the evidence for this episode and that in the mid-Cretaceous has often been confused.

Tertiary structuring was driven by the collision between India and Eurasia and the opening of the South China Sea. A recent model shows Indochina to have undergone extrusion towards the SE during the Oligo-Miocene (Hall, 1996). This has led to the present-day NW-SE transtensional stress regime (Polachan and Sattayarak, 1989).

STRATIGRAPHY

The stratigraphy of the Vientiane area is summarised in the tectonostratigraphic section (Fig. 4) and the stratigraphic column (Fig. 5). The following discussion summarises the regional and local stratigraphy in relation to the tectonic history given above. Lao nomenclature is based on that proposed by Ha Luong Tin and Do The Que (1991) and Lovatt Smith et al. (1996), with further modifications and additions based on Thai stratigraphy (e.g. Sattayarak, 1983; D.M.R. Geological Map, 1987; Mouret, 1994; and Racey et al., 1996).
Sedimentary sequences

The Palaeozoic rift/drift sequence is composed of the Loei and Ratburi Groups, which generally comprise marginal-marine to outer-shelf siliciclastics and carbonates, although deeper-marine facies outcrop in some areas (e.g. the Nam Duk area of the Phetchabun Foldbelt in Thailand). Three periods of platform carbonate deposition have been recognised at outcrop from Monument's fieldwork in Laos: Devonian, Early Carboniferous and Permian. Lateral facies variations within the same unit, controlled by palaeo-topographic factors (Wielchowsky and Young, 1985), are an important feature of the Permian units. From a hydrocarbons perspective, the Permian strata are the most significant part of this sequence, as discussed in greater detail in the sections below on source and reservoir rocks.

The Triassic sequence is composed of alluvial, fluvial, and lacustrine sedimentary rocks (Sattayarak et al., 1989), and also, around the Nan-Uttaradit suture, volcaniclastic and volcanic rocks. The Phulekphay Formation (Nam Phong equivalent) has been moved from the Khorat Group to the Triassic Group in Lao stratigraphy on the basis of recent biostratigraphic studies of NE Thailand outcrops (Racey et al., 1994; 1996) which have dated it as late Norian to Rhaetian. The Norian Huai Hin Lat Formation has not been seen...
at outcrop in the Vientiane area but in NE Thailand contains alluvial and lacustrine facies which, in areas of restricted drainage, contain hydrocarbon source rocks. The Triassic Group is as yet un-named in Lao stratigraphy.

The Late Jurassic — Cretaceous sequence (Khorat and Phon Hong Groups) consist of continental fluvial and alluvial red beds. Continental evaporitic facies are present in the Thangon Formation at the base of the Phon Hong Group. The stratigraphically equivalent Maha Sarakham Formation has been dated as Albian-to-Cenomanian by Sattayarak et al., 1991.

Unconformities

The three sedimentary sequences are separated by two regional, erosive unconformities representing suturing or related events discussed above. The mid- to Late Triassic unconformity is not well-imaged by seismic data, but represents a time discontinuity of at least 10 MM yrs and is associated with major structuring (Mouret et al., 1994).

The base-Khorat unconformity records major regional uplift and peneplanation followed by uniform ''sag'' subsidence. On seismic data, the youngest reflectors which it truncates have been biostratigraphically dated as Triassic (probably Late Triassic) in the Kuchinarai structure (Sattayarak et al., 1989). However, over pre-existing basinal areas the angularity disappears. A basal conglomerate is sometimes associated with the unconformity surface.

The base-Khorat unconformity has historically been assigned to the base of the Nam Phong Formation and dated as Late Triassic. However, the removal of the Nam Phong (Phulekphay) Formation from the Khorat Group to the Triassic Group raises the question of whether the position of the unconformity is higher in the sequence. First, there is little or no time gap between the ages of the Nam Phong and underlying Huai Hin Lat Formations in which such a major unconformity could have developed. The long (50 MM yrs) Jurassic hiatus which is indicated to exist between the Phu Kradung and Nam Phong Formations (Racey et al., 1994; 1996) is a more logical position for the unconformity. Secondly, in the Sayabouri Basin in western Laos, the unconformity lies above sedimentary and volcanic rocks which have been dated as Middle to Late Jurassic (Stokes et al., 1996). Thirdly, in outcrops in the SW of the Khorat Plateau Basin, an angular unconformity has been shown to exist between the Phu Kradung and Nam Phong Formations (Mouret, 1994). In summary, although further research is required, the weight of evidence suggests that the unconformity is of Late Jurassic age and lies at the base of the Khorat Group now represented by the Nam Set (Phu Kradung) Formation. This correlates with the revised age of final closure of the Nan-Uttaradit suture.

Three other important unconformities, associated with the previously-described tectonic events, are present. The first is inferred to occur at the base of the Ratburi Group (Kozar et al., 1992), although there is currently little evidence to support this. This correlates with closure of the Song Ma suture in the Early Carboniferous. The second is at the base of the Phon Hong Group, coinciding with the distant suturing of Western Burma and Sibamasu. A basal conglomerate or boulder bed is sometimes present at outcrop (Fig. 6a; Howlett, 1993). The seismic resolution at the level of this unconformity is often poor, making it hard to study. Finally, Tertiary uplift and erosion has led to the present-day surface outcrop pattern (Figs. 2 and 3).

STRUCTURE

The surface structure of the Vientiane area is illustrated in Fig. 3. The area is sited around the junction of the major regional north-south and NW-SE trends. Surface structure within the area of outcrop of the Khorat Group is dominated by inversion features related to these two trends. The Khorat Monocline in the west follows the north-south trend related to the uplifted Phetchabun Foldbelt. This fold exposes the entire Khorat Group in continuous section. In the east an uplifted anticlinorium, the Nam Leuk Uplift, follows
Fig. 4. Tectonostratigraphy (Permian to Eocene) of the Vientiane area.
the NW-SE trend. Eroded Khorat Group (Champa Formation) outcrops over its topographic crest, which has a maximum relative relief of around 1,500 m compared to the Vientiane Plain. In the core of the largest Khorat Group anticline, in Lake Ang Nam Ngum, there is an outcrop of Permian Nalang Limestone lying unconformably below the Triassic Phulekphay Formation, which in turn lies unconformably below the base of the Khorat Group. In the centre of the Vientiane area, the Late Cretaceous Phon Hong Group is exposed in the Vientiane Plain, and beds are horizontal except around local Thangon Formation salt diapirs. A large east-west reverse fault in the Lake Ang Nam Ngum area defines a third trend.

Seismic and other geophysical data have revealed the nature of inversion in the area, and give some indication of the pre-inversion structural history. The structure of the subsurface is illustrated in the two seismic sections (Figs. 6a and 6b: note that there is a horizontal exaggeration of approximately two times at 1.0 sec. (TWT) on the seismic data due to display parameters).

From a hydrocarbons perspective, there are two main areas of interest:

(1) **The Vientiane Plain**

The basinal Vientiane Plain lies over a shallow basement platform which is interpreted to have existed from the Palaeozoic to the Late Jurassic. The platform also persisted as a relatively high area during Early Cretaceous regional thermal subsidence, shown by the Khorat Group isopach of 1,800 m, which compares with over 3,000 m to the north around Ban Phohnhong and 4,300 m to the south in the Phu Phan area (Sattayarak and Polachan, 1990). The Vientiane Plain basin only developed relatively recently, during mid-Cretaceous inversion (Lovatt Smith et al., 1996).

The northern margin of the basement platform in the region of Fig. 6a consists of two reverse faults, which are interpreted to have originally been normal extensional faults during the Palaeozoic and Triassic. Magnetic and seismic data show that this margin extends west from Fig. 6a, parallel to the Nam Ngum River. This indicates that the E-W trend was active during Palaeozoic extension and deposition.

(2) **The Nam Leuk Uplift**

The structures associated with this uplift and its margins contain the key elements of the main petroleum “play” in the Vientiane area. The internal structure of the Palaeozoic interval, which contains both source and reservoir rocks, is not well resolved by seismic data, but reflectors of this age are interpreted to be present throughout the area of the Uplift in a series of normal fault blocks some of which have undergone subsequent reversal. The Triassic potential source unit overlies the Indosinian unconformity at the top of the Palaeozoic, in a strongly-onlapping sequence. The Triassic was deposited in a NW-SE trending basin which thickens to over 2,000 m in the centre of the Uplift between Fig. 6a and 6b. The Khorat Group blankets the Uplift and the adjacent Vientiane Plain.

Two principal phases of compressional structuring are interpreted to have occurred from the seismic data:

First, a **Late Jurassic** episode is demonstrated by truncation of Triassic and Ratburi Group reflectors by the base-Khorat unconformity. In the hanging wall of reverse fault No. 1 (Fig. 6a), the thickness of the missing Triassic and Palaeozoic section is calculated to be over 700 m. The hanging-wall fold “F” of fault No. 3 (Fig. 6b) is a similar Late Jurassic structure, but it has not subsequently been reactivated.

Secondly, **mid-Cretaceous inversion** reactivated the NW-SE trend (Lovatt Smith et al., 1996). Towards the south (Fig. 6a), the majority of compression has been taken up by reverse movements on pre-existing normal faults (e.g. Nos. 1 and 2) on the margins of the Vientiane basement platform. Fault No. 1 is associated with a positive gravity
Fig. 5. Stratigraphy and hydrocarbon potential of the Vientiane area.
anomaly, which is shown by computer modelling to be due to the density contrast between the hanging-wall Palaeozoic and foot-wall Mesozoic strata west of structure "A". In the north (Fig. 6b), the different structural configuration led to folding of the Khorat Group. In both areas, the amount of inversion uplift is around 1,300 m.

**PETROLEUM GEOLOGY**

**Exploration History**

The exploration history of NE Thailand has recently been reviewed by Assavaritiprom et al. (1995). Considering that the average exploration well density is approximately one well per 10,000 square km (an area 1.5 times the size of a UK North Sea quadrant), the Khorat Plateau Basin is under-explored in relation to other hydrocarbon provinces. This is due mainly to a combination of the relatively poor rates of exploration drilling success (statistically, between 1:7 and 1:19 for commercial and potentially-commercial discoveries), and the previous lack of a gas market. The latter factor has now improved, and exploration activity in both Laos and Thailand is undergoing renewal.

In Laos, petroleum seeps (such as those at Gnommelat and Muang Phin: Fig. 2) have been known for many years (Hoffet, 1937). A French consortium drilled an exploration well near the Gnommelat seep during the 1930s, but had no success. Prior to the award of the Vientiane Contract Area to Monument in 1991, there had been very little petroleum exploration in the area. However, gas was discovered near Vientiane in 1985 in a shallow borehole (LK 26: Fig. 2), which had been drilled for potash exploration in the Phon Hong Group in the Vientiane Plain. Geochemical analysis of this gas indicated that it was of geothermal origin.

Monument's exploration programme initially consisted of fieldwork, laboratory analysis and geological mapping at 100,000 scale. This was followed by airborne gravity (2,146 km) and airborne magnetic (6,450 km) acquisition and interpretation. Finally, some 495 km of 2-D seismic and coincident surface gravity data were acquired in two phases.

**Source rocks and hydrocarbons**

**NE Thailand**

The gas discovered in NE Thailand has not yet been correlated geochemically or isotopically with a particular source horizon. Gas from the Nam Phong field is dry and is interpreted, presumably from the structural and stratigraphic setting, to have been sourced from the Permo-Triassic interval (Assavaritiprom et al., 1995).

Geochemical data from Late Triassic Huai Hin Lat Formation source rocks have shown the presence of high maturity, oil- and gas-prone lacustrine claystone source rocks with good to fair source richness (Sattayarak et al., 1989; Chinoroje and Cole, 1995).

The Permian Upper and Lower Clastic Formations have also been mentioned as potential source rocks (Sattayarak et al., 1989). Both units consist of shallow-marine to deltaic facies containing coals (Mouret, 1994).

**Hydrocarbons in the Vientiane area**

Gas from a depth of 127 m (Thangon Formation) in the LK-26 borehole (Fig. 3) flowed with a maximum flare height of 15 m for 24 hours and again for a further 10 hours before the well was plugged with cement. The gas was found to contain C1 to C4 hydrocarbon components demonstrating a geothermal origin. The C1 to C2 ratio was 17:1, a much higher wetness than that of the gas at Nam Phong, which therefore suggests a less mature and/or more oil-prone source. This is consistent with the burial history of the sedimentary section at the well location, which lies over shallow basement in the Vientiane Plain. The only mature source-rock interval which is interpreted from seismic data to be present in this area is a thin covering of Late Triassic strata lying directly over the basement at a
depth of some 2,500 m. A small, high-angle fault shown by seismic data to the west of the discovery may have provided the migration conduit.

Source rocks in the Vientiane area

Gas-prone source rocks have been identified in the Vientiane area at outcrop in the Carboniferous Nam Thom Formation of the Loei Group (coals with up to 80% TOC), the Late Permian Phalat Formation (claystone with up to 7.3% TOC), and the Cretaceous Phu Phanang Formation (thin coals with up to 71% TOC).

No Triassic source rock has been discovered due to limited and poor exposure, but seismic data is interpreted to show a widespread subsurface distribution of this unit, thickening to 2,000 m in the Triassic basin under the Nam Leuk Uplift. Any hydrocarbons generated in this basin are likely to have migrated towards the basin margins along the Indosinian unconformity surface.

Maturity analyses indicate that vitrinite reflectance in the Cretaceous sample is 0.72% (i.e. in the oil “window”); 1.6% in the Permian sample (gas-condensate “window”); and between 1.01% and 4.67% (oil to dry-gas “window”) for the Carboniferous samples. This shows a variety of burial histories for the Carboniferous. The analyses indicate that the Palaeozoic samples have generated most of their hydrocarbons, leaving little source potential at the present. The Cretaceous sample has source potential, but comes from a sequence dominated by red-beds; it is considered unlikely that there is a sufficient volume of this source rock for it to be a significant source interval.

Burial history of the Vientiane area

Burial history and hydrocarbon generation history modelling (Fig. 7) has been carried out at locality “C” on Fig. 6a, using source-rock and maturity data from the above samples and also from Huai Hin Lat Formation outcrop samples from NE Thailand. The burial history model was based on the regional tectonic history and stratigraphy already described, including continuous uplift from 60 MM years ago to the present. Palaeo-geothermal gradients were based on standard worldwide values for similar tectonic settings.

The model shows that the Carboniferous gas source would have become spent by the end of the Triassic. The Permian source rock would have generated significant amounts of gas during the Cretaceous burial. The Huai Hin Lat Formation source rocks also had the potential to generate significant quantities of liquids (13 kg/tonne of rock) during this time.

Reservoir rocks

Permian carbonates in NE Thailand

The Permian Pha Nok Khao Formation is the only formation which has been proved to be of commercial reservoir quality by drilling in NE Thailand, despite the presence of numerous other potential reservoir intervals in the stratigraphic column (Fig 5).

The commercial significance of the Carbonates as a reservoir is demonstrated by the production history of the Nam Phong gasfield, which came on stream in 1990 and has consistently produced 60 MM SCF gas per day from five wells. Flow rates from production tests in single zones have been as high as 20 MM SCF gas per day, 135 b/d water in Nam Phong-6 (Assavaritiprom et al., 1995).

Exploration drilling statistics show why many explorers consider the predictability of carbonate presence and reservoir quality to be a significant risk factor in the Khorat Plateau Basin. Of 14 exploration wells which have targeted this horizon (excluding Chonnabor-1, which was lost), only nine encountered the carbonate; of these, only four found it to have reservoir quality, despite the presence of significant gas “shows” (Assavaritiprom et al., 1995).
Fig. 6a. Interpreted seismic line VTN 93-01, Vientiane area. (Location on Fig.3).
Fig. 6b. Interpreted seismic line VTN 93-04, Vientiane area. (Location on Fig. 3).
Failure to encounter the carbonate target in three wells (Kuchinarai-1, Sakhon-1 and Huai Muk-1) was due to drilling inverted Permo-Triassic grabens, so that instead of the carbonate, siliciclastic strata were encountered (Assavaritiprom et al., 1995). These tests were in a similar structural setting to Phu Phra-1 (Fig. 8) which also encountered Triassic at the same level. In the fourth well, Yang Talat-1, the carbonates were absent through erosion or non-deposition on the flanks of a large basement high.

In areas of good seismic data, the carbonate unit has a transparent seismic character which distinguishes it from other units. High-quality seismic data should therefore reduce the risk of failure to encounter the carbonate.

Published petrographic and production test data from the carbonates are interpreted as showing that a relationship exists between periodic sub-aerial emergence during the Permian and reservoir quality. The lack of reservoir quality and dolomitised facies in the Dao Ruang-1 Permian carbonate has been partly explained by a lack of subaerial exposure (Chinoroje and Cole, 1995). Petrographic data from 500 core samples from wells in the Nam Phong area, and diagenetic models based thereupon (Kozar et al., 1992), can also be interpreted to link the development of volumetrically-significant porosity in dolomitised carbonates with surface exposure and freshwater-related diagenesis during deposition and early burial. Dawson and Racey (1993) identified an exposure event which was associated with marked dolomitisation and the development of a significant unconformity within Permian carbonate outcrops in NE Thailand.

Permian palaeo-highs are the areas where sub-aerial exposure, and hence reservoir development, would have been most likely to have occurred. This hypothesis is supported by seismic data over the Nam Phong-1 and Chonnabot-1 wells (Fig. 8), where good reservoir quality (or indications of good reservoir quality) were encountered. These data show that the carbonates were deposited in platform settings.

Seismic data over Dao Ruang-1 (Chinoroje and Cole, 1995) could be interpreted to show that the well was drilled in an off-platform location, which may have been too far from emergent areas to have been affected.

Fracturing has also been shown to have had a significant but variable contribution on reservoir quality. Microfracturing enhances porosity and permeability in the Nam Phong area wells (Kozar et al., 1992). This could be linked with the surface exposure processes described above. However, later, tectonically-induced fracturing has introduced porosity-occluding calcite cement (Chinoroje and Cole, 1995) whose distribution is difficult to predict (Kozar et al., 1992).

Permian carbonates in the Vientiane area

Permian carbonates (Nalang Limestone Formation) crop out in several localities in the Phetchabun Foldbelt and also in the core of the Nam Leuk Uplift in Lake Ang Nam Ngum (Figs. 2 and 3). Lithologies in the Ang Nam Ngum outcrop include fossiliferous packstone/wackestones and quartzose packstones. Fossils identified are echinoderm débris (crinoid ossicles and brachials), ostracods, bivalves, bryozoans, gastropods, green algae and foraminifera. The foraminifera are dated as ?Dzulfian to Dorashmian (Late Permian). A platform-margin depositional setting is demonstrated by these data. These may represent the youngest Permian carbonates yet known in the region.

Interpretation of the presence of Ratburi Group from seismic data in the north of the Nam Leuk Uplift (Fig. 6b) is based on proximity to the Ang Nam Ngum Permian carbonate outcrop (Fig. 3), since the quality of seismic data in the Palaeozoic section here is poor. Along strike to the south (Fig. 6a), the seismic character of the Ratburi unit is clearer, and is similar to that of proved carbonate in NE Thailand. The platform, “B”, and inverted margin “A” (Fig. 6a), have a similar depositional setting to the Nam Phong field and Chonnabot (Fig. 8), and it is considered likely that reservoir rock will be present in the carbonates within these structures.
Fig. 7. History of hydrocarbon generation, Nam Leuk Uplift (Location “C”, Fig. 6a).

Khorat Group siliciclastics

Sandstone reservoir rocks in the Khorat Group have been tested at Phu Phra-1 (Fig. 8), which flowed gas and water at low rates in two open-hole tests; and at Yang Talat-1, which flowed water at a rate of 2,400 b/d (DMR, open-file report). A comprehensive analysis of the reservoir potential of this group was carried out by Canham et al. (1996), who noted that there was a decrease in reservoir quality with increasing depth of burial due to compaction effects and an increase in the detrital clay content in the older formations.

In the Vientiane area, sandstone outcrops from the Khorat Group have been analysed for porosity and permeability. There is a good correlation between the two, with maximum values of around 20% porosity and 18 mD permeability in a sample from the Phu Phanang Formation, decreasing to 3-5% porosity and less than 0.1 mD in the Nam Set
Formation. Petrography indicates that the absence of pore-filling, authigenic minerals is
the main reason for good reservoir quality. These figures show that sandstones from
higher in the Khorat Group have the potential to be fair- to good-quality gas reservoir.

At the base of the Khorat Group regionally, there occur conglomerates, sandstones or
claystones, depending on the precise nature of the lithologies in the underlying Indosinian
erosion surface. This interval, together with the upper part of the underlying Permian
limestones and dolomites, tested gas in the Phu Horm-I well at rates of 4 MM SCF gas
per day (Assavaritiprom et al., 1995). Elsewhere in the Khorat Plateau Basin, this horizon
is a proven seal. In the Vientiane area, outcrop of this basal conglomerate shows it to
consist of an impermeable, argillaceous, red-brown matrix containing angular to
sub-rounded clasts of Palaeozoic and Basement lithologies. No reservoir quality has
been observed in any of the Laos outcrops.

**Triassic sandstones**

Triassic sandstones from the Khorat Plateau Basin are generally tight where they have
been analysed for porosity and permeability, due to diagenesis related to deep burial
(Canham et al., 1996; Sattayarak et al., 1989). Where burial has not been as deep, for
example on the margins of the basin, better reservoir quality can be expected. The
Mukhdahan-I well, in the east of the Khorat Plateau Basin, had a significant gas “show”
in Triassic sandstones (Assavaritiprom et al., 1995).

No Triassic reservoir rocks have been identified at outcrop in the Vientiane area. Triassic volcanioclastics with no visible porosity outcrop in the Phetchabun Foldbelt and
in the Lake Ang Nam Ngum area. There is expected to be less volcanic influence in the
area of the Nam Leuk Uplift, but burial is likely to have been too deep for any poro-perm
to have been preserve in lacustrine and fluvial sandstones.

**Basement**

Basement reservoir rocks are unproven in the Khorat Plateau Basin. However, recent
exploration results in Tertiary basins nearby (e.g. offshore Vietnam) are a reminder that
weathered and/or fractured basement can be a productive reservoir. The Yang Talat-I
well in NE Thailand penetrated a section of peneplaned acoustic basement consisting of
Lower Carboniferous granite, which was overlain by an erosion-related conglomerate
(Sattayarak et al., 1989). Reservoir quality may be present in either of these lithologies.
No basement is exposed in the Vientiane area, but in persistent platform structures such
as that labelled “D” (Fig. 6a), weathered basement, which may be granitic, may be
present and may provide a significant secondary reservoir target.

**Seal**

**NE Thailand**

Overpressure in the Nam Phong field and in the Chonnabot-I well, where formation
pressures at the base of the Khorat Group were 19.5 pounds per gallon equivalent mud
weight, testify to the effectiveness of the top-seal for the Pha Nok Khao Formation
reservoir.

The regional top-seal in the Nam Phong (Fig. 8), Dong Mun and Phu Horm gas
discoveries is interpreted from well and seismic data published by Kozar et al. (1992)
to be strata in the lower part of the Khorat Group. These beds are geometrically conformable
with the structure of inversion traps (e.g. Nam Phong and Chonnabot: Fig. 8). Regionally,
the section consists of conglomerates, claystones, siltstones and tight sandstones (Mouret
et al., 1993; Racey et al., 1994 and 1996; Canham et al., 1996).

Additional potential seals which lie below the base-Khorat unconformity in successful
Permian carbonate-reservoir traps are indicated from data published by Kozar et al.
(1992). Undifferentiated seismic units of Permian Upper Clastics Formation or the
KHORAT GROUP

Nam Phong gas field, a reactivated and inverted Permian fault block.

Chonnabot, a reactivated Permian basement high

Phu Phra, an inverted Permian half-graben

Interpreted distribution of Phu Nok Khao Lat.

Fig. 8. Geoseismic sections of key "play" tests in NE Thailand. Reinterpreted from Kozar et al. (1992).
Triassic Group are shown by these authors as thin caps over the crests of Permian carbonate traps or as down-flank wedges (e.g. Nam Phong and Chonnabot: Fig. 8). No gas tests have been reported from these intervals, indicating that they may act as seals. Lithologies which are potentially sealing have been reported regionally in both of these units (Sattayarak et al., 1989; Mouret, 1994).

Vientiane area

In the Vientiane area, sealing lithologies in the Khorat Group, the Triassic Group and the Permian Phalat Formation have been identified at outcrop. The lower part of the Nam Set Formation at the base of the Khorat Group consists mainly of thickly-bedded, reddish-brown and purple micaceous claystones and siltstones, with subordinate brown and grey micaceous sandstones with low porosity. This lithology is similar to that described in NE Thailand, and is therefore expected to be a good seal.

The Triassic Phulekphay Formation section unconformably overlies the Nalang Formation and outcrops in the south of Lake Ang Nam Ngum (Fig. 3). Here, the Phulekphay Formation consists of conglomerates consisting of Permian carbonate clasts in an argillaceous matrix, alternating with light grey to light brown calcareous siltstones and claystones, with interbedded small, calcareous sandstone lenses and occasional thin, white, beds of micritic limestone. This section may form a potential seal for the underlying carbonates.

The Phalat Formation outcrops in the Phetchabun Foldbelt to the west of Vientiane, and comprises well-bedded, fine to very fine, laminated sandstones, grey-brown siltstones and claystones with occasional coals and limestones. The sandstones have no visible porosity; therefore this unit is expected to be a good seal.

Potential intraformational seals for the Khorat sandstone “play” are present as interbedded claystones and siltstones in the Khorat Group. Tight limestones between porous dolomitic intervals in the Nalang Formation carbonate also have the potential to be intra-formational seals within the Nalang Formation (Fig. 5).

Traps

NE Thailand

The complex structural history of the Khorat Plateau Basin has led to a variety of trap types. However, most drilling has been targeted at base-Khorat level structural closures formed during mid-Cretaceous and Tertiary inversion. Three such structures, which have been tested by drilling in NE Thailand, are shown in geo-seismic section (Fig. 8).

The Nam Phong structure (Fig. 8) consists of a north-south trending, fault-bounded, inversion anticline overlying a reactivated and eroded, tilted Permian fault block. During the Permian, the crest of the fault block developed as a carbonate platform and margin (Kozar et al., 1992). At the level of the top of the carbonate reservoir, gross structural closure is provided by the inversion anticline which contains the regional lower Khorat Group top-seal and there is additional down-flank closure within the palaeo-structure of the fault-block beneath by the Triassic Group and Upper Permian Clastics.

The NNE-SSW Chonnabot structure (Fig. 8) is a larger, more persistent Permian platform than Nam Phong, but has a similar structural history and trapping style. Although the Chonnabot-I well was lost due to a combination of high pressure and lost circulation, it has been interpreted that the top of a porous Permian carbonate was encountered at TD (Kozar et al., 1992). The gas “kick” which occurred at this level also suggests the presence of a gas column.

The potential for stratigraphic trapping in the Permian carbonate reservoirs is demonstrated by the Dong Mun-1 gas discovery, whose location is shown in Fig. 2. Seismic data (Kozar et al., 1992) shows that this trap is created largely by the depositional relief of a platform-margin carbonate build-up.
Several unsuccessful tests have drilled inversion anticlines which overlie a Permo-Triassic depocentre, similar to the Phu Phra structure (Fig. 8). Although gas shows were encountered in the Khorat Group and Triassic sandstones in Phu Phra-1, reservoir quality is reported to be lacking (Assavaritiprom et al., 1995). Such palaeo-low structures are therefore not prospective for the carbonate “play”.

**Vientiane area**

The two interpreted seismic dip sections over the Nam Leuk Uplift (Figs. 6a and 6b) show several structures with trapping potential.

The southern section (Fig. 6a) shows three Permian carbonate reverse-fault, hanging-wall structural “highs” labelled “A”, “B” and “C” (Fig. 6a), which are contained within the Nam Leuk Uplift inversion anticlinorium. The regional Lower Khorat Group seal is ubiquitous. In “A” and “C”, the inversion-related relief at the level of the top of the Ratburi Group target is enhanced by the palaeo-structure of the fault block, which provides additional trapping potential providing that the Triassic Group is an effective sealing unit. Potential traps also exist within the Khorat Group in the inversion folds above these structures. These structures are interpreted to have been in existence prior to the final period of hydrocarbon generation in the Late Cretaceous (Fig. 7).

In the north (Fig. 6b), structure “F” is a hanging-wall fold at Permian carbonate level, which formed primarily during Late Jurassic compression. It would therefore have been present throughout Cretaceous hydrocarbon generation. Structure “E” is associated with a reversed Palaeozoic antithetic normal fault to fault No. 3. All of the present-day relief in this structure is interpreted to have been generated during mid-Cretaceous inversion. In both structures, the Permian carbonate trap is overlain by the Triassic potential source and seal. A potential trap also exists for the Khorat Group reservoir play in the inversion anticline overlying structure “E”.

**CONCLUSIONS**

The Vientiane area is judged to contain all the elements required for the presence of a petroleum “play” similar to that which has already been proved to be commercial in NE Thailand.

The pre-latest Permian Nalang Limestone Formation provides the most prospective reservoir targets. Khorat Group sandstones, Triassic Group sandstones and weathered granite in the acoustic basement provide higher-risk targets.

The most significant aspects of the area’s petroleum potential can be summarised as follows:

1. Hydrocarbons of geothermal origin, thought to be sourced from Late Triassic rocks, have been encountered in a shallow borehole in the Vientiane Plain. Both the Triassic and the Permian source intervals are interpreted from seismic data to be present in substantial thicknesses in this and other parts of the area.

2. Burial history modelling indicates that the main period of hydrocarbon generation was the Cretaceous.

3. Nalang Formation carbonates have been mapped at a number of outcrops in the area and are also indicated on seismic data. Data from NE Thailand shown that variations in depositional setting and burial history within this unit have affected reservoir quality; we predict that reservoir quality will be highest in Permian palaeo-highs.

4. Sealing lithologies for the Permian carbonates have been shown at outcrop to occur in the basal part of the Khorat Group, the Late Triassic and the Late Permian Phalat Formation. Some risk is attached to the sealing potential of the latter two units, but not to the basal part of the Khorat Group.

5. Structural highs of similar style and history to those which contain hydrocarbons
in NE Thailand are interpreted from seismic data to occur in the study area. We suggest that these highs developed during Late Jurassic compression, reactivated by mid-Cretaceous inversion. The Permian Nalang Formation is exposed below the base-Khorat Group and Triassic potential seals in the core of one such anticline, demonstrating the existence of prospective trapping styles at the surface.

ACKNOWLEDGEMENTS

The Authors would like to thank the Government of Lao PDR, in particular the Department of Geology and Mines (Ministry of Industry); Monument Resources (Overseas) Ltd; Novus Petroleum; and Shlapak Development Company for permission to show previously-unpublished data from Laos. The Authors have been involved in much of the Monument group’s geophysical and geological exploration programme. They would like to thank Tim Burnhill and other colleagues at Monument; John Hurst (Novus); Nares Sattayarak and Songpope Polachan (Department of Mineral Resources, Thailand); and colleagues at Amerada Hess (UK) for their help and advice. The interpretations of the data from the Monument group’s work programme in this paper are entirely those of the Authors. Journal review was by Dr A. Racey (British Gas), whose comments improved the paper and are acknowledged.

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