

Present-day stress and pore pressure fields in the Cuu Long and Nam Con Son Basins, offshore Vietnam

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Abstract

Knowledge of the in situ, or contemporary stress field is vital for planning optimum orientations of deviated and horizontal wells, reservoir characterization and a better understanding of geodynamic processes and their effects on basin evolution.

This study provides the first documented analysis of in situ stress and pore pressure fields in the sedimentary formations of the Cuu Long and Nam Con Son Basins, offshore Vietnam, based on data from petroleum exploration and production wells.

In the Cuu Long Basin, the maximum horizontal stress is mainly oriented in NNW–SSE to N–S in the northern part and central high. In the Nam Con Son Basin, the maximum horizontal stress is mainly oriented in NE–SW in the northern part and to N–S in the central part of the basin.

The magnitude of the vertical stress has a gradient of approximately 22.2 MPa/km at 3500 m depth. Minimum horizontal stress magnitude is approximately 61% of the vertical stress magnitude in normally pressured sequences.

The effect of pore pressure change on horizontal stress magnitudes was estimated from pore pressure and fracture tests data in depleted zone caused by fluid production, and an average pore pressure–stress coupling ratio ($\Delta S_h/\Delta P_p$) obtained was 0.66. The minimum horizontal stress magnitude approaches the vertical stress magnitude in overpressured zones of the Nam Con Son Basin, suggesting that an isotropic or strike-slip faulting stress regime may exist in the deeper overpressured sequences.

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1. Introduction

Knowledge of the present-day stress can provide a better understanding of recent and present-day deformation and has been increasingly studied (Zoback, 1992; Mariucci et al., 1999; Reinecker and Lenhardt, 1999). Furthermore, in situ stress is of key importance in petroleum exploration and production and is a primary control on borehole stability (Bradley, 1979), reservoir drainage and flooding patterns (Bell, 1996), fluid flow in fractured reservoirs (Sibson, 1994), hydraulic fracture stimulation (Shlyapobersky and

Chudnovsky, 1994), and fault seal breach by reactivation (Hillis, 1998).

One principal stress is normally assumed to act vertically in sedimentary basins, and hence, the present-day stress tensor can be obtained by determining four components: the vertical stress magnitude, minimum and maximum horizontal stress magnitudes and the orientation of the maximum horizontal stress (Bell, 1996). However, it is effective stress and not total stress that controls rock deformation (Jaeger and Cook, 1969). Furthermore, changes in stress and pore pressure are directly linked to one another (Addis, 1997; Tingay et al., 2003). Increases in stress magnitudes have been demonstrated in overpressured zones (Yassir and Bell, 1994), and reductions in pore pressure are associated with a decrease in minimum

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horizontal stress magnitude (Teufel et al., 1991; Addis, 1997). Hence, pore pressure is also a key component and it is critical to ascertain the relationship between pore pressure and horizontal stress magnitude in overpressured and depleted sequences.

The Cuu Long and Nam Con Son Basins of offshore Vietnam are areas of active hydrocarbon production, both from the sedimentary sequences and from the fractured pre-Cenozoic basement. Some researchers have conducted studies on paleo-tectonics and paleo-stress orientations based on structural styles observed in outcrop and on seismic data sets (Borisov, 1996; Schmidt et al., 2003; Cao and Mai, 2004). However, the in situ stress tensor in onshore and offshore Vietnam is poorly understood. Herein, we used petroleum industry fracture test and wellbore logging data to characterize the present-day state of stress of the Cuu Long and Nam Con Son Basins, offshore Vietnam. We then use pore pressure data and introduce approaches based on poroelastic theory to provide estimates of the rate of horizontal stress magnitude variations during depletion associated with petroleum production.

2. Geological setting of the Cuu Long and Nam Con Son Basins

2.1. Geological summary of the Cuu Long Basin

The Cuu Long Basin is the Tertiary sedimentary basin located offshore southeast Vietnam, covering an area of approximately 250 km × 100 km and is a major oil production province in Vietnam (Fig. 1). The Cuu Long Basin is a NE–SW trending extensional basin that was initially formed by rifting during the early Oligocene (Nguyen and Le, 2003). Three local depocentres exist in the area studied herein (termed northern, central and eastern). The age of the basin fill sediments ranges from Eocene to Quaternary (Figs. 2a and 3), and the maximum thickness of the sediments is about 8 km (Vo et al., 1997; Phan et al., 2003). Narrow grabens developed during the first phase of extension and a broader downwarping produced a shallow sag basin. The axial zone of the basin subsided rapidly again in the late Oligocene. During the late Early Miocene to early Middle Miocene, a widespread marine incursion flooded the basin, depositing the Bach Ho shale, a thick shale section, which acts as a regional seal. The Late Miocene and the overlying Pliocene-Quaternary sediments were deposited during transgressive/regressive cycles of the modern Cuu Long delta. They appear to be controlled by the changes in eustatic sea level.

2.2. Geological summary of the Nam Con Son Basin

The Nam Con Son Basin is also the Tertiary rift basin located offshore southeast Vietnam and is located adjacent to the Cuu Long Basin (Fig. 1). It covers an area of approximately 90,000 km². It is also a major gas produc-

tion province in Vietnam. The basin is situated at the intersection of two major tectonic systems such as Red River fault system and Three Pagoda fault system in the Gulf of Thai Lan which are related to Indochina extrusion and the South China Sea opening. The basin is oriented NE–SW in the northern part while it is N–S in the southern part. Two major depocenters exist in the region of the Nam Con Son Basin studied herein (termed the northern and central depocenters).

The age of the basin fill sediments ranges from Oligocene to Quaternary (Figs. 2b and 3), and the maximum thickness of the sediments is about 10 km. Extension related to the Eocene-Oligocene opening of the South China Sea resulted in the development of NE–SW trending half-grabens, which became filled with rift sequences. As thermal subsidence continued and the individual discrete half-grabens were filled, the sediment provenance became more regional and resulted in the basin-wide deposition of fluvial sediments from the west. Sag sequences trended upwards from non-marine to marine and display more marine features toward east, due to overall transgression and backstepping of deltas during the earliest Miocene. Toward the end of the Middle Miocene, NW–SE extension associated with a change in spreading direction of the South China Sea led to enhanced topographic relief within the basin center and a structurally controlled facies pattern, in which carbonate systems were restricted to platform or footwall locations while deeper shelf and slope facies were deposited within the graben. In the Late Miocene, the Nam Con Son Basin was again tectonically reactivated by a mild inversion event, followed by thermal subsidence, resulting in the deposition of large carbonate reefal buildups and infilled sandy turbidities. The depositional process was interrupted during the early Pliocene due to major transgression (Hoang, 2002, 2003).

3. In situ stress orientation in the Cuu Long and Nam Con Son Basins

The breakouts and drilling-induced tensile fractures in borehole walls yield a reliable estimate of the horizontal stress orientation (Brudy and Zoback, 1999). Breakouts are stress induced elongations of the wellbore cross-section caused by compressive failure of the borehole wall (Plumb and Hickman, 1985). Drilling-induced tensile fractures are formed due to tensile failure of the borehole wall and are principally oriented sub-parallel to the borehole axis (Bell, 1996). In near-vertical wells, the breakout direction indicates the orientation of the minimum horizontal stress while drilling-induced tensile fracture is oriented in the direction of the maximum horizontal stress (Kirsch, 1898; Bell and Gough, 1979).

The orientation of well-bore failure can be determined from geophysical logging data such as acoustic image logs (e.g. the Borehole Televiwer), resistivity image logs (such as the Formation Micro Imager, or FMI) and four or six arm caliper logs. Only acoustic (Borehole Televiwer

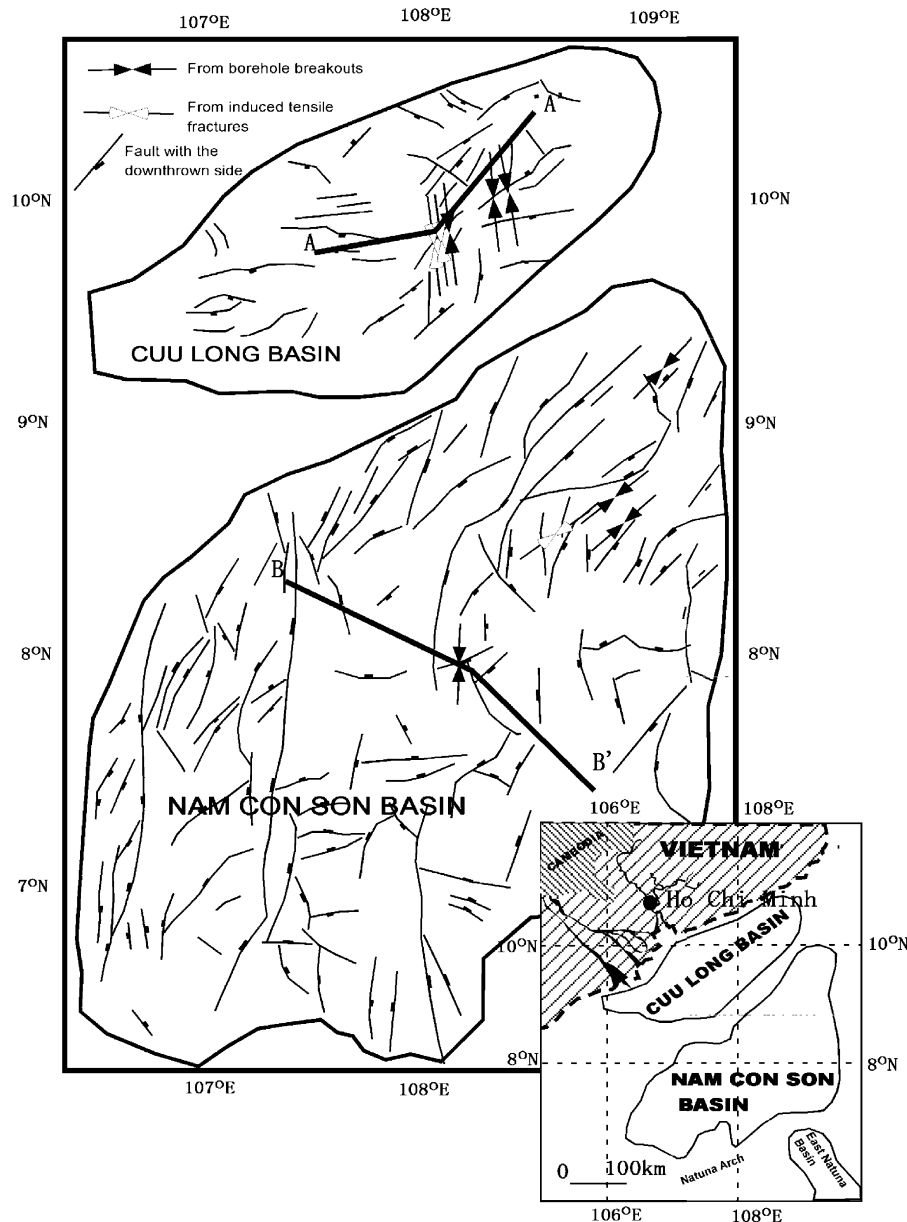


Fig. 1. Maximum horizontal stress orientations in the Cuu Long and Nam Con Son basins.

(BHTV) and CAST-V) and resistivity image logs (FMI) were used for breakout and drilling induced tensile fracture analysis herein.

We used logging data from vertical wells to avoid the interpretation of keyseating (elongation of the borehole cross-section caused by abrasion of the drill string or bit against the wellbore wall in deviated wells) and because breakout and drilling-induced tensile fracture orientation may not directly yield horizontal stress orientations in deviated boreholes (Plumb and Hickman, 1985; Peska and Zoback, 1995). The interpreted stress orientations from each borehole were quality ranked according to the World Stress Map ranking criteria. Stress orientations herein ranged from A to B quality (Zoback, 1992; Sperner et al., 2003). Quality A data are assumed to record the

orientation of maximum horizontal stress to within 10–15°, quality B data to within 15–20°.

In the Cuu Long Basin, breakouts and drilling-induced tensile fractures were observed in the Lower Miocene (Bach Ho Formation) in four wells. In the Nam Con Son Basin, borehole breakouts and drilling-induced tensile fractures were observed at five wells and these were situated in the Middle Miocene, Lower Miocene and Oligocene sedimentary rocks and in the fractured basement. The BHTV, CAST-V and FMI data from wells in the area show no systematic change of stress orientations with depth.

The maximum horizontal stress orientation in the Cuu Long Basin ranges from NNW–SSE to N–S in the northern depocenter and central high (Fig. 1). In the Nam

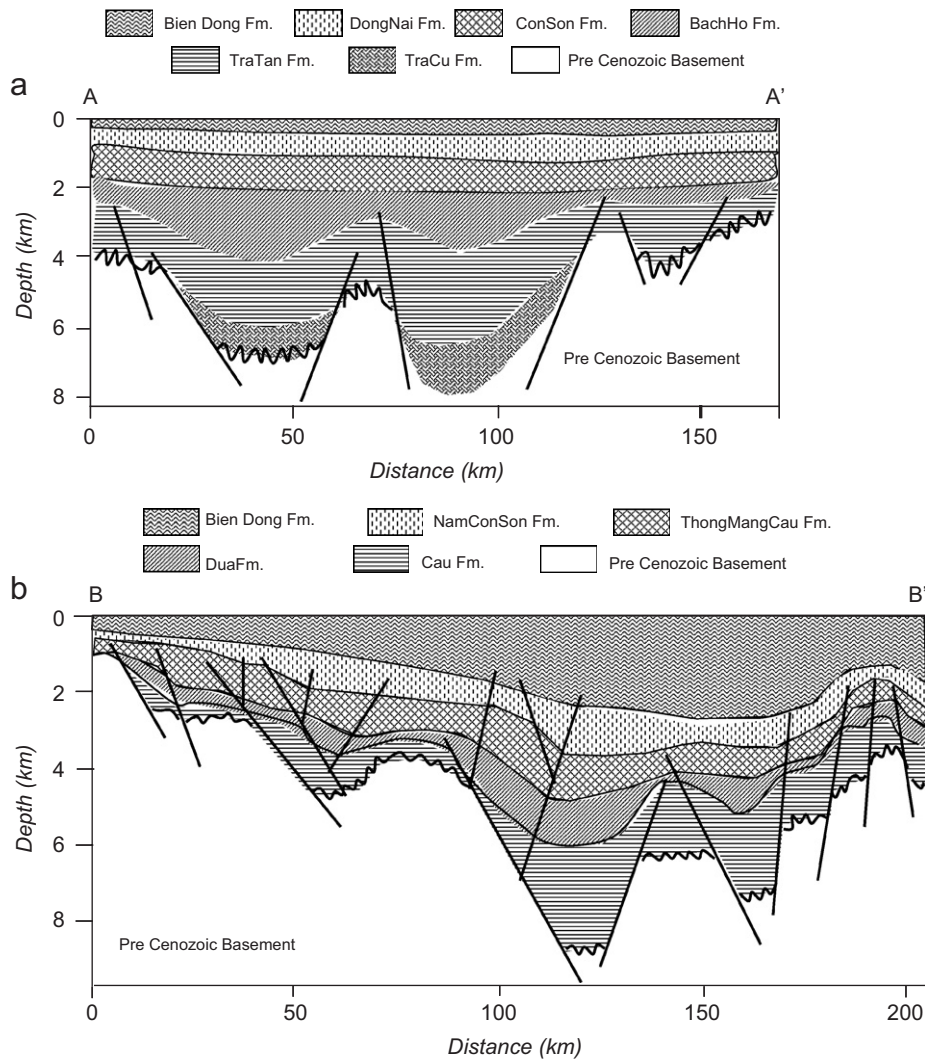


Fig. 2. Geological cross-sections of (a) the Cuu Long Basin and (b) the Nam Con Son Basin.

Con Son Basin, the maximum horizontal stress is mainly oriented in NE–SW in the northern depocenter and N–S in the central part of the basin (Fig. 1).

4. Pore pressure in the Cuu Long and Nam Con Son Basins

Pore pressure was derived from repeat formation tests (RFT) and drill stem tests (DST) data from exploration and production wells. In order to use a reliable pore pressure value, the stress analysis in each well was conducted as close as possible to RFT depth or DST depth. In our initial determination of the stress tensor, we used pressure data from exploration wells only, so that all pressures are ‘virgin’ pressures and have not been depleted by production. ‘Virgin’ pore pressures in the Cuu Long Basin are nearly hydrostatic except for the upper Oligocene section (Fig. 4). Pressure build-up observed at 3200 m corresponds to a thick shale layer in upper Oligocene.

On the other hand, moderate to severe overpressures are observed in the Nam Con Son Basin. The moderate overpressures were observed mainly from depths deeper than

1100 m in the southern part and the severe overpressures from depths deeper than 2500 m in the northern part of the basin (Fig. 5). Pressure build-up observed at 2500 m corresponds to thin calcareous mudstone layer, suggesting that thin but very low permeability formation can hold overpressure.

Our preliminary basin modeling simulation has suggested that both disequilibrium compaction and hydrocarbon migration/accumulation have contributed to overpressure (Mai et al., 2004, 2006). Further study is under progress to evaluate the origin of overpressure in the basins.

5. In situ stress magnitudes in the Cuu Long and Nam Con Son Basins

5.1. Vertical stress magnitude (S_v)

Overburden stress at any depth z was determined by integrating density log data using the equation:

$$S_v = g \left(\int_0^{Z_B} \rho_{\text{sea}} dz + \int_{Z_B}^Z \rho_b dz \right), \quad (1)$$

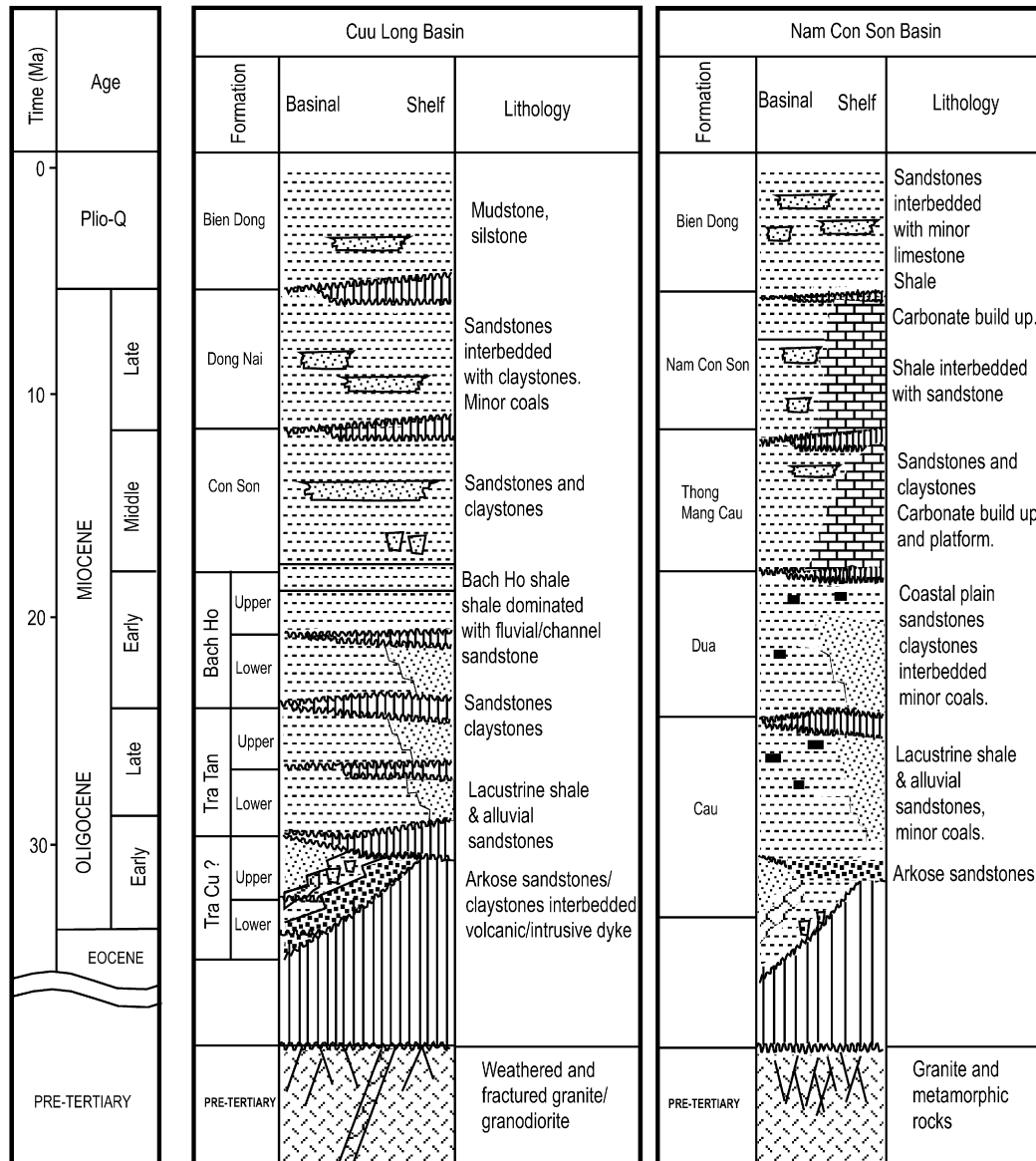


Fig. 3. Generalized stratigraphic columns in the Cuu Long Basin (left) (modified after [Nguyen and Le, 2003](#)) and Nam Con Son Basin (right) (modified after [Hoang, 2003](#)).

where S_v is the overburden stress, z_B is the sea bottom depth, ρ_b is the bulk density from density logs, ρ_{sea} is the density of sea water, and g is the gravitational acceleration.

The calculation of vertical stress requires knowledge of bulk density from the sea bed to the depth of interest. Bulk density is referred from the environment-corrected density logs and bulk density measurements of core samples near sea bed in geotechnical studies. For interval lacking density log data (few hundred meters below surface), we used the average bulk density value of 1.9 g/cm^3 .

Combining data from several wells within the basin provides regional profiles of overburden stress with depth in the Cuu Long and Nam Con Son Basins (Figs. 4 and 5).

5.2. Minimum horizontal stress magnitudes

Minimum horizontal stress magnitude (S_h) was measured by fracturing techniques such as leak-off tests and mini-fracture tests in sandstone layers.

Fracture closure pressure (P_c) is usually interpreted to be equal to the minimum horizontal stress magnitude ([Gjønnes et al., 1998](#); [White et al., 2002](#)):

$$S_h = P_c. \quad (2)$$

During these tests, the mud pressure is raised by pumping fluid into the well bore below the casing shoe (leak-off tests) or into an isolated wellbore interval (mini-fracture tests). Once pressure records indicate that a fracture has been initiated in the wall of borehole, pumping is halted and the pressure decline monitored. The fracture

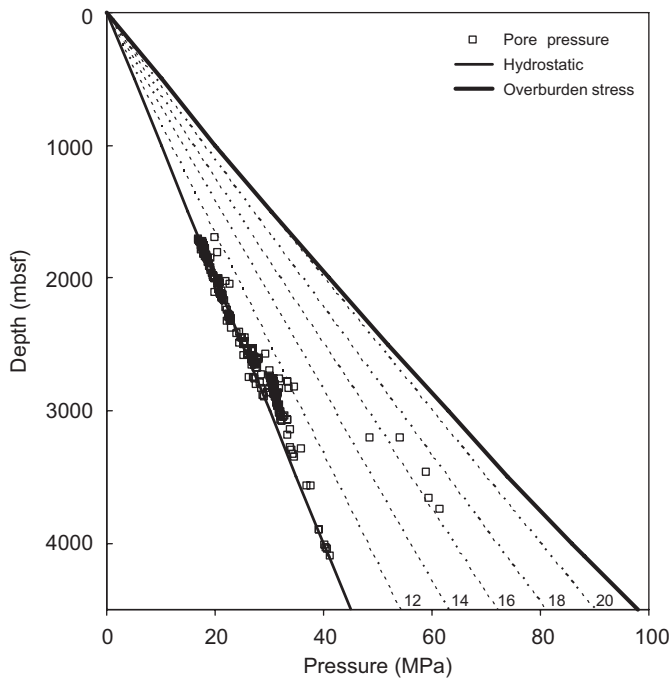


Fig. 4. Overburden stress and pore pressure in the Cuu Long Basin. Numbers in the figure indicate the pressure gradient in MPa/km.

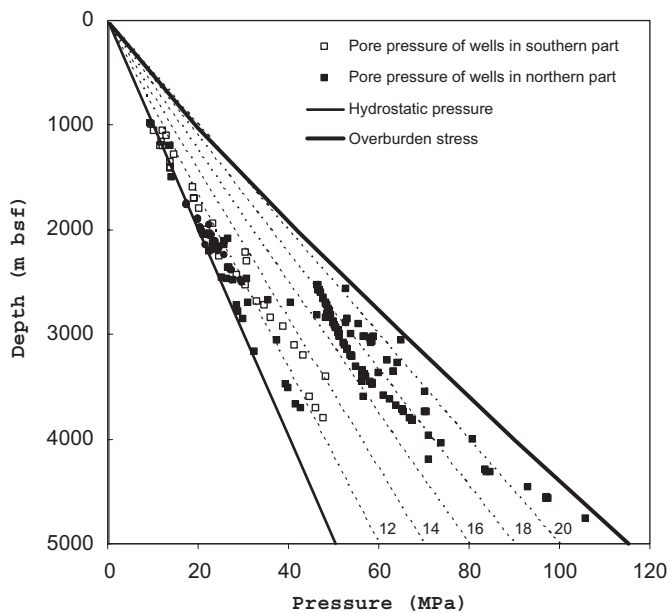


Fig. 5. Overburden stress and pore pressure in the Nam Con Son Basin. Numbers in the figure indicate the pressure gradient in MPa/km.

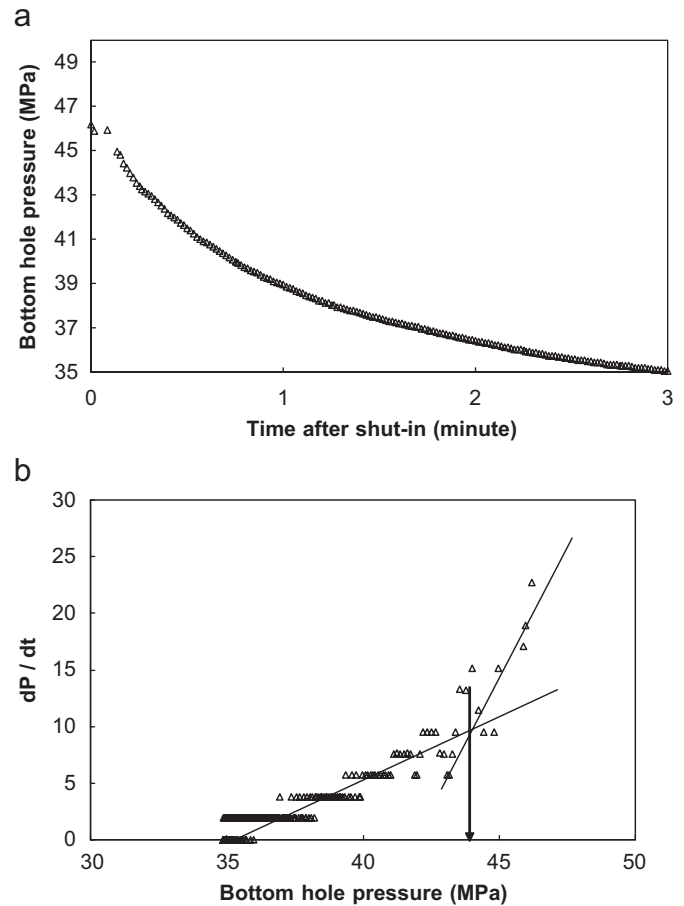


Fig. 6. An example of the determination of fracture closure pressure: (a) measured bottom hole pressure and (b) cross-plot of bottom hole pressure versus the time derivative of the pressure.

closure. The fracture closure pressure was determined by the pressure value where the two linear segments crossed over (Fig. 6b).

We obtained minimum horizontal stress from extended leak-off tests in five wells in the Cuu Long Basin (Fig. 7) and four wells in the Nam Con Son Basin (Fig. 8). The minimum horizontal stress values came from hydrostatic pore pressure, depleted and overpressured sections.

5.3. Effect of the change of pore pressure on stress magnitudes in depleted sections in the Cuu Long Basin

According to the poroelastic theory, the change in pore pressure (ΔP_p) causes the change in horizontal stress (ΔS_h) (Biot, 1941; Engelder, 1993). For a uniaxial deformation condition, the relationship can be written as

$$\Delta S_h = \alpha \frac{1 - 2\nu}{1 - \nu} \Delta P_p. \quad (3)$$

Here, ΔP_p is the deviation from reference pore pressure condition (hydrostatically pressured) and ΔS_h (ΔS_H) is also

closure pressure is estimated from the pressure at which there is a major change in slope on the decline curve. There are numerous techniques for determining the fracture closure pressure, however herein, we used the bilinear pressure-decay-rate method by Lee and Haimson (1989). In this method, a cross-plot of time derivative of pressure (dP/dt) versus pressure (P) was constructed using pressure data after shut (Fig. 6a), which yields two linear segments representing the pressure behavior before and after fracture

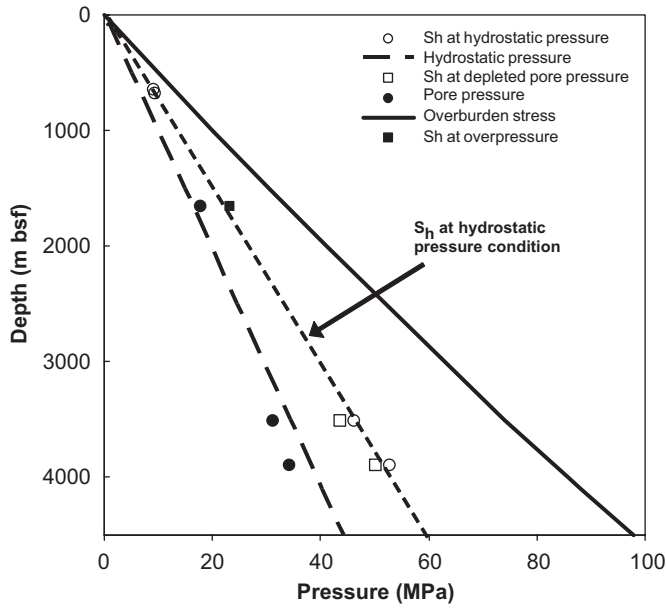


Fig. 7. Minimum horizontal stress magnitudes in the Cuu Long Basin. Also plotted are the estimated minimum horizontal stresses at hydrostatic pore pressures from the data collected in the depleted sections. Note that the minimum horizontal stress magnitude in normally pressured sequences displays an approximately linear relationship with depth.

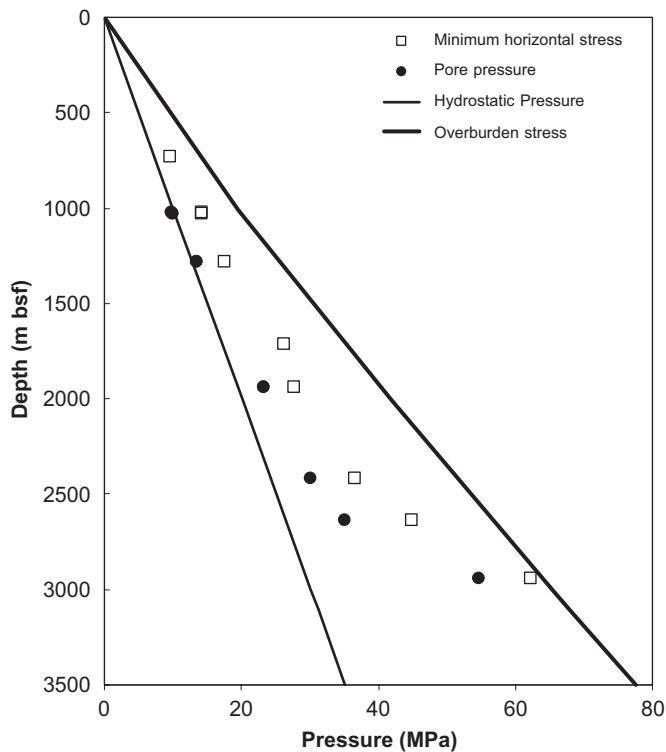


Fig. 8. Minimum horizontal stress obtained from extended leak-off tests in the Nam Con Son Basin. Overburden stresses and pore pressures where minimum horizontal stresses were measured are also plotted.

the deviation from minimum horizontal stress in normal pore pressure conditions.

To use Eq. (3), it is necessary to estimate α and ν . The effective stress coefficient (α) is related to drained bulk

modulus (K) andunjacketed bulk modulus (K_s) by the equation (Nur and Byerlee, 1971):

$$\alpha = 1 - \frac{K}{K_s}. \quad (4)$$

From rock compressibility analysis, the drained pore bulk moduli (K_p) were measured together with porosity (ϕ) data. The drained pore bulk modulus can be related to α , ϕ , and K by the following equation (Wang, 2000).

$$\frac{1}{K_p} = \frac{\alpha}{\phi K}. \quad (5)$$

From Eqs. (4) and (5), we get

$$\alpha = 1 - \frac{K_p}{\phi K_s + K_p}. \quad (6)$$

Assuming a K_s value that is equal to 37 GPa, a typical value for quartz (Gary et al., 1998), and using measured K_p and ϕ values from core samples, we can calculate α as a function of ϕ . Applying the empirical equation proposed by Fabre and Gustkiewicz (1997) yields the following relationship between the effective stress coefficient (α) and porosity (ϕ) (Fig. 9):

$$\alpha = 1 - \exp\left(7.5 \tan \frac{\phi\pi}{2}\right). \quad (7)$$

Because no Poisson's ratio data were obtained from core sample analyses, we estimated Poisson's ratio using sonic logs and rock compressibility data. The undrained Poisson's ratio (ν_u) can be estimated from sonic logs using the equation:

$$\nu_u = \frac{2 - \Delta t_s^2 / \Delta t_c^2}{2(1 - \Delta t_s^2 / \Delta t_c^2)}, \quad (8)$$

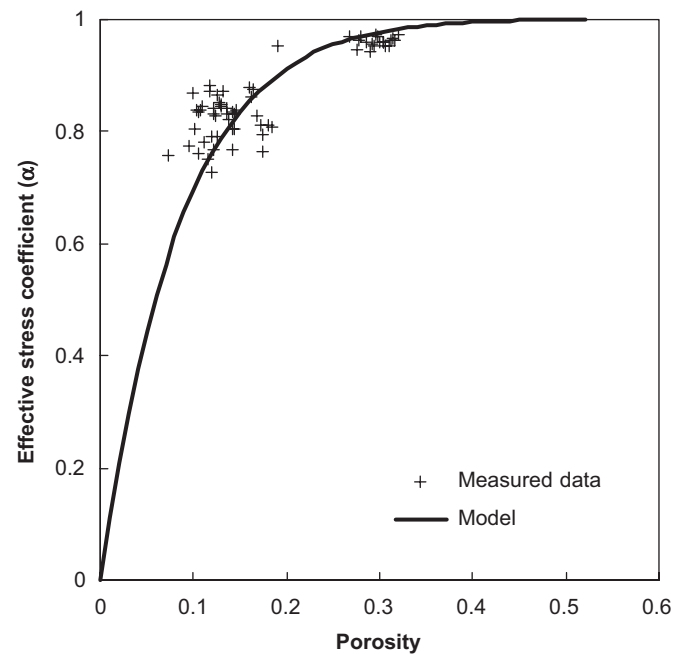


Fig. 9. Relationship between effective stress coefficient and porosity for sandstone in the Cuu Long Basin.

Table 1
Results of estimating horizontal stresses at hydrostatic pressure condition in the Cuu Long Basin

Well	ν	α	$\alpha \frac{1-2\nu}{1-\nu}$	ΔP (MPa)	S_h at depleted condition (MPa)	S_h at hydrostatic condition (MPa)
Well A	0.08	0.785	0.72	−3.61	44.83	47.42
Well B	0.126	0.7	0.6	−4.4	50.12	52.76

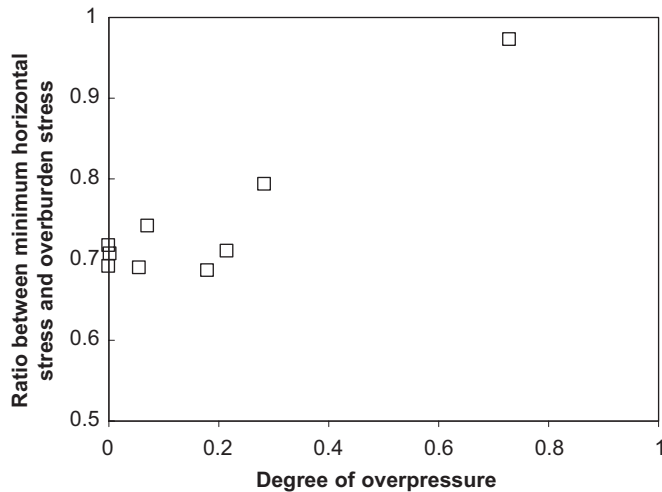


Fig. 10. Cross-plot of pore pressure gradient versus the ratio between the vertical stress and minimum horizontal stress.

where Δt_s and Δt_c are the shear transit time and compression transit time, respectively. Drained Poisson's ratio can be related to undrained Poisson's ratio using Skempton's coefficient (B) (Wang, 2000) and is expressed as

$$\nu = \frac{3\nu_u - \alpha B(1 + \nu_u)}{3 - 2\alpha B(1 + \nu_u)}, \quad (9)$$

$$B = \frac{1/K - 1/K_s}{1/K - 1/K_s + \phi(1/K_f - 1/K_s)}, \quad (10)$$

where K_f is the bulk modulus of the pore fluid. In this analysis, we assumed the bulk modulus of the pore fluid to be 2.3 GPa, a value of water.

Using measured depleted pore pressure values and estimated poroelastic parameters (α and ν), we calculated ΔS_h at two depths in the Cuu Long Basin where pore pressure was depleted due to hydrocarbon production. Then, using the obtained $\Delta S_h(\Delta S_H)$ and measured horizontal stress data, we estimated the horizontal stresses at hydrostatic pore pressure conditions (Table 1).

The combination of measured horizontal stress data in normally pressured sections and estimated magnitudes from depleted intervals suggests that minimum horizontal stress increases linearly with depth at hydrostatic pore pressure conditions (Fig. 7).

5.4. Effect of the change of pore pressure on stress magnitudes in the Nam Con Son Basin

It is interesting to note that the minimum horizontal stress magnitude in the highly overpressured sequences approaches the vertical stress magnitude at the deeper part of the basin (Fig. 8). Empirical relationship between pore pressure gradient and the ratio between vertical stress and the minimum horizontal stress shows that an isotropic or strike-slip stress regime may exist in the overpressured sequences of the Nam Con Son Basin (Fig. 10).

6. Conclusions

This study provides the first assessment of the present-day state of stress in the Cuu Long and Nam Con Son Basins. The following results were obtained from this analysis:

1. In the Cuu Long Basin, the maximum horizontal stress is mainly oriented in NNW–SSE to N–S in the northern part and central high. In the Nam Con Son Basin, the maximum horizontal stress is mainly oriented in NE–SW in the northern part and to N–S in the central part.
2. In the Cuu Long Basin, minimum horizontal stress is interpreted to increase linearly with depth in hydrostatic pressure condition.
3. Minimum horizontal stress magnitudes are estimated to be less than the vertical stress magnitude in normally pressured sequences, in both the Cuu Long and Nam Con Son Basins.
4. The effect of pore pressure change on horizontal stress magnitudes was estimated from pore pressure and fracture tests data in depleted zone caused by fluid production, and an average pore pressure–stress coupling ratio ($\Delta S_h/\Delta P_p$) obtained was 0.66.
5. The minimum horizontal stress magnitude approaches the vertical stress magnitude in overpressured zones of the Nam Con Son Basin, suggesting that a isotropic or strike-slip faulting stress regime may exist in the deeper overpressured sequences.

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