Quantitative evaluation of synsedimentary fault opening and sealing properties using hydrocarbon connection probability assessment

Likuan Zhang, Xiaorong Luo, Qianjin Liao, Wan Yang, Guy Vasseur, Changhua Yu, Junqing Su, Shuqin Yuan, Dunqing Xiao, and Zhaoming Wang

ABSTRACT

Hydraulic behaviors of faults in sedimentary basins have been paid close attention in studies of hydrocarbon migration and accumulation because of their important functions in basin hydraulic circulations. In previous studies, however, the function of faults in hydrocarbon migration is characterized by the sealing capacity of faults. In fact, sealing is only an impressive and time-dependent aspect of the hydraulic behavior of faults, which may act as seals during some periods and as pathways some time later. Therefore, in hydrocarbon migration studies, sealing indices may successfully be used in some cases but not in others. In this article, we introduce an empirical method (termed the fault-connectivity probability method) for assessing the hydraulic connecting capacity of a fault for hydrocarbon migration over geological time scales. The method is based on the recognition that observable hydrocarbon in reservoirs should result from the opening and closing behavior of the fault during the entire process of hydrocarbon migration. In practice, the cumulative petroleum migration through a segment of the fault zone is identified by the presence (or not) of hydrocarbon-bearing layers on both sides of the segment. Data from the Chengbei step-fault zone (CSFZ) in the Qikou depression, Bohai Bay Basin, northeast China, were used

---

Manuscript received July 2, 2009; provisional acceptance September 9, 2009; revised manuscript received November 25, 2009; final acceptance December 14, 2009.
DOI:10.1306/12140909115

AUTHORS

Likuan Zhang ~ *Key Laboratory of Petroleum Resources Research, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing 100029, China; zhanglikuan1979@163.com*

Likuan Zhang is currently a postdoctoral researcher at the Institute of Geology and Geophysics, Chinese Academy of Sciences. He received a B.A. degree in petroleum geology from Jilin University, China, an M.S. degree from Northwestern University, China, and a Ph.D. from the Institute of Geology and Geophysics, Chinese Academy of Sciences. His research interests concern fluid flow in fault zones, numerical basin modeling, and hydrocarbon migration in petroleum systems.

Xiaorong Luo ~ *Key Laboratory of Petroleum Resources Research, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing 100029, China; luoxr@mail.igcas.ac.cn*

Xiaorong Luo is a research scientist in the Chinese Academy of Sciences and has B.S. and M.S. degrees in geology from Northwestern University, China, and a Ph.D. in geophysics from the University of Montpellier, France. His research in the last 30 years has been in petroleum geology, currently focusing on numerical modeling, geopressuring, and hydrocarbon migration and accumulation.

Qianjin Liao ~ *Petroleum Exploration and Development Research Institute of Dagang Oilfield Company Ltd., Tianjin 300280, China*

Qianjin Liao received his B.A. degree in geology from Southwestern Petroleum Institute, and his M.S. degree in geochemistry from the Institute of Exploration and Development, PetroChina. He is currently a manager of the Petroleum Exploration and Development Research Institute of Dagang Oilfield Company. His research interests are related to the evaluation of hydrocarbon resources and hydrocarbon systems.

Wan Yang ~ *Key Laboratory of Petroleum Resources Research, Chinese Academy of Sciences, IGG, Beijing 100029, China; present address: Department of Geology, Wichita State University, Wichita, Kansas 67260*

Wan Yang obtained a Ph.D. from the University of Texas at Austin in 1995 and is currently an associate professor at Wichita State University,

teaching sedimentology and terrigenous clastic depositional systems. He has worked on depositional systems analysis, sequence and cyclostratigraphy, paleoclimatology, and reservoir characterization of marine and nonmarine siliciclastic and carbonate rocks in China and the United States.

Guy Vasseur ~ *SISYPHE, UMR7619, University Pierre et Marie Curie, 75252 Paris Cedex, France*

Guy Vasseur received an engineering degree from Ecole Polytechnique (Paris) in 1963 and a Doctorat d'Etat degree (Ph.D.) from the University of Paris in 1971. He then became a senior scientist of Centre National de la Recherche Scientifique and worked at the Universities of Montpellier 2 and Paris 6 in various domains of geophysics. His main domain of competence is the modeling of heat and mass transfer in the Earth's crust.

Changhua Yu ~ *Petroleum Exploration and Development Research Institute of Dagang Oilfield Company Ltd., Tianjin 300280, China*

Changhua Yu is an engineer at the Petroleum Exploration and Development Research Institute of Dagang Oilfield Company. He received a B.S. degree from Jianghan Petroleum Institute, China, in 1998. His works focus on the structural controls on fluid flow in petroleum systems.

Junqing Su ~ *Petroleum Exploration and Development Research Institute of Dagang Oilfield Company Ltd., Tianjin 300280, China*

Junqing Su got an M.S. degree in geology from Yangtze University, China. He did geological research for the Petroleum Exploration and Development Research Institute of Dagang Oilfield Company and has more than 20 years of exploration experience. His research interests focus on 3-D seismic interpretation and comprehensive analysis of petroleum systems.

Shuqin Yuan ~ *Key Laboratory of Petroleum Resources Research, Chinese Academy of Sciences, IGG, Beijing 100029, China; present address: Petroleum Exploration and Development Research Institute of Dagang Oilfield Company Ltd., Tianjin 300280, China*

Shuqin Yuan is a senior expert in the Petroleum Exploration and Development Research Institute of Dagang Oilfield Company. She has an M.S. degree in geology from Yangtze University,

to develop this method. Fluid pressure in mudstones, normal stress perpendicular to fault plane, and shale gouge ratio are identified as the key factors representing fault-seal capacity. They are combined to define a nondimensional fault opening index (FOI). The values of FOI are calculated from the measured values of the key factors, and the relationship between FOI and fault-connectivity probability on any fault segment is established through statistical analysis. Based on the data from the CSFZ, when the FOI is less than 0.75, the fault-connectivity probability is 0; when FOI ranges from 0.75 to 3.25, the corresponding fault-connectivity probability increases from 0 to 1 following a quadratic polynomial relationship; when FOI is greater than 3.25, the fault-connectivity probability is 1. The values of fault-connectivity probability can be contoured on a fault plane to characterize the variations of hydraulic connective capacity on the fault plane. The applicability of this concept for other oil fields (in particular, the quantitative relationship between FOI and fault-connectivity probability) has still to be ascertained.

INTRODUCTION

Faults may act as either barriers to fluid flow or conduits (Smith, 1966; Karlsen and Skeie, 2006). Fluid flow along faults causes changes in temperature, pressure, and stresses within and surrounding fault zones (Sibson, 1981; Vasseur and Demongodin, 1995; Xie et al., 2001; Gratier et al., 2002). Obviously, the opening and closing behavior of a fault controls hydrocarbon migration and accumulation and, therefore, the distribution of hydrocarbon fields in petroliferous basins (Selley, 1998; Harding and Tuminas, 1989).

Studies on faults serving as flow barriers or conduits (Knipe, 1989; Sorkhabi and Tsuji, 2005) have been conducted through outcrop observations, lab experiments, and numerical simulations to characterize the geometry, composition, deformation, and diagenesis of fault zones. In fault zones, several observed physical and chemical properties have been proposed as proxy data to evaluate the timing and duration of fault opening and closing (Smith, 1966; Weber et al., 1978; Engelder, 1979; Allen, 1989; Knipe, 1992, 1997; Antonelini and Aydin, 1994; Gibson, 1994; Berg and Alana, 1995; Sorkhabi and Tsuji, 2005).

A variety of approaches have been used to characterize the sealing ability of faults to study their impact on fluid flow. Perkins (1961) emphasized that the juxtaposition of sandstones may destroy the sealing capability of faults. However, he noticed that faulted sandstones may be sealed by mudstones squeezed into the sandstones during faulting. Allen (1989) stated that stratal discontinuity across a fault must be studied three dimensionally. Smith (1966) introduced some theoretical considerations on sealing and nonsealing faults based on the capillary model of Hubbert (1953). To characterize the sealing heterogeneity along fault planes, several parameters, such as clay smear potential, shale smear factor, and shale gouge ratio (SGR), were proposed to estimate the degree of mudstone smearing within fault zones and to evaluate the seal capacity of faults (Bouvier et al., 1989; Lindsay et al., 1993; Yielding et al., 1997). Using outcrop observations, Hasegawa et al. (2005) and Kachi et al. (2005) designed several seal capacity parameters to describe the three-dimensional (3-D) sealing characteristics of faults and emphasize the heterogeneity of fault-seal capacity. These detailed studies have pushed the concept of fault-seal capacity from qualitative toward quantitative (Sorkhabi and Tsuji, 2005). However, most of these previous studies are based on the present characteristics of a fault, whereas hydrocarbon accumulation involves the sealing characteristics of the faults during the entire past migration process. Indeed, this entire migration process may be very long because of the limited hydrocarbon migration flux through fault zones (Byerlee, 1993; Haney et al., 2005) and/or because of the very slow maturation of hydrocarbons in the source rocks.

In reality, active tectonics associated with faults are discontinuous processes (Sibson et al., 1975; Hooper, 1991), and faults open and close episodically as a result of a variety of geologic processes (e.g., earthquake cycles; Sibson, 1981; Hooper, 1991). With respect to their hydrodynamic properties, faults have a ubiquitous property: they may act either as seals or as preferential pathways for fluid flow (Yielding et al., 1999). Therefore, any comprehensive study of hydrocarbon migration through faults should take this dual behavior into account as well as its temporal evolution. Indeed, it is widely accepted that, in a fault zone, fluid can flow in pulses from one compartment to another, in relation with the earthquake rupture of existing seals (Byerlee, 1993; Lockner and Byerlee, 1995; Haney et al., 2005).

Hydrocarbon flow occurring during fault opening should leave some indications that can be used to identify whether and where the fault was open (Sorkhabi and Tsuji, 2005). Indicators, such as veins related to faulting and diagenetic mineralogy and fluid inclusions within and adjacent to fault zones, are equivocal in many cases and require extensive testing and analyses many samples. This is feasible for outcrop studies but is difficult for core analysis because of the scarcity of cores in fault zones. Other types of proxy are needed to assess fault opening and closing, and its seal capacity.

China. Her research focuses on hydrocarbon systems and the potential of hydrocarbon plays in petroliferous basins.

DUNQING XIAO ~ *Petroleum Exploration and Development Research Institute of Dagang Oilfield Company Ltd., Tianjin 300280, China*

Dunqing Xiao received a B.A. degree in geology from the China University of Geoscience. He is a principal geologist in the Petroleum Exploration and Development Research Institute of Dagang Oilfield Company, with research interests on geological conditions of oil and gas accumulation and exploration of oil and gas plays.

ZHAOMING WANG ~ *Research Institute of Exploration and Development, PetroChina, Beijing 100083, China*

Zhaoming Wang received a B.S. degree in petroleum geology from the China University of Petroleum, Dongying, and an M.S. degree and Ph.D. from the Institute of Geology and Geophysics, Chinese Academy of Sciences. He has worked in the Shengli oil field. Currently, he is working in the Institute of Exploration and Development, PetroChina. His interests are in the study of resource assessment of sedimentary basins and hydrocarbon migration.

ACKNOWLEDGEMENTS

This study was supported partly by the Chinese National Major Fundamental Research Developing Project (2006CB202305) and partly by the Chinese National Natural Science Foundation (40772090). The study could not have been possible without support from Dagang Oil Company Ltd. We appreciate the permission from Dagang Oil Company to publish this work. We thank Beicip-Franlab for providing the Temis3D software used for the pressure modeling. We appreciate the comments and encouragement from A. C. Aplin and three reviewers, Stephen Naruk, Barry J. Katz, and Alexander A. Kitchka, which have helped improve the manuscript. The AAPG Editor thanks the following reviewers for their work on this article: Barry J. Katz, Alexander A. Kitchka, and Stephen J. Naruk.

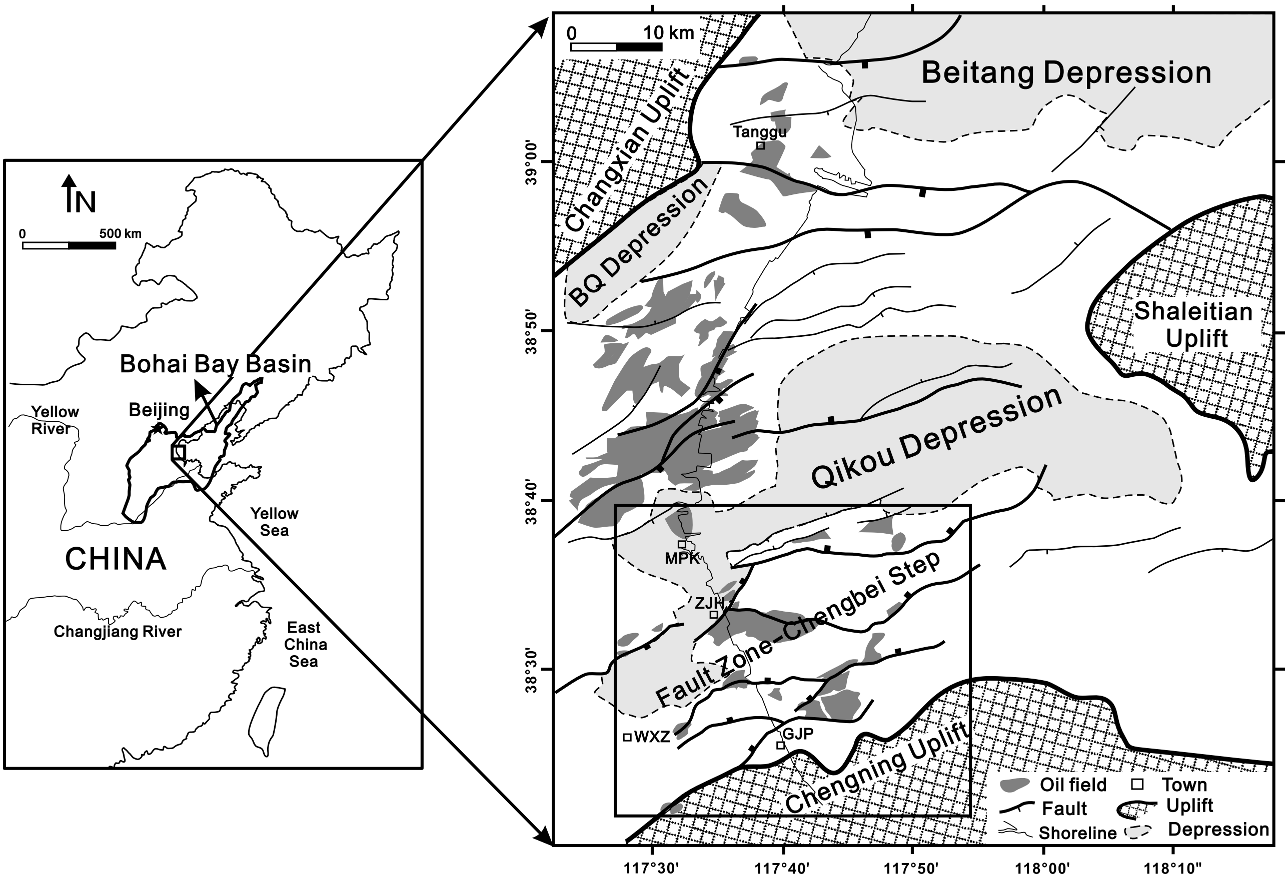


Figure 1. Location map of the Chengbei step-fault zone, as outlined by a square on the right panel, on the southern slope of the Qikou depression in Bohai Bay Basin, eastern China.

The purpose of this study is to propose such proxies, which can be used to characterize the seal capacity of faults in the Chengbei step-fault zone (CSFZ), Bohai Bay Basin, China. Our approach in studying fault-seal capacity is to consider the long-term hydrocarbon migration process as a cumulative effect of many small increments of migrating hydrocarbons through a segment of a fault zone, such as the migration episodes that occur during earthquakes. The presence of hydrocarbon accumulations in footwall and hanging-wall reservoirs is therefore used as a calibration criterion indicating cumulative fault opening and closing cycles for migration over geological time. A method of quantitative assessment of 3-D fault opening and closing at different locations on a fault plane is proposed, and the opening and closing behavior on a fault plane during the entire migration history may semiquantitatively be described using a concept of fault-connectivity probability.

GEOLOGICAL SETTING OF THE CHENGBEI STEP-FAULT ZONE

Structure, Stratigraphy, and Petroleum System

The CSFZ is located on the slope between the Chengning uplift and Qikou depression in the Bohai Bay Basin, northeast China (Figure 1). It covers an area of approximately 550 km^2 (212 mi^2), with three/fifths of the field offshore. The structural framework is a gentle slope cut by multiple step-like normal faults in the Cenozoic strata (Wang et al., 2003). The CSFZ, as well as the entire Bohai Bay Basin, has experienced a rifting episode composed of two phases: a Paleogene synrift phase and a Neogene to Quaternary postrift phase (Li et al., 1998). The tectonic evolution is related to strike-slip movements along the Tanlu fault and Qinling structural zone (Xu, 1980, Yang and Xu, 2004). The Cenozoic strata are composed of continental clastic

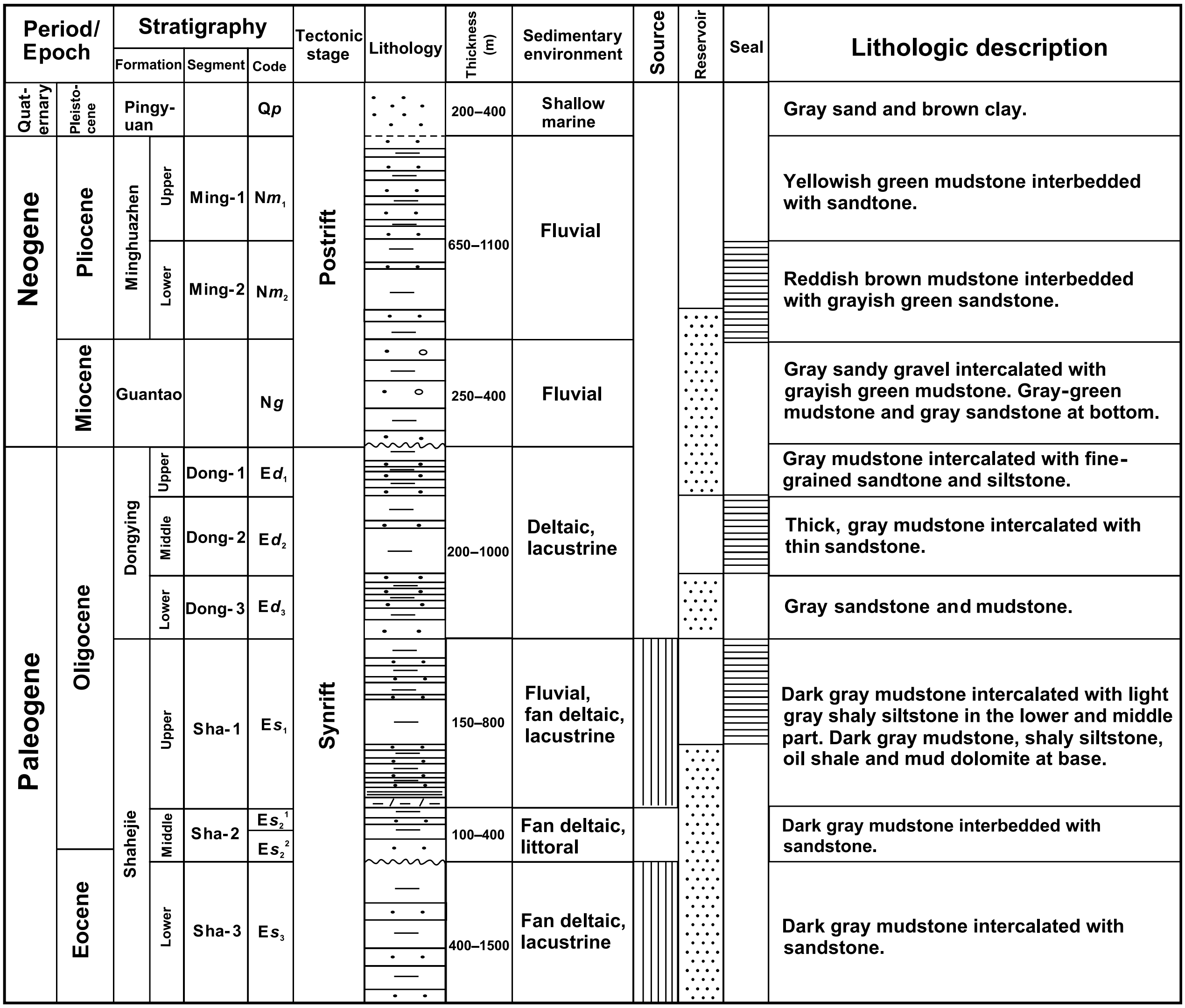


Figure 2. Summary diagram showing chrono- and lithostratigraphy, tectonic stages, and characteristics of the petroleum system in the Chengbei step-fault zone (after Yuan et al., 2004).

deposits, with a total thickness of 2000–5000 m (6562–16,404 ft) (Figure 2). The Paleogene synrift deposits include the Shahejie and Dongying formations. The Neogene to Quaternary sequence consists of the Guantao, Minghuazhen, and Pingyuan formations. A regional unconformity separates Paleogene and Neogene strata (Yuan et al., 2004).

Oil–source rock correlation shows that hydrocarbons in the CSFZ were derived from source rocks composed of dark-colored mudstones of the Sha-1 and Sha-3 members of the Shahejie Formation in the Qikou depression (Wang et al., 2006) (Figure 2). The major reservoir rocks include fan deltaic and lacustrine littoral sandstones of the Sha-2 and Sha-3 members of the Shahejie Formation, delta-front and prodeltaic sandstones of the Dong-1 and Dong-3 members of the Dongying Formation, and Neogene fluvial sandstones (Yuan et al., 2004) (Figure 2). Thick mudstones in the middle Sha-1 and Dong-2 members and lower Minghuazhen Formation constitute regional seal rocks (Yu et al., 2006) (Figure 2).

Petroleum exploration in the CSFZ began in 1965. During the last 43 yr, 11 oil and gas fields have been discovered (Figure 3). More than 140 exploratory wells have been drilled, and a 3-D seismic survey covers nearly all major structures. A large quantity of exploration and development data are available to study fault-seal capacity in the CSFZ (Figure 3).

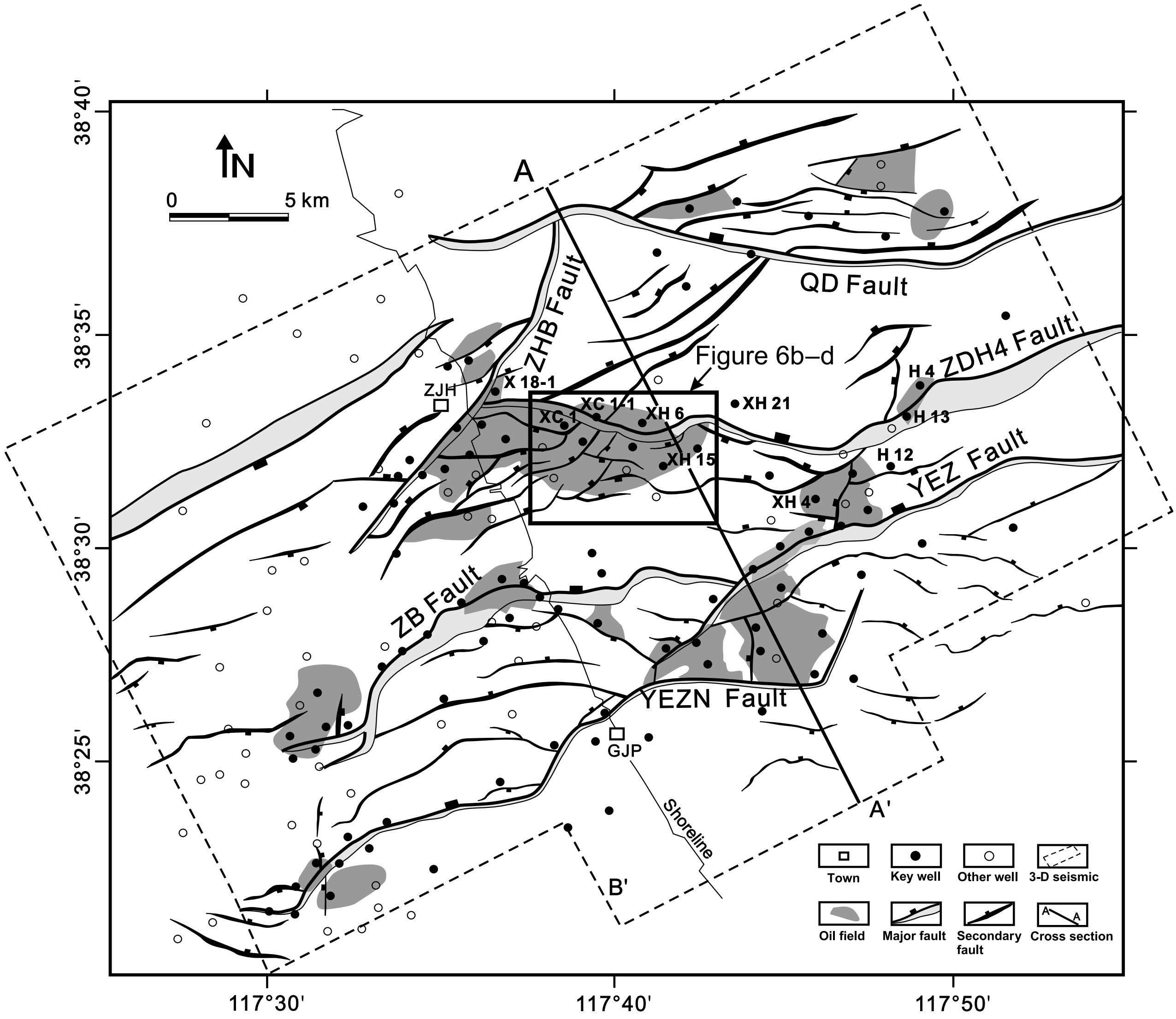


Figure 3. Faults, oil fields, key wells used in this study (black dots), other wells (black circles), and 3-D seismic data sets (dashed line rectangles) in the Chengbei step-fault zone. Faults are mapped at the top of the Shahejie Formation. Section AA' is presented in Figure 4. QD = Qidong; YEZ = Yangerzhuang; YEZN = Yangerzhuangnan; ZB = Zaobei; ZDH4 = Zhangdonghai 4; ZHB = Zhangbei.

Movement of Faults and Hydrocarbon Expulsion

The study area has experienced regional transtension since the end of the Mesozoic (Li et al., 1998), resulting in extensive faulting. Major faults, which controlled the structural framework and depositional history, include the Qidong (QD), Zhangdonghai 4 (ZDH4), Zaobei (ZB), Yangerzhuang (YEZ), Yangerzhuangnan (YEZN), and Zhangbei (ZHB) faults (Yuan et al., 2004; Yu et al., 2006) (Figure 3). Seismic interpretation indicates that they are synsedimentary faults (Figure 4). In general, these faults are parallel to each other, striking in a northeast or nearly east–west direction and dipping toward the depression to the north. The distribution of discovered hydrocarbon accumulations is closely related to the faults (Figure 3). These faults appear to be important factors in hydrocarbon migration and accumulation.

In this study, the incremental movements along a given fault are assumed to be the result of multiple tectonic episodes in the CSFZ. The fault growth index, defined as the ratio between the thicknesses of the same formation measured on both sides of the fault plane (Childs et al., 2003), was used to

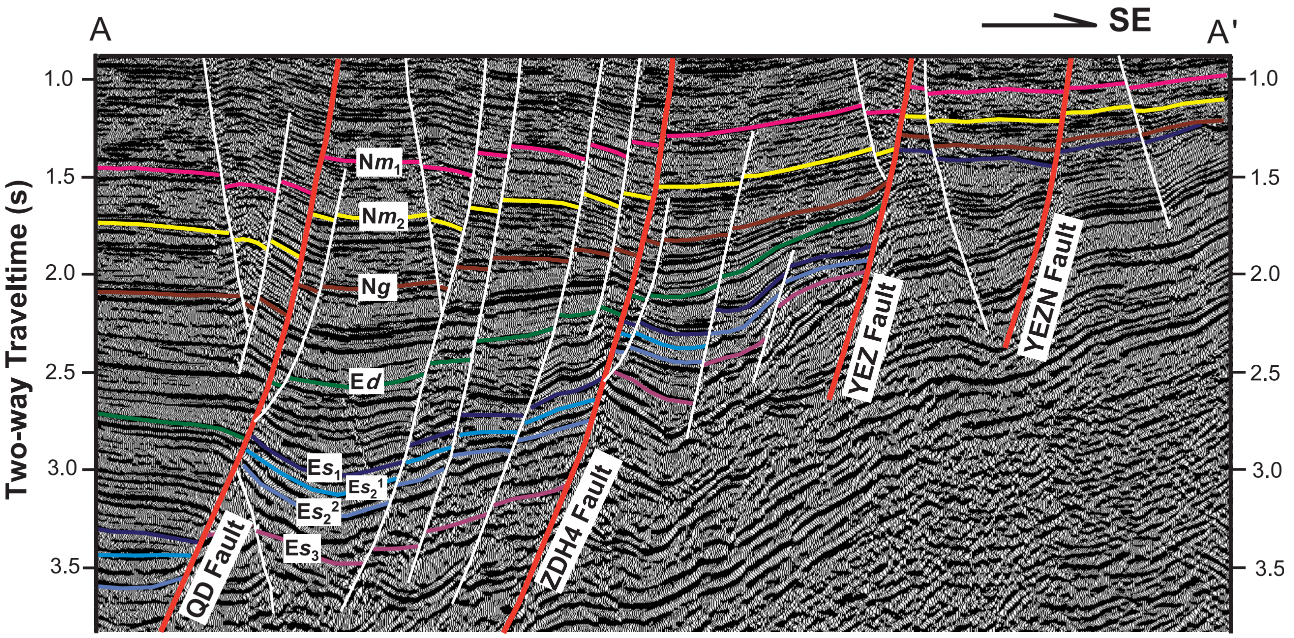


Figure 4. Interpreted seismic section AA′ (see the location in Figure 3), showing major faults and stratigraphic intervals in this study. QD = Qidong; ZDH4 = Zhangdonghai 4; YEZ = Yangerzhuang; YEZN = Yangerzhuangnan.

analyze the development and activity of growth faults in the study area (Zhang et al., 2007). They revealed the occurrence of three major episodes of intensive faulting during the deposition of the Shahejie, Donying, and upper Minghuazhen formations, respectively. The tectonic intensity had been decreasing from the Paleogene to the Neogene.

Basin modeling applied to the whole region (Figure 3) indicates that hydrocarbon was expelled from source rocks during two major episodes (Wang et al., 2006; Yu et al., 2006). The first episode was at the end of the Dongying (~26 Ma) when source rocks in the Sha-3 member became mature. Hydrocarbon expulsion ceased because of regional uplifting and erosion at the end of the Paleogene. Therefore, this early episode of hydrocarbon expulsion was short, and the amount of expelled hydrocarbon was limited. Major expulsion occurred during the second episode from the late Miocene to Quaternary (Wang et al., 2006). The deposition of the Neogene Guantao and Minghuazhen formations caused maturation and hydrocarbon generation in the Sha-3 and Sha-1 source rocks. Hydrocarbon expulsion peaked at the end of the Minghuazhen (~2 Ma).

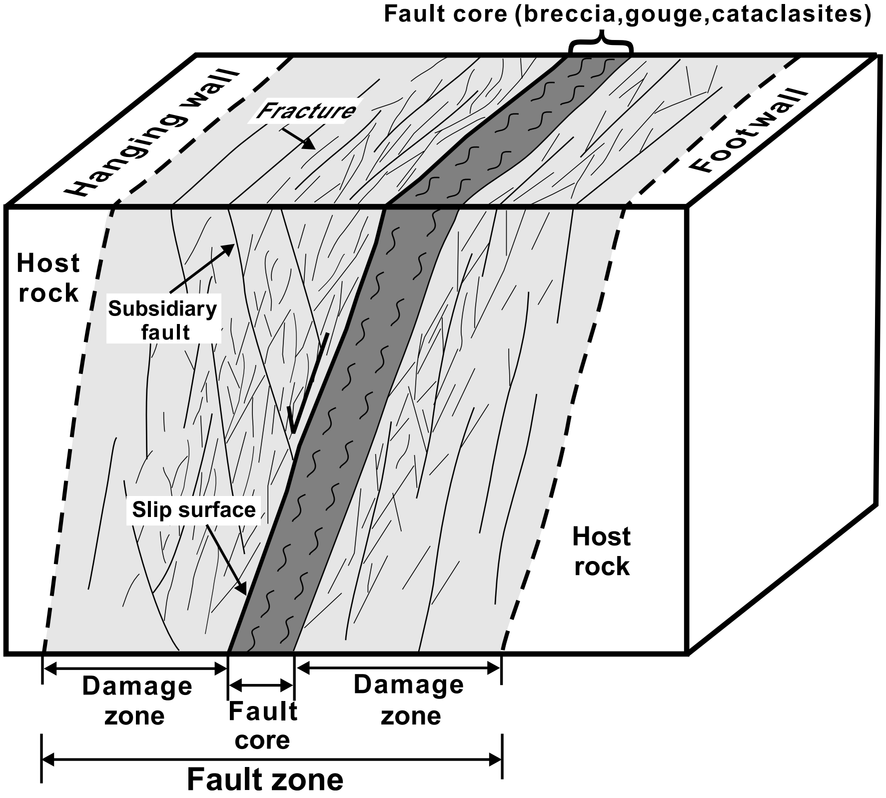
FAULT CONNECTIVITY AND PROBABILISTIC INTERPRETATION

We characterized the fault opening or closing on a statistical basis and developed the concept of fault-connectivity probability.

Fault Opening and Closing

A fault is not a simple discontinuity but instead a zone consisting of a fault core and a surrounding damage zone (Chester and Logan, 1986; Smith et al., 1990; Forster and Evans, 1991; Chester et al., 1993; Bruhn et al., 1994; Caine et al., 1996) (Figure 5). The fault core represents the part of a fault zone where most of the displacement is accommodated and consists of slip surfaces, fault gouge, breccias, and cataclasites (Chester and Logan, 1986; Chester et al., 1993; Caine et al., 1996; Clausen et al., 2003). The damage zone may be composed of subsidiary faults, faulted rocks, and fractures (Chester and Logan, 1986; Chester et al., 1993; Bruhn et al., 1994; Caine et al., 1996; Jourde et al., 2002). This definition of a fault zone requires the evaluation of its overall behavior and particularly that of its

Figure 5. Conceptual model of elements in a fault zone (modified from Chester and Logan, 1986; Smith et al., 1990; Bruhn et al., 1994; Caine et al., 1996).



potential hydrocarbon-carrying capacities during the entire history of hydrocarbon migration.

Furthermore, consider that the commercial quantity of hydrocarbons having migrated through fault zones must be a result of multiple events (such as earthquakes) that occurred over a long-term geologic period. The present distribution of hydrocarbons along a fault is the consequence of these multiple episodes of migration and accumulation. At any time, any point on the fault has the potential to act as a barrier or conduit. However, the behavior of this point during a single displacement event cannot be evaluated because hydrocarbon migration processes corresponding to this single faulting event cannot be assessed. Nevertheless, the cumulative effects of these events can be identified so long as some of these events leave a preserved trace.

Identifying Fault Connectivity

The presence or absence of hydrocarbon-filled reservoirs on both sides of a fault gives a quantitative indication on whether the fault has been open during at least some of the events occurring as a function of geological time. For a given location on the fault, an open and close indicator may be constructed as explained in the following paragraph, where it is applied to the CSFZ.

This study concentrates on faults that have been drilled extensively on both their footwalls and hanging walls so that sufficient data are available to better characterize the history of fault opening and closing. Actually, the CSFZ is particularly convenient for the use of hydrocarbons as an indicator of fault opening and closing. This is because hydrocarbons accumulated principally during a relatively short period from the Miocene to Pliocene (Yu et al., 2006). Since then, the study area has kept subsiding without significant changes in tectonic style (Wang et al., 2003).

As illustrated on Figure 3, the six main faults of the CSFZ clearly connected with oil and gas discoveries are selected. The precise relationship between the fault geometry and the occurrence of hydrocarbons in reservoirs may be assessed using data from exploration wells and 3-D seismic surveys. Figure 6 presents an enlargement of the eastern part

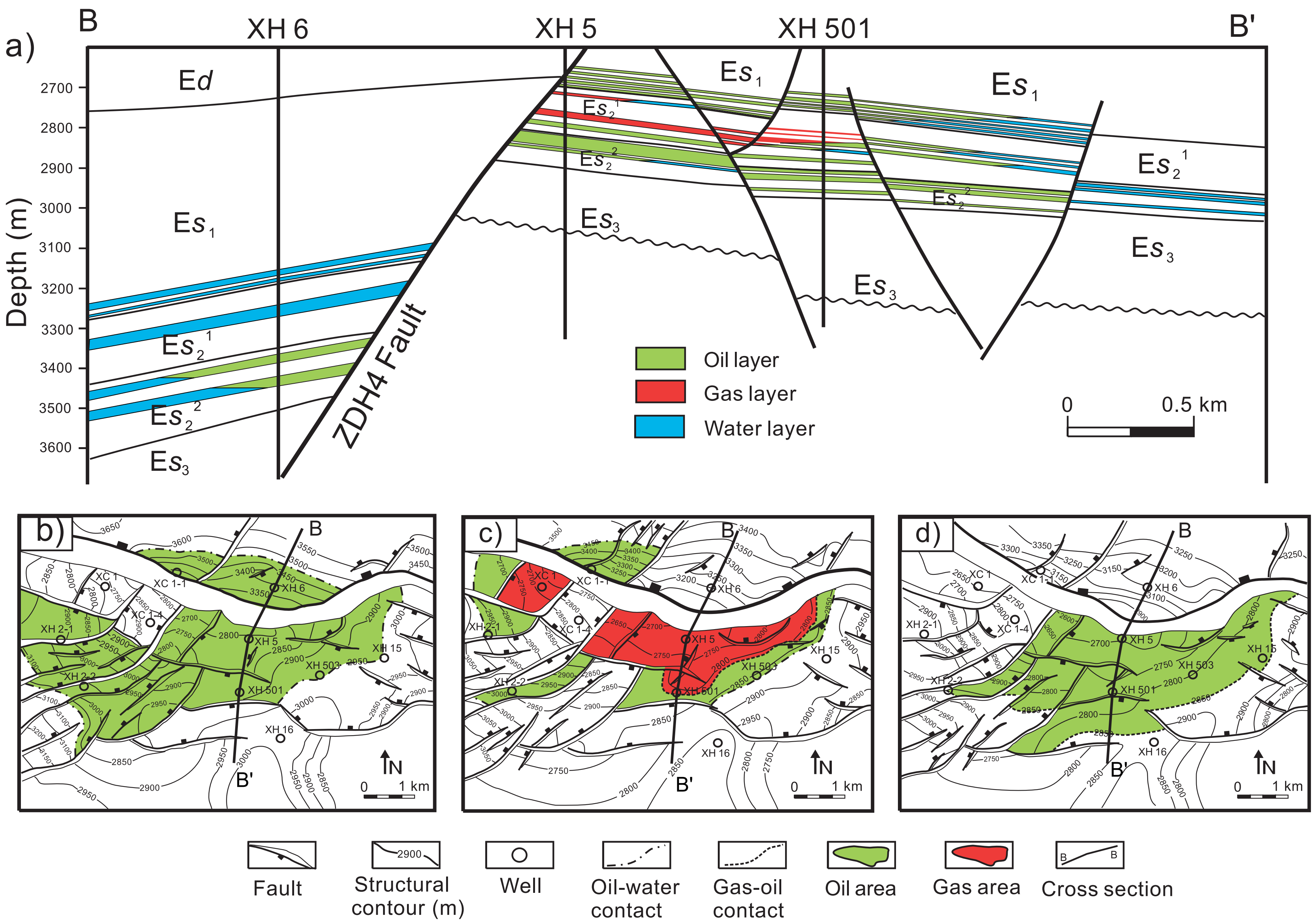


Figure 6. Detailed configuration of the eastern part of the Zhangdonghai 4 (ZDH4) fault. (a) A cross section showing the deep part of the fault zone and the occurrence of hydrocarbons. The location is on panels b, c, and d. (b, c, d) Maps showing the horizontal extent of the oil-bearing layer in Es$_2^2$, Es$_2^1$, and Es$_1$ (see Figure 2), and the contour maps at the top of these intervals. The contour interval is 50 m.

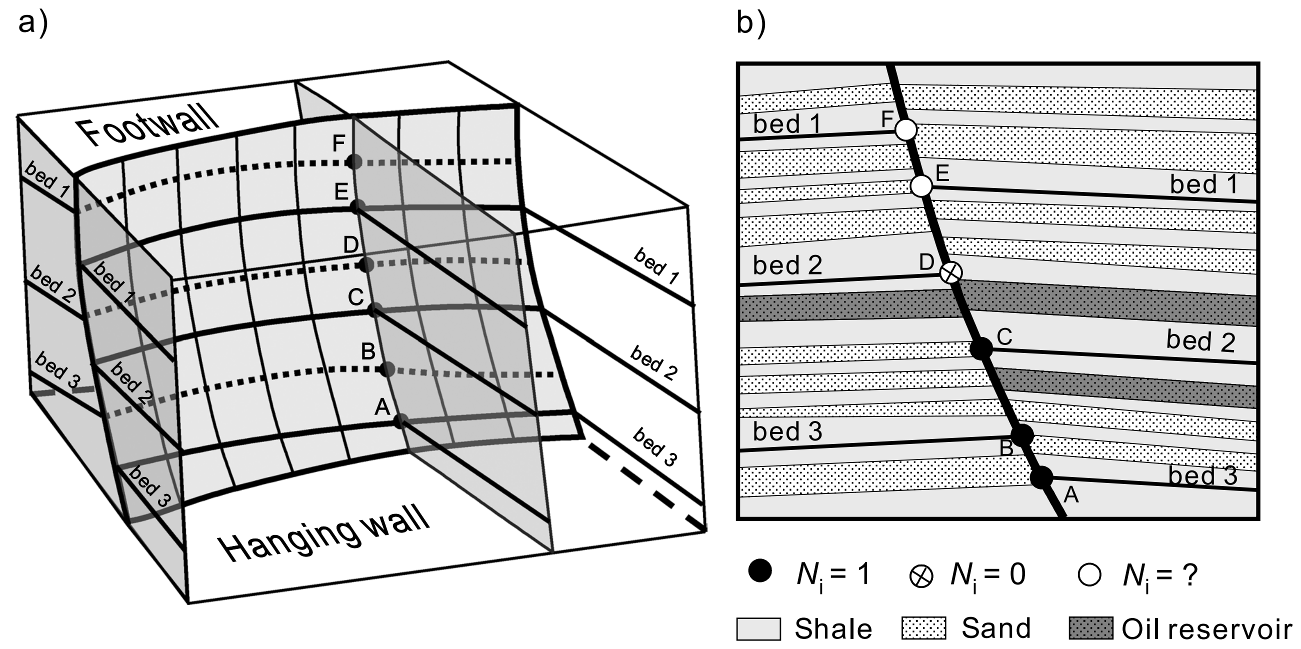


Figure 7. Determination of fault connectivity on the basis of hydrocarbon occurrence. (a) Schematic block diagram showing a numerical model of a normal fault and positions of several stratigraphic intervals at the footwall and hanging wall on the fault surface. (b) Sketch demonstrating the criteria used for identifying whether a fault was open. From the occurrence of hydrocarbon, nodes A, B, and C were clearly open, node D remains closed, and the state of nodes E and F were not certain during migration. N_i is defined as the fault-connectivity index. For a given node, $N_i = 1$ indicates the fault has opened for migration, $N_i = 0$ indicates the fault kept closing, and $N_i = ?$ means the effect of the fault cannot be identified and the node will not be taken into account in statistical analysis.

of fault zone ZDH4. A cross section perpendicular to the main fault (Figure 6a) displays the major horizons interpreted from 3-D seismic data, together with major reservoirs. The lateral extent of the oil-bearing layer (as well as the oil-water contacts) and the topography at the top of the Es_2^2, Es_2^1, and Es_1 reservoirs (Figure 6b–d) emphasize that, in most occasions, faults acted as a seal with respect to the reservoirs. However, hydrocarbons that accumulated in the footwall cannot be from the local source rock of Es_1 or Es_3 because it is poor and immature in this area. Oils must have been fed through openings of normal fault ZDH4 (Figure 6a), which extend from the base of Es_2^2 in the footwall to the top of Es_2^1 in the hanging wall.

On a cross section of the fault plane, we identify particular points (called grid nodes) as the top of each bed in both the hanging wall and the footwall (Figure 7a). Assuming that the fault is the only possible pathway, the opening and closing state of such a node on the fault during the migration period is determined by identifying the hydrocarbon presence or absence in reservoirs above that node on both sides of the fault plane. Four possible scenarios may occur and are used to identify whether the node had served as a migration path. The four scenarios can be described as follows (Figure 7b): (1) the reservoirs below contain hydrocarbons and the ones above do not (the case of point D on Figure 7b); (2) reservoirs both above and below the node contain hydrocarbons (the case of point C on Figure 7b); (3) the reservoirs above the node contain hydrocarbons and those below the node do not (the case of points A and B on Figure 7b); and (4) reservoirs both above and below the node do not contain hydrocarbons (the cases of points E and F on Figure 7b). It is not difficult to assess that, in scenarios 2 and 3, the node must have been open at some time during migration; on the contrary, in scenario 1, no hydrocarbon accumulation above this node exists at present, and thus, the node was probably closed during migration. In the last scenario, it is unknown whether the node was open or closed during migration.

At the scale of the CFSZ, many such cross sections, which include both structural information

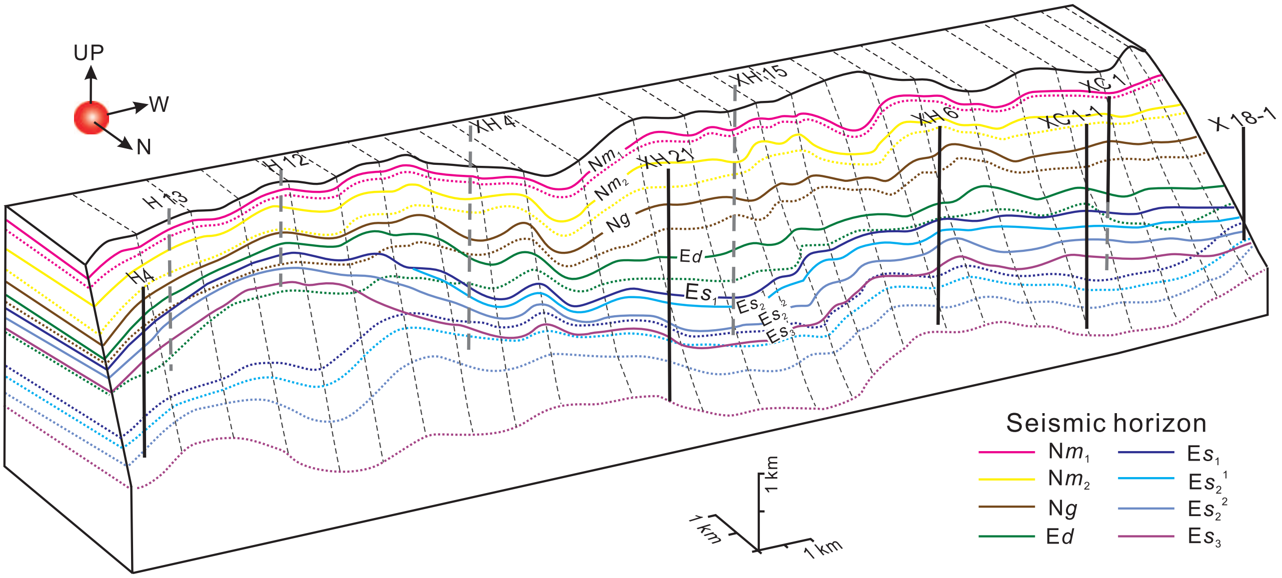


Figure 8. Structural block diagram of the footwall of fault ZDH4. The positions of stratigraphic intervals are marked as solid lines on the footwall and as dashed lines on the hanging wall.

and indications of hydrocarbon occurrence, may be constructed. A systematic study, derived from available seismic sections, is therefore performed. The geometrical and structural data are first digitized for grid mapping of the main faults. An example of such mapping is shown on Figure 8, which presents a perspective view of the footwall of fault ZDH4. The traces of the main horizons (both of the hanging wall and of the footwall) as well as the traces of seismic cross sections are the basic elements of this grid. Based on the mapping of the oil and gas shows, assessing the connectivity of the fault at various nodes of a grid is commonly possible.

Fault-Connectivity Indicator as a Probabilistic Criterion

Sixteen cross-well seismic sections perpendicular to six selected major faults are used to analyze the fault connectivity during migration. At each intersection point between the fault plane and a carrier bed (Figure 7b), a binary index, termed the "fault-connectivity index" (N_i), is defined as 0 when evidence for migration is absent and 1 when evidence for migration is present. If the evidence is inconclusive, the corresponding data point is discarded. About 120 data points are compiled, each being assigned with an open/close index.

The relevance of this index to the actual opening and closing of a fault is debatable. First, it is possible that part of the migration occurs in other pathways instead of the main fault. For instance, small faults or cracks generally accompanying master faults in extensional basins could channel a substantial fraction of the migrated hydrocarbons. There also is an implicit assumption (Figure 7) that, at each data point, hydrocarbon migrates in a 2-D plane perpendicular to the fault. In fact, it is likely that pathways along the fault are much more complex than being depicted here and their exact 3-D geometry is difficult to assess. A statistical approach may be effective in countering this complexity. At a given point on the fault, it is convenient to consider the fault-connectivity index as a binary variable with a value of 0 or 1. The probability that the index has a value of 1 depends on the position of the point on the fault and is a function of other variables of the fault, such as physical parameters characterizing the environment and history of the fault. The previously collected data allow the characterization of this probability relationship as follows.

For a specified value range of some physical parameters associated with a fault (e.g., depth, dip and strike of the fault, throw of the fault, fluid pressure, stress, shale smear index, etc.), the probability that the fault would be open is defined as

$$N_{\mathrm{p}} = n/N \tag{1}$$

where n is the number of nodes where the fault-connectivity index is equal to 1 and N is the number of nodes where the migration history can be assessed unequivocally (Figure 7).

ASSESSMENT OF PHYSICAL PARAMETERS

Many geologic factors and processes control whether faults serve as barriers or conduits for hydrocarbon migration, such as fault-plane attitude, displacement, lithology, and mechanical properties of offset strata, burial depth, juxtaposition of lithology across the fault plane, fault gouges, stress direction and magnitude, fluid properties, temperature and pressure conditions, etc. (Bouvier et al., 1989; Knott, 1993; Lindsay et al., 1993). However, a good predictive method in assessing fault connectivity for hydrocarbon migration should use data that are routinely available (Yielding et al., 1997).

In this study, burial depth, dip and strike of the fault, throw of the fault, fluid pressure, stress, and shale smear defined by the SGR are used to characterize fault opening and sealing. Among these parameters, normal stress and fluid pressure are expected to have direct impact on the open and closed behavior of a fault. An analysis of a set of available physical data shows that fluid pressure and normal stress are well correlated with most other parameters except SGR. The SGR represents the sealing properties of a fault, which also influence the fluid flow regardless of whether the fault is open or closed (Yielding et al., 1997). Thus, fluid pressure, stress, and SGR can be regarded as representative parameters to characterize the effects of fault behavior on hydrocarbon migration.

Fluid Pressure in Mudstones

Fault opening during active faulting is expected to be positively correlated with fluid pressure in mudstones (P) adjacent to the fault. This is because the mechanical strength of rock strata decreases with increasing pore-fluid pressure (Hubbert and Rubey, 1959; Jaeger and Cook, 1979). In an interbedded shale-sandstone package, overpressure may serve as a trigger of fault opening (Byerlee, 1993; Luo, 2004), especially when the fluid pressure is much larger than the hydrostatic pressure. The coupling of faulting and overpressure starts with the accumulation of fluid pressure, resulting in a decrease of effective stress and mechanical strength of rock strata, fracturing and draining fluids out of the sandstones.

Once a fault opens, the rate of pressure release within mudstones is much smaller than that within permeable sandstones (Luo, 1999); therefore, faults can easily seal before any significant pressure decrease occurs in mudstones (Luo et al., 2003). During such a short-term opening of a fault, the abnormal pressure in permeable sandstones is released, whereas the pressure within mudstones remains mostly unchanged (Luo, 1999; Luo et al., 2000).

Fluid pressure in mudstones may be estimated from acoustic logs, which are available to this study in only a limited number of boreholes. To estimate the pressure in shale along the whole fault system for a given geological period, we used a 3-D numerical basin model calibrated against the available data. The Temis3D software package of Ungerer et al. (1990) and Schneider et al. (2000) was used. Sediment compaction is assumed to be the main fluid-pressure generation mechanism. Present pressures deduced from acoustic logs in 60 wells are reduced following the method of Magara (1978). They serve as calibration points for the numerical basin model, which allow one to derive the field of fluid pressure throughout the basin. The resulting fluid pressure on the ZDH4 fault surface during the deposition of the uppermost Minghuazhen Formation (~2 Ma) is mapped in Figure 9a.

Stress Normal to the Fault Plane

The tightness of small fractures within fault zones mostly depends on the normal stress (δ) applied to the fault plane. High normal stress would cause plastic deformation during faulting and closure of fractures (Harding and Tuminas, 1989). On the contrary, for low normal stress, fractures may be open and serve as conduits to fluid flow (Zhou et al., 2000; Lu and Ma, 2002).

The normal stress component on a fault plane can be calculated from the position and orientation of the fault plane and the knowledge of the subsurface stress field (Jaeger and Cook, 1979). The magnitude of the effective stress component normal to the fault plane is determined by the dip angle of the fault plane, burial depth, and the direction and magnitude of tectonic stress. For listric growth faults, the dip angle decreases with depth, causing the gravity component of the overburden perpendicular to the fault plane to increase, promoting fault closing.

The current stress field in this area was measured by Qu et al. (1993) and Xu et al. (1996). Xu et al. (1996) estimated the stress using hydrofracturing in 50 wells in this area. The maximum stress is vertical in the area, and the larger horizontal stress is in the direction of 55–80° (Qu et al., 1993). The maximum stress, σ_1, was evaluated to be equal to the weight of overburden. The values of the horizontal principal stresses, σ_2 and σ_3, following the burial depth, were estimated from the measurements of Xu et al. (1996). The fault-dip angle can be obtained from seismic interpretation. The normal component of stress was mapped on the surface of fault ZDH4 (Figure 9b).

Shale Gouge Ratio

Clay or shale smeared into the fault zone has been considered as an effective mechanism to seal a fault (Weber et al., 1978; Bouvier et al., 1989; Lindsay et al., 1993; Gibson, 1994; Yielding et al., 1997; Alexander and Handschy, 1998). The porosity and permeability of a fault zone decrease with an increasing amount of smear corresponding to mudstones incorporated into the fault zone. Various parameters were proposed to estimate the amount of muddy fault smears on the basis of observed distributions of mudstones within fault zones (e.g., Bouvier et al., 1989; Lindsay et al., 1993; Yielding et al., 1997). The SGR of Yielding et al. (1997) is commonly used for heterogeneous siliciclastic strata (Sorkhabi and Tsuji, 2005). It is defined as the ratio between the throw of the fault and the total thickness of mudstones within the throw.

$$\mathrm{SGR} = \frac{\sum_{i=1}^{n} h_i}{L} \times 100\% \qquad (2)$$

where SGR is in percent, L is the throw in meters, h_i is the thickness of the ith mudstone bed, and n is the number of mudstone layers within the throw. The SGR includes, therefore, two factors that correlate with fault seal: the lithologies of faulted strata and the amount of displacement. Thus, SGR should be an efficient parameter in evaluating the tendency of the fault to be smeared.

Mudstone thickness data come from gamma-log analysis near the fault zones. The depth difference between the footwall and hanging wall for each horizon defines the fault throw for that horizon, which is used to interpolate the throw at the fault grid points. The SGR at every grid node can be calculated using equation 2. The SGR values may be mapped on the fault surface (Figure 9c).

FAULT-CONNECTIVITY PROBABILITY AS A FUNCTION OF PHYSICAL PARAMETERS

As explained above, it is expected, at least on a statistical basis, that some relationship between fault-connectivity probability can be deduced from hydrocarbon occurrence on both sides of a fault and the selected parameters can be deduced independently from well and seismic data concerning the physical properties of the fault with respect to its ability to open or close during some events. On selected fault planes, values of physical parameters at each grid node are estimated, and the status of the fault, open or closed, is evaluated qualitatively according to the procedure discussed above. After removing the equivocal data, a set of 117 data nodes are finalized.

The SGR values are separated into 10 intervals. For each interval, the corresponding fault-connectivity probability (N_{p} in equation 1) is

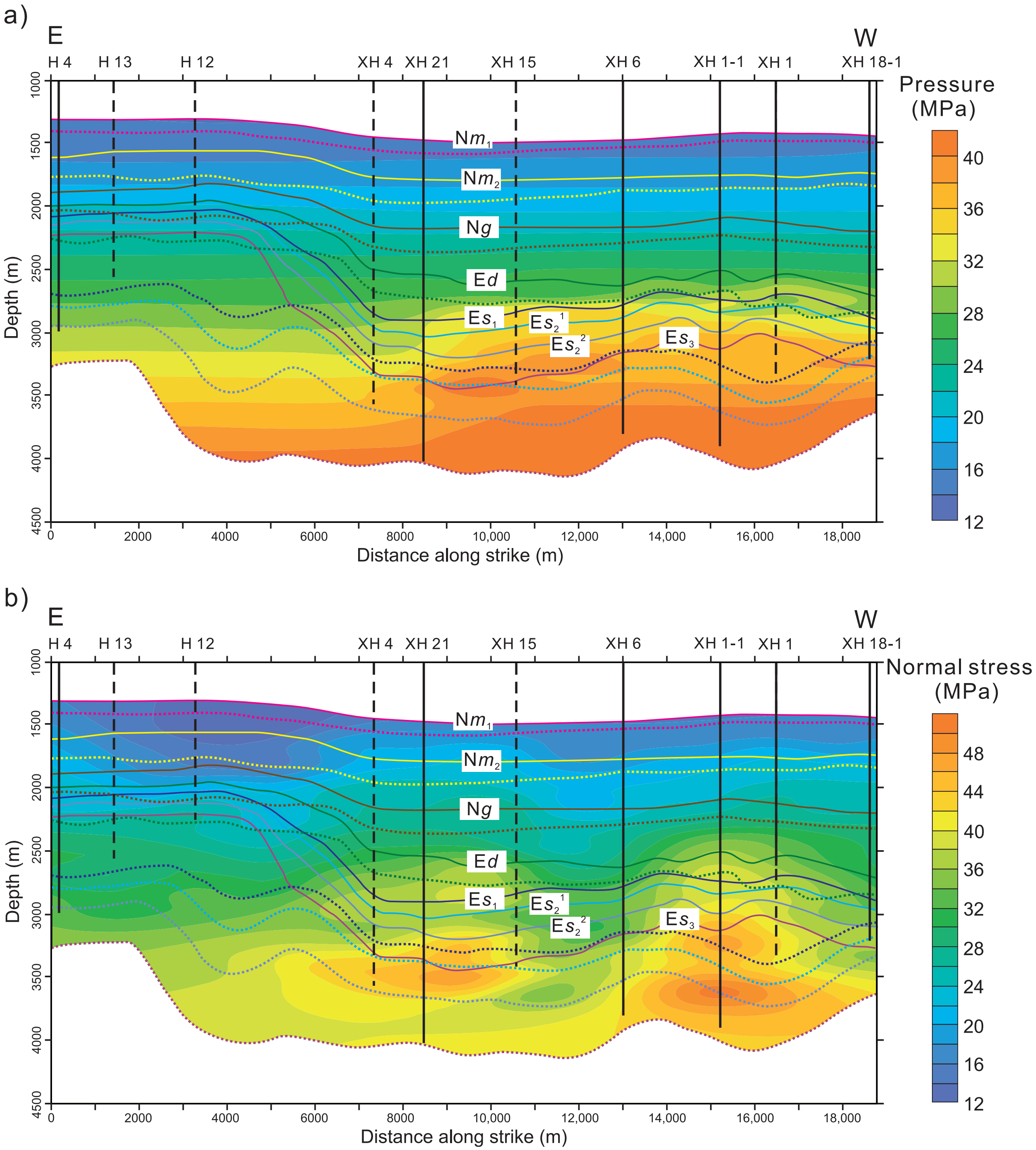


Figure 9. Distribution of various parameters on the surface of fault ZDH4 projected onto a vertical plane. (a) Fluid pressure in mudstones (*P*), (b) stress normal to fault plane (δ), (c) shale gouge ratio (SGR), and (d) fault-connectivity probability on the same fault plane.

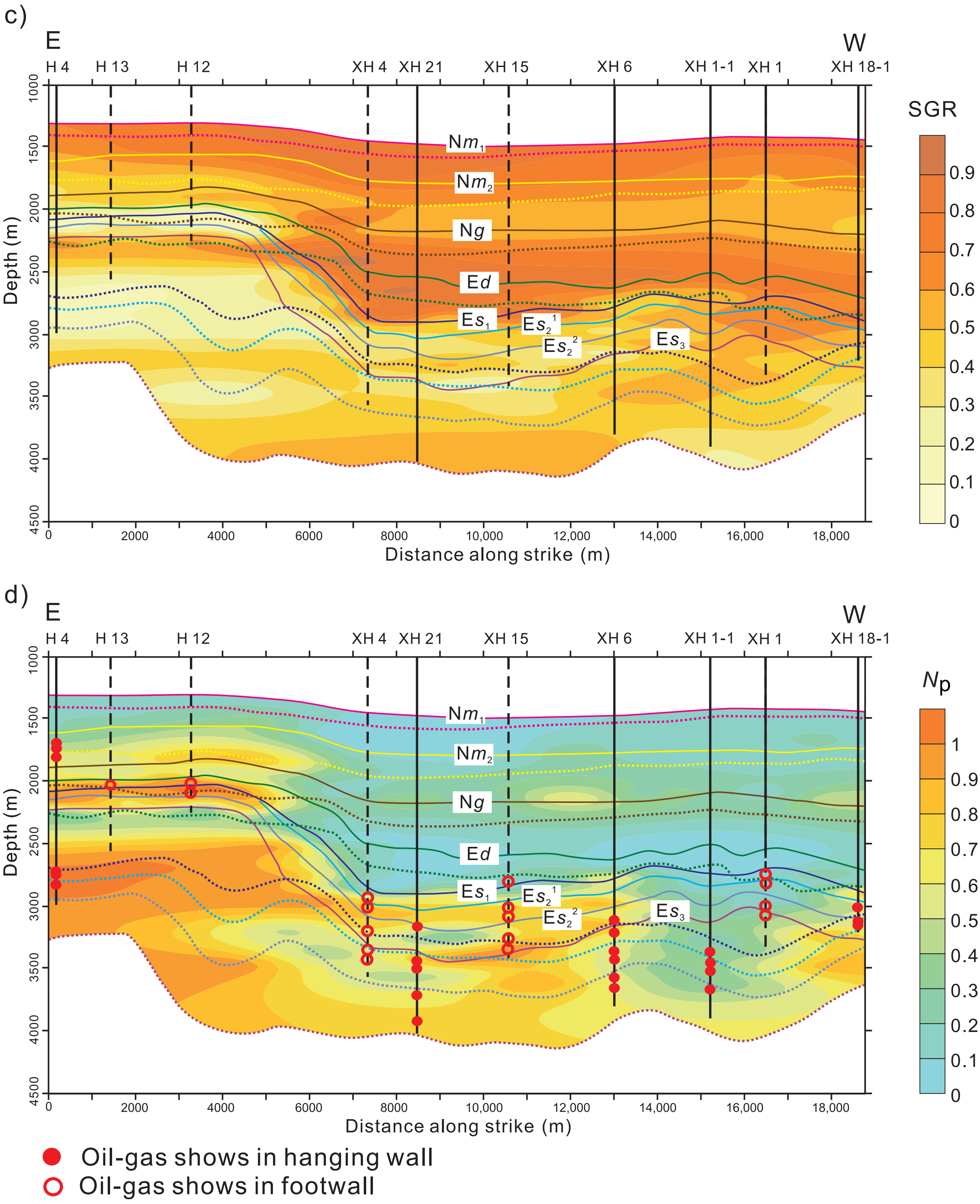


Figure 9. Continued.

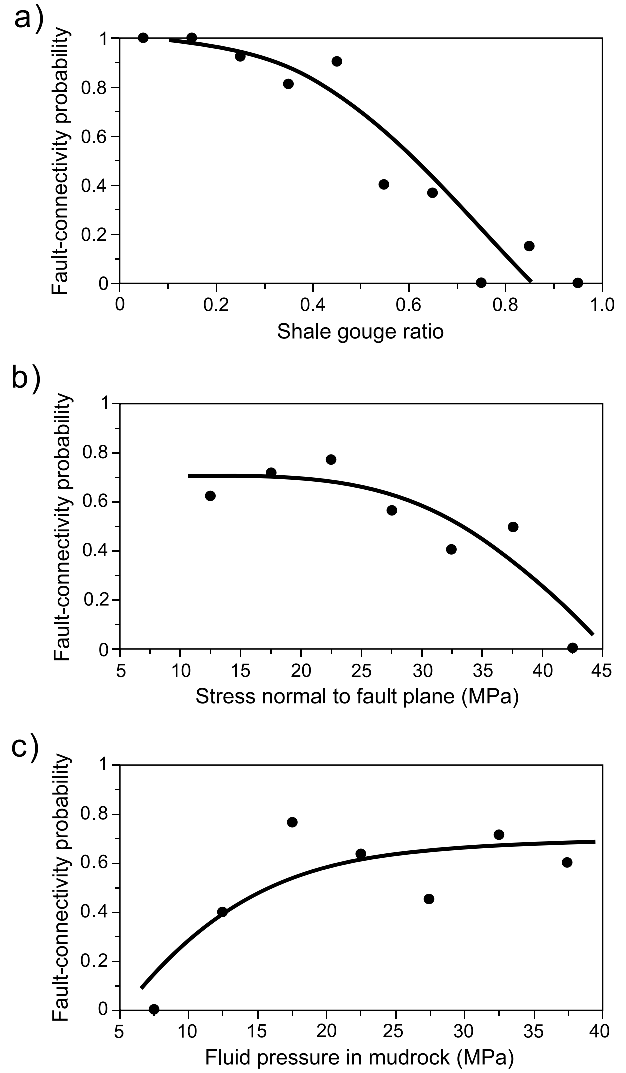


Figure 10. Crossplot illustrating the relationship between fault-connectivity probability and (a) shale gouge ratio (SGR), (b) stress normal to fault plane, and (c) fluid pressure in mudstones.

computed. Figure 10a illustrates a clear negative trend of N_p vs. SGR, indicating that a smeared fault segment would have less chance to open.

In Figure 10b, seven intervals of normal stress values are used to estimate the relative proportions of connected occurrence. This proportion is again interpreted as the probability that a fault could be open for this range of normal stress. A clear negative trend of N_p vs. δ is observed, indicating that a fault subject to great normal stress would have less chance to open.

In Figure 10c, seven intervals of fluid-pressure values are used to plot the relative proportions of connected occurrence. A clear positive trend of N_p vs. P is observed, indicating that a fault with high overpressure has a better chance to be open.

As a result of the comparisons presented in Figure 10, the fault-connectivity probability appears to depend significantly on the three independent physical parameters, SGR, δ, and P, on a statistical basis. The next step is to proceed to a multiparameter approach to improve the assessment of the fault-connectivity probability.

Fault Opening Index

To combine these three parameters, an FOI is defined as a dimensionless coefficient.

$$\mathrm{FOI} = \frac{P}{\delta \mathrm{SGR}} \tag{3}$$

The FOI is the ratio between the parameter favoring fault opening, represented by the fluid pressure in mudstones near the fault and the parameters promoting fault closing, such as the mudstone smear factor and the normal stress on the fault plane. This functional dependence is justified by the observed relationship among individual parameters and by the fact that the FOI is dimensionless.

Fault-Connectivity Probability as a Function of the Fault Opening Index

The relationship between FOI and fault connectivity for fluid flow is empirical through the study of discovered oil fields. The FOI values were calculated using data of SGR, mudstone fluid pressure, and normal stress, and the corresponding fault-connectivity indices were similarly identified by the statistical method mentioned above (Figure 7).

The 117 FOI values (on independent locations of faults) are divided into 8 intervals with an increment of 0.5. The number of total nodes (N) and the number of nodes that had served as migration pathways (n) are counted for every interval (Figure 11a). Presented as a percentage, the values of $N_p = n/N$ within a statistical range define the

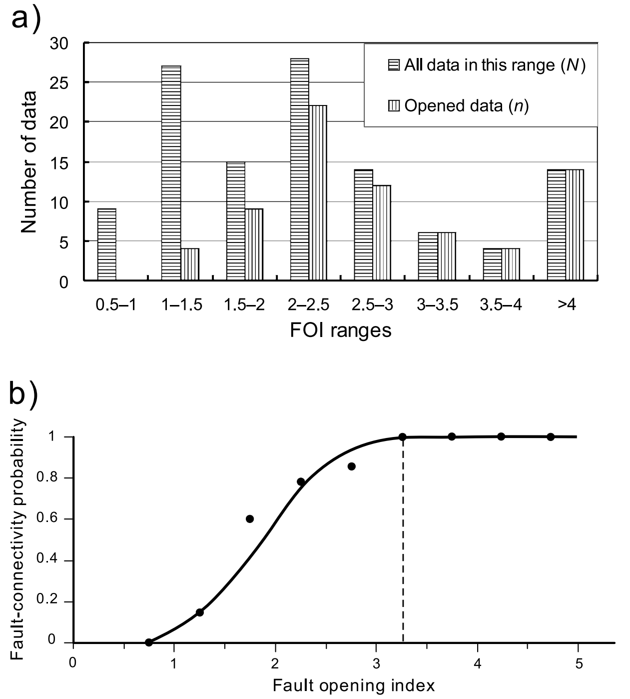


Figure 11. (a) Distribution of the number of total nodes (*N*) and the number of nodes that served as migration pathways (*n*) in each statistical range of the fault opening index (FOI) value. (b) Relationship between fault-connectivity probability and FOI.

fault-connectivity probability. Our compilation (Figure 11b) indicates that fault-connectivity probability is 0 for FOI values smaller than 0.75; a quadratic polynomial relationship between FOI and N_p is present where FOI ranges from 0.75 to 3.25; and the fault-connectivity probability is equal to 1 for FOI values larger than 3.25. The value of $N_\mathrm{p} = 1$ indicates that the node behaved as a migration pathway.

The interpolation of these statistical results leads to the following relationship.

$$N_\mathrm{p} = \begin{cases} 0 \\ -0.1197\,(\mathrm{FOI})^2 + 0.8931\,(\mathrm{FOI}) - 0.6564 \\ 1 \end{cases}$$

$$\begin{array}{r} \mathrm{FOI} \le 0.75 \\ 0.75 < \mathrm{FOI} < 3.25 \\ \mathrm{FOI} \ge 3.25 \end{array} \qquad (4)$$

Where N_p is the fault-connectivity probability and FOI is the fault opening index.

Characterization of Fault Opening and Closing

Using equation 4, N_p can be estimated for any grid node, in particular, those where no hydrocarbon has been discovered yet.

Taking fault ZDH4 as an example, Figure 9d illustrates the distribution of estimated N_p on a fault plane. On this fault, connectivity probability N_p varies over a wide range. For example, the area west of the H12 well, where the Sha-3 ($\mathrm{E}s_3$), Sha-2 ($\mathrm{E}s_2{}^2$ and $\mathrm{E}s_2{}^1$), and Sha-1 ($\mathrm{E}s_1$) members are present, has a probability generally greater than 0.6, except in between the XH1 well and XH6 well, where the probability is low (<0.4), indicating the low potential of a fault opening. The probability is very low (<0.1) in the area of the Sha-1 member ($\mathrm{E}s_1$) and Dongying Formation (E*d*) on the footwall, where the fault was likely sealed. As a result, hydrocarbons in the carrier beds of the Shahejie Formation (including $\mathrm{E}s_3$, $\mathrm{E}s_2{}^2$, $\mathrm{E}s_2{}^1$, and $\mathrm{E}s_1$) in the hanging wall would not be able to migrate upward into the Neogene reservoirs on the footwall along the fault. Instead, hydrocarbons would have migrated into reservoirs within the $\mathrm{E}s_2{}^2$, $\mathrm{E}s_2{}^1$, and $\mathrm{E}s_3$. The lack of discoveries in the Neogene reservoirs in this area supports this interpretation. In the area east of the H12 well, the fault plane against $\mathrm{E}s_3$, $\mathrm{E}s_2{}^2$, $\mathrm{E}s_2{}^1$, and $\mathrm{E}s_1$ in the hanging wall and $\mathrm{E}s_3$ to the Guantao Formation(N*g*) in the footwall both have high (>0.5) connectivity probability, indicating fault opening. The fault plane may have been closed in the area against the lower Minghuazhen Member ($\mathrm{N}m_2$). Hydrocarbon accumulations have been discovered in N*g* and $\mathrm{N}m_2$, supporting the interpretation from fault-connectivity probability.

DISCUSSIONS

Fault movement is mostly episodic (Hooper, 1991; Byerlee, 1993; Xie et al., 2001): stress accumulating over a period would create new faults and/or cause the movement of preexisting faults, resulting in a sudden release of stress and fluids. Faulting would cease once stress and strain reach equilibrium, and another cycle of stress accumulation would follow (Roberts and Nunn, 1995). In general, faults are open during faulting and can serve as vertical and lateral hydrocarbon migration pathways (Hooper, 1991; Anderson et al., 1994), whereas faults are generally closed during the period of quiescence and would serve as barriers to hydrocarbon migration (Fowler, 1970; Bouvier et al., 1989). In fact, a fault zone is not entirely open during faulting; instead, it is open in some segments or places and closed in others (Haney et al., 2005). Fault closure during faulting may be caused by several processes: for example, ductile strata matching across the fault zone, sealing by fault gouge, smearing of mudstones, or enclosure of a segment of an open fault zone by low-permeability strata across the zone and closed fault zones above and below, resulting in an increase of the length and complexity of pathways for fluid flow (Byerlee, 1993; Lockner and Byerlee, 1995). When faulting ceases, some of the open fractures close due to a change in stress field, whereas other open fractures are cemented or welded by precipitates from trapped fluids. The cementation is very fast and can be regarded as instantaneous once faulting ceases at a geologic time scale (Ortoleva, 1994).

The generation or activation of a fault and the displacement of strata across the fault are the cumulative results of many tectonic episodes, each of which corresponds likely to some enhancement of earthquake activity. In addition, the generation and expulsion of hydrocarbons in and from the source rocks occur over a long geologic period. The currently observed hydrocarbon accumulations that were migrated along fault zones are the cumulative products of many episodes of fault opening and associated hydrocarbon migration. Thus, the study of fault opening and closing with regard to hydrocarbon migration on the basis of observed or discovered distribution of hydrocarbon accumulation should be conducted on the basis of a time scale comparable to the cumulative processes, not with a time scale of individual events of fault opening and closing.

In addition, a fault is in fact a fault zone, which is composed of a series of smaller subsidiary faults and fractures (Chester and Logan, 1986; Chester et al., 1993; Bruhn et al., 1994; Caine et al., 1996; Jourde et al., 2002). Not all the subsidiary faults and fractures are open during an episode of fault movement; instead, they close or open from time to time and episode to episode, affecting each other in a complex way. As a result, fluid flow occurs three dimensionally along the fault zone; and its exact flow path changes from episode to episode (Lockner and Byerlee, 1995). The observed hydrocarbon accumulation is the final integrated result of all episodes of fluid flows along all fault planes, fractures, pore spaces, and permeable rock bodies within a fault zone. Hence, the evaluation of fault opening and closing at a basin scale should be conducted for the fault zone as a whole, and a fault zone should not be classified as absolutely open or closed regardless of its scale, type, and other characteristics (Luo et al., 2003).

In establishing the statistical model of fault opening and closing, only the presence and absence of hydrocarbons in reservoirs above and below a given grid node, along the same vertical plane, were considered. Fluid flow is in reality three dimensional, and fluid may flow horizontally between grid nodes. Moreover, some open microcracks in flexure zones of extensional basins could divert part of the migrating flow. This could introduce erroneous interpretation of reservoir leakage or accumulation. Another bias could be introduced by the fact that stresses and fluid pressures are obtained from present measurements, whereas migration occurs over long periods during which these physical parameters could vary. Therefore, the various inaccurate interpretations could introduce unpredictable errors to the proposed analysis and justify a probabilistic approach.

In areas with limited drilling, the availability of accurate values of various parameters required for calculating FOI and N_p is a challenge. For example, mudstone content in footwalls and hanging walls can only be estimated from interpreted depositional systems. However, the uncertainties in estimating these parameters would certainly lower the accuracy for evaluating FOI and N_p.

Finally, the concept and model of fault-connectivity probability has been developed for a given geological context on the basis of characteristics of extensional faults in the sedimentary basins of eastern China. The relevance of this model in basins with similar geological settings seems likely although the parameters of the FOI/N_p relation should be adapted. Its applicability for other settings such as reverse or strike-slip faults would require further tests.

CONCLUSIONS

Opening and closing of fault zones to hydrocarbon migration are controlled by complex factors and cannot be accurately evaluated on the basis of a single factor. A parameter that incorporates several factors is needed to better characterize fault opening and closing. The cumulative opening or closing behavior of a point on a fault plane to hydrocarbon migration can be established by the presence or absence of hydrocarbons in the reservoirs in the footwall and hanging wall. The concept and model of fault-connectivity probability proposed in this study incorporate fluid pressure, stress normal to the fault plane, and SGR and can be used to quantitatively characterize fault opening and closing. The method is effective in evaluating the history of fault opening and closing to hydrocarbon migration in the CSFZ of Dagang field, Bohai Bay Basin. It improves the characterization of fault zones as potential hydrocarbon migration pathways and is a step further in establishing the complete framework of hydrocarbon carrier systems in petroliferous basins.

REFERENCES CITED

Alexander, L. L., and J. W. Handschy, 1998, Fluid flow in a faulted reservoir system: Fault trap analysis for the Block 330 field in Eugene Island, south addition, offshore Louisiana: AAPG Bulletin, v. 82, p. 387–411.

Allen, U. S., 1989, Model for hydrocarbon migration and entrapment within faulted structures: AAPG Bulletin, v. 73, p. 803–811.

Anderson, R., P. Flemings, S. Losh, J. Austin, and R. Woodhams, 1994, Gulf of Mexico growth fault drilled, seen as oil, gas migration pathway: Oil & Gas Journal, v. 92 (June 6, 1994), p. 97–103.

Antonelini, M., and A. Aydin, 1994, Effect of faulting on fluid flow in porous sandstones: Petro-physical properties: AAPG Bulletin, v. 78, p. 355–377.

Berg, R. R., and A. H. Alana, 1995, Sealing properties of Tertiary growth faults, Texas Gulf Coast: AAPG Bulletin, v. 79, p. 375–393.

Bouvier, J. D., C. H. Kaars-Sijpesteijn, D. F. Kluesner, C. C. Onyejekwe, and R. C. Van der Pal, 1989, Three-dimensional seismic interpretation and fault sealing investigations, Nun River field, Nigeria: AAPG Bulletin, v. 73, p. 1397–1414.

Bruhn, R. L., W. T. Parry, W. A. Yonkee, and T. Thompson, 1994, Fracturing and hydrothermal alteration in normal fault zones: Pure and Applied Geophysics, v. 142, p. 609–644, doi:10.1007/BF00876057.

Byerlee, J. D., 1993, Model for episodic flow of high pressure water in fault zones before earthquakes: Geology, v. 21, p. 303–306, doi:10.1130/0091-7613(1993)021<0303:MFEFOH>2.3.CO;2.

Caine, J. S., J. P. Evans, and C. B. Forster, 1996, Fault zone architecture and permeability structure: Geology, v. 24, p. 1025–1028, doi:10.1130/0091-7613(1996)024<1025:FZAAPS>2.3.CO;2.

Chester, F. M., and J. M. Logan, 1986, Implications for mechanical properties of brittle faults from observations of the Punchbowl fault zone, California: Pure and Applied Geophysics, v. 124, p. 79–106, doi:10.1007/BF00875720.

Chester, F. M., J. P. Evans, and R. L. Biegel, 1993, Internal structure and weakening mechanisms of the San Andreas fault: Journal of Geophysical Research, v. 98, p. 771–786, doi:10.1029/92JB01866.

Childs, C., A. Nicola, J. J. Walsha, and J. Wattersonc, 2003, The growth and propagation of synsedimentary faults: Journal of Structural Geology, v. 25, p. 633–648, doi:10.1016/S0191-8141(02)00054-8.

Clausen, J. A., R. H. Gabrielsen, E. Johnsen, and J. A. Korstgård, 2003, Fault architecture and clay smear distribution: Examples from field studies and drained ring-shear experiments: Norwegian Journal of Geology, v. 83, p. 131–146.

Engelder, J. T., 1979, Cataclasis and the generation of fault gouge: Geological Society of American Bulletin, v. 85, p. 1515–1522, doi:10.1130/0016-7606(1974)85<1515:CATGOF>2.0.CO;2.

Forster, C. B., and J. P. Evans, 1991, Hydrogeology of thrust faults and crystalline thrust sheets: Results of combined field and modeling studies: Geophysical Research Letters, v. 18, p. 979–982, doi:10.1029/91GL00950.

Fowler, W. A. J., 1970, Pressures, hydrocarbon accumulation, and salinities—Chocolate Bayou field, Brazoria County, Texas: Journal of Petroleum Technology, v. 22, p. 411–423.

Gibson, R. G., 1994, Fault-zone seals in siliclastic strata of the Columbus Basin, offshore Trinidad: AAPG Bulletin, v. 78, p. 1372–1385.

Gratier, J. P., P. Favreau, F. Renard, and E. Pili, 2002, Fluid pressure evolution during the earthquake cycle controlled by fluid flow and pressure solution crack sealing: Earth Planets Space, v. 54, p. 1139–1146.

Haney, M. H., R. Snieder, J. Sheiman, and S. Losh, 2005, A moving fluid pulse in a fault zone: Nature, v. 437, p. 46, doi:10.1038/437046a.

Harding, T. P., and A. C. Tuminas, 1989, Structural interpretation of hydrocarbon traps sealed by basement normal fault blocks at stable flank of fore-deep basins and at rift basins: AAPG Bulletin, v. 7, p. 812–840.

Hasegawa, S., R. Sorkhabi, S. Iwanaga, N. Sakuyama, and O. A. Mahmud, 2005, Fault-seal analysis in the Temana field, offshore Sarawak, and Malaysia, *in* R. Sorkhabi and Y. Tsuji, eds., Faults, fluid flow, and petroleum traps: AAPG Memoir 85, p. 43–58.

Hooper, E. C. D., 1991, Fluid migration along growth faults in compacting sediments: Journal of Petroleum Geology, v. 14, p. 161–180, doi:10.1111/j.1747-5457.1991.tb00360.x.

Hubbert, M. K., 1953, Entrapment of petroleum under hydrodynamic conditions: AAPG Bulletin, v. 37, p. 1954–2026.

Hubbert, M. K., and W. W. Rubey, 1959, Role of fluid pressure in mechanics of overthrust faulting: Bulletin of the Geological Society of America, v. 70, p. 115–205, doi:10.1130/0016-7606(1959)70[115:ROFPIM]2.0.CO;2.

Jaeger, J. C., and G. Cook, 1979, Fundamentals of rock mechanics: London, Chapman and Hall, 593 p.

Jourde, H., E. A. Flodin, A. Aydin, L. J. Durlofski, and X. H. Wen, 2002, Computing permeability of fault zones in eolian sandstone from outcrop measurements: AAPG Bulletin, v. 86, p. 1187–1200.

Kachi, T., H. Yamada, K. Yasuhara, M. Fujimoto, S. Hasegawa, S. Iwanaga, and R. Sorkhabi, 2005, Fault-seal analysis applied to the Erawan gas-condensate field in the Gulf of Thailand, *in* R. Sorkhabi and Y. Tsuji, eds., Faults, fluid flow, and petroleum traps: AAPG Memoir 85, p. 59–78.

Karlsen, D. A., and J. E. Skeie, 2006, Petroleum migration, faults and overpressure: Calibrating basin modeling using petroleum in traps—A review: Journal of Petroleum Geology, v. 29, p. 227–256, doi:10.1111/j.1747-5457.2006.00227.x.

Knipe, R. J., 1989, Deformation mechanisms—Recognition from natural tectonites: Journal of Structural Geology, v. 11, p. 127–146, doi:10.1016/0191-8141(89)90039-4.

Knipe, R. J., 1992, Faulting processes and fault seal, *in* R. M. Larsen, H. Brekke, B. T. Larsen, and E. Talleras, eds., Structural and tectonic modeling and its application to petroleum geology: Amsterdam, Elsevier, p. 325–342.

Knipe, R. J., 1997, Juxtaposition and seal diagrams to help analyze fault seals in hydrocarbon reservoirs: AAPG Bulletin, v. 81, p. 187–195, doi:10.1306/3B05B376-172A-11D7-8645000102C1865D.

Knott, S. D., 1993, Fault seal analysis in the North Sea: AAPG Bulletin, v. 77, p. 778–792.

Li, S. T., F. X. Lu, and C. S. Lin, 1998, Evolution of Mesozoic and Cenozoic basins in east China and their geodynamic background (in Chinese): Wuhan, China University of Geosciences Press, 238 p.

Lindsay, N. G., F. C. Murphy, J. J. Walsh, and J. Watterson, 1993, Outcrop studies of shale smears on fault surfaces: International Association of Sedimentologists Special Publication 15, p. 113–123.

Lockner, D., and J. Byerlee, 1995, An earthquake instability model based on faults containing high fluid-pressure compartments: Pure and Applied Geophysics, v. 145, p. 718–745.

Lu, Y. F., and F. J. Ma, 2002, Controlling factors and classification of fault seal (in Chinese): Journal of Jilin University (Earth Science Edition), v. 33, p. 163–167.

Luo, X. R., 1999, Mathematical modeling of temperature-pressure transient variation in opening fractures and sedimentary formations (in Chinese): Oil and Gas Geology, v. 20, p. 1–6.

Luo, X. R., 2004, Quantitative analysis on overpressuring mechanism resulted from tectonic stress (in Chinese): Chinese Journal of Geophysics, v. 47, p. 484–493.

Luo, X. R., J. H. Yang, and Z. F. Wang, 2000, The overpressuring mechanisms in aquifers and pressure prediction in basins (in Chinese): Geological Review, v. 46, p. 6–10.

Luo, X. R., W. L. Dong, J. H. Yang, and W. Yang, 2003, Overpressuring mechanisms in the Yinggehai Basin, South China Sea: AAPG Bulletin, v. 87, p. 629–645, doi:10.1306/10170201045.

Magara, K., 1978, Compaction and fluid migration, practical petroleum geology: Amsterdam, Elsevier, 319 p.

Ortoleva, P. J., 1994, Basin compartments and seals: AAPG Memoir 61, p. 1–477

Perkins, H., 1961, Fault closure-type fields, southeast Louisiana: Gulf Coast Association Geological Society Transactions, v. 11, p. 203–212.

Qu, G. S., H. Zhang, and H. Ye, 1993, The principal stress orientations by the borehole breakouts in Huanghua depression (in Chinese): North China Earthquake Sciences, v. 11, p. 9–18.

Roberts, S. J., and J. A. Nunn, 1995, Episodic fluid expulsion from geopressured sediments: Marine and Petroleum Geology, v. 12, p. 195–202, doi:10.1016/0264-8172(95)92839-O.

Schneider, F., S. Wolf, I. Faille, and D. Pot, 2000, A 3-D basin model for hydrocarbon potential evaluation: Application to Congo offshore: Oil and Gas Science and Technology-Review Institut Francais du Pétrole, v. 55, p. 3–13, doi:10.2516/ogst:2000001.

Selley, R. C., 1998, Elements of petroleum geology: New York, Academic Press, 470 p.

Sibson, R. H., 1981, Fluid flow accompanying faulting: Field evidence and models, *in* D. W. Simpson and P. G. Richards, eds., Earthquake prediction—An international review: American Geophysical Union Monograph, Maurice Ewing Series 4, p. 593–603.

Sibson, R. H., J. Mc. M. Moore, and A. H. Rankin, 1975, Seismic pumping—A hydrothermal fluid transport mechanism: Journal of the Geological Society, v. 131, p. 653–659, doi:10.1144/gsjgs.131.6.0653.

Smith, D. A., 1966, Theoretical considerations of sealing and non-sealing faults: AAPG Bulletin, v. 50, p. 363–374.

Smith, L., C. B. Forster, and J. P. Evans, 1990, Interaction of fault zones, fluid flow, and heat transfer at the basin scale, *in* S. P. Neuman and I. Neretnieks, eds., Hydrogeology of low permeability environments: Hydrogeology Selected Papers 2, p. 41–67.

Sorkhabi, R., and Y. Tsuji, 2005, The place of faults in petroleum traps, *in* R. Sorkhabi and Y. Tsuji, eds., Faults, fluid flow, and petroleum traps: AAPG Memoir 85, p. 1–31.

Ungerer, P., J. Burrus, B. Doligez, Y. Chenet, and F. Bessis, 1990, Basin evaluation by integrated two-dimensional modeling of heat transfer, fluid flow, hydrocarbon generation, and migration: AAPG Bulletin, v. 74, p. 309–335.

Vasseur, G., and L. Demongodin, 1995, Convective heat transfer in sedimentary basins: Basin Research, v. 7, p. 67–79, doi:10.1111/j.1365-2117.1995.tb00096.x.

Wang, G. Q., J. F. Qi, and Y. F. Yue, 2003, Formation and evolution of the Cenozoic tectonics within and surrounding the Qikou sag (in Chinese): Chinese Journal of Geology, v. 38, p. 230–240.

Wang, G. Z., S. Q. Yuan, and L. Xiao, 2006, Source conditions in Chengbei fault-step area and analysis on hydrocarbon migration (in Chinese): Journal of Oil and Gas Technology, v. 28, p. 200–203.

Weber, K. J., G. Mandl, F. Pilaar, F. Lehner, and R. G. Precious, 1978, The role of faults in hydrocarbon migration and trapping in Nigerian growth fault structures: 10th Annual Offshore Technology Conference Proceeding, v. 4, p. 2643–2653.

Xie, X., S. T. Li, W. L. Dong, and Z. L. Hu, 2001, Evidence for hot fluid flow along faults near diapiric structure of the Yinggehai Basin, South China Sea: Marine and Petroleum Geology, v. 8, p. 715–728, doi:10.1016/S0264-8172(01)00024-1.

Xu, J. W., 1980, Lateral shifting of the Tanlu fault and its geological significance: Proceedings of the Symposium of International Exchanges for Earth Sciences, p. 129–142.

Xu, Z. H., X. Wu, S. F. Qi, and D. N. Zhang, 1996, Characteristics of contemporary tectonic stress in Beidagang oil field and its vicinity (in Chinese): Petroleum Exploration and Development, v. 23, p. 78–81.

Yang, Y., and T. Xu, 2004, Hydrocarbon habitat of the offshore Bohai Basin, China: Marine and Petroleum Geology, v. 21, p. 691–708, doi:10.1016/j.marpetgeo.2004.03.008.

Yielding, G., B. Freeman, and D. T. Needham, 1997, Quantitative fault seal prediction: AAPG Bulletin, v. 81, p. 897–917.

Yielding, G., J. A. Øverland, and G. Byberg, 1999, Characterization of fault zones for reservoir modeling: An example from the Gullfaks field, northern North Sea: AAPG Bulletin, v. 83, p. 925–951.

Yu, C. H., J. Q. Su, S. Q. Yuan, D. J. Sheng, R. M. Duan, and L. K. Zhang, 2006, Analysis of main control factors on oil and gas accumulation in Chengbei fault-step area, Dagang oil field (in Chinese): Sedimentary Geology and Tethyan Geology, v. 26, p. 88–92.

Yuan, S. Q., X. L. Ding, J. Q. Su, and S. F. Zhang, 2004, The research on forming conditions of reservoir in Chengbei step-fault zone, Dagang oil field (in Chinese): Journal of Jianghan Petroleum Institute, v. 26, p. 8–9.

Zhang, L. K., X. R. Luo, Q. J. Liao, J. Q. Yuan, D. J. Sheng, D. Q. Xiao, Z. M. Wang, and C. H. Yu, 2007, Quantitative evaluation of fault sealing property with fault connectivity probabilistic method (in Chinese): Oil and Gas Geology, v. 28, p. 181–191.

Zhou, X. G., B. S. Sun, C. X. Tan, H. B. Sun, R. Z. Zheng, and C. X. Ma, 2000, State of current geo-stress and effect of fault sealing (in Chinese): Petroleum Exploration and Development, v. 27, p. 127–131.