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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.

The Place of Faults in Petroleum Traps

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"The incompleteness of available data in most geological studies traps some geologists."

Orlo E. Childs in *Place of tectonic concepts in geological thinking* (AAPG Memoir 2, 1963, p. 1)

"Although the precise role of faults has never been systematically defined, much has been written that touches on the subject. One thing is certain: we need not try to avoid them."

Frederick G. Clapp in *The role of geologic structure in the accu mulation of petroleum* (Structure of typical American oil fields II, 1929, p. 686)

ABSTRACT

Ever since Frederick Clapp included fault structures as significant petroleum traps in his landmark paper in 1910, the myriad function of faults in petroleum migration and accumulation in sedimentary basins has drawn increasing attention. Fault analyses in petroleum traps have grown along two distinct and successive lines of thought: (1) fault closures and (2) fault-rock seals. Through most of the last century, geometric closure of fault traps and reservoir seal juxtaposition by faults were the focus of research and industrial application. These research and applications were made as structural geology developed quantitative methods for geometric and kinematic analyses of sedimentary basins, and plate tectonics offered a unified tool to correlate faults and basins on the basis of the nature of plate boundaries to produce stress. Over the last two decades, compartmentalization of reservoirs by fault seals has been more intensively investigated as three-dimensional seismic images better resolve

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DOI:10.1306/1033713M853128

fault structures. Geometric characterization of fault architecture, identification of various sealing processes in fault zones, and quantitative appraisal of petrophysical properties of fault rocks have significantly advanced in recent decades.

Fault-seal analyses have shifted from two-dimensional fault juxtapositions to three-dimensional models encompassing fault surfaces, fault transmissibility, and juxtaposed reservoir units. Current methodologies for fault-seal assessment mostly address normal faults in clastic reservoirs. Fault sealing processes in thrust faults and in carbonate reservoirs represent important blind spots in our knowledge. Shale smear has been effectively applied for sealing assessment of syndepositional faults in sandstone-claystone successions. However, fault-seal analyses based merely on shale smear ignore other important sealing processes, notably cataclasis and cementation in fault zones. During their active stages, faults are conduits of subsurface fluids, irrespective of any sealing mechanism that operated before fault rupture. Therefore, a comprehensive fault-seal assessment needs to be a four-dimensional model integrating fault motions, fault-zone processes, and fluid flow. This remains a major challenge. However, integration of in-situ fault stress analysis and fault-seal analysis has provided a technological breakthrough. The realization that fault rocks are low-permeability and high-capillarity features in sedimentary basins has given an economic impetus for exploration of fault traps. The shift from modeling of single-phase fluid flow to multiphase or even mixed-phase fluid flow along and across fault zones will be of more value to these exploration efforts. Recent studies have transformed the old polarized view of faults as either leaks or seals into realistic notions of more complex fault-fluid flow behavior. Current shortcomings in fault-seal assessment are largely caused by the scarcity of detailed data and the need for robust calibration of numerical models. This implies that empirical data will form the cornerstone of near-future advances in fault-seal methodologies.

INTRODUCTION

The term "trap" was first used in 19th century courts in the United States on legal grounds that petroleum, like wild animals, has a "fugacious" nature and becomes property of the person on whose land they were trapped (Dott and Reynolds, 1969, chapter 13). Over the past century, the notion of trap has been associated separately or jointly with oil location, reservoir, closure, or seal. In a modern sense (North, 1985; Biddle and Wielchowsky, 1994; Vincelette et al., 1999), a petroleum trap has three components: (1) a three-dimensional (3-D) geometric closure, (2) seal rocks (including a cap rock or top seal, a lateral or side seal, and also possibly a bottom seal) with sufficient capillary pressure to overcome the buoyancy pressure of hydrocarbons, and (3) a reservoir rock with sufficient porosity to store hydrocarbons if charged from a source rock and with sufficient permeability to yield hydrocarbons if drilled (Figure 1). Ideally, the physical properties of subsurface fluids should also be added to this list as a fourth component (Hubbert, 1953; Schowalter, 1979; England et al., 1987; Watts, 1987; Sales, 1993; Vincelette et al., 1999) because "traps are not simple receivers of fluid into otherwise empty space; they are focal points of active fluid exchange" (North, 1985, p. 254). However, in petroleum exploration, detailed knowledge of subsurface fluids is the last data to become available for trap evaluation; hence, the famous phrase attributed to W. C. Finch: "A trap is a trap, whether or not it has a mouse in it" (Rittenhouse, 1972, p. 13).

Petroleum basins are structurally deformed sedimentary basins, in which faults of various sizes and styles occur. Faults also occur in all types of structural traps. Even "a fold trap is seldom completely free from faulting" (Levorsen, 1967, p. 242) and "in very many anticlinal traps the fundamental structure is a fault, not a fold" (North, 1985, p. 253). Much attention has recently been given to these forced folds (Cosgrove and Ameen, 2000) or fault-related folds (Anastasio et al., 1997; Wilkerson et al., 2002). Faults are not passive features; they are significant factors in impeding or enhancing subsurface fluid flow. Faults are associated with all elements and processes of the petroleum system. Figure 2 depicts the myriad functions that faults have in petroleum systems and basins.

The function of faults in petroleum traps may be viewed from two perspectives: (1) fault closure traps and (2) fault-rock seals. These roughly correspond to the juxtaposition faults and membrane-sealing faults of Watts (1987) and to the passive and active fault sealing

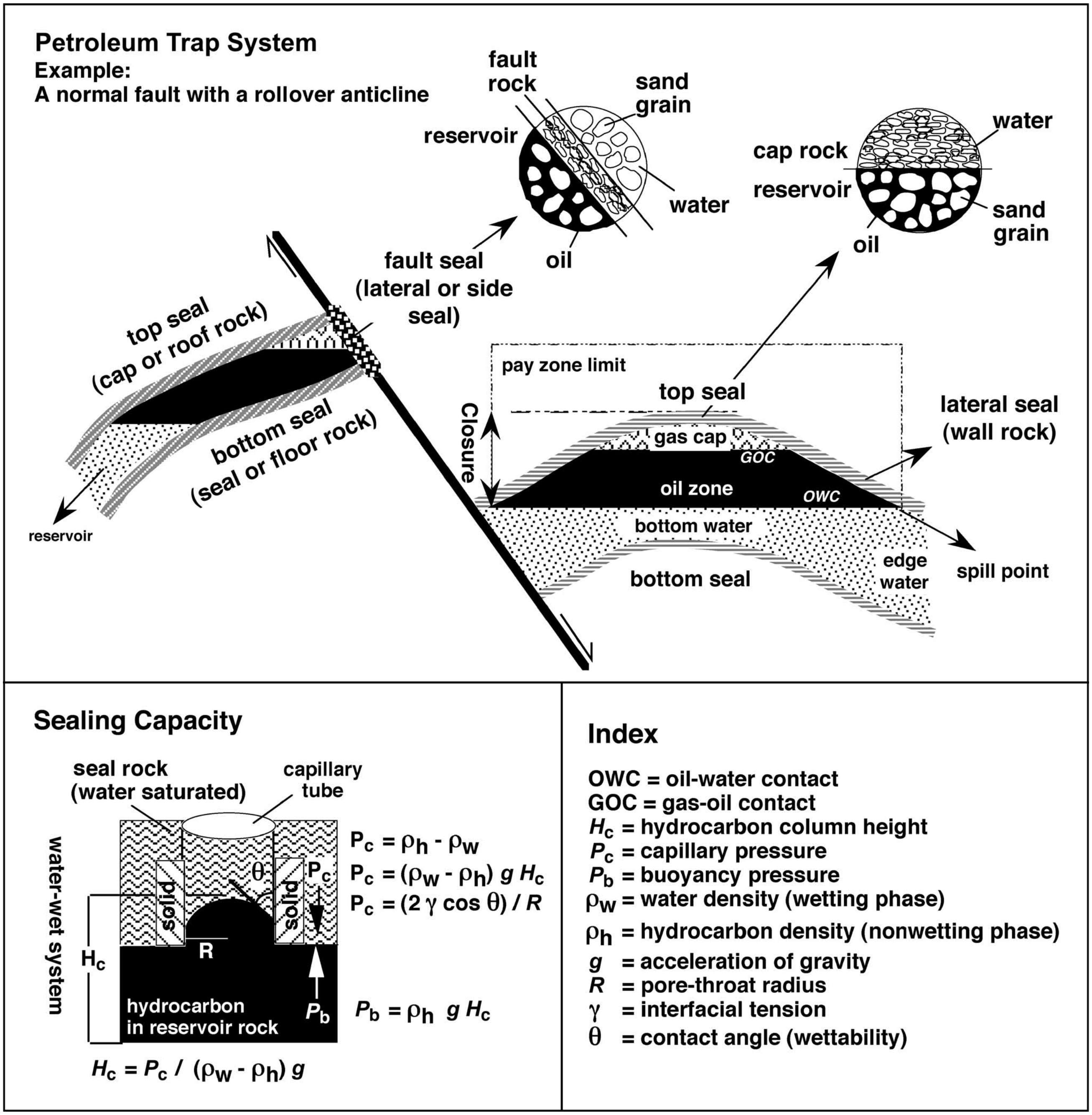

FIGURE 1. Components of a structural trap system and a comparison of a fault trap with an anticlinal trap (a rollover anticline associated with the same normal fault). The sealing capacity of both cap rock (top seal) and fault seal (side seal) is controlled by the capillary pressure of the rock as described quantitatively in the lower diagram. Petroleum is accumulated when the capillary pressure of seal rock is equal to or exceeds the buoyancy pressure of petroleum in the reservoir (Schowalter, 1979; Watts, 1987).

of Weber (1997), respectively. Our usage of "fault closure trap," however, refers not only to lithological juxtaposition across a fault but also to the structural configuration and geometric style of a fault trap. Fault-rock seals result from mechanical and chemical changes that take place along the fault plane and in fault zones as a result of faulting processes; these changes may make the fault plane or zone a barrier to hydrocarbon flow.

The purpose of this chapter is to set the stage for this AAPG Memoir by outlining the historical development of concepts and methods in fault-trap analysis and briefly discussing the functions of faults in petroleum basins at the trap-reservoir scale. In our review, we have focused on fault closures in petroleum traps and petrophysical properties of fault-seal rocks. In preparing this introductory chapter for the volume, we have

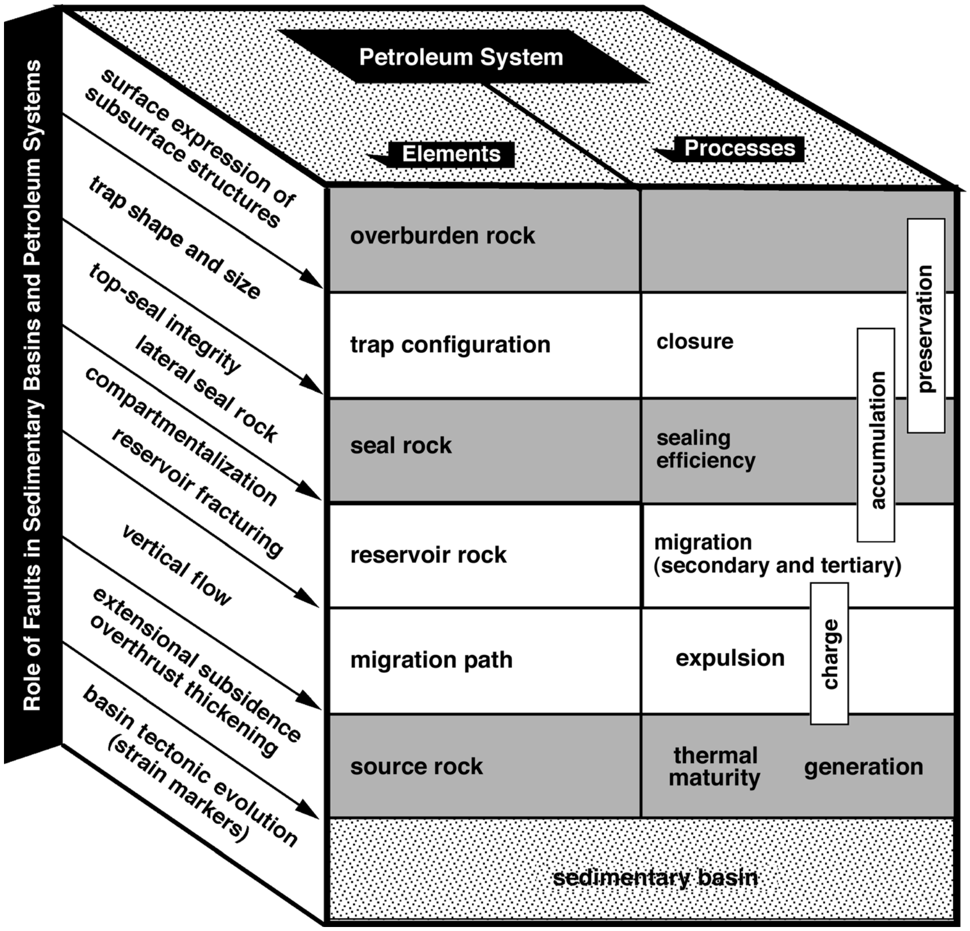

FIGURE 2. A schematic presentation of various elements and processes involved in the petroleum system approach (based on Magoon and Dow, 1994, with some modifications to accommodate the prospect risk evaluation methodologies, e.g., Rose, 2001) and the role of fault analysis in each component.

addressed petroleum geoscientists (instead of fault-seal experts) so that it has a broad readership. This is not an exhaustive review of the subject and "the reader must accept as an apology the increasing difficulty of keeping pace with rapid progress of geology" (Lyell, 1842, p. xiii).

HISTORICAL BACKGROUND

In the second half of the 19th century, anticlines were considered to be major petroleum traps, and faults were commonly ignored. Clapp (1929, p. 686) referred to this period as follows: "The role of faults, although still perhaps imperfectly known, was sadly misunderstood for half a century after the discovery of oil in the United States; and operators, believing faults to be dangerous phenomena, tried to avoid them. The popular superstition against faults was so strong that for years it permeated the geological fraternity, and many government and private sectors recommended the avoidance of faulted structures. The absurdity, as we understand it to be, was commonly expressed in the once-familiar words: 'The country appears too much broken up.'"

Although there is truth in Clapp's remarks, we should not totally blame the oil explorationists of his age given the state of drilling technology and subsurface structural knowledge in the late 19th and early 20th centuries.

The second period began in the first decade of the 20th century, with Clapp's pioneering efforts to classify petroleum traps on the basis of various structural elements, including a distinct category for faults (Clapp, 1910, 1917). During this period, fault closure and juxtaposition traps were identified in the field. A milestone was the publication of *Structure of Typical American Oil Fields* (two volumes, edited by Sidney Powers, 1929), which was the proceedings volume of the "Symposium on the Relation of Oil Accumulation to Structure" held at the AAPG Annual Meeting in Tulsa in March 1927. This was followed by a third volume (edited by J. V. Howell) in 1948, also resulting from a symposium under the same title.

During the second period, several attempts were made to classify petroleum traps, and faults were commonly included in these classifications (Clapp, 1910, 1917; Wilson, 1934, 1942; Heald, 1940; Prison, 1945; Wilhelm, 1945; Levorsen, 1967). The increasing attention to the function of fault structures in petroleum basins during this second period is evident in the papers presented at the Fourth Annual Meeting of the AAPG, New York, March 28–31, 1955, which were later published in a volume of more than 1000 pages, *Habitat of Oil* (Weeks, 1958). It contained 55 papers covering many petroliferous fields around the world, and a cursory review of the volume shows that structural features appear prominent in most of these papers. The editor of the volume, Lewis Weeks, cited 18 questions in his lead article that were important for understanding the "habitat of oil and some factors that control it" and among them was this: "... whether or not faults normally act as conduits or as barriers to migration?"

Despite a few allusions from exploration geologists to the importance of fault seals (McKnight, 1940; Wilhelm, 1945; Willis, 1961), the second stage paid more attention to fault style and juxtaposition (but little attention to fault-rock seals). This latter aspect was highlighted in the third period, which can be traced back to the work of Perkins (1961) and Smith (1966) in the Louisiana fields. Perkins (1961) identified flowage shale barrier (later called shale smear by Weber and Daukoru, 1975) as a fault-sealing mechanism in addition to fault juxtaposition and reverse drag (rollover anticline). Smith (1966) applied the theory of capillary pressure to fault-zone material. Works published by Shell geologists on sealing faults in the Niger Delta (Weber and Daukoru, 1975; Weber et al., 1978) drew attention to the importance of shale smear in growth faults. Pittman's (1981, but first presented at the AAPG Annual Meeting in 1978) work on fault-rock fabrics and petrophysical characteristics was also among the pioneering efforts of the third period. Smith (1980) and Watts (1987, but first presented at the AAPG Annual Meeting in 1985) not only popularized the terms "sealing faults" and "fault seals" with the titles of their articles but also offered elegant theoretical frameworks for fault-seal analysis.

Despite these efforts, fault-sealing analysis in the 1980s was in its infancy (some may argue that it still is). In his 400-page synthesis of knowledge of petroleum traps prior to 1990, Jenyon (1990) devoted only half a page and one figure to fault sealing (with references to the works of Smith and Watts). The past two decades have witnessed a revolutionary development of fault-seal studies both in the academe and in the petroleum industry. As a result of these studies, an appreciable amount of knowledge has been gained on fault-sealing processes and hydraulic properties of faults in sedimentary basins. The Appendix at the end of this chapter chronicles some of these recent developments in fault-seal studies.

FAULTS IN THE CLASSIFICATION OF PETROLEUM TRAPS

Various classification schemes of petroleum traps indicate how the functions of faults have been viewed by different workers, based on field experiences over time. An inherent danger always exists in these classifications because "almost all geological structures, if viewed in enough detail, have unique geometries and histories" (Harding and Lowell, 1979, p. 1016). Nevertheless, as Gould (1989, p. 98) once remarked, "classifications are theories about the basis of natural order, not dull catalogues compiled only to avoid chaos." Classifications and generalizations provide conceptual tools for comparison, analysis, and prediction, which are helpful in the exploration of sedimentary basins where subsurface structures are not directly observed. Therefore, by tracing various schemes of trap classification that have been proposed over the past century, we also get a sense of the progression of theories on the place of faults in petroleum traps and an evaluation of the current theories against their predecessors.

Table 1a presents several trap classifications proposed in the first half of the 20th century (Clapp, 1917; Wilson, 1934, 1942; Heald, 1940; Prison, 1945; Wilhelm, 1945), and Table 1b shows major trap classifications proposed by various workers in the second half of the 20th century (Levorsen, 1967; Harding and Lowell, 1979; North, 1985; Milton and Bertram, 1992; Biddle and Wielchowsky, 1994). The advent of the plate tectonic theory in the 1960s provided a unified framework to correlate sedimentary basins (e.g., Dickinson, 1974) and fault traps (e.g., Harding and Lowell, 1979) on the basis of the nature of plate boundaries as stress engines. The most recent (and a very comprehensive) trap classification has been offered by Vincelette et al. (1999), who have adopted hierarchical levels (system, regime, class, subclass, style, superfamily, and variety) similar to the biological classification of organisms. Figure 3 schematically shows the Vincelette et al.'s (1999) classification of fault-dominated traps, with some modifications in the wording and presentation of details.

A review of petroleum trap classifications shows that researchers have adopted one or a combination of four basic schemes, i.e., basin tectonic, morphological, genetic, and fluid dynamic schemes, and as such, faults have been viewed in these four schools of thought briefly described below:

1) Basin tectonic schemes (Harding and Lowell, 1979; Harding and Tuminas, 1989; Vincelette et al., 1999), in which the tectonic habitat and style of structures on a basin scale is the main component of trap classification. For example, thick-skinned (basement-involved) tectonics vs. thin-skinned (basement-cover-detached) tectonics is the fundamental factor in the trap classification proposed by Harding and Lowell (1979) (Table 1b) and has been followed by Bally (1983) and Lowell (2002).
2) Morphological schemes, in which the shape and spatial relations of trap-forming features are primarily considered. For Wilhelm (1945) and North (1985), the presence or absence of a convex shape in the trap is a fundamental classifying factor. Milton and Bertram (1992) consider the presence of single-seal vs. polyseal traps and the conformable vs. unconformable (tectonic or erosional) relations of the reservoirs to top-, bottom-, and side-sealing surfaces (Table 1b).

Table 1a. Place of faults in the classification schemes of structural traps during the first half of the 20th century.

Clapp (1910, 1917, 1929)	Wilson (1934)	Heald (1940)	Prison (1945)	Wilhelm (1945)
I. Anticlinal structures II. Synclinal structures III. Homoclinal structures IV. Domes V. Unconformities VI. Lenticular sands VII. Rock cavities VIII. Faulting structures a. on the upthrown side b. on the downthrown side c. overthrusts d. horsts	A. Reservoirs closed by deformation of strata A.1. closed by folding A.2. offset by faulting A.3. combined folding and faulting A.4. cutting by salt or igneous intrusions A.5. developed in joint fissures and crush zones B. Reservoirs closed by porosity variations B.1. lenses in sandstones B.2. lenses in limestones and dolomites B.3. lenses in igneous and metamorphic rocks B.4. truncated and sealed strata C. Reservoirs closed by combination of folding and varying porosity D. Reservoirs closed by combination of faulting and varying porosity	I. Structural traps a. synclines b. anticlines c. salt structures d. hydrodynamic e. fault II. Varying permeability traps a. caused by sedimentation b. caused by groundwater c. truncation and sealing	I. Petrologic (stratigraphic) traps II. Combination petrologic and structural traps III. Structural traps III.1. closure by folding III.2. closure by changes in dip III.3. closure by faulting a. normal fault b. reverse fault c. graben d. horst III.4. closure by folding and faulting	A. Convex trap reservoirs B. Permeability trap reservoirs C. Pinch-out trap reservoirs D. Fault trap reservoirs a. single fault segment reservoirs b. parallel fault-block reservoirs c. fault-wedge (intersecting faults) reservoirs F. Piercement trap reservoirs

3) Genetic schemes, in which the origin and formation of closure is the main consideration. Levorsen's (1967) threefold classification of traps as structural, stratigraphic, and combination traps is a textbook example of this scheme. For fault traps, the genetic classifications (Prison, 1945; Biddle and Wielchowsky, 1994; Jenyon, 1990; Vincelette et al., 1999) have commonly followed the slip direction of fault planes, i.e., normal, reverse, wrench, or oblique-slip faults, which, in turn, arise from distinct stress regimes (i.e., tension, compression, couple and shear, and torsion and rotation), acting on faults.
4) Fluid dynamic schemes (Hubbert, 1953; Gussow, 1954; England et al., 1987; Sales, 1993, 1997; Bradley and Powley, 1994; Heum, 1996; Bjørkum et al., 1998; Brown, 2003), in which the migration of hydrocarbons through the basin and the dynamic interactions of hydrocarbons with sealing features are considered.

Sales (1993, 1997) has worked out a classification of petroleum traps as gas-dominated, oil-dominated, and gas-and-oil-dominated classes, considering the multiphase fluid flow in the basin (as initially discussed by Gussow, 1954) in relation to the structural spillpoint and sealing capacity of a trap.

Bradley and Powley (1994) have distinguished between capillary seal and pressure seal. The former is controlled by a capillary tube (interconnected pore-throat size and surface tension between the wetting fluid and hydrocarbon) and prevents the migration of hydrocarbon but allows brine flow. The latter is characterized by effectively closed pore throats and virtually zero permeability, thus inhibiting the movement of both hydrocarbons and brine. Capillary seals fail when the buoyancy pressure of hydrocarbons in the reservoir exceeds the capillary pressure of seal rock; pressure seals fail when the internal fluid pressure of seal rock exceeds its fracture pressure. Pressure seals are thought to enclose abnormally pressured reservoirs, although the processes responsible for the formation of pressure seals are poorly known.

Heum (1996), who first used the term "fluid dynamic classification," has suggested five different components (capillary seal, pressure seal, hydraulic resistance seal, water-derived leakage, and hydraulic-fracturing

Table 1b. Place of faults in the classification schemes of petroleum traps during the second half of the 20th century.

Levorsen (1967)	Biddle and Wielchowsky (1994) Modern Version of Levorsen (1967)	Harding and Lowell (1979) (Based on Structural Styles and Plate Tectonic Habitat)		North (1985)	Milton and Bertram (1992) (Based on Relation of Sealing Surfaces with Top Seals)	
I. Structural traps a. folding b. faulting (both normal and reverse faults) c. fracturing d. salt intrusion e. combination	I. Structural traps IA. Fold dominated Fault related (a) fault bend, (b) fault propagation (c) fault drag, (d) fault drape Fault-free (e) lift off, (f) chevron/kink band (g) diapir, (h) differential compaction IB. Fault dominated (a) basement-involved normal fault (b) detached listric normal fault (c) reverse fault with fault-bend fold (d) reverse fault with ductile deformation	Basement-cover detached styles	1. Decollement fold-and-thrust (stress: compression habitat: convergent transpression) 2. Detached normal faults (stress: extension habitat: passive margins) 3. Salt and shale structures (stress: density contrast habitat: divergent)	I. Convex traps a. buckle- and thrust-fold traps (tangetial movements) b. bending fold traps (vertical movements) c. traps of immobile convexity (buried hills, reefs, drape folding)	One-seal closures	Code C drape anticline, fold anticline, depositional mound [sealing surface conformable with top seal] Code U burried hill, erosional remnant [sealing surface unconformable with top seal] Code CT high-side fault closure [sealing surface conformable + tectonic relation with sealing surface] Code UT high-side fault closure [sealing surface unconformable + tectonic relation with top seal]
II. Stratigraphic traps a. primary (lenses of clastic and igneous rocks) b. secondary (lenses of biochemical rocks)	IC. Piercement ID. Combination fold and fault II. Stratigraphic traps IIA. primary (depositional) IIB. unconformities IIIC. secondary	Basement-involved styles	1. Wrench fault (stress: couple habitat: transform convergent) 2. Basement thrust blocks (stress: compression habitat: convergent transpression) 3. Extensional faults (stress: extension habitat: divergent transtension) 4. Basement warps and arches (stress: thermal, isostasy habitat: plate interiors)	II. Nonconvex traps a. depositional wedgeout b. erosional wedgeout c. isolated (Lenticular) wedgeout d. permeability pinch-out e. fault cutoff	Poly-seal closures	Code U/C subcrop trap [sealing surface unconformable with top seal and conformable with bottom seal] Code C/U onlap trap, incised-valley fill, lowstand wedge trap [sealing surface conformable with top seal and unconformable with bottom seal] Code CT/C overfull high-side fault closure [sealing surface conformable + tectonic relation with top seal and conformable with bottom seal] Code C/T low-side fault closure [sealing surface conformable relation with top seal and tectonic with bottom seal] Code C/F shale-out, diagenetic seal, fault-gouge seal, tar seal [sealing surface conformable relation with top seal and facies change with bottom seal]
III. Combination traps (including salt domes)	III. Combination traps IV. Hydrodynamic traps					

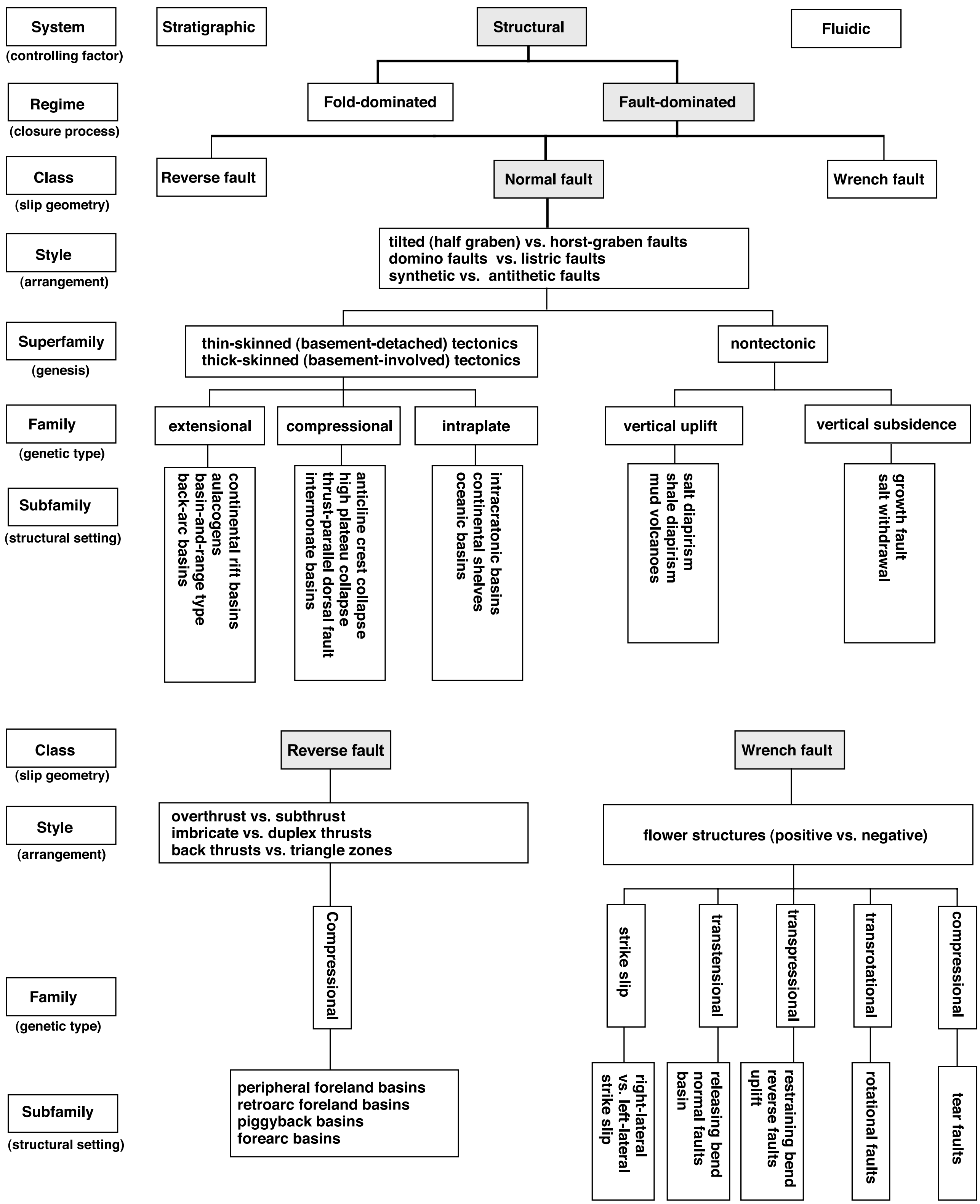

FIGURE 3. A classification of fault traps according to the hierarchical scheme proposed by Vincelette et al. (1999), with more details on the styles of fault structures and the basin types in which the fault structures occur.

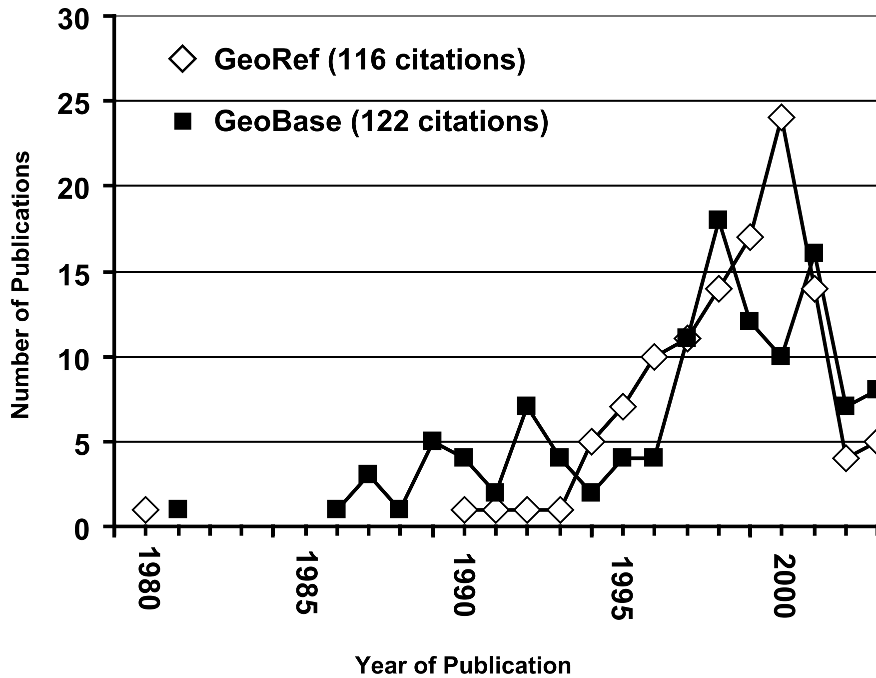

FIGURE 4. A histogram of publications (articles and conference presentations) on fault seal in the reference databases GeoRef and GeoBase (the year 2003 is incomplete).

leakage), with varying importance with respect to water-flow potential or hydrocarbon-flow potential in the trap.

Fluid dynamic classifications are significant because they shift the focus from static to dynamic traps and, thus, better capture the subsurface reality. Nevertheless, fluid dynamic analyses of petroleum traps are less effective as predictive models because of the complexities in integrating petroleum charge (generation and migration), structural movements in the basin, and physical properties of reservoir seal rocks.

RECENT ATTENTION TO FAULT SEALS

Although results of fault-seal analyses are relatively new in exploration and production activities compared to reservoir simulation or seismic interpretation, several petroleum geologists have hinted at the existence and importance of fault seals through the years. Three quotations are noteworthy here. McKnight (1940, p. 133), in his report on the geology of Utah, stated: "The fault has apparently acted as an avenue of escape for the petroliferous material rather than as a seal across the ends of the broken and tilted rocks." Wilhelm (1945, p. 1568) wrote: "Normally a reservoir in a fault trap is sealed at the fault plane by impermeable strata against the reservoir bed by the action of faulting. However, fault planes lined with thinnest veneers of plastic clay or pulverized fault gouge of low permeability may separate oil reservoirs from water-logged porous sands that lie in juxtaposition." Willis (1961, p. 6–24) remarked: "Fault surfaces provide many different possibilities for the development of the proper geometry for a trap. Often there will be a zone of gouge, or broken rock, associated with the fault surface which is capable of acting as an impermeable barrier to oil."

Evaluation of fault sealing and leaking has become a focus of intense research over the past two decades. Figure 4 shows the number of publications (both articles and conference presentations) on fault seal cited in two reference databases (GeoRef® and GeoBase®). Although this is not a complete list (definitely not for the year 2003), both databases show a dramatic increase in fault-seal publications in the second half of the 1990s.

In a 1995 report on technological needs envisioned by oil companies, the National Petroleum Council (1995) identified fault-seal analysis as one of the hot areas in exploration. Based on a survey of 16 oil companies, the Industrial Task Force (2001) noted that the detection, characterization, and prediction of faults and fractures and their impact on production are at the top of the agenda for developments in petroleum geology. This recent attention to fault-seal analysis begs the question "why?"

Characterization of faults in petroleum basins has traditionally posed a major challenge because of the inherent complexity of fault zones, scarcity of quantitative knowledge on petrophysical properties of faults, less accessibility to sampling and examining fault zones in petroleum wells, and difficulties in correlating the outcrop observations of faults to subsurface conditions. Although none of these factors has waned, three other factors, in turn, have motivated fault-seal studies as follows:

1) It has been increasingly recognized that faults are too important to be ignored in petroleum exploration, reservoir management, and production strategy. Fault geometry (size and shape), for instance, partly controls the volumetric estimation of petroleum reserves in a given pool. Moreover, fault-seal evaluation helps drilling plans because if a fault is known to provide a lateral barrier to hydrocarbon flow at given pay zones, wells drilled parallel to the fault (along fault dip) and down to the deepest fault-bounded accumulation may tap multiple

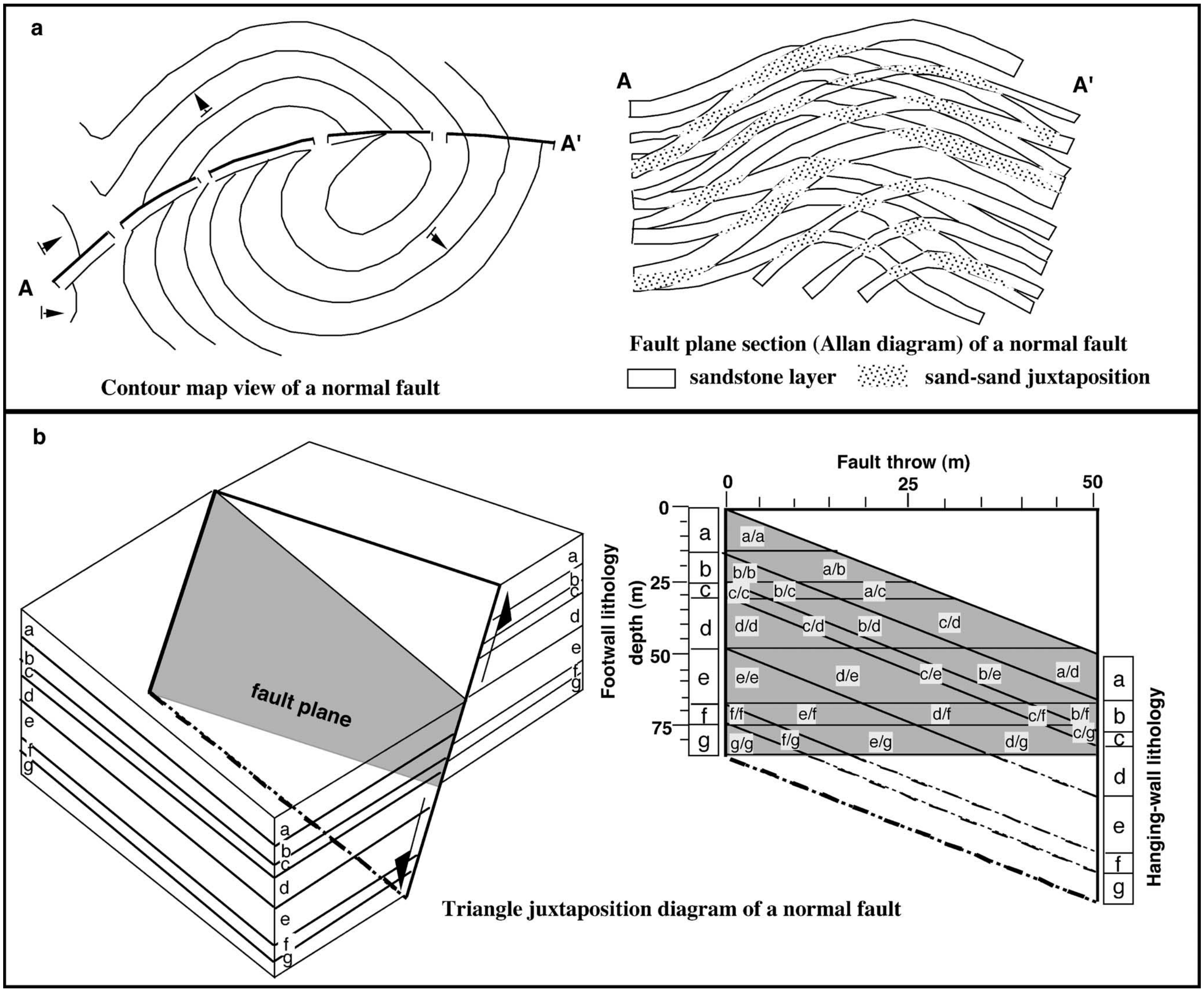

FIGURE 5. Two schemes of juxtaposition diagrams on a fault surface used currently in petroleum industry: (1) fault plane section or Allan diagram (Allan, 1989); (b) triangle juxtaposition diagram (Knipe, 1997).

hydrocarbon pay zones (if present) on both hanging-wall and footwall sides.

2) With a decrease in discovery of giant oil fields in the recent decades, reservoirs compartmentalized by faults have become economically attractive targets.
3) The development of high-resolution, 3-D seismic technology and borehole image logs has refined the identification and visualization of subsurface fault structures.

FAULT JUXTAPOSITION TRAPS

Fault juxtaposition of a reservoir rock against a low-permeable rock was recognized as early as 1910 (Clapp, 1910), and diagrams of fault traps appeared in the first textbook on petroleum geology (Hager, 1915). Evaluation of fault juxtaposition traps as depicted on structural cross sections is still a useful method, especially because it considers the entrapment on the scale of pay zones (Bailey and Stoneley, 1981). However, a comprehensive fault-trap evaluation should not rely simply on two-dimensional fault juxtaposition because petroleum traps have a 3-D closure geometry.

A powerful technique for fault juxtaposition analysis was developed by the late Urban Allan. It constructs the juxtaposition of footwall and hanging-wall sedimentary layers on a fault plane (along-strike fault surface). The resulting graphs are called fault plane sections (Allan, 1989) or, simply, Allan diagrams (Figure 5a). This technique was first presented as ''composite cross sections'' by Read and Watson (1962) in their classic geology textbook and was extensively improved and applied to petroleum exploration by Allan as early as 1967 in Texas. Allan first presented his graphical technique in 1980 at the AAPG Research Conference on Seals for Hydrocarbons held in Colorado and finally published it in 1989. The computerization of Allan diagrams in the last decade (e.g., Hoffman et al., 1996) has provided a quick-view tool for evaluating the potential areas of fault trapping (caused by sandstone-shale juxtaposition) or potential reservoir communication (caused by contact between sandstone layers). Allan (1989) contended that a fault plane itself has no sealing properties, and that sandstone-sandstone contacts are simply pathways through which hydrocarbons migrate vertically as they move back and forth across the fault. His notion may have been true for the growth faults he studied; however, more recent studies on fault-rock properties and shale smear phenomena refute such a simplified notion. Allan diagrams provide a useful tool for (1) lithological mapping of the fault plane and (2) displaying various fault-rock properties (such as shale gouge ratio and permeability) on the juxtaposed layer contacts.

Triangle-shaped juxtaposition diagrams have also been employed for fault-sealing assessment by Bentley and Barry (1991) (fault-type panel), Childs et al. (1997) (sequence-throw juxtaposition diagram), and Knipe (1997) (juxtaposition diagram). In these diagrams (Figure 5b), a slice of fault plane is depicted in the form of a triangle, in which the horizontal axis shows fault throw (from 0 to the maximum fault throw in the study area), and the vertical axis on the left of the diagram shows the thickness (depth section) of stratigraphic layers on the upthrown side of the fault. The stratigraphic layers of the downthrown section are overlain (juxtaposed) on the triangle for different fault throw intervals. Similar to Allan diagrams, fault-rock properties, such as permeability or shale gouge ratio, can also be displayed (color-coded) on the triangle diagrams. However, unlike Allan diagrams, the triangle juxtaposition diagram is a hypothetical slice of a fault plane, which simulates fault-rock properties for juxtaposed layers for questions like "what if fault throw is *n*?"

Precise fault juxtaposition analyses should consider (1) the type of the juxtaposed seal rock and (2) the nature of fault rock between the juxtaposed units, because different types of juxtaposed seal rocks or fault rocks will have different capillary pressures.

The juxtaposed seal rock can be ranked according to its position on the scale of ductility-brittleness, i.e., halite, anhydrite, organic-rich shale, clay-rich shale, silty shale, certain limestones, sandy shale, clay-rich sandstone, tight dolomite, cemented sandstone, and quartzite, in an order of more ductile toward more brittle (Downey, 1984; Skerlec, 1999). Robert Sneider's scale of these seal rocks (Sneider et al., 1991, 1997) is a useful tool to rank the juxtaposed seal rocks on a fault surface because his quantitative scheme includes various types of seal rocks in terms of their capillarity based on numerous measurements.

Furthermore, the existence of fault rock between the juxtaposed rocks should also be considered. Figure 6 shows an example from Iran where an anhydrite formation (the Miocene Mishan formation, which is a regional seal rock in the Zagros foreland basin) is juxtaposed against a fractured limestone (the Oligocene–Miocene Asmari Formation, which is a major reservoir rock in the region), but fault gouge has also developed between the juxtaposed formations. In such a case (which is a norm instead of an exception as field observations of fault zones testify), the sealing capacity is controlled by the rock (either juxtaposed seal rock or the intervening fault rock), which has a higher capillary pressure to counteract the maximum buoyancy pressure of hydrocarbons exerted against fault rock or juxtaposed seal rock (if fault rock fails by capillarity). Therefore, a quantitative appraisal of fault rocks is necessary for fault-trap analysis, and this theme is reviewed in the following section.

FIGURE 6. The Khurgu fault in the Zagros foreland basin, southern Iran. Fault juxtaposition of Asmari limestone (a major reservoir rock in the subsurface) against Mishan anhydrite (a regional seal rock) with intervening fault gouge (about 1 m [3 ft] thick). In such juxtaposition traps, the higher capillary pressure of either juxtaposed seal rock or fault rock determines the sealing capacity of the fault. This high-angle reverse fault was not reactivated in the 1977 Khurgu earthquake (magnitude 7). Drawn from a photograph in Berberian et al. (1977).

FAULT-ZONE ARCHITECTURE, FAULT-SEALING PROCESSES, AND PETROPHYSICAL PROPERTIES

Several published articles discussing fault-sealing mechanisms and assessment are available (e.g., Smith, 1966, 1980; Weber, 1986, 1997; Watts, 1987; Mitra, 1988; Nybakken, 1991; Knipe, 1992, 1993; Knott, 1993; Berg and Avery, 1995; Harper and Lundin, 1997; Knipe et al., 1997, 1998; Yielding et al., 1997; Skerlec, 1999; Aydin, 2000; Wehr et al., 2000; Sorkhabi et al., 2002, 2003). In this section, we will briefly discuss how the current knowledge quantifies the petrophysical properties and sealing capacity of fault zones.

Fault Architecture

A working concept of fault architecture is necessary as a first step in fault-sealing assessment. Numerous outcrop mapping (e.g., Bruhn et al., 1990; Knipe, 1992; Antonellini and Aydin, 1994; Caine et al., 1996; Burhannudinnur and Morley, 1997; Walsh et al., 1998) as well as subsurface investigations (e.g., Wallace and Morris, 1986; Gibson, 1994; Shipton et al., 2002) have demonstrated that a fault is rarely a simple slip plane but a relatively narrow zone of deformation dissecting the host rock. The fault zone may be divided into fault core and fault damage zone (Caine et al., 1996). The fault core contains the main slip plane and is characterized by one or more types of fault rocks (Sibson, 1977; Knipe et al., 1997). The fault damage zone surrounds the fault core and is characterized by abundant fractures (joints, shear fractures, veins, deformation bands, etc.) that form before and during faulting and act as a transition zone from undeformed host rock to fault rock.

This two-component (fault core and fault damage zone) model is a simplified view of fault architecture at the outcrop scale. Fault architecture is further complicated by factors and processes such as fault-associated folding, fault stepping at heterogeneous layer boundaries, occurrence of multiple slip planes in a fault zone, sharp changes in fault dip angle, incorporation of rock blocks (fault lenses) from wall rock into the fault zone, and so on.

Fault-sealing Processes and Fault Rocks

Several distinct processes that generate fault rocks have been identified in sedimentary basins (Sibson, 1977; Watts, 1987; Mitra, 1988; Knipe, 1989, 1992; Knipe et al., 1997; Weber, 1997; Fisher and Knipe, 1998; Gibson, 1998). These processes include cataclasis, development of deformation bands in porous sandstones and in unconsolidated sandstones (disaggregation zones), clay smearing, development of clay matrix gouge (framework phyllosilicate) in impure, immature sandstones, cementation (chemical diagenesis), and pressure solution. These fault-rock types resulting from these processes are summarized as follows:

1) Cataclasite: Cataclasis is a friction-dependent mechanism of brittle deformation involving both fracturing and rigid-body rotation (Engelder, 1974). Cataclastic fault rocks are characterized by grain-size reduction and porosity collapse caused by fracturing and crushing of grains and fragments in the host rock. Sibson (1977) distinguishes between fault gouge (with visible lithic fragments of <30% in rock matrix) and fault breccia (with visible fragments of >30%) on a textural basis. Cataclasites may become lithified or remain incohesive rock material after faulting, depending on confining pressure and other subsurface environmental conditions.
2) Deformation bands: Deformation bands (Aydin, 1978) have been observed as millimeter-thick planar structures in porous sandstones and have been variously called "granulation seams" (Pittman, 1981) or "cataclastic slip bands" (Fowles and Burley, 1994). Bruhn et al. (1990) and Antonellini and Aydin (1994) demonstrated in their studies of Jurassic sandstones in Utah, United States, that deformation bands occur as solitary features far away from fault zones but increase in abundance toward the fault and form an anastomosing pattern in the fault zone surrounding the main slip plane. This seems to suggest that faulting in porous sandstones is an evolutionary process beginning with solitary deformation bands and culminating in the main slip plane (Antonellini and Aydin, 1994).
3) Disaggregation zones: As defined by Knipe et al. (1997), these are deformation bands that show little fracturing and occur in little consolidated, clean sandstones.
4) Clay smear or shale smear: Faulting in a sand-mud succession may cause smearing of soft clay material from source layers into the fault zone (Weber et al., 1978; Lindsay et al., 1993; Lehner and Pilaar, 1997). Lindsay et al. (1993) identified three mechanisms for clay smear, including clay abrasion on a sandstone surface during fault movement, shale shearing along fault planes, and ductile injection of clay material into fault zones. In the last decade, several algorithms, such as shale smear factor (Lindsay et al., 1993), clay smear potential (Bouvier et al., 1989; Fulljames et al., 1997), shale gouge ratio (Yielding et al., 1997; Freeman et al., 1998), and smear gouge ratio (Skerlec, 1999), have been proposed to use this phenomenon for evaluating the sealing capacity of normal faults in clastic reservoirs. These algorithms are not equivalent but are based on different

assumptions of shale smear; therefore, their results should be interpreted with particular attention to what the algorithms mean in terms of smear processes (Naruk et al., 2002). The current calibrations for these algorithms are based on empirical evidence from petroleum fields in deltaic environments and syndepositional faults and can be applied to this type of field (Sorkhabi et al., 2002).

5) Framework-phyllosilicate fault rock (Knipe et al., 1997) or clay matrix gouge (Gibson, 1998): This type of fault rock occurs in impure, immature sandstones (with a detrital clay content of 15–40% according to Knipe et al., 1997, or containing >30% clay + mica + lithics and <60% quartz according to Gibson, 1998) by smearing and mixing of clay minerals during faulting. It is a clay and shale smear process operating on a small scale in a sandstone unit.
6) Cemented fault rock: The porosity and pore connectivity in rocks are effectively reduced by cementation, which occurs in sedimentary reservoir rocks during burial and chemical diagenesis (Bjørlykke, 1983), as well as in fault rocks (Knipe, 1993; Mozley and Goodwin, 1995; Hippler, 1997; Knipe et al., 1997; Sverdrup and Bjørlykke, 1997; Hadizadeh and Foit, 2000) because of flow of hydrothermal fluids through fault-zone fractures or growth of new mineral phases in fault rocks as a result of fault-induced changes in temperature and pressure. A variety of cements, including quartz, calcite, dolomite, kaolin, anhydrite, pyrite, and barite, may fill fractures and pore spaces in fault-zone rocks. Fault-associated cementation (''precipitation sealing'') has been studied both experimentally (Tenthorey et al., 1998) and theoretically (Aharonov et al., 1998).
7) Stylolite: Pressure solution is a process of diffusive mass transfer along grain contacts. It has been widely observed in fine-grained quartz and calcite-bearing rocks at elevated temperatures, as well as in shear zones (Rutter, 1983; Hadizadeh, 1994). Pressure solution is a combined mechanical and chemical process of porosity reduction and crack sealing that may be associated with fault zones (e.g., Gratier et al., 1994; Peacock et al., 1998).

Permeability Distribution in Faulted Reservoirs

Understanding the pattern of permeability heterogeneity that faults induce in reservoir rocks is of great importance for reservoir simulation. Here, we describe the results of two studies that shed light on this issue.

Evans et al. (1997) reported gas permeability measurements on plugs from the Precambrian granitic rocks in the Washakie Range, Wyoming, United States, where the East Fork thrust faults occur. Measured at an effective stress of 3.4 MPa (493 psi), the protolith samples had permeabilities in the range of 10^{-18}–10^{-17} m^2 (10^{-6}–10^{-5} d); samples from fault damage zone showed higher permeabilities in the range of 10^{-16}–10^{-14} m^2 (10^{-4}–10^{-2} d) (i.e., 10–1000 times greater than protolith permeability); samples from fault core (indurated gouge or clay-rich foliated cataclasite) had the lowest permeabilities ($<10^{-20}$–10^{-17} m^2; $<10^{-8}$–10^{-5} d). Furthermore, these authors demonstrated that permeability in fault core samples measured perpendicular to the fault plane was lower than that measured parallel to the fault plane.

Fowles and Burley (1994) reported permeability and porosity data (measured on plugs) from the Lower Permian sandstones (Penrith Formation) in the Vale of Eden Basin in northwest England and their equivalent rocks (the Locharbriggs Sandstone) in southwest Scotland. These sandstones are dissected by normal faults of mainly late Paleozoic age, and the fault rocks are characterized by anastomosing cataclastic slip bands (similar to deformation bands first observed by Aydin, 1978, in eolian sandstones in Utah). These authors found that both porosity and permeability increased from the undeformed sandstone toward the faults but decreased drastically in deformation band fault rock, and that the permeability of the fault rock perpendicular to the fault plane was the lowest.

Overall, the results of studies by Fowles and Burley (1994) and Evans et al. (1997) are consistent in terms of permeability distribution in a faulted area. These results are significant, considering the differences in the study areas, rock types and ages, and fault types. The slight permeability increase from undeformed rock to fault damage zone observed in both studies may be attributed to the abundance of fractures in this zone. Indeed, outcrop studies on faulted sandstones in the southwestern United States (Anders and Wiltschko, 1994) and faulted limestones in Israel (Becker and Cross, 1996), as well as a subsurface study on a faulted carbonate reservoir in the Arabian Gulf (Ericsson et al., 1998), have shown that the frequency of fractures increases from undeformed rock to fault damage zone. This may explain the slightly higher permeability of the fault damage zone, as also documented by Caine and Tomusiak (2003) in brittle faults in the Precambrian crystalline rocks of the Colorado Rocky Mountain Front Range. However, as Knipe (1993) has noted, cementation processes in the fault damage zone may heal fractures and hence reduce permeability, and this possibility should also be considered, especially in deeper areas of basins having significant hydrothermal fluid flow. The drastic decrease of permeability in fault rocks is attributed to textural and mineralogical changes (e.g., Knipe, 1992, 1993).

In view of these results and interpretations, a simple model for permeability distribution in a faulted

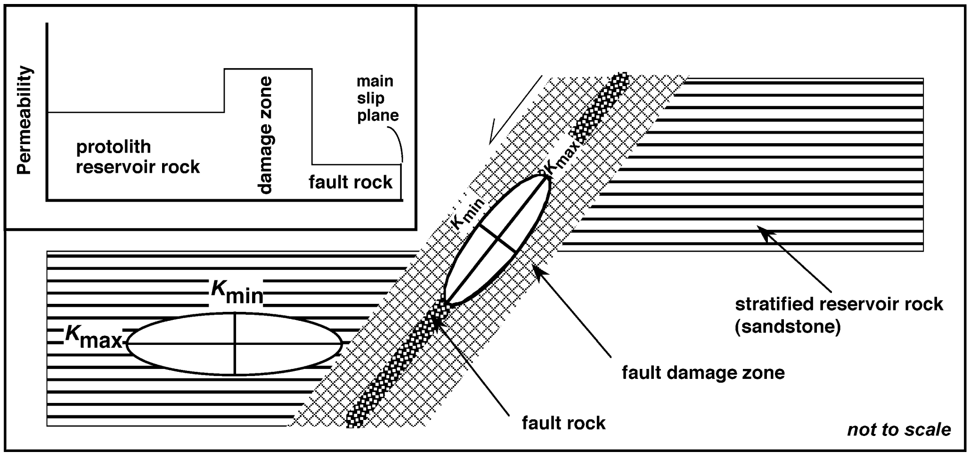

FIGURE 7. A simplified model for distribution of single-phase permeability in a faulted reservoir (clastic) rock. The insert shows that permeability increases from protolith (undeformed reservoir rock) to fault damage zone (caused by fault-associated fractures) but decreases rapidly in the fault rock (based on studies by Fowles and Burley, 1994; Evans et al., 1997). The diagram shows permeability ellipsoids for both reservoir rock and fault zone, in which the fault induces a permeability inversion in the rock. Note that maximum permeability in a stratified (laminated) rock is horizontal but becomes parallel to slip plane in a fault zone caused by fracture network, whereas minimum permeability is vertical in sedimentary layers but becomes horizontal in a fault zone caused by fault rock fabric. The figure is a schematic presentation of concepts; it is not to scale.

clastic reservoir is depicted in Figure 7. In this model, the fault induces a permeability inversion in the reservoir rock characterized by two distinct permeability ellipsoids. In bedded reservoir rocks, horizontal permeability is commonly several times larger than vertical permeability (North, 1985; Al-Qahtani and Ershaqi, 1999), but the permeability ellipsoid is inverted in fault zones where horizontal permeability (perpendicular to fault plane) is the minimum, whereas maximum permeability is parallel to the fault plane.

Fault-rock Permeability

In the last decade, several researchers have attempted to quantify the permeability of fault rocks. One definite result from their studies is that the permeability depends largely on the type of fault rock. Figure 8 is a plot of 322 fault-rock permeability measurements (on normal faults in clastic reservoirs) compiled from Antonellini and Aydin (1994), Fowles and Burley (1994), Knipe et al. (1997), Leveille et al. (1997), Fisher and Knipe (1998), Gibson (1998), and Sperrevik et al. (2002) and categorized according to fault-rock types. Overall, the data show that deformation bands have the highest permeability, whereas cemented fault rocks and clay smear samples show the lowest permeability.

The capability to predict fault-rock permeability is very helpful for reservoir simulation and field production (e.g., Lia et al., 1997; Wehr et al., 2000). Two empirical approaches to estimate fault-rock permeability in normal faults and clastic reservoirs are discussed here.

The first approach considers the reduction of permeability from undeformed (host) reservoir rock to fault rock (Leveille et al., 1997; Fisher and Knipe, 1998). Figure 9 is a compilation of permeability measurements on 66 pairs of host rock and fault rock reported by Antonellini and Aydin (1994), Fowles and Burley (1994), Leveille et al. (1997), Fisher and Knipe (1998), and Gibson (1998). All data pertain to normal faults in sandstone rocks. The fault rocks show reduced permeability by one to three orders of magnitude compared to the host rocks. Cemented fault rocks have the lowest permeability, deformation bands show the highest permeability, and cataclastic fault rocks have intermediate permeability. To employ this permeability reduction approach in the oil fields, we need data on reservoir rock permeability, empirical calibrations for various fault-rock types and fault types, and a realistic understanding of what fault-rock type is expected to be present in a given case. This approach, although still in its infancy, has promising potential as a predictive tool.

The second approach uses relationships between clay content (determined mainly by the x-ray diffraction analysis of samples) and one-phase permeability measured in fault rocks, and assumes that a higher content of clay minerals or clay-size minerals in a rock results in lower permeability. Two empirical calibrations for this approach have been reported as follows:

1) Manzocchi et al. (1999)

$$\log K_{\mathrm{f}} = -4\mathrm{CCR} - 0.25\log(D)(1-\mathrm{CCR})^5$$

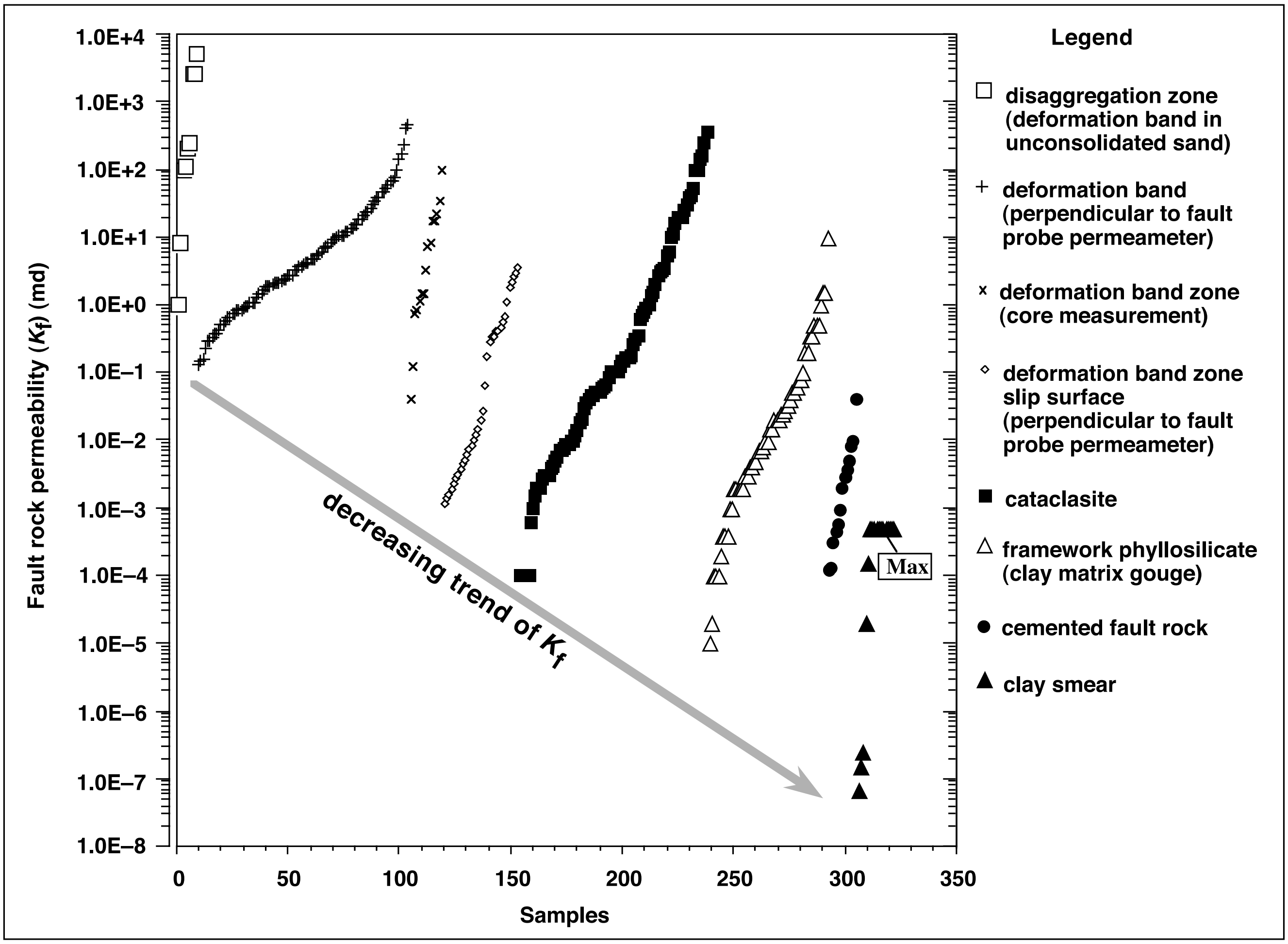

FIGURE 8. Data on 322 fault-rock permeability measurements categorized according to fault rock types: disaggregation zone (deformation bands in unconsolidated sands, as defined by Knipe et al., 1997); deformation bands (individual bands) (as defined by Aydin, 1978); deformation band anastomosing zone; fault-slip planes in deformation band zones; cataclasites; framework phyllosilicate (clay matrix gouge) in immature sandstones (Knipe et al., 1997; Gibson, 1998); cemented fault rock; and clay smear (Lindsay et al., 1993). Permeability data on deformation bands were mostly obtained from measurements on outcrop samples using a probe minipermeameter (gas permeability); all other permeabilities were determined on plug samples (perpendicular to fault) using either gas or water flow. The small box Max for clay smear data indicates that permeability measurements hit the detection limit; therefore, permeability values may be even smaller. Overall, the data show a trendline (marked by the gray arrow) according to fault-rock type, with the clay smear samples having the lowest permeability. Data sources include Antonellini and Aydin (1994), Fowles and Burley (1994), Knipe et al. (1997), Leveille et al. (1997), Fisher and Knipe (1998), Gibson (1998), and Sperrevik et al. (2002).

where K_f is the fault-rock permeability (millidarcys), CCR is the clay content ratio in the fault rock (fraction 0.0–1.0), and D is the fault displacement (meters). This calibration is based on a compilation of reported data (references given in Manzocchi et al., 1999) and indicates that higher CCR and D values yield lower permeability values in fault rocks.

2) Sperrevik et al. (2002)

$$K_f = a\exp\{-[b\mathrm{CCR} + cZ_{\max} + (dZ_f - e)(1 - \mathrm{CCR})^7]\}$$

where K_f is the fault-rock permeability (millidarcys), Z_{max} is the maximum subsurface depth (meters) of the fault rock under consideration, Z_f is the depth (meters) at the time of faulting, CCR is the clay content ratio (fraction), and other symbols are empirically derived constants: $a = 80{,}000$; $b = 19.4$; $c = 0.00403$; $d = 0.0055$; and $e = 12.5$. This calibration is based on data from nearly 100 normal faults in the North Sea and shows that higher clay contents and greater depths result in lower permeabilities in fault rocks. The incorporation of a depth factor in this calibration is important,

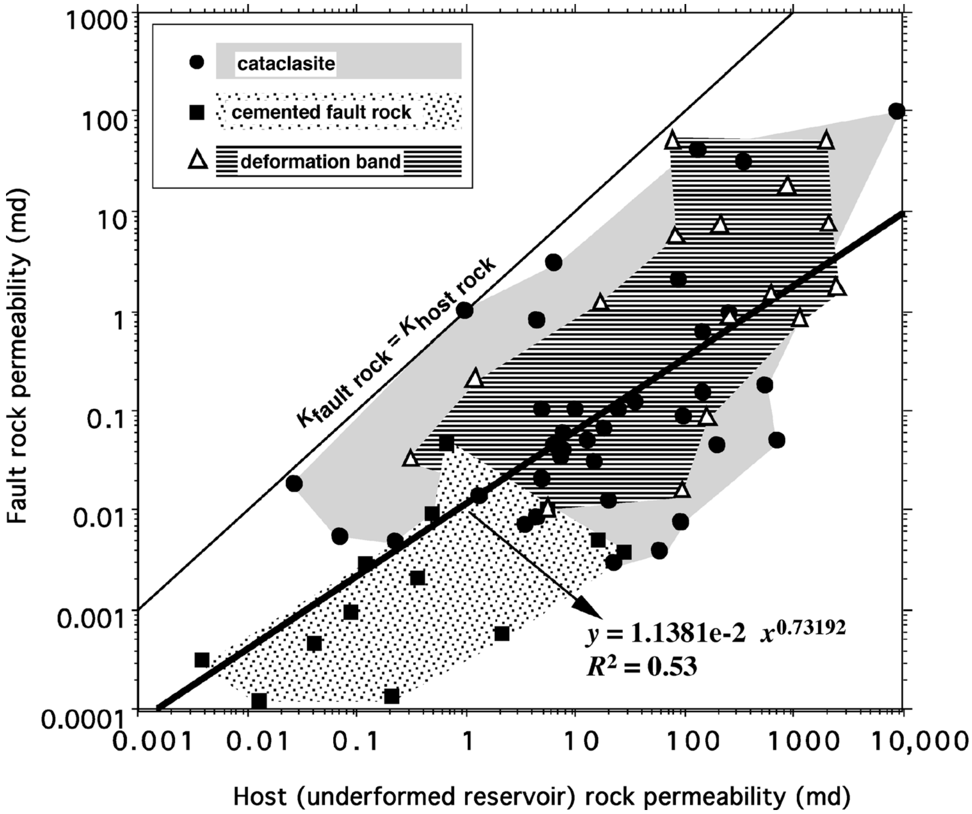

FIGURE 9. Plot of a data set containing 66 pairs of host rock and fault rock permeability (compiled from Antonellini and Aydin, 1994; Fowles and Burley, 1994; Leveille et al., 1997; Fisher and Knipe, 1998; Gibson, 1998). All data pertain to normal faults in sandstone rocks. The fault rocks show reduced permeability by one to three orders of magnitude compared to the associated undeformed rocks. Cemented fault rocks have the lowest permeability, and deformation bands show the highest permeability.

because several studies have demonstrated that fault-rock permeability is partly controlled by confining pressure (e.g., Morrow et al., 1984; Evans et al., 1997; Faulkner and Rutter, 1998) similar to test results of intact rock samples that show an inverse relationship between permeability and confining pressure (e.g., Brace, 1978).

The clay content permeability approach is simplistic because it ignores other processes such as cementation in fault zones, but it is a quick-evaluation tool that can be applied to normal faults in mudstone-sandstone sequences from which the empirical calibrations have been derived. It should be noted that the uncertainty range in both the above-mentioned calibrations is currently one to two orders of magnitude because of uncertainty in the empirical data.

Data on fault-rock permeability also provide insight into the sealing probability of fault rocks because very good cap rocks commonly have intrinsic permeabilities of less than 1 md (about $<10^{-16}$ m^2) (Cossé, 1993), and an unpublished database of top-seal rocks at the Japan National Oil Corporation (JNOC [presently Japan Oil, Gas and Metals National Corporation]) shows that more than 90% of them have permeabilities of less than 5 md ($<5 \times 10^{-15}$ m^2).

Fault-rock permeability data can also be used in reservoir simulation. Knowing reservoir rock permeabilities and the lengths of two reservoir blocks separated by a fault, fault-rock permeability, and fault-zone thickness derived from an empirical relationship between fault displacement, D, and fault-zone thickness, T_f (where $T_f = D/66$, according to data compilation by Manzocchi et al., 1999), transmissibility multipliers (the permeability ratio of $K_{with\ fault}/K_{without\ fault}$) can be derived for reservoir grids and incorporated in reservoir-simulation models (Knai and Knipe, 1998; Manzocchi et al., 1999, 2002).

Hydrocarbon Column Heights in Fault Traps and Capillary Pressure of Fault Rocks

The accumulation and volume of hydrocarbons in fault traps depend on the following factors:

1) Capillary pressure of the cap rock: A higher capillary pressure will hold more hydrocarbons in the reservoir (e.g., Berg, 1975; Schowalter, 1979).
2) Integrity of the cap rock: Hydraulic fracturing (Hubbert and Rubey, 1959; Capuano, 1993) in overpressured cap rocks as well as structural (fold-related or fault-related) fracturing (Ingram and Urai, 1999) in overstressed cap rocks leads to a breaching of the top seal. For this reason, given the same capillary pressure, thicker cap rocks provide better sealing probability than thinner layers.
3) Thickness of the juxtaposed seal rock in relation to the amount of fault offset: If fault entrapment is caused by the juxtaposition of low-permeable (sealing) rock against the reservoir, a thicker seal

rock with a fault displacement equal to its thickness will hold more hydrocarbons than one with a fault having less displacement ("self-juxtaposed reservoirs" of Gibson, 1994).

4) Capillary pressure of the fault rock: A higher capillary pressure in the fault rock (Watts, 1987) will hold more hydrocarbons in the reservoir. However, comparing the capillary pressures of cap rock and fault rock, the lower capillary pressure will determine hydrocarbon column height.
5) Water pressure in the fault fill: Recently, Brown (2003) has highlighted the importance of water-overpressured or water-underpressured fault rock (compared to reservoir water pressure) as a factor in addition to capillarity in controlling hydrocarbon column height. Overpressured fault rock increases the height of the sealed petroleum column.
6) Structural spillpoint: Traps with deeper spillpoints than their crests will provide larger closure for holding hydrocarbons in the reservoir.
7) Thickness of reservoir (pay zone): Given similar capillary conditions of seal rock and similar porosity of reservoir rock, a thicker reservoir holds a larger volume of hydrocarbons charged to the reservoir.
8) Oil/gas ratio: Hydrocarbon gases have about three times higher buoyancy pressure than liquid petroleum. Therefore, oil column height also partly depends on the ratio of later-migrated gas that has displaced oil in the reservoir.

Capillary pressure is a key factor in petroleum accumulation on a geological timescale (e.g., Berg, 1975; Schowalter, 1979; Watts, 1987; Vavra et al., 1992). Ideally, the capillary (displacement or entry) pressure of a fault rock should be directly determined (by the mercury-injection method). However, with no access to fault-zone materials in drill cores, the ultimate goal of fault-seal assessment should be the ability to predict the capillary pressure of the fault rock. Petroleum traps are commonly assumed to be water-wet systems. This is true for the majority of cases (Cossé, 1993), although it is not always the case. Therefore, the water-wet assumption is a limitation of the prediction methods of capillary pressure in seal rocks.

One method currently used for predicting the capillary pressure of fault rocks is based on the relationship between clay content and capillary pressure (Gibson, 1998; Childs et al., 2002; Yielding, 2002). Recently, Bretan et al. (2003) have proposed the following calibration between clay content (computed shale gouge ratio in petroleum fields) and capillary pressure (estimated from across-fault pressure differences in the same studied fields):

$$\mathrm{FRP_c} = 10^{(\mathrm{SGR}/27 - C)}$$

where $\mathrm{FRP_c}$ is the fault-rock capillary pressure (in bar); SGR is the shale gouge ratio (Yielding et al., 1997); and C is a calibration factor related to depth: C is 0.5 for burial depths of less than 3000 m (9850 ft); C is 0.25 for depths of 3000–3500 m (9850–11,500 ft); and C is 0 for depths of greater than 3500 m (11,500 ft).

A second empirical approach is based on the relationship between single-phase permeability and capillary (displacement) pressure. This assumption is valid because both permeability and capillary pressure are petrophysical properties of a porous medium, in which permeability is directly related to connected porosity, and capillary pressure is inversely proportional to connected porosity. Beginning with the work of Purcell (1949), reservoir engineers have tried to quantify the relationship between permeability and capillarity.

Harper and Lundin (1997) have proposed the following theoretical equation relating capillary pressure (P_c) to permeability (K):

$$P_c \propto K^{-0.5} \quad \text{and} \quad \log P_c = \log 65.453 K^{-0.5056}$$

Sperrevik et al. (2002) have determined single-phase permeability and mercury-injection capillary pressure for numerous samples from North Sea oil fields, including host rocks (sandstones) and fault rocks (disaggregation zone, phyllosilicate framework, and cataclastic fault rocks). Figure 10 plots the data of Sperrevik et al. (2002), as well as those reported previously by Schowalter (1979), Swanson (1981), Berg and Avery (1995), Harper and Lundin (1997), Fisher and Knipe (1998), and Gibson (1998). Two significant results emerge from these data.

First, a power-law regression line is obtained for the relationship between fault-rock permeability (K_f in millidarcys) and fault-rock capillary (displacement) pressure ($\mathrm{FRP_c}$ in pounds per square inch) as follows:

$$\mathrm{FRP_c} = 55.402 \times K_f^{-0.4273}$$

This is very similar to the theoretical equation proposed by Harper and Lundin (1997).

Second, as noted by Sperrevik et al. (2002), the power-law regression lines for both sandstone reservoir rocks and fault rocks are very similar (Figure 10), indicating that both faulting and sedimentary processes in sandstones produce rock materials in which permeability and capillarity follow the general percolation properties of porous media (Sperrevik et al., 2002). The validity of this relationship and interpretation is unknown for cemented fault rocks (which are absent in the data set). Nevertheless, it appears that the theoretical and empirical relationships between petrophysical properties (porosity, permeability, and capillarity), which have been developed for clastic reservoirs,

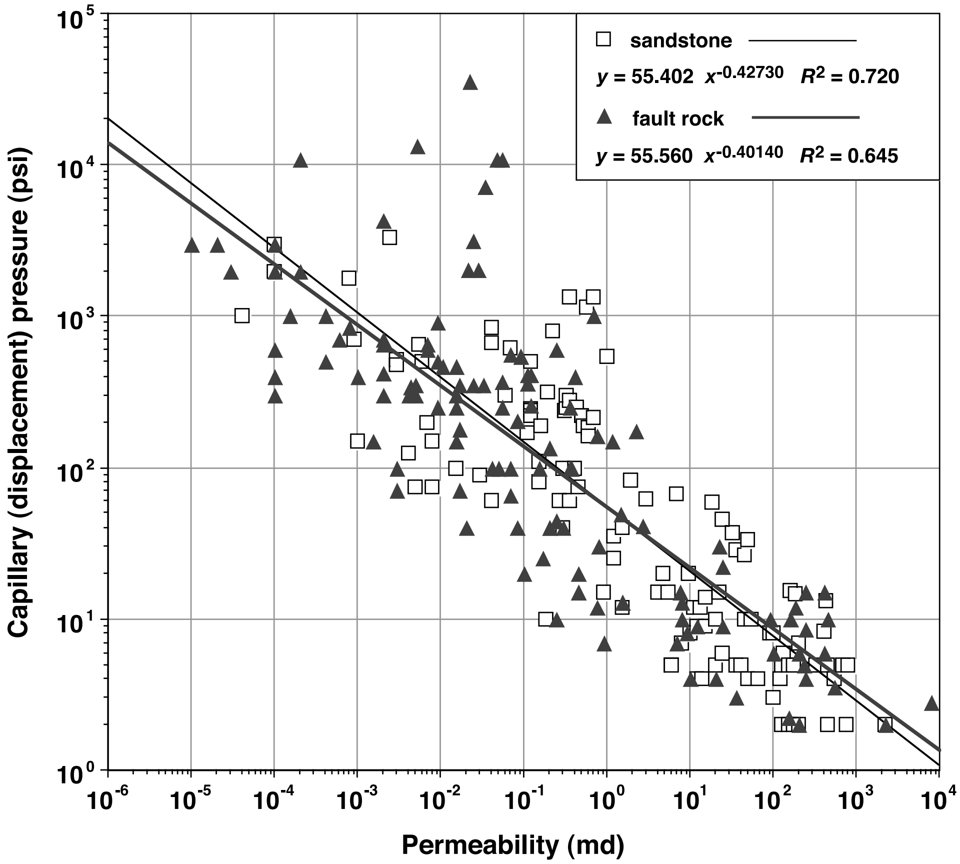

Figure 10. Plot of a data set containing 244 pairs of gas permeability (md) and capillary pressure (psi) (displacement pressure in mercury injection tests) for fault rocks and sandstone rocks compiled from Schowalter (1979), Swanson (1981), Berg and Avery (1995), Harper and Lundin (1997), Fisher and Knipe (1998), Gibson (1998), and Sperrevik et al. (2002). Note that both fault rocks and reservoir rocks exhibit very similar regression lines, implying that both sedimentary and faulting processes in sandstones produce rock materials whose hydraulic properties follow the same percolation laws of porous media.

may also be applicable to cataclastic fault rocks produced by normal faults in clastic reservoirs.

Hippler (1997) used the following equation relating permeability to capillary pressure, first proposed by Thompson et al. (1987):

$$K = C(L_c)^2(\sigma/\sigma_0)$$

where K is permeability (darcys); C is a constant that relates the conductivity of the capillary structure of equivalent size L_c to the permeability of the same path (the work of Thompson et al., 1987, indicates that C is 1/226); L_c is the capillary pore-throat diameter (in micrometers) associated with the first connected path in a mercury injection test; σ is the electrical conductivity of the rock saturated in brine solution; and σ_0 is brine conductivity. According to Archie's (1942) law for homogenous saturated media, σ/σ_0 can be approximated by φ^2, where φ is porosity.

Manzocchi et al. (2002) suggested the following equation for permeability-capillarity relationship in fault rock, derived from a previous analysis by Ringrose et al. (1993) for sediments:

$$P_c = C(1 - S^5)S^{-2/3}(\varphi/K)^{0.5}$$

where $C = 3$ gives capillary pressure in bar; S is the effective wetting phase saturation; φ is porosity; and K is single-phase permeability (millidarcys).

DIRECT FAULT-SEAL EVALUATION

Where data are available, a comparison of the depths of the oil-water contacts and/or oil-gas contacts on both sides of a fault gives direct evidence for the sealing or leaking behavior of the fault (Smith, 1980). Equal oil-water contact levels on both sides of a fault, for instance, indicate cross-fault leaking. Smith (1980) has worked out hypothetical scenarios for fluid-fluid contact levels across faults and the implications for fault sealing or leakage.

Similarly, a comparison of pore pressure trends in reservoir rocks on both sides of a fault provides direct insight of the sealing (if a pressure difference is present at the same depth) or leaking (if pressure is the same at a given depth) behavior of the fault (Skerlec, 1999). These direct, data-intensive approaches to fault-sealing assessment can be used to calibrate other methods of fault-seal prediction (e.g., Yielding et al., 1997).

BARREN FAULT TRAPS AND AN INTEGRATED FAULT-TRAP EVALUATION

In the beginning of this chapter, we quoted the well-known phrase, ''A trap is a trap, whether or not it has a mouse in it.'' Nevertheless, given the high costs of drilling wells, petroleum explorationists try to avoid barren traps as much as possible. There are many reasons for dry wells. A database of Japan National Oil Corporation, including 92 exploration targets around the world, indicates the following causes for exploration failures and dry wells (Figure 11):

1) Source rock factors (15%), such as insufficient volume or poor quality of source rock (in terms of organic content, thermal maturity, or expulsion efficiency) to generate petroleum in the basin
2) Reservoir rock factors (17%), which mainly include the poor quality of reservoir rock to hold or transmit petroleum
3) Closure factors (10%), i.e., lack or misinterpretation of 3-D closure geometry necessary for entrapment
4) Seal rock and preservation factors (17%), including the lack or inefficiency of seal rocks and, hence, the leakage of hydrocarbons
5) Migration factors (41%), such as the wrong timing of migration and structural development or lack of effective migration pathways (i.e., faults, fractures, and permeable carrier beds), although there were good source rocks, reservoirs, and traps in the explored basin

Fault-trap analysis should particularly consider the following three factors:

1) Fault timing: Productive traps with fault seals are those in which the fault formed prior to the last charge of hydrocarbons to the reservoir. This implies that the chronology of structural development with respect to source rock maturation and hydrocarbon migration is crucial for fault entrapment. Faults in sedimentary basins can be reasonably dated from stratigraphic comparison of sedimentary layers on both sides of a fault. In addition, the application of low-temperature radiometric techniques to fault-zone materials (either recovered from drill cores or collected from exposed sections of a given fault), such as the $^{40}Ar/^{39}Ar$ dating of potassium feldspar and of cleavage-filling mica, fission-track dating of apatite, zircon, or pseudotachylyte, (U-Th)/He dating of apatite, thermoluminescence, and electron-spin resonance methods, can be helpful. Note that the last two methods have a dating range of 10^3-10^5 yr and are thus useful for dating active faults, whereas the first three methods are applicable to greater than 10^5-yr events. Noller et al. (2000) give up-to-date information on various dating methods applicable to faults in sedimentary basins.
2) Fault-seal failure: Although a fault may have been a sealing feature in the geological past (as inferred from shale gouge ratio data), it is equally crucial to know if the fault seal has remained intact or has been breached under the contemporary stress conditions of the basin in which the fault occurs. Faults are highly conductive of fluids during their active times. For example, after the 1995 Kobe earthquake in Japan, many of the nearby springs showed a sevenfold increase in flow rate (Sato et al., 2000). In the last two decades, a powerful technology has emerged for in-situ stress analyses using borehole images (borehole breakouts and drilling-induced tensile fractures) obtained by acoustic and electrical televiewers, in conjunction with drilling pressure data (drilling mud injection and leak-off tests) (e.g., Zoback and Healy, 1992). In-situ stress data can be used to evaluate the failure potential of faults (e.g., Bell, 1990; Finkbeiner et al., 1997, 2001; Ferrill et al., 1999; Wiprut and Zoback, 2000; Jones and Hillis, 2003).
3) Top-seal failure: Corcoran and Doré (2002) have discussed four top-seal leakage mechanisms, namely, tectonic breaching (fold-related tensile fractures and minor faults in top seal), capillary leakage, overpressure leakage (hydraulic fracturing in cap rock), and molecular transport (diffusion) of natural gas through the cap rock. Ingram and Urai (1999) have demonstrated that top-seal leakage through subseismic faults and fractures depends partly on mudrock properties such as brittleness and partly on fracture behavior (shear vs. dilational fractures).

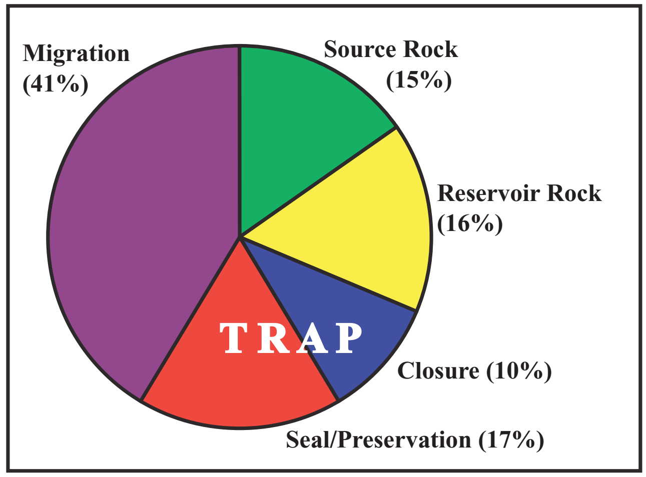

FIGURE 11. Causes of exploration failures and dry wells according to a database of 92 exploration targets at the Japan National Oil Corporation. See text for explanation of the factors. Although closure and seal and preservation have been grouped as trap factors, part of migration related to trap timing may also be considered as a trap factor.

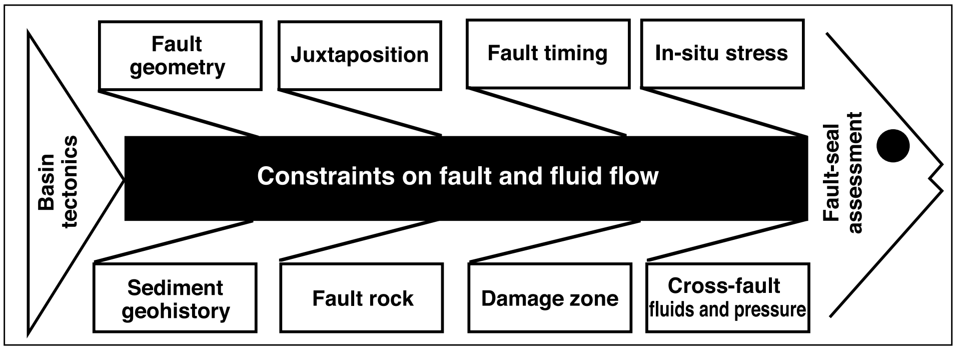

FIGURE 12. A fish-bone schematic presentation of a strategy for fault-seal assessment. Nine components are identified, which contribute directly or indirectly to the fluid-flow properties of fault structures. Components are arranged from left to right roughly according to the scale and the stagewise availability of data to evaluate each component. For example, basin tectonics is placed at the tail of the fish-bone diagram because of its largest scale and early-stage available data in exploration; in-situ stress and cross-fault pressure analyses are placed in the rightmost boxes because of their more refined scale and last-stage available data.

A science-based petroleum exploration strategy requires that fault-seal evaluation be integrated with basin tectonics and basin modeling (geohistory analysis and source rock maturation modeling).

Information gained from basin tectonics is helpful for understanding the evolution, kinematic interactions, geometric styles, and robust structural/seismic interpretation of faults. Faults formed in intraplate, continental collision, subductional, passive-margin, continental rift, back-arc, and wrench basins represent particular tectonic styles that place first-order constraints on petroleum traps (e.g., Harding and Lowell, 1979; Harding and Tuminas, 1989).

Geohistory analysis (Van Hinte, 1978; Allen and Allen, 1990) provides information on sedimentary evolution of a basin and thus helps us understand the initial conditions of sediments subjected to faulting processes. Knipe et al. (2000) have argued that geohistory should be incorporated as a fundamental parameter in fault-seal assessments.

Various schemes have been proposed for an integrative, systematic approach to fault-seal assessment (e.g., Mitra, 1988; Allard, 1997; Knipe et al., 1997; Skerlec, 1999; Grauls et al., 2002; Jones and Hillis, 2003). Figure 12 is our attempt of summing up this chapter and of supporting the previous authors' concepts.

PROGRESS, PROBLEMS, AND PROSPECTS

Faults are known to have dual functions in subsurface fluid flow in sedimentary basins; they can both enhance and impede fluid flow. Some lines of evidence, such as the occurrence of oil and gas seeps and geothermal springs in areas of active faults and the presence of hydrothermal deposits and mineral veins in fault zones, demonstrate the function of faults in fluid migration. However, numerous measurements of low-permeability fault rocks and field evidence for fault compartmentalization of petroleum reservoirs indicate that faults can form effective seals.

Although much more remains to be learned about fault-sealing processes, the recent studies have transformed the old polarized views of faults as either barriers or conduits into a more realistic framework. The realization that a fault can seal at one point but leak at another point on its along-strike surface, that it may seal laterally but allow migration vertically, that it can leak while active but seal later, and that it may seal one fluid phase but transmit another is no small achievement of the last decade (Aydin et al., 1998; Skerlec, 1999).

Methodologies for fault-seal assessment are associated with uncertainties, as discussed by Hesthammer and Fossen (2000), Wehr et al. (2000), and Yielding (2002). These uncertainties arise from several sources, including the mapping of fault geometry from seismic images, characterization of subsurface stratigraphy and subsurface pressure regimes from well logs, and application of outcrop geology to subsurface structures and rocks. Therefore, the validity of fault-sealing assessment is dependent on how to best reduce these uncertainties.

Currently, fault-sealing assessment is reasonably applicable to normal faults in clastic reservoirs for which data are available. Even in these cases, field calibrations of clay-smear fault rocks surpass our quantitative appraisal of other sealing processes. Furthermore, our knowledge of fault-sealing processes in thrust faults and for faults in carbonate reservoirs is very poor. It is therefore expected that fault-sealing processes in thrust faults and carbonate reservoirs, in addition to more sophisticated analyses and calibrations for normal faults in clastic reservoirs, will be a focus of research and development in the coming years.

Studies of fault-sealing processes and fault-trap structures have and will continue to render a great service to petroleum exploration and production, as well as contribute to our scientific understanding of faults and faulting processes. These structures and processes have shaped our planetary environment through devastating earthquakes operating on the scale of seconds to the formation of high mountain ranges and deep basins persisting for millions of years. During the last century, the petroleum industry has developed such fields as micropaleontology, sequence stratigraphy, seismic imaging, and basin modeling as powerful tools in geoscience. Fault-seal research continues this noble tradition and affirms the motto of AAPG's 2002 Annual Convention in Houston: "Our heritage is the key to global discovery."

ACKNOWLEDGMENTS

We express our gratitude to numerous researchers in the academe and industry who have contributed to Japan National Oil Corporation's Project on Evaluation of Traps and Seals (1997–2003); some of them are represented by their articles in this volume. Our thanks also are extended to our colleagues who have supported the project in managing positions, including Satoshi Sasaki, Hisashi Ishida, Masanori Okamoto, Uko Suzuki, H. Hasegawa, Daichi Sato, and Masamichi Fujimoto. We also greatly appreciate John Lorenz, Jack Thomas, Jim Handschy, Steve Naruk, Raymond Levey, and David Curtiss for reading this article and for their comments to improve it; we alone, however, are responsible for any error.

APPENDIX: MILESTONES (SYMPOSIA, CONSORTIA, AND PUBLICATIONS) ON FAULT SEALS, FAULT ROCKS, FAULT TRAPS, AND FAULT-ASSOCIATED FLUID FLOW (1980–2003)

Abbreviations

AAPG	American Association of Petroleum Geologists
AGU	American Geophysical Union
EAGE	European Association of Geoscientists and Engineers
EUG	European Union of Geosciences
GSA	Geological Society of America
GSL	Geological Society (London)
ISRM	International Society for Soil and Rock Mechanics
NPF	Norsk Petroleums-forening
SPE	Society for Petroleum Engineers
USGS	United States Geological Survey

1980

Downey, M. W., and T. T. Schowalter, convenors, 1980, AAPG Research Conference on "Seals for Hydrocarbons," Keystone, Colorado.

Deformation Mechanisms, Rheology, and Tectonics Conference on "The Effect of Deformation on Rocks," Göttingen, Germany: Proceedings, *in* Lister, G. S., H.-J. Behr, K. Weber, and H. J. Zwart, eds., 1981, Tectonophysics, v. 78, p. 1–698.

Carreras, J., and P. R. Cobbold, eds., 1980, Sheared zones in rocks: Journal of Structural Geology, v. 2, p. 1–287.

1981

Smith, D., 1981, Sealing and non-sealing faults in Louisiana Gulf Coast salt basin: AAPG Bulletin, v. 64, p. 145–172.

Carter, N. L., M. Friedman, J. M. Logan, and D. W. Stearns, 1981, Mechanical behavior of crustal rocks, "Handin Volume," AGU Geophysical Memoir 49, 236 p.

1982

Deformation Mechanisms, Rheology, and Tectonics Conference on "Planar and Linear Fabrics of Deformed Rocks," Zürich, Switzerland: Proceedings, *in* P. L. Hancock, E. M. Kalper, N. S. Macktelow, and J. G. Ramsay, eds., 1984, Journal of Structural Geology, v. 6, p. 1–221.

International Conference on "Strain Patterns in Rocks," Rennes, France: Proceedings, *in* P. R. Cobbold and W. M. Schwerdtner, eds., 1983, Journal of Structural Geology, v. 5, p. 255–470.

Workshop on "Chemical Effects of Water on the Deformation and Strengths of Rocks," Carmel, California: Proceedings, *in* S. H. Kirby and C. H. Scholz, eds., 1984, Journal of Geophysical Research, v. 89, p. 3991–4358.

AGU Chapman Conference on "Fault Behavior and the Earthquake Generation Process," Snowbird, Utah: Proceedings, *in* K. J. Coppersmith and D. P. Schwarz, eds., 1984, Journal of Geophysical Research, v. 89, p. 5669–5927.

1983

Bally, A. W., ed., 1983, Seismic expressions of structural styles, three volumes, AAPG Studies in Geology 15, The Layered Earth, v. 1, 195 p.; Tectonics of Extensional Provinces, v. 2, 336 p.; Tectonics of Compressional Provinces/Strike-slip Tectonics, v. 3, 411 p.

1984

International Conference on "Multiple Deformations in Ductile and Brittle Rocks," Bermagui, Australia, organized by the Geological Society of Australia: Proceedings, *in* P. C. Hancock and C. M. Powell, eds., 1985, Journal of Structural Geology, v. 7, p. 269–501.

International Conference on "Thrusting and Deformation," Toulouse, France, to mark the 100th anniversary of Archibald Geikie's definition of 'thrust fault:' Proceedings, *in* J. P. Platt, M. P. Coward, J. Deramond, and J. Hossack, eds., 1986, Journal of Structural Geology, v. 8, p. 215–492.

Stanford Rock Physics and Borehole Geophysics Consortium, started at Stanford University, California (leaders: Amos Nur for rock physics and Mark Zoback for borehole geophysics).

1985

Deformation Mechanisms, Rheology, and Tectonics Conference on "Tectonic and Structural Processes on a Macro-, Meso-,and Micro-scale," Utrecht, The Netherlands: Proceedings, *in* H. J. Zwart, M. Martens, I. Van Der Molen, C. W. Passchier, C. J. Spiers, and R. L. M. Vissers, eds., 1987, Tectonophysics, v. 135, p. 1–251.

International Conference on "Deformation of Sediments and Sedimentary Rocks," University College, London: Proceedings, *in* M. E. Jones and R. M. F. Preston, eds., 1987, Deformation of sediments and sedimentary rocks: GSL Special Publication 29, 350 p.

International Conference on "Fluid Flow in Sedimentary Basins and Aquifers," Geological Society (London): Proceedings, *in* J. C. Goff and B. P. Williams, eds., 1987, Fluid flow in sedimentary basins and aquifers: GSL Special Publication 34, 230 p.

Fault Analysis Group founded at University of Liverpool, England (moved to University College, Dublin, Ireland, in 2000) (leaders: Jun Watterson at Liverpool and John Walsh at Dublin).

1986

International Conference on "Shear Strain in Rocks," Imperial College, London: Proceedings, *in* P. R. Cobbold, D. Gapais, W. D. Means, and S. H. Treagus, eds., 1987, Journal of Structural Geology, v. 9, p. 521–778.

1987

Watt, N. L., 1987, Theoretical aspects of cap-rock and fault seals for single- and two-phase hydrocarbon columns (originally presented at the AAPG Annual Meeting in 1985): Marine and Petroleum Geology, v. 4, p. 274–307.

Deformation Mechanisms, Rheology, and Tectonics Conference on "Geological Kinematics and Dynamics: In Honor of the 70th Birthday of Hans Ramberg," Uppsala, Sweden: Proceedings, *in* C. Talbot, ed., 1988, Acta Universitatis Upsaliensis, Bulletin of the Geological Institution of the University of Uppsala, New Series 14, 286 p.

Conference on "Deformation of Crustal Rocks," Mount Buffalo, Victoria, organized by the Specialist Group in Tectonics and Structural Geology of the Geological Society of Australia: Proceedings, *in* A. Ord, ed., 1989, Tectonophysics, v. 158, p. 1–354.

1988

Foster, N. H., and E. A. Beaumont, compilers, 1988, Traps and seals: AAPG Treatise of Petroleum Geology Reprint Series 6–7 (reprint of 42 articles); and Foster, N. H., and E. A. Beaumont, compilers, 1988, Structural concepts and techniques (reprints of 93 articles): AAPG Treatise of Petroleum Geology Reprint Series 9–11, v. 1, 723 p.; v. 2, 479 p.; v. 3, 651 p.

International Conference on "Friction Phenomena in Rocks," Fredericton, United Kingdom: Proceedings, *in* J. G. Spray and P. J. Hudleston, eds., 1989, Journal of Structural Geology, v. 11, p. 783–831.

Applied Geodynamics Laboratory Research (focusing on salt tectonics) founded at the Bureau of Economic Geology, University of Texas at Austin (leader: Martin Jackson).

1989

Allan, U., 1989, Construction fault plane-juxtaposition diagrams (nicknamed "Allan Diagram"): AAPG Bulletin, v. 73, p. 803–811.

NPF Conference on "Structural and Tectonic Modelling and Its Application to Petroleum Geology," Stavanger, Norway: Proceedings, *in* R. M. Larsen, H. Brekke, B. T. Larsen, and E. Talleraas, eds., 1992, Structural and tectonic modelling and its application to petroleum geology: Amsterdam, Elsevier, 549 p.

International Conference on "The Geometry of Normal Faults," London: Proceedings, *in* A. M. Roberts, G. Yielding, and B. Freeman, eds., 1991, The geometry of normal faults: GSL Special Publication 56, 264 p.

Deformation Mechanisms, Rheology, and Tectonics Conference, Leeds University, United Kingdom: Proceedings, *in* R. J. Knipe and E. H. Rutter, eds., 1990, Deformation mechanics, rheology, and tectonics: GSL Special Publication 54, 535 p.

ISRM/SPE International Symposium on "Rock at Great Depth," Pau, France: Proceedings, *in* V. Maury and D. Fourmaintraux, eds., 1990, Rock at great depth, three volumes: Rotterdam, A. A. Balkema, 1620 p.

1990

Beaumont, E. A., and N. H. Foster, eds., 1990–1993, Structural traps, 8 volumes: AAPG Atlas of Oil and Gas Fields, v. 1, 232 p.; v. 2, 267 p.; v. 3, 355 p.; v. 4, 382 p.; v. 5, 305 p.; v. 6, 304 p.; v. 7, 347 p.; v. 8, 328 p.

The Brace symposium on "Fault Mechanics and Transport Properties of Rocks," Massachusetts Institute of Technology, Cambridge: Proceedings, *in* B. Evans and T.-F. Wong, eds., 1992, Fault mechanics and transport properties of rocks: New York, Academic Press, 542 p.

Duba, A. G., W. B. Durham, J. W. Handin, and H. F. Wu, eds., 1990, The brittle-ductile transition in rocks (the "Heard Volume"): AGU Geophysical Memoir 56, 243 p.

International Conference on "Mechanics of Jointed and Faulted Rock," Technical University of Vienna, Austria: Proceedings, *in* H. P. Rossmanith, ed., 1990, Mechanics of jointed and faulted rock: Rotterdam, A. A. Balkema.

GSL Meeting on "Absolute Dating of Fault Movements," London: Proceedings, *in* R. H. Maddock, ed., 1992, Journal of Geological Society (London), v. 149, p. 249–301.

Rock Fracture Project Consortium began at Stanford University, California (leaders: David Pollard and Atilla Aydin).

1991

Sessions on "Fluid Seals" and "Quantification of Faults and Their Effect on Fluid Flow," AAPG Annual Convention in Dallas.

Deformation Mechanisms, Rheology, and Tectonics Conference on "Mechanical Instabilities in Rocks and Tectonics," Montpellier, France: Proceedings, *in* J.-P. Burg, D. Mainprice, and J. P. Petit, eds., 1992, Journal of Structural Geology, v. 14, p. 893–1109.

International Conference on "The Geometry of Naturally Deformed Rocks," ETH, Zurich, Switzerland, in celebration of John Ramsay's 60th birthday: Proceedings, *in* M. Casey, D. Dietrich, M. Ford, and A. J. Watkinson, eds., 1993, Journal of Structural Geology, v. 15, p. 243–671.

Petroleum Group of the Geological Society of London's Meeting on "Minipermeametry in Reservoir Rocks," Edinburgh, United Kingdom: Proceedings in Marine and Petroleum Geology, v. 10, p. 298–351.

Fault Dynamics Group started at Royal Holloway University of London, focusing on analog modeling of faults (leader: Ken McClay).

1992

Session on "Pressure Seals and Abnormally Pressured Reservoirs," AAPG Annual Convention, Calgary, Canada.

International Conference on "Fractured and Jointed Rock Masses," Lake Tahoe, California: Proceedings, *in* L. R. Myer, C.-F. Tsang, N. G. W. Cook, and R. E. Goodman, eds., 1995, Fractured and jointed rock masses: Rotterdam, A. A. Balkema, 772 p.

GSA Penrose Conference on "Applications of Strain: From Microstructures to Orogenic Belts," Halifax, Canada: Proceedings, *in* M. T. Brandon, J. R. Henderson, W. D. Means, and S. Patreson, eds., 1994, Journal of Structural Geology, v. 16, p. 437–612.

Symposium on "Influence of Fluids on Deformation Processes in Rocks," International Geological Congress, Kyoto, Japan: Proceedings, *in* C. J. Spiers and T. Takeshita, eds., 1995, Tectonophysics, v. 254, nos. 3–4, p. 121–297.

Rock Deformation Research group started at University of Leeds, United Kingdom (leader: Robert Knipe).

1993

Session on "Reservoirs, Traps, Seal Integrity," AAPG Annual Convention, New Orleans.

AAPG Hedberg Research Conference on "Seals and Traps: A Multidisciplinary Approach," Crested Butte, Colorado.

USGS Conference on "Mechanical Effects of Fluids in Faulting," Fish Camp, California: Proceedings, *in* S. Hickman, R. Sibson, and R. Bruhn, eds., 1993, USGS Open File Report, 94-228; and in S. Hickman, R. Sibson, and R. Bruhn, eds., 1995, Journal of Geophysical Research, v. 100, p. 12,831–13,132.

Deformation Mechanisms, Rheology, and Tectonics Conference on "Structures and Tectonics at Different Lithospheric Levels" held in Graz, Austria: Proceedings, *in* E. Wallbercher, W. Unzong, and M. Brandmayr, eds., 1994, Journal of Structural Geology, v. 16, p. 1495–1575.

GeoFluids Conference, Torquay: Proceedings, *in* J. Parnell, ed., 1994, GeoFluids: Origin, migration, and evolution of fluids in sedimentary basins: GSL Special Publication 78, 372 p.

1994

Ortoleva, P. J., ed., 1994, Basin compartments and seals (project results of Gas Research Institute in 1992): AAPG Memoir 61, 477 p.

AAPG Hedberg Research Conference on "Abnormal Pressures in Hydrocarbon Environments," Golden, Colorado: Proceedings, *in* B. E. Law, G. F. Ulmishek, and V. I. Slavin, eds., 1998, Abnormal pressures in hydrocarbon environments: AAPG Memoir 70, 270 p.

Sessions on "Evaluation of Traps and Seal" and "Seal Types and Characteristics," AAPG Annual Convention, Denver: Proceedings, *in* R. C. Surdam, ed., 1997, Seals, traps, and the petroleum system: AAPG Memoir 67, 317 p.

ISRM/SPE International Conference EUROCK94, Delft, The Netherlands: Proceedings, *in* Rock mechanics in petroleum engineering, Rotterdam, A. A. Balkema, 992 p.

Seal Evaluation Consortium started at Pennsylvania State University, Philadelphia (leader: Terry Engelder).

Research consortium entitled GeoPop (Geoscience Project into Overpressure) launched by three British universities (Durham, Newcastel, and Herriot-Watt) (leader: Richard Swarbrick).

1995

Meeting on "Structural Geology in Reservoir Characterization," Imperial College, London, organized by the Petroleum Group of GSL: Proceedings, *in* M. P. Coward, T. S. Daltaban, and H. Johnson, eds., 1998, Structural geology in reservoir characterization: GSL Special Publication 127, 266 p.

Meeting on "Scaling Laws for Fault and Fracture Populations— Analysis and Applications," Royal Society of Edinburgh, United Kingdom: Proceedings, *in* P. A. Cowie, R. J. Knipe, and I. G. Main, eds., 1996, Journal of Structural Geology, v. 18, p. 1–383.

Deformation Mechanisms, Rheology, and Tectonics Conference on "Thermal and Mechanical Interactions in Deep-seated Rocks," Prague, Czechoslovakia: Proceedings, *in* K. Schulmann, ed., 1997, Tectonophysics, v. 280, p. 1–197.

Second International Conference on "Mechanics of Jointed and Faulted Rock," Vienna, Austria: Proceedings, *in* H. P. Rossmanith, ed., 1995, Mechanics of jointed and faulted rock: Rotterdam, A. A. Balkema, 1068 p.

GSA Penrose Conference on "Fault-Related Folding," Banff, Alberta, Canada: Proceedings, *in* D. J. Anastasio, E. A. Erslev, and D. M. Fisher, eds., 1997, Journal of Structural Geology, v. 19, p. 243–602.

1996

NPF Conference on "Hydrocarbon Seals: Importance for Exploration and Production," Trondheim, Norway: Proceedings, *in* P. Møller-Pedersen and A. G. Koestler, 1997, Hydrocarbon seals: Importance for exploration and production: Amsterdam, Elsevier, 263 p.

Conference on "Faulting, Fault Sealing and Fluid Flow in Hydrocarbon Reservoirs," University of Leeds, Edinburgh: Proceedings, *in* G. Jones, Q. J. Fisher, and R. J. Knipe, eds., 1998, Faulting, fault sealing, and fluid flow in hydrocarbon reservoirs: GSL Special Publication 147, 320 p.

AAPG/EAGE Research Symposium on "Compartmentalized Reservoirs: Their Detection, Characterization, and Management," Woodlands, Texas.

Session on "Risking Fault Seal: Examples from Exploration and Production," AAPG Annual Convention, San Diego.

International Conference on "Structures and Properties of High Strain Zones in Rocks," Verbania-Pallanza, Italy: Proceedings, *in* E. H. Rutter, A. Boriani, K. H. Brodie, and L. Burlini, eds., 1998, Journal of Structural Geology, v. 20, p. 111–320.

Rock fractures and fluid flow: Washington, D.C, National Academy of Sciences, 551 p.

1997

Session on "Diagenesis Associated with Faults, Folds, and Fractures," AAPG Annual Convention, Dallas.

GSA Penrose conference on "Faults and Subsurface Fluid Flow," Taos, New Mexico: Proceedings, *in* W. C. Haneberg, P. S. Mozely, J. C. Moore, and L. B. Goodwin, eds., 1999, Faults and subsurface fluid flow in the shallow crust: AGU Geophysical Monograph 113, 222 p.

Meeting on "Structural Controls and Genesis of Economic Resources: Mineral and Hydrocarbon Deposits," Dublin, Ireland: Proceedings, *in* K. McCaffrey, L. Lonergan, and J. Wilkinson, eds., 1999, Fractures, fluid flow, and mineralization: GSL Special Publication 155, 328 p.

Deformation Mechanisms, Rheology, and Tectonics Conference on "Deformation Mechanisms in Nature and Experiment," Basel, Switzerland: Proceedings, *in* S. M. Schmid, R. Heilbronner, and H. Stünitz, eds., 1999, Tectonophysics, v. 303, p. 1–319.

GeoFluids II: Second International Conference on "Fluid Evolution, Migration and Interaction in Sedimentary Basins and Orogenic Belts," Belfast, Ireland: Proceedings, *in* J. Parnell, ed., 1998, Dating and duration of fluid flow and fluid-rock interaction: GSL Special Publication 144, 284 p.

Consortium on Utah Faults, Fluids, and Fractures (UF^3) started at Utah State University and University of Utah (leaders: James Evans and Craig Forster).
Reactivation Research Group began at University of Durham, United Kingdom (leader: Robert Holdsworth).
Project on Evaluation of Traps and Seals at Japan National Oil Corporation, 1997–2003.

1998

AAPG Hedberg Research Conference on "Reservoir Scale Deformation: Characterization and Prediction," Bryce, Utah.
Special Session on "Faults: Seals or Migration Pathways?," AAPG Annual Convention, Salt Lake City, Utah.
International Forum on "Pressure Regimes in Sedimentary Basins and Their Prediction," Houston, and sponsored by the Houston chapter of the American Association of Drilling Engineers: Proceedings, *in* A. R. Huffman and G. L. Bowers, eds., 2002, Pressure regimes in sedimentary basins and their prediction: AAPG Memoir 76, 238 p.
International Conference on "Evolution of Structures in Deforming Rocks," Canmore, Alberta, in honor of Paul F. Williams: Proceedings, *in* W. Blecker, C. Elliott, S. Lin, and C. R. van Staal, eds., 2001, Journal of Structural Geology, v. 23, p. 843–1178.
ISRM/SPE Symposium EUROCK98, Trondheim, Norway: Proceedings, *in* Rock Mechanics in Petroleum Engineering, two volumes, Richardson, Texas: Society of Petroleum Engineers, 952 p.
Third International Conference on "Mechanics of Jointed and Faulted Rock," Vienna, Austria: Proceedings, *in* H. P. Rossmanith, ed., 1998, Mechanics of jointed and faulted rock: Rotterdam, A. A. Balkema, 658 p.
Chester, F. M., T. Engelder, and T. Shimamoto, eds., 1998, Rock deformation: The Logan volume: Tectonophysics, v. 295, p. 1–257.
Fracture Research and Application Consortium (FRAC) began at the Bureau of Economic Geology, University of Texas at Austin.
Consortium Project on "GeoFluids" began at Pennsylvania State University, Philadelphia (leader: Peter Flemings).
Consortium Project on "Stress and Diagenesis as Controls on Fault Flow" (STADIA) began by the Edinburgh Rock Mechanics Consortium at University of Edinburgh and Heriot-Watt University (leaders: Bryne Ngwenya and Brian Crawford).

1999

Beaumont, E. A., and N. Foster, eds., 1999, AAPG handbook on exploring for oil and gas traps, 1150 p.
Symposium on "Dynamics of Fluids in Fractured Rocks," Lawrence Berkeley National Laboratory, California: Proceedings, *in* B. Faybishenko, P. A. Witherspoon, and S. M. Benson, eds., 2000, Dynamics of fluids in fractured rocks: American Geophysical Union Geophysical Monograph 122, 400 p.
"Deformation Mechanisms, Rheology, and Tectonics Conference," Neustadt an der Weinstrasse, Germany: Proceedings, *in* G. Dresen and M. Handy, eds., 2001, International Journal of Earth Sciences (Geologische Rundschau), v. 90, p. 1–210.
International Conference on "Textural and Physical Properties of Rocks," University of Göttingen, Germany: Proceedings, *in* B. Leiss, K. Ullemeyer, and K. Weber, eds., 2000, Journal of Structural Geology, v. 22, p. 1527–1873.
Session on "Fault-related Folds: The Transition from 2-D to 3-D" at GSA Annual Meeting, Denver: Proceedings, *in* M. S. Wilkerson, M. P. Fischer, and T. Apotria, eds., 2002, Journal of Structural Geology, v. 24, p. 591–904.
Session on "Fault Rocks," EUG 10, Strassburg, France.

2000

NPF Conference on "Hydrocarbon Seal Quantification," Stavanger, Norway: Proceedings, *in* A. G. Koestler and R. Hunsdale, eds., 2002, Hydrocarbon seal quantification: Amsterdam, Elsevier, 263 p.
Joint GSA/GSL Conference on "The Nature and Tectonic Significance of Fault Zone Weakening," London: Proceedings, *in* R. E. Holdsworth, R. A. Strachan, J. F. Magloughlin, and R. J. Knipe, eds., 2001, The nature and tectonic significance of fault zone weakening: GSL Special Publication 186, 342 p.
Session on "Successful Techniques to Evaluate Traps and Pressure Compartments," AAPG Annual Convention, New Orleans.
GeoFluids III: Third International Conference on Fluid Evolution, Migration, and Interaction in Sedimentary Basins and Orogenic Belts (July 12–14), Barcelona, Spain: Proceedings, *in* Journal of Geochemical Exploration, v. 69–70, p. 1–714.
Consortium on Hydrocarbon Sealing Potential of Faults and Cap Rocks began at Australian Petroleum Cooperative Research Center (APCRC) (leader: John Kaldi).
Short Course and Field Trip on "Characterization and Modeling Fluid Flow in Fault and Fracture Zone: The Reality and the Idealized" (by J. Caine, J. Evans, and C. Forster), GSA Annual Meeting (November 13–16), Reno, Nevada.

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Gordon Research Conference on "Rock Deformation: Deformation Mechanism and Mode of Failure Transitions in Rocks," Barga, Italy.

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EAGE International Conference and Fieldtrip on "Fault and Top Seals: What Do We Know and Where Do We Go?," Montpellier, France, and sponsored by Shell and TotalFinaElf.

Session on "Why Do Traps Fail?," at AAPG International Meeting, Barcelona, Spain.

GSL Meeting on "Micro-to-Macro Finale: Understanding the Micro-to-Macro Behaviour of Rock-Fluid Systems," London, United Kingdom.

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