Understanding tectonic stress in the oil patch: The World Stress Map Project

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Knowledge of the present-day tectonic stress is essential for numerous applications in petroleum exploration and production and in civil and mining engineering, such as improving the stability of boreholes and tunnels and enhancing petroleum production through natural or induced fractures. The World Stress Map (WSM) Project is a collaborative project between academia, industry, and government that is building a comprehensive global database of present-day stress information to better understand the state and sources of contemporary tectonic stress in the lithosphere (Figure 1).

The WSM is a public-domain project that has, since 1986, compiled a database of more than 14 000 quality-ranked present-day stress indicators and which provides its stress database, stress maps, software, and services free of charge. The WSM has provided key insights into the state of plate-scale and regional stress fields in the earth's crust and revealed that these are primarily controlled by forces exerted at plate boundaries, in particular mid-ocean ridges and continental collision zones. However, comparatively little is known about the state of stress at smaller regional-to-local scales, especially in sedimentary basins where knowledge of the local stress field is critical for improving borehole stability, designing hydraulic fracture stimulations and planning of water-floods. While some sedimentary basins exhibit roughly uniform stress fields (e.g., the Western Canada Basin), many others exhibit numerous small-scale variations in stress orientation (e.g, central North Sea). Local scale stress variations are believed to result from complex far-field forces, geological structures (e.g. diapirs, faults) and mechanical contrasts (e.g. evaporites, overpressured shales). However, the occurrence and origins of small-scale stress fields in sedimentary basins remain poorly understood, primarily through a lack of stress data. Indeed, very little is known about the state of stress in the world's major petroleum provinces, including the Middle East, northern Africa, and the offshore Gulf of Mexico, despite almost 20 years of data collection and the widespread application of stress data for issues affecting petroleum exploration and production.

Herein, we summarize the WSM database and services and examine the sources of stress that control plate- to local-scale stress variations in the crust, with a particular emphasis on present-day stress fields in sedimentary basins. We also summarize the WSM's database and services and some initial results of the Present-Day Stress in Sedimentary Basins initiative, which is compiling a database of stress orientations in the oil-patch to better understand forces controlling stresses in sedimentary basins and to provide a valuable foundation for petroleum geomechanical studies.

The World Stress Map Project. The WSM is a fundamental project for understanding contemporary tectonics and

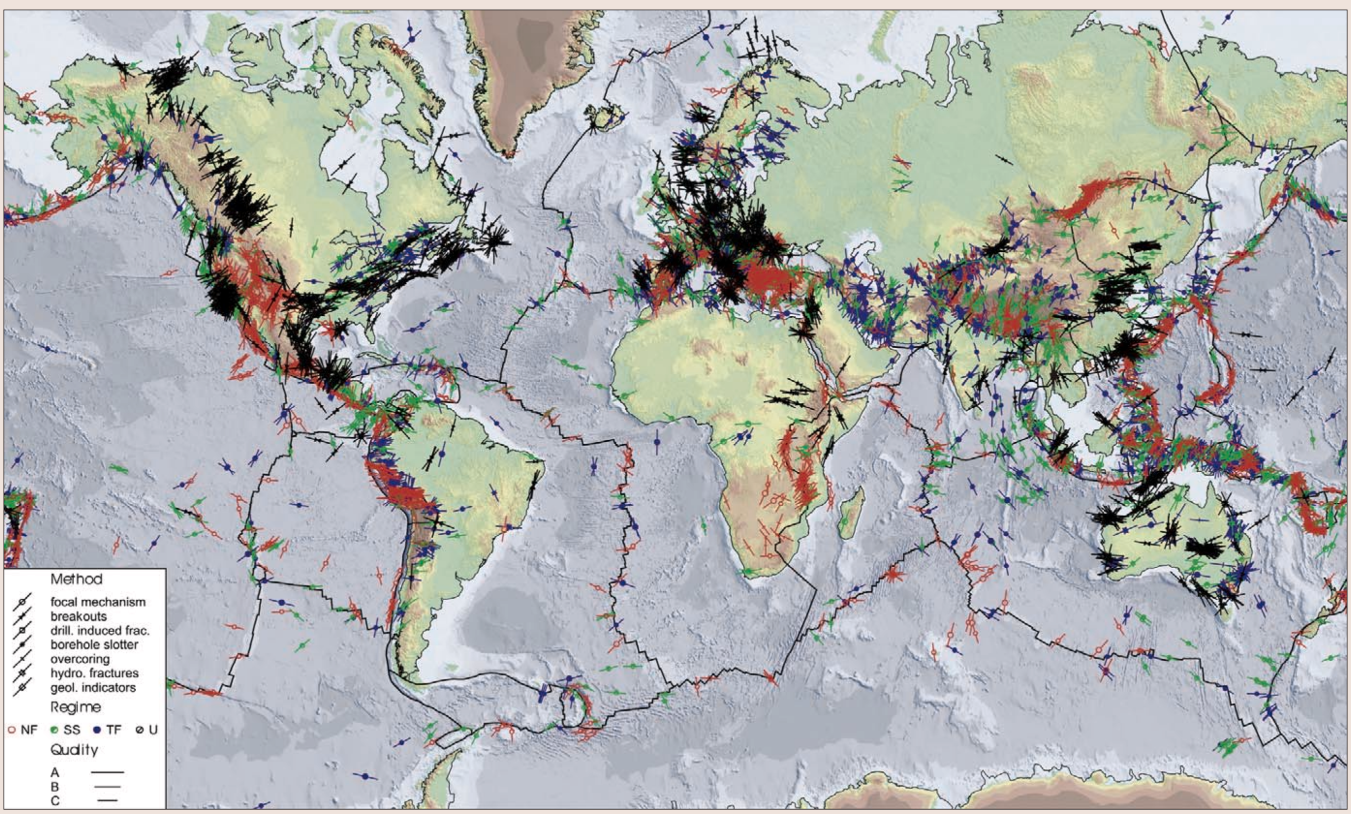

Figure 1. The World Stress Map consisting of more than 10 500 A-C quality stress indicators from a variety of stress measurement techniques. NF = normal faulting stress regime (red). SS = strike-slip (green). TF = thrust fault (blue). U = undefined (black). See legend for more details on symbols. All data and maps are freely available on the WSM Web site: www.world-stress-map.org.

geodynamic processes. The WSM started as a project of the International Lithosphere Program. From 1986 to 1992, the WSM was led by Mary Lou Zoback and involved more than 30 scientists worldwide. Since 1995, the WSM has been a project of the Heidelberg Academy of Sciences and based at the University Karlsruhe in Germany, but it remains a collaborative effort of scientists and engineers worldwide. The project's primary focus is the development and compilation of the extensive, quality-ranked stress database. The 2005 database contains more than 14 000 maximum horizontal stress orientations interpreted from a range of contemporary stress indicators within the upper 40 km of the lithosphere.

Methods for determining horizontal stress orientation. The present-day stress information in the WSM database is estimated from a variety of methods, primarily earthquake focal mechanism solutions, borehole breakouts and drilling-induced tensile fractures (from borehole image or multi-arm caliper log data), in-situ stress measurements (overcoring, hydraulic fracturing) and geologic indicators, such as fault slip and volcanic vent alignment (for a description of these methods see Zoback, 1992). Each technique provides information on the stress field in different depth ranges. Earthquake focal mechanism solutions typically provide information on the state of stress in the deeper crust (5-40 km). In-situ stress measurements such as overcoring and hydraulic fracturing are most commonly used to determine stress orientations and magnitudes in mines and civil engineering projects (e.g., tunnels) and, hence, typically provide stress measurements in the top 1 km of the crust. Geologic indicators such as fault slip analysis provide stress information at the surface. However, herein we focus on stress orientation determination in the oil patch, which is primarily estimated from borehole breakouts and drilling-induced tensile fractures.

Breakouts and drilling-induced tensile fractures are caused by the stress concentration that occurs around boreholes (and around any subsurface opening). Borehole breakouts are stress-induced elongations of the wellbore cross-section and are formed when the circumferential stress concentration at the wellbore wall exceeds that required to cause compressive failure of the formation. The elongation of the wellbore cross-section is the result of compressive shear failure on intersecting conjugate planes, which causes pieces of the borehole wall to spall off (Figure 2a). The maximum stress at the borehole wall occurs perpendicular to the maximum horizontal stress in vertical boreholes and, hence, borehole breakouts develop perpendicular to the maximum horizontal stress orientation. Drilling-induced tensile fractures are caused by tensile failure of the borehole wall and form when the wellbore stress concentration is less than the tensile strength of the rock. Drilling-induced tensile fractures form parallel to the maximum horizontal stress orientation in vertical boreholes (Figure 2b).

Borehole breakouts can be interpreted from oriented four- or six-arm caliper log data (e.g., the High-Resolution Dipmeter Tool) or from acoustic or resistivity image logs (e.g., Formation Micro Imager, Simultaneous Acoustic and Resistivity Imager). The four- or six- arm dipmeter logging tools provide data on the borehole dimensions in 2-3 directions, respectively, which can be used to estimate the shape of the borehole cross-section and distinguish borehole breakouts from nonstress-induced wellbore elongations, such as washout and key-seating. Image logs provide a more reliable and direct means of interpreting breakouts. Breakouts appear on resistivity image logs as a pair of broad, poorly resolved, conductive zones that are parallel to the borehole axis and separated by approximately 180° (Figure 2a). Breakouts appear on acoustic image logs (primarily the traveltime image) as a pair of wellbore elongation zones parallel to the borehole axis and separated by approximately 180°. Drilling-induced tensile fractures cannot be reliably interpreted from four- or six-arm caliper log data, but appear as pairs of narrow conductive features (on resistivity images) or low-amplitude features (on acoustic images) that are generally parallel to the borehole axis and separated by approximately 180° (Figure 2b). Breakout and drilling-induced tensile fractures, in addition to being the primary source of stress information in sedimentary basins, also provide very accurate and reliable stress orientations. breakouts and drilling-induced tensile fractures constitute the majority of the highest quality (A- and B-quality) stress data in the WSM database.

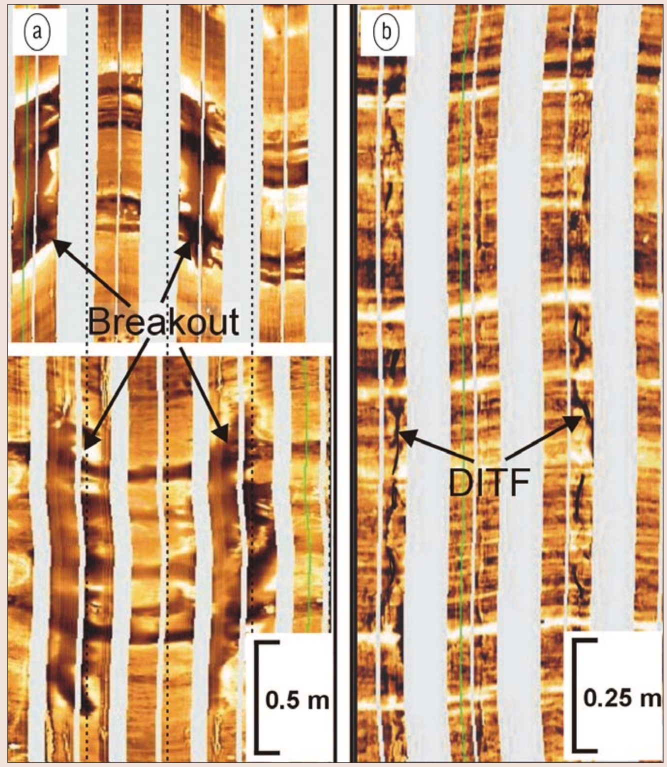

Figure 2. *Examples of (a) borehole breakouts and (b) drilling-induced tensile fractures (DITF) observed on a resistivity image log (Formation Micro Imager). Borehole breakouts are poorly resolved, conductive zones separated by 180° and form perpendicular to the maximum horizontal stress orientation. DITFs are narrow conductive fractures that are typically subparallel to the borehole axis and separated by 180°. DITFs form parallel to the maximum horizontal stress orientation.*

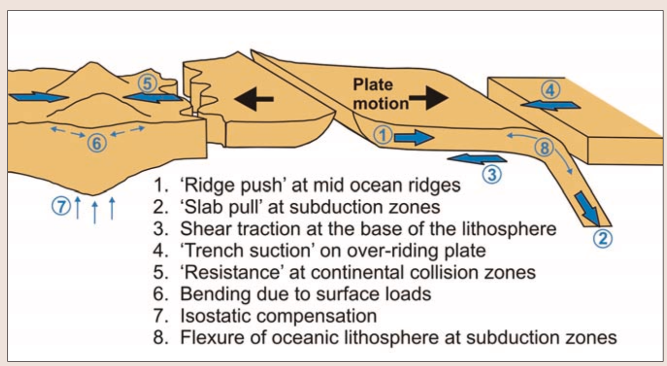

Figure 3. *Forces controlling the present-day tectonic stress field at the plate-scale (large blue arrows) and broad regional scales (small blue arrows). (Adapted from Zoback et al., 1989)*

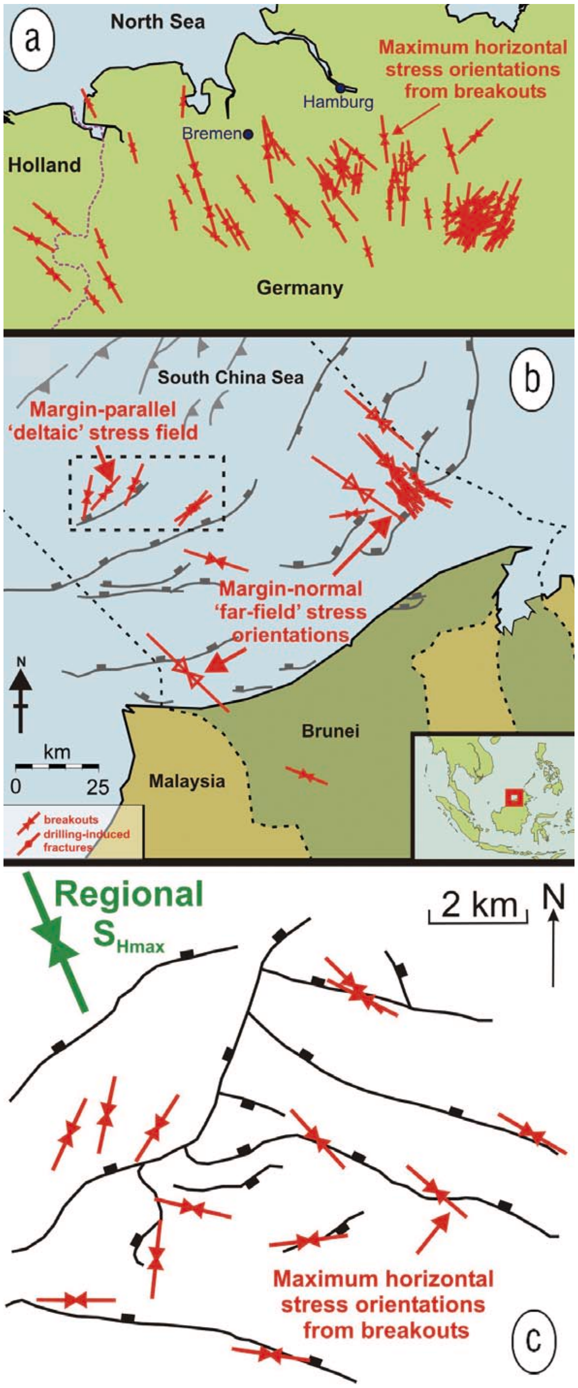

Figure 4. Examples of regional- and local-scale stress field variations in sedimentary basins. (a) Data from borehole breakouts in the North German Basin indicate a regional "fan shaped" stress pattern, with maximum horizontal stress orientations trending from NW-SE in the west to NE-SW in the east. Stress rotation is believed to be the result of a complex interaction between far-field forces exerted by the Alpine front, mid-Atlantic ridge and "pinning" of the Trans-European Suture Zone. (b) The Baram Delta province of Brunei exhibits two orthogonal stress orientations, a "local" margin-parallel (NE-SW) stress field in the outer shelf (boxed region) caused by the shape of the deltaic wedge (see Figure 5) and a margin-normal (NW-SE) stress field in the inner shelf caused by far-field stresses. Note that Miocene deltaic structures in the inner shelf are orthogonal to the present-day stress field, indicating stresses in the inner shelf have rotated 90° since the Miocene. (c) Present-day stress orientations in Quad 15 of the northern North Sea are parallel to the strike of nearby faults and largely inconsistent with the regional stress orientation, suggesting that the faults are controlling the local stress field (After Yale, 2003).

Quality-ranked stress data. A notable feature of the WSM is that every stress indicator in the database is quality-ranked according to internationally developed criteria and is also referenced so that the origin or interpreter of the data point can be traced. The WSM quality ranking system ranges from A-quality (highest; stress orientation accurate to within ±15°) to E-quality (lowest; no reliable stress orientation) and provides an easy assessment of the accuracy, scale, and reliability of each stress indicator. For example, an A-quality stress orientation estimate from borehole breakouts requires the observation of at least 10 consistently oriented breakouts (with a standard deviation <12°) in a single borehole with a total breakout length of over 300 m. Furthermore, the quality ranking of all stress indicators facilitates the comparison of stress data determined from different methods and depths. In general, A, B, and C quality stress indicators are considered reliable for use in analysis of tectonics.

The WSM Web site and services. The WSM is a completely free and public domain project and hence, its entire database and stress maps are available for download at *www.world-stress-map.org*. Users can download any of 65 premade stress maps or create their own custom-made stress map (including their own data) using the Create A Stress Map Online (CASMO) module. The WSM Web site has rapidly become a widely used and invaluable resource for investigating recent tectonics and for applying in-situ stress information to geologic and engineering applications. More than 60 000 stress maps have been downloaded free-of-charge from the site since it went online in 1999. The largest users of the WSM project are geoscientists and engineers from the petroleum industry, who download an average of more than 4000 maps per year. In addition to the database and stress maps, the WSM provides free software to aid users in the interpretation, visualization, and application of present-day stress information.

Results of the WSM Project. *Plate- and large-scale sources of stress in the lithosphere.* The first WSM database release (in 1992) contained more than 4400 reliable stress indicators and provided fundamental insights into the nature and scale of forces that drive geodynamics and crustal deformation at the plate and broad regional (several hundred km) scale. These early outcomes of the WSM revealed that plate-scale contemporary stresses in North America, South America, and Europe are predominately parallel with plate motion. The correlation of stresses and plate motions suggests that the first-order intraplate stress field is the result of forces generated at plate boundaries, primarily midocean ridge "push," subducting slab "pull," trench "suction," and traction at the base of the lithosphere (Figure 3). The WSM's initial phase also revealed that second-order sources of stress, such as isostatic compensation and lithospheric flexure, have a major influence on broad-scale stress fields (Figure 3).

The initial phase of the project provided key revelations into the state and origin of tectonic stress. However, large gaps still remained in the WSM global database, with only very sparse data sets compiled for South America, Africa, Australia, southeast Asia, and the Former Soviet Union. The collaborative efforts of the WSM and numerous individual researchers and stress projects (e.g., the Australasian Stress Map Project) have subsequently expanded the current global stress database to more than 14 000 indicators, including more than 10 500 reliable (A-C quality) indicators (Figure 1). Much of this newly added data is from regions where data were previously sparse or absent (such as in Australia, Eastern Europe, and southeast Asia) and has revealed further insight into broad-scale stresses. In particular, stress data

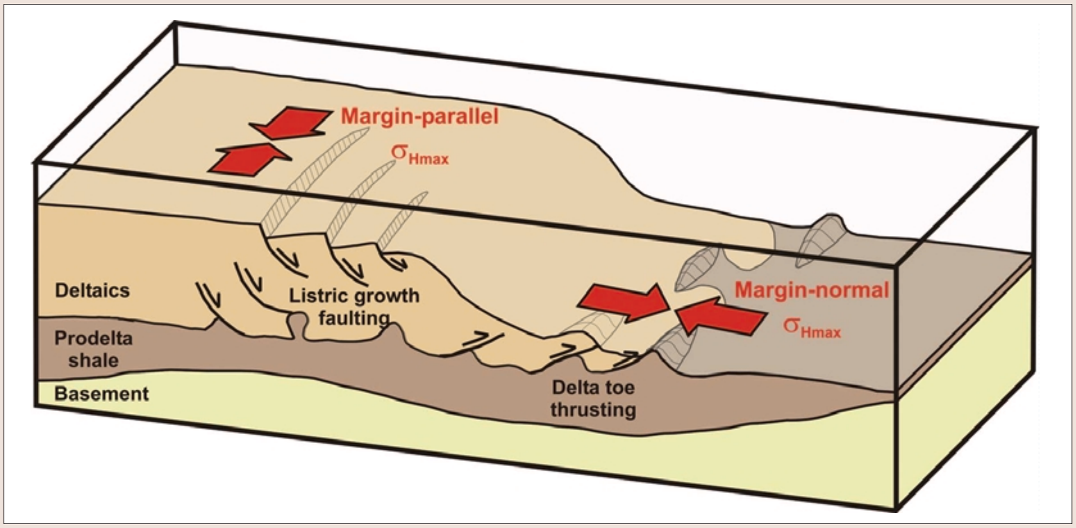

Figure 5. Schematic relationship between present-day stress and structures in passive-margin Tertiary deltas (adapted from Yassir and Zerwer, 1997). The convex upward shape of the clastic wedge promotes gravity-driven extension toward the delta toe, resulting in margin-parallel maximum horizontal stress orientations on the shelf and margin-normal thrusting in the delta toe.

from Australia has demonstrated that forces exerted at continental collision zones also have a critical influence on the plate-scale stress field (Figure 3). Furthermore, large amounts of new data have also been collected in regions with significant data sets (such as sedimentary basins in western Europe) and have provided new insights into regional-to-local scale stress fields.

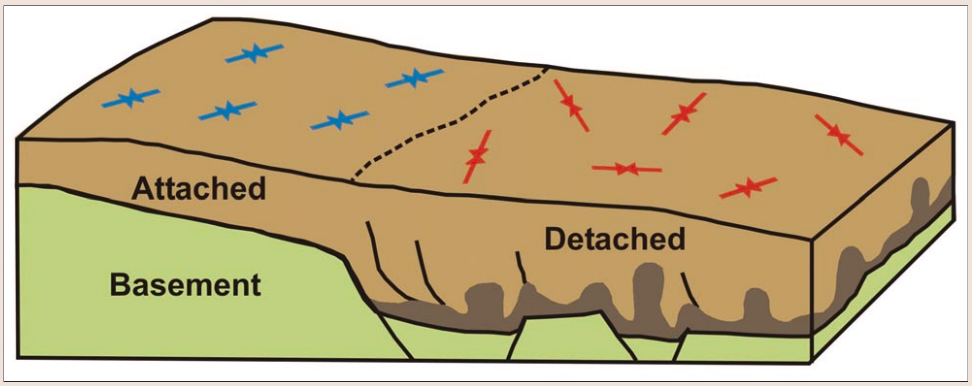

Figure 6. Schematic diagram of stress orientations in regions that are mechanically attached (on the left) or detached from the basement (on the right). Attached regions commonly exhibit consistent stress orientations (blue symbols), generally in line with the broad regional or plate-scale stress field. Stresses in the detached regions are controlled by smaller-scale sources of stress and commonly exhibit highly varied and complex stress orientations (red symbols). Sources of detachment include evaporite layers, overpressured shales, or mechanically "weak" subhorizontal faults. This scenario is observed in the central North Sea, where sequences underlain by the Zechstein evaporites exhibit highly variable stress orientations (after Bell, 1996).

Regional- to local-scale stress fields in sedimentary basins. Present-day stress orientations from borehole breakout and drilling-induced tensile fractures are available for approximately 70 sedimentary basins worldwide. This data allow examination of smaller-scale influences on the stress field. Regional- and local-scale stress perturbations have not been examined as extensively as plate- and regional-scale stress fields and, indeed, are not observed in some high-resolution stress data sets (e.g., the Western Canada Basin). However, despite the plate-scale correlation of maximum horizontal stress orientations with plate motion, numerous high-resolution stress data sets from sedimentary basins indicate that stress orientations are widely scattered in some regions and that orientations can be highly deviated locally from the regional stress orientation (Figure 4).

There are numerous suggestions for the source of the smaller-scale stress fields observed in some sedimentary basins. Regional-scale stress rotations may purely be the result of far-field forces, such as those exerted at plate boundaries or by sediment loading at continental margins. For example, the "fan-shaped" stress rotation observed in the North German Basin is thought to result from the complex interaction of forces exerted by the Alpine front, the mid-Atlantic ridge and "pinning" of the Trans-European Suture Zone (Figure 4a). The regional-scale state of stress in sedimentary basins can also be controlled by the sedimentary structure. Tertiary deltas classically exhibit a margin-parallel maximum horizontal stress orientation on the shelf (e.g., the Mississippi Delta and the outer shelf regions of the Baram Delta) due to the overall convex upward geometry of the deltaic wedge (Figure 5 and Figure 4b). This convex-upward deltaic geometry is also expected to result in the maximum horizontal stress at the delta toe being oriented orthogonally to the margin (Figure 5). The regional stress field may also be affected by topographic variations and by the removal of overburden or deglaciation.

The stress field in sedimentary basins is locally deflected near some geologic structures such as faults and diapirs. The borehole breakouts observed in Quad 15 (Witch Ground Graben) of the northern North Sea indicate that local maximum horizontal stress orientations vary between fault blocks and are highly perturbed from the regional NNW-SSE stress direction (Figure 4c). The maximum horizontal stress orientations within Quad 15 are approximately parallel to the strike of neighboring normal and wrench faults, suggesting that the faults are controlling or deflecting the present-day stress field (Figure 4c). Local-scale stress perturbations (away from the effect of topography) are believed to be the result of mechanical contrasts (e.g., near "weak" material such as salt, overpressured shale, or uncemented fault zones) or through fault activity.

Local-scale stress perturbations are postulated to be greater in regions that are mechanically detached from far-field stresses. Sedimentary basins can be detached from far-field stresses by a mechanically "weak" evaporite, mobile shale or highly overpressured layer that does not allow far-field "basement" stresses to be transmitted into the overlying sequences, resulting in smaller local sources of stress being dominant (Figure 6). For example, sections of the cen-

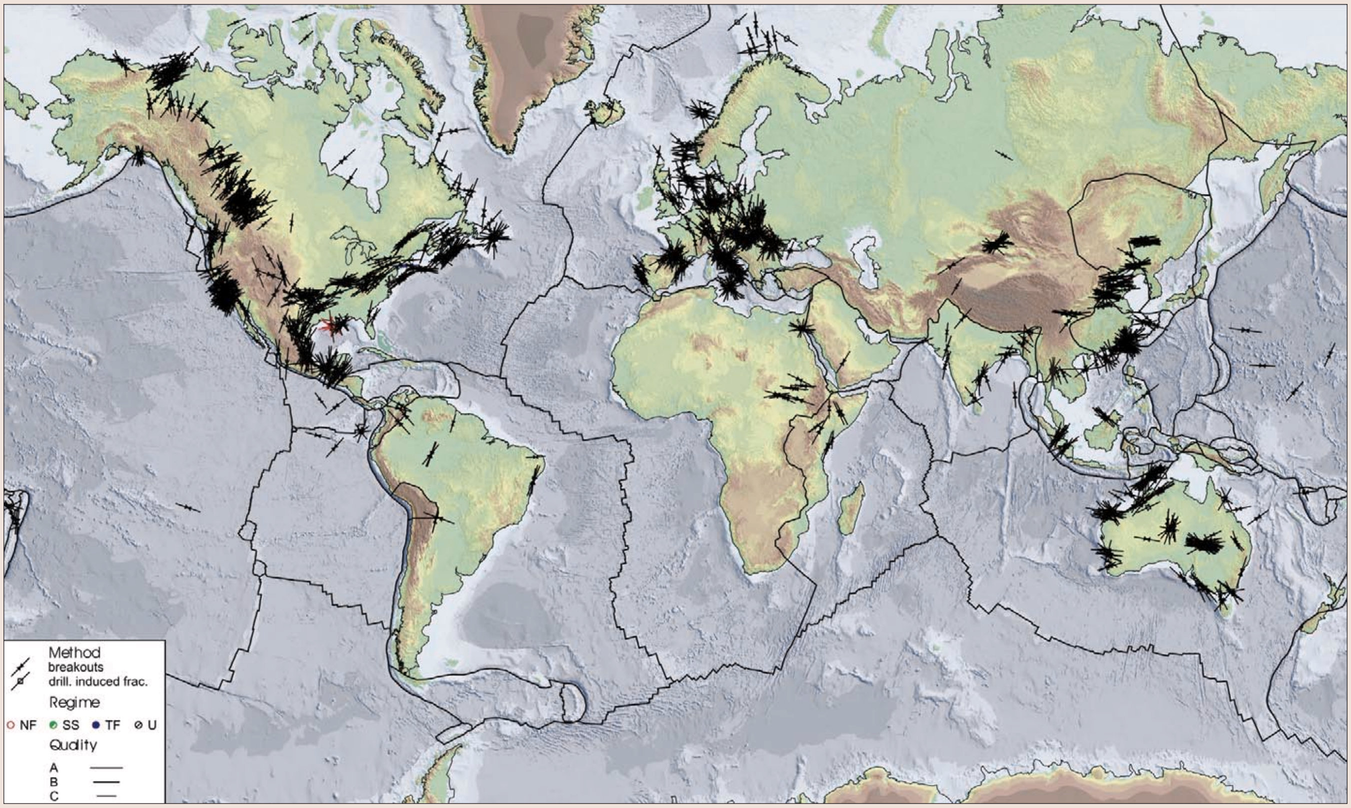

Figure 7. Distribution of A-C quality stress indicators derived from petroleum industry logging data (borehole breakouts and drilling-induced tensile fractures) in the WSM database. Data sets exist and are freely available in approximately 70 sedimentary basins in North America, Europe, Asia, and Australia. However, the state of present-day stress is largely unknown in most of the world's major petroleum provinces such as the Middle East, North and West Africa, the Caspian Sea, and southeast Asia. Such borehole-derived stress data can be directly applied to petroleum geomechanics applications such as fracture stimulation, reservoir drainage patterns and borehole stability, and to understand the forces controlling tectonics. However, the lack of data in many regions prevents users from effectively applying this valuable knowledge to issues affecting petroleum exploration and production. The WSM is currently engaged in a major collaborative initiative with petroleum companies worldwide to determine and understand the present-day stress fields in these regions.

tral North Sea that are underlain by the Zechstein evaporites exhibit no preferential stress orientation whereas the northern North Sea exhibits a broadly uniform regional stress field. However, it is important to note that not all evaporite layers are associated with highly varying local stress fields. The stress orientations and "fan-shaped" stress field in the North German Basin are observed in sequences both above and below the Zechstein evaporites, indicating that the Zechstein evaporites are not acting as a mechanical detachment in the North German Basin and in stark contrast to the highly perturbed stresses in the central North Sea.

The influence of local sources of stress (versus larger far-field sources of tectonic stress) is related to both the magnitude and relative orientation of plate and regional-scale stresses. The influence of local sources of stress is believed to be greater in regions where the horizontal stress magnitudes are approximately equal. Additionally, smaller-scale stress sources that are at high angles to the far-field stress orientation will have relatively stronger influence on the local stress field. For example, the NE-SW oriented local "deltaic" stress field in the Baram Delta province is overprinting the "regional" NW-SE stress field (Figure 4b). Hence, the in-situ stress must be considered as a complex function resulting from all forces acting, from large-scale plate boundary forces to local-scale forces near faults and diapirs.

State of stress in sedimentary basins: Still more questions than answers! The WSM database provides unique insights into the occurrence and controls on the regional- and local-scale stress field in sedimentary basins. However, regional- to local-scale stress fields remain poorly understood in many tectonic settings and basin types (e.g. carbonate platforms), primarily due a lack of borehole breakout data in most of the world's major petroleum provinces (Figure 7). Indeed, very little is known about the state of stress in regions such as the Middle East, northern Africa, Niger Delta, Caspian Sea, and the offshore Gulf of Mexico (Figure 7). For example, the WSM database contains only one reliable present-day stress indicator from wellbore logging data in the entire Arabian Peninsula. This fundamental lack of knowledge regarding the state of stress in most of the world's major petroleum provinces precludes a proper understanding of the occurrence and forces controlling small-scale stress fields. Furthermore, this lack of data and understanding of the origin of the basin- to reservoir-scale stress field prevents geoscientists and engineers from effectively applying this knowledge toward key issues in the oil patch.

Applications of present-day stress data in the oil patch. Present-day stress information is commonly applied to resolve problems affecting petroleum exploration and production, including:

- borehole stability
- reservoir drainage and flooding patterns
- fluid flow in naturally fractured reservoirs
- hydraulic fracture stimulation
- seal breach by fault reactivation

The full present-day stress tensor (magnitudes and orientations) is required to resolve these issues in detail.

However, knowledge of the maximum horizontal stress orientation alone can be applied to improve reservoir drainage, water floods, and hydraulic fracture operations and is critical element in all petroleum geomechanics studies.

The present-day maximum horizontal stress orientation is a primary control on fluid flow in the subsurface, both in fractured and unfractured rocks. Active faults and tensile fractures are able to transmit large volumes of fluid and thereby breach hydrocarbon traps. Active normal or strike-slip faults often strike subparallel or at approximately 30° to the present-day regional maximum horizontal stress orientation respectively. Natural or induced hydraulic fractures in a normal or strike-slip stress regime are predominately vertical and open against the minimum horizontal stress and hence, strike in the maximum horizontal stress orientation. Hence, nonsealing faults are often observed to strike approximately within 30° to the regional maximum horizontal stress direction (Figure 8). Furthermore, fluid flow associated with flooding operations in reservoirs is preferentially in the direction of the maximum horizontal stress, and changes in pumping rates are also more strongly correlated between well pairs that are parallel to the maximum horizontal stress orientation (Figure 8).

The regional and small-scale variations in the maximum horizontal stress orientation displayed in Figure 4 have a critical impact on aspects of field development and petroleum exploration in these regions. Hydraulic fracture stimulation is often used to enhance production in low-permeability reservoirs in the North German Basin. However, fracture design must incorporate the regional change in stress orientation, whereby induced fractures will be oriented approximately NW-SE in the western and approximately NNE-SSW in the eastern sections of the basin (Figure 4a). Fault seal breach by reactivation is an exploration risk in the Baram Delta province. Faults in the outer shelf region of Brunei strike parallel to the maximum horizontal stress orientation and are at a higher risk of reactivation and seal breach than faults in the inner shelf, which strike perpendicular to the present-day stress direction (Figure 4b). The change in stress orientation and reactivation risk appears to have a major impact on the regional hydrocarbon distribution in Brunei. All major hydrocarbon fields discovered in Brunei lie on the onshore and inner shelf regions (low risk of seal breach), whereas only comparatively smaller fields have been discovered in the outer shelf (high risk of seal breach). Borehole instability is a common problem in the North Sea. The mechanical stability of boreholes can be improved by drilling in the orientation that reduces the stress concentration around the borehole. The most stable deviation direction in a normal faulting stress regime ($\sigma_v > \sigma_{Hmax} > \sigma_{hmin}$), believed to presently exist in the North Sea, is perpendicular to the local maximum horizontal stress orientation. Therefore, the most stable drilling direction in Quad 15 will vary between fault blocks, and drilling perpendicular to the regional maximum horizontal stress orientation may result in drilling instability issues such as stuck pipe or collapsed borehole (Figure 4c).

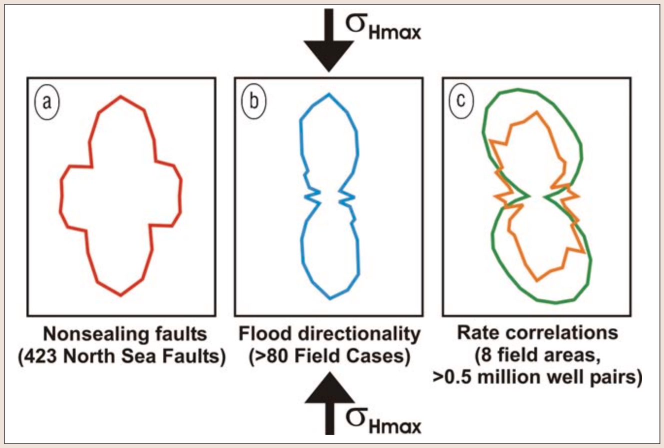

***Figure 8.** Relationship between present-day maximum horizontal stress orientation and subsurface fluid flow (after Heffer and Lean, 1993; Heffer et al., 1997). (a) Comparison between the strike of 423 nonsealing faults and the regional stress direction in the northern and southern North Sea, where the length of axes is proportional to the percentage of nonsealing faults observed. Note that most of the observed nonsealing faults strike subparallel to the maximum horizontal stress. These faults are easier to be reactivated and breached in the present-day stress field. (b) Comparison of flood directionality versus stress in more than 80 fields worldwide. (c) Comparison between the present-day local stress orientation and the strength of correlation between injector and producer histories from more than 500 000 well pairs in eight fields. Rate correlation analysis was conducted using raw monthly production volumes (in green) and where long-period effects (e.g., annual cycles) have been removed (in orange). Note that subsurface fluid flow during injection is predominantly focused in the maximum horizontal stress direction. This focusing of subsurface fluid flow is hypothesized to result from the lower effective stress that acts on faults, fractures, and possibly even grain-grain contacts striking in the maximum horizontal stress direction.*

The Present-Day Stress in Sedimentary Basins initiative: A collaborative effort to understand stress orientations in the oil patch. The numerous and valuable applications of present-day stress information in the oil patch highlight the importance of understanding the state and origin of stresses in sedimentary basins and, in particular, the influence of smaller-scale stress fields. Although broad-scale stress fields have been more widely studied, it is the less well understood regional and local state of stress that is critical for petroleum exploration and production. Hence, in 2004, the WSM began a major endeavor to map the present-day stress field in sedimentary basins worldwide, in order to enhance our understanding of plate- to reservoir-scale stresses in the crust and to build a valuable public resource for issues affecting petroleum exploration and production. The Present-Day Stress in Sedimentary Basins initiative is a collaboration between the WSM and petroleum companies in which the WSM is undertaking free stress orientation analysis of relevant borehole logging data from company archives with the proviso that the average stress orientation for each well be incorporated into the WSM database. This initiative is open to all interested petroleum companies as part of the WSM's public commitment to mapping and understanding the present-day state of stress in the lithosphere. The Present-Day Stress in Sedimentary Basins initiative has already undertaken collaborative stress orientation studies with 10 petroleum companies in various regions worldwide, including North Africa, southeast Asia, and North America. Participating companies are directly applying the valuable results of these collaborative stress studies to issues such as borehole stability and hydraulic fracture stimulation. Furthermore, by compiling the stress data from numerous regions, or from several operators in one region, the WSM is building a quality-ranked database that will allow a greater understanding of the state and origin of stress fields in sedimentary basins.

Conclusions. The World Stress Map Project has spent almost 20 years compiling a comprehensive public domain database of present-day stress information. The quality-ranked stress database, stress maps, and software are available free of charge from the WSM Web site (*www.world-stress-map.org*).

The 2005 WSM database has more than 14 000 stress indicators and reveals unique insights into the state and sources of stress in the lithosphere. Contemporary intraplate stresses are primarily controlled by forces acting at plate boundaries (e.g., ridge push and slab pull) and large intraplate tectonic forces (e.g., lithospheric bending and isostatic compensation). However, high-resolution data sets from petroleum industry data indicate that regional- to local-scale stresses in sedimentary basins can be greatly influenced by geologic structures and mechanical contrasts. Understanding local and regional scale stresses has critical implications for petroleum exploration and production, yet little information is publicly available on the state of stress in sedimentary basins, particularly in the world's major petroleum provinces. The WSM is undertaking free stress orientation studies with petroleum companies in a major collaborative effort to determine the state and origin of contemporary stress in sedimentary basins worldwide. By undertaking mutually beneficial stress studies, the WSM and the petroleum industry are working together to build a highly valuable public resource to aid scientists and engineers worldwide.

Suggested reading. "In-situ stresses in sedimentary rocks (Part 1): measurement techniques" by Bell (*Geoscience Canada*, 1996). "In-situ stresses in sedimentary rocks (Part 2): Applications of stress measurements" by Bell (*Geoscience Canada*, 1996). *Stress Regimes in the Lithosphere* by Engelder (Princeton, 1993). "Earth stress orientation—a control on, and guide to, flooding directionality in a majority of reservoirs" by Heffer and Lean (*Reservoir Characterization III*, 1993). "Novel techniques show links between reservoir flow directionality, earth stress, fault structure and geomechanical changes in mature water floods" by Heffer et al. (*SPE Journal*, 1997). *The Australian Stress Map* by Hillis and Reynolds (Geological Society, Special Publication 157, 2000). *Tectonic Stress in the Earth's Crust: Advances in the World Stress Map Project* by Sperner et al. (Geological Society Special Publication 212, 2003). "Ridge forces, absolute plate motions, and the intraplate stress field" by Richardson (*Journal of Geophysical Research*, 1992). "Fault and stress magnitude controls on variations in the orientation of in-situ stress" by Yale (Geological Society Special Publication 209, 2003). "Stress regimes in the Gulf Coast, offshore Louisiana: Data from well-bore breakout analysis" by Yassir and Zerwer (*AAPG Bulletin*, 1997). "Global patterns of tectonic stress" by Zoback et al. (*Nature*, 1989). "First- and second-order patterns of stress in the lithosphere: The World Stress Map Project" by Zoback (*Journal of Geophysical Research*, 1992). TLE

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