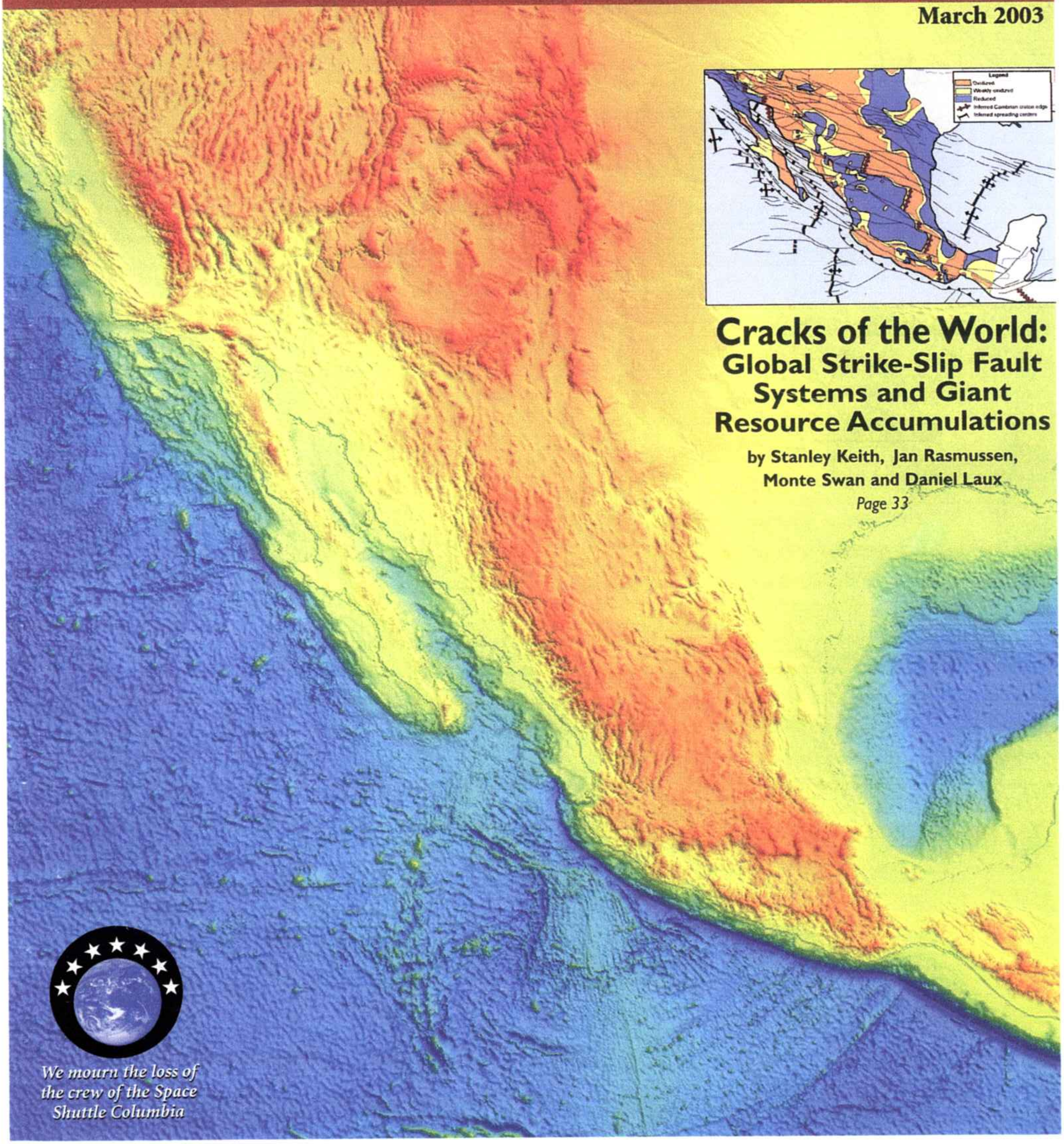
HGS Bulletin

Volume 45 Number 7

Houston Geological Society

March 2003



Cracks of the World:
Global Strike-Slip Fault Systems and Giant Resource Accumulations

by Stanley Keith, Jan Rasmussen, Monte Swan and Daniel Laux

Page 33

We mourn the loss of the crew of the Space Shuttle Columbia

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Cracks of the World:
Global Strike-Slip Fault Systems and Giant Resource Accumulations

Evidence is mounting that the Earth is encircled by subtle necklaces of interconnecting, generally latitude-parallel faults. Many major mineral and energy resource accumulations are located within or near the deeply penetrating fractures of these "cracks of the world." Future exploration for large petroleum occurrences should emphasize the definition, regional distribution, and specific characteristics of the global crack system. Specific drill targets can be predicted by understanding the local structural setting and fluid flow pathways in lateral, as well as vertical conduits, detectable through patterns in the local geochemistry and geophysics.

Future exploration for large petroleum occurrences should emphasize the definition, regional distribution, and specific characteristics of the global crack system.

The faults in the cracks of the world fracture system typically move in transcurrent (strike-slip) motions that are tied to plate tectonics. One of the dynamic driving forces in plate tectonics derives from revolutions about the Earth's rotational axis. Familiar plate tectonic driving mechanisms, such as mantle convective overturn or gravitational trench-pull, become second-order driving forces that are subordinate to the Earth's spin axis. The scale of the kinematic reference frame thus shifts from crustal plate motions to motions between spheres (that is, lithosphere-asthenosphere differential rotations).

At a more local scale, introduction of magma and hydrothermal fluids into the global "crack system" commonly is coincident with kinematic activity in the faults. Indeed, analysis of mineral and chemical fractionation patterns produced during sequential introductions of the hot fluids offers new tools for kinematic and dynamic analysis of the global-scale fracture system. Particularly important are lateral compositional patterns in the mineral zone artifacts of hydrothermal plumes. These lateral patterns reflect motion related to the strike-slip kinematics and inject a new laterality and conceptual opportunity into exploration for commodities deposited by the ascending hydrothermal plumes. The global scale and interconnected nature of the strike-slip fault system in both continental and oceanic crustal materials first became apparent from a regional geotectonic study of Mexico.

The Mexico "Mega-Shear" System

A recent tectonic synthesis of Mexico ore deposits and tectonics has implications for worldwide giant petroleum accumulations and resulted from the incorporation of new constraints related to the regional geographic distribution of crustal oxidation states. Oxidation state is an indicator of oxygen fugacity—essentially the amount of oxygen available for reaction in the Earth's crust. It is as fundamental an Earth property as magnetics or gravity and can be measured directly by the ferric/ferrous ratio in rock or inferred from the whole-rock mineralogy or commodity (element) present. Regional crustal oxidation state patterns shown on the oxidation state map of Mexico (Figure 1) were based on ferric/ferrous ratios, mineral assemblages, and geochemistry from about 2900 plutons and mineral systems.[1]

Petroleum accumulations of all sizes throughout the globe correlate with source and reservoir rocks of low oxidation state where ferric-ferrous ratios are equal to or less than 0.6. In the Mexico region, over 500 additional oil and gas field occurrences were used to constrain crustal oxidation state. Petroleum occurrences can regionally coexist with other ➢ *continued on page 35*

[1]A mineral system is a geographically defined area of alteration, metallization, or hydrocarbon accumulation deposited in a fractionated, zoned reaction sequence from a compositionally distinct, hydrothermal fluid/plume derived from a specific, identifiable source or sources. A magma-metal series mineral system is a mineral system that contains geochemical, mineralogical, and petrological characteristics (in terms of spatially and temporally related magmatism or fluid/volatile expulsions from metamorphosed igneous sources in the basement) that can be classified according to the magma-metal series taxonomy (Keith, 2002; Keith, 1991; Keith and others, 1991; Keith and Swan, 1995; Wilt, 1995).

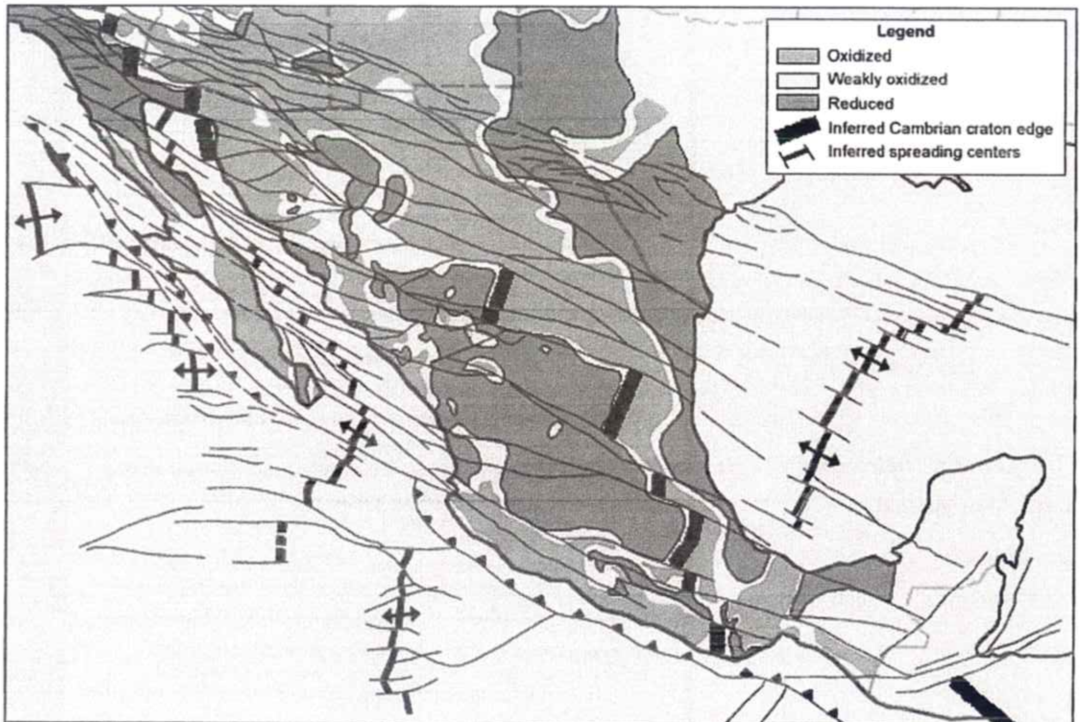

Figure 1—Mexico mega-shear system, showing Cambrian craton edge for western North America in Mexico, inferred ridge system in Gulf of Mexico based on SEASAT gravity, and crustal oxidation state contour map based on pluton ferric:ferrous ratios and associated mineral system compositions.

commodities (such as diamond, gold, and tin, antimony, mercury, lithium, and tantalum) that require low oxidation states for their stability throughout the source-transport-deposition process. Consequently, maps of the regional crustal oxidation state in any particular area are useful as a regional exploration tool for petroleum and many metallic commodities.

The Mexico oxidation state map produced a striking zig-zag pattern (Figure 1). When this is combined with an oxidation state map for the western United States, a southeastward offset of the inferred Cambrian craton edge is apparent. It extends for some 3500 km from Cajon Pass west of Los Angeles, CA, to Guatemala City, Guatemala. The southeastward offset is accomplished on west-northwest-striking fault elements that form a giant, country-wide shear system referred to as the Mexico "mega-shear". The well-known "Texas zone" forms the northernmost structural element of the shear system and the Motagua/Polochic fault system forms the southernmost element. Fault elements within the shear system are defined by sharply telescoped oxidation state gradients, where at least two levels of oxidation state are crossed in very short distances, on the order of 30–50 km. A similar pattern was found for the inferred Cambrian craton edge, which comprises offset segments of north-northeast-striking zones of telescoped oxidation states.

The overall pattern confirms the "Sonoran mega-shear" concept originally proposed by Anderson and Silver (1979). The sense of displacement of the inferred Cambrian margin is along an approximately N50W trend, sub-parallel to the trace of the proposed mega-shear. Individual offsets, however, occur along east-west- to west-northwest-striking, apparently deep-seated fault zones that traverse the entire country of Mexico and adjacent areas. If the 3500-km offset is restored and the Gulf of Mexico is closed, Mexico and northern Central America form a southward-pointed mega-peninsula that fits neatly to the coast of northwestern South America, west of Columbia and Ecuador. This reconstruction elegantly removes the long-known "Bullard-fit problem."

West-northwest-striking fault offsets are also apparent on the gravity map of the Gulf of Mexico (Sandwell and Smith, 1995) on a northeast-trending regional high that has similar characteristics to incipient mid-ocean rifts. For this reason, we believe this north-northeast-trending gravity high was a mid-ocean ridge during the original opening of the Gulf of Mexico. Numerous west-northwest trending transform faults offset the ridge crest along trends similar to those in the present Gulf of California (Figure 1).

The mega-shear system is not confined to the country of Mexico and adjacent regions. Individual fault elements in the Mexico mega-shear extend outward into the Pacific Basin, where they link with the Pacific oceanic fracture system between 18°N and 42°N. A similar, even more dramatic connection is achieved when the Mexico mega-shear system is extended to the east-southeast, where it links, structural element for structural element, with the central Atlantic fracture system between the equator and a latitude of 18°N (Figure 2). In both the Pacific and Atlantic ocean basins, the oceanic ridge system displays an apparent left offset of some 3500 km, in accord with the offset on the Mexico mega-shear system.

The specific offsets in the Atlantic Basin and their presumed Mexican analogs are particularly indicative of a linkage. At the southern end of the Atlantic transform/ ➢ continued on page 37

shear system, large apparent left-lateral offsets of the Atlantic mid-ocean ridge along the Romanche fracture system match well with large offsets of the inferred Cambrian craton edge along the Motagua/Polochic/Cayman trough fault system from its initial position in the Chortis block of Nicaragua-Honduras. This large offset is matched by several minor 50- to 100-km offsets in both the central Atlantic and Mexico mega-shear. About two-thirds of the way northward into both systems, another large offset occurs at the Guinea fracture zones in the Atlantic and the Monterrey-Parras fracture system in north-central Mexico. A series of smaller offsets occurs until the northernmost offset of about 150 km (Barracuda fracture in the Atlantic and the central portion of the Texas zone in southwestern Arizona and southeastern California).

A global network of transform faults apparently links ocean basin to ocean basin through the continents. The continents may not be tectonically inert, rigid blocks: rather, they are active, kinematic participants of the oceanic spreading process.

The Mexico mega-shear, when correlated with its Atlantic and Pacific analogs, goes halfway around the world—extending for about 180° of longitude and ranging from 18° to 25° of latitude in width. The total accumulated offset of 3500 km has incrementally occurred within the last 200 million years. Much of the offset occurred between 175 and 145 Ma, between 125 and 85 Ma, and between 56 to 38 Ma, based on ages of oceanic floor. These offsets in the ocean floor correlate with major tectonic events in Mexico. The offsets occurred at 1) the Oxfordian opening of the Gulf of Mexico, 2) the mid-Cretaceous formation of the Bisbee Trough in the north part of the Mexico mega-shear system, and 3) the Eocene opening of the Cayman Trough and left-slip movements on the correlative Motagua-Polochic fault system throughout Guatemala.

Implications for a New Plate Tectonic Paradigm

If the above global-scale observations are accepted, then mobilistic, terrane-based paradigms of plate tectonics may have to be revised. The mobilistic paradigm of plate tectonics has traditionally assumed that the continental plates are rigid and "float" as passive rafts on a global "conveyor belt" system linked to oceanic-spreading processes. The above mega-shear observations suggest that the continents are also active participants in the oceanic-spreading process. A global network of transform faults apparently links ocean basin to ocean basin through the continents. The continents may not be tectonically inert, rigid blocks: rather, they are active, kinematic participants of the oceanic spreading process. Indeed, the "pre-breakup" fracture architecture of the continents may control the specific locations of the emergent oceanic fracture systems during incipient breakups of continental assemblies such as Pangea. Also, the motion between continental and oceanic plates is not free-faced or disconnected at the trench plate boundaries. Tears in subducting oceanic crust and fracture zones in oceanic crust are anchored to, and connected with, analog fractures in the adjacent and overriding continental plate at the subduction zone interface. They are long lived and play important roles in hydrocarbon formation.

Dynamically, the transform faults can be viewed as manifestations of large-scale motions between the lithosphere and the asthenosphere. The mega-shears largely coincide with latitude-parallel motions that define approximate great-circle planes that are perpendicular to poles of rotation approximately coincident with the Earth's rotation axis. Northward bends in this global crack system (for example, those in the Indian Ocean basin) may reflect a long-term, tectonic wobbling effect around the spin axis. This wobbling may be a manifestation of the non-perfect, oblate-spheroid shape of the Earth and the non-perfect gravity distribution within the planet.

In this more fixist view of plate tectonics, the fundamental motions of the various surface plates are along east-west lines. North-south translations are subordinate, but locally important (for example, the northward translation of India in the northward "wow" segment). Also, in the segments of east-west translations, north-south plate translations after 200 Ma between the North American and Pacific plates in this model appear to be less than the distance between two large, east-west, oceanic fracture zones (about 300 km).

The kinematic reference frame in this new, fixist paradigm changes from a relativistic continental scale to an absolute spherical scale. In the relativistic viewpoint, Africa is commonly held fixed and the other lithosphere plates are moved relative to Africa. In the fixist viewpoint, the lithosphere and asthenosphere are moving clockwise, or eastward, relative to the spin axis as viewed from the South Pole. The clockwise, eastward motion induces contrasting mega-tectonic patterns depending on whether the subduction zones dip in the direction of spin or against the spin. Thus, subduction zones that dip east in the same direction as the flow are flatter, and subduction zones that dip west against the flow direction are steeper. Slab segmentation allows asthenosphere flow "through" subducting oceanic plates.

Dips on the subduction zones suggest a net eastward flow of the asthenosphere relative to the lithosphere. This net eastward motion is recorded by hot spot tracks, such as the Hawaiian hot spot track. This also suggests a net eastward ➢ *continued on page 39*

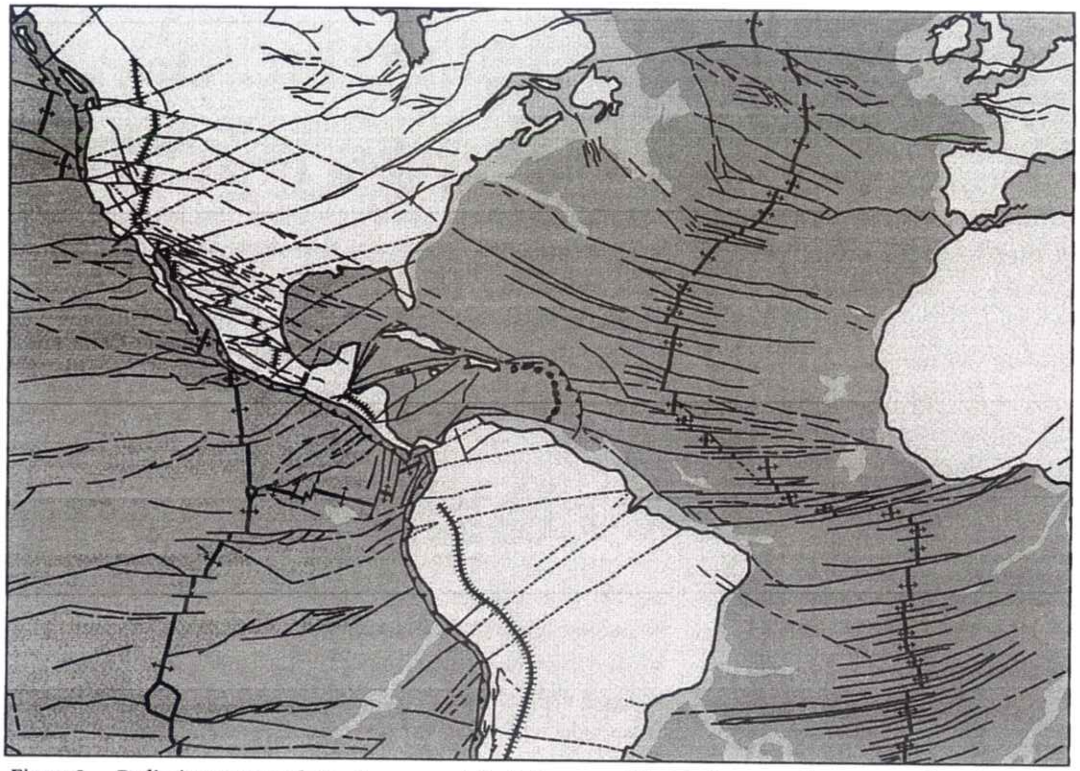

Figure 2— Preliminary map relating transcurrent fault elements of the Mexico mega-shear to transform fracture systems in the adjoining Atlantic and Pacific ocean basins.

motion of the asthenosphere relative to the lithosphere. In the case of the Hawaiian hot spot track, the asthenosphere is moving east-southeastward relative to the lithosphere at about 8 cm/yr since 43 Ma. Similarly, the Yellowstone hot spot is moving east-northeastward at 5.7 cm/yr since 16 Ma, suggesting an east-northeast moving asthenosphere relative to the lithosphere.

At a more global scale, the ultimate reference frame becomes the orientation of the spheres around the Earth's spin axis. In the prevailing plate tectonic viewpoint, plate restorations were exercises in large-scale kinematics. In the newer, more fixist perspective, kinematics can be more easily integrated with dynamic considerations, such as core dynamics, hot spot generation, geo-magnetism, etc. The above model is in accord with and expands upon a similar model of terrestrial plate dynamics developed by Doglioni, (1990, 1992, and 1993).

Summary and Implications for Petroleum Resources

Future petroleum exploration should emphasize domains of reduced crust where deformation is associated with slab-tears and regional trans-current faulting that are related to the global crack system in both continental and oceanic regions.

The tectonic and metallogenic analysis of Mexico revealed patterns of crustal oxidation state and a country-wide, west-northwest fracture system that offsets the inferred Cambrian craton edge some 3500 km westward from its position within the Chortis block of Central America. Furthermore, this fracture system integrates with oceanic fracture systems in both the Pacific and central Atlantic ocean basins and offsets both ridge systems in each ocean basin by similar amounts – 3500 km.

It is now becoming apparent that the Earth is girdled by generally latitude-parallel faults. The tectonic motion of associated plates is tied to transcurrent movement on the strike-slip faults that links continental geology to ocean basin geology. Consequently, the bordering continents are also active players in the spreading history of a given ocean basin. Indeed, the continental architecture may determine the initial positions of the oceanic spreading centers and associated transform faults. These global observations suggest that the ultimate plate tectonic dynamic driving force may revolve around the Earth's rotational axis. Familiar plate tectonic driving mechanisms, such as mantle convective overturn or gravitational trench-pull, become second-order driving forces relative to the Earth's spin axis.

Much of the world's major energy resource accumulations seem to be associated with the deeply penetrating fractures of the cracks of the world. These global cracks control the ascension of magmatic and hydrothermal fluids from depth. Under reduced conditions these fluids may be hydrocarbon stable and could be responsible for fractionation of extensive amounts of hydrocarbon during cooling and deposition in low-pressure sites of the cracks of the world.

Future exploration for giant petroleum fields should emphasize the definition, regional distribution, and specific characteristics of the global crack system. Because of the lateral strike-slip kinematics that accompany emplacement of given hydrothermal fluid plumes, specific drill targets at occurrence sites will be lateral as well as vertical to known resource occurrences. For example, petroleum resources in the largest hydrothermal mineral deposit in the world, the Ghawar field of Saudi Arabia (Cantrell et al., 2002), may be related to deposition of ➢ *continued on page 41*

regional-scale hydrothermal dolomites in a north-northeast-trending dextral slip zone that is 175 miles long and 30 miles wide. This zone is but one element of the previously mentioned north-south segments in the global fracture system.

In conclusion, we believe that significant new energy and mineral resources remain to be discovered by integrating resource occurrences with studies of crustal oxidation state, crustal fluid generation, hydrothermal plume fractionation/zonation, deep cracks, and a globally interconnected fracture system. ■

Biographical Sketch

STANLEY B. KEITH has over 30 years of successful exploration experience in minerals and energy. Upon earning BS and MS degrees in geology from the University of Arizona, he became a field and research geologist focused on mineralogy, geologic mapping, stratigraphy, tectonics, and isotopic age dating. At Kennecott and the Arizona Geological Survey in the mid-1970s he recognized an empirical relationship between mineral deposits and magma series. He co-founded MagmaChem Exploration in 1983 for mineral exploration, working on numerous exploration and research projects for both mineral and energy exploration companies. Currently he is a founding researcher with Sonoita Geoscience Research, an industry-supported consortium that applies hydrothermal and economic geological theory and techniques to petroleum exploration.

JAN C. RASMUSSEN earned her BS and MS in geology, specializing in sedimentary petrology and stratigraphy, and a PhD in economic geology, from the University of Arizona. She is an expert on the geology of the southwest and has written many books, field trip guides, and articles about Arizona geology, mostly as Jan C. Wilt, during her employment at the Arizona Geological Survey. She was a member of the Arizona Oil and Gas Conservation Commission for 10 years, and its chairman for 2 years. Over 30 years as a geologist, she has worked for Woodward-Clyde, the Arizona Geological Survey, and as independent consulting geologist associated with MagmaChem since 1984. She is a founding researcher with Sonoita Geoscience Research.

MONTE M. SWAN received his degrees in geological engineering and geology from Michigan Technological University in 1970 and the University of Arizona in 1975. He has more than 30 years of experience as an international exploration and research geologist in both the mineral and oil and gas industries. Swan's early career with Kennecott Geologic Research focused on basement structure and he spent extensive time performing field mapping. While a co-founder of MagmaChem Exploration, he co-developed the MagmaChem technology that has contributed to ten major gold and copper discoveries on three continents while managing MagmaChem's Colorado office. More recently his structural and engineering experience has led to a new fluid migration model in strike-slip settings. He is a founding researcher with Sonoita Geoscience Research.

DANIEL P. LAUX has over 19 years experience as an exploration and mine geologist. He received a BS in geology from Arizona State University in 1983. Laux worked in copper mines in Arizona and gold mines in Nevada, and has explored for mineral resources throughout western North America. His association with MagmaChem Exploration began in 1984 where he developed a passion for obtaining, manipulating, and analyzing geological data. He currently provides support for computer and GIS applications for Sonoita Geoscience Research.

Acknowledgement

The authors wish to thank Kara Bennett for reviewing this paper.

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Don't miss "Global Geophysical Trends" by Mike Bahorich at the Emerging Technology Dinner Meeting on April 3, 2003

Mike Bahorich of Apache Corporation will be the featured speaker for the Emerging Technology Dinner Meeting to be held on April 3, 2003 at the Westchase Hilton. Mr. Bahorich invented two technologies that are used extensively by the oil industry, the Coherence Cube, a method that reveals stratigraphic features and numerically highlights 3-D seismic fault surfaces, and interval/volume attribute mapping, now available on most geoscience workstation software platforms. He is currently serving as the SEG President for the 2002-2003 term.