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Paleostress directions from the preferred orientation of closed microfractures (fluid-inclusion planes) in sandstone, East Texas basin, U.S.A.

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Abstract—Closed extensional microfractures are useful indicators of paleostress directions in shallowly buried quartz-cemented quartz-arenites of the Lower Cretaceous Travis Peak Formation, a tabular sandstone and shale unit approximately 670 m thick that was deposited in the gradually subsiding northern Gulf of Mexico basin. The closed microfractures are syndiagenetic fluid-inclusion-rich planes that have an ENE strike that is subparallel to contemporary quartz-filled extension veins and regional normal faults, indicating that closed microfractures contain the maximum paleostress direction. These microstructures are potentially useful for mapping paleostress trajectories in passive margin and platform settings, particularly where samples are obtained from core. Previous experimental studies of microfracture closure suggest that microfractures evolved into fluid-inclusion planes by dendritic quartz precipitation. In East Texas, microfracture closure may have occurred at temperatures as low as 85°C and depths as shallow as 1500 m.

INTRODUCTION

FEW reliable microscopic kinematic indicators are known for weakly deformed sedimentary rocks such as those in passive margin and platform settings. Small-scale structures that reflect far-field stresses include joints and veins (macrofractures) (Hancock 1985), but in subsurface studies the usefulness of macrofractures is limited by inadequate core recovery and the common failure of core orientation methods in hard, fractured rocks (Nelson *et al.* 1987). Moreover, widely spaced vertical macrofractures are easily missed by vertical core. Structural analysis of subsurface sedimentary rocks with simple strain histories would be improved if reliable paleostress directions could be obtained from thin-section-scale observations.

This study describes the occurrence and orientation of closed extensional microfractures (microscopic planes of secondary fluid inclusions) in the Lower Cretaceous Travis Peak Formation sandstone from the northern Gulf of Mexico basin. Microfractures evolved into fluid-inclusion planes during diagenesis by dendritic precipitation of quartz, either by local-scale diffusive mass transfer ('healing') or by precipitation of material transported over distances greater than grain scale ('sealing') (Lemmlein & Kliya 1960, Smith & Evans 1984). Such planes have been used as indicators of paleostress directions in metamorphic rocks (Tuttle 1949), granites (Holzhausen 1977, Plumb *et al.* 1984, Lespinasse & Pêcher 1986, Kowallis *et al.* 1987) and strongly folded and faulted sedimentary rocks (Knipe & White 1979, Dula 1981, Mitra 1987). In contrast to these deformed rocks, the Travis Peak Formation has had a simple burial history and there are no folds or faults in the areas where core was obtained. Closed microfractures have not previously been sought in such rocks, possibly because closure processes are believed to operate only at higher temperatures (>200°C; Kowallis *et al.* 1987) than many shallowly buried sedimentary rocks have experienced. Results of this study are applicable to the general cases of kinematic analysis of shallowly buried sedimentary rocks in passive margin and platform settings and deformation of massive sandstone during shallow burial and lithification.

GEOLOGIC SETTING

The study area in East Texas is in the northern Gulf of Mexico basin (Figs. 1 and 2), which formed by rifting initiated in the late Triassic to Middle Jurassic as Pangea began to fragment (Buffler *et al.* 1980). Rifting produced thinning and heating of the lithosphere, which subsequently cooled and gradually subsided (Nunn *et al.* 1984), forming a passive margin basin. A thick sequence of predominantly shallow-water Mesozoic and Cenozoic sedimentary rocks, including the Lower Cretaceous Travis Peak Formation, was deposited in East Texas during this thermal subsidence phase of basin evolution.

The Travis Peak Formation extends in the subsurface across East Texas, North Louisiana and southern Mississippi. It rests on limestone at the top of the Jurassic Cotton Valley Formation and is overlain by limestone of the Cretaceous Sligo Formation (Saucier *et al.* 1985). In the study area the Travis Peak is approximately 670 m thick, and depths to the top of the formation range from 1790 to 2925 m. The formation consists of interbedded fine-grained quartz-arenite and subarkose, with subsidiary mudstone. Detrital grains have point contacts that show little grain–grain interpenetration and few stylolites, but abundant quartz cement, averaging 17% whole rock volume, has reduced permeability in much of the formation to less than 0.1 mD (Dutton & Land 1988). Sandstone contains vertical

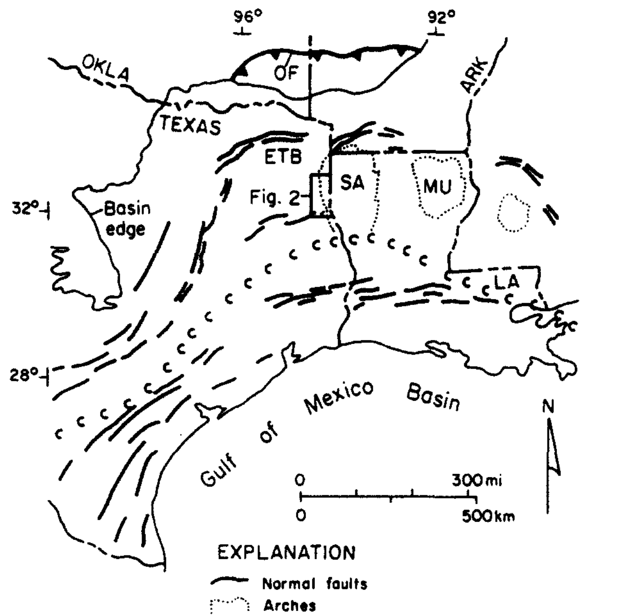

Fig. 1. Regional tectonic setting of the study area in the northern Gulf of Mexico passive margin basin. SA—Sabine arch, MU—Monroe uplift, ETB—East Texas basin, c—Cretaceous shelf edge, OF—Paleozoic Ouachita fold and thrust belt. Basin edge is mapped at the base of the Lower Cretaceous.

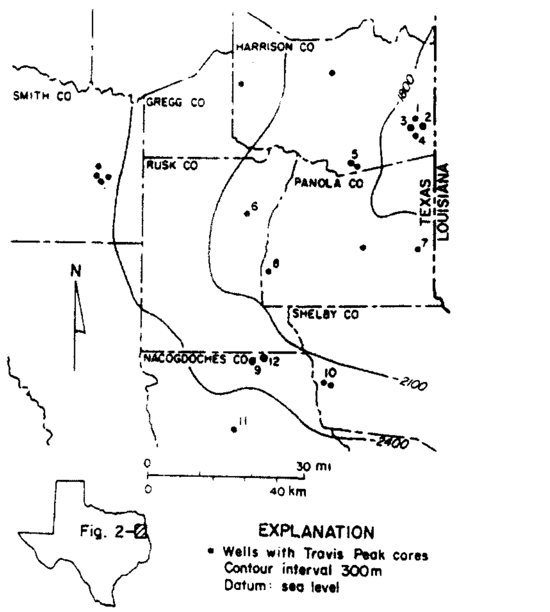

Fig. 2. Location of wells with Travis Peak Formation core used in this study. Contours show structure on top of the Travis Peak. Well 1, Arkla Scott No. 5; 2, Holditch Howell No. 5; 3, Mobil Cargill No. 14; 4, Marshall Abney No. 2; 5, Reynolds Marshall No. 1; 6, Amoco Kangerga No. 1; 7, Marshall Werner Sawmill No. 5; 8, Clayton Williams Sam Hughes No. 1; 9, Prairie Prod. Mast No. 1-A; 10, Arkla Lilly No. 2; 11, Ashland Expl. SFOT No. 1; 12, Holditch SFE No. 2.

ENE-trending macroscopic extension fractures (veins) that are partly filled with quartz and ankerite (Laubach 1988a).

The northern Gulf of Mexico structural province is characterized by gently (commonly less than 1°) dipping beds, open periclinal folds, normal faults and, locally, various structures caused by diapiric movement of salt. The wells cored in this study are located on the west flank of the Sabine arch, a large low-amplitude paleogeographic high that marks the eastern side of the East Texas sub-basin (Fig. 1) (Jackson & Laubach 1988). Episodic movement on E- and NE-trending normal fault zones (Jackson 1982) indicates that mild SSE-directed Mesozoic and Cenozoic extension and SSE-trending least horizontal stress prevailed in East Texas throughout much of the burial history of the Travis Peak Formation.

Current stresses in the Travis Peak primarily reflect loading by overlying sedimentary rocks. The orientation of the greatest principal stress is vertical, and the least principal stress, which is approximately 60% of the vertical stress, is generally oriented SSE, orthogonal to regional ENE-trending faults.

METHODS

Microstructure of Travis Peak Formation rock was determined from 150 thin sections selected from more than 400 m of 10 cm diameter core from eight wells (Fig. 2). Core orientation was by standard techniques (Nelson *et al.* 1987, Laubach 1989). Results generally have an uncertainty of less than 15° within a given well. Samples were cut from core containing veins (macrofractures) and from oriented core that lacked veins. The existence of post-depositional fluid-inclusion planes in weakly deformed sandstone may be readily overlooked because planes are widely spaced and are easily observed only at magnifications that are higher than those routinely employed in sedimentary petrographic studies. Representative thin sections were studied with cathodoluminescence petrography.

Fluid-inclusion-plane attitude was measured on the universal stage from 20 sets of three orthogonal thin sections from one well, Howell No. 5 (Fig. 2, well 2). Because of the small size of the fluid-inclusion planes, it was impossible to identify the same plane in different thin sections to check orientation estimates made with the universal stage. For other wells with oriented core, microfracture attitude at a given depth was determined from single thin sections.

PHYSICAL CHARACTERISTICS OF THE CLOSED MICROFRACTURES

Quartz-cemented quartz-arenites in the Travis Peak Formation contain microscopic (0.1–2 mm long) transgranular and intragranular fluid-inclusion planes, interpreted to be closed microfractures (Figs. 3 and 4). Transgranular planes crosscut grains and quartz cement and therefore post-date deposition of the sandstone. In contrast, intragranular planes terminate within grains or at original grain boundaries and do not cross quartz cement, and have a random orientation. They are probably inherited from a source rock of Travis Peak grains. Transgranular planes occur in closely spaced arrays directly adjacent to veins and as isolated planes in

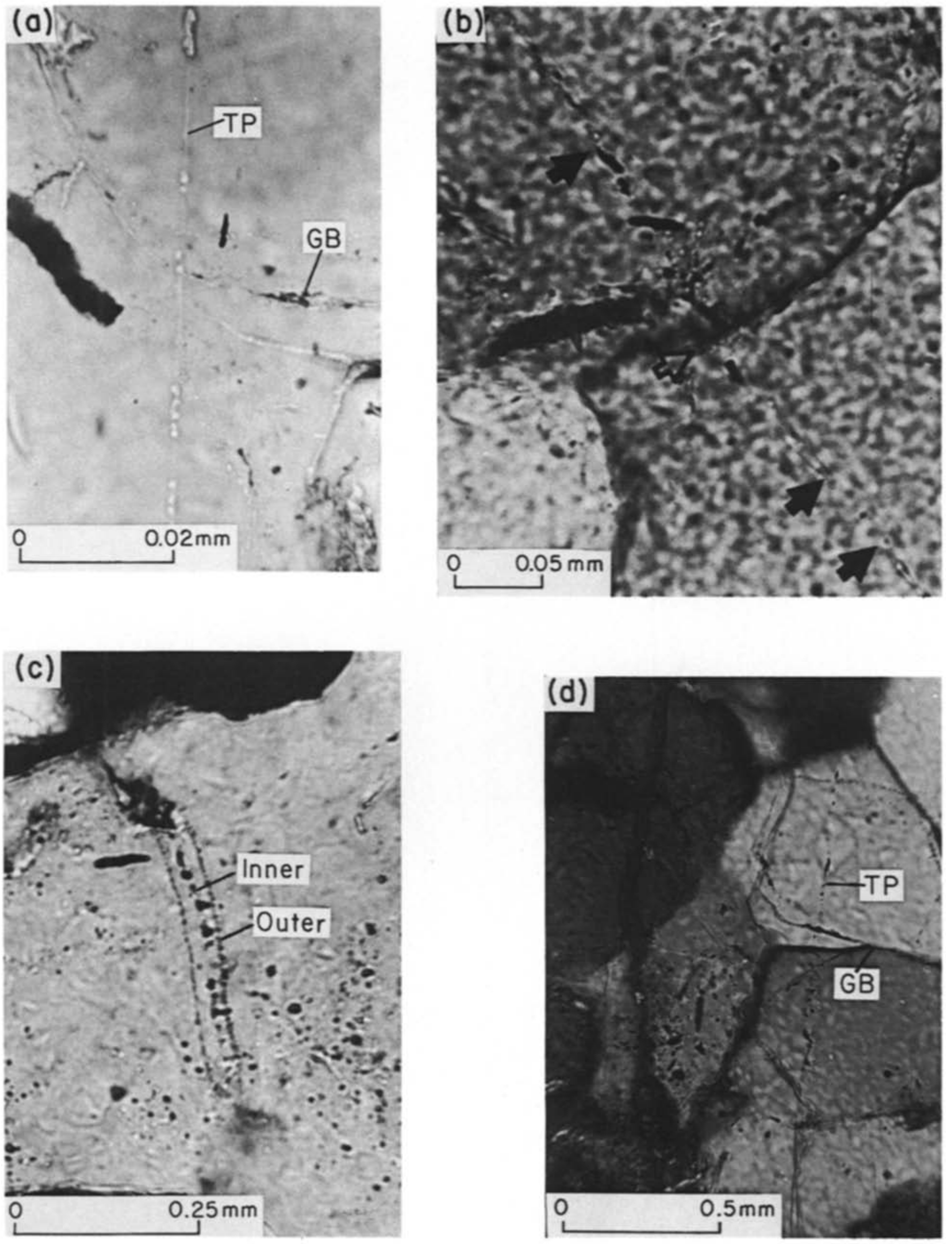

Fig. 3. Photomicrographs of isolated closed microfractures in Travis Peak sandstone. (a) Fluid-inclusion plane (TP), well 8 (2162 m). GB = grain boundary. (b) Plane (indicated with arrows) crossing grain boundary, well 9 (2792 m). Note tabular aspect of fluid inclusions. (c) Several planes of fluid inclusions arranged in a symmetric pattern, well 3; arrows indicate inner and two outer planes. (d) Plane (TP) transecting several grains and cement, well 1 (2271 m).

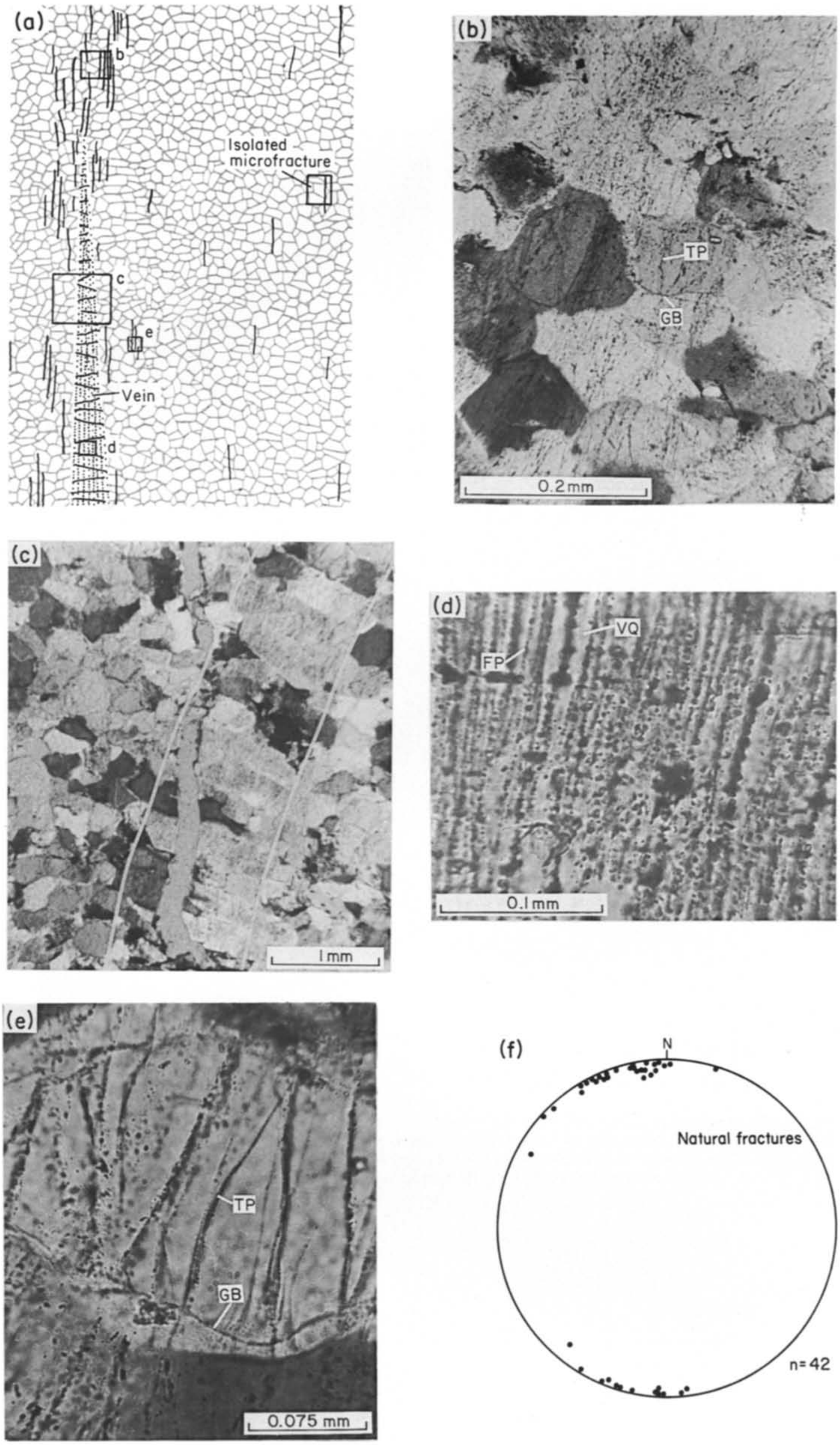
(a)
b
Isolated microfracture
c
e
Vein
d
(b)
TP
GB
0.2 mm
(c)
1mm
(d)
VQ
FP
0.1 mm
(e)
TP
GB
0.075 mm
(f)
N
Natural fractures
n=42

Fig. 4.

rock that lacks veins. Planes are 1–10 μm wide. Locally, dilation parallel to transgranular planes is indicated by quartz-filled discontinuities within disseminated impurities in detrital grains. Grain boundaries are not offset across the traces of transgranular planes (Fig. 3a).

Closed microfractures are composed of closely spaced, small (<10 μm) fluid inclusions that show shapes transitional between tubes and spheres (Fig. 3). Locally, regions of tabular, plate-shaped pores or open microfractures grade laterally into fluid-inclusion planes composed of coplanar cylindrical or spherical inclusions. Fluid inclusions are generally arranged in a single plane, but locally multiple planes occur composed of two outer planes of minute fluid inclusions symmetric about an inner plane of coarser inclusions (Fig. 3c). Commonly intragranular planes consist of widely spaced, irregularly shaped, unequal-sized inclusions, but locally they have small, uniformly shaped, well-aligned inclusions that resemble those in transgranular planes.

The small size of many inclusions in closed microfractures (1–5 μm) hinders microthermometric analysis. Fluid inclusions in the closed microfractures are composed of a single colorless, non-fluorescent phase, possibly a brine. Fluid inclusions in both transgranular and intragranular planes are surrounded by quartz that is in optical continuity with host grains and that appears to have the same luminescence as the quartz cement.

Closed microfractures are generally perpendicular to bedding and are commonly subvertical, but locally, inclinations as gentle as 40° are present. Planes cross cement and grains that have different crystallographic orientation with no deflection, indicating that there is no crystallographic control of plane orientation. Some planes emanate from grain–grain contacts and pass through or near grain centers (Fig. 3b). Other planes cut cement and grains randomly (Fig. 3d) and do not have any specific geometric relation to grain centers or grain–grain contacts. Isolated planes are typically 0.1–0.4 mm long, but locally are as much as 2 mm long. In less highly cemented sandstone, long planes occur where grains are arranged in vertical pillars, but in highly cemented sandstone (>17% rock volume) long planes crosscut grains and cement without regard to grain arrangement.

Microfracture occurrence is highly dependent on rock type, with the greatest number occurring in quartz-cemented quartz-arenites (Fig. 5). Point counts show as many as 10–15 planes per cm^3 in the most highly quartz cemented sandstone, but 0–4 fractures in a single thin section are more typical in less highly cemented sandstone. Microfractures are rare or are absent in rocks with clay matrix, abundant clay cement, or more than a few percent detrital feldspar or calcite cement. Coarser, more poorly sorted rocks tend to contain more planes than do very fine-grained, well-sorted, rocks. Abundance of closed microfractures in Travis Peak samples that do not contain macroscopic veins is much lower than that of some strongly deformed metasedimentary rocks where spacing of fluid inclusion planes may be 0.5 mm or less (Knipe & White 1979, Laubach 1988b). Because of the preferred orientation of microfractures described below, the apparent abundance varies with thin section orientation.

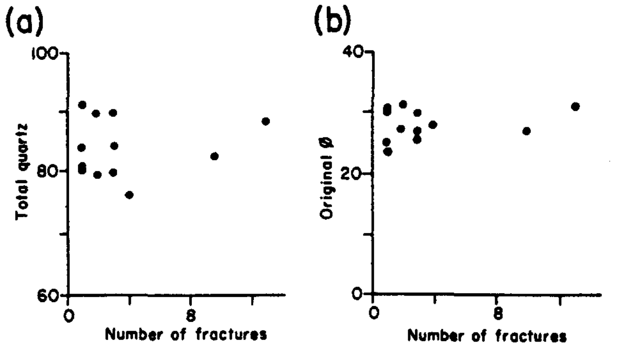

Fig. 5. Relation of number of isolated microfractures in a single thin section to (a) volume of total quartz (detrital quartz plus quartz cement), (b) original porosity (=intergranular volume).

Closed microfractures are most numerous near veins, where they may constitute as much as 2% of the bulk volume of the rock. High concentrations of planes occur within 3–5 mm of veins and in rock adjacent to the ends of veins (Fig. 4b). Closed microfracture spacing in these areas may be as little as 0.25–0.5 mm, and these microfractures are also longer (2–3 mm) than isolated microfractures. The increase in microfracture abundance adjacent to veins (Fig. 6) suggests that microfractures and veins are contemporaneous. Abundant microfractures near veins could result from cracking in the process zone of a growing vein.

Microfractures and adjacent veins are generally subparallel where they occur in the same core. In two samples from the Howell No. 5 well, the mean strike of microfractures is parallel to the strike of the associated vein and most microfractures in the thin section are within 20° of the strike of the vein (Fig. 6). In the SFE No. 2 well, numerous closed microfractures are subparallel to the ENE strike of adjacent veins (Figs. 4a & b).

In rocks that lack veins, microfractures also have a preferred orientation (Fig. 7). Mean strikes of these isolated microfractures vary across the study area, but

Fig. 4. (a) Drawing based on macroscopic crack–seal vein from depth of 3008 m in SFE No. 2 (well 12). Background pattern = sandstone grains and cement; short solid lines = transgranular fluid-inclusion planes seen in cross-section; horizontal lines within vein = columnar quartz crystals normal to vein walls; dotted lines = crack–seal planes parallel to vein walls. The location of microstructures in photomicrographs (b)–(e) are indicated. (b) Multiple, parallel closed microfractures (TP) in rock beyond the termination of the vein. (c) Cross-section of vein, with vein margin indicated. Open crack cutting diagonally across vein was created during sample preparation. (d) Detail of crack–seal fluid-inclusion planes within vein. Planes parallel vein margin. FP = fluid-inclusion plane; VQ = vein quartz. (e) Several closely spaced subparallel closed microfractures (TP) crossing grain boundary. GB = grain boundary. (f) Lower-hemisphere equal-area projection of poles to macroscopic veins, well 12.

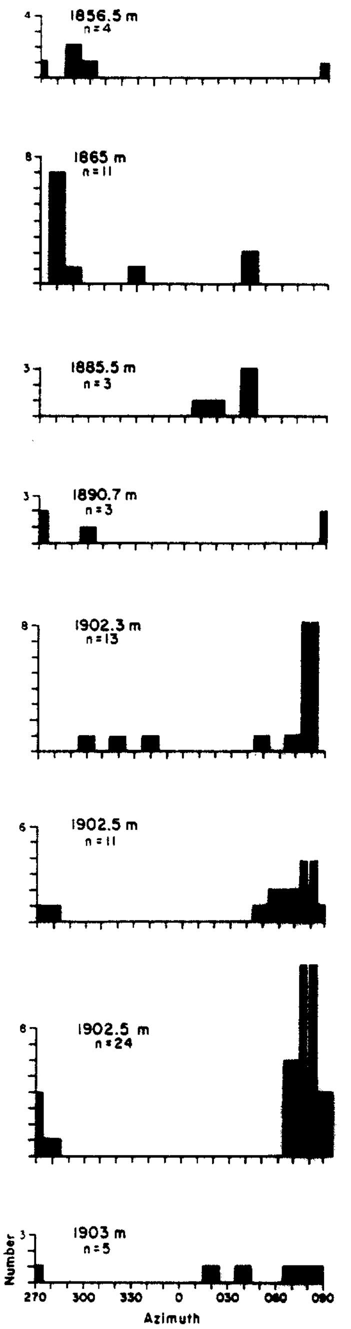

Fig. 6. Preferred orientation of closed microfractures in a single well. Histograms showing number of microfractures that strike in the indicated range. Samples are from various depths in well 2. White bar in histogram indicates strike of macroscopic vein in core from that depth.

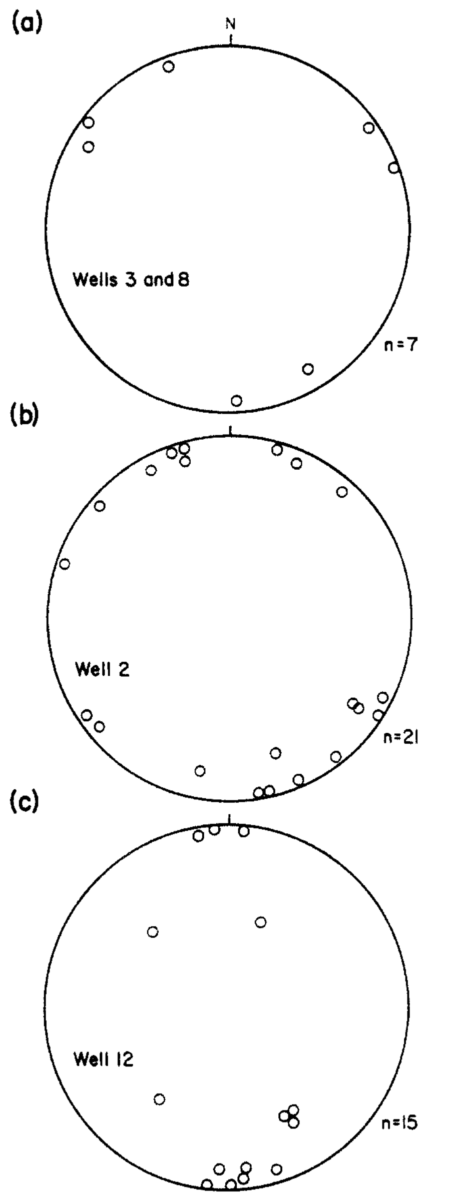

Fig. 7. Lower-hemisphere equal-area projections of poles to closed microfractures not adjacent to macroscopic veins (isolated microfractures). (a) Several depths, well 3 and 8. (b) Planes from several samples from 1903 m, well 2. (c) Several depths, well 12.

generally strike ENE. In the Howell No. 5 well the mean strike is 066 ± 15° and in the SFE No. 2 well mean strike is 084 ± 18° (Fig. 7). Dispersion in microfracture strike is low within a given thin section, where planes are commonly subparallel, but between samples from different depths in the same well, fluctuation in mean microfracture strike is commonly as much as 30° (Fig. 7). Strike of isolated microfractures ranges from 020 to 335°. The vector mean strike of all oriented isolated microfractures measured in this study is 075 ± 21° (95% confidence level). The resultant of the vector mean (R) of 0.6 indicates large strike dispersion. Isolated microfractures are less numerous than microfractures in rocks with veins, so preferred orientation of isolated microfractures is more difficult to document; differences in strike between samples could reflect core orientation errors since the microfractures are not from the same thin section or core piece. Differences in strike between wells may in part reflect real regional differences in natural fracture strike that cannot presently be fully documented because of the lack of a sufficient number of oriented veins; macroscopic veins in the Travis Peak have a large dispersion in strike even within a single well (Fig. 4f).

VEINS (MACROFRACTURES) AND NORMAL FAULTS

The strikes of extensional veins (macrofractures) and normal faults indicate SSE extension in East Texas (Figs. 1 and 4f). Veins within the Travis Peak strike ENE

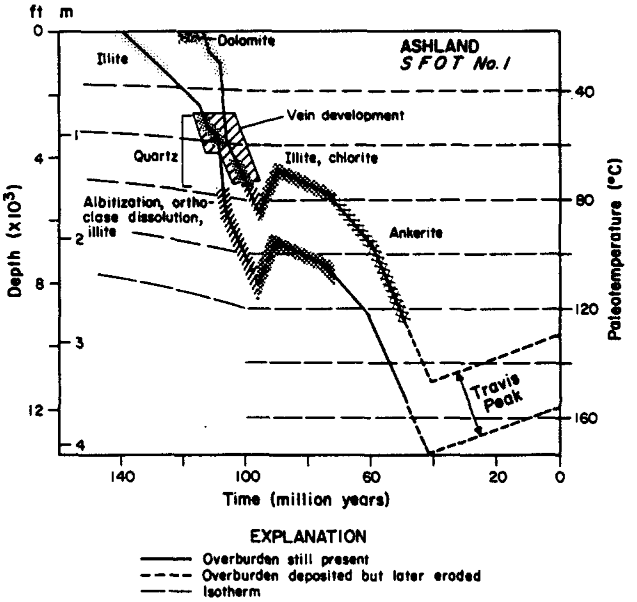

Fig. 8. Representative burial-history curves for the top and base of the Travis Peak Formation (well 11) (modified from Dutton & Land 1988), showing interpreted depths at which major diagenetic events occurred. The depth of formation of macroscopic veins (Laubach 1988a) is also indicated.

to E, with a range of strikes from 028 to 130° and a mean strike of 083°. Veins are subvertical and lens-shaped in cross-section, with widths ranging from microscopic (<0.05 mm) to 5 mm. Quartz and subsidiary ankerite are the main vein-filling minerals. Veins primarily occur within sandstone, and they are most common in rocks with extensive quartz cement. Vein spacing of as little as 2–3 cm occurs locally, but spacing is generally greater than 10 cm. Core from much of the Travis Peak lacks macroscopic veins.

Textures in veins are locally diagnostic of open space filling and record an episodic history of mineral deposition. The sequence of mineral deposition in veins matches the paragenetic sequence of cements (Fig. 8). Microstructures in vein quartz indicate that quartz precipitation was contemporaneous with vein opening (Fig. 4). Vein quartz consists of columnar crystals oriented normal to vein walls. The crystals are subdivided by planes of fluid inclusions that are continuous across multiple quartz columns, parallel to fracture walls, and symmetric about the center line of the fracture (Figs. 4c & d). These microstructures indicate vein growth by crack–seal deformation mechanisms (Ramsay 1980), with each subdivision resulting from an episode of fracture (vein opening) and incremental crystal growth. Fluid inclusions within veins are larger, more irregularly shaped, less closely spaced than the small, uniform inclusions comprising closed microfractures. Locally, fluid inclusions within veins contain internal bubbles that indicate the presence of two phases within the inclusion.

Normal faults were active syndepositionally over 120 Ma and formed by processes associated with gravitationally induced creep of the underlying Jurassic Louann salt (Jackson 1982). Processes that have been recognized include movement on a décollement in salt, crestal extension and collapse over salt pillows and turtle structures, and salt withdrawal. Although faults are distant from the wells sampled in this study and are not the direct cause of the observed veins and microfractures, stratigraphic evidence of repeated movement on these faults suggests that mild SSE-directed extension prevailed in East Texas throughout much of the burial history of the Travis Peak Formation.

CONDITIONS OF MICROFRACTURE CLOSURE

The burial and thermal histories of the Travis Peak Formation (Dutton & Land 1988) indicate shallow-burial (<3900 m), low-temperature (<170°C) conditions for the formation of fluid-inclusion planes. Closed microfractures are in cores from depths ranging from 1800 to 3034 m. Burial-history curves show that the maximum burial depth for the base of the Travis Peak Formation was less than 3900 m (Fig. 8). Most samples in this study are from the upper part of the Travis Peak, where maximum depth of burial would have been less. The geothermal gradient in the study area is 38.3°C km^{-1}, but it may have been higher in the past due to rift-related heating (Dutton & Land 1988). Isotopic compositions of cements, as well as vitrinite reflectance and thermal gradient data, indicate that the maximum temperature reached by the deepest part of the Travis Peak Formation sampled was less than 170°C (Fig. 8). Microfractures must have formed at shallower depths and lower temperatures than these.

The depth of cement precipitation estimated from burial-history curves and the isotopic composition of quartz and ankerite (Dutton & Land 1988) are also indicators of the depth of vein formation, since the paragenetic sequence in veins and matrix is the same (Fig. 8) (Laubach 1988a). Moreover, preliminary microthermometric analysis of fluid inclusions in veins in one well suggests entrapment temperatures of 85–100°C, consistent with the low-temperature, shallow-burial depth conditions of fracture formation inferred from the burial history. If closed microfractures are contemporaneous with veins, as the increase in microfracture abundance adjacent to veins suggests, microfractures may have formed while the top of the Travis Peak was within 1500 m of the surface, when the temperature in the formation was between 75 and 85°C.

The morphology of the fluid-inclusion planes suggests that they are derived from microfractures by healing or sealing processes (Lemmlein & Kliya 1960). Experimental results show that microfractures can evolve into fluid-inclusion planes either by dissolution and reprecipitation of minerals on a local scale by diffusive mass transfer ('healing'), or by precipitation of material transported over distances greater than grain scale ('sealing') (Smith & Evans 1984). The fluid-inclusion planes resemble planes in granite and metamorphic rock interpreted to be healed microfractures (Tuttle 1949, Simmons & Richter 1976, Sprunt & Nur 1979), but no compelling evidence was found to discriminate between these processes in the Travis Peak. Crack–seal structures in macroscopic veins (Fig. 4) indicate precipitation of silica transported over distances greater than grain scale, but structures that might indicate reopening of microfractures are rare in transgranular planes (Fig. 3c). Cathodoluminescence studies show no differences in luminescence between quartz cement and quartz in isolated fluid-inclusion planes, suggesting that quartz between fluid inclusions is compositionally similar to that of the quartz cement. Local gradations from tabular inclusions to planes of evenly spaced, spherical inclusions suggest that fracture healing has occurred (Smith & Evans 1984). The temperature and pressure under which fractures heal or seal in nature are poorly known, but the rapidity of experimental healing in the 200°C range in the presence of water suggests that this process could operate in the diagenetic environment (Burrus 1981, Smith & Evans 1984).

CLOSED MICROFRACTURES AS KINEMATIC INDICATORS

Transgranular fluid-inclusion planes in the Travis Peak Formation are microfractures that evolved into fluid-inclusion planes in the diagenetic environment. Planes that are continuous across cement or several sedimentary grains must have formed *after* sandstone deposition, and cannot be inherited from source rocks that ultimately provided clastic grains for the Travis Peak. Lack of grain boundary offset indicates that they were extension fractures.

Isolated closed microfractures in the Travis Peak are paleostress direction indicators because they are derived from extensional microfractures and because they have a preferred orientation on the scale of a thin section. They also have a consistent orientation over a wide region. Microfracture attitude generally does not reflect stress concentrations between individual grains (i.e. Gallagher *et al.* 1974), probably because the pervasive quartz cement made the rock mechanically homogeneous. Instead, microfractures have a range of attitudes similar to those of veins. Isolated microfractures from a narrow depth range in a single well (Fig. 7c) show fluctuation in strike that is comparable to the fluctuation in strike of macroscopic veins (Fig. 4f). Where veins and microfractures occur in the same samples, differences between them in strike are small (Fig. 6). These results suggest that closed microfractures can be used to determine fracture attitudes in Travis Peak sandstone.

The ENE preferred orientation of closed microfractures is similar to the mean strike of regional normal faults and veins in the study area. All of these structures indicate SSE late Mesozoic and Cenozoic extension. The fluctuation in the strike of isolated microfractures from a wide region (Fig. 7), together with the range of attitudes of macroscopic veins suggests that paleostress trajectories vary across the eastern margin of the East Texas basin. Macro- and microfractures are subparallel to the modern greatest horizontal stress in East Texas, reflecting the near parallelism of modern and paleostress trajectories in this area.

In sedimentary rocks deposited in passive margin basins during thermal subsidence, macroscopic veins are among the most reliable indicators of strain history (Hancock 1985). Fracture orientations are difficult to obtain in subsurface studies of such rocks because of sparse fracture occurrence and failure of core orientation methods. In highly cemented, hard sandstones like those of the Travis Peak, the problem of obtaining oriented core is especially severe, and macrofractures may further interfere with core orientation procedures. In one Travis Peak well in this study, only one oriented macrofracture was obtained in over 130 m of core. Because core orientation methods are generally more successful in rock that lacks macrofractures (Nelson *et al.* 1987), the widespread occurrence in quartz-cemented sandstone of closed microfractures that have a preferred orientation can significantly augment analysis of subsurface fracture attitudes. In this study, analysis of closed microfractures approximately doubled the number of oriented fractures and provided information on fracture attitude in areas where no macroscopic veins were successfully oriented by conventional techniques.

In addition to providing needed data for tectonic analysis of regions with simple burial histories, information on fracture attitude has practical applications for structural analysis of many low permeability hydrocarbon reservoirs such as the Travis Peak Formation, where natural fracture orientation can have a significant influence on reservoir quality and reservoir stimulation engineering operations (Laubach 1989). The close relationship between the occurrence of pervasive quartz cement and the formation of quartz veins and closed microfractures in the Travis Peak suggests that similar closed microfractures may be present in other sandstones where low permeability is the result of quartz cementation.

CONCLUSIONS

The burial and diagenetic history of the Travis Peak Formation shows that fluid-inclusion planes formed by healing or sealing of microfractures at temperatures less than 200°C, and perhaps at temperatures as low as 85°C, and depths of as little as 1500 m. These results agree with experimental studies that document rapid reprecipitation of dendritic quartz in microfractures at 200°C in the presence of water (Smith & Evans 1984). Results from the Travis Peak show that microfracture closure at shallow depths and low temperatures is more common in sedimentary rock than previously thought.

Closed microscopic extension fractures are parallel to macroscopic veins where both occur in the same rock. Isolated microfractures have a preferred orientation that is similar to the ENE strike of regional normal faults and macroscopic extension veins, indicating that the closed microfractures are normal to the regional extension direction. Because oriented core containing veins is difficult to obtain, isolated closed microfractures may be useful in core-based studies of slightly deformed rock for determining natural fracture strikes and mapping paleostress trajectories.

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REFERENCES

Buffler, R. T., Watkins, J. S., Shaub, F. J. & Worzel, J. L. 1980. Structure and early geologic history of the deep central Gulf of Mexico. In: *Proceedings of the Symposium on the Origin of the Gulf of Mexico and the Early Opening of the Central North Atlantic Ocean.* Baton Rouge, Louisiana State University, School of Geoscience, 3–16.

Burrus, R. C. 1981. Hydrocarbon fluid inclusions in studies of sedimentary diagenesis. In: *Fluid Inclusions: Applications to Petrology* (edited by Hollister, L. S. & Crawford, M. L.). *Miner. Ass. Canada, Short Course Handbook* **6**, 138–156.

Dula, W. F. 1981. Correlation between deformation lamellae, microfractures, macrofractures, and in situ stress measurements, White River uplift, Colorado. *Bull. geol. Soc. Am.* **92**, 37–46.

Dutton, S. P. & Land, L. S. 1988. Cementation and burial history of a low-permeability quartz-arenite, Lower Cretaceous Travis Peak Formation, East Texas. *Bull. geol. Soc. Am.* **100**, 1271–1282.

Gallagher, J. J., Friedman, M., Handin, J. & Sowers, G. M. 1974. Experimental studies relating to microfracture in sandstone. *Tectonophysics* **21**, 203–247.

Hancock, P. L. 1985. Brittle microtectonics: principles and practice. *J. Struct. Geol.* **7**, 437–458.

Holzhausen, G. R. 1977. Sheet structure in rock and some related problems in rock mechanics. Unpublished Ph.D. dissertation, Stanford University.

Jackson, M. P. A. 1982. Fault tectonics of the East Texan Basin. The University of Texas at Austin, Bureau of Economic Geology Geological Circular 82-4.

Jackson, M. L. W. & Laubach, S. E. 1988. Cretaceous and Tertiary compressional tectonics as the cause of the Sabine Arch, East Texas and North Louisiana. *Trans. Gulf Coast Ass. geol. Soc.* **38**, 245–256.

Knipe, R. J. & White, S. H. 1979. Deformation in low grade shear zones in the Old Red Sandstone, S.W. Wales. *J. Struct. Geol.* **1**, 53–66.

Kowallis, B. J., Wang, H. F. & Jang, B.-A. 1987. Healed microcrack orientations in granite from Illinois borehole UPH-3 and their relationship to the rock's stress history. *Tectonophysics* **135**, 297–306.

Laubach, S. E. 1988a. Subsurface fractures and their relationship to stress history in East Texas basin sandstone. *Tectonophysics* **156**, 37–49.

Laubach, S. E. 1988b. Fractures generated during folding of the Palmerton Sandstone, Eastern Pennsylvania. *J. Geol.* **96**, 495–503.

Laubach, S. E. 1989. Fracture analysis of the Travis Peak Formation, western flank of the Sabine Arch, East Texas. The University of Texas at Austin, Bureau of Economic Geology Geological Circular 89-4.

Lemmlein, G. C. & Kliya, M. O. 1960. Distinctive features of the healing of a crack in a crystal under conditions of declining temperature. *Int. Geol. Rev.* **2**, 125–128.

Lespinasse, M. & Pêcher, A. 1986. Microfracturing and regional stress field: a study of the preferred orientations of fluid-inclusion planes in a granite from the Massif Central, France. *J. Struct. Geol.* **8**, 169–180.

Mitra, S. 1987. Regional variations in deformation mechanisms and structural styles in the central Appalachian orogenic belt. *Bull. geol. Soc. Am.* **98**, 569–590.

Nelson, R. A., Lenox, L. C. & Ward, B. J. 1987. Oriented core: Its use, error and uncertainty. *Bull. Am. Ass. Petrol. Geol.* **71**, 357–368.

Nunn, J. A., Scardina, A. D. & Pilger, R. H., Jr. 1984. Thermal evolution of the north-central Gulf Coast. *Tectonics* **3**, 723–740.

Plumb, R. A., Engelder, T. & Yale, D. 1984. Near-surface in situ stress 3. Correlation with microcrack fabric within New Hampshire granites. *J. geophys. Res.* **89**, 9350–9364.

Ramsay, J. G. 1980. The crack–seal mechanism of rock deformation. *Nature* **284**, 137–139.

Saucier, A. E., Finley, R. J. & Dutton, S. P. 1985. The Travis Peak (Hosston) Formation of East Texas and North Louisiana. SPE/DOE Joint Symposium on Low Permeability Reservoirs, SPE Paper 13850, 15–22.

Simmons, G. & Richter, D. 1976. Microcracks in rocks. In: *The Physics and Chemistry of Minerals and Rocks* (edited by Strens, R. G. J.). Interscience, New York, 105–137.

Smith, D. L. & Evans, B. 1984. Diffusional crack healing in quartz. *J. geophys. Res.* **89**, 4125–4135.

Sprunt, E. S. & Nur, A. 1979. Microcracking and healing in granites: new evidence from cathodoluminescence. *Science* **205**, 495–497.

Tuttle, O. F. 1949. Structural petrology of planes of liquid inclusions. *J. Geol.* **57**, 331–356.