Fault frequency and strain

Alan P. Morris, David A. Ferrill, and Ronald N. McGinnis
DEPARTMENT OF EARTH, MATERIAL, AND PLANETARY SCIENCES, SOUTHWEST RESEARCH INSTITUTE, 6220 CULEBRA ROAD, SAN ANTONIO, TEXAS 78238, USA

ABSTRACT

Faults are among the most numerous deformation features on Earth and are common on other planetary bodies in the solar system. Small faults, in terms of either displacement or trace length, outnumber large faults, and the distribution is well-described by some form of power-law relationship. However, this observation may be of limited practical use for inferring fault populations in inaccessible locations. Toward developing a practical approach to fault prediction, we measured the spacing, orientations, slip directions, and slip form of power-law relationship. However, this observation may be of limited practical use for inferring fault populations in inaccessible locations. Toward developing a practical approach to fault prediction, we measured the spacing, orientations, slip directions, and slip magnitudes (our measure of fault size) of exposed normal faults in outcrops of Cretaceous carbonate rocks in Texas. Using data from these observed faults, we calculated extensional strain for each study locality, and we demonstrate that fault frequency correlates with extensional strain. This approach provides a tool for estimating fault frequency in areas where strain can be inferred or determined and for extrapolating fault frequency from data sets with limited resolution.

INTRODUCTION

Earth’s crust is the source of hydrocarbons and groundwater, which are essential fluids for modern human habitation, and it provides sites for disposal of waste products such as carbon dioxide and high-level radioactive waste. The rock layers that make up Earth’s crust have in most cases been deformed and contain deformation features that influence the ability to extract resources or sequester waste. Faults are among the most ubiquitous and important of geologic structures, and the ability to identify and characterize faults is an essential component of many applied geoscience pursuits, including exploration for oil and gas, groundwater management, waste disposal, and hazard assessment.

In this paper, we explore whether there is a correlation between fault frequency and bulk extensional strain in Earth’s crust under conditions where rock deformation is dominated by brittle faulting. An understanding of a relationship such as this would be useful because independently derived or estimated strain information could be used to predict fault frequency. This relationship would also be useful for predicting the abundance and distribution of small faults; for example, those that accompany the largest faults that are readily mappable in a region or volume of rock. To explore the relationship between extensional strain and fault frequency, we measured a suite of one-dimensional samples (e.g., scan lines and key bed transects) within exposed normal fault systems in Cretaceous carbonate rocks in south-central and west Texas. We calculated extensional strain using measured fault spacing, orientations, slip directions, and magnitudes, and then summed the contribution of each fault to determine the fault strain in the principal extension direction. We show that fault frequency correlates directly with bulk extensional strain. This approach provides an empirical tool for estimating fault frequency in areas where the strain can be inferred or determined and for extrapolating fault frequency from data sets with limited resolution.

BACKGROUND

Much attention has been paid to the scaling characteristics of faults (e.g., Walsh and Watterson, 1988; Marrett and Allmendinger, 1991, 1992; Dawers et al., 1993), driven in part by the need to characterize faults that are below the resolution of seismic-reflection data for hydrocarbon reservoirs (e.g., Pickering et al., 1997). The most commonly used parameter in these studies is some measure of fault size, usually trace length, and some form of power-law, or similar, relationship is used to describe fault-size distributions (e.g., Scholz and Cowie, 1990; Marrett and Allmendinger, 1991; Cowie and Scholz, 1992; Peacock and Sanderson, 1994; Schultz and Fossen, 2002). However, because faults are not evenly distributed throughout Earth’s crust, simply knowing that the fault-size distribution obeys a power law does not permit the characterization (number, size, displacement) of fault populations for specific areas. Some other determinant of the fault population, for example, the fault frequency, is required. In this paper, we use well-exposed normal faults to test whether fault frequency correlates positively with bulk strain. This approach is potentially useful because many types of data analysis and modeling techniques enable estimation of strain distribution through portions of Earth’s crust.

Our study focused on Cretaceous carbonates in extensional tectonic settings of south-central and west Texas (Ferrill and Morris, 2003, 2008) and measured strain as total extension perpendicular to average fault strike. More than 50% of the world’s hydrocarbon reserves are estimated to be contained in carbonate rocks. The Cretaceous carbonates of south-central and west Texas analyzed in this study are hydrocarbon reservoirs in the Texas Gulf Coast and west Texas regions, and they represent well-exposed analogs for many Middle East carbonate reservoirs that are also Cretaceous in age. In addition, along the trend of the Balcones fault zone from Uvalde to Austin, Texas, these rocks host one of the most prolific and economically important carbonate aquifer systems in the world (e.g., Ferrill et al., 2004, and references therein).

Field Methods

Detailed fault data were gathered along either a linear scan line or along individual limestone beds (i.e., key bed transect). The linear scan line method was used where a key bed transect was not practicable for accessibility reasons. No special characteristics were sought in a key bed except that it had to be easily recognizable. Not all faults present in an exposure intersected the scan line, and not all faults that intersected the scan line extended across the entire exposure. In each survey, all
visible faults that intersected the chosen scan line were measured. In this study, we define a fault as a discrete fracture or fracture system that exhibits either: (1) measurable displacement of a primary geological feature (e.g., bedding, sedimentary structure, or fossil) that is greater than the physical width of the fracture or zone; or (2) visible evidence of slip (e.g., slickenline indicators). Exposures characterized in this investigation included road cuts, a construction excavation (HL Chapman location), and a gorge cut by flood waters below a reservoir spillway (Spillway Falls locality).

For each fault, we measured fault orientation in terms of strike and dip, fault slip direction in terms of rake of slickenlines on the fault surface, and displacement parallel to the slickenlines along the fault plane. Where no slickenline indicators were observed, the rake was assumed to be 90° (i.e., dip-slip). This assumption is reasonable for the fault systems considered here because more than 75% of faults analyzed have measurable slip magnitude and rake, and of these, more than 90% have rakes within 5° of pure dip slip. Approximately 99% of the faults measured have normal or normal-oblique displacement. Fewer than 1% of the measured faults exhibit reverse displacement. Displacements as small as 0.005 m were recorded, and no faults in this study have displacements greater than could be determined from the exposed rock.

**Determination of Average Strike Direction from Field Data**

Field data were analyzed to determine average strike direction for each exposure using a Fisher-type analysis (e.g., Cheeney, 1983). The measured faults are predominantly normal dip slip. In addition, lines of intersection between faults and bedding are approximately horizontal with a narrow range of strike variation, and therefore a bed-parallel direction perpendicular to average fault strike is a good approximation of the principal extension direction for the fault system at that exposure. This principal extension direction is the direction in which the strain is summed.

**Scan Line Length and Orientation, and Fault Frequency**

In most exposures, scan-line orientation is dictated by the orientation of the road cut or other exposure. Therefore, the scan lines are typically not perpendicular to the average fault strike. For each fault survey, the orientation and length of the measured scan line were recorded so that fault data could be corrected for its contribution to the overall extension represented by the observed fault population. In most instances, the location of the fault along the scan line was recorded; however, in the few cases where fault locations were not recorded, the number of faults along the scan-line length was used. The faults were projected onto the bed-parallel direction perpendicular to the average fault strike for that locality to obtain a fault frequency, which was calculated as number of faults per meter.

**Strain Determination**

Each fault’s extension parallel to bedding and perpendicular to the average fault strike was calculated for each locality. The sum of all of these extensions represents the bulk or total extension (longitudinal strain) for that locality, which we express as a percentage,

\[ \% = \frac{\sum ext\ m}{L - \sum ext\ m} \times 100, \]

where \( \sum ext\ m \) is the sum of all fault extension values perpendicular to the average fault strike, and \( L \) is the scan-line length projected perpendicular to the average fault strike. Treated in this way, each fault can be placed into the locality-specific population according to its contribution to the bulk extension.

At three of the localities, a small number of reverse faults was recorded. These faults are interpreted as the result of local stress perturbations generated by dip variations in the predominantly normal fault system, and these reverse faults were incorporated into the overall strain estimation and fault count.

**Fault Frequency versus Strain**

Fault frequency is heterogeneous in all of the scan lines measured in this study. However, this is not necessarily known a priori, and we have opted to treat each scan line as a single population. Fault spacing is the inverse of fault frequency, and it can be useful for direct comparisons between localities. Average fault spacing (measured perpendicular to the average fault strike for each locality) ranges from 0.35 m (Spillway Falls) to 21.75 m (Highway 281, 3; Figs. 1 and 2), where standard deviations are close to or greater than the average. A plot of 13 data sets from normal fault systems in south-central and west Texas demonstrates that there is a positive correlation between fault frequency and bulk strain (Fig. 1). This relationship is fit by a line (Fig. 1) defined by frequency expressed in faults per meter = 0.13 × strain (expressed as percent extension). The data presented here suggest that this relationship is reasonably consistent up to ~15% total extension by faults.

**Fault Displacement Distribution**

Another characteristic of these normal fault data sets is that displacement, expressed as extension parallel to the average extension direction for a given exposure, is not partitioned equally among the faults present (Fig. 2; Marrett and Allmendinger, 1992; Walsh et al., 1991; Scholz and Cowie, 1990). In all cases, smaller displacement faults are more numerous than larger displacement faults, yet the largest 30% of the total fault population accommodates 70% or more of the total extension. This is consistent with the previous work of Scholz and Cowie (1990). Fault displacement distributions illustrated in Figure 2 show some variability but a consistent pattern. Shapes of individual fault displacement distributions can be approximated by an equation of the form:

\[ y = 100 \left( \frac{x}{mx} \right)^k, \]

where \( y \) is cumulative percent of total extension, \( x \) is cumulative percent of total faults ranked by displacement, and \( k \) is a constant that determines the shape of the curve (Fig. 3). There is a generally positive, although weak, correlation between \( k \) and bulk longitudinal strain.

Fault populations are commonly regarded as having a power-law relationship between frequency and size: fault populations contain many more small faults than large faults, and a relatively small proportion of largest-displacement faults accommodates most of the total displacement within the population. The precise relationship between fault frequency and bulk strain is likely to be complicated by, and linked to, such variables as rock type; mechanical stratigraphy (particularly rock competence contrast and layer thicknesses); competing rates of fault nucleation versus fault linking and coalescence; and processes active during deformation (also determined by mechanical stratigraphy and pressure–temperature–strain-rate conditions).

There is likely to be a fault frequency that represents a saturation value for any system (e.g., Ackermann et al., 2001; Wojtal, 1986, 1996;
Fault frequency and strain

Sims et al., 2005). The saturation value will also be constrained by these same variables.

Extensional faults like those analyzed in this paper are important controls on permeability in faulted carbonate reservoirs. The results presented here provide the basis for predicting or estimating fault frequency from strain estimates in normal faulting regimes. Strain estimates may come from data-derived estimation such as fault-accommodated strain used in this study, outer arc extension bending strain over a dome or anticlinal crest (Ramsay, 1967; Ferrill and Morris, 1997; Morris and Ferrill, 1999), tangential elongation around a curved orogenic belt (Ferrill and Groshong, 1993), or displacement gradients along faults (Ferrill and Morris, 2001; Morris et al., 2004). Strain estimates also may come from geomechanical modeling or geometric-kinematic forward models. Fault frequency can be estimated as a function of percent extension using the relationship shown in Figure 1. The displacement distribution could be assumed to be in the form of the distributions illustrated in Figures 2 and 3. Assuming that the strain (extension) associated with the observable faults can be measured and that the total strain can be estimated, then the cumulative extension of the measured faults (abscissa in Fig. 3) can be computed. By projecting this value of cumulative extension to the empirical distribution curves and choosing suitable values for k and fault frequency (based on total extension; Fig. 1), we can compute the missing portion of the distribution as illustrated in Figure 4.

Worked Examples

We illustrate this methodology with two worked examples using the fault data from La Cantera N and the Spillway Falls localities. These data sets consist of 63 and 35 observed faults and corrected scan-line lengths of 58.1 m and 14.2 m, respectively, with heaves (calculated from direct measurements of displacement and slickenlines) perpendicular to average fault strike ranging from 0.0009 m to 1.4858 m. If we assume that we can only detect faults in these examples with displacements greater than 0.1 m, then seven faults will be observed at the La Cantera N locality, and eight faults will be observed at the Spillway Falls locality; total observed heave perpendicular to average fault strike would be 3.57 m and 1.54 m, respectively. We then follow this procedure:

1. Assume a percentage of total extensional strain represented by the observed faults.

Figure 1. Fault frequency versus percent extension for the localities in this study.

Figure 2. Fault displacement distribution plotted as cumulative fault contribution to total extensional strain, normalized by total extensional strain. Shaded area represents largest 30% of total fault population. Numbers in parentheses after each locality name are range of fault displacement followed by length of scan line perpendicular to the average fault strike and the number of faults observed in the scan line.

Figure 3. Modeled fault displacement distributions. Curves are labeled with k values (see Equation 2).
2. Calculate the total extensional strain.
3. Using the linear regression relationship in Figure 1, determine the total number of faults that should be present in the locality for the total extensional strain from step 2.
4. Using
   (a) calculated total number of faults,
   (b) assumed total extensional strain,
   (c) assumed percentage of total extensional strain represented by the observed faults, and
   (d) heaves of the observed faults perpendicular to the average fault strike for that locality, construct the uppermost portion of the normalized displacement distribution curve (“observed faults” shown as solid black curves in Fig. 4).
5. Construct a complete “k” curve using the calculated total number of faults that intersects the lowest point of the curve obtained previously; the “tail” of the normalized displacement distribution curve will be the section of this curve from the intersection point to the origin (“simulated faults” shown as dashed line curves in Fig. 4).

The resulting hybrid curves are not ideal “k” curves because the fault displacement distributions are only approximated by “k” curves. However, the range of results for likely values of strain represented by the observed faults (≥70% of total strain; see Fig. 2) provides reasonable estimates of the total number of faults present and their displacement distributions in both examples (Figs. 4A and 4B).

DISCUSSION

This work and a companion study (Morris et al., 2009) indicate that bulk strain and mechanical stratigraphy are important determinants of fault displacement distributions. More sophisticated curve fitting will be required to further improve our approach to representing fault displacement distributions. Although our analysis has focused on carbonate rocks deformed primarily by extension at shallow crustal depths (Ferrill et al., 2004, and references therein), other methods of fault displacement characterization have been successfully applied to different tectonic regimes (e.g., Wells and Coppersmith, 1994). With more field data, relationships introduced here can be extended to other rock types, deformation conditions, and tectonic regimes.

CONCLUSION

Fault frequency is positively correlated with bulk extension in normal fault systems developed in Cretaceous carbonates of south-central and west Texas. This relationship holds true for data sets with strains ranging from 0% to 15% extension. These results can be used to predict the frequency of smaller faults and their displacement distributions in other carbonate rocks deformed in normal faulting regimes using strain as the predictive indicator. Predicting the frequency of smaller faults can help to (1) improve the resolution of hydrocarbon reservoir modeling, (2) better understand groundwater flow paths, and (3) provide better characterization of distributed faulting in potentially hazardous geologic environments.

ACKNOWLEDGMENTS

This work was supported by internal research and development funding from the Southwest Research Institute under project number R9677. The Guadalupe-Blanco River Authority granted us permission to conduct research in the Canyon Lake Gorge, Comal County, Texas. We thank Kevin Smart and Gary Walter for helpful reviews, and Steve Wojtal for comments that considerably sharpened the focus of the paper.
REFERENCES CITED


Printed in the USA