Understanding Fractured Carbonate Reservoirs

Our understanding of fractures in carbonate reservoirs is hindered by low data density, which prevents effective fracture attribute mapping. Despite the advent of image logs and new core-recovery techniques, fracture data are frequently incomplete and sometimes misleading. Sparse sampling of large fractures remains unavoidable. From the interwell region, information is confined to seismic identification of faults and layer curvature. Although there may be a link between layer curvature and fracture intensity in situations where fractures develop during or after layer flexure, if fracturing predates flexure there is no such relationship. Collection of meaningful, systematic data at the well bore and extrapolation into the interwell volume are significant challenges.

New techniques, developed initially in siliciclastic rocks and that use microstructures to predict orientation, population systematics, and openness of macrofracture sets, have been applied to fractured carbonates. We have been able to collect microfracture data in several dolomite studies. Calibration of the microfracture populations with observed macrofracture populations in outcrop analogs is under way. For example, we are conducting an investigation of interwell heterogeneity in Permian Clear Fork dolomite reservoirs found in the Permian Basin of West Texas and New Mexico. The approach is to study the stratigraphy, fractures, and petrophysics of outcrop analogs (Clear Fork exposures) in the Sierra Diablo Mountains, West Texas, and to apply the results to subsurface Clear Fork reservoirs, principally the South Wasson Clear Fork reservoir. We envisage that both the techniques that are developed and the results will be applicable to a wide range of fractured carbonate reservoirs.

Macrofractures in limestones and chalks show many characteristics similar to those of the macrofractures observed in siliciclastic rocks (e.g., power-law aperture-size distributions), but populations of microfractures have proved more difficult to observe in the samples we have studied. In the case of the Austin Chalk, the fracture intensity is so low that even the microfractures have very low intensities on the scale of a thin section. Low fracture intensity limits the technique we have developed to fracture-quality prediction and determination of fracture orientation. Scaling work in these cases requires the use of outcrop analogs. However, information gained from the fracture quality assessment can help to steer outcrop-analog selection because structural diagenesis histories of rocks at outcrop can be matched to those of subsurface rocks as closely as possible.

For subsurface studies, we quantify fracture attributes and flow potential on a bed-by-bed basis using samples from whole core, if available, and wireline-sidewall cores if whole
core has not been taken. Horizontally orientated thin sections are taken in order to establish the fracture orientation(s), crosscutting relationships, and structural diagenesis of each sample. Structural diagenesis encompasses the relative timing of cementation and fracturing and the relative proportions of different cements that have precipitated before, during, and after each fracturing event, termed pre-, syn- and postkinematic cements, respectively. Because fracture systems in carbonate reservoirs are diverse in origin, a new emphasis on structural diagenesis research is essential. All too often, unjustified assumptions are made about relationships between fractures and large-scale structures, without reference to rock properties at the time of fracturing, as affected by diagenetic history. Patterns of cementation within developing fractures have been established through studies of siliciclastic rocks, allowing us to predict whether macrofractures are likely to be open to fluid flow. The complexity of carbonate diagenesis makes this work a special challenge in carbonate reservoirs, but we see some parallels in the basic pattern of fracture mineral fill. It is common for a synkinematic cement to line the fracture, with bridges of that cement extending across the fracture from one wall to the other. The porosity of that fracture after this phase of cementation either remains open (Fig. 1a) or becomes occluded by a postkinematic cement, either partly (Fig. 1b) or completely (Fig. 1c). Observations of fracture populations, however, indicate that there is a fracture aperture-size control over the extent to which the synkinematic cement fills the fracture. Most microfractures are completely filled with synkinematic cement, whereas macrofractures may have some porosity after synkinematic cement precipitation has ceased. The aperture size at and above which porosity may be preserved is termed the emergent threshold. Observations to date reveal that the emergent threshold is approximately 1 cm in limestones but less than 1 mm in dolomites. The geochemical controls over this phenomenon are to be modeled as part of a new project.

Subcritical crack growth is an important mechanism for natural fracture development. Boundary element geomechanical models have been developed that show that fracture spacing and clustering are sensitive to the subcritical crack growth index, n, which is the exponent used to describe power-law dependence of crack velocity on stress intensity. A testing rig has been developed for measuring the subcritical crack index in sedimentary rocks. We have carried out subcritical crack index measurements on chalk and dolomite samples. The next stage is to input the results into the geomechanical models in order to predict two-dimensional fracture architecture on a bed-by-bed basis. The results of the models may be compared with empirically derived models for fracture-population attributes such as aperture, length, and spacing. This approach is intended to improve assessment of mechanical and fracture stratigraphy and interwell fracture-pattern prediction. The attributes of the whole fracture population, which impact the flow properties of the system, may then be used to improve flow simulations. The combination of these core-based techniques represents a holistic view of the fracture-rock system that could lead to a renaissance in carbonate fracture studies.
Figure 1. Photomicrographs of fractures showing different degrees of mineral fill. (a) Fracture in Austin Chalk outcrop. Synkinematic euhedral calcite crystals line the fracture, pointing into open pore space in the fracture center. The left-hand end of the fracture is completely filled by this cement. (b) An early phase of calcite cement lines this fracture, and a later phase of calcite (coarser pale grains) has precipitated over the earlier calcite, forming mineral bridges. Postkinematic quartz partly infills the remaining pore space. This 1.2-mm-wide fracture is from the Upper Cretaceous Agua Nueva Formation from Southern Mexico. (c) Outcrop of opening-mode fracture in the Pennsylvanian Marble Falls Limestone at Pedernales Falls State Park. An early, pale-colored calcite cement lines and bridges the fracture. A later, dark cement (composition not currently known) completely fills the fracture. Lower scale bar = 0.5 mm.