by Alfred Lacazette,
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Walking Through Fractured Reservoirs and Failed Seals

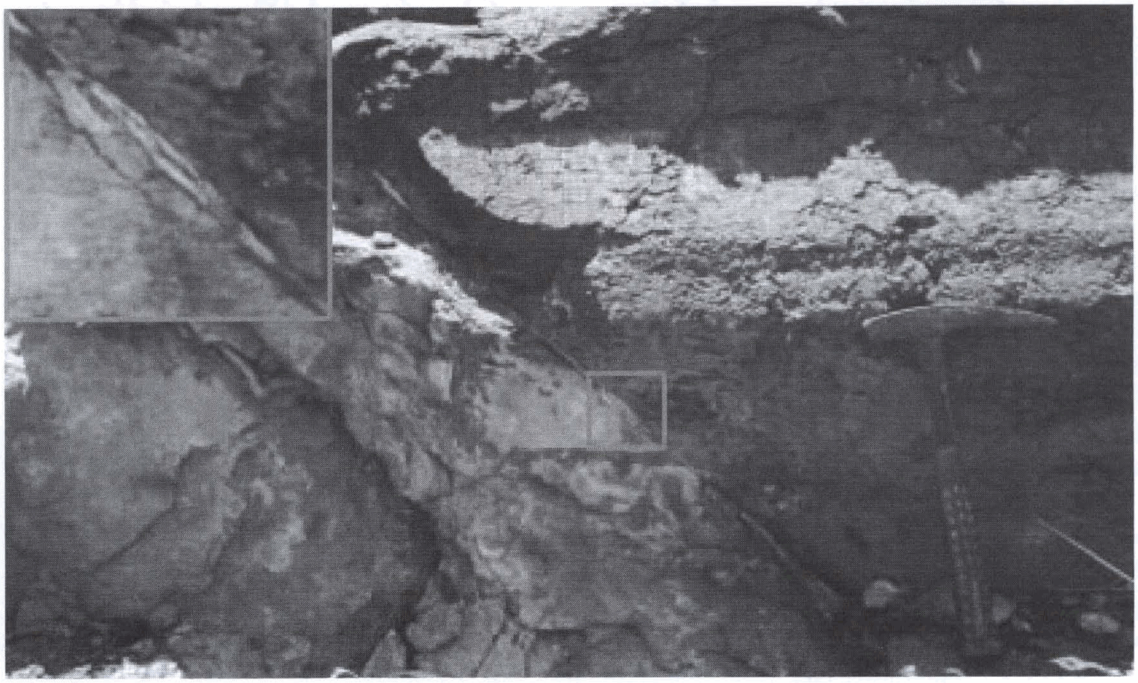

Figure 1: *Deformation band in Pismo Formation sandstones in a railroad cut next to the Arroyo Grande oil field in Southern California. The deformation band separates tar-filled sandstone (right) from clean sandstone (left). The detailed photo (inset at upper left) shows that the deformation band itself is oil-free. The Arroyo Grande field produces heavy oil from wells as shallow as 800 ft. Sedimentary layers can be traced across the deformation band showing that there is little offset across it. Deformation bands only form in sandstones and chalks with porosities >15%; in other words: they only form in excellent reservoir rocks. Deviated wells in this reservoir could link-up isolated compartments.*

The talk is an overview of natural rock fracture geology from a "walking through the reservoir" perspective. The material is presented largely from the perspective of fractured reservoir problems but is equally applicable to seal failure by fracturing. Different types of rock fractures, their morphology and geometry, the morphology and geometry of fracture systems, and their fluid-flow behavior will be illustrated with high-quality 35mm slides of rock fractures and fracture systems. Fracturing is a scale-independent phenomenon, so outcrop scale photos accurately represent oil-field sized features. Basic aspects of rock fracture mechanics, image log interpretation, and reservoir development are introduced by showing field photos and then describing and illustrating the industrial application. The slides are from various parts of the world, especially North America, the Andes and Vietnam. Examples of topics that will be discussed include:

The importance of fracture type. Different types of natural rock fractures (joints, faults etc.) have different fluid-flow behaviors (Figure 1), obey different spacing and size laws and

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Social 11:15 a.m., Lunch 11:45 a.m.

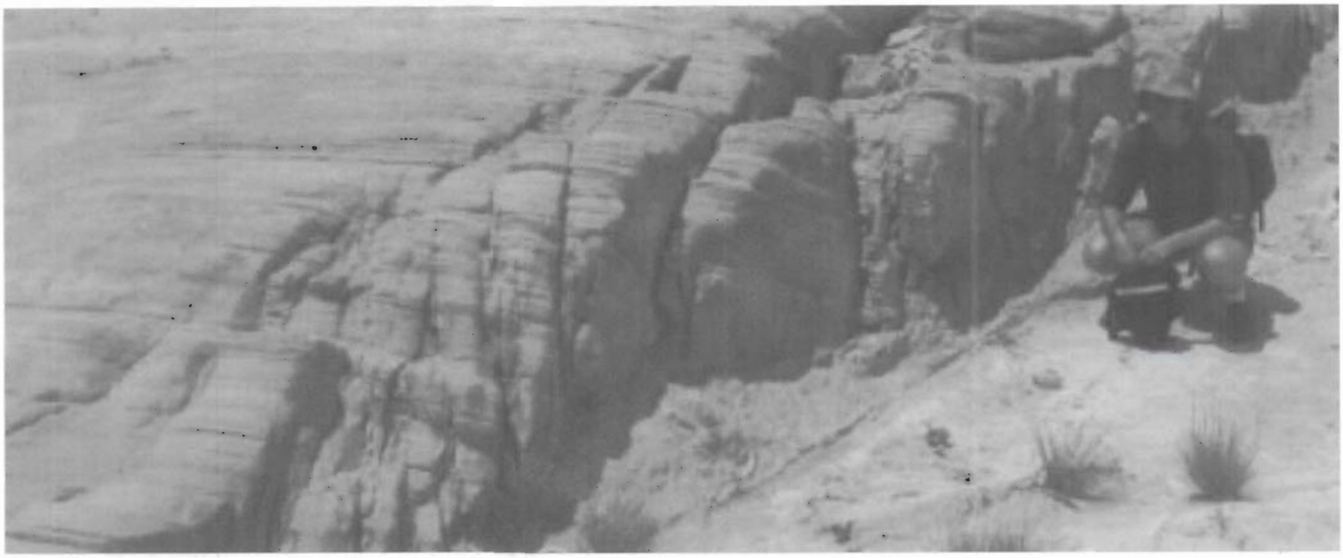

Figure 2: *This fault zone in sandstones consists of the impermeable gouge zone that the person is on and a damage halo consisting largely of pinnate joints, which are permeable. Pinnate joints are an important type of fracture because they are one of the few slip-sense and slip-direction criteria that can be recognized in image logs.*

form in different orientations relative to fracture-generating stresses. Joints and faults provide a clear example of fluid-flow behavior differences: Unmineralized joints (extensional fractures) are open and have clean, undamaged walls so they are conductive and fluids enter them readily. The fluid-flow behavior of faults (shear fractures) varies substantially depending on the fault's characteristics. Clean faults can be as conductive as joints, although porosity damage in the walls may slow fluid entry. Brecciated fault zones can be extremely permeable and may store fluid in much the same way as a sedimentary bed, but fault gouge can be a flow barrier. Damage halos around faults may be permeable even if the fault zone itself is impermeable, as shown in Figure 2.

Fracture sets, fracture systems and polyphase deformation. A fracture set is a group of fractures of the same type that have similar orientations, morphologies and other properties that are thought to have formed during the same geologic event. The influence of a single fracture set on reservoir permeability is strongly dependent on the connectivity of the fractures, which is largely governed by fracture interactions during growth. A fracture system is the total fracture network in a rock mass and may be composed of several fracture sets that formed during different geologic events. Subsequent deformations can reactivate fractures and substantially improve reservoir connectivity, although reactivation can also lead to seal failure.

Fracture localization. A number of factors (including stratigraphy, tectonics, structure and geochemistry) can concentrate fractures in particular subsurface volumes. For example: In weakly deformed rocks, fractures may be developed fairly uniformly throughout a formation. However, folding localizes strain resulting in intense fracturing of well-defined rock volumes with similar deformational histories, as shown in Figures 3A & 3B. The deformational history of a rock volume does not necessarily correspond to its present dip or location on a structure. Quantitative structural analysis may be needed to identify fracture domains of this type.

Biographical Sketch

ALFRED LACAZETTE (Al) has over fourteen years experience in fractured reservoir analysis and petroleum-related structural geology. Al earned an MS in Geology under Nicholas Rast at the University of Kentucky in 1986. His MS research concerned detailed structural mapping and tectonic studies in the Southern Appalachians. He earned a PhD in Geoscience under Terry Engelder at Penn State in 1991. His doctoral research on natural fractures, fractured reservoirs and mechanical aspects of fluid-rock interaction was funded by Texaco and the Gas Research Institute.

After completing his doctorate Al worked for five years at Texaco's E&P lab as the company's fractured reservoir specialist. In 1996 he moved to Western Atlas as part of a joint venture that he developed between Texaco and Western Atlas (now Baker Atlas) to develop improved image log interpretation and subsurface fracture analysis software. In addition to the software project, his work at Atlas consisted of R&D in image log quality control, advanced image log technologies, development of algorithms to characterize subsurface fracture populations from borehole data, teaching, definition of geologic data types

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Figure 3A: *Extensional fault-bend folding above a flattening bend of a normal fault results in extensional strain and fracturing of the extended fold limb. The rectangle shows the location of heavily fractured rock in the extended fold limb.*

Figure 3B: *Note that the extensional strain was accommodated by both normal faulting and jointing. Few fractures are present in the footwall block and to the left of the axial plane that divides the passive limb from the extended limb.*

for a corporate-wide database project, and consulting work. He joined the FracMan group of Golder Associates after Western Atlas was purchased by Baker Hughes. At Golder his work focused on geologic aspects of Discrete Fracture Network reservoir simulation. He is currently an independent consultant working on image log interpretation, core studies, and subsurface and/or field studies of fractured reservoirs and complex structures. He maintains affiliations with several companies, including Golder.

Al has worked on field and subsurface projects in a number of countries including: Algeria, Argentina, Bolivia, China, Colombia, Thailand, the United States, Vietnam, Venezuela, and the former Soviet Union.

Al is currently in his second term as an Associate Editor of the *Bulletin of the American Association of Petroleum Geologists* and is serving as a Compilation Editor for the *AAPG Bulletin.* Visit http://www.NaturalFractures.com/ for details. ❑