Fracturing of Flat-Topped Carbonate Platforms: Implications for Platform-Scale Flow*

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Search and Discovery Article #120038 (2012)*
Posted December 31, 2012

*Adapted from extended abstract prepared in conjunction with poster presentation at AAPG Hedberg Conference, Fundamental Controls on Flow in Carbonates, July 8-13, 2012, Saint-Cyr Sur Mer, Provence, France, AAPG©2013

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Abstract

Because of their heterogeneous structure and their not-so-simple evolution, flat-topped carbonate platforms are expected to display significant lateral changes in the pattern of distributed fracturing. This bears consequences on the path followed by hydrocarbons during the charging stage (migration) and on production schemes during exploitation. Flat-top carbonate platforms are characterized by i) a strong 3D (sub-circular) geometry, and ii) the lateral juxtaposition of first order sedimentological domains with different mechanical properties separated by not-horizontal and not-vertical contact surfaces. The direction and magnitude of stresses and, consequently, the distribution, orientation and type of fractures are predicted to be non-obvious. In addition, rocks of the platform will experience substantial diagenetic changes during subsidence from deposition to maximum burial depth resulting in mechanical properties changing through time.

Combining Finite Element numerical modeling and data from outcropping analogs we map changes in the patterns of fractures affecting flat-topped carbonate platforms from deposition to maximum burial depth thereby providing tools for predicting fractures in buried reservoirs. Numerical models, are inspired by the Latemar platform (Dolomites, N Italy) a nicely exposed, 3*5km wide, 800m thick atoll-like platform we have investigated in the last years and from which we have derived the data on fracture networks discussed in the second part of this contribution.

Fracturing Scenarios

When gravity is the dominant source of stress, very little fracturing takes place close to sea level and <40% of the platform is broken when its top is at a depth of 1,000m. At depths of >1,500m practically the entire platform is predicted to be broken (Figure 1). During subsidence, the maximum principal stress σ_1 is always sub-vertical while the minimum principal stress σ_3 will be sub-horizontal and oriented perpendicular or parallel to the boundary between the first order domains of the platform. Predicting the occurrence of mode I versus mode II fractures remains at the moment challenging.

The introduction of tectonic stresses substantially changes the distribution and properties of the fractured domain defining an upper domain characterized by a sub-horizontal σ_1 and a deeper one in which σ_1 is associated with gravity and is therefore sub-vertical. In the upper domain, the largest deviatoric stress is experienced close to the surface where most of the fracturing will take place. Assuming a tectonic stress of 20MPa, <20% of the platform will be broken (Figure 1); increasing depths within the upper domain will not add any further fracturing as the deviatoric stress decreases in association with increasing contribution by gravity. In this domain σ_2 will be sub-vertical possibly resulting in sub-vertical mode I fractures. The veins shown in the thin section of Figure 2 could be formed under these conditions. Fractures will be aligned with the tectonic stress, neglecting the map-view anisotropy of the platform. At depths below 500-600m, (still in the case of 20MPa tectonic stress) gravity will dominate on tectonics and σ_1 will become sub-vertical. Because of the low deviatoric stress, however, no further fracturing will take place; this could be the domain for the development of stylolites overprinting early veins (Figure 2). When the platform top has reached depths >1,200-1,500m fracturing will pick up again and the platform will be fully fractured below 1,500-2,000m. The fracture orientation will be controlled by a sub-vertical σ_1 and a σ_3 parallel to the tectonic stress. Fractures developed in this region are expected to be sub-vertical, aligned with the tectonic stress.

Fracture Geometries

The way rocks accommodate strain and the quantitative geometry of the fracture networks forming in the broken domains is best constrained analyzing outcropping analogs, in this case, the Latemar. The Latemar platform is fully fractured with predominantly mode I fractures comparable in orientation with those shown in Figure 1. Macroscopically, however, the fractures are not filled. Two sets of fractures are identified which display the same orientations in all three domains, namely the platform interior, margin (not very developed in the Latemar) and slope.

We observe substantial differences in the fractures developed in the three first order domains of the platform. The height of the fractures increases from <2m in the interior to <5m in the slope. Spacings also increase from ca. 0.5 in the interior to 3-5m in the slope. In the platform interior, a slight lithology-dependency is observed with grainstones having large spacings than wackestones. In the platform interior only <50% of the fracture terminations are located at <2cm from the bedding boundary showing that a bed-confined approximation is not justified.

Uncertainties

The predictions we derive from numerical models suffer from two major sources of uncertainties, which should become object of more research. On the one side, there is surprisingly little experimental data constraining the stress conditions (depth and confining pressure) at which i) stylolites form, and ii) mode I fractures are replaced by mode II fractures. Consequently, these structures cannot be fully used to constrain stress conditions during fracturing.

On the other side, mechanical modeling is crucial dependent on bulk mechanical properties, such as Young modulus, which are expected to be substantially different from those that can be measured on samples and reported in the literature. One possible venue for further understanding lies in searching for features, which could act as proxies of bulk mechanical properties. This is the case, for instance, of fractures, the spacing distances and heights of which are known to be directly proportional to the degree of lithification of the hosting rock. This effect has been documented in the Latemar platform.

Impacts on Fluid Flow

In carbonate reservoirs, the presence of fractures will highly influence the fluid flow. In most cases, open fractures will provide a pathway for fluid flow while others will behave as barriers. However, the overall fracture network characteristics will also contribute to the flow behavior. This is particularly evident from the fracture network analysis in the Latemar platform. Having constructed outcrop-based Discrete Fracture Network models for representative localities, we derive permeability values for the three main domain of the Latemar platform.

The results show up to few orders magnitude differences in permeability value. Slope domain, for instance, has much lower permeability as it is less fractured than the platform interior. In case of fracture aperture, wider opening will certainly produce higher permeability. Other parameters such fracture shape (length:height) and orientations, however, contribute only to minor changes in the permeability. Their importance is more significant in justifying the fracture connectivity where wider fracture cluster, i.e. interconnected fractures, is associated with longer fractures and highly dispersed fracture orientation.

Conclusions

Despite their intrinsic simplifications, finite element modeling provides unique insight in the magnitude and distribution of the volume of fractured rocks in a carbonate platform descending from sea level to maximum burial depth. These studies show that significant fracturing occurs at shallow depths, however, affecting only <30% of the platform. The orientation of fractures is strongly dependent on the tectonic scenarios and will be perpendicular/parallel to the main facies boundaries only in the (unlikely) case that gravity is the dominating stress. More commonly, fractures will tend to be aligned along the direction of maximum principle stress. Knowledge of fracture geometries is key for improving predictions in reservoirs hosted by atoll-like carbonate platforms.

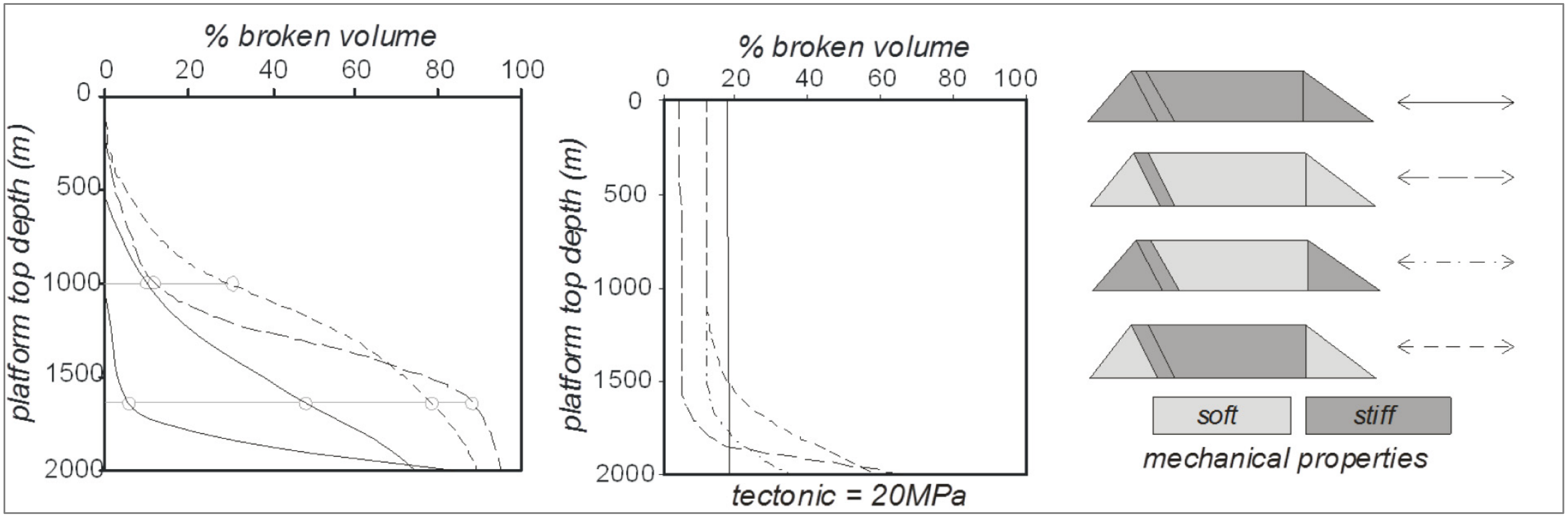

Figure 1. Percentage of broken platform. From left to right: gravity only scenario, gravity with a sub-horizontal stress (20MPa) and key for different mechanical properties curves.

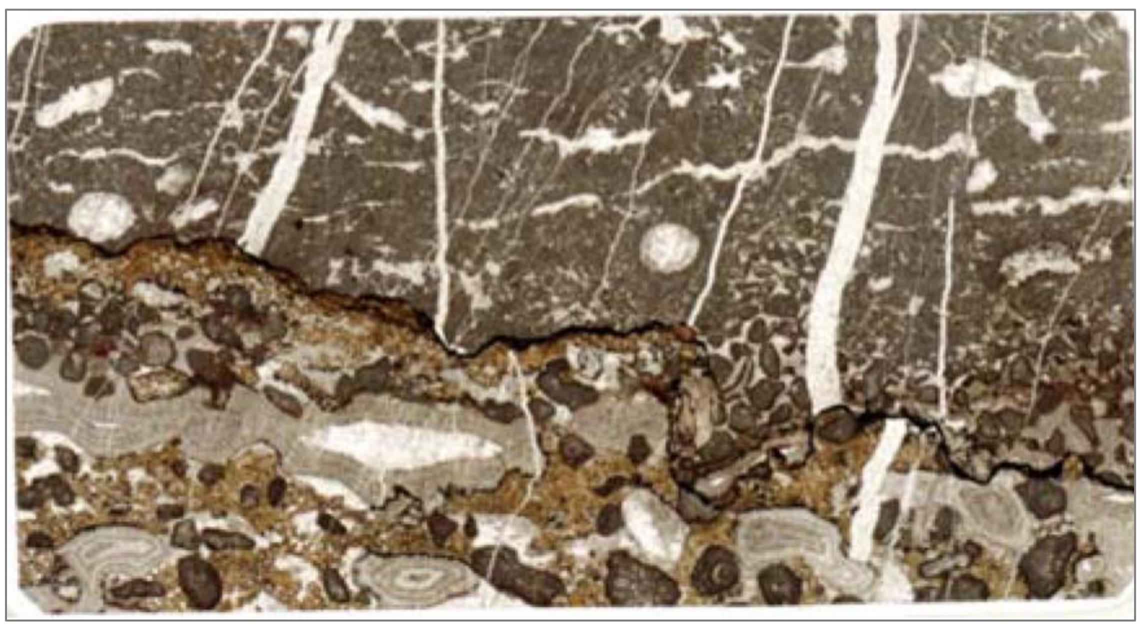

Figure 2. Thin section of carbonate rock from the interior of the Latemar platform. Courtesy of A. Immenhauser and N. Christ (Bochum).