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Fluid circulation and diagenesis of carbonate reservoirs in foreland fold-and-thrust belts: a case study of the Salt Range-Potwar Basin (N-Pakistan)

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Abstract

Exploration in foreland fold and thrust belts is a very challenging task in present-day petroleum exploration. It necessitates a good understanding of pre-, syn- and post-tectonic processes which can be inferred from seismics and forward kinematic modelling. Also with regard to the processes that might affect reservoir units, new insights in the fracturing, cementation and porosity development history has been gained which help to reconstruct the entire fluid flow history. Particular results of a sediment petrological and geochemical study in carbonate and siliciclastic systems in the Potwar Plateau and Salt Range of Pakistan are presented here. Of major interest in reconstructing the paragenetic history is the development of two types of stylolites, i.e. bed parallel stylolites or BPS, which are bed parallel planes and thus compactional in origin, and tectonic stylolites or TS which often are perpendicular planes to sedimentary layering. The latter relate to parallel shortening during tectonic compression. In all systems the fracturing history can be split up into a pre-BPS, a post-BPS but pre-TS, and a post-TS history. The pre-TS fracturing history is mainly rock buffered while the post-TS fractures often reflect intra- as well as extra-formational, i.e. open diagenetic fluid circulations. Of importance from a reservoir point of view is the potential generation of an important karst network which may affect some of the reservoirs in a fore bulge during deformation. Different periods with hydraulic fracturing and development of crack

and seal fractures reflect the generation of overpressures in the system during tectonic deformation. It thus should be possible to model this history and to link the diagenetic history into the deformational history.

Introduction

The study of outcrop analogues often helps to better constrain the controlling features in nearby hydrocarbon reservoirs, especially if core recovery is weak. In the field the sedimentary facies architecture and the diagenesis, which is often considered to exert a major control on reservoir performance in dual porosity carbonates, can be worked out in more detail. This especially accounts for reservoirs occurring in complicated tectonic settings, such as Fold and Thrust Belts. Here, apart from a good knowledge of the pre-, syn-, and post-tectonic evolution, deduced from seismic transects (Roure and Sassi, 1995) and from forward kinematic modelling (Roure et al., 1998, Otuno et al., 2002), an integrated approach combining field and core description, petrography, stable isotope analysis and microthermometry of fluid inclusions often allows to reconstruct fluid flow through time (Muchez et al., 1994; Travé et al., 1998). In these tectonic settings the difference in rock behaviour with respect to fracturing, especially hydraulic fracturing and rock reactivity with respect to expelled fluids during tectonic deformation and subsequent exhumation is often of crucial importance. In the framework of the SUBTRAP-Consortium project (1998-2001), the Paleogene carbonates of the Potwar Plateau and Salt Range have been studied in detail.

Geological setting

The Potwar Plateau and Salt Range are located in the western foothills of the Himalayas, in northern Pakistan. It extends over 120 km from the Main Boundary Thrust (MBT) in the north to the Jhelum River in the south (Fig. 1). The Jurassic siliciclastic sequences are best exposed in the Salt Range. While the Paleozoic to Eocene carbonates series are also well documented by well data within the southern Potwar. However, only Paleocene series are currently exposed in surface outcrops or have been drilled to date in the northern Potwar (Jaswal et al., 1997).

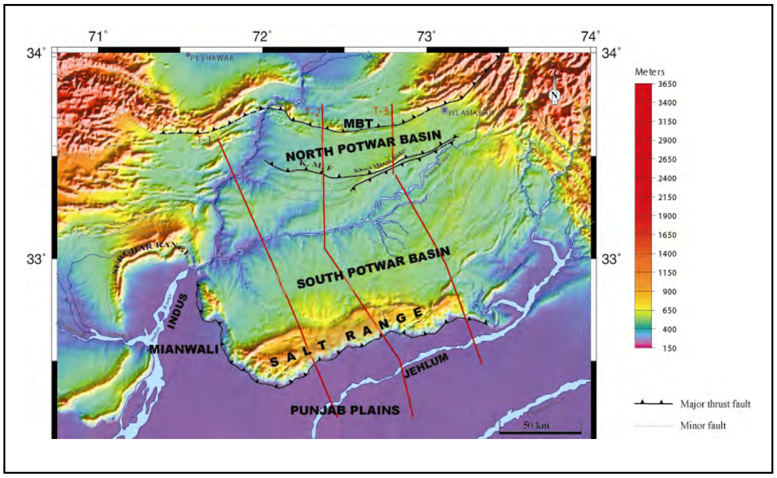

Fig. 1 : Numerical topographic map of the Salt Range-Potwar Basin with the location of the three SUBTRAP transects along which kinematic modelling has been carried out.

2D forward kinematics of the reservoirs

The structural architecture of the Potwar Plateau and Salt Range has been reconstructed based on the kinematic modelling of an eastern transect : line 3 (see Fig. 1). Initial passive margin geometries are restored by means 2D- balancing techniques. The THRUSTPACK 6.2 described in Sassi and Rudkiewicz (1999) was used to control the instant geometry of the selected regional transects, from the onset of the deformation till present. By integrating syn-kinematic erosion and sedimentation processes and coupling various paleo-thermometers (Tmax, Ro, apatite fission cracks), accurate burial curve and thermal history are provided for each potential reservoir interval (Sassi et al., 1998).

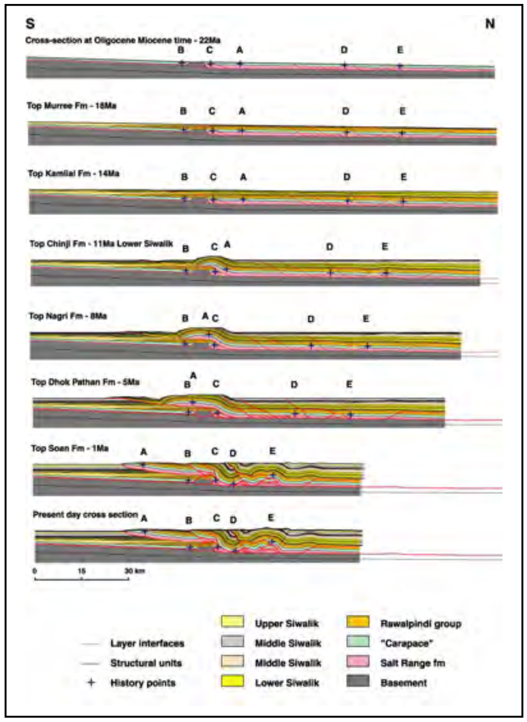

Fig. 2 : Structural evolution of the Potwar Plateau and Salt Range using THRUSTPACK software.

Carbonate Reservoirs

The relative incidence and interactions of depositional environments and subsequent synorogenic dewatering processes on the evolution and prediction of their overall reservoir characteristics has been worked (1998, SUBTRAP carbonate report).

<u>Controls of deposional environments and early diagenetic processes</u>

The initial mineralogic composition of the carbonate (i.e, its relative content in calcite, aragonite or dolomite), is largely controlled by the paleoenvironment. Early dolomitization is occurred in platform setting, whereby sea-level changes and interaction between meteoric and sea water, as well as development of hypersaline settings where also evaporite precipitated play a major role (Fig. 3). Interactions with meteoric water induced dissolution of evaporite interbeds and caused brecciation and collapse of former dolomitic layers (Fig. 4). Such early dolomites have been evidenced in the Eocene Chorgali series. Paleosol and karst development at the top of the Chorgali reservoirs explains the evolution of vug porosity as well as the recrystallisation of marine constituents and resetting of geochemical signals.

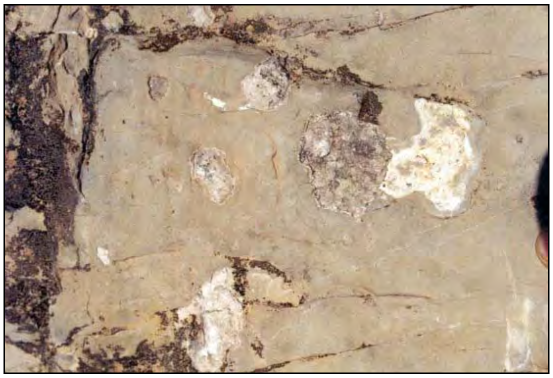

Fig.3: Pseudo-nodule of anhydrite

Fig.4 : Breccia-collapse

Emersion episode and karstification

Emersion events and interactions of carbonate reservoirs with meteoric water are common. This frequently results in the development of dissolution features and karstification (positive input), but also eventually in the deposition of zoned calcite cements (negative output). In our case, early cemented karst vugs relate to regional emersion of the foreland as a result of the bending of the lithosphere in forebuldge areas. This explanation fits perfectly for the karst commonly documented at the top of the Eocene carbonate reservoirs in Pakistan (Fig. 5), and which can be dated as Oligocene in age, as it is transgressively overlain by the flexural Neogene deposits of the Rawalpindi and Siwalik groups.

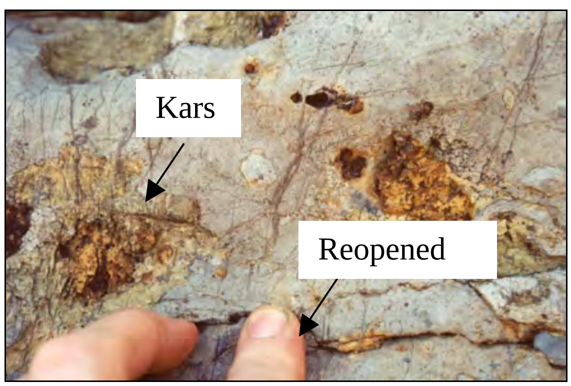

Fig. 5 : Karstification and development of reopened layer parallel stylolites (LPS) rich in pyrite.

Effects of burial and synorogenic diagenesis on residual matrix

Secondary matrix porosity can develop as a result of subsequent dissolution or late dolomitization of the carbonate rock matrix during burial history. In contrast, other diagenetic cements are likely to fill the residual porosity and to contribute into a damaging of the reservoir.

Hydrothermal brines and high temperature dolomitization

Hydrothermal brines are relatively common features in areas of active flow of compaction water, for instance when the fluids can be channelized along high porosity/permeability horizons, and near potential vertical conducts such as mud diapirs and thrust faults (Benchilla et al., 2001). High temperature dolomitization of carbonate reservoirs was also evidenced, resulting in the development of saddle dolomite and coeval secondary porosity development, relating to the same type of fluid transfers in areas of active tectonics.

Deformation features and development of secondary fracture porosity

Vertical and horizontal compaction

The bed-parallel stylolitic planes resulting from vertical compaction develop in a foreland setting before deformation of the carbonate reservoirs. When not cemented, they can still account for potential conducts for horizontal fluid transfers, thus resulting in active dissolution and development of secondary porosity. However, they are frequently associated with cementation and permeability reduction in the host rock, thus resulting in an overall decrease of the vertical transfers. Seemingly, stylolitic planes perpendicular to the bedding develop immediately prior to the thrust emplacement. For the Paleogene carbonates, LPS features are selectively reactivated and re-opened during subsequent folding.

Dewatering processes and development of overpressures

Hydraulic fractures develop within the Eocene carbonate reservoirs, attesting of episodes of overpressure. Evidence of such hydrofracturing system are obvious in the North Potwar Deformed Zone (NPDZ), particularly in the Chorgali Pass outcrop. Here seven distinct fracturing episodes of which some reflect overpressuring were recognized at the top of the Chorgali reservoirs. These observations reflect the complex fracturing evolution typical in the “Fold and Thrust Belts”.

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