Impact of coeval tectonic and sedimentary-driven tectonics on the development of overpressure cells, on the sealing, and fluid migration –Petroleum potential and environmental risks of the Makran Accretionary Prism in Pakistan

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The tectonic evolution of the Makran accretionary prism is resulting from the continuous subduction to the North of the Arabian/Indian plates below the Eurasian blocks. Subduction processes started during Cretaceous time, and the tectonic accretionary prism developed progressively southeastward. The 3D evolution of the prism is not only controlled by tectonic processes (architecture of the slab, changes in orientation & speed of convergence), but also by the strong impact of the sedimentary parameters on the deformation style. Structural architecture results from the N-S shortening of the sediment deposited in the migrating trench, which are scrapped over an oceanic (to the west) and a stretched continental crust (to the East close to transform fault system). To understand the present-day 3D architecture and the localization of overpressure zones it is obvious that sedimentary origin and rates as well as the place were sediment deposited is a first order parameter.

Sedimentary supply

History of the sedimentation in the Pakistani Makran can be described in two large periods:

(1) Since Eocene times, the Makran trench was progressively filled by erosion products, which have been conveyed by the paleo-Indus River (from Himalayan erosion). The deltaic to deep-slope sediment progressively involved in the deformation, were coming successively from the deposition of the Himalayan detritics forming the Katawaz delta (Paleogene times), and the paleo-Indus delta (up to Middle-Miocene times).

(2) During Middle Miocene times, due to the re-organisation of the relief along the transform fault system, a drastic change occurred inducing the transfer of the Indus River East of the Kirthar-Sulaiman Ranges. From this time, the sedimentary detritics were produced by the erosion of the prism itself.

From this time, the deposition of the Himalayan-derived sediment has been transferred south of the Murray Ridge to the present-day position Indus delta.

Structural evolution

The complex tectonic style of the prism is characterized by: (1) a basal décollement level located within Paleogene or Cretaceous series, which deepens progressively from 6-8 km at the deformation front down to 11-12 km depth onshore; (2) an internal structure depending on several parameters: the lithology which is controlled by the regional and/or local depositional environment (determining the extension of secondary "décollement levels"); and the sedimentary loading which control the dynamics of the pressure conditions.

We infer than the deformation propagation is directly linked to the origin, rate and location of the sediment deposits, which has changed through times:

* during the 1st period, all the sedimentary input arrived from the Eastern back-side of the growing prism, and were deposited laterally along the trench.

* during the 2nd period, a large part of the sedimentation was directly transferred all along the Makran, from the northern Inner units (backside) to the south. Sediment series were, either trapped in small or large "piggy-back basins" (developed as a platform) on the frontal units, or supplied by a diffuse hydrographic net, through small rivers and canyons across the frontal units up to the abyssal plain.

Mud volcanoes and overpressure generation

Based on field data, re-processed seismic data, and new bathymetric and seismic data acquired in 2004 during the CHAMAK oceanographic survey, regional sections have been analyzed *(Ellouz-Zimmermann et al 2007)*. A couple of local detachments have been observed above the late Cretaceous-Early Paleogene basal one. Close to the shelf area, the disharmonic late Miocene slope series can be considered as the uppermost detachment level, along with the compressive but also extensive deformation propagated, introducing a disconnection between surface and Middle Miocene structures.

The huge sedimentary loading superimposed to the regional shortening conditions, contributed to develop overpressure conditions within Late Miocene (Parkini fm) at depth. Linked with these deep pressure cells, fluid and mud mobilization have been recognized at surface. Onshore in the Coastal Range, a spectacular "belt" of active mud volcanoes outlined the episodic decompression processes, and expelled products, mud and fluids (i;e. water and gas) represent a "window" for the deep processes. Mud, and fluids (waters and gas) have been sampled and analyzed on several of these mud volcanoes, as well as in the core samples from the CHAMAK survey.

Analytical results

The origin of the mineral fraction of the mud expelled in the mud volcanoes has been attributed to the late Miocene series (from nannoplancton datings).

Geochemical analyses (including noble gas isotopes) of the gas sampled from three mud volcanoes and one gas seepage indicate a thermogenic signature, showing that source-rocks have generated gas at depth. Meanwhile, the other samples from coastal mud volcanoes show a bacterial signature, as well as offshore from long cores (sampled with the Calypso of Marion Dufresne II on BSR). Spatial organization of the "thermogenic signature" mud volcanoes implies a connection with deeper levels than Parkini Fm, probably linked with fluid migration along major faults.

Thermal variation of the heat flow have been calculated over the frontal Makran zone, on the base of 1) of the geothermic gradient calculated on thermal T°C measurements sampled on the Chamak cores, 2) then calibrated on the present-day heat flow values with conductivity parameters from BGR measurements and 3) finally along seismic profiles, interpolated with the largely recognizable BSR (Bottom-simulating-reflectors) modeling using the previously determined conductivity parameters.

Conclusion

Integrating the structural, sedimentological and geochemical new results, we propose a conceptual model of the architecture of the structural traps-reservoirs system and of the fluid migration mechanisms in the Pakistani Makran accretionary prism.