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The effects of diagenesis on the reservoir characters in sandstones of the Late Cretaceous Pab Formation, Kirthar Fold Belt, southern Pakistan

Muhammad Umar [a,b], Henrik Friis [c,*], Abdul Salam Khan [d], Akhtar Muhammad Kassi [a], Aimal Khan Kasi [d]

[a] Geology Department, University of Balochistan, Quetta, Pakistan
[b] Department of Environmental Sciences, Comsats Institute of Information Technology, Abbottabad, Pakistan
[c] Department of Earth Sciences, Aarhus University, Denmark
[d] Centre of Excellence in Mineralogy, University of Balochistan, Quetta, Pakistan

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ABSTRACT

The Maastrichtian Pab Formation in the southern part of Pakistan is composed of fine- to very coarse-grained texturally mature quartz arenite and subordinate sublitharenite varieties. The sandstones have undergone intense and complex diagenetic episodes due to burial and uplift. Diagenetic modifications were dependent mainly on the clastic composition of sandstone, burial depth and thrust tectonics. Diagenetic events identified include compaction, precipitation of calcite, quartz, clay minerals and iron oxide/hydroxide, dissolution and alteration of unstable clastic grains as feldspar and volcaniclithic fragments as well as tectonically induced grain fracturing. The unstable clastic grains like feldspar and lithic volcanic fragments suffered considerable alteration to kaolinite and chlorite. Dissolution and alteration of feldspar and volcanic lithic fragments and pressure solution were the main sources of quartz cements. Mechanical compaction and authigenic cements like calcite, quartz and iron oxide/hydroxide reduced the primary porosity, whereas dissolution of clastic grains and cements has produced secondary porosity. Chlorite coatings on clastic grains have prevented quartz cementation. Coarse-grained, thick bedded packages of fluviodeltaic, shelf delta lobe and submarine channels facies have higher average porosity than fine-grained, thin bedded and bioturbated sandstone of deeper shelf and abyssal plain environments and these facies are concluded to be possible future hydrocarbon prospects.

1. Introduction

The Pab Formation is part of the sedimentary succession (Table 1) in the Kirthar Fold Belt in southern Pakistan. Thick marine siliciclastic successions of the Pab Formation are well exposed in the study area which is approximately 350 km long and 225 km wide (Fig. 1). The formation ranges in thickness from 50 m to 450 m and is thinning toward the south. The formation is mainly composed of sandstone interbedded with subordinate mudstone and marl. The sandstone is commonly light brownish grey, greenish grey, yellowish brown, medium to very coarse-grained (in places pebbly), moderately to well sorted, subrounded to well rounded quartz arenite (some sublitharenites). Marl is cream white and very light grey, finely laminated, and thin bedded. Mudstone is commonly brownish grey, grey and bioturbated at places. The formation was deposited on the tectonically controlled western margin of Indian Plate. Two contrasting depositional systems were identified (Khan et al., 2002; Umar, 2007), as shallow marine (Northern Depositional System) and fluviodeltaic to deep marine turbidites (Southern Depositional System). Three facies associations were identified as transitional from proximal to distal settings as shoreface, shelf delta lobe and deeper shelf facies associations in the Northern Depositional System. The paleocurrent was consistently from east to west in this part. Two successive deep marine turbidite systems, sand-rich basin floor lobes and sand-rich slope fans, were identified in the Southern Depositional System (Eschard et al., 2003, 2004; Umar, 2007). The lower part of the formation is regarded as sand-rich basin floor turbidite lobes in a distal setting (north) and their corresponding bypass surface in the proximal setting. The upper part of the formation has been interpreted as sand-rich slope fan turbidite systems and is made up of stacked slope channel and associated spill-over lobe deposits. The most proximal part of this system is exposed only to east-southeast (Fig. 1), and was deposited in fluvio-deltaic environments (Section 11; Fig. 1).

The Pab Formation conformably overlies and underlies the Mughal Kot Formation and Khadro Formation of the Rani Kot Group respectively. The Mughal Kot Formation is composed of dark

* Corresponding author. Address: Department of Earth Sciences, Aarhus University, DK-8000 Aarhus C, Denmark. Tel.: +45 8942 2561; fax: +45 8613 9248.
E-mail address: henrik.friis@geo.au.dk (H. Friis).

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Table 1
Stratigraphic succession of the Kirthar Fold Belt, southern Pakistan.

Age	Group	Formation	Lithology
Holocene		Recent–subrecent	Mixture of clay, sand and gravel
Unconformity			
Pleistocene		Dada Formation	Boulders and pebble conglomerates with subordinate coarse-grained sandstone
Pliocene		Manchhar Formation	Sandstone and shale interbedded with subordinate conglomerate
Unconformity			
Miocene		Gaj Formation	Shale, sandstone with subordinate limestone and conglomerate
Oligocene		Nari Formation	Sandstone interbedded with shale
Eocene		Kirthar Formation	Fossilifereous limestone interbedded with shale and marl
		Ghazij Formation	Dominantly shale with minor sandstone
Paleocene	Rani Kot Group	Lakhra Formation	Intraclastic limestone and shale
		Bara Formation	Sandstone and shale
		Khadro Formation	Sandstone, shale and marl
Maastrichtian		Pab Formation	Sandstone intercalated with marl and mudstone
Campanian		Mughal Kot Formation	Marl, arenaceous limestone, mudstone and sandstone
Early–Late Cretaceous	Parh Group	Parh Limestone	Biomicritc limestone
		Goru Formation	Micritic limestone with shale, siltstone and sandstone
		Sembar Formation	Shale, siltstone and marl
Disconformity			
Jurassic	Ferozabad Group	Anjira Formation	Limestone interbedded with shale and marl
		Malikhore Formation	Oolitic limestone with subordinate shale and marl
		Kharrari Formation	Limestone, shale, marl and minor sandstone
Base not exposed			

grey, greenish grey and black marine shale with minor marl and limestone. The Khadro Formation consists of greenish grey to dark grey marine shale and limestone.

The primary reservoir targets for hydrocarbon exploration in most parts of Pakistan are the Sui Main Limestone (Eocene) and the Pab Formation (Maastrichtian) e.g., in Sui, Pirkoh, Loti, Dhodak, Jandran and Savi Ragha fields (Beswetherick and Bokhari, 2000; Dolan, 1990; Kadri, 1995; Sultan and Gipson, 1995; Hedley et al., 2001; Fitzsimmons et al., 2005). The source rocks of the Pab Formation are marine shales of the Sembar Formation (Early Cretaceous) and the lower part of the Mughal Kot Formation (Campanian). Both these formations comprise of dark grey to black shale, marl and occasional limestone interbeds of marine environments. Cap rocks are mainly shales of Rani Kot Group (Paleocene) in the study area.

The study area (Fig. 1) is located within the Kirthar Fold Belt (part of the West Pakistan Fold Belt) (Bannert et al., 1992; Jadoon, 1991) on the western suture zone of Indian and Eurasian Plates. It provides good outcrops of the Pab Formation which is considered to have hydrocarbon potential and good trapping conditions. Diagenetic studies of the Pab Formation have not earlier been carried out in this part of Pakistan. This paper aims to provide a general account of the diagenesis of sandstones of the Pab Formation and concentrates on the following objectives:

1. the diagenetic evolution of the sandstones,
2. the sequence of diagenetic processes and products with respect to time and burial history,
3. grain fracturing due to ophiolite thrusting and uplifting,
4. assessing the effects of diagenesis on the composition and reservoir quality of the sandstones.

2. Geological setting

The Kirthar Fold Belt has formed in response to the collision of the Indian continent with Eurasia (Powell, 1979; Bender and Raza, 1995). Based on differences in tectonic style and stratigraphic variations, the Kirthar Fold Belt may be divided into a number of smaller structural units (Fig. 2). Before collision of the Indian and Eurasian Plates the Kirthar Fold Belt acted as passive margin until Late Eocene time. Major continental collision was initiated in the Early Eocene and was completed by Pliocene to Early Pleistocene times (Waheed and Wells, 1990). In Early–Late Cretaceous time the western margin of the Indian Plate was separated from the Madagascar Plate, and the Indian Plate started a rapid movement towards north (Scotese et al., 1988; Gnos et al., 1997) with anticlockwise rotation towards northwest. During this time the Indian passive margin was greatly affected by active normal faults and fragmentation into basins of different bathymetry.

When the Indian Plate was passing over the Reunion Hot Spot during Late Cretaceous time, the Indian Shield area to the east was thermally uplifted and huge amounts of sand-rich sediment were supplied to the margin and deposited as the Pab Formation in a variety of tectonically controlled intra-slope basins. During Paleocene time a widespread transgression resulted in a reduction of the supply of coarse terrigeneous clastics to the basin, and pelagic to hemipelagic shale and shallow marine limestone of the Rani Kot Group were deposited. Emplacement of the Bela and Muslimbagh ophiolites occurred on the western continental margin of the Indian Plate during the Paleocene (Allemann, 1979; Tapponier et al., 1981; Gnos et al., 1998). This affected the margin and a flexural foreland basin started developing in the west while passive margin sedimentation continued on the eastern margin as the Ghazij Shales and the shallow marine limestone of the Kirthar Formation. The studied area subsided and deep marine clastic sedimentation of the Nari Formation took place in the Oligocene and piled up additional overburden. Eventually, the collision between the Indian and Eurasian plates resulted in the uplift of the Himalayan mountain belt on the northern margin and the Sulaiman and Kirthar mountain belts on the western margin. Compressional deformation continued until Pliocene–Pleistocene time and is recorded in imbricated thrust sheets in the Kirthar Fold Belt (Niamatullah et al., 1986). Then a major uplift caused exposure of the entire succession and deep erosion resulted in an unconformity between the Gaj and the fluvial Manchhar Formation (Pliocene). The Manchhar Formation and the Dada Conglomerate were deposited in Pliocene–Pleistocene time in estuarine and fluvial environments respectively.

The exact rate and amount of erosion and deposition above the Pab Formation is difficult to estimate in outcrops because of complex tectonics, thrusting of ophiolites, and variations in palaeoto-