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ORIGINAL PAPER

Structural styles, hydrocarbon prospects, and potential in the Salt Range and Potwar Plateau, north Pakistan

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Abstract The Salt Range/Potwar Plateau (SRPP) is part of the Himalayan foreland and an important petroleum province in north Pakistan. The hydrocarbons are commonly produced from stacked Cambrian to Eocene clastic and carbonate reservoirs which have an average thickness of 1 km. These strata are overlain by at least 5 km of Miocene and younger continental molasse sedimentation in the deepest part of the foreland basin. Surface and subsurface (seismic interpretations and borehole data) geology combined with the timing and the patterns of sedimentation has allowed to interpret the deformation as thin skinned, with a detachment in weak Eocambrian evaporates and the development of ramp-and-flat structures, since about 8 Ma. We have reviewed the structural interpretations with new borehole logs, field geology, and reserve estimates in this paper to precisely define oil-field structures with a view on future exploration. As a result of this work, 12 oil fields are classified as three detachment folds, four fault-propagation folds, four pop-ups, and one triangle zone structure. The latter two are identified as better prospects with the last one as the best with estimated reserves of 51 million barrels of oil (MMBO). Hence, the triangle zones along with other ramp-and-flat structures from the North Potwar Deformed Zone (NPDZ) are recognized to provide potential future prospects. Finally, a 40-km-long structural cross section from NPDZ is used to discuss complex deformation of the triangle zone and duplex structures as future potential prospects. About 55 km of shortening across the NPDZ during Plio-Pleistocene time is calculated, which has important bearing on the geometry of prospects, reserve calculations, and the future exploration.

Keywords Prospects · Detachment folds · Fault-propagation folds · Fault-bend folds · Pop-up structures · Triangle zone

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Background

The Salt Range/Potwar Plateau (SRPP) was first drilled for hydrocarbons in 1866 at Kundal (western Salt Range) in the Himalayan foreland fold-and-thrust belt. The discovery of oil occurred in 1914 with the completion of a shallow 214-ft well in the Miocene Murree Formation (sandstone). Eighteen oil and three gas fields have been discovered between 1914 and 1996 in the SRPP (Fig. 1). Many wells have been abandoned due to drilling and structural complications, e.g., high pressure, excessive thickness of the seals, unexpected faults, and dips variation. The several prospects which were unsuccessfully tested in the 1950s and 1960s were successfully reexamined with additional seismic data (Quadri and Quadri 1998; Moghal et al. 2007). Several studies based on integrated borehole and seismic data have been carried out in 1980s and 1990s to address overall structural style and the mechanics of deformation (Lillie et al. 1987; Pennock et al. 1989; Jaume and Lillie 1988; Treloar et al. 1992; Grelund et al. 2002). The deformation is interpreted as thin skinned over a weak detachment, extending over a wide zone of deformation with gentle topography and symmetrical structures. Complex deformation in the form of imbricate and duplex structures was reported from the northern part of the plateau identified as the North Potwar Deformed Zone (NPDZ) (Jaswal et al. 1997; Jadoon et al. 1997). This zone of deformation has been examined by combining seismic data, borehole data, and paleomagnetic data with constraints from surface geology for an

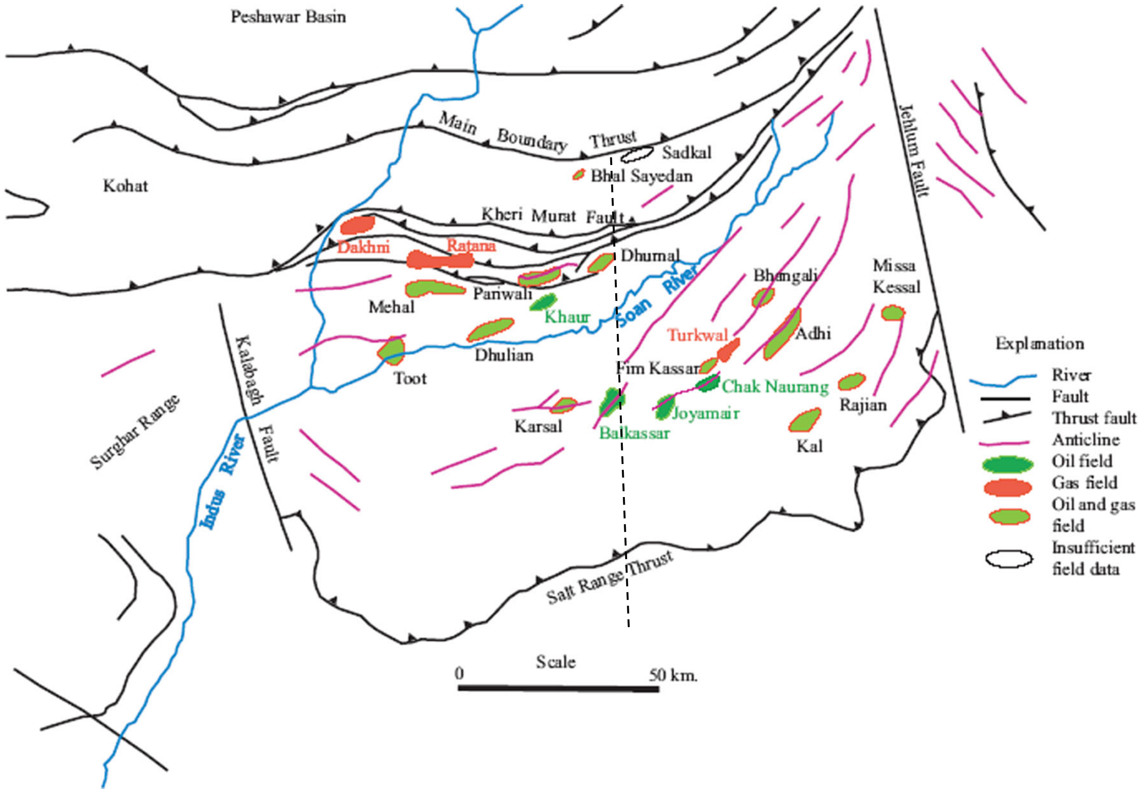

Fig. 1 Generalized structural and oil-field map of the study area (Wandrey et al. 2004)

understanding of the complex structures and their development (Jaswal et al. 1997; Jadoon and Frisch 1997; Jadoon et al. 1997, 1999). As a result, 55 km of shortening was calculated across the NPDZ between 8–5 Ma in the NPDZ (Jadoon et al. 1997). This is in addition to about 21 km which was calculated across the SRPP south of the Soan Syncline (Lillie et al. 1987; Pennock et al. 1989). Most of the oil fields south of the Soan Syncline are discovered in a zone of gentle deformation of Neogene sedimentation (Figs. 1 and 2).

More recently, borehole and seismic data were re-examined for a detailed structural interpretation along three regional cross sections across the SRPP (Moghal et al. 2007). The cross sections based on seismic data interpretation provide a general overview of the structures to the south of the Soan Syncline, whereas complex structures to the north of the Soan Syncline are either not addressed or inadequately presented. In order to better understand the structural styles, knowledge of their geometry and development is critical, which is addressed in this article.

The presence of a basal *décollement*, slip of strata along a fault, and its translation into a fold (prospect) is a regular feature of thin-skinned deformation (Chapple 1978). Simple ramp-and-flat geometry of a fold has been elaborated into more a complex imbricate and duplex style of deformation (Dahlstrom 1970). The geometrical rules have been defined for how a fold at the surface is related to kink bands with panels of variable dips and faults in the subsurface (Boyer and Elliot 1982; Suppe 1983; Mitra 1986). An understanding of these rules and their application to petroleum exploration is regarded to improve drilling success, which is addressed in this paper with examples of the SRPP. Alternately, more data are always desired to constrain the subsurface geometry of oil fields, such as Mesa Kaswal and Fimkassar in the SRPP which were re-examined successfully with additional seismic constraints (Moghal et al. 2007).

In this paper, we combine our present (Wazir et al. 2012) and previous work (Jadoon and Frisch 1997; Jadoon et al. 1997, 1999) with other studies (such as Lillie et al. 1987; Moghal et al. 2007) with new data (borehole logs and reserve estimates) to study the structural styles of the oil fields with an aim to (1) precisely interpret the structural geometry of oil fields, (2) describe geometrical elements of each one of these styles with the support of seismic data from the SRPP, and (3) statistically analyze reserves and production from each one of these styles to assess their potential. This study not only increases our knowledge about the oil-field structures and their potential in the SRPP but also is rather applicable to other fold belts for hydrocarbon exploration and interpretation of traps.

Our interpretation is build upon the rules laid down by earlier workers for the interpretation of fold-and-thrust belts (Dahlstrom 1970; Boyer and Elliot 1982; Suppe 1983; Mitra

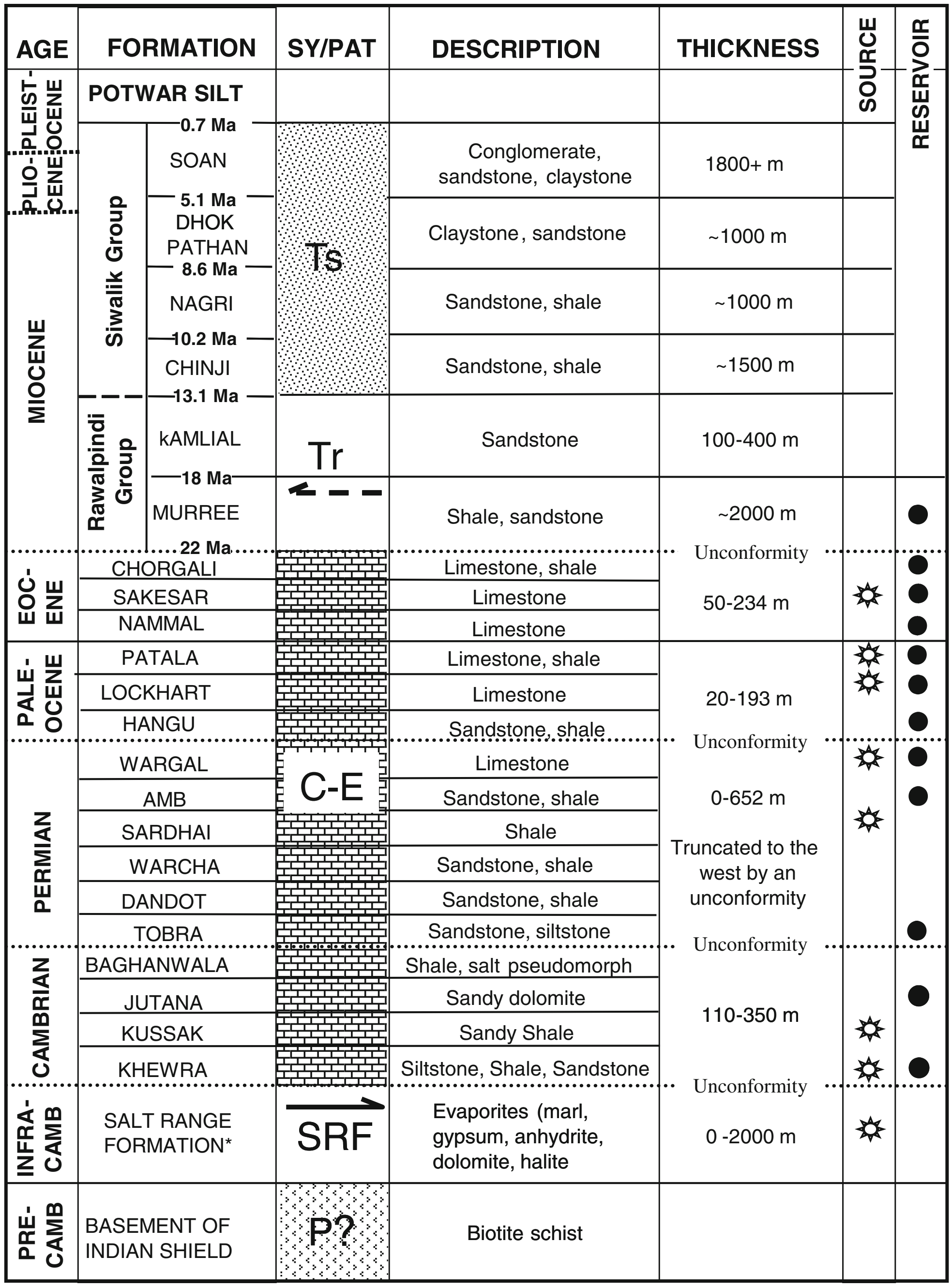

Fig. 2 Generalized stratigraphic column of the Potwar Basin (modified from Jaswal et al. 1997; Wandrey et al. 2004)

1986), structural interpretations, mechanics of deformation (Lillie et al. 1987; Pennock et al. 1989; Jaswal et al. 1997; Jadoon and Frisch 1997; Jadoon et al. 1997; Jadoon et al. 1999; Moghal et al. 2007), petroleum system analysis (Grelund et al. 2002; Wandrey et al. 2004; Cooper 2007; Fazeelat et al. 2010; Asif and Fazeelat 2012), detailed timing of sedimentation and deformation for basin modeling (Johnson et al. 1982a; Burbank and Raynolds 1988), and field work across 40-km width within the NPDZ, where steep to overturned molasse sediments of the Murree Formation (Rawalpindi Group) are the most common.

Sedimentation and petroleum system

In the SRPP, a full sequence of Eocambrian to Quaternary strata is both exposed and drilled (Fig. 2). Generally, the strata can be divided into three stratigraphic and structural units: (1) thick (>1 km) Eocambrian evaporites that serve as a detachment, (2) a competent Cambrian to Eocene platform sequence that serves as a source/reservoir, and (3) Miocene mostly fluvial molasse sediments that serve as seals with an upper detachment and synsediment deformation.

The Paleocene Patala Formation is generally believed to serve as a source rock for much of the hydrocarbons in the SRPP (Moghal et al. 2007; Fazeelat et al. 2010). However, the petroleum geochemistry of the Potwar basin based on heterocyclic and polycyclic aromatic hydrocarbons has allowed validating the generation of hydrocarbons from three different types of source rocks (Asif and Fazeelat 2012). The study shows organic matter (OM) derived from a highly oxic/deltaic environment to suboxic marine environment influenced by biodegradation and a marine oxic depositional environment without biodegradation effects. The potential source rocks are the Eocambrian Salt Range Formation, the Cambrian Khewra and Kussak Formation, the Permian Wargal Formation, the Sardhai and Chidru Formation, the Paleocene Lockhar and Patala Formation, and the Eocene Sakesar Formation (Wandrey et al. 2004; Asif and Fazeelat 2012). The corresponding rock types are producing hydrocarbons in many cases from more than one reservoir. With age variation, they are alluvial and shoreface sandstone (Cambrian), glacial deposits, sandstone and limestone (Permian), continental sandstone (Jurassic and Cretaceous), shelf carbonates (Paleogene), and alluvial sandstone (Miocene), which are all drilled (Fig. 3). The distribution of producing reservoirs by age, type, and number of fields in which they are drilled is shown in Fig. 4 (modified from Wandrey et al. 2004) for an idea of their potential and production history. It shows that hydrocarbons have so far been dominantly produced from the Cenozoic carbonate reservoirs. Carbonate reservoirs are low-porosity fractured reservoirs. The clastic reservoirs have porosity values of 5–30 % with an average of 15 % and permeability between 5 and 300 mD (Khan et al. 1986; Wandrey et al. 2004).

Generally, Eocambrian to recent strata preserves a full record of sedimentation since the Phanerozoic along the northern margin of the Indian plate. The Eocambrian evaporites are analogous to the Harmuz salt in Iran and evaporites in Oman (Wandrey et al. 2004). They are overlain by a Cambrian succession comprised of marine shale followed by massive braided-stream sandstone, glauconitic shoreface, and near-shore sandstone and sandy carbonate deposits. This succession is followed by a hiatus until the Permian. The Lower Permian Tobra Formation tillites are part of the Gondwana-wide Permo-Carboniferous glaciation and reflect a much cooler paleoclimate. The deposition of clastic and carbonate sedimentation during much of Permian, Triassic, Jurassic, and Cretaceous time represent shelf and marine stages, followed by the onset of the Himalayan orogeny with collision of the Indian and Eurasian plate at about 65–55 Ma (DeCelles et al. 2004; Green et al. 2008).

The Neogene history of deformation is recorded in the fluvial clastic molasse sedimentation in the SRPP (Fig. 2). These sediments are extensively studied for patterns of sedimentation and deformation with age constraints (22 Ma onwards) primarily based on magnetostratigraphy (Johnson et al.

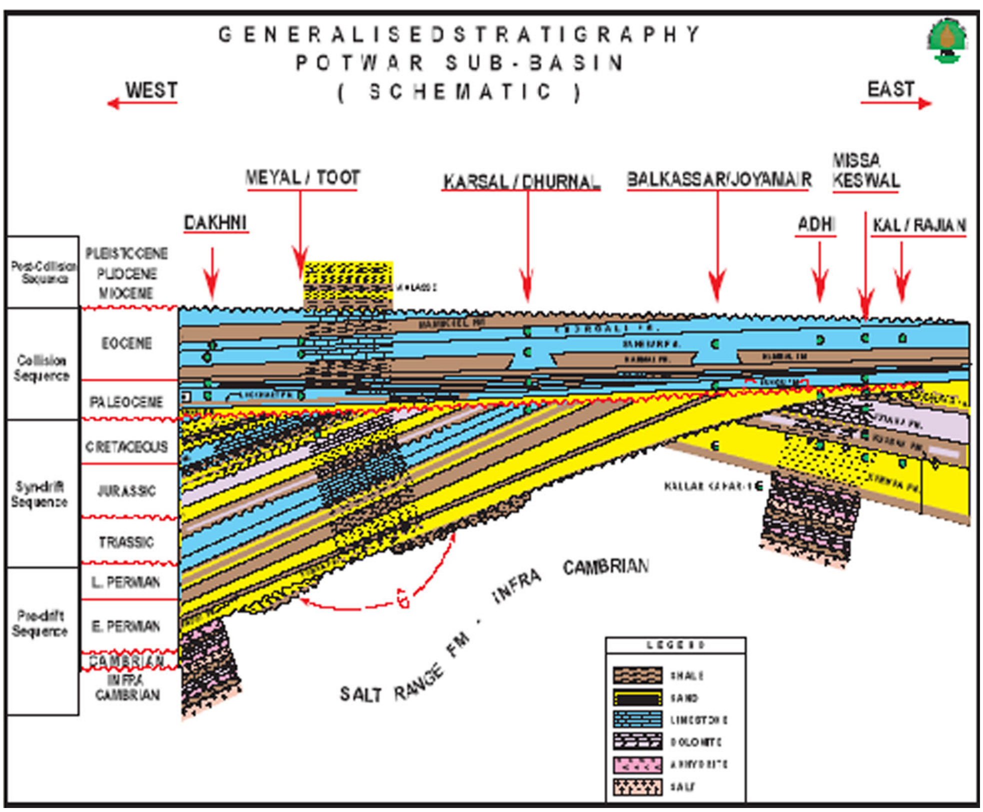

Fig. 3 Stratigraphic fence diagram across the Salt Range/Potwar Plateau. See the presence of major unconformities and variation of source and reservoir rocks in the region (from Moghal et al. 2007)

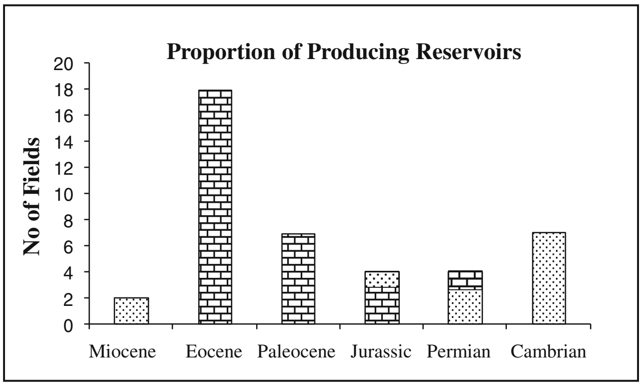

Fig. 4 Distribution of producing reservoirs by age, type, and number of fields in which they are drilled (modified from Wandrey et al. 2004)

1982a, b; Burbank and Raynolds 1984, 1988). As much as about 5 km of Neogene molasse deposits of the Rawalpindi and Siwalik Groups are presently preserved in the deepest part of the foreland basin along the Soan Syncline. The Upper Miocene Siwalik Group disappears north of the Soan Syncline where the Lower Miocene Rawalpindi Group is largely exposed, whereas the Rawalpindi Group is absent in the foredeep based on drilling of the Lilla-1 well (Fig. 5). The presence and absence of Upper and Lower Miocene clastic strata at one location or the other raise several questions concerning structural interpretations and basin modeling, i.e. whether this gap is related to a deposition hiatus, tectonic thrusting, or both.

Foreland deformation

The SRPP represents the active deformation of the Himalayan foreland fold-and-thrust belt in northern Pakistan. It extends over a width of ~130 km bounded between about 300-km-apart tear faults. The wide zone of deformation has gentle topography (envelops <1°) which implies rapid southward translation of the thrust sheet over a weak *décollement* (Jaume and Lillie 1988; Davis and Lillie 1994). This is similar to the foreland deformation of the Pine Mountain fold-and-thrust block of the central Appalachians (Rich 1934; Harris and Milici 1977), the Jura Mountians of the Northern Alpine Foreland Basin in Europe (Laubcher 1981), and the Himalayan foredeep in India (Raiverman et al. 1983; Jadoon et al. 1993, 1994).

The style of deformation in the SRPP changes across the Soan River, which flows along the axis of a regional NE-SW syncline (Fig. 1). The region south of the Soan Syncline is dominated by folds and the emergent Salt Range thrust (SRT), whereas the region north of the Soan Syncline is characterized by complex folding and faulting in the NPDZ (Jaswal et al.

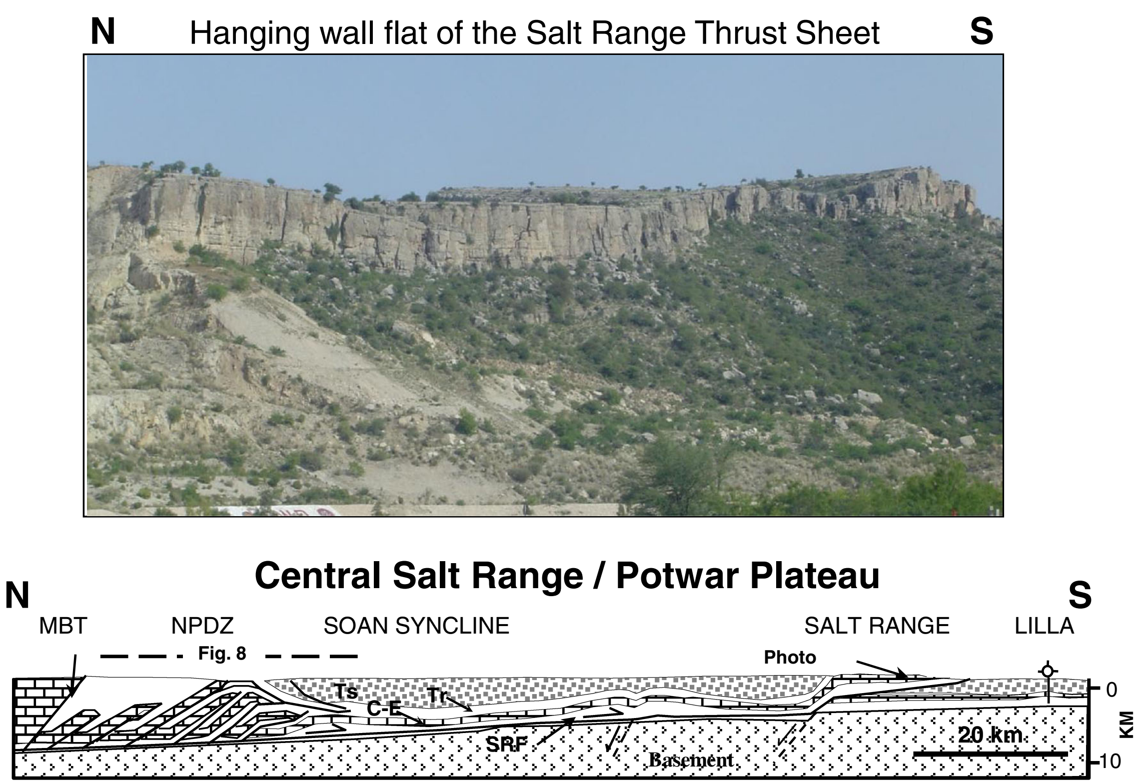

Fig. 5 Structural cross section across the central Salt Range/Potwar Plateau (from Lillie et al. 1987). The photograph shows field expression of the Salt Range thrust sheet. *Abbreviations*: *SRF* Eocambrian Salt Range Formation, *C-E* Cambrian to Eocene, *SRT* Salt Range Fault, *Tr* Tertiary Rawalpindi Group, *Ts* Tertiary Siwaliks. The field photo shows a hanging-wall flat of the Salt Range thrust sheet over the footwall flat, as an example of typical ramp-and-flat structures

1997; Jadoon et al. 1997, 1999). The overall deformation can be best demonstrated along a regional cross section through the central SRPP (Fig. 5). Along this cross section, the Lilla well was drilled in the foredeep (Jhelum plain) penetrating to the Salt Range Formation in the core zone of a gentle anticline. The Salt Range Formation serves as a *décollement* and is exposed along the Salt Range thrust. The thrust sheet is about 90 km long and has a classic flat–ramp–flat geometry. The ramp part of the thrust sheet is located over a north-dipping basement normal fault. About 20 km of shortening is calculated along the thrust sheet between 2.1–1.6 Ma in the central SRPP (Baker et al. 1988) which is interpreted to be first active at about 5 Ma (Burbank and Beck 1991). Much of this shortening is accompanied by the development of the several structures between 5 to 2 Ma in the eastern SRPP (Johnson et al. 1982b; Jadoon et al. 1997).

The complex deformation of the NPDZ took place between the Main Boundary Thrust (MBT) and the Soan Syncline. The MBT runs all along the Himalayas and juxtaposes platform strata (Eocene) against the molasse strata. It is considered to be active until about 8 Ma (Jadoon et al 1997). The NPDZ has acted as a subsiding trough with a rapid rate of sedimentation between 11 and 8 Ma and deformed largely between 8 and 5 Ma (Burbank and Beck 1989; Jadoon et al. 1997). Subsequently, the *décollement* has propagated southward, and the motion has been translated to the Salt Range thrust, which was interpreted as active at about 5 Ma with erosion and northward transportation of the sediments from its tip (Burbank and Beck 1991). The northern limb of the Soan Syncline in the eastern NPDZ is interpreted to have tilted between 2.1 to 1.9 Ma based on the deposition of the Lei Conglomerate (Raynolds 1980; Burbank and Raynolds 1984).

The fluvial clastic molasse sedimentation in the foreland basin provides a record of late stage of subduction and major mountain uplift in the SRPP (Fig. 2). These sediments are extensively studied for patterns of sedimentation and deformation with age constraints, primarily based on magnetostratigrapy (Johnson et al. 1982a; Johnson et al. 1982b; Burbank and Raynolds 1984; Burbank and Raynolds 1988). The Miocene fluvial molasse strata are widely exposed in the region with deformation of the Salt Range since about 5 Ma (Fig. 5). However, the older (22–13 Ma) dominantly sandstone strata (Rawalpindi Group with Murree and Kamlial Formations) are exposed along the northern part of the deformed foreland basin, whereas the younger Siwalik Group (13 Ma to present) is dominantly exposed south of the Soan Syncline and was drilled in the foredeep (Lillie et al. 1987).

Compressional structural styles

The fold-and-thrust belts show important prospects for hydrocarbon exploration. They exhibit either thick or thin-skinned deformation with or without involvement of the basement in the deformation, respectively. The latter is observed as the most common with about 156 billion barrel of oil (BBO) calculated reserves as compared to 77 BBO in thin-skinned fold-and-thrust belts (Cooper 2007). The Zagros fold belt, alone, interpreted as both thin and thick skinned is estimated to contain 233 BBO, which is 49 % of the hydrocarbon reserves in the fold belts (Cooper 2007).

In thin-skinned deformation, strata are detached along a *décollement* and deformed above it. As a result, a variety of compressional structural styles are possible in a thrust system. They are extensively studied with the identification of a relationship between a fold and a fault leading to the development of particular structural geometry (Boyer and Elliot 1982; Jones 1982; Suppe 1985; Mitra 1986). The knowledge of how fold and faults are related leads to a better understanding of foreland structures that is widely applied for hydrocarbon exploration.

The exploration in the SRPP has been extended to structurally complex areas, along with re-evaluation of oil fields with further seismic data acquisition and interpretation. A large amount of seismic data has been produced and interpreted from the SRPP for an understanding of overall deformation and mechanics (Lillie et al. 1987; Jaume and Lillie 1988; Pennock et al. 1989; Jaswal et al. 1997; Jadoon and Frisch 1997; Jadoon et al. 1997, 1999; Moghal et al. 2007). The information is reviewed for precise definitions of oil-field structures and to determine their potential as prospects. This work is elaborated by structural models of each type, supported by the seismic data, from the SRPP for geometrical constraints. Finally, a 40-km-long balanced cross section of the north Potwar is used to discuss the future potential prospects in a zone of complex deformation. Thus, this is an effort to provide an insight into the structural styles of the oil fields with application to hydrocarbon exploration in the SRPP and elsewhere in similar settings.

The fault-related folds in sedimentary strata generally exhibit a kink style of folding, whereby a sudden change of dip is observed across axial surfaces. Thus, the geometry of folds (prospects) may drastically change at depth. Their understanding allows predicting these changes laterally and vertically across a prospect. Alternately, misinterpretations may lead to a variation in predicted depths of the targets, and/or failure of reaching them is quite common. Therefore, geometrical constraints on prospects are expected to increase drilling success. This work has application to the Himalayan and other thin-skinned fold-and-thrust belts, alike. Through this study, the tectonic structures of oil fields in the SRPP are characterized as detachment folds, fault-propagation folds, fault-bend folds (Salt Range itself), pop-ups, and triangle zones (Fig. 6; Tables 1 and 2). The general characteristics of these structures are provided in the preceding section.

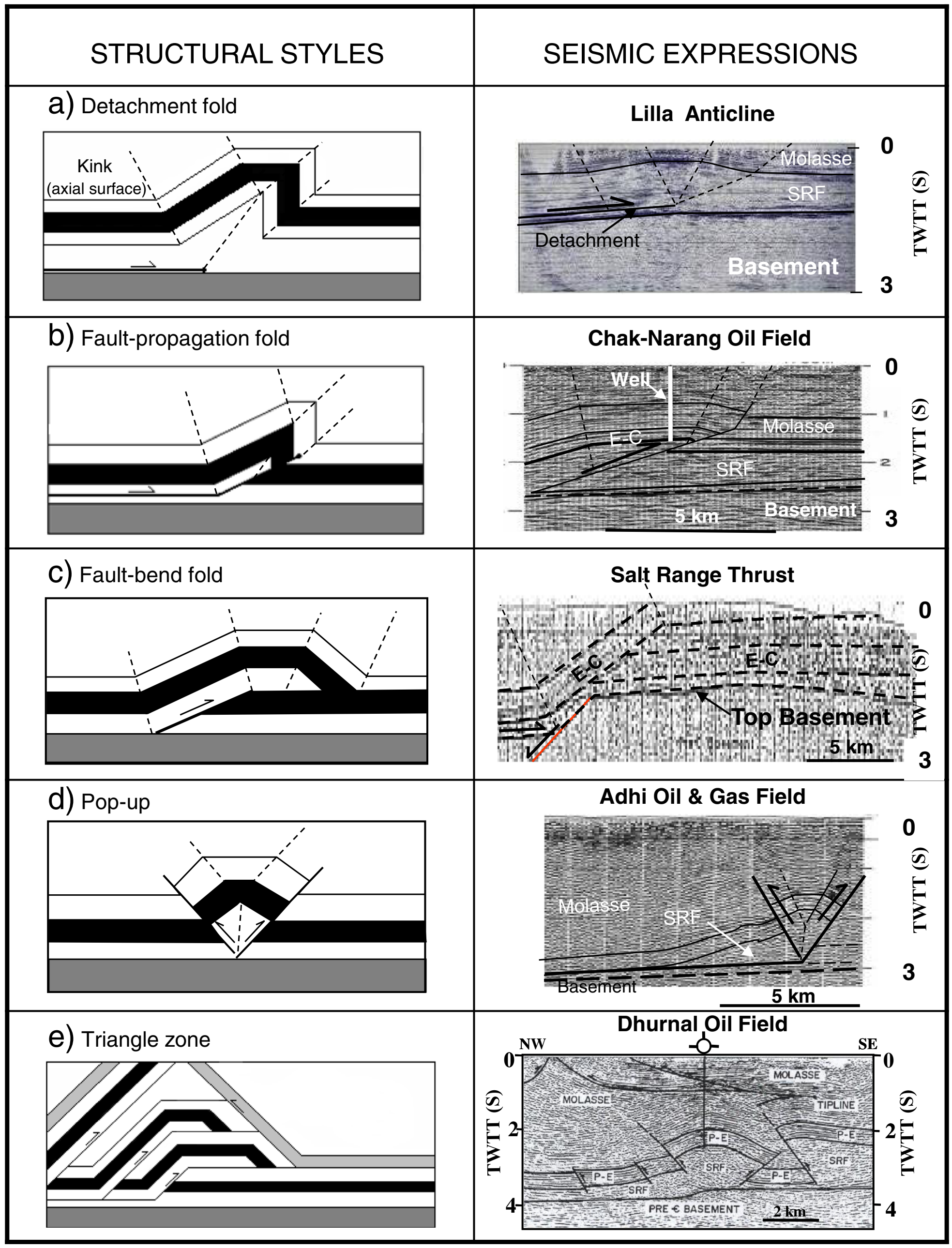

Fig. 6 Geometrical models with support of seismic expressions of compressional structural styles from the SRPP. Slice of seismic profiles are from Lillie et al. (1987), Pennock et al. (1989), and Jaswal et al. (1997). *Abbreviations* are the same as in Fig. 5

Detachment folds

Detachment folds form by buckling of strata over a *décollement* surface. The buckling of strata is induced to accommodate compression and slip, as strain is imposed on a set of mechanically incompetent and competent layers (Fig. 6a). Folding initiates as resistance offered by the competent unit is overcome, and shearing motion along the detachment is initiated with the development of a detachment fold (Mitra 2003; Suppe 1985).

General characteristics of detachment folds are as follows: (1) There is usually an incompetent layer at the detachment which fills the core of the fold with excessive thickness due to ductile deformation, (2) the frontal axial plane or kink band ends at the tip of the detachment, (3) detachment folds are usually upright and symmetric to moderately asymmetric, with the steep limb facing the thrusting direction, and (4) competent layers usually maintain their original thickness.

Figure 6a shows the seismic expression of the Lilla anticline in the form of a detachment fold. The structure is located at the tip of the *décollement* in the foredeep (Jhelum plain) of the SRPP (Fig. 5). The *décollement* is located in the weak Eocambrian evaporites that are drilled at a depth of 1,707 m in the Lilla-1 well. The platform sequence in this well comprises only 274-m-thick Cambrian strata which are directly overlain be the Miocene Chinji and Nagri Formations. If the absence of

Table 1 Summary and structural styles of oil fields

No.	Oil field	Discovery	Operator	Style	Reference
1	Adhi (A)	1979	PPL	PU	Pennock et al. 1989
2	Balkassar (B)	1946	OXY	DF	Lillie et al. 1987
3	Chak-Naurang (CN)	1987	OGDCL	FPF	Treloar et al. 1992
4	Dakhni (D)	1983	OGDCL	FPF	Lillie et al. 1987
5	Dhurnal (D)	1984	OXY	TZ	Jadoon et al. 1999
6	Dhulian (DL)	1935	POL	FPF	Moghal et al. 2007
7	Fimkassar (F)	1981	OGDCL	PU	Treloar et al. 1992
8	Joyamair (J)	1944	POL	DF	Wandrey et al. 2004
9	Khaur (KH)	1914	POL	FPF	Jadoon et al. 1999
10	Meyal (M)	1946	OGDCL	PU	Lillie et al. 1987
11	Messa Kaswal (MK)	1991	POL	PU	Moghal et al. 2007
12	Toot (T)	1968	OGDCL	DF	Lillie et al. 1987

Exploration data are from Kadri (1995)

DF detachment fold, *FPF* fault-propagation fold, *PU* pop-up, *TZ* triangle zone, *OXY* Occidental Petroleum Corporation, *OGDCL* Oil and Gas Development Company Limited, *POL* Pakistan Oilfields Limited

Mesozoic and Tertiary platform strata in this well is related to the development of a flexural bulge due to the load of the Himalayas, a north-dipping normal fault along the ramp region of the Salt Range thrust sheet (Fig. 6c) in the basement or uplift and subsidence during the Permian rift-and-drift stage of the Indian plate is not known. The thick incompetent Salt Range Formation is distinct on the seismic profile and fills the core of the fold with excessive thickness due to its ductile deformation. The buckling of competent strata is visible across the kink bands (dashed lines) with the frontal one ending at the tip of the detachment. The fold is upright with low structural relief and moderate degree of asymmetry due to a relatively steep frontal limb.

Three other oil fields in this study are interpreted as detachment folds. They include Balkassar, Joyamair, and Toot oil fields (Table 1). Balkassar and Joyamair oil fields are located in the central SRPP south of the Soan Syncline, whereas the Toot oil field is located in the eastern SRPP north of the Soan Syncline (Fig. 1). They are all developed by detachment of the sedimentary sequence from the basement. They all are less than 10 km wide (half wavelength) with a general NE–SW trend. The Toot oil field, however, is more circular, possibly due to the combined effect of salt and compression tectonics (Fig. 1). This is consistent with the presence of excessive thickness of the Salt Range Formation in the western SRPP and abundance of salt diapers along the Kalabagh fault in the southwest part of the SRPP (Moghal et al. 2007). The structures are upright but asymmetrical with the Toot and Balkassar oil fields both having a steeper southern limb, contrary to the Joyamair oil field which has a steeper northern limb. Generally, the detachment folds are the most outer-most structures in the fold-and-thrust belts, such as the Lilla anticline in the SRPP. The presence of the Balkassar oil field and others in the Potwar Plateau is indicative of their presence in the internal part of the thrust system as well. Review of the seismic data shows that all three of them are located where the basement is irregular, either in the form of a ramp or a normal fault. Thus, their presence in the internal part of the system is probably facilitated by the stress accumulation and buckling of strata along basement irregularities which may serve to act as speed breakers and development of structures along them. Oil is produced from stacked Mesozoic–Paleozoic clastic and Eocene–Paleocene carbonate reservoirs in these fields (Fig. 3).

Table 2 Classification of the oil fields

Type	No.	Oil fields
Detachment fold	3	B, JM, T
Fault propagation fold	4	CN, DK, DL, KH
Pop-up	4	A, DR, MK, M
Triangle zone	1	DR

See Table 1 for abbreviations

Fault-propagation folds

This is a fold that develops at the tip of a blind thrust, as it steps up from the basal *décollement* (Fig. 6b). They occur at ramps. Strata at the base of the ramp are shortened by thrusting, whereas strata above the fault are shortened entirely by folding. During the development of fault-propagation folds, folding and ramping are synchronous events. Ramps are placed where faults have a cut-up section (generally at an angle around 10° to 30°). Fault-propagation folds are characterized by (1) a distinct asymmetry with a steep forelimb and a gentle back limb, (2) the frontal synclinal axial plane that ends at the fault tip, (3) folds that get tighter downward, (4) slip on the fold that decreases towards the fault tip, and (5) upward (listric) curvature of the fault that produces a syncline at the back of the system (Suppe 1985). Strata of variable but predictable dip panels across axial surface (kinks) are common features of these structures.

A seismic profile of the Chak-Naurang Field with interpretation of a fault-propagation fold is shown in Fig. 6b. The Chak-Naurang-1A was drilled in the crestal part of the fold to a depth of 2,687 m in the Salt Range Formation. The thickness of the Cambrian to Eocene (C-E) strata in the well is 544 m. Seismic data shows how a blind thrust steps up from the *décollement* and a fold develops at its tip. The fold is located over the ramp region of the fault and shows a slip of about 1 km along the base of the Cambrian decreasing to zero in the Tertiary clastic strata, which is a characteristic feature of the fault-propagation folds. Thus, the slip of about 1 km is entirely accommodated by folding. The ramp is placed where faults have a cut-up section, with a gentle dip of about 30°, but it is curved with a dip of about 45° as it approaches the competent unit (base of the Cambrian) with the development of a relatively narrow back limb and broader hinge zone. Generally, asymmetry with a steep forelimb and a gentle back limb can be seen. The frontal synclinal axial plane ends at the fault tip. The kinks die out in the fault, and strata in the footwall remain undeformed.

Four oil fields are classified as fault-propagation folds (Table 1). They are Chak-Naurang, Dakhni, Dhulian, and Khaur oil fields (Fig. 1; Table 2). In all cases, strata are detached from the basement and deformed with a general NE–SW trend of the structures. In these, the Dhulian and the Khaur oil fields have peculiar lenticular surface expression implying a relatively higher degree of contraction which is also depicted by the excessive amount of salt accumulation in the core zone of Dhulian. This is probably why the fields are laterally extensive as compared to the others (Fig. 1). All of them with the exception of Chak-Naurang are located in the NPDZ. The former three have a steeper northern limb with hindward vergence. The hindward vergence is either due to complex deformation or mechanics of deformation that depicts the presence of symmetrical foreland and hinterland verging structures over a weak *décollement*. The orogenic contraction is interpreted not to exceed about 1 km in each of these cases, reflecting a limited extent of the structures. Oil is dominantly produced from carbonate reservoirs of Eocene and Paleocene age (Fig. 3).

Fault-bend folds

A fold that develops over a flat–ramp–flat (staircase) geometry of a thrust is termed as a fault-bend fold or ramp anticline (Fig. 6c). In fault-bend folds, ramping precedes folding. Thrusts mostly propagate along zones of weakness within a sedimentary sequence, such as mudstones or salt layers; these parts of the thrust are called flats. As hanging-wall strata move up a ramp, they are tilted parallel to the inclination of the ramp but largely recover their original dip once they passed the ramp. A syncline–anticline pair is formed. The syncline is located above the basal transition from flat to ramp and the anticline above the top transition from the ramp to flat. The flat and ramp regions are bounded by the kink bands which systematically merge in the fault (Fig. 6c). Continued displacement on a thrust over a ramp produces a characteristic fold geometry known as a ramp anticline or more generally, as a fault-bend fold (Suppe 1983).

General characteristics of a fault-bend fold are as follows: (1) These structures form when a fault is not straight and has a flat–ramp–flat geometry, (2) ramping proceeds folding, and (3) a syncline–anticline pair is formed. They are not found as prospects yet in the SRPP. This may largely be related to the generally limited displacement along thrusts in the southern Potwar Plateau. The Salt Range itself serves as an example of this case (Fig. 5). A field picture of the Salt Range shows a hanging-wall flat of the thrust sheet over the footwall flat implying a large degree of translation along the thrust sheet.

The seismic profile of the Salt Range provides a clear example of the flat–ramp–flat (staircase) geometry of a thrust (Fig. 6c). It shows tilted and flat strata along the thrust sheet, parallel to the footwall ramp and flat. Continued displacement of about 20 km (Baker et al. 1988) along the Salt Range thrust over the ramp has given it a characteristic geometry of a fault-bend fold. The development of the fault-bend folds may largely be related to the generally significant displacement along the thrust sheets. Pariwali oil field in the central NPDZ is observed to exhibit such geometry over a blind fault of about 5-km displacement (Moghal et al. 2007). The Pariwali-1 well was drilled to a depth of 5,318 m into the Permian Sardahi Formation. About 4,602 m of clastic Miocene strata is drilled in this well and gives an idea of overburden for basin modeling.

Pop-ups

A section of hanging-wall strata that have been uplifted by the combination of a foreland and a hinterland verging thrust is known as a pop-up structure (Fig. 6d). Pop-ups are characterized by (1) the presence of two thrust faults with dips towards each other, (2) folding of a stack of competent layers between the thrusts, (3) folding by rotation of limbs, and (4) the presence of a flat crestal part between the limbs (Fig. 5). The flat crestal strata bend along two kink bands that merge at depth into one kink which, in turn, merges into the paired faults deep in the section.

A seismic profile across the Adhi Oil Field in the eastern SRPP serves as a good example of a pop-up structure (Fig. 6d). It shows the detachment and a section of uplifted hanging-wall strata along a foreland and hinterland verging thrust of opposite vergence. About 3–4 km of uplift of the strata is visible as a consequence of about 2 km of slip along each thrust fault. Furthermore, accumulation of excessive amount of the evaporites in the core zone of the anticline is also visible.

Four, out of 12 oil fields, are found to exhibit a pop-up structural style. They are Adhi, Messa-Kaswal, Fimkassar, and Meyal (Tables 1 and 2). The former two are located in the eastern SRPP south of the Soan Syncline. The Fimkassar and Meyal Oil Fields are located in the central and western SRPP (Fig. 1). They have general NE–SW to E–W trends and are cored by Eocambrian evaporites, similar to the Adhi. Four wells to a depth of 1,064 m were drilled before discovery of gas condensate in Adhi-5 which was drilled to a depth of 2,810 m. In this well, 2,290-m Miocene clastics and 488-m platform Cambrian–Tertiary strata are encountered. Hydrocarbons are produced from the stacked Tertiary, Mesozoic, and Paleozoic reservoirs, including both carbonates and clastics (Fig. 3).

Pop-up structures are observed to be more common in the SRPP. Dakhni and Khaur oil fields are interpreted as fault-propagation folds, in part with the presence of paired faults (Moghal et al. 2007). The Dhurnal oil field is located in a triangle-zone setting as described in the preceding section but also exhibits a pop-up geometry. It appears that pop-up structures evolve from the fault-propagation folds with increasing degree of shortening, similar to that as discussed by Butler et al. (1987) and found by sandbox modeling (Lui et al. 1992).

Triangle zones

A triangle zone is generally defined as a triangular area, bounded by a backthrust below tilted strata at the foreland side of the thrust belt and a floor thrust that terminates updip in the back thrust (Fig. 6e). The space between the two thrusts is occupied by a deformed (core) wedge of competent strata. Thus, they develop with the presence of two detachment levels. The core–wedge in this setting represents duplex strata, and the sequence above the back thrust is called a roof sequence (Jones 1982; Jadoon and Frisch 1997, 1999). Thus, a triangle zone is characterized by the (1) absence of an emergent (back) thrust, (2) presence of surface monoclinal expression, and (3) repetition of strata in the form of a duplex (core–wedge) between a blind floor and an emergent back thrust.

The Dhurnal oil field is an example of a triangle zone in the NPDZ (Table 1). The field was discovered in 1984 by drilling through a surface monocline according to seismic interpretation (Fig. 6e). The floor thrust is located in the regional *décollement* of the Eocambrian evaporites. The roof (back) thrust is located at the interface above the Miocene Murree Formation. Thus, the core–wedge is comprised of the Cambrian to Miocene strata deformed between the two faults.

The Dhurnal-3 well is drilled in a triangle-zone setting to a total depth of 4,890 m with 3,751-m thickness of Miocene clastics and 1,053-m thickness of the Cambrian–Eocene platform sequence (Figs. 2 and 7). To date, it is the largest oil field

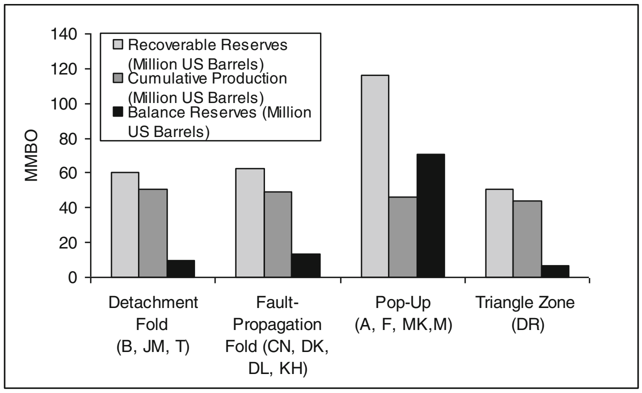

Fig. 7 Statistical analysis of structural styles of oil fields and hydrocarbon reserves. Reserved are based on information from Kadri (1995). *Abbreviations* are the same as in Table 1

in the SRPP with estimated reserves of 51 million barrels of oil (MMBO) (Kadri 1995), revised to 114 MMBO (Jaswal et al 1997; Jadoon et al. 1999). We have used the former number in our statistical analysis, as data for this study are extracted from the same author. Oil is produced from stacked reservoirs from the Dhurnal oil field (Fig. 3).

Reserves and production

In this section, we focus on estimation and statistical analysis of reserves and production to differentiate between best performing prospects (Fig. 7; Table 3). The estimate of reserves in Table 3 shows the Khaur oil field of fault-propagation fold geometry as the smallest, with about 4.3-MMBO original recoverable reserves, and the Dhurnal oil field of triangle-zone geometry as the largest, with about 51-MMBO original recoverable reserves. The cumulative recoverable reserves of the three oil fields of a detachment fold geometry (Balkassar, Joyamair, and Toot) are calculated as 60 MMBO which is comparable with 62.85 MMBO of the four oil fields of a fault-propagation fold geometry (Chak-Narang, Dakhni, Dhulian, and Khaur; Table 4; Fig. 7). The cumulative recoverable reserves of four oil fields of pop-up geometry (Adhi, Fimkassar, Meyal, and Messa-Kaswal) are calculated as 116.5 MMBO. Thus, they are observed to contain more hydrocarbons as compared to the former ones. The cumulative recoverable reserves of one oil field of triangle-zone geometry (Dhurnal) are calculated as 51 MMBO. These are re-assessed as 114 MMBO (Jaswal et al. 1997; Wandrey et al. 2004).

The analysis shows the triangle-zone structures as the best prospects followed by the pop-up structures. However, recoverable reserve estimates of 34 MMBO for Balkassar oil field and 42 MMBO for Dhulian oil field with detachment fold and fault-propagation fold geometry, respectively, reflect their

Table 3 Summary of oil fields, reserves, structural styles, and potential

No.	Oil fields	Year of discovery	Original recoverable reserves (million US barrels)	Cumulative production (million US barrels)	Balance recoverable reserves (million US barrels)	Type/Potential
1	A	1979	10.22	03.60	06.62	PU=H
2	B	1946	34.01	32.49	01.52	DF=M
3	CN	1987	04.70	02.17	02.56	FPF=L
4	DK	1983	12.44	01.23	11.21	FPF=H
5	DR	1984	50.94	43.85	07.08	TZ=M
6	DL	1935	41.40	41.36	00.04	FPF=L
7	F	1981	30.00	4.912	25.08	PU=H
8	J	1944	10.45	06.78	03.67	DF=M
9	KH	1914	04.31	04.18	00.13	FPF=L
10	M	1946	42.50	35.29	07.29	PU=M
11	MK	1991	34.73	02.39	32.36	PU=H
12	T	1968	15.80	11.45	04.34	DF=M

Reserves are based on Kadri (1995)

Black, grey, and open circles represent high potential, potential, and depleted fields

Abbreviations are the same as in Table 1. *H*, *M*, *L* refers to high, medium, and low potential

potential for accumulation of significant amounts of hydrocarbons as well depending upon their size and reservoir thickness. Generally, a detachment fold is observed to evolve into a fault-propagation fold and the latter either into a fault-bend or a pop-up structure. This implies a generally higher degree of orogenic contraction along the pop-ups with the development of favorable prospects. A sizeable discovery is much desired to improve the reserves, particularly when many old fields are at the verge of depletion.

Based on recoverable reserves, we characterize the oil fields as minor (<10 MMBO), medium (10–30 MMBO), and major (>30 MMBO) in the SRPP. The potential of small to medium-size fields is identified to the south of the Soan Syncline in a structurally simple setting, whereas the potential of medium to major-size fields is to the north of the Soan Syncline in a structurally more complex setting.

Hydrocarbon prospects and potential

Hydrocarbon prospects

The presence of a basal *décollement* and transition of faults into folds with a sudden change of dip across axial surfaces (kinks) are regular features of thin-skinned deformation (Chapple 1978). Simple buckling of strata or its translation along ramp-and-flat structures leads to the development of several structural styles. The discovered oil fields in the SRPP exhibit their styles as detachment folds, fault-propagation folds, pop-ups, and triangle zones (Table 1). The triangle zone and/or duplex structures followed by pop-ups are recognized as the most favorable trap-forming geometry. The former three types of prospects are located throughout the SRPP with their concentration in zones of relatively simple deformation. The latter one (triangle zone) discovered with the help of seismic data by drilling through a surface syncline is located in a structurally complex setting. They are commonly recognized with surface expressions of a monocline and are reported with significant accumulation of hydrocarbons elsewhere, such as in the foreland basins of the Canadian Rockies (Jones 1982), the Alps (Müller et al. 1988), and the Andes (Ramos 1989).

Hydrocarbon exploration

Our structural analyses show that hydrocarbons have been discovered from most of the relatively simple structural traps, and exploration is now extended to more complex structures.

Table 4 Summary of structural styles and cumulative hydrocarbon reserves of selected oil fields in the SRPP

Type (name)	Recoverable reserves (million US barrels)	Cumulative production (million US barrels)	Balance reserves (million US barrels)
Detachment fold (B, JM, and T)	60	51	9
Fault-propagation fold (CN, DK, DL, and KH)	62.85	49	13.85
Pop-up (A, F, MK, and M)	116.5	46	70.5
Triangle zone (DR)	51	44	7
Total	290	190	100

Abbreviations of oil fields are the same as in Table 1

Drilling of Margala-1 in NPDZ that was spud on 17 July 2010 and plugged on 24 January 2011 for unknown reasons is an example. Currently, post-drilling evaluation is in process for this well, and the potential of discovered fields is being reassessed. Therefore, it is important that the geometry of prospects is interpreted for further exploration. In this respect, a link between Miocene molasse sedimentation and deformation has to be established. In the NPDZ, the presence of only the Lower Miocene Murree Formation raises several questions. Is it because of sedimentation, deformation, or both requires to be adequately addressed in the NPDZ. This research serves as a basis for our future work focused on the detailed geometry of individual fields for their evolution, stress distribution, and fractures in low-porosity carbonate reservoirs (Jadoon et al. 2007).

A 40-km-long structural cross section depicts the general structural style of the eastern NPDZ (Fig. 8a). It shows triangle-zone geometry along the northern flank of the Soan Syncline followed by flat-and-ramp structures and surface exposures of subvertical to overturned strata of the Miocene Murree Formation further north. Triangle-zone structures require the presence of two detachments bounding deformed strata. The upper detachment reflects hindward vergence with an example of the Dhurnal back thrust in our cross section (Fig. 8a) similar to the Canadian Rockies (Fig. 8b), and the eastern Sulaiman fold belt (Fig. 8c). The younger strata above the back thrust are tilted and exposed and continuously eroded in response to duplex structures between the two detachments.

Triangle-zone structures are recognized as important prospects in the fold-and-thrust belts. They are interpreted to extend over a region of about 100 km with a 30-km-wide zone of deformation in the eastern NPDZ (Jadoon et al. 1997; Jaswal et al. 1997; Jadoon et al. 1999). Here, they occur with NE–SW structural trend between the Khairi-Murat thrust and the Soan Syncline (Fig. 8a). The blind and emergent thrusts in the triangle zone are interpreted with a displacement of 2 to about 13 km based on seismic reflection data (Jadoon et al. 1999). Those with a higher degree of displacement such as the Khairi-Murat thrust are observed to extend over a wider region as compared to those with a limited degree of

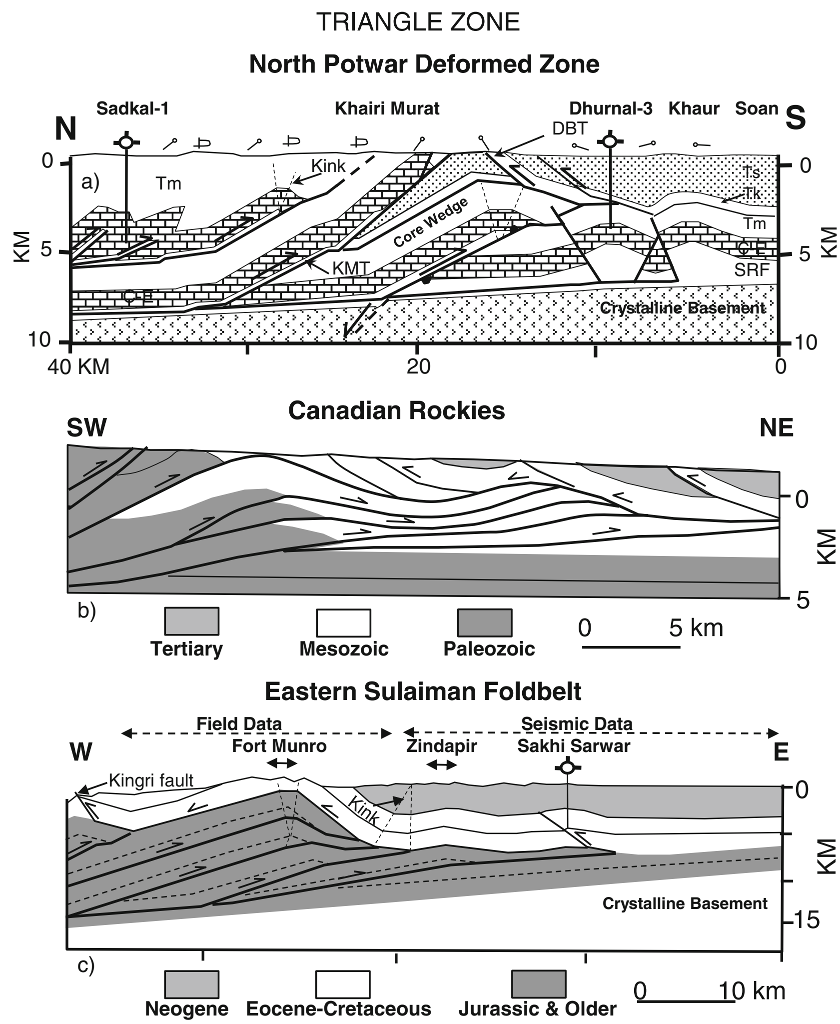

Fig. 8 Examples of triangle-zone geometry and flat-and-ramp anticlines from the following: **a** Eastern NPDZ (modified from Jadoon et al 1999), **b** Canadian Rocky Mountains (modified from Jones 1982). **c** Eastern Sulaiman fold belt (modified from Humayon et al. 1991). The presence of two detachments, the presence of monoclinal expression of tilted strata over the back thrusts, and the presence of a relatively thick stratigraphic section are common in all three sections. *Abbreviations* in the cross section of the NPDZ are the same as in Fig. 5 with *TK* as Kamlial Formation (Rawalpindi Group)

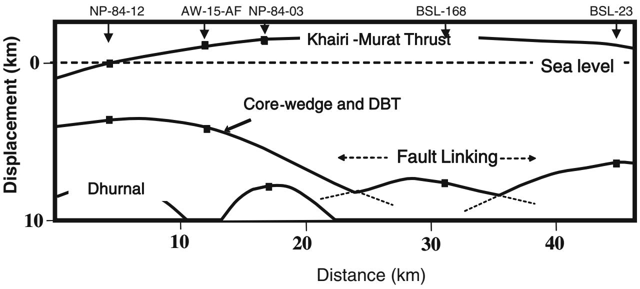

Fig. 9 Stratigraphic separation diagram based on fault length and displacement along the Khairi-Murat triangle zone in the eastern NPDZ. Fault length and displacement are based on seismic reflection interpretation. The *diagram* shows linking of smaller faults (prospects) into larger ones with increasing displacement

displacement such as the Dhurnal pop-up. Thus, prospects of variable length and structural closure are interpreted with a stratigraphic separation diagram which is based on the displacement and length of several thrusts from the Khairi-Murat triangle zone (Fig. 9). The figure shows three sets of structures from the buried fault tip line of the Dhurnal to the exposed Khairi-Murat thrust (Figs. 1, 8a, and 9). The small-scale faults of 2-km displacement and structural relief are observed along the fault tip line. These blind thrusts appear to link with increasing displacement and length evolving through a core–wedge into an emergent thrust (Khairi-Murat) of 13 km of displacement. The mechanism of linking of smaller blind thrusts into larger emergent thrusts is similar to that as observed by Davison (1994) and illustrated in Fig. 9 with an example of the NPDZ.

The presence of a linked fault system in the NPDZ depicts the existence of hydrocarbon traps of variable size, which are yet to be explored. The example of Dhurnal as a pop-up shows that propagating blind thrusts having a small displacement are capable of retaining moderate to large quantities of hydrocarbons. Herein, we have illustrated the potential of the core–wedge as a structural trap in a triangle zone between the south-dipping Dhurnal back thrust and the north-dipping Khairi-Murat thrust, similar to the Canadian Rockies.

Conclusions

In this paper, we have reviewed the oil-and-gas field structures and existing reserves in the SRPP which is located in the Himalayan foreland in north Pakistan. Oil is produced from a stack of Cambrian to Eocene clastic and tight fractured carbonate strata that have a cumulative thickness of about 1 km. Prospects are dominated with the thrust fault-related anticlines over a weak basal detachment in the Eocambrian evaporites. Foreland and hinterland vergent thrusts with symmetrical structures are quite common due to the presence of a thick layer of evaporates along the *décollement*, to the south of Soan Syncline. Our structural analysis of 12 oil fields show common compressional structural styles as detachment folds, fault-propagation folds, pop-ups, and triangles zones in the SRPP.

Original recoverable reserves of about 290 MMBO were limited to only 100 MMBO with the production and depletion of the existing fields in 1995. Based on recoverable reserves, we have characterized the oil fields as minor (<10 MMBO), medium (10–30 MMBO), and major (>30 MMBO) in the SRPP. Minor and major oil fields are interpreted to depict fault-propagation fold and pop-up/triangle-zone structures, respectively. The potential of minor to medium-size fields is identified to the south of the Soan Syncline in a structurally simple setting with limited displacement of blind thrusts, whereas the potential of medium to major-size fields is identified, in the NPDZ, to the north of the Soan Syncline in a structurally complex setting.

The triangle-zone structures are recognized in the NPDZ between the Khairi-Murat thrust and the Soan Syncline. They are characterized with a core–wedge between a back thrust (upper detachment) and a floor thrust (lower detachment). Furthermore, they show an increase in displacement, toward the north, along blind thrusts from the fault tip line. Dhurnal, with pop-up geometry, is recognized as a major oil field with about 2 km of displacement along the paired blind thrusts at the fault tip line. The core–wedge, toward the north, is recognized with about 4.5-km displacement along a blind thrust with a considerable lateral extent of the prospect, as compared to the Dhurnal. The increase in length of the prospects is linked with the increase in the length of the blind thrusts with increasing displacement. The potential of triangle-zone structures in the NPDZ are yet to be assessed as prolific oil-and-gas fields similar to the Canadian Rockies and elsewhere.

Much of the deformation of the SRPP has occurred since about 8 Ma with sedimentation and deformation of the clastic Siwalik Group strata, constrained by the magnetostratigraphy and fission-track dating (Johnson et al. 1982a, b; Burbank and Raynolds 1984, 1988; Burbank and Beck 1989). Thus, many of the oil fields may have evolved since this time. The northern limb of the Soan Syncline is tilted over the Dhurnal oil field where it is interpreted to deform between 1.9 and 2.1 Ma with out-of-sequence deformation. The potential of hydrocarbon in such young structural traps has important bearing for hydrocarbon exploration in the Himalayas.

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