**Active Tectonics of Western Potwar Plateau-Salt Range, Northern Pakistan
from InSAR Observations and Seismic Imaging**

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Abstract

The foreland fold-and-thrust belt of northern Pakistan is located at the western end of the Himalayan arc, where salt tectonics is responsible for structural styles, hydrocarbon source areas and seismicity. Three sub-regions of fold-and-thrust belt are the Potwar Plateau-Salt Range, Kohat Plateau-Surghar Range and the Bannu Basin-Khisor Range. The difference in deformation intensity between these regions is mainly attributed to the presence, or absence, of an Infra-Cambrian salt layer. This study investigates the active tectonics of the Potwar Plateau and Salt Range region, emphasizing the role of salt, using the Small Baseline Subset Interferometry (SBAS) technique and 2-D seismic interpretations. Ten PALSAR images and four seismic

profiles from western Potwar Plateau-Salt Range region were used. SBAS results, derived from PALSAR images spanning from 2007 to 2010, suggest that the Potwar Plateau-Salt Range is active with the western portion of the region experiencing an uplift at an average rate of around 10 mm/yr. Two uplift anomalies were observed, which were interpreted as zones of transpression and salt diapirism. Time-migrated seismic profiles show that the salt layer acts as a detachment. Our results show that salt has different roles in different regions of the fold-and-thrust belt; in the Potwar Plateau region the salt layer acts as a detachment, while in Salt Range salt flow-induced structures are prominent. The integration of SBAS and 2D seismic interpretation reveals that the deformation of western Potwar Plateau-Salt Range is influenced by two main faults, the dextral Kalabagh fault and the Main Frontal Thrust. Finally, this work was compared to the Kuqa fold-and-thrust belt in western China due to their structural similarities.

1. Introduction and tectonic setting

The collision of India with Eurasia resulted in crustal deformation along an arc-shaped convergence zone: the Himalayan-Tibetan orogeny (Hodges, 2000; Molnar, 1984; Yin & Harrison, 2000). Currently, the Indian plate slides northward into the Eurasian plate at an estimated rate of 45mm/yr and this leads to a tectonically active region, which has suffered several devastating earthquakes (Bilham, 2006) (**Fig. 1**). An earthquake (7.9 magnitude) occurred in the northwestern Himalayas near Muzafarabad, Pakistan on October 8, 2005 claiming the lives of around 86,000 people (Peiris et al., 2006; USGS (**Fig. 1**). Furthermore, this convergence generated a southward progression of large north-dipping thrusts

Fig. 1. Map of the study area in northern Pakistan. The Chaman Fault marks the western boundary of the Himalayas. KF: Kalabagh Fault, JF: Jhelum Fault, PBF: Pezu-Bhittani Fault, MMT: Main Mantle Thrust, MKT: Main Karakorum Thrust, MBT: Main Boundary Thrust, MFT: Main Frontal Thrust. (Modified from Pivnik, 1992; Ali, 2010; Ul-Hadi et al., 2012). The yellow rectangle is the location of the ALOS PALSAR scenes that were used in InSAR processing. Black and white lines are 2D seismic lines that were interpreted [Lines 1-4 are shown in Fig. 4A-D]. The map also shows the distribution of earthquakes (red circles) in the study area. Focal mechanisms along the MFT and the Kashmir region show active compressional deformation with a slight oblique slip component (Dziewonski et al., 1981; Ekstrom et al., 2012; Ekstrom & Nettles, 1997). Sargodha High is a basement uplift located to the south of the fold-and-thrust belt. The arrow (inset) shows the current estimated movement of the Indian plate (Bilham, 2006). The location of Fig. 3 is indicated by the red box.

to accommodate crustal thickening/shortening; from north to south, the Main Karakorum Thrust (MKT), Main Mantle Thrust (MMT), Main Boundary Thrust (MBT) and Main Frontal Thrust (MFT) (Banerjee & Burgmann, 2002; Butler et al., 1989; Sella et al., 2002) (**Fig. 1**). These thrust faults separate the Himalayan orogeny into structurally and geologically distinct blocks (Hodges, 2000; Molnar, 1984; Moore & Twiss, 1995; Yin & Harrison, 2000). Located between the Main Boundary Thrust and the Main Frontal thrust is the foreland fold-and-thrust belt, which is a common feature of orogenic belts (**Fig. 1**). Since fold-and-thrust belts are located far from the center of orogenic belts, they tend to experience most of the current deformation (Dahlen et al., 1984; Dahlen & Suppe, 1988; Moore & Twiss, 1995). Focal mechanisms along the Main Frontal Thrust show that active compressions are occurring along this fault (**Fig. 1**). Some focal mechanisms also show minor oblique slip component.

Located at the western edge of the Himalayan arc is the foreland fold-and-thrust belt of northern Pakistan (**Fig. 1**). They have unique landforms where regions of relatively flat topography, referred to as basins or plateaus, are followed by relatively elevated regions to the south, referred to as ranges. The basins are filled with Miocene to recent molasse sediments originating from the Himalayan orogeny, while the ranges expose older sedimentary layers that have been thrust over younger layers. The fold-and-thrust belt of northern Pakistan consists of three main regions: the Potwar Plateau-Salt Range, Kohat Plateau-Surghar Range and Bannu Basin-Khisor Range (**Fig. 1**). The study area covers western Potwar Plateau-Salt Range, which is an area that is experiencing transpressional deformation due to the relative motion of dextral Kalabagh fault and the Main Frontal Thrust. The Kalabagh fault delineates the western limit of the Potwar Plateau and is an important aspect to active tectonics in this region (**Fig. 1**). Recent geodetic studies have suggested that the Kalabagh fault is still active, with an average slip rate of

around 5.3 mm/yr (Chen & Khan, 2010; Jouanne et al., 2014). Moreover, a GPS study indicates that the Potwar Plateau is moving southward at rate of 5 mm/yr (Jouanne et al., 2014).

The fold-and-thrust belt of Potwar Plateau-Salt Range is underlain by thick salt and is bounded to the east by the sinistral Jhelum fault (Butler et al., 1987; Jaume & Lillie, 1988). The Kalabagh and Jhelum faults are believed to be related to the fact that thick salt is present in the Potwar Plateau-Salt Range and absent or thinning to the east of the Jhelum fault and west of the Kalabagh fault (Davis & Engelder, 1985; Sarwar & De Jong, 1979; Seeber et al., 1981) (**Fig. 1**). **Fig. 1** shows that the Potwar Plateau is translated more southwardly than the adjacent Kohat Plateau, with the Kohat Plateau experiencing relatively higher deformation. The difference in structural styles and deformation intensities between them is mainly attributed to the nature of their respective detachment layers (Cotton & Koyi, 2000; Jaume & Lillie, 1988; Khan et al., 2012; Yeats et al., 1984). The detachment layer for the Potwar Plateau is at the level of a weak Infra-Cambrian salt layer, the Salt Range formation. Due to the weak nature of the detachment's lithology, which resulted in its low shear stress, the overburden slides effectively along the sole thrust without significant resistance (Davis & Engelder, 1985). Another important feature of salt is the presence of salt mines along the southern boundary of the Salt Range, delineated by the Main Frontal Thrust, which may be related to salt tectonics.

This observation shows the importance of the salt layer in studying the complex, thin-skinned deformation of this region (Chapple, 1978; Jaume & Lillie, 1988). In order to fully understand how the fold-and-thrust belt of northern Pakistan deforms, the regional faults and the local lithological variability, such as salt and overburden thickness, must be taken into account. Previous models explaining the deformation of this region have been mainly based on geological

field works, seismic profiles and well data (Cotton & Koyi, 2000; Jadoon et al., 2014; Jaume & Lillie, 1988; Khan et al. 2012; Yeats et al., 1984). A recent approach in studying the Kohat Plateau by Satyabala et al. (2012) using Interferometric Synthetic Aperture Radar (InSAR) gives new insight into how fold-and-thrust belts currently deform. Similarly, this work utilizes InSAR in order to better understand the current deformation pattern of western Potwar Plateau-Salt Range and the Kalabagh fault.

This work focuses on the active tectonics of western Potwar Plateau and Salt Range, with emphasis in the identification of actively deforming structures. Two methods were used in this study: SBAS (Small BAseline Subset), an InSAR processing technique and 2D seismic interpretation. SBAS was used to map the surface deformation of the southwestern region of the Potwar Plateau-Salt Range from 2007 to 2010. Results show that the Salt Range underwent uplift up to 15 mm/yr. 2D seismic sections and published well data give a clear picture of the subsurface structures of the Salt Range formation. This work provides a clear evidence for active transpressional deformation and salt diapirism at the western Salt Range. Furthermore, the presence of salt in this region affects the deformation of Potwar Plateau and the Salt Range differently. In the Potwar Plateau, the salt acts as the detachment layer, while salt diapirism is prominent in the Salt Range.

2. Methodology

2.1. SBAS (Small Baseline Subset) InSAR data processing

InSAR is a powerful tool in detecting crustal deformation and movements of salt structures over a large spatial area with centimeters to millimeters accuracy (Berardino et al., 2002; Lanari et al., 2007; Massonnet et al., 1993). In contrast to point-based GPS studies, InSAR

provides spatial and temporal deformation patterns, which can be used to identify large-scale active features. For example, it has been used to map and model a salt dome in Iran (Aftabi et al., 2010), and the displacement of the Kalabagh fault between the Potwar Plateau-Salt Range and the Kohat Plateau-Surghar Range systems (Chen & Khan, 2010). One of the common approaches in detecting slow deformation is the Small Baseline Subset Interferometry (SBAS) (Berardino et al. 2002; Lanari et al., 2007), which derives incremental displacements by inversion of temporal phase profiles effectively reducing atmospheric effects, topographic uncertainties and/or orbital errors. SBAS technique has been successfully used to study deformation trends of calderas and major cities, such as Phoenix, USA, Houston, USA and Nanjing, China (Berardino et al., 2002; Casu et al., 2005; Huang & He, 2008). Ten ascending SAR images from the Phased Array type L-band Synthetic Aperture Radar (PALSAR) sensor onboard the Advanced Land Observing Satellite (ALOS) over a period of 3 years between January 2007 and March 2010, were used in this study (**Table 1**). The SAR images cover western Salt Range (**Fig. 1**).

A total of 32 InSAR pairs were generated using normal baseline thresholds of 50% of the critical baseline for the spatial baseline and 600 days for the temporal baseline. Fig. 2 shows the time-baseline plot for the PALSAR images that were used for SBAS processing. The interferograms were processed using the SARscape modules of ENVI software from EXELIS VIS Information Solutions. The processing steps include the co-registration of the image pairs, interferogram generation, interferogram flattening using Shuttle Radar Topography Mission (SRTM) version 4 (<http://srtm.csi.cgiar.org/>) digital elevation model (DEM), Goldstein filtering (Goldstein & Werner, 1998) and coherence generation. A complex multi-look operation taking

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Table 1

A list of the PALSAR data used in SBAS approach. The images were collected in Fine Beam Single mode (FBS) and Dual mode (FBD) with 34.3 degrees off-nadir angle on path/row of 533/640. The image collected on May 27th, 2008 was used as the master image for all interferograms. Final displacement was estimated with respect to the first acquisition date (January 7th, 2007), to which a null displacement was assigned.

Paired Granule	Date	Beam Mode	Normal/Critical Baseline (m)	Days
ALPSRP050860640	Jan 07, 2007	FBS	0	0
ALPSRP057570640	Feb 22, 2007	FBS	1920/ -13080	46
ALPSRP084410640	Aug 25, 2007	FBD	2689/ -13080	230
ALPSRP091120640	Oct 10, 2007	FBD	2899/ -9810	276
ALPSRP104540640	Jan 10, 2008	FBS	3437/ -13080	368
ALPSRP111250640	Feb 25, 2008	FBS	3971/ -13080	414
ALPSRP124670640	May 27, 2008	FBD	4155/ -9810	506
ALPSRP158220640	Jan 12, 2009	FBS	741/ -13080	736
ALPSRP191770640	Aug 30, 2009	FBD	2005/ -9810	966
ALPSRP218610640	Mar 02, 2010	FBS	3091.15/ -13080	1150

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Fig. 2. Normal baselines used for SBAS processing at western Potwar Plateau and Salt Range. Green diamonds represent valid interferogram pairs, while the yellow diamonds refer to the SBAS master image (May 27th, 2008). Final displacement was estimated with respect to the first acquisition date (January 7th, 2007), to which a null displacement was assigned.

138 one look in range and five looks in azimuth was performed to produce ground resolution of about
139 15 m.

140 Phase contributions due to the earth's topography from the interferograms were removed
141 during the flattening step using the simulated phase corresponding to the reference DEM at the
142 SAR imaging geometry. Residual phase ramps due to imprecise orbit knowledge was estimated
143 and removed using a best fitting linear phase ramp of reference points determined along orbital
144 fringes. A combination of minimum cost flow (MCF) network (Costantini, 1998) and Delauney
145 3D method (Hooper & Zebker, 2007) was employed for phase unwrapping. The phase errors,
146 caused by the atmospheric signal, are correlated in space and were removed. Atmospheric phase
147 screening was conducted to estimate and remove atmospheric effects before the final
148 displacement velocities were calculated. The spatial variation of the atmospheric phase in the
149 same acquisitions is typically small over spatial scale and much stronger over time. A low pass
150 spatial filter (at 1.2 km x 1.2 km window) on each single acquisition, followed by a high-pass
151 filter on the time series images, was used to screen the atmospheric phase component of the
152 signal.

153 It is worth noting that the displacement from InSAR is a relative measure in the line of
154 sight (LOS) direction. Ground control points with assumed zero deformation (motionless) were
155 selected as reference points for SBAS processing chain. The criteria for identifying such pixels
156 may include a temporal coherence value of 0.75 or greater, unwrapped phase value close to zero
157 and flat areas identified from a topographic map projected at LOS direction. The mean
158 displacement value calculated over the ground control points was subtracted from the
159 displacement image, as it is supposed to be "zero" over these motionless points. Therefore, it is

likely that the absolute values of cumulative displacements were affected by the selection of the ground control points.

2.2 2D-Seismic

The seismic data were provided by the Directorate General of Petroleum Concessions (DGPC) of Pakistan. The seismic lines were acquired during 1978 to 1981 by the Oil and Gas Development Company Limited (Pakistan) using dynamite as source, with the length of the profiles ranges from 25 to 45 km. Four seismic reflection profiles were interpreted for structural and stratigraphic information (**Fig. 3**). The details of the interpreted seismic lines are presented and discussed in section 3.2. All of the seismic lines (Lines 1-4) overlap the PALSAR images. The overlapping lines were utilized in the interpretations of the InSAR surface displacement result. Line 3 (A-A'), line 4 (B-B') and line 2 (C-C') are oriented north-south, while line 1 (D-D') is oriented east-west (**Fig. 3**). Information from well Karang-01 (TD: 1091 meters) from Leathers (1987) was used to interpret the seismic lines (**Fig. 3**). The interpretations of the seismic lines reveal the subsurface structures, which include strike-slip faults, variable thicknesses of the Salt Range Formation, the basement ramping to the south and the southward tapering of the overburden. Petrel Schlumberger software was used for interpretation with the assistance of published well data and published velocity models (Chen, 2009; Pennock, 1988). Seismic attributes, such as instantaneous phase, were used to easily detect horizons and faults.

3. Results and analysis

3.1 SBAS surface displacement map

Fig. 3 shows the accumulated total displacement in mm along the Line of Sight (LOS) averaged for the duration of approximately 3 years (January 7th, 2007 to March 2nd, 2010). Overall, the western Potwar Plateau-Salt Range has moved toward the satellite as indicated by a decrease of the sensor-to-target slant range distance. On ascending path, the ALOS satellite was moving north with its antenna pointed to the right. Therefore, a decrease in the slant-range distance can be regarded as a westward shift, uplift or both. We attributed this movement primarily to an uplift for the following reasons: 1) from the general tectonics of the area, we know that the plateau is on the hanging wall side of the Main Frontal Thrust system, where uplift is expected; 2) A GPS observation deployed in central Potwar plateau, which indicated that there was a south-southeast (SSE) motion of about 3 mm/yr rate relative to the Indian plate (Khan et al., 2008) (**Fig. 1**). The GPS observation is consistent with the InSAR displacement map that shows a very low displacement rate at around 4 to 5 mm/yr in the same region (**Fig. 1**). This suggests that the observed deformation is predominantly caused by surface uplift. However, the rate of uplift is not consistent over the whole map, with uplift rates that generally range from 4-11 mm/yr. Moreover, two uplift anomalies are observed (denoted by Zone A and Zone B in **Fig. 3**). Both zones experienced an uplift rate of around 15 mm/yr. With the assistance of detailed geological maps and cross-sections of the Salt Range by Gee (1980 & 1989), we interpreted Zone A (Sakesar) as a transpression zone and Zone B (Warcha Salt Mine) as a salt tectonic zone. This shows that deformation is strongly affected by localized geological events. In the case of Zone A, the combination of the interpreted strike-slip

201 fault and the Main Frontal Thrust creates a dextral transpression zone, where significant uplift
202 may occur. The interpreted strike-slip fault is clearly observed as a linear feature on the InSAR
203 displacement map, located to the northwest of Zone A. This dextral strike-slip fault is believed to
204 be related to the Kalabagh fault. The eastern fault block has a displacement rate in LOS of
205 approximately 7.5 mm/yr and the western fault block has around 0-2 mm/yr displacement rate.
206 Although Zone A coincides with the region of highest topography in Salt Range, with the
207 Sakesar Mountain peaking at 1522 meters, we believe that due to the active Kalabagh fault, it is
208 very probable that uplift did occur. In addition, mapped faults coincide very well with the
209 southern limits of uplifted Zone A. This strongly shows that tectonic has a role in the
210 deformation of this region.

211 By contrast, Zone B is surrounded by exposed salt, where an active salt mine (Warcha
212 Salt Mine) is located. The Warcha Salt Mine is administered by the Pakistan Mineral
213 Development Corporation (PMDC), where dome-like salt structures are mined. The anomalous
214 surface deformation of Zone B suggests that salt diapirism may be the cause of the uplift, which
215 is controlled by active transpressions and compressions in this region. This is a further
216 confirmation that internal deformation of Potwar Plateau and Salt Range is not consistent along
217 the strike of the Main Frontal Thrust, which may be attributed to local factors such as faulting,
218 salt tectonics, basement geometry, overburden geometry or all of them combined.

219 In addition, the eastern part of the displacement map was not interpreted due to
220 unwrapping error in InSAR processing. The identification and interpretation of active structures
221 were only performed for the western half of the displacement map. This error could be attributed
222 to the lack of reliable interferograms due to insufficient number of SAR images for SBAS

processing. Areas of low coherence are shown as regions of no data, which is mainly due to highly vegetated areas.

3.2 Structural styles from seismic interpretation

Four time-migrated seismic reflection profiles were interpreted (**Fig. 4A-D**) along with available well and velocity model information. Four seismic lines (Lines 1-4), overlapping InSAR displacement map, are located in western Potwar Plateau-Salt Range (**Fig. 3**). Four main stratigraphic layers were distinguished, which are from the top, the molasses section (Siwalik and Rawalpindi from Pleistocene to Miocene), the carbonate platform (Eocene to Cambrian), the Infra-Cambrian Salt Range Formation (SRF) and the Pre-Cambrian basement. **Fig. 5** shows a more detailed stratigraphy of the Potwar Plateau-Salt Range region. The most distinguishable layer in the seismic profiles is the carbonate platform. This layer is characterized by very strong reflectors in the seismic profiles. Below the platform, the SRF is characterized by a seismically transparent layer. The boundary between the SRF and the basement rock is also a strong reflector, which is mainly due to the high acoustic impedance difference. The Siwalik and Rawalpindi groups are identified as moderate parallel reflectors. In all of the seismic profiles, the boundary between the Siwalik and the Rawalpindi is inferred. Generally, the carbonate platform thickness is consistent throughout all the profiles. The SRF has the most variation in thickness, which is due to its ductile nature. The descriptions of the interpreted seismic lines are as follows:

3.2.1 Western Potwar Plateau-Salt Range (Fig. 4A, 4B, 4C and 4D)

In general, the seismic profiles show that the thickness of the Salt Range Formation is directly related to overburden thickness. Also, it is clear from the seismic interpretation that the detachment layer is located in the Salt Range formation. For instance, Line 3 shows an area of

246 salt weld or thinning of salt on the north side of the line (**Fig. 4A**). Faults were interpreted above
247 this area, which suggests that the salt evacuation, most probably to the south, disturbed the
248 overlying sedimentary layers (**Fig. 4A**). This observation also correlates well with the thickness
249 of the overburden, especially the Rawalpindi and Siwalik molasse section. Due to differential
250 loading, salt escapes from higher load (thick overburden) to region of lower load to the south.
251 Due to the relatively rigid nature of the Cambrian-Eocene platform ‘floating’ above the ductile
252 salt layer, it tends to break apart, resulting in faults. Another important observation is that there is
253 no presence of a basement normal fault, which can be seen in central Potwar Plateau (Faisal &
254 Dixon, 2014; Jaume & Lillie, 1988). Instead, the Pre-Cambrian basement appears to flex
255 upwards towards Salt Range.

256 Although to a lesser extent, Line 4 also shows similar structures; a faulted zone of
257 Cambrian to Eocene platform is interpreted above a thinning salt zone (**Fig. 4B**). In addition, the
258 molasse sections, the Rawalpindi and Siwalik formations, are relatively undisturbed, except for
259 some minor faults. Another important observation is the north-dipping normal fault of the Pre-
260 Cambrian basement rock. However, the throw of the normal fault is relatively less than those in
261 central Potwar Plateau (Faisal & Dixon, 2014; Jaume & Lillie, 1988). This suggests that the
262 basement normal fault does not play a major role in the ramping of western Salt Range. Line 2
263 shows a basement normal fault with a small throw (**Fig. 4C**). This indicates that the basement
264 normal fault is mainly prominent in central Potwar Plateau. The southern portion of the line
265 shows a gentle syncline followed by a gentle anticline to the north. Thicker molasse was
266 deposited in the syncline, which increases the load and pushes the salt to the north, into the
267 anticline. Moreover, it is clear that the salt detaches the overlying Cambrian to Eocene platform

and the Rawalpindi/Siwalik layers from the Pre-Cambrian basement. The north-dipping detachment surface, which is also the thrust surface, is likely to be in the Salt Range Formation.

Line 1 runs through the Kalabagh fault (**Fig. 4D**). Most of the line is located to the west of the Kalabagh fault and has a different stratigraphy (**Fig. 3**). The formations that were interpreted are, from the oldest layer, the Pre-Cambrian basement, Cambrian strata, Permian strata, Mesozoic strata, Lower Tertiary strata, Chinji and Nagri formations. These layers are mainly parallel and undisturbed. However, two faults were interpreted to the east of the line. A thrust fault separates the parallel strata to the west from the over-thrusted Salt Range strata. A possible right-lateral strike-slip fault is also interpreted and this is consistent with the SBAS displacement map (**Fig. 3**).

In general, the seismic interpretation of western Potwar Plateau-Salt Range can be summarized as the following:

1. Most of the structural deformation, such as thrust faults and folds are striking east-west. This shows that most of the compressional forces are oriented north-south. The general folding that occurs is gentle, symmetrical and can be characterized as low-frequency folds. Most of the structures are south-verging.
2. The basement normal fault is absent or has relatively small throw. However, the Pre-Cambrian basement shows an upward flexing towards the south. This may explain the translation of the hanging wall without much internal deformation.
3. The Salt Range Formation (SRF) varies in thickness from 900 meters to 3500 meters, which is a direct consequence of the variability in overburden thickness. Salt tends to escape higher load area (synclines) into lower load area (anticlines).

Fig. 4A. Interpreted Line 3. The Karang-01 well intersects this line to the south. The Salt Range Formation acts as a detachment layer. Faulting generally occurs above the Salt Range Formation, which may be due to salt flow. Also, strong reflectors at the bottom of the Salt Range Formation were interpreted as a layer of anhydrite or gypsum.

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Fig. 4B. Interpreted Line 4. The structural style is similar to the previous line. The Salt Range Formation acts as a detachment layer. Faulting generally occurs above the Salt Range Formation, which may be due to salt flow. Also, strong reflectors at the bottom of the Salt Range Formation were interpreted as a layer of anhydrite or gypsum. Another important observation is the presence of a basement normal fault, with a relatively small throw, located to the north of the line.

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Fig. 4C. Interpreted Line 2. The Salt Range Formation acts as a detachment layer. A basement normal fault is interpreted. The thickness of the SRF varies, with thicker salt under anticlinal structures and thinner salt under synclinal structures. Also, strong reflectors at the bottom of the Salt Range Formation were interpreted as a layer of anhydrite or gypsum.

Fig. 4D. Interpreted Line 1. Most of the line is located west of the Kalabagh fault and has a different stratigraphy. The layers are mainly parallel and undisturbed. However, they are truncated by the Main Frontal Thrust. Also, a dextral strike-slip fault was interpreted, which correlates well with the InSAR displacement map.

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Age	Group	Formation	General Descriptions	Thickness (m)
PLIO-CENE	SIWALIK	SOAN	Conglomerate, sandstone, claystone	~5300
MIOCENE		DHOK PATHAN	Claystone, sandstone	
		NAGRI	Sandstone, shale	
		CHINJI	Sandstone, shale	
	RAWALPINDI	KAMLIAL	Sandstone	~2200
		MURREE	Shale, sandstone	
EOCENE	C-E CARBONATE PLATFORM	CHORGALI	Limestone, shale	~200-1500
PALEOCENE		SAKESAR	Limestone	
		NAMMAL	Limestone	
		PATALA	Limestone, shale	
PERMIAN		LOCKHART	Limestone	
		HANGU	Sandstone, shale	
		WARGAL	Limestone	
		AMB	Sandstone, shale	
		SARDHAI	Shale	
		WARCHA	Sandstone, shale	
		DANDOT	Sandstone, shale	
CAMBRIAN		TOBRA	Sandstone, siltstone	
		BAGHANWALA	Shale, salt pseudomorph	
		JUTANA	Sandy dolomite	
		KUSSAK	Sandy shale	
		KHEWRA	Siltstone, shale, sandstone	
INFRA-CAMBRIAN	SRF	SALT RANGE FORMATION	Evaporites – halite, marl, gypsum, dolomite, anhydrite	~0-2000
PRE-CAMBRIAN	BASEMENT INDIAN SHIELD		Biotite schist	

Fig. 5. A detailed stratigraphic column of Potwar Plateau-Salt Range (Modified from Faisal & Dixon, 2014; Jadoon et al., 2014).

1. Other than some thrust faults cutting across the overburden layers (molasses section and carbonate platform), the suprasalt layers are relatively undeformed. The carbonate platform, which is the most distinguishable layer in the seismic section, has a constant thickness of roughly 600 meters. The faulted rigid Cambrian-Eocene carbonate platform can be described as ‘floating’ on the ductile salt layer.
2. A southern portion of the dextral Kalabagh fault was interpreted, with the help of SBAS displacement map (**Fig. 3**).

3.3 Tectonic Interpretation

By integrating the InSAR results and seismic interpretation, this work focuses on the tectonic and structural framework of western Potwar Plateau-Salt Range region. Previous studies have shown that the Potwar Plateau-Salt Range is a thin-skinned foreland fold-and-thrust riding on thick Infra-Cambrian salt (Faisal & Dixon, 2014; Jaume & Lillie, 1988). Studies have also been done comparing the structural styles of the Potwar Plateau and the adjacent Kohat Plateau. Essentially, the salt layer in this region affects the advance of both the Potwar Plateau as well as the Kohat Plateau. It is suggested that the Potwar Plateau advanced more southward due to the Salt Range formation acting as a detachment layer (Cotton & Koyi, 2000; Jaume & Lillie, 1988). This is evident in the fact that the Kohat Plateau has more internal deformation than the Potwar Plateau. The key is the basal shear stress between the overburden and the basement rock. In the Potwar Plateau, the salt layer acts as a lubricant and decreases the shear stress and cohesion significantly. This is supported by more internal deformation in the Kohat Plateau than the Potwar Plateau.

The deformation mechanics of this region is proposed to be analogous to a bulldozed wedge of snow (bulldozer model) that is moving on a ductile substrate (Cotton & Koyi, 2000; Lillie et al., 1987). The wedge is essential for the generation of a thin-skinned fold-and-thrust belt, such as the Potwar Plateau-Salt Range (Chapple, 1978; Davis et al., 1983). The wedge is thickest at the back part near the Main Boundary Thrust and thins out in the direction of the Main Frontal Thrust.

3.3.1 Role of Salt Range Formation (SRF)

The Salt Range Formation was interpreted as the layer between the strong reflectors of the carbonate platform and the basement rock. It is evident from the folding of the overburden and the relatively unchanged basement floor that the detachment is located in the SRF which acts as a lubricant between them. As a result of only the overburden advancing southward on the mechanically weak salt layer, this region is categorized as a thin-skinned fold-and-thrust system. Furthermore, it is clear from geological maps and the seismic data that the salt layer did not reach the surface in the Potwar Plateau region (Gee, 1980; Gee & Gee, 1989). This indicates that the SRF is mainly acting as a detachment layer. However, exposed salt and salt mining are prominent in the Salt Range and these salt structures are mainly concentrated near the Main Frontal Thrust, suggesting that salt flow may play a significant role towards the south. Evidence from the InSAR map supports this idea (Zone B) (**Fig. 3 and Fig. 6**).

The seismic interpretations show that the salt thickness varies from 900m to 3500m. These variations are mostly due to the folding of the overburden. The salt in synform areas will tend to move to antiform structures, creating salt-cored anticlines. However, the scale of overburden deformation for the Potwar Plateau is very broad and the folding occurs over long

distances (around 5-10km). Therefore, looking through a broader scale, the SRF has a relatively consistent thickness throughout the Potwar Plateau. Seismic Line 3 shows the collapse of the faulted Cambrian-Eocene platform, which may be due to salt evacuation to the south (**Fig. 4A**).

Our results suggest that the Salt Range formation has two main roles in this fold-and-thrust belt: the salt layer acts as a decollement for the Potwar Plateau region and salt flow becomes prominent in the Salt Range. Salt is mechanically weak and is less dense than the surrounding rocks (Hudec & Jackson, 2007). Therefore, the buoyancy force tend to push the salt upwards through the overburden. However, if the overburden is too hard or too thick for the buoyancy force to overcome, the salt will stay in place or move laterally. This is the case for Potwar Plateau, where the overburden is around 3-5 km in thickness, which is further strengthen by folding and thrusting due to compressional forces. Furthermore, as the fold-and-thrust belt is further compressed, the salt is further pressurized tectonically to move southward toward Salt Range. This movement is due to differential loading, where salt flows from higher pressure (back of wedge) to lower pressure (front of wedge) region (Hudec & Jackson, 2007).

Zone B, located near the Warcha Salt Mine, shows a significant uplift from 2007 to 2010 (**Fig. 3**). This may be due to salt diapirism. In order for salt diapir to move into its overburden, the rocks of the overburden, occupying that space, must be removed or displaced (Hudec & Jackson, 2007). This removal of the overburden may be due to uplift and erosion of the hanging wall (overburden), which is widespread along the Main Frontal Thrust. This may explain the prominence of salt mines and salt diapirism along the Main Frontal thrust. Furthermore, since Zone B experienced an anomalous uplift, this suggests that it may be a teardrop diapir. Teardrop diapirs.

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Fig. 6. A simple drawing of the interpreted structures from the InSAR displacement map. The Potwar Plateau-Salt Range can be divided into three distinct regions: from the north, the NPDZ (Northern Potwar Deformation Zone), the Soan Syncline and the Salt Range. The black dashed lines represent boundaries between these regions. Two cross sections were drawn, shown in Fig. 7.

are common in compressional salt basins and are mainly controlled by regional tectonics (Hudec & Jackson, 2007). As compression continues, teardrop salt diapirs will rise due to tectonic pressurization.

3.3.2 The movement rate of the dextral Kalabagh fault

Zone A is interpreted as an oblique compression zone (**Fig. 3**). Transpressional zones are strike-slip structures that are undergoing an oblique shortening deformation due to compressional forces (Dewey et al., 1998). These zones are usually regions of uplift. A similar uplifted structure can be seen to the south of Bannu Basin, where the dextral Pezu-Bhittani fault intersects the Main Frontal Thrust (**Fig. 1**). Zone A is located at the point where strike-slip deformation transition into mainly compressional deformation. The uplifted Zone A is directly related to the movement of the Kalabagh fault.

Using InSAR, the slip rate of the fault was calculated in a study by Chen & Khan (2010). According to their study, the internal deformation of the Potwar Plateau is greater than the deformation at the front of the MFT. However, our results suggest that most of the deformation is concentrated near the MFT. Fig. 3 and Fig. 6 show the interpreted dextral fault intersecting Zone A. It is likely to be a right-lateral strike-slip fault due to the different rate of displacement for western (0-2 mm/yr) and eastern (7.5 mm/yr) fault blocks. This suggests that the western boundary of the Potwar Plateau transitions from a purely right-lateral transform fault (Kalabagh fault) to the north into a transpressional deformation region near the Main Frontal Thrust. This is consistent with a study by McDougall & Khan (1990). According to their work, the minimum average displacement rate near the Indus River is around 7-10 mm/yr. Additionally, Chen & Khan (2010) calculated an average rate of displacement of 5-6 mm/yr for the Kalabagh fault.

390 Their results show that different parts of the Kalabagh fault move at different rates. These
391 movements may be due to the distribution and thickness of salt.

392 The different rates of movement of different regions of the Kalabagh fault and the Salt
393 Range seems to support the Caterpillar model by Oldham (1921). According to an InSAR study
394 by Satyabala et al. (2012), the movement of the Kohat Plateau can be equated to a caterpillar. In
395 this model, the plateau moves in blocks of rock, where a block above a weak layer (salt) moves
396 forward and a block that lacks salt is locked due to friction. The block of rock that is locked
397 could accumulate energy and be released as a big earthquake, such as the magnitude 6
398 earthquake that occurred in 1992 (Satyabala et al., 2012). In order for that to occur, the salt layer
399 underneath the Kohat Plateau must have thickness variations, where some blocks are locked
400 whereas some move aseismically (Satyabala et al. 2012). This model may better explain the
401 current deformation of the Kalabagh fault and the western Potwar Plateau-Salt Range.

402 Moreover, a recent GPS study (data from 2006-2012) by Jouanne et al. (2014), suggests
403 that the western portion of the Potwar Plateau-Salt Range is not active, which is contradictory to
404 our findings. This may be explained by the lack of GPS stations in western Salt Range. Only one
405 of their GPS station overlaps our InSAR displacement map, which is located to the east of the
406 InSAR map.

407 Overall, our InSAR results show that western Potwar Plateau-Salt Range region and the
408 Kalabagh fault may still be tectonically active, especially in the western region of the Salt Range
409 (**Fig. 3 and Fig. 6**). The InSAR displacement map shows that the region is mostly uplifted from
410 2007 to 2010 with two main uplift anomalies, which may be due to zones of transpression and
411 salt diapirism. **Fig. 6** shows our interpretations based on the InSAR results.

3.3.3 Comparison with Kuqa fold-and-thrust belt, China (Across-strike structural variations)

The Kuqa foreland fold-and-thrust belt is located in Xinjiang Uyghur Autonomous Region, China (Lat: 41° 53' 20.28" N, Long: 81° 50' 03.38" E), where it is underlain by Palaeogene evaporite layer. Similar to the Potwar Plateau-Salt Range, the Kuqa belt has three main regions (Refer to figures 2 and 5 from Chen et al., 2004). Northward, closer to the mountain belt is the highly deformed zone, the Trailing Edge (equivalent to the North Potwar Deformation Zone in Potwar Plateau) (**Fig. 6 and Fig. 7a**). This is followed southward by the Transitional Belt, where a broad syncline is located (equivalent to the Soan syncline of the Potwar Plateau), and finally the Leading Edge (equivalent to the Salt Range) (**Fig. 7a**). Modeling studies have successfully emulated these different regions of the Potwar Plateau-Salt Range (Cotton & Koyi, 2000; Faisal & Dixon, 2014). These distinct features of the foreland fold-and-thrust belt are mainly influenced by the presence of a weak lithological layer, Salt Range formation in this case, which acts as a detachment for the overriding layers.

Another important observation from the Kuqa belt is that exposed salt structures are also seen near the Leading Edge, which may be due to the thrusting of the salt. This uplifted region is eroded after some time, leading to the exposure of the salt at the surface (Chen et al., 2004). Furthermore, the thickest salt is located under anticlinal structure, where the overburden is thinnest.

Fig. 7b is a cross-section that goes through both Zone A and Zone B (**Fig. 6 and Fig. 7b**). The transpression zone is dominated by thrust faults, which may be the main cause of the anomalous uplift of Zone A. This uplift increases the overburden load in Zone A and in turn

pushes the salt to the south towards Zone B, where salt diapirism is believed to be active (**Fig. 7b**).

3.3.4 Comparison with structural style of central and eastern Potwar Plateau-Salt Range (Along-strike structural variations)

The deformation in eastern Salt Range is very different than its western counterpart, which can be seen in the different structural styles between them (Refer to figures 2, 6, 10 and 12 from Jaume & Lillie, 1988). Jaume and Lillie (1988) argued that this difference is mainly due to the thinning of salt to the east. According to a recent study by Qayyum et al. (2014), this is unlikely as they pointed out the generally similar stratigraphy along-strike. The Main Frontal thrust sheet is internally undeformed in western Salt Range, while it is internally folded and faulted in eastern Salt Range (Qayyum et al., 2014). This is clearly shown in Line 3 (**Fig. 4A**) showing relatively undeformed thrust sheet for western Salt Range. Furthermore, Qayyum et al. (2014), suggested that the variations in their structural styles are due to different ramping mechanism: translation versus telescoping. Central Salt Range underwent translation, with relatively low internal deformation for the allochthon. Basically, translation ramping mechanism works by sliding of overburden subhorizontally over basement normal fault, which resulted in a repetition of strata (Qayyum et al., 2014). This is very similar to western Salt Range, with a minor difference in that normal fault basement ramp is absent in western Salt Range (Jaume & Lillie, 1988). This is also evident in our seismic interpretations (**Fig. 4A-D**). In contrast, the eastern portion of Salt Range underwent telescoping, with high internal deformation including thrust faults, anticlines and pop-

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Fig. 7a. Cross-section of western Potwar Plateau-Salt Range (Modified from Jaume & Lillie, 1988). Refer to Fig. 6 for location of profiles. The dashed yellow line along the bottom of the Salt Range Formation signifies the interpreted anhydrite/gypsum layer. Additional faults were also added. These faults may be due to the collapse of the Cambrian-Eocene platform due to salt escaping. NPZ: Northern Potwar Deformation Zone.

Fig. 7b. This profile crosses Zones A and B. The faults were drawn according to the geological maps by Gee (1980). The yellow arrows show the possible movement of salt from Zone A (transpression zone) to Zone B (salt diapirism). The uplift in Zone A due to thrusting may increase the load on the salt, pushing it southward and feeding more salt into Zone B, where salt diapirism is active. This in turn creates uplift in Zone B. The respective uplift rates are labeled above the profile (mm/yr).

up structures. The normal fault basement ramp is also not present in eastern Salt Range, with no repetition of sedimentary layers (Qayyum et al., 2014).

Our seismic interpretation agrees with the translation mechanism, which is similar to central Salt Range. The lack of internal deformation in the hanging wall of the thrust sheet suggests that the overburden slides smoothly over a flexed upward basement. This basement flexure may be related the Sargodha High, located south of western Salt Range, where it is believed to be the forebulge of the Punjab foreland basin. This suggests that the main control on the deformation of western Potwar Plateau-Salt Range is the movement along Kalabagh fault and the Main Frontal Thrust.

4. CONCLUSIONS

This work has provided clear evidence that the western Potwar Plateau-Salt Range is still tectonically active. The InSAR results show that most of western Salt Range underwent uplift, from 2007 to 2010, at an average rate of 10 mm/yr. Two uplift anomalies, with uplift rate of 15 mm/yr, were interpreted as related to zone of transpression and salt diapirism. However, the results also suggest that most of the deformation is tectonically induced by compression and transform zones. Similar to the Kuqa fold-and-thrust belt, the Potwar Plateau has three main equivalent regions, with the salt playing two roles in their deformation: salt acting as a detachment in the Transitional Belt and salt diapirism occurring in the Leading Edge.

Seismic interpretation shows that western Potwar Plateau and Salt Range have different structural styles than eastern Potwar Plateau-Salt Range. This is mainly due to ramping mechanism, where western and central Salt Range underwent translation while eastern Salt

Range underwent telescoping (Qayyum et al., 2014). However, the hanging wall of western Salt Range has been translated over a flexed Pre-Cambrian basement.

InSAR and seismic data, two very different datasets, were utilized in this study. Both data provided different views of this region. While InSAR showed the vertical movements in the region, the seismic data display how those movements deformed the subsurface. The lack of internal deformation in this region can be related to salt due to its weak nature. This work supports the idea that the Potwar Plateau may be deforming similar to the Caterpillar model by Oldham (1921). This is mainly due to the varying rates of movement along the Kalabagh fault. Our study shows that the salt layer acts as a decollement in the Potwar Plateau region, while salt flows are prominent in the Salt Range. Finally, this work shows how powerful InSAR can be in the study of active tectonics.

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