Macrostructures vs microstructures in evaporite detachments: An example from the Salt Range, Pakistan

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A R T I C L E   I N F O

Article history:
Received 22 January 2015
Received in revised form 31 March 2015
Accepted 2 April 2015
Available online 24 April 2015

Keywords:
Salt Range
Pakistan
Evaporite detachment
Microstructures
Fold-thrust belt

A B S T R A C T

The Salt Range, Pakistan is the surface expression of an evaporite detachment over which the Potwar Plateau fold-thrust belt has moved. Whilst previous publications regarding this region have focused on the petroleum prospectivity, deformation, and large-scale processes, this paper characterises the Salt Range detachment at the meso- (10 cm to 10s of metres) and micro-scale (cm to μm) and examines correlations to the macro-scale (10s of metres to kms). Two detailed scaled cross sections are analysed alongside structural measurements to characterise the detachment at the meso-scale with optical analysis of microstructures that formed during deformation characterising the micro-scale. Both ductile and brittle features observed in cross section indicate composite deformation processes acting simultaneously; this contrasts with models of salt detachments behaving homogeneously. Microstructural analysis indicates processes of grain boundary migration and crystal lattice distortions. The microstructurally revealed competition between intra-crystalline deformation and recrystallization at shallow depths and low temperatures links passes up-scale to mesoscale evaporite mylonites and progressively in the weaker units, whereas more brittle processes operate in the stronger lithologies in this near-unique outcrop of a the emergent toe of a major salt-bearing detachment fault. © 2015 Elsevier Ltd. All rights reserved.

1. Introduction

Shortening of the Earth’s crust is commonly accommodated by fold-thrust belts that are mechanically decoupled from the underlying rocks by a detachment zone or horizon (Dahlstrom, 1969; Davis et al., 1983). The creation of fold-thrust belts is typically the result of far-field stresses, near-field stresses, or a combination of both (e.g. King et al., 2010; King and Backé, 2010; Morley et al., 2011b). The driving force of deformation defines whether the fold-thrust belt is thin-skinned, internally driven deformation, or thick-skinned where far-field stresses are dominant; a combination of both is possible depending on the nature and number of active detachment layers (Morley and Guerin, 1996; King et al., 2010; Morley et al., 2011b). Detachments are typically units of overpressured shale or salt and it is the extent of these units that determines the area of related deformation (Dahlstrom, 1990; Morley and Guerin, 1996; Rowan et al., 2004). The style of deformation within fold-thrust belts is strongly influenced by the nature of the detachment, such as strength of the overlying strata, lithology, pore-pressure, coefficient of friction, dip and dip direction of the detachment (Davis et al., 1983; Jaumé and Lillie, 1988; Dahlstrom, 1990; Koyi and Vendeville, 2003; Suppe, 2007; Simpson, 2010).

The South Potwar Basin, Pakistan, is an example of a distal foreland fold-thrust belt detaching over a thick salt layer, the Salt Range Formation (Krishnan, 1966; Jaumé and Lillie, 1988; Jaswal et al., 1997). The fold-thrust belt is being driven by a combination of far-field stresses (continent–continent collision) and near-field stresses (gravity gliding) (Jaumé and Lillie, 1988; Davis and Lillie, 1994) and represents the southernmost expression of the Himalayan orogenic deformation (Jaumé and Lillie, 1988; Davis and Lillie, 1994; Grelaud et al., 2002). Sediments of the Potwar Plateau are transported aseismically over the 2 ± 1° northward dipping basement, though local asperities within the detachment facilitate some seismic activity (Davis and Lillie, 1994; Satyabala...
A down-to-the-north, normal, basement fault observed in seismic section (lines CW-13 and KK-4) causes the Salt Range Thrust to propagate to the surface forming the eponymous Salt Range (Fig. 1C) (Lillie et al., 1987; Baker et al., 1988). Buttressing of the southward-moving allochthonous Potwar Plateau against this fault accumulated stress at the site of this basement fault (Davis and Lillie, 1994; Cotton and Koyi, 2000). The increased stress, distal sediment loading, and salt lubricated faulting resulted in thrusting of the Neoproterozoic to Eocene rocks comprising The Salt Range above Quaternary sediments of the Punjab Plain (Fig. 1D) (Jaswal et al., 1997; Yeats et al., 1984).

Analyses of fold-thrust belts are extensively documented at the macro-scale (10's of kms), in the form of regional cross-sections, seismic interpretation, satellite data, and physical and numerical modelling (Lillie et al., 1987; Dirkzwager and Dooley, 2008; Chen and Khan, 2009; King et al., 2010; Morley et al., 2011b); yet few have attempted to explore the detailed structure of detachments at outcrop or smaller scale (e.g. Hansberry et al., 2014). Studying detachments at outcrop scale presents a number of difficulties; the majority of currently active detachments occur in inaccessible submarine settings, whilst the few active subaerial fold-thrust belts have insufficient degrees of erosion to allow surface outcrop of the detachment (Hansberry et al., 2014). Our recent fieldwork, carried out in the area of Khewra, Pakistan, has focused on the structures within the Salt Range Detachment (Fig. 1A and B).

Here, we present structural observations and cross-sections within the Salt Range Formation and use these to characterise the meso-scale structure of the detachment. Samples taken along these cross-sections were analysed using an optical microscope to characterise the microstructural features of the detachment. We then discuss the meso- and micro-scale control on the larger-scale fold-thrust belt geometry.

2. Geological setting

2.1. Regional setting

The Salt Range exposes Neoproterozoic to Eocene sedimentary rocks of the Salt Range, Jhelum, Nilawahan, and Chharat Groups up to the Eocene Sakesar Limestone Formation, which forms the highest peak (Fig. 1D). The interior and direct hanging-wall of the Salt Range Thrust is composed of the Neoproterozoic Salt Range Formation, which forms the detachment underlying the associated fold-thrust belt to the north. This detachment is responsible for the observed thin-skinned contractional wedge geometry in the fold-thrust belt (Lillie et al., 1987). On a larger scale, the Salt Range mirrors the geometry of the Himalayan Orogen displaying a roughly E-W trend as it is a distal structure of the same orogenic event.

Fig. 1. Location map, cross section, stratigraphy column. (A) Location map of the study area. (B) Geological map of the eastern Salt Range and Potwar Plateau. The dashed line AB indicates the approximate transect of the cross section in (C). MBT = Main Boundary Thrust, NPDZ = North Potwar Deformation Zone, KMF = Khari Murat Fault, SB = Soan Backthrust, SS = Soan Syncline, RF = Riuwat Fault, DT = Domeli Thrust, SRT = Salt Range Thrust (after Kovalevych et al., 2006). (C) Cross section through the NPDZ, SS, and Salt Range showing imbricate stacking, pop-up and/or pop-down structures, and a thickened zone of salt above a basement fault, respectively (after Cotton and Koyi, 2000). (D) Stratigraphic column of the units within the study area (after Grelaud et al., 2002). (E) Salt Range Member subdivisions (After Sameeni, 2009 and Ghazi et al., 2012).
2.2. Stratigraphy

The stratigraphy can be segregated into four major, mechanical and lithostratigraphic, units (Fig. 1D) (Khan et al., 1986; Grelaud et al., 2002).

The oldest unit is the Precambrian crystalline basement of the Indian plate that crops out 80 km south of the Salt Range in the Kirana Hills (Gee, 1989). It is thought to be exposed as the current forebulge created through loading of the Himalayas on the Indian Plate (Yeats and Lawrence, 1984; Lillie and Yousef, 1986; Duroy et al., 1989).

Ediacaran to early Cambrian evaporites of the Salt Range Formation overlie this basement and form the structural detachment (Jaumé and Lillie, 1988; Grelaud et al., 2002). This unit consists of a crystalline halite base intercalated with potash salts and over lain by gypsumiferous marl, which is covered by gypsum–dolomite with inefrequent seams of oil shale (Ghazi et al., 2012).

Lying above the Salt Range Formation are Cambrian to Eocene platform deposits that vary between 200 and 500 m thick. The Cambrian and Permian deposits of the Jhelum and Nilawahan Groups comprise red, maroon and purple sandstones, siltstones, and shale, which are over lain by Late Permian to Eocene fossiliferous carbonates (Ghazi et al., 2012). Mechanically the Jhelum and Nilawahan Groups are often referred to as one homogenous ‘carapace’ as they decouple above the evaporite detachment with little internal deformation (Butler et al., 1987; Lillie et al., 1987). The youngest unit is separated from the underlying stratigraphy by a non-depositional Oligocene unconformity (Grelaud et al., 2002). It is a ~ 6 km thick Miocene to Quaternary age syn-orogenic deposit of the Rawalpindi and Siwalik Groups that formed from the simultaneous uplift and erosion during the Himalayan Orogeny.

2.3. Structural history

From south to north, the region comprises the Salt Range, South Potwar Basin, Soan Syncline, and North Potwar Deformation Zone (Fig. 1B). The North Potwar Deformation Zone is bound to the north by the Main Boundary Thrust and is characterised by imbricate duplexing in the footwall of the Main Boundary Thrusts (Cotton and Koyi, 2000). Abutting the North Potwar Deformation Zone to the south is the Soan Syncline’s northern limb hosting the Soan Backthrust. This northern limb is upturned forming a monocline while further south and into the South Potwar Basin salt cored anticlines and pop-up structures occur (Fig. 1B and C) (Cotton and Koyi, 2000). The significant deformation style difference between the North Potwar Deformation Zone, Soan Syncline, and South Potwar Basin is due to the presence of the Salt Range Formation evaporite detachment (Lillie et al., 1987). The Salt Range itself results from southwards movement of the Potwar Plateau being buttressed by an E-W striking, down to the north basement normal fault. The southward movement and thickening of the Salt Range Formation beneath the hanging wall is attributed to salt withdrawal and migration instigated by differential loading by prograding basin fill and deformation front (Cotton and Koyi, 2000). The accumulated stress and continued southward progression, combined with the basement fault, caused internal imbrication of the detachment and ramping of the Salt Range Thrust, which accommodate approximately 25–30 km of shortening (Baker et al., 1988; Cotton, 1997; Cotton and Koyi, 2000). The presence of Neoproterozoic to early Cambrian gypsumiferous deposits within the Hazara District, north of the MBT, combined with the coeval similarly restricted marine deposits in southern Oman, Iran, and north-west India suggest widespread evaporite deposition across the area (Lillie et al., 1987; Kovaleyvych et al., 2006; Smith, 2012).

The presence of the Salt Range Formation evaporites has accommodated the southward transport of the Potwar Plateau almost aseismically, while maintaining an extremely narrow cross-sectional taper (Davis and Lillie, 1994; Satyabala et al., 2012). Jaumé and Lillie (1988) suggested that the northern Potwar Plateau was initially a relatively high-angle (~1.7°) taper fold-thrust belt caused by frictional sliding on a non-salt lithology prior to 2 Ma. Transposition over the salt basin halted the intense deformation thus eliminating the necessity of the large taper. Subsequent erosion resulted in the present-day low-angle taper and topography. Deformation within the Salt Range occurred at 5 Ma and again at 2 Ma, the hiatus between these two stages is believed to be caused by break-back thrusting on the northern limb of the Soan Syncline (Lillie et al., 1987; Burbank and Beck, 1989). Recent earthquakes within the Kohat Plateau, to the north-west, and the Potwar Plateau indicate that the detachment may still be currently active. These earthquakes occur where the salt detachment has evacuated and a highly frictional weld of carapace sediments lies directly on basement, focusing stress (Satyabala et al., 2012).

3. Methodology

3.1. Structural data

During our recent field season in the Salt Range two cross-sections were completed. The first section was taken from a sideway within the working Khewra Salt Mine on the CH22 drive. (Fig. 2) The Billianwala Salt Member (Fig. 1E), which comprises crystalline halite rock salt with banded layers of marl and potash, forms the entirety of the mine and is the main detachment horizon (Butler et al., 1987; Leathers, 1987; Jaumé and Lillie, 1988; Grelaud et al., 2002). This section was chosen due to the quality of exposure and features displayed along it. The cross-section is 25 m long and trends N-S bending slightly in the southern end to a NE–SW trend (Fig. 3). The second cross-section was taken through a road cutting on Khewra Road, 3.5 km north of the town of Khewra. This road cutting displays a large continuous outcrop of gypsumiferous marl of the Sahwal Marl Member with numerous inclusions of blocky and sheared gypsum from the Bandarkas Gypsum Member (Fig. 1E). This cross-section also trends N-S and measures 110 m in length. As the primary transport direction of the Salt Range is towards the south, exposures trending N-S are ideal for observation and analysis of their true geometry.

Detailed scaled diagrams were made displaying the meso-scale bedding and foliation. Other structural features were encountered including duplexes, folds, fractures, and shear planes. Structural measurements were recorded at known (measured) locations for all structural features and bedding where possible.

3.2. Sample preparation and methodology

Thin sections were created from five samples taken from the Salt Range, Pakistan (Table. 1). Thin sections were prepared using the methods laid out in Urai et al. (1985). Sample SRLR-05 was prepared unoriented as its coarsely crystalline structure displayed no discernible fabric. Two blocks cut from sample SRLR-06 were prepared: one, along the X–Z plane and two, along the Y–Z plane, where X–Y is the foliation plane. Samples were cut into appropriately sized blocks and adhering to glass slides with araldite epoxy before being ground and lightly polished with kerosene as a lubricant. The samples were then chemically etched in a slightly undersaturated (~5.5 M) NaCl solution containing 0.8 w% FeCl3·6H2O. After 40 s this etchant was removed by a powerful stream of kerosene and the specimen immediately dried using hot air.
The mechanical polishing stage caused a significant issue in that inclusion of much harder minerals formed resistant nodules on the slide surface as they are far more resistant to mechanical wear than the surrounding halite. These nodules would often break away leaving long scours or gouges in the polished halite surface. The later etching stage significantly reduced the appearance of these, although some are still visible.

4. Results

The results presented here were collected and analysed with classic structural techniques in the form of cross sections and optical microscopy. The locations for each cross section and all samples taken are presented along with descriptions and analyses for each (Table. 1).

4.1. Cross sections

Two structural cross-sections were made during recent fieldwork to Khewra, Pakistan (Fig. 1B). The map of the Khewra Mine, below, presents a north to south cross-sectional view of the mine's distribution of informal sub-units and workings (Fig. 2).

4.1.1. Section 1: Khewra salt mine section

This cross section was constructed from structural measurements, scaled diagrams, and photos taken within the working Khewra Salt Mine (Fig. 3) along the N-S running mine drive CH22. The section roughly crosscuts the bedding and foliation trend. A strong foliation parallel to lithological boundaries may represent highly transposed primary bedding though no unambiguous primary bedding features could be identified. Bedding generally dips to the NW in the Khewra region, which is concurrent
with the foliation dip-data collected (mean dip/dip direction of 44/348).

The southern end of the section begins in an orange and white layered halite that, from 10 m, sharply transitions into a layer of maroon-coloured potash marl containing relatively competent halite boudins (Fig. 3, sub-sections 1 & 2), which the foliation anastomoses around (Fig. 4B and D). This changes at 17 m to a 2 m thick, pink to red, massive coarsely crystalline halite layer (Fig. 3 sub-section 3). Between 19 m and 23 m there is another potash marl layer though it is purer with fewer and smaller halite boudins (Fig. 3 sub-section 4). The remainder of the section returns predominantly to orange and white halite. Between 13 m and 17 m blast fractures are clearly visible.

Within the large halite layers very few structures are visible aside from the layering (Fig. 4A). This layering is compositional with red and orange layers comprising potassium salts and clay layers interspersed with halite. The layering transitions into a pink to red massive halite layer at 17 m, which is 2 m thick and coarsely crystalline. Between 19 m and 23 m there is another potash marl layer though it is purer with fewer and smaller halite boudins (Fig. 3 sub-section 4). The remainder of the section returns predominantly to orange and white halite. Between 13 m and 17 m blast fractures are clearly visible.

### Table 1

Sample analysis table. This table lists the samples and provides specific details including locations, descriptions, and analyses conducted for each.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Location</th>
<th>Description</th>
<th>Optical analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>SRLR-01</td>
<td>Khewra Gorge</td>
<td>Wavy laminar opaque gypsum of the Bandarkas Gypsum Member.</td>
<td>×</td>
</tr>
<tr>
<td>SRLR-02</td>
<td>N 32° 39’ 48.3”</td>
<td>Black organic rich shale</td>
<td>×</td>
</tr>
<tr>
<td>SRLR-03</td>
<td>E 73° 00’ 17.2”</td>
<td>Laminar opaque gypsum forming part of a fold</td>
<td>×</td>
</tr>
<tr>
<td>SRLR-04</td>
<td>Sawal Village</td>
<td>Coherent large blocky gypsum with weathered surface grooves</td>
<td>×</td>
</tr>
<tr>
<td>SRLR-05</td>
<td>Khewra Mine</td>
<td>White and very coarse crystalline halite with minor orange potash marl inclusions</td>
<td>×</td>
</tr>
<tr>
<td>SRLR-06</td>
<td>N 32°38’52.8”</td>
<td>Coarsely crystalline halite with large bands and inclusions of red maroon potash marl</td>
<td>×</td>
</tr>
<tr>
<td>SRLR-07</td>
<td>Khewra road cutting</td>
<td>White and grey micro-crystalline gypsum from a large foliated block</td>
<td>×</td>
</tr>
<tr>
<td>SRLR-08</td>
<td>N 32°38’55.4”</td>
<td>Thin wavy slivers of fibrous selenite in red marl</td>
<td>×</td>
</tr>
<tr>
<td>SRLR-09</td>
<td>E 72°59’37.8”</td>
<td>Gypsum cataclasite with angular fragments of gypsum in red marl matrix</td>
<td>×</td>
</tr>
<tr>
<td>SRLR-10</td>
<td>to</td>
<td>Foliated gypsum slivers staked like plates with small amounts of red marl</td>
<td>×</td>
</tr>
<tr>
<td></td>
<td>N 32°38’52.5”</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>E 72°59’40.0”</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Specific locations in Fig. 3

Fig. 4. Mine feature photos. A collection of detailed photos displaying specific features from the Khewra Mine cross-section (Fig. 3). (A) White halite with orange potash marl inclusions forming layers. (B) Boudins of clear and white halite in halite and potash marl. (C) Large multicrystallite boudins of halite and potash within a potash marl layer adjacent to a large layer of clear and white coarsely crystalline halite. (D) Larger scale photo of Fig. 3B displaying the anastomosing nature of the potash marl layers. (E) Halite boudins in potash marl indicating sense of movement and textural variation. (F) Massive white halite with thin potash marl layers.
minerals. Some of the white halite is completely transparent, forming glass-like parts of the outcrop. The potash layers range in colour from a deep maroon to a light salmon pink. Hand specimen and thin section petrography with energy dispersive spectrometry (EDS) has revealed that polyhalite, halite, gypsum, and clay minerals are present in varying amounts. A study by Kovalevych et al. (2006) has found polyhalite, \( \text{K}_2\text{Mg}_4\text{SO}_4\cdot\text{H}_2\text{O} \), halite \( \text{NaCl} \), gypsum \( \text{CaSO}_4\cdot2\text{H}_2\text{O} \), and clay minerals are present in varying amounts. The same study also found kainite \( \text{Mg}_4\text{SO}_4\cdot4\text{KCl}\cdot11\text{H}_2\text{O} \) within salt samples from the same mine. Notably, all the documented potassic minerals in the Khewra Mine are hydrated, with high levels of magnesium sulphate, unlike the sylicate or carnallite that typified original potash precipitates in marine-derived Cambrian brines (Warren, 2006). Anhydrite \( \text{CaSO}_4 \), which is the calcium sulphate phase in the deeper subsurface equivalents, has been telogenetically rehydrated to gypsum in both the mine and the road sections. Macroscopically, hydration recrystallisation textures are interlaced with the textures of syntectonic deformation. The asymmetric lozenge shape and orientation of the halite boudins indicates a top-to-south non-coaxial shear component movement along the foliation (Fig. 4E).

The transposed bedding/shear foliation in this cross-section have a consistent dip and dip direction with a mean orientation of 44°/348°. With the exception of a few outliers, the pole to plane density is focused in the lower right quadrant (Fig. 5A). The rose diagram presents the orientation trend of the bedding/shear foliation measurements (Fig. 5B). The extremely divergent poles of the fracture measurements are due to blast fractures formed during excavation (Figs. 5A and 3).

### 4.1.2. Section 2: Khewra road section

Constructed from structural measurements, detailed scaled sketches, and photos taken from a road cutting on the Khewra Road 3.5 km north of the town of Khewra, this cross section transects through the Sahwal Marl Member that makes up, almost exclusively, the entire outcrop of the Salt Range Formation within the Salt Range mountains (Fig. 6). From end-to-end the section is composed of red gypsum marl with steeply dipping white gypsum mylonites. Compositionally the gypsiferous marl varies from roughly 70–90% gypsum. A strong S–C fabric is evident throughout the outcrop and is visible wherever slivers of gypsum are present. These slivers are 1–3 cm thick and form plate-like sheets in cross section continuing along strike into the outcrop, tapering at their margins (Fig. 7E). Internally, these gypsum sheets preserve fine, sub-mm-scale, foliation planes. On a larger scale the marl is cut by grey gypsum-rich cataclasites, some of which are sheared (Fig. 7A and B). Coherent, deformed, gypsum clasts also occur within the marl, the shape of which may reflect its precursor nodular diagenetic formation (Fig. 7C). Isolated white gypsum slivers will occasionally appear in large homogeneous sections of the red marl. Larger blocks of white gypsum are distinctly visible, often they are foliated and occasionally lineated with slicken lines showing a top-to-south sense of movement (Fig. 6). With the exception of the solid coherent blocks of gypsum, the entire outcrop is friable and breaks easily when handled.

The shear fabrics are the most notable structural features present throughout the Khewra Road section, though extremely well exposed on the southern end (Fig. 6). Discrete low angle thrusts cut the steeply foliated gypsum mylonites, between 0 m and 7 m, creating a classic S–C fabric with a top-to-south sense of movement (Fig. 7D).

Equal-area lower hemisphere stereographic projections of orientation measurements taken here show a distinct trend, the pole-to-plane density profiles for both foliation and shear planes show strong correlation demonstrating moderate to steep NW dips (Fig. 8A and B), with the shear planes being consistently shallower dipping than the foliation, consistent with the S–C relationship. Some shear planes plot in the NW quadrant. Fracture measurements show a more varied spread, plotting consistently in the top NW quadrant though some also plot in the S and SW. The foliation dip directions displayed on the rose diagram show a mean dip of 348°. These observations suggest that the shear fabrics have a top-to-south component of movement.
orientation of 352° (Fig. 8D); this aligns well with the rose diagram of transposed bedding/shear foliation measurements taken from the Khewra Mine cross-section of 348° and indicates a widespread similarity in the observed structures (Fig. 5B).

4.2. Microscopic analysis

Five samples underwent optical analysis: three samples, SRLR-04, -07 and -09, from different locations were composed of

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Fig. 6. Road cross section. A detailed scaled cross-section from a road cutting outcrop through the Salt Range, Sahwal Marl and Bandarkas Gypsum Members above a composite panorama photo section of the road cutting outcrop exposure. A–E Indicate locations of detailed feature photos (Fig. 7).

Fig. 7. Road feature photos. A collection of detailed photos displaying specific features from the Khewra Road cutting outcrop (Fig. 6). (A) Gypsum cataclasite in Sahwal Marl. (B) Sheared elongate translucent gypsum clasts in gypsum rich cataclasite. (C) Lenses and blocky clasts of gypsum in red marl. (D) S–C fabric in red gypsum marl with numerous gypsum slivers. (E) Sheared gypsum slivers defining the foliation in the red gypsum marl. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
gypsum, the other two samples, SRLR-05 and -06, came from within the Khewra Mine and are both composed of halite. The aforementioned samples SRLR-04 and -07 are predominantly featureless being entirely composed of gypsum microspar with few inclusions. Sample SRLR-09 shows remarkably different features within the same sample. Containing approximately 40% impurities, the marl is easily distinguishable by the red/white colour contrast (Fig. 9B and C). Large grains of pure gypsum microspar interstitial with more gritty gypsum are selvedged by red clay (Fig. 9B) is in stark juxtaposition with the strongly deformed and apparently chaotic substructure not visible in the purer samples (Fig. 9C). Small inclusions of organic matter are also present and likely sourced from the rare oil shale seams after assimilation during deformation (Fig. 9E and F). The chaotic nature of the samples is further expressed in photomicrographs which show the random orientation of veins and comprehensive amalgam of clay and gypsum (Fig. 9G and H). Having been taken from within a gypsum marl cataclasite the significant brittle deformation observed is expected, this also demonstrates the retention of deformation structures within the meso-scale brittle components of the detachment.

Sample SRLR-05 was taken from the massive crystalline halite layer whilst sample SRLR-06 came from a potash marl-rich layer to allow for a comparison between the two (Fig. 3). Thin sections made from sample SRLR-05 showed smaller, 1–5 mm, and a few much larger, 0.5–2 cm, subhedral halite crystals (Fig. 9A and D). The larger crystals demonstrated typical cubic cleavage in the form of...


of large black lines forming distinct orthogonal steps. Many of the large and medium sized grains share smooth gently curving or lobate boundaries sometimes with brine films between which are interpreted to be a result of significant grain boundary migration. In sections where many medium–large grains are in close proximity the cleavage observed in each grain is oriented very differently, which is a strong indication that the crystallographic orientation is similarly different, at least in the plane of the thin section (Fig. 9D). Such strong misorientation paired with rounded grain boundaries and the well interlocked nature of the grains lends heavily to the interpretation that major recrystallisation occurred after period of significant deformation.

Sample SRLR-06 displayed a varied range of features including transitioning halite grain sizes, inclusions of gypsum pseudomorphed after anhydrite, and clay material (Fig. 10). Sample SRLR-06 contains predominantly halite with some gypsum, potash salts, and clay minerals. This sample displays massive recrystallised halite grains exhibiting cubic cleavage though orthogonal steps allude to crystal lattice distortions (Fig. 10A). Aside from these massive grains, the remainder of the halite crystals in the sample form smaller sub-angular to rounded grains between 50 and 500 µm with brine films, and inclusions, along boundaries (Fig. 9B). A mass of gypsum crystals, forming in laths or as aggregates, in a clay matrix is typically found separating these different halites (Fig. 10A and D). Alternatively, the gypsum laths form wholly within larger coherent halite crystals without any clay (Fig. 10B, D, and E). The gypsum laths also form a felt texture; this and their lath shaped crystals indicate likely alteration after anhydrite (Fig. 10D and E) (Warren, 2006). The clay material masses are interpreted to have behaved as aquifers hosting percolating fluids that further aided in the recrystallisation process and potentially acted as a nucleation point for later recrystallisation, likely related to thrust related uplift and telogenesis (Holliday, 1970; Artieda, 2013; Moragas et al., 2013).

5. Discussion

5.1. Structural significance

Whilst previous work and more recent works have focused on large km scale sections through the entire stratigraphy (e.g. Gee, 1980; Lillie et al., 1987), the sections presented here focus specifically on the detachment zone of the Salt Range from regional to micro scales. The structural measurements presented in Figs. 5 and 8 are internally consistent and also correlate with the regional scale dip direction established in the literature (Lillie et al., 1987; Cotton and Koyi, 2000). The average dip of foliation (48°/C176°) is steeper than that usually associated with thrust faults. This over-steepening may be due to the ramping of the detachment over the basement normal fault. Alternatively, it may result from internal back-rotation of the detachment foliation due to forward-propagation duplex-like imbrication, similar to that seen in ‘standard’ brittle thrusts (Boyer and Elliott, 1982). Although foliation does not necessarily form parallel to the thrust, the distance over which this deformation has occurred and the ductile nature of salt over geological time commonly results in parallel alignment. The detachment boundary with the units above is parallel and conformable, yet the anastomosing fabric planes and intra-fabric asymmetric sigma clasts also demonstrate that the fabric formed by non-coaxial shear. The nature of salt deformation is extremely ductile due to the inherent weakness of halite. However, the
presence of boudins within the first cross-section and cataclasites demonstrate that the mixed evaporitic mineralogy provokes a much more complicated rheology between relatively brittle and ductile minerals and possibly zones, especially if water contents varied within the salt mass.

The rheological heterogeneity is a likely response to differing levels of evaporite mineral solubility, which occur in the various halite bearing layers in the Khewra Mine; mineralogical variation across unit to unit in the mine will act to control relative permeability and recrystallisation intensity in both the mesogenetic and telogenetic realms (Warren, 2006; Moragas et al., 2013). In addition to grain size reduction during deformation, recovery of euhedral crystal textures in the mine section is tied to the varying solubilities as deformed strata are uplifted and pass from the mesogenetic realm into the telogenetic realm. The telogenetic realm is where the deformed and thrusted sedimentary rocks enter the zone of renewed active phreatic water crossflows. Our interpretation of resetting of at least some portion of the halite crystal parameters is reinforced by the mineralogies of the various potash minerals now present in the salt mine. All of the current potash mineral assemblages (polyhalite, kainite, leonite and kieserite) in the Khewra Mine are hydrated and enriched in MgSO$_4$. This is in stark contrast to the precursors (sylvite and possibly carnallite altered to sylvite with burial) that first precipitated from marine-derived brines in the Cambrian evaporite basin (Smith, 2012). Inclusion temperatures in coarsely crystalline halites are known to have been reset to lower values during exhumation of the Salt Range halite in the Lesser Himalayan thrust in the nearby Jammu region. Yet the interlayered dolomite beds and clays preserve inclusion and mineralogical evidence of higher burial temperatures (Singh and Singh, 2010). This again illustrates the preferential entry of active phreatic waters into the more soluble salt layers during telogenesis. Textures in the rims of the coarsely crystalline halites in the Khewra mine section are defined by selvages clay and gypsum, implying that the salt crystals are the result of growth into a stressed accommodation space, possibly related to a time typified by cross-flows of relatively undersaturated waters. The combination of micro- and meso-scale structure demonstrates the synchronicity of deformation and brine induced recrystallisation and recovery (Figs. 4, 7, 9 and 10).

The road cross-section illustrates the diversity of deformational features present in this poly-mineralic evaporitic succession (Fig. 6). Notably, all gypsum now seen in outcrop is derived from anhydrite in the subsurface (Holliday, 1970). The S–C fabric in
the road section is indicative of a combined brittle–ductile rheology. Thin slivers of mm-spaced foliated sheared gypsum distributed within the Sahwal Marl pick out the steep fabric in the foliated domains between the discrete shallow-dipping shear planes (Fig. 7D and E). However, in contrast to ‘classic’ S–C fabrics (Berthé et al., 1979), the ‘S’ planes do not appear to be pure-shear features as, locally, the fabric has a pronounced mineral-aggregate lineation and preserves asymmetric clasts that suggest a top-to-the-south simple shear component. The localised shearing during deformation led to the orientation and stretching of the gypsum into the current mylonite slivers. The presence of the cataclasites provides a change in style from ductile to brittle deformation, interpreted to be due to exhumation of the total succession into a diagenetic environment where anhydrite is altering to gypsum and significant volumes of halite are being leached and remobilised by crossflows of phreatic water.

This brittle change shares a link to the large (metre to decametre-scale) clasts of foliated gypsum. These clasts either formed isolated, or thin, gypsum/anhydrite interbeds in the marl or larger, broken off, coherent masses of pure gypsum/anhydrite from the Bandarkas Gypsum Member that were included within the Sahwal Marl during deformation.

The brittle–ductile deformation preserved in the gypsum-marl lithologies of the road-cuts contrasts with the near exclusive ductile fabrics seen in the halite within the mine. In the near surface (in the mine), the halite is relatively rheologically strong, when compared to the potassic salts in the mine. The halite succession is also much more coherent than the adjacent friable gypsum marl, which is acting as a relative aquifer compared to the halite-dominant section that is acting as a relative aquitard as it dissolves mostly from its edges inward (Warren, 2006).

When acting as a detachment at depth, though, the weaker unit is the halite due to its great propensity to flow under even minor burial conditions (Warren, 2006). On a relative scale the rheology of both halite and the gypsum marl are orders of magnitude weaker than the sedimentary rocks above (Urai et al., 2008). As such the red gypsum marl would still have acted as a rheologically weak horizon, much like the halite unit, though it has responded to deformation and uplift quite differently. The presence of these fabrics gives a good indication that the entire Salt Range Formation was accommodating the deformation of the overlying strata.

5.2. Meso- and micro-scale deformation

Halite crystals in the mine show two endmember styles (i) medium–crystalline clear grains showing sub-rounded sutured edges, with local zones of biaxial elongation and (ii) coarse-grained halite crystals with edge selvages defined by clay and gypsum plates, and no obvious preferred growth directions (Fig. 10A, C, and E). This dichotomy is not unexpected as halite is known to readily recrystallise through grain boundary migration in the presence of brine fluids (Schenk and Urai, 2004) and to recrystallise in any phreatic environment that oscillates between halite undersaturation and supersaturation (Warren, 2006). The medium-crystalline halite comprising the majority of the layered samples at the meso- and micro-scale samples from the mine exhibits a granular pressured-sutured edge texture that preserves a distinct shape fabric (sample SRLR-06, Fig. 10C and D), which corresponds to the fabric in the hand specimen of sample SRLR-06: 62/250.

The strong foliation displayed in the Khewra Mine cross-section (Fig. 3) is supported at a grain-scale by the shape fabric preserved in the texturally-older deformed halite. Samples SRLR-05 and -06 also show coarsely-crystalline halite crystals that locally appear to destroy the smaller, deformed crystals. These coarser crystals are interpreted to result from post deformational crystal recovery. Coarsely crystalline halite displays a range of grain sizes. One interpretation is that coarser halite crystals represent a progressive assimilation of small grains into larger ones, leading eventually to complete recrystallisation into coarsely crystalline halite (Figs. 9A, D and 10A). Such textures would then be analogous to the experimental observations of Park and Means (1996).

However, the consistent sharp boundary to coarse crystalline halite ocelli and layers, a lack of transitional crystal remnants at the boundaries of the coarse halite crystals, and the consistent association with a clayey, gypsum selvage, argues that the coarse halite crystals are a response to crossflows of dense telogenetic brines percolating downward along the thrust stratigraphy as halite was dissolving shallower in the thrust. The creation of a dense halite-saturated brine plume moving into a stress induced void, created during phreatic crossflow is typical of evaporite units beginning to experience hypogene karstification (Warren, 2006).

The presence of halite stalactites and stalagmites in some sections of the mine clearly shows that, at least today, halite-saturated waters are migrating through the mine geology. The most likely explanation for the coarsely crystalline halite is that the smaller crystalline grains preserving distinct thrust-related deformation textures have been locally recrystallised by fluid-assisted dissolution/reprecipitation during the early stages of telogenesis, resulting in coarsely crystalline halite. As this coarsely-crystalline halite precipitated during early entry into the telogenic realm it shows no relationship to the deformation fabrics preserved in the adjacent unaltered halites.

The differences in deformation style we observe between the two cross sections contrasts with the current perception and modelling practice that evaporites act as homogeneous, ductile, mobile layers (e.g. Chapple, 1978; Jackson and Talbot, 1986; Vendeville and Jackson, 1992; Morley and Guerin, 1996; Rowan et al., 2004; Rowan and Vendeville, 2006; Dirkzwager and Dooley, 2008). The ductile deformation observed within the Khewra Mine cross-section is as expected for a detachment in rock-salt; however, the local heterogeneity of the potash marl layers exhibit a rheological change between the lithologies allowing for the formation of halite boudin-like zones of coarse-crystalline halite. As the halite-bearing zone and the adjacent gypsiferous marls are uplifted to the surface, all halite is leached from the detachment and only gypsum remains to indicate the former halite-lubricated thrust zone. The loss of halite volume in the at-surface thrust zone creates further karstic accommodation space where veins of satin-spark gypsum grow in the various marls, with brittle conjugate orientations tied to halite loss (Gustavson et al., 1994; Moragas et al., 2013).

Thus, we see a transition from purely ductile deformation to the incorporation of more brittle features. The change of deformation style is more prominently exposed in the brittle gypsum cataclasites and blocks of microspar gypsum observed in the Khewra Road cross-section. Though both ductile deformation, in the form of S–C fabrics and gypsum slivers, and brittle deformation, as displayed by the gypsum cataclasites and boudins, are present; the proportions of ductile to brittle deformation are more even. This indicates that as a whole the detachment is quite varied in its proportions of ductile to brittle deformation are more even. This indicates that as a whole the detachment is quite varied in its proportions of ductile to brittle deformation are more even.
6. Conclusions

The Salt Range in northern Pakistan is an ideal location for studying an active salt detachment as it presents ample opportunity for sample collection and detailed structural analysis at both outcrop and in the subsurface. In our attempt to characterise the detachment at the meso-scale we presented two detailed cross-sections:

- The Khewra Mine cross-section establishes the compositional variability present within the Billianwala Salt Member through which it was taken. The structures observed illustrate mineralogical and rheological differences within a predominantly ductile material.
- The Khewra Road cross-section through the Sahwal Marl Member shows the Salt Range Formation is not a single unit but a combination of lithologies which display strain through brittle, ductile and brittle–ductile mechanisms.

Both cross-sections show consistent NW dipping bedding and foliation at 348° and 351° respectively, which mirrors the large-scale structures of the overriding fold-thrust belt and more distal Himalayas. Both intervals also show the influence of near surface alteration, these factors must be understood and incorporated into a structural interpretation.

Optical analyses of samples were conducted in order to characterise the halite at a micro-scale. Though evidence for grain boundary migration and lattice distortions were identified, the significant recrystallisation observed throughout, hinders our ability to substantiate a relation between the micro-scale and meso-scale. As no direct correlation between the meso-scale and micro-scale structures was made it is impossible to state whether the specific microstructures observed here can be linked to larger-scale fold-thrust belt geometry. A large volume of research has been undertaken to understand the flow and transport properties of salt (Jackson and Talbot, 1986; Urai et al., 1987, 2008). As such our predictions of the relationships between meso- and micro-scale structures are reasonable, since it is well established that microstructures are recorded within halite grains when the correct criteria are met (Urai et al., 1987; Warren, 2006). Further research in this area should include many more samples for analysis and samples located below the active phreatic zone in order to reduce or eliminate the recrystallisation damage to the deformed microstructures. Well core samples are perfect candidates, though the number of wells drilled into salt detachments of actively deforming fold-thrust belts is exceedingly small.

Much work has been undertaken studying the mechanical properties of halite (Urai et al., 1986, 1987; Schlèder and Urai, 2005; Desbois et al., 2010). The composition of the Salt Range detachment involves significantly more evaporite minerals than just halite, and probably reflects the more general case that the application of halite rheology to the mechanical properties to detachments in general is somewhat inaccurate. Further study in this region is required to determine whether a significant difference in large-scale deformation is produced as a result of this detachment compositional heterogeneity and whether the more brittle evaporites accommodate deformation or if the primary halite layer forms a singular major slip horizon.

Acknowledgements

This work was funded by the Australian Research Council grant DP120101560. ASC is funded by ARC future fellowship FT120100340. The authors would like to thank the National Centre of Excellence in Geology, University of Peshawar and the Pakistan Academy of Sciences for their support and hospitality as well as the Khewra Mine Deputy Manager of mining Mr. Irfam Ahmad and Chief Engineer Mr. Bakhtiar Ali for allowing us access and sampling within the Khewra Mine. The contributions to this paper by Richards, King and Collins form TRaX Record 302.

References


