The dynamics and interaction of compaction bands in Valley of Fire State Park, Nevada (USA): implications for their growth, evolution, and geostatistical property

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Abstract

Geometry, geostatistics and microstructures of two sets of high-angle compaction bands within Aztec Sandstone are investigated for the purpose of characterizing their dimensions, distributions, and growth dynamics. Both sets generally terminate at the dune boundaries. The first set of compaction bands is longer than the second set, which is thought to be controlled by the depositional architecture. The macroscopic thickness of single compaction bands varies from zero at their tips to maximum values, 3 to 10 mm commonly within the central parts. The compaction bands often cluster into zones, the thickness of which increases by addition of a new band sub-parallel to the previously formed bands. The average thickness of a given zone does not change significantly except for a limited number of places along their lengths and a high thickness/distance gradient at their ends. The high thickness anomalies in the thickness distribution plots along the zones correspond to local complexities such as eye structures, steps, and intersections of converging or diverging bands and may reach to about 35 cm. Microstructural analysis of single compaction bands highlights the presence of two typical portions, a thin portion and a thick portion. The thin portion of the band contains pockets of tightly packed grains surrounded by large pores in the band. The thick portion is characterized by an almost homogeneously distributed compaction throughout the band. The thin

portions are found close to the tips, whereas the thick portions occur primarily in the central parts of the bands. Two other characteristics of both single bands and zones of bands in high resolution images are that their thicknesses appear to be smaller and that their lateral boundaries are unexpectedly rough with respect to their appearance in outcrops and hand samples, the latter of which may play an important role in their lateral growth.

34

1. Introduction

Deformation bands are tabular structures of strain localization in porous rocks and sediments (Aydin, 1978). The length (dimension along strike) of bands usually ranges from meters to tens of meters, while their thickness ranges from a few millimeters to a few centimeters. This results in a large aspect ratio of length vs. thickness. Kinematic classification of deformation bands includes shear, dilation, and compaction bands or a combination of these modes (e.g. Aydin et al., 2006; Fossen et al., 2007; Torabi and Zarifi, 2014). A characteristic formation mechanism of these bands is grain rearrangement at micro-scale known as particulate flow, which sometimes is followed by grain breakage and cataclasis. Aside from being highly intriguing structures, deformation bands induce petrophysical anisotropy in porous rocks in which they occur and could hamper fluid flow in aquifers and reservoirs due to their reduced porosity and permeability, thereby affecting the production of geo-fluids and contaminant transport (Antonellini et al., 1994; Torabi et al., 2013; Sternlof et al., 2005; Deng et al., 2015b).

Microscopic studies of single cataclastic deformation bands, which include both compaction and shear components, have revealed important changes in thickness, microstructure, and petrophysical properties measured along the bands (e.g. Torabi and Fossen, 2009). This kind of variations has not been captured by the theoretical or the experimental works on

53 deformation bands (e.g. Rudnicki, 2003 and 2011; Holcomb et al., 2007 and the references
54 therein; Fortin et al., 2006; Skurtveit et al., 2013).

55 To the best of our knowledge, there is no numerical model capable of predicting the natural
56 variation in thickness and microstructures along localized bands; although some numerical
57 studies have used a predefined length-scale that resulted in a particular thickness with a
58 good match of the observations (Besuelle et al., 2006). Chemenda (2011) and Chemenda et
59 al. (2012) have investigated the evolution of arrays of deformation bands (shear and
60 compaction bands) using Drucker- Prager constitutive model. These authors, by using
61 various values of dilatancy factor and hardening modulus, modelled deformation bands that
62 thicken in the middle and thin toward the tips, consistent with the anti-crack model
63 previously proposed by Mollema and Antonellini (1996) and Sternlof et al. (2005).

64 Displacement distribution along deformation bands with shear component and the related
65 scaling law have been studied by Fossen and Hesthammer (1997). They interpreted their
66 field data in terms of the linkage and growth of these structures. In spite of all these
67 research efforts, the geometrical, geostatistical and microstructural properties of
68 deformation bands, especially of compaction type, and the factors controlling their length
69 and thickness variation remain poorly understood.

70 The sequential addition of bands adjacent to each other with spacing much smaller than the
71 average background spacing is the basic mechanism for increasing of deformation band zone
72 thickness. This mechanism was identified a long time ago from shear band patterns in the
73 field by Aydin and Johnson (1978), later on supported by Shipton and Cowie (2001), and
74 Shipton et al. (2002) and eventually reproduced in laboratory experiments by Mair et al.
75 (2000). Although, compaction band thicknesses, both for single and zones, are generally

76 different from those of shear bands, the basic mechanism of widening or growth of zone
77 appears to be similar for both types of structures. The geometrical, statistical and
78 kinematical studies of compaction bands and compaction band zones and their detailed
79 architecture are very few, if any (e.g., Sternlof, 2006; Tondi et al., 2012; Cecinato and Gajo,
80 2014).

81 In the current study, we have focused on two sets of high-angle to bedding compaction
82 bands (CBs) in the Jurassic aeolian Aztec Sandstone exposed in a broad area over the Valley
83 of Fire State Park, Nevada, USA (Fig. 1). Since beds are low-angle, then the compaction
84 bands high-angle to bedding are essentially high-angle (with respect to horizontal). The term
85 “high-angle” explicitly suggests that they are different from compaction bands that form
86 sub-parallel to bedding.

87 Specifically, we have integrated field measurements of length, thickness, spacing, and
88 microstructure of compaction bands exposed at selected localities at Valley of Fire with the
89 objectives of determining the nature and mechanism of growth of compaction bands, and of
90 characterizing their length and thickness distribution. Our statistical results may also be used
91 to improve mechanical and geological models of aquifers and reservoirs that involve
92 compaction bands. The variations in the thickness and length of the bands and their dynamic
93 interactions in a zone could be applied in the fluid flow simulations of geological models of
94 aquifers and reservoirs (e.g., Antonellini et al., 2014) in the future. These variations might
95 lead to an increase of the tortuosity of the flow paths in aquifers/ reservoirs, which might
96 hamper fluid movement underground. The aforementioned effects may hence have
97 consequence for applications into contaminant migration, CO₂ sequestration, and
98 hydrocarbon production.

2. Host rock characterization

The Aztec sandstone is a cross-bedded aeolian sandstone with about 1400 m thickness, which comprises three sedimentary and diagenetic units: a lower red alteration, a middle buff alteration unit and an upper orange alteration unit (Fig. 1a). We have studied compaction bands in these rocks in four sites in the Valley of Fire Park. This includes a site close to White Domes (hereafter called “H” after Hill’s (1989) pioneering study of this site), a site to the west of Rainbow Vista (named Twist by us, hereafter called “T”) and a third site is located close to Silica Dome (the site studied by Sternlof (2006), and hence called “S” site). The fourth site is located nearby the parking lot # 2 in the park, which is called “P” in this study.

Fig.1.

Host rock samples were extracted by drill cores from the three localities (H, T, and S). These samples were used for grain size analysis as well as density and porosity measurements in the laboratory. Because of the poor degree of lithification, it was possible to turn the sample into loose sand simply by rubbing them in a hard bowl for sieve analysis. The results of the grain size analysis were used to define the sorting of the rocks.

Fig. 2.

Using the formula in Eqs. 1 and 2, the inclusive graphic deviation (Folk, 1968) or D , which is a measure of sorting, was calculated for each sample (a total of 7 samples) where d is the diameter of particle in millimeters.

$$\varphi = -\log_2 d = -\left[\frac{\log_{10} d}{\log_{10} 2}\right] \quad (1)$$

$$D = \frac{\phi_{84} - \phi_{16}}{4} + \frac{\phi_{95} - \phi_5}{6.6} \quad (2)$$

121

122 The grain size analysis of the samples shows that the host rocks at H and S sites are coarser
 123 than the host rock of T site (Fig. 2). All the samples are sorted, but T sample ($D=0.32$, very
 124 well sorted) is better sorted than H ($D=0.55$, moderately well sorted) and S ($D=0.64$,
 125 moderately well sorted) samples.

126 Among the samples, S sample has the highest bulk density and the lowest porosity (2012
 127 kgm^{-3} , 22%, respectively). The bulk density and porosity of the other two samples,
 128 respectively, are: H (1940 kgm^{-3} , 24%) and T (1917 kgm^{-3} , 26%).

129 **3. Geological setting**

130

131 The Aztec sandstone has undergone two major tectonic phases: a compressional
 132 deformation during the late Cretaceous Sevier Orogeny followed by a dominantly
 133 extensional and strike-slip faulting phase known as the Basin and Range deformation, which
 134 started primarily in Middle Miocene and continues to the present day (Bohannon, 1979;
 135 1983).

136 Compaction bands formed during the early compressive phase and represent the oldest
 137 structures in the area. They are offset by shear bands and overprinted by joints and sheared
 138 joints associated with the extension and younger normal and strike-slip faulting (Hill, 1989;
 139 Flodin and Aydin, 2004; Eichhubl et al., 2004; Sternlof, 2006; Aydin and de Joussineau, 2014).
 140 We have studied two sets of high-angle to bedding compaction bands in the middle buff

alteration unit, in four different sites in the Valley of Fire State Park, NV (see Fig. 1a for the locations).

The first (dominant) set of high-angle compaction bands usually strikes toward NNW and dips toward the east with an average values of 334, 71 attitude in S and T sites (Sternlof, 2006 and Deng and Aydin, 2012), apart from those in H and P sites, which strike NW but dip toward SW (Fig. 1b). This former set was also recognized by Hill (1989) who labelled it as “T1”. The second (sub-dominant) set of high-angle compaction bands has an average orientation of 229, 52 at the four study locations (Fig. 1b). This set was called “T2” by Hill [1989] and was also described by other investigators: Sternlof (2006); Eichhubl et al. (2010); Deng and Aydin (2012). In addition, a third set of wiggly compaction bands exists (on average 172, 68) that bisects the two sets of high-angle compaction bands (Fig. 1b). The two sets of high-angle compaction bands are generally straight, whereas the third set with a wiggly geometry has two orthogonal segments being generally parallel to the two primary sets with straight trace geometry.

Aside from these three sets, there is at least one more set parallel to bedding named bed-parallel compaction bands by Aydin and Ahmadov (2009). Because the length parameters of the last two sets are either difficult to measure or controlled by primarily the high-angle bands, we focused on the two sets of high-angle compaction bands in this study.

4. Field measurements and microstructural studies

We have studied length and thickness distributions of compaction bands (both single and zone) along the two sets of high-angle compaction bands labeled with 1 (first set) and 2 (second set) in each site (Figs 3 and 4). We address the dynamic interaction between the mapped compaction band and the cross-cutting compaction and shear bands and investigate how these interactions might affect the local thickness of band. Drill cores (around 50 samples) were taken along the bands (see Figs. 3 and 4 for single bands). Detailed photographs before and after the drilling were also taken. Polished thin sections of samples were studied by both optical and electron microscopes using Backscatter or BSE images. BSE images of thin sections were used for porosity calculation of single bands and their adjacent host rocks. We used the Matlab-based image processing method described by Torabi et al. (2008).

4.1 Single compaction bands

Length and thicknesses of a total of 14 single bands were measured in the field, which include four from each set of bands in the three sites H, S, and T as presented in Figs. 3 and 4. Two additional data sets from site T (T1b-14 and T2b-14) are provided in Figs. 5 and 6.

Fig. 3

Fig. 4

The compaction bands in the first set are consistently longer than the second set (Fig. 5a). These bands are also thicker than those in the second set at one site, the H site, but they are thinner in the two other sites (S and T), Fig. 5b.

A detailed investigation of field pictures and measurements (Figs. 3-6) and microscopic image analysis of compaction bands shows that there is a substantial reduction in the

thickness near the tips for both sets of high-angle compaction bands. Based on our data the exceptions are thought to be related to the interaction between the single compaction band and other bands in the vicinity (Figs. 3-6).

Fig. 5

Fig. 6

A microphotograph of the compaction band S1 is illustrated in Fig. 7. This band cuts across fine-grained layers; however no shear offset can be detected. Porosity reduction can be observed within the compaction bands. The compaction took place by means of pore collapse and pressure solution at the grain contacts. The grains often show concavo/convex contacts (plastic deformation) without considerable grain breakage.

Fig. 7.

The microscopic study reveals that only the samples from the S site show more profound compaction bands both in the coarse- and fine-grained layers. Though the thickness along these bands changes at a millimeter scale, its variation seems not to be influenced by changes of grain size along the band (Fig. 7). The comparison between microscopic (thin section) and macroscopic (field) thicknesses of the single compaction bands shows that the microscopic thickness in most cases is smaller than the macroscopic one.

In general, the compaction bands are characterized by thin ($\leq 2\text{ mm}$) and thick ($\geq 2\text{ mm}$) portions under the microscope. The thin portion of the bands (T1-4 and H2-4) presented in Fig. 8, are mainly observed nearby the tip of those bands that are not disturbed by the presence of other neighboring bands. The thin portions with diffuse and irregular boundaries are made of pockets of grains forming tight packages which are separated by large pores from the rest of the band or the surrounding host

210 rock. The thick portion of the bands has also diffuse and irregular boundaries but the compaction is
211 almost homogeneously distributed throughout the band (Fig. 9). The large pores could be scarcely
212 found in the thick bands (Fig. 9). The thick portions are generally found in the central portion of the
213 bands.

214 Figs. 8-9

215 **4.2 Compaction band zones**

216 We collected field data on the CB zones or clusters (i.e., length and thickness) from the three
217 sites; H, T, and P, (the same locations marked in Fig. 1a) and identified their patterns and
218 growth processes. The compaction bands in site H occur primarily in four sets: two major
219 orthogonal high- angle compaction bands as H1 and H2 sets with a subsidiary set of wiggly
220 bands bisecting the first two major sets, which were identified and mapped by Hill (1989).
221 The fourth set is oriented parallel to bedding similar to those described by Aydin and
222 Ahmadvov (2009) and Deng and Aydin (2012), thus is not visible in map view, which is the
223 reason for not considering it for the current detailed study except where it affects the length
224 and thickness variation of the three sets mentioned above. An example of the architecture
225 of the compaction band zone H1, which is composed of several closely spaced clusters of
226 sub- parallel individual bands, is shown in Fig. 10b.

227 The thickness profiles of four high-angle to bedding compaction band zones are presented in
228 Fig. 11. The first two plots in Figs. 11a and 11b are for H1 and H2 marked in Fig. 10a. We
229 have used two criteria in order to measure the thickness of the CB zones presented in this
230 figure. The first criterion includes the measured thickness of individual strands plus the host
231 rock between them and the second criterion includes only the thickness of the strands, and
232 therefore is almost always lower than the first one.

233 Upon closer inspection, it appears that the average thicknesses of these compaction band
234 zones do not change substantially along a large portion of the zones except for a few spikes
235 representing extreme local thickness values. Nearly flat thickness trends outside of the
236 spikes are approximately bracketed between black dashed lines in the plots. The spikes in
237 the thickness plots are due to geometric complexities that will be described later on. The
238 other important observation is that the zones terminate at or near dune boundaries or sub-
239 boundaries, and other zones at high-angle at the surveyed zones as documented in Figs. 12a,
240 b and c. These terminations are commonly sharp and have a steep thickness vs. distance
241 gradient, which may be characterized as blunt tip profiles.

242 Detailed photographs of H1 and H2 zones from H site (Figs. 10a, b, c, see Fig. 1 for location)
243 show a single, double and multiple compaction bands (Figs. 13). The single band in the
244 middle of (13a) shows partially overlapping bands with a hook-shaped interaction feature
245 (marked as 2), which is commonly referred to as an “eye” structure (Antonellini and Aydin,
246 1994; Aydin and Ahmadov, 2009). A tighter eye structure also marked as “2” is identified in
247 Fig. 13b. The double compaction bands on the far right side of (13a) and (13b) are perfectly
248 parallel for most of their extent. See the upper 2/3 of the trace length in (13a) before the
249 band on the right diverges. The zone on the left-hand side in (13a) includes several bands
250 with an aggregate thickness of about 8 cm. The veneer of cover at the surface of this zone is
251 due to bed-parallel shearing cutting across the compaction bands. According to Aydin and de
252 Joussineau (2014) the bed-parallel shearing took place at a later time. The eye structures
253 result in increasing thickness of the zones. Notice that the thickness of the parent
254 sandstones between the diverging bands (spacing between the neighboring bands) increases
255 moving away from the initial zone resulting in greater zone thicknesses. Diverging bands like

256 these create ambiguity as to what the thickness of the compaction band zones is, and more
257 importantly, how to define compaction band clusters.

258 The spikes in the thickness distribution along compaction band zones correspond to
259 geometric complexities in the zone architecture as shown in the simplified map at the
260 bottom of the Figure 14. These parts with anomalously high thickness values are mapped in
261 detail in Fig. 15. Here, similar to the previous examples, the overlaps or eye structures
262 marked as “1” and “2” in Fig. 14, are the sites of significant zone thickness increase. The
263 other complexity marked as “3” at the trace map is due to the intersection and coalescence
264 of some bands of both parallel and orthogonal to the set surveyed (Fig. 15).

265 Figs 10-15.

266 We examined the microstructure of both single and multiple strands within the zones of
267 compaction bands. The multiple strands encompass slightly deformed host rocks with higher
268 porosity between the strands (Figs 16 and 17). Irregular and diffuse boundaries were
269 observed for both cases (Figs. 16 and 17). The microstructure of the individual strands is
270 similar to that of single compaction bands and includes pockets of tightly packed grains
271 separated by large pores (Fig. 16). The single strands are usually thinner if they are located
272 by the tip of the zone (for example T1Z-1 in Fig. 16) and their thickness is comparable to the
273 field measurements of the corresponding zone. The continuous and preserved fine-grained
274 layers across the bands reveal that these zones did not resolve any observable shear offset
275 (T1Z-1 in Fig. 16).

276 If a zone includes several strands, it is difficult to capture all the strands within a single
277 sample and a standard thin section. Therefore it is hard to compare its microscopic and
278 macroscopic thicknesses (Fig. 17).

We also studied a double band at T site, where the band first diverges into two bands. This geometry is captured both in the field and in the photomicrograph (sample T2D-2, Fig. 18a). There are several strands that are connected to these two bands along the scan-line in the field that make spikes and anomalies in the zone thickness (Fig. 11d). The bands converge again at 3.5 m distance. Here the two bands appear to be a single compaction band both in the field and under the microscope (sample T2D-3 in Fig. 18b). In sample T2D-2, there are two distinguishable strands. The total thickness of these bands is 7 mm in the field (each band is 3 mm-thick and they are spaced 1 mm). In thin section the thickness of each CB appears to be smaller. The bands within sample T2D-3 are 2.5 mm thick in the field, which is comparable to thickness measured in thin section (Fig. 18b). The microstructure observed in T2D-2 and T2D-3 samples resembles the thin portion of single compaction bands with pockets of compact grains separated by large pores. However the texture of the band in sample T2D-3 is more compacted with diffuse irregular boundaries (Fig. 18).

Figs. 16-18

5. Discussion

The microstructure within compaction bands can be subdivided into two groups: thin and thick portions of the bands. The thin portion of the bands contains pockets of tightly packed grains surrounded by large pores, whereas the thick portions of bands involve more compaction, which appear to be almost homogeneous throughout the thick portions. The growth of a compaction band in Aztec sandstone was in all likelihood progressive, with increasing strain occurring perpendicular to the maximum principal stress. Sternlof (2006) reported pockets of tightly packed grains outside CBs in his thin sections and interpreted

304 them as incipient compaction bands. Though, some of the pockets of grains in Aztec
305 sandstone could be of depositional origin, these pockets may have later participated in the
306 compactive strain localization process. The large pores around such pockets of tightly packed
307 grains may have been due to tensile stresses associated with the volume reduction there as
308 conceptualized in Fig. 19. These pockets may represent early stages of incremental growth
309 of compaction bands and could later act as stress concentrators or asperities (Katsman et al.,
310 2005; Sternlof et al., 2005, Fortin et al., 2006; Zhou and Aydin, 2010; Cheung et al., 2012).
311 These asperities represent locus for stress concentration and plastic strain accumulation
312 enhancing the tendency of the band to further widen and lengthen during its growth. The
313 coalescence of these pockets is thought to be responsible for the thin portions of the bands
314 detected in the microscopic images. Upon further growth of the band (longitudinally and
315 laterally), pore collapse and pressure solution contribute further compaction in the thick
316 portions of the band.

317 Fig. 19

318 Our observations confirm that a single compaction band does not have a perfectly tabular
319 geometry with smooth planar boundaries and constant thickness but rather a band with
320 enhanced thickness in the central part and with diffuse and irregular boundaries. The
321 documentation of irregular compaction band boundaries in this study may prove to be
322 critical considering the role of asperities as stress risers at the flanks of the volume reduction
323 bands (Zhou and Aydin, 2010).

324 Numerical modeling reveals that the stress is higher at the tip of the bands with respect to
325 their flanks (Katsman et al., 2006a; Zhou and Aydin, 2010; Meng and Pollard, 2014).

326 The lower stress at the flanks of a single compaction band results into a small aspect ratio of
327 the band (T_{max}/L) implying that a further increase in length does not necessarily cause a
328 proportional increase in thickness (Katsman et al., 2006a and 2006b).

329 Considering that models for compactive strain localization such as Eshelby inclusion
330 (Sternlof, 2005), anti-crack (Fletcher and Pollard, 1981) and the so called Localized Volume
331 Reduction Structure (Katsman et al., 2006b) assume constant volume within the inclusion or
332 closing structure, the variation in packing and pore distribution that we documented within
333 the compaction bands in our study, is critical. Our porosity measurements along individual
334 bands also show some variation, which we attribute to inhomogeneity of the micro-texture
335 and/or interaction with other bands (Table 1). This may be an important factor responsible
336 for the variation of porosity and permeability determined by image analysis from a small
337 area (Deng et al. 2015b).

338 Apart from some local anomalies, the first set of high-angle compaction bands is generally
339 longer than the second set of high-angle compaction bands (Figs. 5 and 6). This observation
340 may be explained by comparing the strike of dune boundaries and the strike of each
341 compaction band set. Indeed, the first set of high-angle compaction bands has similar strikes
342 as the longitudinal dune boundaries whereas the second set strikes normal to these dune
343 boundaries as documented by Deng and Aydin (2012). These authors demonstrated that the
344 compaction band domains (assemblages of compaction bands of different orientations) are
345 mostly confined within the depositional domains (dune units characterized by certain
346 cross-beds orientation therein). This phenomenon could be related to the strength
347 anisotropy of localized compaction (Deng and Aydin, 2015) induced by the cross-bedding
348 related anisotropy, which was measured to be about 13% (Deng et al., 2015a). Because

349 cross-bed orientation controls the formation and distribution of compaction bands, and
350 these structures tend to terminate at dune boundaries, the maximum length and width of
351 dune units are generally larger than or equal to those of the compaction band domains.
352 Conversely, if a certain compaction band set strikes at high angle (say normal) to the dune
353 boundary, this set will be limited by the width of the dune. Because, the average length of
354 the dune units is generally larger than their width (Deng and Aydin, 2012), the length of the
355 first set of CB is therefore larger than that of the second set. On the other hand, the spacing
356 of compaction bands is controlled by dune heights rather than their lengths, which are rarely
357 measurable. We considered the spacing of the compaction band zones in order to identify
358 and measure the zone thicknesses only.

359 The interaction of bands and development of zones could be explained by a series of
360 schematic diagrams that illustrate major mechanisms of growth of compaction band zones in
361 the Valley of Fire State Park (Fig. 20). The first geometric array is a simple case in which two
362 sub parallel compaction bands (sometimes referred to double bands) happened to be closely
363 spaced (Figs. 20a1, a2, and a3). If two bands of comparable lengths are parallel and overlap
364 completely, the thickness of such a zone is approximately constant (grey line on the top of
365 Fig. 20a1). This thickness is defined by the sum of the thicknesses of the individual bands
366 plus the thin sliver of the parent rock in between. Another scenario involves two sub-parallel
367 bands which overlap only for a small portion of their lengths (Fig. 20a2). In this case the
368 thickness profile shows an abrupt increase corresponding to the overlapping zone. Aside
369 from the individual band thicknesses, the separation or spacing between the bands at the
370 overlap area determines the maximum thickness. If the interaction between two adjacent
371 bands is strong enough, they may conjoin each other forming a hooking geometry or an eye
372 structure similar to the shear bands described by Antonellini and Aydin (1994). Fig. 20a3

373 shows a case of diverging (or converging) pattern of bands. This phenomenon introduces a
374 great deal of ambiguity for estimating the thicknesses along such zones because it is not
375 straightforward to determine when the diverging or converging band is no longer part of the
376 zone. Care should be taken to handle these cases.

377 Compaction band zones with more than two bands are idealized in Figs. 20 b1 to b4. The
378 thickness distribution of the zones composed of parallel multiple bands with complete
379 overlap is similar to that of double bands but with greater thickness values based upon the
380 number of the bands as shown in (Fig. 20b1). However, it is commonly the case that parallel
381 multiple bands do not have total overlaps along all their lengths and individual components
382 may have variable lengths as shown in (Figs 20b2, b3, and b4). For these cases, thickness
383 distribution varies from one part to another as a function of their local architecture. Some of
384 the scenarios for the potential complexities and the local architecture of the zones are
385 illustrated in Figs. 20b2 through b4. The case represented in (20b4) is particularly common:
386 partially overlapping en-echelon bands diverge sequentially from both sides of the zone in
387 such a way that the actual total thickness along the zone remains more-or-less the same.
388 The splays of this nature can be seen in the field photographs in Figs. 12 through 15. These
389 splays are almost always wiggly or crooked (Hill, 1989; Mollema and Antonellini, 1996;
390 Eichhubl et al., 2010), which are composed of shorter segments in the orientations of the
391 nearby two sets represented by orthogonal dashed lines in Fig. 20b4.

392 Fig. 20.

393 We have shown that compaction band zones thicken by sequential addition of new bands.
394 Thicknesses of the individual bands as well as the manner, in which new bands are added,
395 are important factors contributing to the total thicknesses of compaction band zones and

their maximum values. One of the critical issues has to do with the definition of a compaction band zone, a more quantitative analysis of which is underway (Roy et al., 2014).

The thickness distribution of compaction band zones appears to vary significantly along their lengths. We attribute these abrupt variations or spikes to structural complexities such as overlaps, coalescences, and intersections. In addition, the terminations of the zones at dune boundaries and the merging of some bands onto these interfaces commonly result in large thickness/distance gradients and blunt tip profiles. These large gradients are attributable to the anisotropy and heterogeneity associated with the depositional architecture of the dunes in which compaction bands occur. However, excluding a limited number of anomalous thickness values and large gradients at or near the terminations, the zone thicknesses show surprisingly small variations along their lengths.

Compaction band zones are critical for fluid flow in a direction perpendicular to the zone because the effective permeability in this direction is a harmonic average of matrix permeability and compaction band permeability (Antonellini and Aydin, 1994, p. 372) and therefore, dominated by the low compaction band permeability. This effect will be enhanced by the cumulative thickness of the bands in the zone. However, this trapping is effective if the longitudinal boundaries of the dune hosting them have large dimensions.

6. Conclusions

The length of individual bands usually ranges from a few meters to a few tens of meters, while their thickness ranges from a few millimeters to about ten millimeters. The first set of high-angle compaction bands, which strike parallel to the first order longitudinal dune boundaries are longer than those in the second set almost orthogonal to the first set.

Single compaction bands when viewed under microscope appear to be generally thinner than when viewed by naked eye on the outcrop and hand samples. The microscopic images of compaction bands also reveal highly rough boundaries as opposed to appearance of the same bands having highly regular planar boundaries in hand samples and outcrops. Single compaction bands typically have two portions: thin portions (≤ 2 mm) and thick portions (≥ 2 mm) under the microscope. The thin portions are usually observed near the tips of the bands, while the thick portions mostly occur in the bands' central areas. Isolated pockets of tight grains along the bands are thought to be remnants of their incremental growth process that is not well-understood. In general, the heterogeneous distribution of tightly packed grains as well as the pores around them indicates a noticeable variation of porosity within compaction bands, which is in contrast to the assumptions in a majority of the models used to simulate compaction bands. The porosity reduction in the band with respect to the host rock (~6%-12%) and its heterogeneous nature could hamper the permeability and conductivity within the band and could influence the fluid flow within reservoirs containing such bands.

Compaction bands in the study area commonly occur in zones, which terminate at, or are truncated by, the dune boundaries and other compaction band zones at high-angle to them. In a few cases, members of a compaction band zone turns sharply and follows cross beds. In general, the length of compaction band zones is controlled by the architecture and geometry of the dunes in which they form. Aside from some limited number of large anomalous thickness values as high as about 35 centimeters, thickness of compaction band zones remains almost constant, on the order of several centimeters, along their traces except large thickness gradients at their ends. The anomalous values or spikes in the compaction band

zone thickness/distance plots in the study area are shown to be related to structural complexities such as overlaps, coalescences, and intersections with neighboring bands.

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Table 1. Porosity measurements using BSE images of thin sections of samples that were collected;

Band name	Thickness mm	Distance cm	Host rock porosity %	CB porosity %	porosity change %
H1-1	3	6.8	22.7	16.3	6.4
H1-2	9	100	25.8	16.4	9.4
H1-4	6	570	24.9	17	7.9
H2-1	5	10	26	14.6	11.4
H2-2	4	150	26.4	14.6	11.8
H2-4	2	280	30	19.7	10.3
S1-2	6	100	17	8.8	8.2
S1-5	2	650	19.3	9.8	9.5
S2-2	4	100	19.4	8.9	10.5
S2-3	3	150	22	10.4	11.6
T1-2	5	150	18.4	10.2	8.2
T1-3	5	218	22.6	13.9	8.7
T1-4	6	450	22	11.2	10.8
T1-5	3	650	24.9	16	8.9
T2-1	1	0	23.4	11.2	12.2
T2-3	5	150	23.5	11	12.5
T2-4	4	250	19	11.9	7.1

Fig. 1. a) Geological map of Valley of Fire State Park, NV (slightly modified after Flodin and Aydin, 2004). The study locations are marked on the map as H, T, S, and P (see the explanations in the text). b) The attitudes of bands and the bedding of their host rocks are plotted in the stereograms (Schmidt net, lower hemisphere). In these plots, crosses present poles to the bedding, solid black circles, pole to the first set of high-angle compaction bands (CB); open red circles, poles to the second set of high-angle compaction bands in each site. Open black squares are poles to the average orientations of the wiggly bands in the H site.

Fig. 2. Grain size distribution for all the host rock samples collected from the detailed study locations. Note that T is finer ($\sim 125\mu\text{m}$, fine sand) than H and S samples ($300\text{--}125\mu\text{m}$, medium to fine sand). For classification of the phi-scale and sorting the sandstones, see the text.

Fig. 3. Mosaic pictures of the first set of single high-angle compaction bands; the band (labeled 1) surveyed in the field. Open circles show the location of drilled cores and thin section samples to be described later. Note the length of each band is specified on the top left of each picture. Details of each compaction band and the interacting bands (such as other compaction bands, shear bands, and wiggly bands) around each band are identified and marked on the pictures. The thickness and length of the bands are not to scale in these pictures, but the steel measuring tape is about 1.5 cm wide.

H2: 2.8 m

H2-14: 1.42 m

— Compaction band
— Shear band
— Wiggly band

S2: 2.4 m

S2-14: 4.10 m

T2: 2.5 m

T2a-14: 2.97 m

Fig. 4. Mosaic pictures of the second set of high-angle single compaction bands (marked 2) surveyed in the field. Open circles show the location of cores and thin section samples to be described later. The length of each compaction band is specified on the top left of the picture. Details of each compaction band and the intersecting bands (such as other compaction bands, shear bands, and wiggly bands) around are identified and mapped on the pictures. Note that the thickness and length of the bands are not to scale in these pictures, but the metal measuring tape is about 1.5 cm wide.

Fig. 5. a) Length distribution of single compaction bands at each site. Note that the first set of high-angle compaction bands (the dominant set labeled 1) is always longer than the second set (labeled 2). b) Band thickness distribution (min, max, and average) distribution of single compaction bands for different sites.

Fig. 6. Thickness profiles measured along single bands from the first set in (a) and the second set in (b) of high-angle compaction bands at the three sites, labelled H, T, and S.

Fig. 7. A mosaic picture of part of S1-5 thin section from the first set of compaction bands showing compact and interpenetrated grains inside the band (bounded by red lines). Note that no shear offset is detectable across the layer with fine grains (bounded by black dash lines).

a) T1-4 (6 mm measured in the field)

c)

d)

b) H2-4 (2 mm measured in the field)

a) H2-1 (5 mm measured in the field)

b) Host rock

c) Compaction band

Fig. 9. Microstructure of H2-1 compaction band from the H site. a) A mosaic photomicrograph of the thin section showing a compaction band with highly irregular and diffused boundaries (red dashed lines). At this scale, it is hard to distinguish segments of the boundaries along certain parts. b) BSE image of the host rock adjacent to the band; c) BSE image of compaction band showing compacted pockets of grains and some large pores (the white arrows point examples for large pores). See Fig. 4 for the location of the sample.

Fig. 10. a) Google map of a dune with partial dune boundary (in green) in H site. Two major sets of high-angle compaction band zones (H1 and H2), which were surveyed in this study, are parallel and perpendicular, respectively, to the longitudinal boundary of the dune. b) A map showing the detailed architecture of H1 at a small area in nearly 3D, thanks to erosion.

Fig. 11. Thickness vs. Distance of the H1 (a) and H2 (b) zone of CBs in H site. (c) and (d) Thickness vs. Distance of T1 and T2 zones of CBs at T site. The grey and black arrows point at the two tips, and the white arrows point at the spikes at the thickest part of the CB zones. Arrow #1 on T1 zone demonstrate the place of an eye structure and arrow # 2 the place of the band divergence. On T2 zone, arrows #1 and 2 demonstrate the location of two eye structures and arrow # 3, the location of the band divergence. The dashed lines bound the actual thickness of the CBs which make up the zone.

Fig. 12. a) Detailed map of the south tip of the H1 zone. Wiggly CB merges into the zone of CBs, which abuts and terminates against a cross-bed. b) Detailed map of the western tip of the H2 zone. Shear bands offset the CBs zone, whereas wiggly CBs merge into the zone. At the western most tip (top of the photo), the strands turn and become parallel to the dune boundary. c) Detailed map of the northwest tip of the H1 zone showing the divergence of two of the strands that become parallel to bedding. The other two strands terminate immediately after the dune boundary marked in the photograph.

Fig. 13. Maps showing detail structural architecture of three areas in H site (see also Fig. 9 for broader views) with anomalously high thickness values. a) The first two (1 and 2) are associated with overlaps or eye structures and the last one (3) includes an intersection of the zone by a minor zone and coalescence of bands among the two zones. b) a merging band (1) and an eye structure (2); c) Wiggly bands that are merging to the zone.

Fig. 14. a) Google map of the P site with arrows marking the compaction band zone on the northeast side of the park road. b) Thickness vs. Distance plot of the compaction band zone. The thickness values between the dashed lines are representative of the zone made up of subparallel individual bands. The three spikes correspond to certain portions marked as 1, 2, and 3 along the zone with identifiable structural complexities, either eye structures (1 and 2) or sub parallel zones intersected by another zone perpendicular to the surveyed zone (see Fig. 12 for details). Note that the tips of this zone are not exposed.

Fig. 15. Detailed maps of the three structural complexities with anomalous zone thicknesses as shown in Fig. 11. (a) First eye structure (1 in Fig. 11) which is relatively simple, a few wiggly/crooked compaction bands (black lines) are merging into the zone. (b) Second eye structure (#2) with a more complex geometry, multiple wiggly compaction bands (black lines) merge into, or splay off the zone. (c) Coalescence of compaction band zone (N-S) crosscut by another zone sub-perpendicular to the former. Some bands in the crossing zone merge into the major N-S zone by turning 90 degrees thereby influencing the thickness value of the surveyed zone at this station. Dashed lines are shear bands cutting across the zone.

Fig. 16. Scans of thin sections of individual strands in T1Z zone with their field pictures (insets): a) T1Z-1 sampled near the tip; and b) T1Z-5 sampled at 12 m distance from the tip. c) and d) Parts of mosaic photomicrographs (close up) of thin sections (rectangles in (a) and (b), respectively) of the samples T1Z-1, and T1Z-5 from T site.

Fig. 17. a) Scan of thin section of sample H12-5, which shows a CB zone containing several strands at H site. b) Close up of the mosaic picture (marked by the rectangle in a) showing a single band on the left side, a sliver of host rock, and the rest of the zone which appeared to have four bands based on the field observations. c) Field photograph of the zone after the coring for thin sectioning.

Fig. 18. a) and b) Mosaic photomicrograph of samples T2D-2 and T2D-3 showing a compaction band zone. a) T2D-2 photomicrograph showing two distinct bands at the lower part of the image and a thicker structure at the upper part. b) Another part of the zone showing a thicker structure similar to the upper part of (a). Two kinematical interpretations are plausible: The two bands merged to form a thicker zone or a thick band broke down to form two bands. We favor the former. Black arrows point at tight pockets of grains and large pores within the bands.

(a) Band with
smooth surfaces

(b) Band-normal tension (blue)
due to localized
volume reduction

(c) Band with rough surfaces

Fig. 19. Schematic diagrams showing (a) a band with smooth boundary surfaces; (b) Area under band-normal tensile stress due to localized volume reduction within the band; and (c) a band with rough surfaces. Exaggerated asperities shown on one side only.

Fig. 20. Conceptual diagrams showing types of compaction band zones and the corresponding thickness distributions. (a1) and (a2) are patterns of two over lapping bands and (a3) shows two diverging or converging bands with idealized thickness distributions above the map views. (b1) through (b4) are the potential patterns of multiple compaction bands with idealized thickness distributions above the map views. (b4) is a common pattern made up of parallel echelon compaction bands with their splays (dashed for average orientation) that are generally wiggly or crooked (solid wiggly lines). The sequential merging and diverging of bands from both sides of the zone help to maintain a sustainable overall zone thickness.