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Interactive comment on "Evolution of a highly dilatant fault zone in the grabens of Canyonlands National Park, Utah/USA – integrating field work, ground penetrating radar and airborne imagery analysis" *by* M. Kettermann et al.

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Dear Fabrizio Balsamo,

thank you very much for your helpful and detailed comments. I believe we addressed all of them in a way that greatly improved the manuscript. In the following I will reply to the comments and suggestions provided by you. Figures we changed are attached.

Kind Regards

Michael Kettermann

(1) Orthogonal joints In Figure 4 - and page 1126 (lines 15-24) - there are rose diagrams and photographs showing faults/joints orientations. Joints are either parallel and orthogonal to fault strike. Fault-perpendicular joint are also particularly abundant and well-developed in domains 1 and 2. Although fault-perpendicular joint sets are common in many extensional fault zones developed in several geological contests, in this MS there are no mention about this fault-perpendicular joint set, and no explanation about their origin. I am wondering if they can be integrated in the model proposed by the Authors. A possibility is that such joints, if genetically associated with the extensional faults, are related to the lateral propagation of fault zones which induce a component of stretching parallel to fault strike. Also the tensile stress associated with the bending of down throwing hanging-wall perpendicular to the fault strike could locally induce orthogonal joints. Maybe some bedding dip-domain around studied fault zones could help to solve this issue.

–> The origin of the orthogonal joint sets is a complicated topic. However, we think that an origin related to the faulting itself is unlikely because the joints cross grabens and at many locations one joint can be followed from one horst, into the graben floor and onto the next horst. This consistency is unlikely for joints forming related to faulting as graben bounding faults and faults within the graben form at different times and would form different high-angle joints. Additionally, orthogonal joints also exist in places where faulting is less pronounced. The best example would be the Cheslar Lineament, where NW-SE striking joints exceed far beyond the eastern boundary of the grabens. I think that the joint sets are probably related to deformation of the evaporites in the subsurface induced by erosion and related differential loading. Similar to the faults localizing at the tips of the parallel to subparallel joints I would expect that the same process occurs at the orthogonal joints. Instead of forming new ones the fault just localize at the joint-tips as this is the energetically easiest way to fracture the underlying rocks.

We rephrase and extend section 2 to clarify:

“Both joint sets change their orientation slightly towards the south, the NNE set following the change of the graben orientation, the second joint set stays roughly normal to the first one and to the faults with a deviation of up to 30° in the vicinity of eastern Chesler Canyon. According to the considerations of McGill and Stromquist (1979) these joint sets are older than the grabens. Their considerations are based on the variety of different angles between joint strike and graben wall orientation, which are neither consistent with shear nor extensional origin of jointing. Additionally, the observation of joints with regular spacing at exposed graben floors (e.g. northern Devil’s Lane) imply that they are older than the graben faults. Although joints can form in high angle to normal faults due to the faulting (Destro, 1995; Kattenhorn et al., 2000; Balsamo et al., 2008) this does not apply to the grabens of Canyonlands National Park. Joints can be followed through the grabens over very long distances and crossing several faults that developed at different times. A formation of the joints due to faulting would cause the joints to develop differently at different faults, which is not the case here.”

(2) Terminology used Please clarify the term "faulted joint surface", which is expected to be a joint surface subsequently sheared and that, due to shear, accommodate some displacement along the surface. In your case (model), joints remain joints and are passively translated and opened (dilated) due to underlying extensional faulting, so that they show throw and heave. This is explained in the text, but should be clear from the beginning of data presentation to avoid confusion.

–> We agree that the term “faulted joint surface” is misleading in this context and replaced it by clear descriptions of the situation that you correctly described. See also point 11 and 13 of the Minor Points.

Minor Points: 1. Page 1121, line 10: I would remove "in profile" –> Removed “in profile”.

2. Page 1121, line 23-24: what exactly you mean by "produce a mechanical stratigraphy"? please clarify. –> As fault zones and joints can be weaker or stronger or in

case of joints even cohesionless, these structures present localized variations of the mechanical properties of rocks. Faults interact with cohesionless joints. We rephrase the sentence to “This is especially complicated when failure structures of different generations and with different mechanical properties interact with each other.”

3. Page 1122, line 2: which type of reservoir? I would add "sandstone" reservoir. –> added “sandstone” reservoir.

4. Page 1122, line 16: remove "/", use ",". –> replaced “/” by “, “.

5. Page 1127, line 1: add "sites" after Canyon. –> added “sites”.

6. Page 1127, line 10-11: remove "(" before Biggar, and put in brackets the year (1987) of publication. –> Fixed the citation.

7. Page 1127, line 12-13: Remove this sentence, already mentioned: "They were mapped from field observations and orthoimages (for map distribution see Fig. 3)." –> removed the sentence.

8. Page 11278, line 8: you say that throw is 38.5 m, but in Fig. 6A is 38.7 m. Please correct the wrong value. –> 38.7 m is the correct value. Corrected in the text.

9. Page 1128, line 9: you say about 25 m, but in Fig 6A is $\sim$20 m. Please correct. –> $\sim$20m is the correct value. Corrected in the text.

10. Page 1128, line 18: add dipping between "shallow" and "fault" (shallow dipping fault). –> added “dipping”.

11. Page 1128, line 20-27: remove "ourselves". Concepts are confused here, at least for me. Not clear whether you found or not calcite fibers on joint surfaces. Furthermore, the term "faulted joint surface" means that you have a joint which is subsequently sheared. I would pay attention to terminology used. Clarify that your joints are pure tensile fractures with no shear movements (and no slickenlines, fibers, ...). –> We observed calcite coating on joint surfaces, however these are not shear-related cal-

cite fibers but precipitation of calcite solved by rainwater. Rephrased the paragraph: “Moore and Schultz (1999) described slickenlines at calcite-coated joint surfaces, but we did not find any examples of that. Calcite coatings on joint surfaces that subsequently accumulate displacement due to underlying faulting are formed by rainwater flow over the surfaces in streams, thus producing irregular trails of calcite. Further it is possible to form toolmarks on soft calcite coatings by reworking of rockfall debris even in extensional faulting regimes. The majority of our observations point to extensional fracturing, without frictional sliding (Fig. 7).“

12. Page 1132, line 24: "Evidence for dilatant faulting is the occurrence of sinkholes...". OK, but maybe give some more details (like for example dimensions of sinkholes). –> Details such as dimensions and location of the sinkholes are given in section 5 – Field Observations. I think a repetition of these information at this part of the manuscript is not necessary.

13. Page 1133, line 5: same comment as above about "faulted joint surface". If I understood correctly, along these joints you do not have any shear evidence, but they accommodate significant offset and dilation. So I am not sure you can call them faulted joints. I would call joints, explaining that you have offset accommodated along them. –> I agree. We rephrase this sentence to: “Also, during our field work we never observed slickensides at surfaces of unweathered joints that accommodate offset and extension due to reactivation by underlying normal faults.”

14. Page 1133, line 16: could you say at which depth you have - or you expect - the change in dip of the faults? Furthermore, I would say "requires the presence of non-vertical faults in depth" instead of "change in dip of the faults ". –> Expected depth of the change in fault dip is explained later in the same subsection: “Other authors found field evidence for such a vertical change of the fault dips in the grabens of the Canyonlands by investigating crosscut grabens along Y Canyon, Cross Canyon and Lower Red Lake Canyon. Based on observations in these crosscuts McGill and Stromquist (1979) proposed that faults are vertical over about 100 m followed by dips of about 75°

down to the evaporite interface. This observation was confirmed by Moore and Schultz (1999) by investigations in the same area.” We changed the sentence to "requires the presence of non-vertical faults in depth".

15. Page 1135, line 24: Fig. 14. In this figure we see faults dipping ∼80, not subvertical joints. Is this correct? Faults accommodate shear displacement, so one could expect some striations and slickenlines along fault surfaces. This evidence affect your Fig. 15 model? –> It is correct, that these faults show a dip of ∼80°. At this location pre-existing jointing is far less pronounced and regular compared to the northern part of the grabens and does not affect the faulting as much. This is rather an example for the faulting below the vertical joints, nicely showing the syn- and antithetic faulting within a graben. Basically it resembles the faulting within the lower Cutler bed & Honaker Trail Fm of Fig. 15.

16. Page 1136, line 6: "Faults dip with 60-80° ", remove "with", say in which level/lithology they are developed. –> We rephrase the sentence to: “Faults dip 60° - 80° in the lower Cutler bed & Honaker Trail Formation and localize at the lower tip of the vertical joints in the Cedar Mesa Sandstone.”

17. Page 1139, line 24: "fault-joint intersection", do you mean interaction? What exactly mean fault-joint intersection in your model of Fig. 15? –> Fault-joint intersection means the line along which joints and faults intersect. In fact we think that in most cases the faults actually localize at the lower tip of the joints, though. Therefore we rephrase to: “We propose a model of graben formation based on our observations including fault localization at tips of vertical joints, shallow fault dips at depth, graben internal faulting and reactive diapirism.”

Figures: 18. Figure 1. This figure concerns with field photographs, without any geological feature indicated (for example graben, fractures). Maybe would be nice to add some structural features. Also in the caption there are only geographical information, no geological explanation. –> I agree. We added inferred fault lines and marked joint surfaces in the photographs. We extended the caption: “These photographs show the typical caps of the White Cedar Mesa sandstone, inferred faults (dashed lines) along vertical joint surfaces (colored in green) that are typical for this region. A joint set parallel to the faults is well visible. In (b) a block rotating into the graben due to reactivation of a joint by underlying faulting is shown in the west. “

19. Figure 2. Within the geological map of SE Utah there is a rectangle which indicates the investigated area. This rectangle is referred as Fig. 2, while it is the 3rd figure. Accordingly, change 2 with 3. –> Yes. Changed.

20. Figure 4. Add "number of data" in each rose-diagram pertaining to joints and faults measured in each 1 to 4 domain. Moreover, what the grey arrows represent in top left image? Explain in caption. –> Added number of data. Added “Gray arrows indicate the local direction of graben opening.” to the caption.

21. Figure 6. Would be possible to drawn in dotted lines some faults/fractures (inferred) responsible of the visible offsets? Is not possible that the "heave" parameter is overestimated due to preferential erosion of rocks along fractures? –> Indicating fault lines is tricky as the view direction s along-strike. I gave it a try, though, and added a corresponding comment to the caption. Overestimation of the heave due to erosion is of course possible. As neither the exact timing of the opening nor erosion rates are available I don’t see a way to verify the data or account for erosion. I added a sentence to section 7.2 to point towards this: “However, erosion at the fracture surfaces may lead to overestimation of the heave and result in underestimation of fault dips. For a detailed correction of erosion the exact timing of fracture opening and erosion rates over time would be needed which is beyond the scope of this work.”

22. Figure 7. In caption, what you exactly mean by "joint surfaces at faults"? please clarify. This joint shows plumose structures? –> Rephrased to: “Widely unweathered surfaces of joints that accommodated offset due to underlying faulting show no slickenlines or toolmarks at (a) northern Devil’s Pocket, (b) southern end of Devil’s Pocket,

(c) Devil’s Lane relay.” There were no plumose structures.

23. Figure 8. Font size in this figure is too small, and probably not visible in a printed version (at least mine). I suggest to enlarge font sizes up to 7 (minimum). In the western part of the section of GPR profile in "C" there are evidence of growth strata suggested by the green lines. Is this correct? any comment in the text? –> Regarding font size see next comment. Yes, it appears to me as well that at the western graben wall sediments show growth strata. It fits our model, as due to the dilatancy space is created and layers dip towards the open voids. I added notes pointing this out in the following sections: Section 6.1: “Both antennas image sediments dipping towards the graben bounding fault in form of growth strata over a length of 30 -40 m. . .”

Section 7.1: “Layers distinctly dipping towards the graben wall, partly in form of growth strata, require a depression into which they can dip. The GPR profile from Devil’s Lane (Fig. 8) shows an example of this. At both ends of the profile layers dip towards the respective graben wall with growth strata at the western graben wall. The profile from Devil’s Pocket (Fig. 11) partially shows this situation. Layers to the east of fault 1 dip towards the western graben wall and at fault 2 dip occurs from east and west.“

24. Figure 9, 10, 11. Font size in this figure is too small, and probably not visible in a printed version. –> We split the aerial photos from the radargrams and changed the orientation of the latter so they fill a whole page. Additionally, we enhanced the line drawings and changed the background of the drawings to transparent grayscale. This results in 3 more figures, but increases the quality.

Interactive comment on Solid Earth Discuss., 7, 1119, 2015.

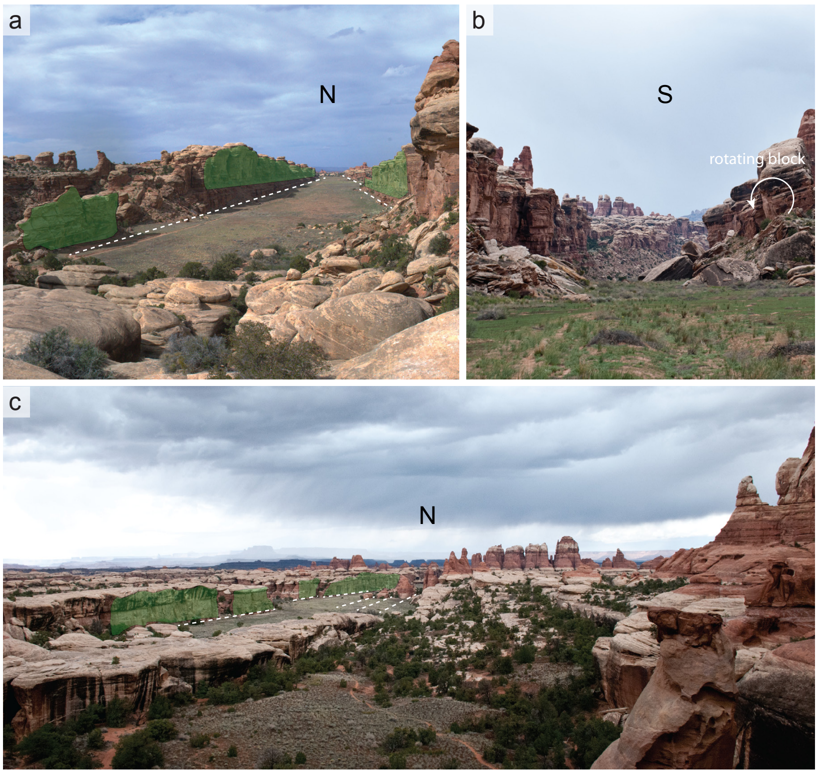

a
N
b
S
rotating block
c
N

Fig. 1.

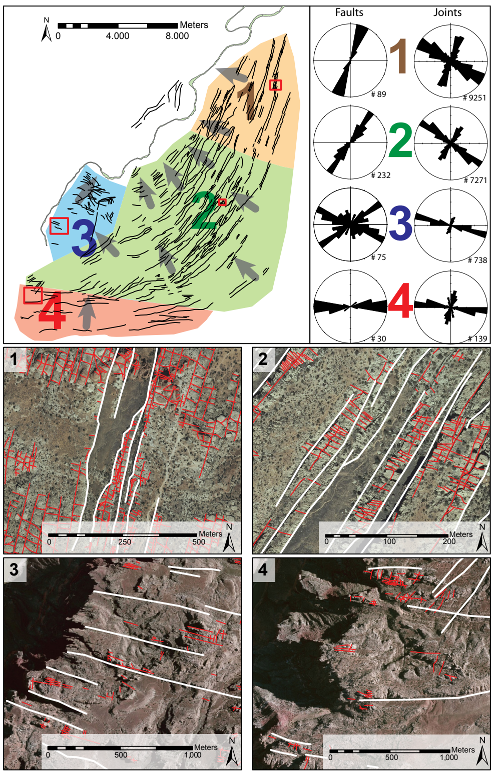

Faults
Joints
1
2
3
4
89
9251
232
7271
75
738
30
139
Meters
0
4.000
8.000
N

Fig. 2.

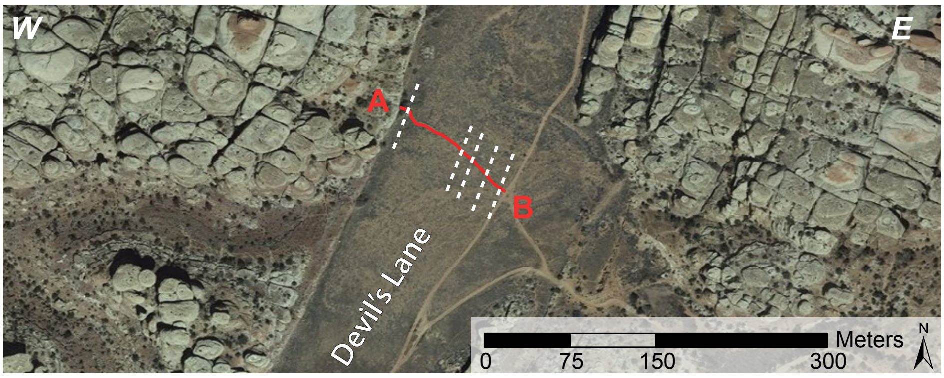

W
E
A
B
Devil's Lane
Meters
0
75
150
300
N

Fig. 3.

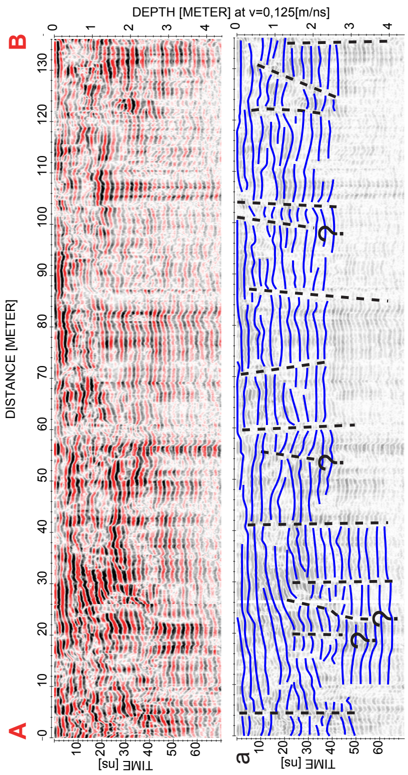
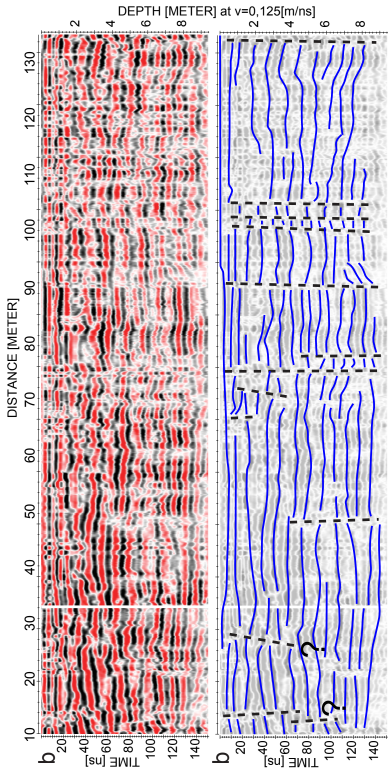
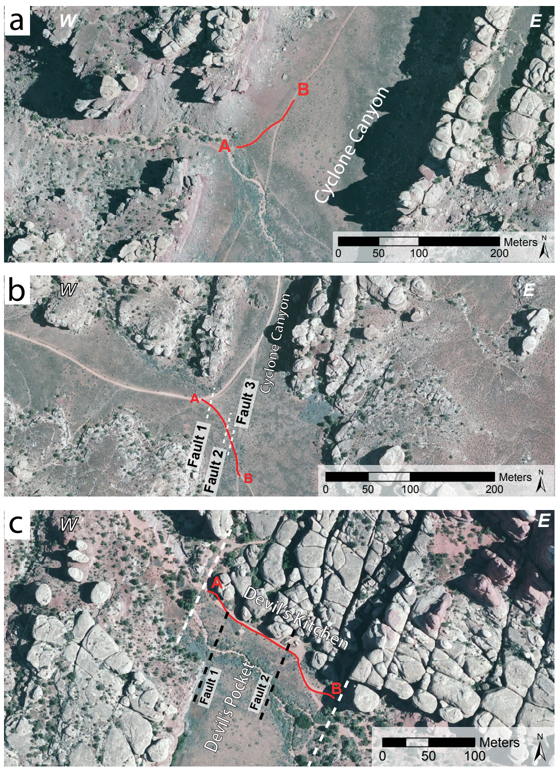

DEPTH [METER] at v=0,125[m/ns]
DISTANCE [METER]
TIME [ns]
TIME [ns]
A
B
a

Fig. 4.



DEPTH [METER] at v=0,125[m/ns]
DISTANCE [METER]
TIME [ns]
b

Fig. 5.



a
W
E
A
B
Cyclone Canyon
Meters
0
50
100
200
b
Fault 1
Fault 2
Fault 3
c
Devil's Kitchen
Devil's Pocket

Fig. 6.

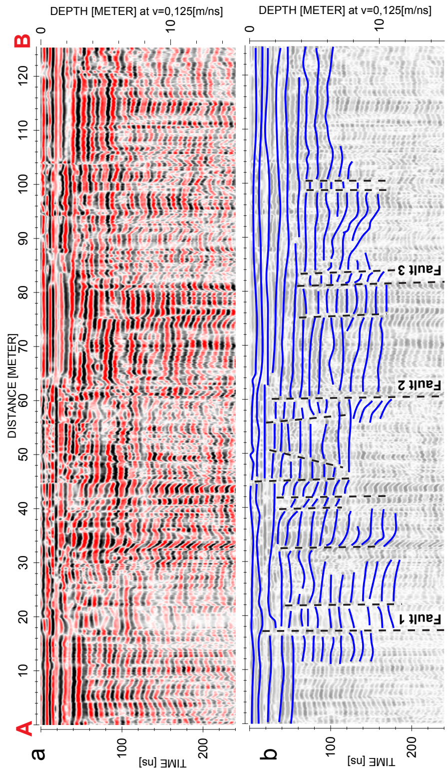

A
B
a
b
DEPTH [METER] at v=0,125[m/ns]
DISTANCE [METER]
TIME [ns]
Fault 1
Fault 2
Fault 3

Fig. 7.

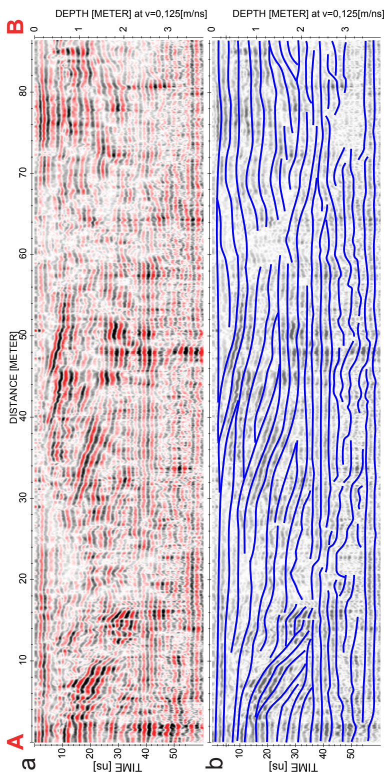
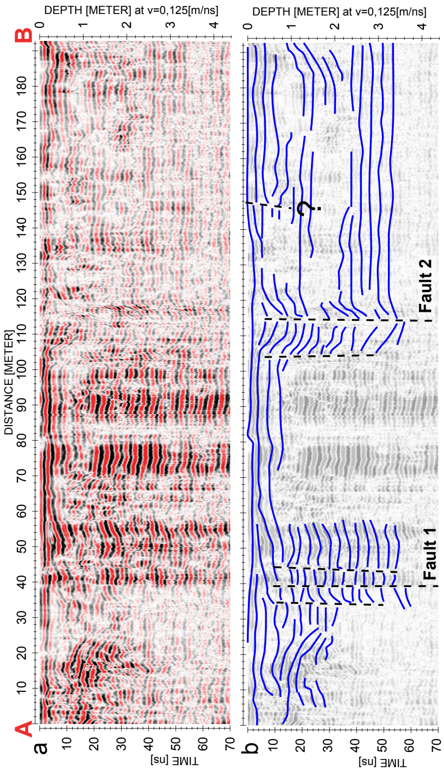
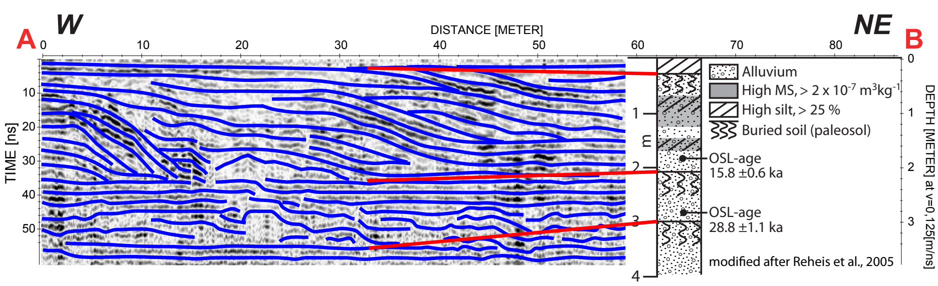

A
B
a
b
DEPTH [METER] at v=0,125[m/ns]
DISTANCE [METER]
TIME [ns]

Fig. 8.



A
B
a
b
DEPTH [METER] at v=0,125[m/ns]
DISTANCE [METER]
TIME [ns]
Fault 1
Fault 2
?

Fig. 9.



A
W
NE
B
DISTANCE [METER]
TIME [ns]
DEPTH [METER] at v=0,125[m/ns]
m
Alluvium
High MS, > 2 x 10-7 m3kg-1
High silt, > 25 %
Buried soil (paleosol)
OSL-age
15.8 ±0.6 ka
OSL-age
28.8 ±1.1 ka
modified after Reheis et al., 2005

Fig. 10.