Clim. Past Discuss.,
doi:10.5194/cp-2016-3-RC1, 2016

Climate of the Past
Discussions

Interactive comment on "An extended history of high-amplitude lake-level changes in tectonically active Lake Issyk-Kul (Kyrgyzstan), as revealed by high-resolution seismic reflection data" *by* A. C. Gebhardt et al.

Anonymous Referee #1

Received and published: 19 February 2016

The manuscript 'An extended history of high-amplitude lake-level changes in tectonically active Lake Issyk-Kul (Kyrgyzstan), as revealed by high-resolution seismic reflection data' by Gebhardt et al presents a detailed and interesting analysis of lake level fluctuations of Lake Issyk-Kul and links the fluctuations to past changes in the atmospheric circulation pattern. This is an interesting aspect because long climate archives from the investigated area are sparse. Unfortunately, no age information are available, which does not allow linking the circulation patterns to specific periods. However, the conclusion that a cyclic pattern caused by changes in the atmospheric circulation pattern exists, is significant and should be published. Hence, I strongly recommend

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publication of this manuscript. However, several modifications are needed prior to final publication. My main concern is the poor data description and documentation. Only one profile crossing deltaic features is shown. The reconstruction of the lake level fluctuations is difficult to follow, as many deltaic sequences are not shown on this profile. I am aware that not all deltas can be shown but it would be good to present some more data, which would at least proof that structures are similar at the western and eastern end of the lake. This is mentioned in the manuscript but not supported by any presented data. These profiles should be described first, which may then act as basis for the interpretation. I am not a native English speaker; hence, I have not made any language corrections.

My main general points of critics are: 1) Show more data and give a better general description of the data. The detailed description of the stratigraphic units as presented now is not really a description. This is more a stratigraphic interpretation, which is not based on a proper description. Fig. 4 can be used for a general description but this figure is even not referenced in the text at all. I suggest to show one profile from the eastern and western parts, each. These profiles should be described first. Explain how you define the stratigraphic sequences in general. Point to the similarities (and diffeences) between the eastern and western area. Mark all the deltaic sequences.

2) Carefully check the usage of terminology for the seismic stratigraphic description/interpretation. E.g., you write that you have erosion at the upper and lower boundary of a unit. Per definition, an erosional truncation is termination of reflectors against an upper boundary caused by erosion. It may well be that both boundaries show erosional features, but then you need to carefully describe, that you have erosional truncation of the unit below the sequence boundary and downlap/baselap/onlap/conformity above the boundary. When describing unconformities, always describe termination above and below the unconformity.

3) You define the topset-foreset roll-over point as a proxy for the lake level at the time of its formation. This is a valid approach. Based on the distribution of the clinoforms,

you can conclude that you had rapid lake –level changes. However, I do not agree that all clinoforms/deltas have been deposited at times of lake-level stillstands. Some of the clinoforms look like forced regression-system tracts, indicating a falling lake level. Others may show some aggradational patterns indicating a slow lake level rise. I agree that the clinoforms indicate relatively constant lake levels or only small changes compared to the rapid changes documented by the different locations of the delataic sequences.

4) Distribution of delta sequences. In order to reconstruct the lake level fluctuations, you use many delta-sequences not shown on your seismic example. You state that most delta sequences have been identified on both sides of the lake but this is not documented. You even do not mark all delta sequences identified on the presented line (Figs 4-7, you list much more in Table 1). Mark them. Why do you have such an incomplete record of deltas on single lines? I assume that this is caused by changing points of sediment input to the lake (as partly discussed in the manuscript) but you should mention this somewhere (distribution of deltas and what causes lateral shifts of deltas).

5) Good overview map is missing showing the general location of the lake and its tectonic setting (I doubt that most people would be able to place the lake on a world map). Many locations are given in the text, which are not shown on any figure. Link between text and figures should be improved.

6) It would be nice to include a small outlook in the conclusions. You clearly state that it would be important to date the delta features in order to establish a solid link between climate and deposited sequences. Come back to this point in the conclusion.

Below you find more specific comments for each chapter and the figures. Good luck!

Below you find more specific comments for each chapter and the figures. Good luck!

Specific comments:

Abstract:

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P1, Line 18: Change ‘identify’ to ‘reconstruct’

P1, Line 19: See general comment concerning lake level still stands. Lake level was relatively constant compared to quick fluctuations in other periods.

P1, Line 21: Delete ‘during the past’

Introduction P2, Line 8: Summarize the previous statements. Something like. The examples demonstrate that lake level fluctuations may document climate change (regional and/or global), changes in basins morphology and barriers, as well as tectonic and volcanic forcing.

P2, Line 9: Refer to figure showing the general location of Lake Issyk-Kul in a broad context. Such a figure is missing. This figure should also include all regional features/locations you mention in the text.

P2, Line 14, 15. Split last sentence to two sentences.

Study area

P2, Line 18-22: Make sure that all locations are shown on a good overview map.

P3, Line 2: Refer to your figures. The link between text and figures should be improved.

P3, Lines 2 – 5: Split sentence to two sentences.

P3, Line 8: Explain how the shelf is separated from the slope.

P3, Line 20: Was the lake ice-covered during the glacials? Did glaciers cover the shelf? Any information?

P5, Line 3: Show Tien Shan Mountains on overview map. Also true for other locations and not mentioned again in this review. Check carefully.

P5, Line 14, 15: Split to two sentences.

Data acquisition and processing

P6, Line 10-14: This statement should be supported by a figure (in the result section).

Results and Interpretation

P6, Line 22: Penetration of 375 m is not documented on any figure.

P6, Line 26: The MTF should be marked on an overview figure.

P7, Line 2: Correct ‘becaoem’

P7, Line 3: ‘The anticline’ has not been introduced before. Some information is needed.

P7, Line 6: I agree that deformation is still active but I cannot see that the uppermost layers still display a slight dip angle.

P7, Line 9: For which period are the sedimentation rates valid? Are they only valid for the Holocene as they are based on short cores? Can you really use them as mean rate for calculating age? You partly comment on this further down but I would expect significant variations of sedimentation rate between humid and arid climatic phases.

P7, Line 19/20: Are these anticlines visible on your data. Not clear. Make clear what results are based on your data.

P8; Line 23: I cannot see the onlap on the figure.

P9, Line 19: Change ‘forming’ to ‘formation’

P9, Line 22 and following: How is the upper boundary of this unit defined?

P10, Line 1-5: Give reference to figures. On Fig 5b, no delta is marked despite the fact that Tab. 1 suggests that delataic sequences 7.1., 7.2 and 7.3 should be visible. I may see one delta but it remains unclear where you interpret the other deltas. Mark all interpreted deltas very clearly on the figure.

P10, Line 8: A sequence may have erosional truncation as upper boundary but not as lower boundary. Hence, the statement that the sequence exhibits erosive upper and lower boundaries is not precise. As for sequence 7, no deltas are marked on Fig. 5 for sequence 6.

P10, Line 12 and following: When describing unconformities, always describe termination above and below the unconformity. The upper boundary of unit 6 shows erosional truncation. I cannot judge the characteristics of the lower boundary of sequence 5. Check very carefully for the description of all sequences. I will not comment on this for the other units. For delta 5.2. I do not see details but it seems to be a forced regression and not a real stillstand.

P10, Line 21 and following: How do you explain the pronounced step in the morphology of the upper boundary of Sequence 3/4?

P11, Line 8: Sequence 3 may fill erosional features but the lower boundary is not erosive. It is the upper boundary of the underlying sequence. Check also for other sequences.

P11, Line 26: This is a correct description (It lies above an erosional unconformity and sediments fill the channels).

P12, Line 3: I assume it should be Sequence 1 (and not 2)

Discussion P13, L3: See general comment concerning lake-level stillstands.

P13, Line 28, Boom gorge has not been introduced before. Refer to Fig. 1, where it is shown.

P15, .Line 10: See previous comment about the anticlines (P7, Line3).

P15, Line 25: What do you mean with ‘May have influenced’ Again, no detailed information about the anticlines is given in the manuscript. The anticlines are not critical for the manuscript but you draw conclusions based on the anticlines without a real presentation of these anticlines.

P16, L1-5: see general comments. Should be illustrated in a figure.

P16, Line 22 – 28: This has already been partly discussed in the previous section but it also partly contradicts the previous section, where it is stated that subaerially exposed terraces may indicate lake levels 100 m higher than present. Clarify.

P18, Line 3, 4: Is there a reason that you are nor listing rainfall/direct precipitation?

Page 18, Line 15: See general comments about lake-level stillstands.

Conclusions

P19, Line 16: Change to 'each stratigraphic section contains at least 2 . . .'

Figures:

Fig. 1: An overview map showing the general location of the lake and regional features is missing. Colour code would be useful. The profiles shown in the manuscript should be marked much clearer (direct reference to the Figure).

Fig. 2: Depth below lake floor scale is a bit confusing. How have you set the zero point? I would recommend changing the scale to depth beneath present lake level.

Fig. 3: OK. If you show a profile from the western shelf, you should mark some of the prominent deltas identified on both profiles.

Figs. 4-7: See comments above. You need to mark all deltas identified on this figure. Much more delta features than marked on the figure are listed in Table 1 for this profile. There is no reference to Fig. 4 in the text.

Fig. 8: OK

Interactive comment on Clim. Past Discuss., doi:10.5194/cp-2016-3, 2016.

Clim. Past Discuss.,
doi:10.5194/cp-2016-3-RC2, 2016

Climate of the Past
Discussions

Interactive comment on "An extended history of high-amplitude lake-level changes in tectonically active Lake Issyk-Kul (Kyrgyzstan), as revealed by high-resolution seismic reflection data" *by* A. C. Gebhardt et al.

Anonymous Referee #2

Received and published: 20 February 2016

General comments (comment refer to page number/line number where indicated)

This is a well presented and scientifically significant study that is very appropriate to be published in the 'Climate of the Past' journal. The interpretations are sound, well-based on data and provide new insights into a highly dynamic paleoclimate regime in Central Asia. Eventhough the data do unfortunately not allow a dating of the presented wet-dry climate cycles ('a reason to drill the lake'), the presentation of these patterns nevertheless provide novel data that are absolutely worth to be reported.

My main concern refers to limited amount of data shown as figures: The figures (beau-

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tifully crafted by the way, a pleasure to look at) focus basically on a single seismic line. The line is spectacular indeed, the seismic stratigraphic interpretation sound and somehow textbook-style, but that same seismic line is shown on 4 full pages with different levels of annotations, way to much. There is no need to show every infilling step of each seismic sequence, the only added value comes in Figs. 6b and 7b, where eroded sequences are reconstructed, but that can also go in a smaller extra figure. What is needed much more are more shown examples. I am curious how representative this singled-out seismic line really is. In fact, many of the discussed delta lobes are not presented but provide crucial elements of the lake-level reconstruction. As reader, I need to see at least 2-3 more examples of seismic lines from other areas of the lake (for instance also the Western delta area), i.e. more of the sequence stratigraphic architecture. This can be done at 'no cost', as Figs. 4-7 can be reduced to one full page, there is plenty of space available. Having said this, I also would appreciate with new figures or maybe also in map view what is really meant with the concept of 'delta lobes' and how they are distributed on both sides of the elongated lake. These lobes, and their vertical and lateral stacking pattern is the key to reconstruct the details of the lake-level curve, so these data are crucial but yet not presented.

I am intrigued by the fact that all sequences and their boundaries on the shown seismic line display a gentle basinward dip. Is this a pattern on all seismic sections, also in the West? Or is this formed by a general forced regressional pattern with falling lake level upon delta progradation? But why is there never an still stand (horizontal progradation) or even an aggradation of a delta sequence upon a gently rising lake level? Is this a function of tectonic subsidence or tilting?

I am also wondering why sequence 5 is not subdivided in two main sequences (currently called subsequences 5.1 and 5.2), as they are separated by a very clear unconformity. What defines the hierarchy of the sequences? On contrast, I am not fully convinced that sequences 2.1 and 2.2 represent clearly two pulses or whether they form a transitional package without major unconformity in-between them. Both of these issues are hard to track, as one shown seismic line alone from the shelf is not sufficient.

Discussion on p.14 about deltas 1.1-1.6 is hard to follow. I cannot judge on he basis of the limited shown data whether 1.1-1.6 is indeed in chronologic order or whether lake level plays as a 'jojo' reshuffling the lobes in maybe a different order? Moreover, the arguments presented for an uplifted nature of the subaerially exposed terraces are a bit weak, I am somehow not convinced in this matter.

Further comments

The English language can be improved in some of the sections....maybe have an English native speaker go through it.

Shorten title by deleting 'An extended history of', just start with 'High-amplitude lake-level fluctuations of....'

1/21: delete one of the two 'past'

1/22: ....from the Mongolian steppe blocking the mid-latitude Westerly's.

2/6: ... AND thermal expansion...

2/6: HenCe (spell checker!!)

2/6: no comma after curve

2/10: Three 'large' on one line, too much!

2/25: The quoted publication (Anselmetti et al., 2006) initially stated indeed glacial/interglacial cycles, which after drilling turned out to be stadial/interstadials, I would change to:....were correlated to wet-dry paleoclimate patterns with lowstands during the stadials and highstands during the interstadial periods (Hodell et al., 2008, Quaternary Science Reviews 27, 1152-1165)

3/2: Lake-level changes as large as 170 m have on one hand been attributed to....

3/5: Awkward short sentences, change to: The impact crater of Lake Bosumtwi

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(Ghana) is....

3/8: ...is purely driven by the evaporation/precipitation ratio.....

3/9: Lake Issyk-Kul, subject of this study, is....

3/21: Figure 1 shows these mountains exactly reversed (N vs. S). Which one is correct?

4/4:' ...and by steep...' poor English, unclear what is meant, reword or make 2 sentences

4/7: can this 110 m depth transition be marked on Fig. 1

4/21: thRough

4/22: Surface-water temperature...

4/26: This is a hydrologically 'bold' statement....any references?

5/16: 2004 is not 'recently'

6/14: avoid one-sentence paragraphs.

Fig. 2: I note a somehow prominent change in basinal sediment geometry (draping vs. filling) at ∼1.1 s twt in the middle of the profile, in particular when correlating to the right side of the figure...is this worth to be discussed?

Make sure final Fig. 2 has sufficient resolution, I have problems seeing for instance the mass-transport deposit.

7/2: became (Spell checker!!)

7/4: Which anticline? Has no been mentioned before

7/4:...dip angle OF the strata....

7/12: two 'however' within 4 words:-(

7/12: But on the figure I only see ca. 200 m of sediments.....the authors report partly 370 m sediment thickness but no evidence is shown.

7/20-25: The longer anticline still is visible on lake floor, correct? It looks like a dipping anticline (towards SW), is that worth to be mentioned? Are the two anticlines aligned in an 'en echelon' pattern? Are these anticlines really tectonic in nature of simply a draping remnant of an underlying basement high?

8/7 and ff.: Use throughout the manuscript 'reflections' instead of 'reflectors'. On seismic data, you only see reflections. Reflectors (=impedance change in the sediment record) cannot have amplitudes.

Seismic facies 3, here the term 'retrogradation' may also be used, or a 'backstepping' delta.

13/6: ...riseS...

13/9:..mainly in the shallower parts of the lake

14/7: this 'some' here and in numerous other places in the text is not elegant: use 'ca.' or even better a '$\sim$'.

14/25: I don't agree with the mentioning of the outflow here: The balance is made by precipitation/inflow and evaporation only (maybe subsurface outflows). The outflow is a result of positive hydrologic balance, thus the difference in the balance, then the lake level is geomorphologically fixed and the system open. If the balance is negative, then the outflow will be zero and the basin closed.

15/10: No one-sentence paragraph

15/20ff: Why don't the authors call the system a half-graben? with the main border fault in the south? It has all indications, correct?

Time constrains on 15/20: suddenly the term 1 Ma pops up? What is the origin? based upon? No age data at all has been presented before!

Discussion on highstands is necessary but what about tectonics as regulator of outflow level? 16/25 ff: It also could suggest that the outflowing area subsided relative to the lake, lowering the topographic outflow point.

The last figure and the general lake-level reconstruction based on ’shallow’ sedimentary sequences is highly reminiscent to another study in a Patagonian hydrologically closed lake where the first- and one co-author were also co-authoring: I would also quote this study, as some of the concepts match very nicely (Anselmetti et al., 2009, Sedimentology 56, 873-892)

One should remove the thick red and blue arrows on last figure and make lake-level lines thicker, that will be much better to visualize these impressive lake-level variations,

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Interactive comment on Clim. Past Discuss., doi:10.5194/cp-2016-3, 2016.

Clim. Past Discuss.,
doi:10.5194/cp-2016-3-RC3, 2016

Climate of the Past
Discussions

Interactive comment on "An extended history of high-amplitude lake-level changes in tectonically active Lake Issyk-Kul (Kyrgyzstan), as revealed by high-resolution seismic reflection data" *by* A. C. Gebhardt et al.

Anonymous Referee #3

Received and published: 22 February 2016

Dear author, I have completed my review of "An extended history of high-amplitude lake-level changes in tectonically active Lake Issyk-Kul (Kyrgyzstan), as revealed by high-resolution seismic reflection data" by Gebhardt et al. The manuscript presents high-resolution sparker profiles from Lake Issyk-Kul and has the potential for being a broad and useful study. I personally enjoyed reading it and highly recommend for its publication. Though, it will need to undergo major revisions before it is acceptable for publication. In my review, I outline both major critiques and minor points in the lists below.

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Major Points:

-I strongly suggest the authors to present more seismic profiles from different parts of the lake; this is indeed lacking in the current manuscript. In particular, profiles showing deltas from the western margin would be great in order to compare their internal/external structure with the ones from eastern part of the lake.

-Significant lacking of citations in the results part. The authors, most of the times, do not cite or refer figures in the text. Sometimes, the figures are not large enough to see points menntioned in the text, for instance erosional boundaries, delta lobes. Hence, as a reader it is rather difficult to judge the interpretation.

-Would it be possible to correlate stratigraphic boundaries towards the deeper parts of the lake? I can see that deep lake sediments are characterized by alternating high- and low-amplitude seismic reflections which most likely reflect transgression and regression periods.

-I am also missing isopach or isochron maps of seismic units in order to understand their thickness variations and thus the source regions through lake evolution. If this is not applicable or doable, it is better to mention the average thickness of individual units and possible source regions in the text.

- I suggest the authors to make a new basemap and draw lakeward boundary of the deltas (color-coded) in order to see their lateral extent along the western and eastern shelves. The distribution of sublacustrine channels can also be superimposed on this map.

-The authors presents and discuss structural setting of the lake, however I do not see any structural map showing faults, anticlines, or synclines throughout the lake as well as its surroundings. I see several seismic profiles crossing the anticline structures on the base map but neither of them is shown. It is worth to discuss the relative timing of these structures based on thickness variations of overlying/underlying sediments. Also a normal fault in the southern part of Profile ik01 (Fig. 2) should be shown.

-I suggest the authors make schematic diagrams (with scale) from East to West showing the formation of deltas throughout the lake formation. The former lake levels should be indicated. This would definitely improve the quality of the manuscript.

Line points:

-Page 6, Line 24. "..presence of a series of faults.." It would be better to show these faults on a map.

-Page 6, Line 25-26. Please locate the "Main Terskey Fault (MTF)" on a map.

-Page 7, Line 2. Change "becaoem" to "became " and "Miocene" to "Miocene"

-Page 7, Line 12. Modify so that it reads, "..However, it is quite likely that . . ."

-Page 7, Line 18-19. "In the southeastern part of the lake, the strata are not inclined as would be expected in this asymmetric basin". Please refer to figure or show a seismic section. I can see that there are various seismic profiles traversing these anticline structures.

Page 7, Line 23-24. "Both anticlines are progressively buried by younger sediments, and the southern one is meanwhile completely leveled by sediments." Please show a seismic section as I cannot confirm whether they are buried or leveled by sediments.

Page 8, Section 4.2 Facies Types. I suggest changing "Facies types" as "Seismic Facies" and the "Facies I" as "Seismic Facies 1 (SF1)". It is easier for descriptions. It is also better to formulate as "SF1 is characterized by. . . " than "this facies type is characterized. . ."

Page 8, Line 11. Clinoforms should be better illustrated; topsets-foresets transitions (if they exist) are not noticeable on the presented seismic profiles. I propose to the authors to add a figure as an example of interpreted delta (for instance, immediately below Fig. 3a; (3b, interpreted section of 3a) in which reflections of topset, foreset and bottomset are pointed.

Page 9, Lines 1-2. “Facies IV may be interpreted as former delta sediments that have been affected by post-depositional processes (e.g. sediment remobilization, slumping, liquefaction) that caused them to loose their internal structure”. They are indeed former delta deposits but I am not sure such reflection configuration was caused by slumping etc. Looking at reflections within Sequences 3/4 in Fig. 4, as a whole package, I do not think it has something to do with slump deposits. Would it be possible that such reflections were due to coarse-grained sediments resulted from rapid loading of rivers?

Page 9, Line 18-19. “The topset-foreset roll-over point is considered as a proxy for the lake level at the time of its forming”. Please give a reference.

Page 9, Line 23. Modify so that it reads, “Sequence 7 (S7) is the. . .” In the following parts you can shorten its name as “S7” instead of “Sequence 7”.

Page 9, Line 16. Please delete “lacustrine”

Page 10, Line 2. “..Some of these occur only in the western delta area (7.5, 7.4)” Please refer or show a seismic section.

Page 10, Line 7. “Sequence 6 is clearly visible both on the western and eastern delta areas.” Please refer to Fig.

Page 10 , Line 8. “. . . rather thin. . .” How much?

Page 10, Line 9. “. . .. delta lobes could be identified at 461 (no. 6.1) and 361 m bll (6.2).” Could you please label these delta lobes in the seismic sections?

Page 10, Line 13. “Sequence 5 is overlaying sequence 6 with an erosional boundary in between (Fig. xx??).

Page 10, Line 14-15. “The bathymetrically higher delta 5.1 exhibits extensive erosion (Fig. 6b)”. I am looking at this figure and it is almost impossible to see the erosional surface. I suggest the authors to show close-up sections to show these features.

Page 10, Line 21. Modify so that it reads, “Sequence 4 overlies . . .”

Page 10, Line 24-25. Modify so that it reads, “In Sequence 4, the delta lobes are characterized by predominantly SF4, but. . .”

Page 10, Line 26. Change “well-layered” into “well-stratified”. Please also make the colors of sequences more transparent so that the internal reflections can be seen clearly.

Page 11, Lines 1-2. “Three delta lobes were identified: the oldest (4.1) at ca. 319 m bll, followed by a delta (4.2) at approximately 250 m bll and a third, younger (4.3), at 397 m bll.” Where are they in the seismic section? Please mark the locations of these deltas.

Page 11, Line 6. “ Sequence 3 could only be clearly identified in the western delta areas;. . .” Please show a seismic profile from the western area which clearly depicts S3.

Page 11, Lines 8-9. “In the western delta complex, Sequence 3 is characterized by a lower boundary that was partially erosive into the underlying sediments but grades into a correlative conformity in other places.” I cannot judge this interpretation as I do not see any figure showing this relationship.

Page 13, Lines 4-5. Instead of using lake level decrease and increase, how about using regression and transgression?

Page 14, Line 3. Change “Subaquatic channels” into “ Sublacustrine channels”

Page 15, Line 18. “. . .subsidence seems to have been relatively constant through time.” Can you quantify the fault activity by looking at thickness variations towards it?

Figure Captions Overall, the figure captions should be improved.

Figures

Fig. 1. Please add an inset map showing large areas of the regions. With the current

map, I cannot say where the Lake Issyk-Kul is located. The depth color bar is missing as well. What about the bathymetry of the lake reconstructed from seismic reflection profiles?

Fig. 2. I suggest including vertical exaggeration for all seismic profiles. Locate the fault on the southern end of the profile. Can you please enlarge the MTDs?

Fig. 3. Please add vertical and horizontal scales.

Fig. 4. It would also be better to give names for the sequence boundaries, such as Sequence boundary 1 (SB1) to SB7. But it is your choice.

Fig. 5. Please switch the Figure 5a and 5b. It should be displayed in an order and should start from Sequence 7. Please do this for the following figures.

Regards

Interactive comment on Clim. Past Discuss., doi:10.5194/cp-2016-3, 2016.

Dear Editor,

I hereby comment the reviewer's comments on my manuscript and outline the changes that were made to the manuscript before resubmission.

Review #1

1) Show more data and give a better general description of the data…
First of all, I added another profile from the western delta to show how similar the profiles are from both ends of the lake. All deltas visible on the two profiles were labeled. Second, description of seismic facies types was improved, and a chapter containing visual description of the three profiles shown was added. Third, a paragraph as well as a figure on the detection of the sequence boundary was added for better understanding how this study was carried out. Fourth, the description of the sequences was kept in the text, but improved, and supported by the points mentioned before, this has lead to a significantly improved description of data.

2) Usage of terminology
Usage of terminology was fully checked and improved throughout the manuscript.
3) Clinoforms deposited not only during stillstands, but also during times of relatively constant lake level
Yes, I agree. This was mentioned in the text.
4) Distribution of delta sequences
In the two profiles from the western and eastern deltas, respectively, all deltas encountered were labeled in consistency with table 1. I also added thoughts on differential sediment supply leading to formation or non-formation of deltas to the manuscript.
5) General map
The regional map in fig. 1 was improved, and an inset showing the location of the lake in its larger setting was added. Geographical names used in the text were added.
6) Outlook
I added a small outlook in the conclusions, stating that only drilling could solve the problem of dating sequences.

Specific comments: All comments were included/text and figures were changed accordingly except of:
P6, Line 22: Indeed, I do not show seismic data down to 375 m. It is not worth changing the seismic figures (information in greater depths as shown in the current figures is sparse, hence showing this part of the profile would only make the resolution of the profiles worse without adding much information). I deleted this statement, it is not crucial for the interpretation.
P7, Line 3; P7, Lines 19/20; P15, Line 10; P15, Line 25: The anticline structure is not crucial for interpretation of lake-level changes in this lake. All tectonic features are subject of a second paper by a student that is currently under work. In order not to jeopardize the student's work, I did not deepen unnecessarily the discussion on tectonic features but just deleted these parts of the text.

Review #2:

Similar to Review #1, additional seismic data is requested by deleting some of the old figures instead. I added one profile from the western delta and labeled all deltas, additionally a map of sequence thickness was added for better visualization of the delta structure described in the text. I did not add a figure explaining the concepts of delta reconstruction – this was not requested by the other reviewers either – but improved the delta zoom-in in the figure on seismic facies, where topsets, foresets and bottomsets were labeled.

All seismic profiles indeed show a gentle basinward dip, similarly on both the western and eastern region. This is now more clearly visible from the second seismic profile that was shown in the manuscript. The reason for this, however, remains unclear. Tectonic subsidence or tilting seems to take place in a north-south direction (shown and discussed on profile ik01) but is unlikely in west-east direction, as profiles from both sides dip towards the lake center.

Sequence 5 was not subdivided into two main sequences as it was interpreted as representing falling lake level. Only where the lower delta was formed, the topsets form onlaps onto the lower strata within the sequence. Considering the newly shown profile from the western delta we think that this becomes clearer. Also for deltas 2.2 and 2.1 it should now be more obvious that these are two different pulses.

I agree that from the previously shown profile it remains unclear if the deltas 1.1 to 1.6 are single deltas. With the new profile it becomes clearer that at least deltas 1.6 and 1.3 were independently built up. Discussion on the subaerially exposed terraces was improved and corrected. In the previous version the 30 m of water depth above the currently formed delta was added to the terrace heights, which was simply wrong. The exposed terraces are strand terraces, not delta lobes. This should now be much more understandable.

Further comments:
All further smaller comments were included and text was changed accordingly. The quote "Anselmetti et al 2006" was replaced and the text adapted. The two mountain chains were mentioned in wrong order in the manuscript before, this was changed. Anything on the anticline was deleted from the text, see comment to review #1. Time constrains on 15/20: The term 1 Ma was not changed in a previous version; it should have been the 800 ka that were estimated from sedimentation rates. This value however is absolutely vage and not needed in this context – it was simply deleted. Laguna Potrok Aike in Patagonia was added to the introduction, including a reference to Anselmetti et al. 2009 as requested.
Not included/changed:
Fig. 2: prominent change in basinal geology at a depth of 1.1 s in profile ik01 – this is not crucial for the current manuscript on lake-level change, but will be discussed in the student's tectonic paper.
14/25: I do not agree that the outflow should not be mentioned here. The lake is located in a tectonic setting, hence a sudden change in outflow by blocking (e.g. by a landslide or another tectonic event) has a direct influence on the hydrologic balance, which is not only driven by E/P but also directly influenced by a sudden change in water volume.
15/20ff: My co-author Ed Sobel is carrying out tectonic work in this region. He did not agree with the term halfgraben for the lake basin that I used in a former version of this manuscript. This term will hence not be used in the revised version.

Review #2:

Major points:
An additional profile from the western part of the lake is now shown, interpreted and labeled similar to the one from the eastern profile. Seismic facies description is also improved, and seismic details allow now to see how sequence boundaries were depicted.
Figures are now more often cited in the results part.
Correlation of stratigraphic boundaries towards the deeper part of the lake is impossible. On one hand, most profiles stop before they reach the lake floor (both figures 5 and 6 show the entire length of the profile). On the other hand, seismic reflections thin out towards the foot of the slope, making it impossible to follow them down into the deeper parts of the lake. It is also likely that the more central part of the lake is strongly dominated by turbidites. The characteristic alternating high- and low-amplitude reflections therefore more likely represent turbidite sequences than the transgressional and regressional periods.
I added a map of sequence thickness, but discussed my concerns about direct interpretation as already outlined in my answer during the open review process. Fig. 8 shows clearly that large

parts of the initial sequences were eroded, and depot centers during deposition are not necessarily reflected by thick sediment packages. In turn, apparent depot centers in the thickness map are not necessarily reflecting the delta lobes, but likely also infill of erosional features into the underlying sequence. In addition, spacing of the seismic lines is in the order of 1-2 km, and in a highly dynamic system such as a delta, this spacing is too big to reliably generate maps (and hence cell size during gridding had to be chosen at 500 m to get reasonable spatial coverage). Having said this, I did also not add a map showing the lakeward boundaries of the deltas.

Structural/tectonic information that was not crucial for discussion of lake-level changes was removed from the manuscript and will be presented in more detail in a subsequent manuscript currently prepared by a student.

Schematic diagram from east to west – I tried several times to draw this but was not successful. I would have liked to show lake evolution as nicely as e.g. in Cukur et al., 2014, their fig. 8 (Cukur et al., 2014: Water level changes in Lake Van, Turkey, during the past ca. 600 ka: climatic, volcanic, and tectonic controls. J Paleolimnol 52:201-214). Unfortunately, in our case (a) we do not have profiles from the eastern delta that reach down to the lake floor. (b) We do not have profiles that cross the lake from the western to the eastern delta. And (c) sequences 7 to 2 were eroded significantly. Additionally, timing of the subaerially exposed terraces that likely form the uppermost level of one of the sequences is unclear. We also do not know if e.g. a higher lake level was eroded (erosional discordances in between sequences). And furthermore profiles do not reach the most proximal part of the lake where another delta lobe is clearly visible from bathymetry, and where older delta lobes may be buried. Drawing such a schematic diagram at present would be highly speculative. This should be postponed until better seismic data and groundtruthing by drilling is available.

Minor points:

All suggestions were included/text and figures changed accordingly. Sequence names were shortened to S1 to S7, and also seismic facies types were changed to SF 1 to SF 4. Deltas in the profiles shown were labeled. Vertical exaggeration was calculated for all seismic profiles and included. Vertical and horizontal scales were added to the figure with the seismic facies types. Color bar was added to fig. 1, and reference to the digital elevation model is given. The only comments that were not included where those on tectonic content, e.g. the anticline structure, see comments to review #1.

List of major changes:

- All figures were improved, a seismic profile from the western delta was added and some redundant figures from the eastern delta were removed
- A figure showing sequence thicknesses was added as well
- Figure 1 now shows the geographic names mentioned in the text
- Seismic profiles are labeled with all deltas visible, in accordance with table 1
- The Results & Interpretation chapter was partly rewritten and reorganized: (a) seismic facies analysis was rewritten and improved. (b) a small subchapter on the identification of stratigraphic sequences was added. (c) description of the seismic profiles was added. (d) description and interpretation of stratigraphic sequences was improved.

The comments by the three anonymous reviewers were very helpful and significantly increased the quality of the manuscript. I would be pleased if you could consider the manuscript in its revised form for publication.

Best regards,

Catalina Gebhardt

High-amplitude lake-level changes in tectonically active Lake Issyk-Kul (Kyrgyzstan) revealed by high-resolution seismic reflection data

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A. C. Gebhardt[1*], Lieven Naudts[2,3], Lies De Mol[3], Jan Klerkx[4], Kanatbek Abdrakhmatov[5], Edward R. Sobel[6], M. De Batist[3]

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Abstract. A total of 84 seismic profiles mainly from the western and eastern deltas of Lake Issyk-Kul were used to identify lake-level changes. Seven stratigraphic sequences were reconstructed each containing a series of delta lobes that were formed during former lake-level stillstands or during slow lake-level increase or decrease. Lake-level has experienced at least four cycles of stepwise fall and rise of 400 m or more. These fluctuations were mainly caused by past changes in the atmospheric circulation pattern. During periods of low lake levels, the Siberian High likely was strong, bringing dry air masses from the Mongolian steppe blocking the mid-latitude Westerlies. During periods of high lake levels, the Siberian High must have been weaker or displaced, and the mid-latitude Westerlies could bring moister air masses from the Mediterranean and North Atlantic regions.

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1 Introduction

In the marine environment, global eustatic sea-level curves are traditionally used to reconstruct the amount of water stored on continents and in the oceans (e.g., Haq et al., 1987; Fleming et al., 1998; Lambeck et al., 2014; Dutton et al., 2015). Sea level is a good measure for the volume of water stored as ice for shorter time periods during which other factors such as tectonic subsidence, seafloor spreading, and thermal expansion can be ignored. Hence, sea-level curves can be used to reconstruct glacial/interglacial cycles on a global scale. During the Last Glacial Maximum, for example, the eustatic sea level was some 125 to 135 m lower than today (e.g., Fleming et al., 1998; Lambeck et al., 2014).

Lake-level curves, in contrast, often store a more local signal that might or might not be controlled by glacial/interglacial cycles. Many lakes with large water bodies and volumes of sediment infill are fed by extensive catchments, and hence provide a powerful tool for understanding paleoenvironmental and paleoclimate change not only on local but also on regional scale. Changes in lake level can be in the order of some meters, but also be much larger than those recorded in the marine environment. Large-scale lake-level changes of up to several hundreds of meters were observed in a series of large lakes, such as Lake Tanganyika (Lezzar et al., 1996), Lake Malawi (Scholz, 2007; Lyons et al., 2015), Lake Van (Cukur et al., 2014), Lake Lisan (Machlus et al., 2000), Lake Peten-Itza (Anselmetti et al., 2006), Laguna Potrok Aike (Anselmetti et al., 2009; Gebhardt et al., 2012), Lake Bosumtwi (Scholz et al., 2002) and Lake Challa (Moernaut et al., 2010). Lake Van is a large lake basin located in eastern Anatolia, Turkey (Degens et al., 1984; Litt et al., 2009). During the past 600 ka, i.e. since its formation, its water level changed by as much as 600 m (Cukur et al., 2014). While climate forcing was identified as the dominant factor in driving lake-level changes in Lake Van, other factors such as volcanic and tectonic forcing could also be observed (Cukur et al., 2014; Stockhecke et al., 2014). Lake Petén Itzá is located in the lowland Neotropics of northern Guatemala on the Yucatan Peninsula. A paleoshoreline was identified at 56 m below present lake level, which means a reduction of ca. 87% of the total water volume at that time (Anselmetti et al., 2006). Lake-level changes in Lake Petén Itzá were correlated to wet-dry paleoclimate patterns with lowstands during the stadials and highstands during the interstadial periods (Hodell et al., 2008). In Laguna Potrok Aike, a maar lake located in Patagonia, lake-level variations of up to 200 m during the past ca. 50 ka point at latitudinal shifts in the Southern Hemisphere

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Westerlies and hence difference in moisture availability (Anselmetti et al., 2009; Gebhardt et al., 2012). Lake Lisan, the late Pleistocene precursor of the Dead Sea, is located in Israel. The ancient lake is not filled with water anymore, but its sediments crop out at several locations around the Dead Sea. Lake Lisan existed between ~70 and 17 ka when it started to recede to the present-day Dead Sea lake level (Schramm et al., 2000). Lake-level changes as large as 170 m (Bartov et al., 2002) have on one hand been attributed to paleoclimate change, but on the other hand, basin morphology and barriers between subbasins are able to modify and restrict lake-level changes in this area (Bartov et al., 2002, and references therein). The impact crater of Lake Bosumtwi is located in Ghana, West Africa. It is rather small with a diameter of ~8 km (Scholz et al., 2002). This lake is hydrologically closed (Shanahan et al., 2006). Lake level in Lake Bosumtwi, therefore, is purely driven by evaporation/precipitation ratio, and the lake, hence, is sensitive on changes in regional (and global) climate.

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Lake Issyk-Kul, subject of this study, is a large lake located in Kyrgyzstan, Central Asia, in a tectonically active region surrounded by the Tien Shan Mountains. It is comparable in size with other large lakes worldwide, and thus likely to archive changes of the atmospheric circulation as well as indications of tectonic changes affecting the lake's drainage basin in its sediments. We use high-resolution sparker seismic data to reconstruct past water-level changes in Lake Issyk-Kul. Possible mechanisms are discussed that led to lake-level changes of up to 400 m. Additionally, the potential of the lake to help unravel regional paleoclimate change is shown.

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2 Study area

2.1 Lake settings

Lake Issyk-Kul is an endorheic lake located in an intermontane basin in the northern part of the Tien Shan Mountains in Kyrgyzstan, Central Asia (42°30' N and 77°10' E, 1607 m altitude) between the relatively rigid Tarim Basin to the south and the Kazakh Platform to the north. The lake is bordered by the high mountains of the Terskei Alatau Range to the south (max. height 5212 m) and the Kungei Alatau Range to the north (max. height 4771 m) (Fig. 1). The lake is elongated: ~180 km E-W and ~60 km S-N. With a surface area of 6232 km^2, Lake Issyk-Kul is the second largest lake in the higher

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altitudes (De Batist et al., 2002). It has a mean water depth of ca. 278 m and an approximate water volume of 1,736 km^3 (Korotaev, 1967; Kodyaev, 1973; Zabirov, 1978).

The lake has a deep central basin with a flat bottom (668 m water depth) that extends over approximately 25% of the present lake area (Fig. 1). Two large-scale shallow platforms characterize the lake at its western and eastern end, with the deltaic area being as wide as 60 km in the eastern and 40 km in the western part. Shelf areas in the north and south of the lake are rather narrow and separated from the central lake basin by steep slopes. At the delta areas, the shelf is divided into two parts, one shallower part with water depths down to 110 m with an average inclination of 0.5°, and the other with water depths between 110 and 340 m and an average inclination of 1° (De Mol, 2006). Incised channels of up to 2-3 km width and 50 m depth are visible on both the eastern and the western shelf (Fig. 1), but are limited to the shallower part of the shelf. They are found in the prolongation of modern river mouths at the eastern part of the lake, and are quite likely connected to former in- and outlets of the Chu river at the western delta (De Mol, 2006). The deeper part of the shelf is characterized by a series of terraces that were interpreted as ancient delta lobes, indicating lower water levels (De Batist et al., 2002).

The lake is fed by a total of 118 rivers and creeks draining an area of 22,080 km^2. These rivers mainly carry meltwater of snow and glaciers, rain and groundwater (Aizen et al., 1995). The largest rivers are the Djyrgalan and Tyup rivers that feed into Lake Issyk-Kul at its eastern end. At present, Lake Issyk-Kul has no outlet, but during its history, it drained through the Chu River at its western end (De Batist et al., 2002). Approximately 640 km^2 of the drainage area are currently covered by glaciers that are located in altitudes of at least 3000 m asl. Most of these glaciers are found on the north flanks of the Terskei Alatau range. During the last glacial period, the glaciers extended down to the coast of Lake Issyk-Kul (Grosswald et al., 1994). It is unclear if the lake was ice-covered during glacials or if the glaciers extended onto the shelf.

Lake Issyk-Kul is oligothrophic to ultra-oligotrophic and well oxygenated through the entire water column down to the lake bottom. Surface water temperature does not drop below 2-3°C in the winter and reaches values of 19-20°C during the summer. The lake is located in an arid area with deserts in the west, followed by semi-deserts and steppe towards east (Merkel and Kulenbekov, 2012). Salinity of the lake water is currently approximately 6 mg/l (Merkel and Kulenbekov, 2012).

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2.2 Tectonic setting

The Tien Shan Mountains are one of the most important intracontinental orogenetic regions in Central Asia. Uplift and exhumation of the crystalline basement with its Paleozoic sediment cover has possibly started in late Oligocene. This has happened as a consequence of the progressive convergence of India and Eurasia after their collision in the Eocene (e.g., Goryachev, 1959; Molnar and Tapponier, 1975; Trofimov, 1990; Abdrakhmatov et al., 2002). During the Cenozoic, several strike-slip faults were active in this area, resulting in a transpressional tectonic context (Vermeesch et al., 2004). Exhumation of the Terskei Alatau and deposition of the basin fill began in the Late Oligocene (Macaulay et al., 2013; Wack et al., 2014; Macaulay et al., 2015). GPS measurements show that the Tarim Basin moves towards the north with approximately 15 to 20 mm per year with respect to Eurasia. The area is tectonically highly active as documented by recent and historic high-magnitude earthquakes (e. g. 1911: M 8.2) that often result in large subaerial landslides and quite likely also trigger large subaquatic mass movements. Most of the present-day tectonic activity is focused along the margins of the intermontane basins. Uplifted Pliocene lacustrine deposits, a clear example of the geodynamic activity in this area, are exposed at the southern shore of the lake. They are truncated by horizontal Quaternary lacustrine terraces, and some of the sediments were identified as deposited or deformed during earthquakes (Bowman et al., 2004).

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3 Data acquisition and processing

First seismic data of the Lake Issyk-Kul sedimentary infill and architecture were acquired in 1982 by the Moscow State University with a total of 31 profiles across the lake. Unfortunately, only a few profiles were ever published (Stavinsky et al., 1984). Additional seismic profiles were acquired in 1997 and 2001 (Fig. 1) by the Renard Centre of Marine Geology (RCMG, Ghent University, Belgium). In 1997, 62 profiles (~990 km) were collected using a CENTIPEDE multi-electrode sparker (150-1500 Hz, operated at 500 J) as acoustic source (Imbo, 1998). In 2001, 40 additional profiles (~600 km) were acquired with the same source, and another 12 profiles using a SIG sparker (200-800 Hz, operated at 500 J). During both surveys, a single-channel streamer (2.7 m length, 10 hydrophones at 0.3 m spacing) was used as seismic receiver (Naudts, 2002). Recording time and shot interval were chosen depending on the water depth of the specific area. The incoming signal was bandpass-filtered between 100 and 3000 Hz and subsequently digitized using a Triton-Elics DELPH2 data acquisition system with a sampling frequency of 5 kHz. Data were later converted to standard SEG-Y format for further processing. Navigation was recorded using a SIMRAD Shipmate GPS system. Seismic processing comprised filtering, deconvolution, migration and amplitude scaling.

For the interpretation of the seismic database, all profiles were imported into KingdomSuite. Prominent sequence boundaries, both erosive and non-erosive, were mapped throughout all profiles except where either the sequences were not imaged due to the geographical location of the profiles or due to limits in acoustic penetration/masking by the multiple. Even though sequence boundaries could not be mapped continuously between the eastern and western stacked-delta complexes, it was still possible to identify the same sequences in both areas due to similar two-way traveltime depths of the individual corresponding delta lobes. Two-way traveltime was converted to depth below lake level (bll) using a sound velocity of 1500 m s^{-1}. Thickness maps for sequence boundaries were generated using the "Natural Neighbour" tool of ArcGIS with a cell size of 500 m. Around the seismic profiles, a buffer of 500 m was calculated and used to mask the grid.

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4 Results and Interpretation

4.1 Seismic facies analysis

The seismic profiles of Lake Issyk-Kul are characterized by a variety of acoustic facies. While the central part of the lake is characterized by inclined strata that were deposited in a layer-cake manner, the slope and shelf are much more diverse in their acoustic image. We here concentrate on the eastern and western slope and shelf areas where we identified four different seismic facies types SF1 to SF4 (Fig. 2). These can be described as follows:

Seismic facies 1 (SF1): This facies type is characterized by parallel to subparallel reflections with high to moderate amplitudes (Fig. 2a). Amplitudes are generally lower in the deeper sequences, which is rather the result of limited acoustic penetration than a real signal. In between the parallel to subparallel reflections a succession of prograding sequences with sinusoidal outer shape are observed (Fig. 2a). These are characterized by moderate to low amplitudes and moderate-continuity reflections. SF1 is found throughout almost all stratigraphic sequences both in the eastern and western delta area. The parallel to subparallel reflections can be interpreted as topsets and bottomsets of a delta, while the sinusoidal sequences are the corresponding foresets. SF1 is hence interpreted as prograding delta lobes with the characteristic lateral and/or vertical succession of topsets, foresets, and bottomsets. The sediments likely consist of coarse-grained material brought into the lake by the large rivers such as the Tyup and Djyrgalan rivers in the eastern and the Chu River in the western delta.

Seismic facies 2 (SF2): This facies type is characterized by parallel to subparallel reflections of high to moderate amplitudes that can be followed over distances of several kilometers (Fig. 2b). The reflections form a drape or onlap onto the underlying reflections, and they are mostly found in locations distal to SF1. This facies is interpreted as distal deltaic sediments, i.e. prodelta sediments, and likely consist of fine-grained material brought by the rivers, possibly intercalated with turbidites.

Seismic facies 3 (SF3): This facies type is characterized by a series of parallel to subparallel reflections with high to moderate amplitudes (Fig. 2c), similar to the topset part of SF1. The reflections form onlaps onto the underlying sequence boundary/reflections as well as onto the overlying layers. Each superjacent reflection is located closer to the shoreline. This facies type is interpreted as transgressional deltaic sediments or backstepping deltas during times of rapid lake-level rise.

Seismic facies 4 (SF4): This facies type is mostly acoustically transparent with low amplitudes (Fig. 2d). Where amplitudes are high enough for reflections to be detected, they are chaotically distributed. This facies is mainly found in the deeper parts of the delta where it forms a thick package of sediments, laterally bounded by sediments of SF2 towards the more distal part of the delta. SF4 may be interpreted as former delta sediments that have been affected by post-depositional processes (e.g. sediment remobilization, slumping, liquefaction) that caused them to loose their internal structure, or they may just consist of coarse-grained sediments.

4.2 Identification of stratigraphic sequences in the seismic profiles

The seismic profiles across the eastern and western delta areas were interpreted in terms of stratigraphic sequences following the principles of Vail et al. (1977). Stratigraphic sequences are always determined by their upper and lower boundaries. Unconformities are easily recognized as surfaces onto which reflectors converge. Erosion truncates older strata that hence form toplaps or onlaps onto the erosional discordance (Fig. 3). Also the occurrence of downlaps, i.e. strata that terminate onto an underlying stratigraphic boundary, is indicative for sequence boundaries. Once the boundary is identified, it can be traced along the entire profile even in areas where it becomes conformable (Fig. 3).

Boundaries between the different sequences in Lake Issyk-Kul are often erosive, but in places they are also non-erosive, i.e. conformable. Erosive boundaries, i.e. erosional unconformities marked by truncation of underlying reflectors and/or irregular morphology, point at a lake-level fall while non-erosive boundaries, i.e. conformities, were formed during times with stagnating or rising lake levels.

Seven stratigraphic sequences were identified. The sequences are imaged on almost all seismic profiles except where they were masked by the lake-floor multiple, where acoustic penetration was limited, or where the location of the profiles was not suited to image that specific sequence.

S3 and S4 were clearly identified on the western profiles, but could not be differentiated from each other on the profiles across the eastern delta area.

4.3 Description of seismic profiles

Profile ik01: Profile ik01 was acquired near the center of the lake and is aligned almost straight in north-south direction (Fig. 1). The profile shows well-layered sediments with a gentle dip towards south (Fig. 3). While the lake floor is not inclined, dip angle increases to roughly 15° at 200 m sediment depth. Small mass-transport deposits are intercalated with the well-layered sediments and are mainly found close to the slopes (Fig. 4).

Profile issyk049: Profile issyk049 is located in the western part of the lake (Fig. 1). It was acquired perpendicular to the shelf to best image the delta sequences below. The profile shows sedimentary layers that generally dip towards east, i.e. towards the lake center (Fig. 5). In profile issyk049, seven different stratigraphic sequences S1 (youngest) to S7 (oldest) could be identified. Underneath the lowermost sequence, more lacustrine sediments are visible, but could not be interpreted due to poor acoustic penetration. The acoustic basement was not detected in this profile. In each of the 7 stratigraphic sequences several deltas could be identified (Fig. 5). In accordance with the other profiles of both the western and eastern area, these deltas could be numbered consequently. Deltas were named x.y where x indicates the sequence in which it was detected, and y indicates number of the delta within this sequence. y starts with 1 for the first delta deposited in this sequence, and is consecutively incremented by 1 for each subsequent delta (Fig. 5). None of the profiles contained all of the delta lobes. For example, for S1 a total of 7 deltas were identified, while only 1.3, 1.5, and 1.6 were observed in profile issyk049. In some cases, deltas were missing because they were eroded after deposition. In other cases, they may not have been deposited at all, maybe due to varying input paths of the sediment. The current rivers on the eastern and the Chu River on the western end of the lake may not always have had the same river bed, mainly during lake-level lowstands, they may have changed their pathway. Sediment supply hence may have limited the buildup of deltas.

Profile issyk019: Profile issyk019 is located in the eastern part of the lake (Fig. 1). Similar to issyk049, it was acquired perpendicular to the shelf to best image the delta sequences below, but it does not extend as far into the basin as the former. The profile shows sedimentary layers that generally dip towards west, i.e. towards the lake center (Fig. 6). In profile issyk019, only 6 different stratigraphic sequences could be identified, and in comparison with the other profiles of both east and west it became obvious that the sequence boundary between S3 and S4 could not be identified in the eastern area. S3 and S4 were hence treated as a combined sequence to stay consistent with the western area. Again, more lacustrine sediments were visible underneath the lowermost sequence but could not be interpreted. The acoustic basement was not detected in this profile either. In each of the six stratigraphic sequences except S3 & S4 several deltas could be identified and numbered accordingly to issyk0149 (Fig. 6).

5 Description and interpretation of stratigraphic sequences

The sequences are described and interpreted in the following sections following the stratigraphic order, i.e. from the oldest sequence (S7) towards present (S1). We use delta depth (expressed in meters below current lake level) as an indicator for past lake-level change. The topset-foreset roll-over point of the prograding clinoforms is considered as a proxy for the lake level at the time of its formation. The current topset-foreset roll-over point is at ~30 m bll, therefore, all delta depths were corrected by -30 m for the lake-level curve. No corrections were made for compaction and/or tectonic subsidence. Sediment thickness for S1 to S6 was calculated using a mean acoustic velocity of 1500 m s^{-1} for conversion between two-way traveltime and depth. Sediment thickness, however, gives only a minimum estimate of the original thickness. Many parts of the sequences were eroded before the deposition of the overlying sequence, which is clearly visible by truncated strata and erosional discontinuities (Fig. 3). Furthermore, additional accommodation space for the overlying sequences was created by incision of rivers into older strata during lake-level lowstands.

S7 is the lowermost sequence that is visible in the seismic profiles (Figs. 5 and 6). Its lower boundary is masked in places by the multiple and/or limited penetration of the acoustic signal. Where its lower boundary is visible, it is clear that the seismic survey did not penetrate down to the acoustic basement, but that S7 is actually overlying sediments of unknown thickness. The upper boundary is defined by truncated strata within S7 and conformable sediment layers in S6 in the distal parts, and can be traced throughout the more proximal part of the profiles. Within S7, a series of 5 delta lobes could be identified, i.e. spatially well-defined parts of the sequence characterized by the seismic SF1. Some of these occur only in the western delta area (7.5, 7.4), some only the eastern delta area (7.2), and some in both areas (7.3, 7.1). The stratigraphic succession of delta lobes 7.1 to 7.5 indicates a stepwise lake-level fall with stillstands at 330, 381, 412, 454, and 504 m bll (Table 1).

S6 is clearly visible both on the western and eastern delta areas. It overlies S7 and is rather thin and forms downlaps onto the underlying and toplaps/onlaps onto the overlying erosional discontinuity in many profiles (Fig. 5). Two delta lobes could be identified at 461 (6.1) and 361 m bll (6.2) (Table 1). S6 can thus be interpreted as deposited during lake-level rise with a first stillstand at 461 and a second stillstand at 361 m bll. Sediment thickness of S6 is increasing with increasing water depth at least in the western delta area (Fig. 7).

S5 overlies S6 (Figs. 5 and 6). It is characterized by two deltas at 284 m bll (5.1) and 364 m bll (5.2) (Table 1). The topographically higher delta 5.1 exhibits extensive erosion on the eastern delta (Fig. 6). The bathymetrically lower delta 5.2 is still visible in the modern lake floor morphology as it is only draped by the overlaying sequences; it forms the current shelf edge. S5 can be interpreted as having formed during a step-wise lake-level fall from a first stillstand at 284 m bll to a second stillstand at 364. It is quite likely that extensive erosion of the upper part of delta lobe 5.1 took place during the deposition of the lower lobe 5.2. Sediment thickness of S5 reveals two distinct depot centers in the western and one in the eastern delta area. Furthermore, sediment thickness could point at a paleo-river channel incised in S6 in the eastern delta area that is not located in the prolongation of one of the present large rivers (Tyup and Djyrgalan, see figure 1).

S4 overlies S5, and it is visible in both the western and eastern delta areas. On the latter, its upper boundary with S3 is unclear due to the fact that S3 is not clearly visible in this area (Fig. 6). S4 in the eastern delta area either includes S3 and the boundary in between is not visible, or S3 is completely eroded here. Sediment thickness for the combined S3&S4 in the eastern area shows increasingly thicker sediments towards the northern part of the delta, and a surprisingly thin thickness with little variance in the area south of 42°30' (Fig. 7). It is likely that erosion was larger in this area, but the causes cannot be addressed with the current seismic database. In the western delta, in contrast, S4 is rather thick (Fig. 7) and its strata are truncated indicating an erosive discontinuity between S4 and S3 (Fig. 3). In S4, the delta lobes are characterized by predominantly acoustically transparent sediments of SF4, but the sequence also contains packages of well-layered prodeltaic sediments of SF2 (Fig. 5) in the distal parts distal of the different delta lobes. Three delta lobes were identified: the oldest (4.1) at ca. 319 m bll, followed by a delta (4.2) at approximately 250 m bll and a third, younger (4.3), at 397 m bll (Table 1). S4 indicates a lake-level rise from a lower stillstand at 319 m bll to a second stillstand at 250, followed by a subsequent lake-level fall with another stillstand at 397 m bll.

S3 could only be clearly identified in the western delta areas (Fig. 5); in the eastern area, S3 either cannot be distinguished from S4, or it is completely eroded (Fig. 6). In the western delta complex, S3 is characterized by a lower boundary that was partially erosive into the underlying sediments but grades into a correlative conformity in other places. Two distinct delta lobes were identified within S3, the older at 330 (3.1) and the younger at 172 m bll (3.2) (Table 1). Thickness of S3 in the eastern delta is highest in presently proximal areas that may have been more distal at the time of their deposition. With the overall shape of the sequences it becomes obvious that the lake is continuously being infilled and getting smaller over time. S3 can be interpreted as having formed during a lake-level rise with two stillstands, one at 330 m bll, followed by a rapid lake-level rise and a second stillstand at 172 m bll.

S2 is visible in almost all profiles in the eastern and western delta areas (Figs. 5 and 6). In the eastern delta area, due to the partial acoustic transparency of the underlying S3 it is not clear if the lower boundary of S2 is erosive or non-erosive; where S3 is not acoustically transparent but layered, the boundary between S2 and S3 seems to be non-erosive. In the western delta area, the lower boundary of S2 is clearly non-erosive. S2 is characterized by 2 delta lobes that were formed at 210 (2.1) and at 250 m bll (2.2) (Table 1). S2 can be interpreted as a succession of step-wise, slow lake-level fall with stillstands at 210 and later at 250 m bll. During the lake-level fall, erosion may have taken place in the upper, proximal parts of the lake that were aerially exposed, but this is not visible in our seismic network. The thickness map of S2 shows a distinct depot center at the center of the eastern delta area. A closer look onto S2, however, reveals that the current sediment thickness is not representing the initial sequence thickness (Fig. 8b). With a closer look on profile issyk019 it becomes obvious that large parts of both delta 2.2 and delta 2.1 were eroded. Where delta 2.1 was initially deposited, a river deeply incised the sediments, making this originally thick part of the sequence the presently thinnest. A second, more elongate, moderately thick depot center in the more proximal part could be a paleo-river channel that was incised into S3. It is located at the prolongation of the current Djyrgalan sub-lacustrine channel and must have formed during a time span with lower-than-present lake level.

S1 could be identified on seismic profiles in both the eastern and western delta areas (Figs. 5 and 6). It contains the uppermost, youngest sediments and its upper boundary forms the current lake floor. It lies above an erosional unconformity with channels deeply incised (up to 35 m) into S2 at several spots (Fig. 8a). Sediments of S1 fill these channels, which is clearly visible in sediment thickness (Fig. 7). In its distal part, it drapes the underlying topography with a shelf break at ca. 340 m and prodeltaic sediments of SF2 deeper down. The lowermost part of S1 forms a small delta lobe (1.1) at approximately 285 m bll. This lobe is overlain by a succession of transgressional units of SF3 (Fig. 8a). On some profiles, a series of smaller delta lobes (1.2 to 1.5) is visible at water depths of 263, 251, 228, and 201 m bll (Table 1). A distinct large delta lobe (1.6) is visible in almost all profiles at a water depth of ca. 153 m bll. Only on profiles issyk024 and ik07 that reach into the shallowest parts of the lake on the eastern delta area, the uppermost, currently active delta lobe (1.7) at 28 m bll was identified. The distal prodeltaic sediments associated with delta lobe 1.7, however, can be identified as thin drape on almost all profiles of both the eastern and western delta areas (Fig. 8a). The lake-floor morphology shows a shelf break at approximately 150 m bll. The large shallow areas above the present-day delta at ca. 30 m bll are characterized by subaquatic channels that begin at the mouths of the large rivers at the eastern shore and in front of the paleo-channel of the Chu River at the western shore. These channels can be followed over the entire plateaus and end at approximately 110 bll. S1 can be interpreted as starting with a relative lake-level lowstand during the formation of its lowermost delta 1.1. During this lake-level lowstand, erosion took place in the hinterland and likely formed the river incisions that are visible at the boundary between S1 and S2 on profile issyk019 (Fig. 8a) and in nearby profiles. The lake-level lowstand was followed by a rapid transgressional phase ending with a slightly slower lake-level rise from 263 to 201 m bll. The sedimentary infill of the deeper channel likely was deposited during this transgressional phase. A second lake-level stillstand took place during the formation of the delta 1.6, followed by the current situation in which delta 1.7 is being deposited approximately 28 m bll.

6 Discussion

6.1 Tectonic origin of the lake

Most of the 84 sparker profiles used in this study are located either in the eastern or western shallow parts of the lake (Fig. 1). While they image the delta areas in great detail, they do not provide much information on the tectonic origin of the lake. Profile ik01 crosses the lake in N-S direction, and here the tectonic nature of the lake becomes obvious: Sediments dip towards the south, pointing to higher subsidence rates in that region (Fig. 4). This is visible to at least 200 m below lake floor. Within the

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Gelöscht: Only profile ik01 crosses the lake completely in the

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Gelöscht: . All profiles show that the sediments are well stratified in a layer-cake manner in the central part of the lake. On profile ik01,

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Gelöscht: the

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Gelöscht: ; in some places, these layers are even recognizable at a sediment depth of ca. 375 m.

imaged lake profiles, the faults responsible for the asymmetry of the basin are not visible, but studies along the southern margin of the lake document the presence of a series of faults roughly parallel to the long axis of the lake (e.g., Burgette, 2008; Macaulay et al., 2014; Macaulay et al., 2015). The north-vergent Main Terskey Fault (MTF) is the most important basin-bounding fault, with over 8 km of structural relief with respect to the lake (Macaulay et al., 2013) (Fig. 1). Apatite fission-track studies show that this structure became active in the latest Oligocene-Early Miocene. In seismic profile ik01, the dip angle of the strata seems to change quite continuously over time with no sign of an abrupt change, and the deformation seems to be still active. This points at an ongoing process. Short cores retrieved from the northern slope reveal that the sediment consists of a mixture of a terrigenous fraction (ranging from coarse sands to silty clays and clays) and a lacustrine micritic carbonate fraction. Reported sedimentation rates vary between 0.47-0.56 mm/yr (Ricketts et al., 2001), 0.49-0.59 mm/yr (Giralt et al., 2004), and 0.23-0.39 mm/yr (Larrasoaña et al., 2011; Gómez-Paccard et al., 2012) for the Holocene, based on ^{14}C and nuclide dating. Using a mean value of 0.45 mm/yr, this points at a minimum age of ca. 830 ka for the lowermost sediment layers visible in the profiles. It is quite likely that the lake is significantly older, because the acoustic basement was not detected in any of the profiles. Deep bore holes and outcrops within the basin adjacent to the lake reveal up to 5 km of Cenozoic strata (Knauf, 1965; Turchinskiy, 1970; Fortuna, 1983); the older lacustrine record is poorly studied. Sedimentation rates used here are derived from cores located proximal to the northern shore, and sedimentation rates might be significantly lower in the central part of the lake. Additionally, large differences in sedimentation rates between glacials and interglacials are to be expected.

6.2 Lake-level curve and age information

Combining all information on lake-level stillstands, delta formation, regressional and erosional phases, a lake-level curve for Lake Issyk-Kul was established (Fig. 9). It comprises 4 phases of lake-level regression (in S7, S5, second part of S4, and S2) and 4 phases of lake-level transgression (S6, first part of S4, S3, and S1). The transition between the different sequences and thus the transition between regression and transgression cannot be clearly described due to the fact that the boundaries are mostly

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Gelöscht: .

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Gelöscht: becaoem

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Gelöscht: MIocene. In the Late Cenozoic, the MTF propagated northward into the Issyk Kul basin; therefore, the anticline within the lake is likely linked to this structure.

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Gelöscht: , as the uppermost layers still display a slight dip angle.

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Gelöscht: However, it

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Gelöscht: however

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Gelöscht: Furthermore, the sedimentation rates used here are derived from cores located proximal to the northern shore, and sedimentation rates might be significantly lower in the central part of the lake.

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Gelöscht: In the southeastern part of the lake, the strata are not inclined as would be expected in this asymmetric basin. This is due to two anticline structures that are visible over a length of ca. 30 km and 10 km, respectively (Fig. 1). The longer ... [1]

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Gelöscht: 8

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Gelöscht: decreases

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Gelöscht: Sequence 7, Sequence

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Gelöscht: equence

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Gelöscht: equence

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Gelöscht: rise (Sequence

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Gelöscht: Sequence 4, Sequence

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Gelöscht: decreases

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Gelöscht: increases

of erosive nature, mainly in the shallower parts of the lake. This is easily explained by the observation that the shallower parts of the sequences were subaerially exposed during the formation of lowstand deltas and thus were subject to erosion.

The lake-level curve in its present form only comprises the deltas/terraces that were formed inside the current lake; subaerially exposed terraces are not imaged in the seismic data, and their distal counterparts, i.e. the distal well-layered prodelta sediments, are likely not identified because they lie concordantly on the underlying sediment.

Different authors describe a series of terraces that are today subaerially exposed. The uppermost terrace in the lake area is located at 1675-1680 m above sea level (asl) (Trofimov, 1990), which is some 70 m above the present-day lake level. Bowman et al. (2004) describe beach cliffs at an altitudinal range of 1620-1640 m asl. These subaerially exposed terraces point at lake levels that were 70 and 13-33 m higher than present. Bowman et al. (2004) date these terraces to ages between 26.0 ± 2.1 ka for the upper ones and 10.5 ± 0.7 ka for the lower ones, which is in agreement with an older date of 26.34 ± 0.54 ka for an upper terrace (Markov, 1971). This means that the lake-level highstand at 33 m above lake level occurred roughly at the beginning of MIS2. Lake Issyk-Kul's lake surface today is almost at the spill-over level. Terraces at 33 and 70 m higher than the current lake surface would mean that the outflow must have been dammed by a dam approximately 33 and 70 m higher than today for a substantial time so terraces could have formed. With the current topography, this scenario is rather unlikely, and the subaerial terraces might also just have been uplifted from their original position. On the other hand, young lacustrine sediments are interbedded with fluvial conglomerates in Boom Canyon (Fig. 1), suggesting that the narrow gorge was dammed in the past. This could have blocked the current lake's spill-over point, maybe resulting in lake levels higher than would be possible today.

Sub-lacustrine channels are visibly incised into S1 (Fig. 1) on the large shallow parts of the eastern stacked-delta complexes. On the eastern complex, these are associated with the prolongation of the rivers that currently feed Lake Issyk-Kul. On the western complex, the paleo-channel marks the ancient position of where the Chu River entered the lake before it was redirected (De Batist et al., 2002). Today the Chu River flows approximately 10 km west of the lake. The channels were likely formed at a lake-level lowstand at 110 m bll, which – taking into account the 30 m of water that are today measured

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Gelöscht: upper

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Gelöscht: upper

Catalina Gebhardt 8.7.16 00:10
Gelöscht: sediments must have fallen dry

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Gelöscht: With the present-day delta being formed in a water depth of approximately 30 m, these

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Gelöscht: 100

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Gelöscht: 43-63

Catalina Gebhardt 8.7.16 00:10
Gelöscht: 63

Catalina Gebhardt 8.7.16 00:10
Gelöscht: some 63

Catalina Gebhardt 8.7.16 00:10
Gelöscht: 100

Catalina Gebhardt 8.7.16 00:10
Gelöscht: some 63

Catalina Gebhardt 8.7.16 00:10
Gelöscht: 100

Catalina Gebhardt 8.7.16 00:10
Gelöscht: gorge

Catalina Gebhardt 8.7.16 00:10
Gelöscht: Subaquatic

Catalina Gebhardt 8.7.16 00:10
Gelöscht: equence

Unknown
Feldfunktion geändert

Catalina Gebhardt 8.7.16 00:10
Gelöscht: some

ontop of the currently active delta – corresponds to a delta depth of roughly 140 m. The channel morphology is still very distinct, pointing at a rather young event during which they were formed, so it is quite likely that they eroded into the subaerially exposed sediments of S1 while delta 1.6 was formed at a water depth of 153 m. Older Russian literature dates this lowstand as following the MIS2 regression marked by the subaerial terraces mentioned above (Markov, 1971; Bondarev and Sevastyanov, 1991). This would imply that delta 1.6 was deposited after a significant lake-level fall of more than 100 m. Seismic data, however, show a succession of a delta (1.1) at a water depth of 285 m bll, a transgressional phase followed by a stepwise increase with small-scale deltas (1.2 to 1.5) at water depths of 263, 251, 228, and 201 m bll before the formation of delta 1.6 at 153 m bll, with no sign of a lake-level highstand in between. It is thus unlikely that lake level was high before the formation of delta 1.6, providing evidence that the subaerially exposed lake terraces might not be located in their original position but significantly uplifted.

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Gelöscht: equence

6.3 Lake-level variations and their trigger mechanisms

Lake-level variations are always a sign of changes in the hydrological regime of a lake. Basically, two different mechanisms can affect the hydrological regime: (i) a change in lake geometry, e.g. (differential) subsidence, a blocking of the outlet stream or, contrarily, the formation of a new outlet, and (ii) a change in the balance between precipitation/inflow and evaporation/outflow.

6.3.1 Changes in lake geometry

Lake Issyk-Kul is located in a tectonically highly active area, which at first glance makes it likely that lake-level changes may have their primary origin in tectonic events. The lake basin is located in the intramontane Issyk-Kul Basin that is separated from the surrounding mountain ranges (the Kunghei Alatau towards north and the Terskei Alatau towards south, Fig. 1) by fault zones. Most of the Late Cenozoic strain has been accommodated by the adjacent mountain ranges, and as a result, the Issyk-Kul Basin and the lake basin in its center have been mostly protected from strong deformation (Abdrakhmatov et al., 2002). This is confirmed by the mostly well-layered sediments observed in the lake; however, evidence for tectonic influence is present (e.g. the tilting of the central basin deposits towards the south, and the occurrence of mass transport deposits likely caused by underwater slope destabilization due to seismic shaking).

Lake-level changes could be linked to tectonically-driven subsidence or exhumation that would (a) either influence the entire lake, (b) parts of it, or (c) the inlets and/or outlets: (a) From the well-layered sediments in the central part of the lake it is quite obvious that the general sedimentation pattern did not change significantly during the time interval which we can observe. The strata are almost perfectly horizontal in W-E direction, but dip gently towards south with dip angles increasing with depth. This points at differential subsidence only between the northern and the southern part of the lake, and the subsidence seems to have been relatively constant through time. In order to generate such a highly dynamic lake-level curve as for Lake Issyk-Kul (Fig. 9) with several cycles of increases and decreases and a total difference of at least 400 m, it is virtually impossible that the lake-level variations were generated by fault driven uplift or subsidence within the lake. A general trend is nonetheless probable and confirmed by the differential subsidence between the northern and southern shore imaged in the sediments, but superimposed by another mechanism that is responsible for the dynamic change in lake level. (b) The two anticlinal structures visible in the eastern part of the lake may have influenced the lake at its eastern end, but given that the delta depths for almost all delta lobes are almost identical on both the eastern and western delta, it is unlikely that these two areas experienced significantly different histories. Even though some delta lobes were only identified on one delta, many other lobes are observed at identical depths on both deltas. In the case of S7, lobe 7.1 was observed in 327 m bll in the west and 333 m bll in the east, lobe 7.2 is missing in the west, 7.3 was observed in 415 m bll in the west and 409 m bll in the east, lobe 7.4 was found at 454 m and lobe 7.5 at 504 m bll in the west only. The differences between east and west are not larger than those between the lobe depths identified within one delta if identified in several profiles. Also, for example lobe 7.5 was only identified on one profile in the western delta. It is therefore likely that those delta lobes that were only observed in one of the deltas are in fact not missing in the other, but were just not identified in our study, either because our seismic profiles were not placed perfectly to image that specific lobe, or maybe even because this lobe was eroded after its deposition. (c) Tectonic events can also influence inlets and outlets of a lake, which

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Gelöscht: within the lake basin

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Gelöscht: the anticline structures in the east,

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Gelöscht: .

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Gelöscht: 8

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Gelöscht: on a time scale of ~1 Ma

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Gelöscht:

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in turn at least partly control lake level. At present, Lake Issyk-Kul is a closed system without any outlet, but in former times, the lake was drained through an outlet at its western end. The Chu River entered the lake in the southern and left it in the northern part of the western delta. At some point during the late Pleistocene, its course changed and it currently bypasses the lake and flows through Boom Canon towards northwest due to a gentle topographic barrier between the river and the lake. This barrier was likely caused by changes in the tectonic settings (Bondarev and Sevastyanov, 1991). This means that Lake Issyk-Kul not only has no current outlet, but also no large inflow through the western delta. Should the Chu River keep its current course, this would result in a decline in sediment accumulation in the western delta, and delta lobes would likely not develop as pronounced in future in this part of the lake. A lake-level rise of 13 m, however, would flood the barrier and reactivate the Chu River as an outflow. In the beginning of the 19th century, Lake Issyk-Kul drained through the Chu River for some 25 years (Merkel and Kulenbekov, 2012). The maximum documented lake level that Lake Issyk-Kul has experienced is at 1,680 m above sea level (asl), i.e. 73 m above present lake level (Trofimov, 1990). With the current topography, it would not be possible to generate terraces at 73 m above lake level, as the lake would overflow at +13 m already. This suggests that during the period where water reached to 73 m above lake level, either the current possible overflow channel – the Boom Canyon - was blocked, or the lake surroundings have been uplifted relative to the lake itself since that time and the +73 m terraces were initially deposited at another – lower – altitude. Or the entire lake basin and lake have been uplifted and all terraces are not at their original position. As the present structural setting would be predicted to raise the range with respect to the lake, the latter scenario seems unlikely. Grosswald et al. (1994) report that alpine glaciers have extended to the present shoreline and likely into the Chu river valley in the past, so they may have dammed the lake and facilitated lake levels higher than currently possible.

It is unlikely that the current bypassing of the Chu River is a common situation in the lake's history. In addition to the blocked outlet, this in fact also means that a large river entering from the west is missing. The pronounced delta lobes that formed contemporarily in the east and west point at sediment sources at both ends during at least the period that is spanned by sequences 7 to 1.

All things considered, we propose that the lake-level fluctuations identified on our seismic data do not originate from tectonic activity only. Tectonic activity in this region might result in an overall trend of the lake level, but not in the highly dynamic, repeated cycles of fall and rise. These must have been the result of significant changes in precipitation and/or evaporation.

6.3.2 Changes in precipitation/evaporation

Today, climate and hence precipitation/evaporation in the Tien Shan is mainly controlled by the interaction between the mid-latitude Westerlies and the Siberian Anticyclone (e.g., Aizen et al., 1997; Zech, 2012). The mid-latitude Westerlies bring moisture from the Aral-Caspian Basin, the Mediterranean, the Black Sea and the North Atlantic (Aizen et al., 2006; Lauterbach et al., 2014), while the Asian summer monsoon has been only of minor importance at least since the Mid Holocene (Cheng et al., 2012). The Siberian Anticyclone reaches south to the Tien Shan area and blocks the mid-latitude Westerlies during winter, which results in low winter precipitation due to the dry air masses of the Siberian High (Aizen et al., 1995; Aizen et al., 2001; Ricketts et al., 2001). Maximum precipitation is observed in spring and summer, and additionally in autumn in areas with altitudes of less than 3000 m (Aizen et al., 2001). Between 1931 and 1990, precipitation has increased significantly in the northern Tien Shan by up to 108 mm (Aizen et al., 2001). Aizen et al. (2001) interpret this increase as a stronger influence of the mid-latitude Westerlies on precipitation, which might result from an increase in global air temperature and a weakening or displacement of the Siberian High. Lake level, however, has fallen by 3 m since 1926 (Ricketts et al., 2001), partly due to Soviet era hydrological projects, but also by increased evaporation due to increased temperature (Romanovsky, 1990; Ricketts et al., 2001; Romanovsky, 2002).

Lake Issyk-Kul is currently mainly fed by riverine input, which in turn is mainly controlled by snow and glacier melt, as well as by rainfall. Lake-level changes are therefore highly dependant on precipitation and evaporation, which in turn are controlled by moisture and air temperature. With lake-level changes of up to 400 m, the lake's archive shows that the interplay between Siberian High and mid-latitude Westerlies has been highly dynamic during the past, and likely since the formation of the lake. Unfortunately, we do not have age information from the delta lobes. Even though some age and

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sediment accumulation information is available from short sediment cores mostly from the mid-slope area (e.g., Ricketts et al., 2001; Giralt et al., 2004), these data are not helpful to estimate ages of the different delta lobes. Delta systems are just too dynamic with large differences in accumulation rates depending on the proximity to the rivers and to their total sediment load (bedload and suspended load) to use generalized accumulation rates. Additionally, erosional contacts between the different sequences could be observed but the amount of missing sediment could not be quantified. Drilling of sediment cores from the different sediment lobes would be required in order to reliably date the lake-level stillstands. Lake Issyk-Kul with its long sedimentary archive therefore provides an ideal drill site to study the history of the interplay between the Siberian Anticyclone, the mid-latitude Westerlies and the Asian summer monsoon through time (Oberhänsli and Molnar, 2012). The lake is located in an area with high relief, implying different climate conditions over short distance. Nevertheless, lake-level changes of up to 400 m are significant and rather a result of large-scale changes in climate patterns rather than of regional differences.

In an arid area such as the Issyk-Kul region, glaciers are highly sensitive to changes in precipitation/evaporation. Evidence from glacial features such as moraines, however, is limited and does not reach further back in time than to MIS6 (e.g., Zech, 2012); in the Kyrgyz Tien Shan, existing ages only reach back to MIS5e (Koppes et al., 2008). Zech (2012) showed that the glaciation in the Tien Shan and Pamir became successively more restricted from MIS4 to MIS2, which was also observed in Siberia with limited ice sheet and glacier extents (e.g., Svendsen et al., 2004; Zech et al., 2011). Zech (2012) interprets this as a result from reduced moisture advection through the mid-latitude Westerlies due to the lee effect when flowing over the massive Fennoscandian Ice Sheet, and additionally by a blocking situation of the Westerlies by a strong Siberian High. Low lake level would likely be caused by low precipitation and, thus, points at a strong Siberian High. This would imply that sequence boundaries 7/6, 5/4, 4/3, 2/1 represent times of a strong Siberian High and weakened mid-latitude Westerlies. Sequence boundaries 6/5 and 3/2, in turn, would point at a displaced or weakened Siberian High, with enhanced moisture input from the mid-latitude Westerlies and, possibly, also by the Asian summer monsoon. The extent of the past glaciations in the Arctic region was variable (e.g., Svendsen et al., 2004; Jakobsson et al., 2014), which makes it likely that the precipitation regime was also different.

Glaciation in the Tien Shan might have been rather limited during arid glacials and lake level may have been low. During glacials with wetter conditions, glaciers may have reached the lake and may even have blocked the outlet, potentially leading to the highest lake levels recorded, higher than during (moist) interglacials without blocked outlet. It is therefore impossible to relate sequence boundaries to glacials or interglacials without direct dating of sedimentary material.

7 Conclusions

A seismic study of mainly the western and eastern delta of Lake Issyk-Kul exhibits seven stratigraphic sequences (S7 = oldest, S1 = youngest). Boundaries between the sequences are often erosive (erosional unconformities), and each stratigraphic sequences contains at least 2 delta lobes formed during past lake-level stillstands. The topset-foreset roll-over point was considered as a proxy for lake-level change. In this context, S7, S5, and S2 can be interpreted as formed during falling lake level, while S6, S3, and S1 indicate a lake-level rise. S4 exhibits a lake-level rise followed by a lake-level fall. Taking into account the subaerially exposed lake terraces, a total of at least 400 m of lake-level change could be observed.

While tectonic reasons may have had some influence on lake-level evolution, they were clearly not causal for the cyclic fall and rise. Changes in precipitation/evaporation are more likely causing changes in water level. Currently, the dry air masses of the Siberian High are strong in winter, blocking the mid-latitude Westerlies. During summer, the mid-latitude Westerlies bring moist air into the area, resulting in precipitation peaks in spring/summer and autumn. Lake-level changes point at changes in the atmospheric circulation pattern during the past. Low lake levels point at less precipitation, likely with a strong and stable Siberian High, and high lake levels may have been caused by a weakened or displaced Siberian High and stronger mid-latitude Westerlies, possibly even influence of the Asian summer monsoon. Dating of the cyclic regression/transgression cycles would be fundamental for a better understanding of the regional climate. Drilling into the delta sediments would be needed to establish a chronostratigraphic framework.

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8 Data availability

Seismic profiles are stored at Renard Centre of Marine Geology, Universiteit Gent, Belgium, and can be obtained from Marc De Batist upon request (Marc.DeBatist@UGent.be).

9 Acknowledgements

The seismic surveys were organized with support of the Belgian Science Policy Office (BELSPO) and of the EU FP5 APELIK project. We like to thank the captain and crew of RV Møltur for the support during the seismic campaigns in 1997 and 2001.

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Fig. 1: Geographical settings of Lake Issyk-Kul. Tracklines of all profiles used in this study are shown in green (data from 1997) and orange (2001). The axes of two anticline structures visible in the seismic profiles in the southeastern part of the lake are marked in red. Grey hatched areas mark the approximate position of the Issyk-Kul Broken Foreland, and turquoise line shows the approximate location of the Main Terskey Fault MTF (after Macaulay et al., 2014). Digital terrain model for lake and surrounding from Delvaux et al. (2001). Small inset shows the location of our study site marked with a yellow star (map generated using the ETOPO1 dataset; Amante and Eakins (2009); Projection: WGS84 UTM Zone 43N).

Fig. 2: Facies types SF1 to SF4 of Lake Issyk-Kul sediments. All examples were taken from profile issyk019 (for location of the profile refer to fig. 1).

Fig. 3: Identification of sequence boundaries of Lake Issyk-Kul sediments. Sequence boundaries could best be determined in places where underlying strata was truncated by erosion and strata hence form onlaps or toplaps onto the erosional discordance. Also where overlying strata form downlaps or onlaps onto the stratigraphic boundary these were easily identified. Once identified, stratigraphic boundaries could also be traced as distinct reflections into places where they separate the upper and lower stratigraphic sequence as a conformity.

Fig. 4: N-S profile ik01. The asymmetric nature of the lake basin is clearly visible with considerably higher subsidence rates towards South.

Fig. 5: Seismic profile issyk049. Upper panel: Seismic data. Lower panel: Linedrawing and interpretation of all sequences identified in the profile. All delta lobes identified in issyk049 are indicated. See figure 1 for location of profile issyk049.

Fig. 6: Seismic profile issyk019. Upper panel: Seismic data. Lower panel: Linedrawing and interpretation of all sequences identified in the profile. All delta lobes identified in issyk019 are indicated. See figure 1 for location of profile issyk019.

Fig. 7: Minimum thickness of sequences in the western and eastern areas. Thickness is converted from two-way traveltime using a seismic velocity of 1500 m s^{-1}. Thickness color scale is similar for all panels and shown in the figure. Color scales for topography and bathymetry are similar to fig. 1. Grey lines show where data were available for thickness

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Gelöscht: N-S profile ik01. The asymmetric nature of the lake basin is clearly visible with considerably higher subsidence rates towards South

Fig. 3:

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Gelöscht: 4: Seismic profile issyk019. Upper panel: Seismic data. Lower panel: Linedrawing and interpretation of all sequences identified in the profiles. Trackline of profile issyk019 is marked in Fig. 1.

Fig. 5: Sequences 6 and 7 on seismic profile issyk019. Upper panel:

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Gelöscht: 6. Lower panel: Sequence 7. Seismic data overlaying the respective sequences is removed.

Fig. 6: Sequences 3 / 4 and 5 on seismic profile issyk019. Upper panel: Sequence 3 and 4. Boundary between these two layers cannot

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Gelöscht: eroded and only sequence 4 is visible. Lower panel: Sequence 5. The missing (eroded) parts of deltas 5.1 and 5.2 are tentatively completed in light colors for better visualization. Seismic data overlaying the respective sequences is removed

calculation. Note that sequences 3 and 4 could only be distinguished in the western delta, while a combined thickness for sequences 3 & 4 was calculated for the eastern delta.

Fig. 8: Sequences 1 and 2 on seismic profile issyk019. Upper panel: Sequence 1 with distinct deltas 1.1 and 1.6 and the transgressional phase. Deltas 1.2 to 1.5 are only visible in parallel profiles, but their relative location is marked. Note that the lower boundary of Sequence 1 is highly erosive with deeply incised channels. Lower panel: Sequence 2. The missing (eroded) parts of deltas 2.1 and 2.2 are tentatively completed in light colors for better visualization. Seismic data overlaying the respective sequences is removed.

Fig. 9: Lake-level curve of Lake Issyk-Kul. Red line: mean value of delta depths; gray shading: standard deviation of delta depths. Numbers correspond to delta numbers in the text and in table 1. Boundaries in between the different sequences are at least partially erosive.

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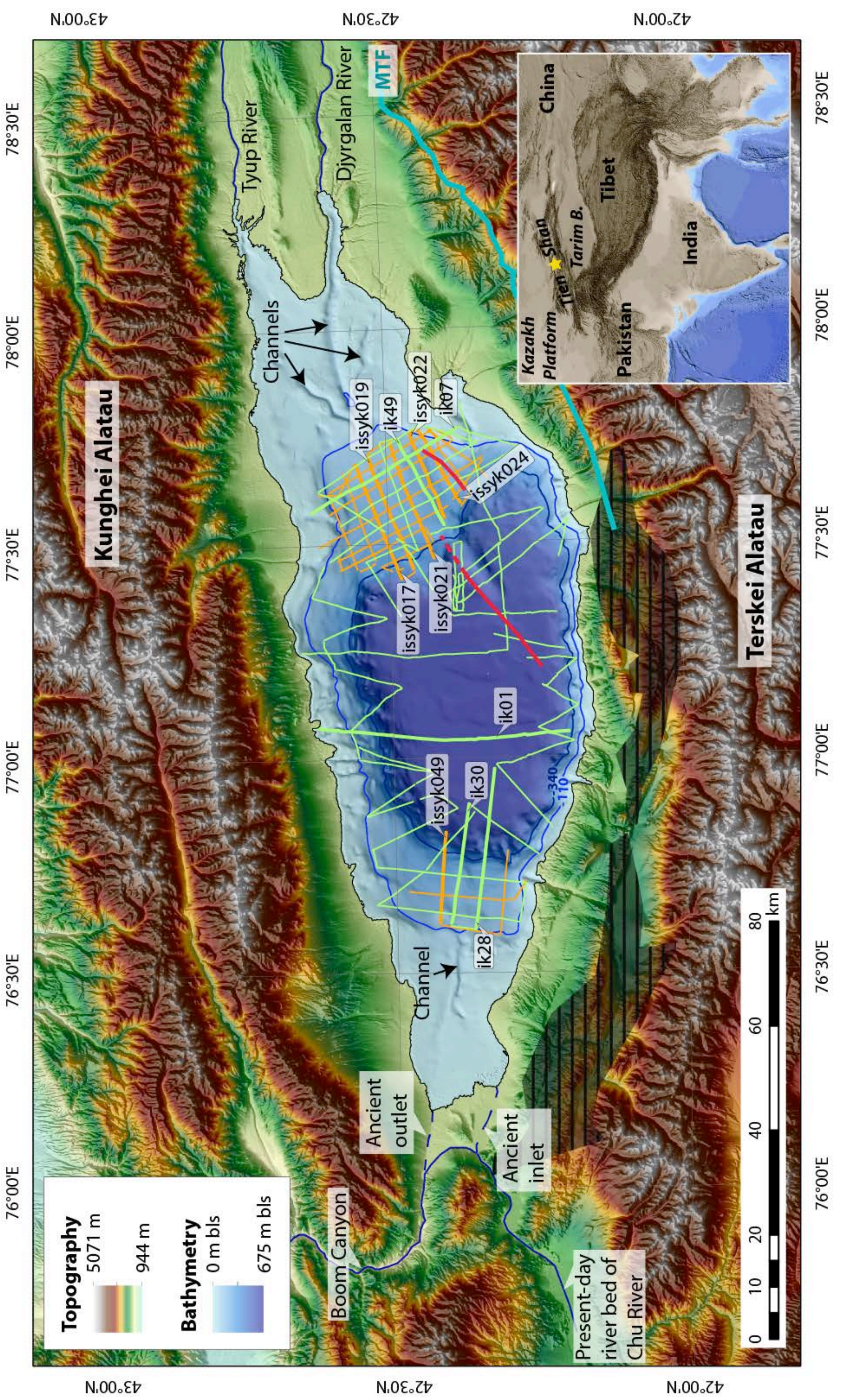
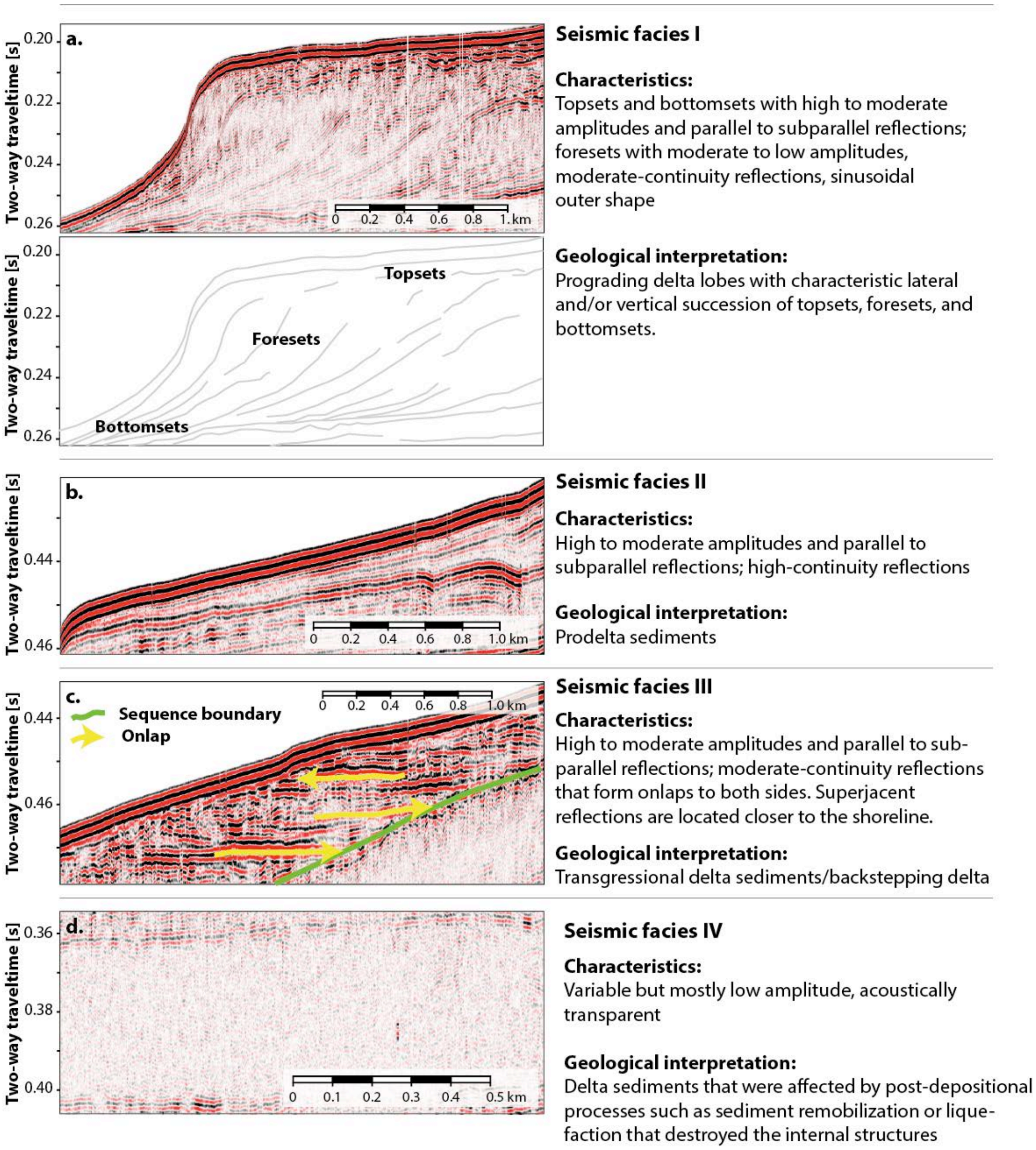


Fig. 1: Geographical settings of Lake Issyk-Kul. Tracklines of all profiles used in this study are shown in green (data from 1997) and orange (2001). The axes of two anticline structures visible in the seismic profiles in the southeastern part of the lake are marked in red. Grey hatched areas mark the approximate position of the Issyk-Kul Broken Foreland, and

turquoise line shows the approximate location of the Main Terskey Fault MTF (after Macaulay et al., 2014). Digital terrain model for lake and surrounding from Delvaux et al. (2001). Small inset shows the location of our study site marked with a yellow star (map generated using the ETOPO1 dataset; Amante and Eakins (2009); Projection: WGS84 UTM Zone 43N).



Seismic facies I

Characteristics:
Topsets and bottomsets with high to moderate amplitudes and parallel to subparallel reflections; foresets with moderate to low amplitudes, moderate-continuity reflections, sinusoidal outer shape

Geological interpretation:
Prograding delta lobes with characteristic lateral and/or vertical succession of topsets, foresets, and bottomsets.

Seismic facies II

Characteristics:
High to moderate amplitudes and parallel to subparallel reflections; high-continuity reflections

Geological interpretation:
Prodelta sediments

Seismic facies III

Characteristics:
High to moderate amplitudes and parallel to subparallel reflections; moderate-continuity reflections that form onlaps to both sides. Superjacent reflections are located closer to the shoreline.

Geological interpretation:
Transgressional delta sediments/backstepping delta

Seismic facies IV

Characteristics:
Variable but mostly low amplitude, acoustically transparent

Geological interpretation:
Delta sediments that were affected by post-depositional processes such as sediment remobilization or liquefaction that destroyed the internal structures

Fig. 2: Facies types SF1 to SF4 of Lake Issyk-Kul sediments. All examples were taken from profile issyk019 (for location of the profile refer to fig. 1).

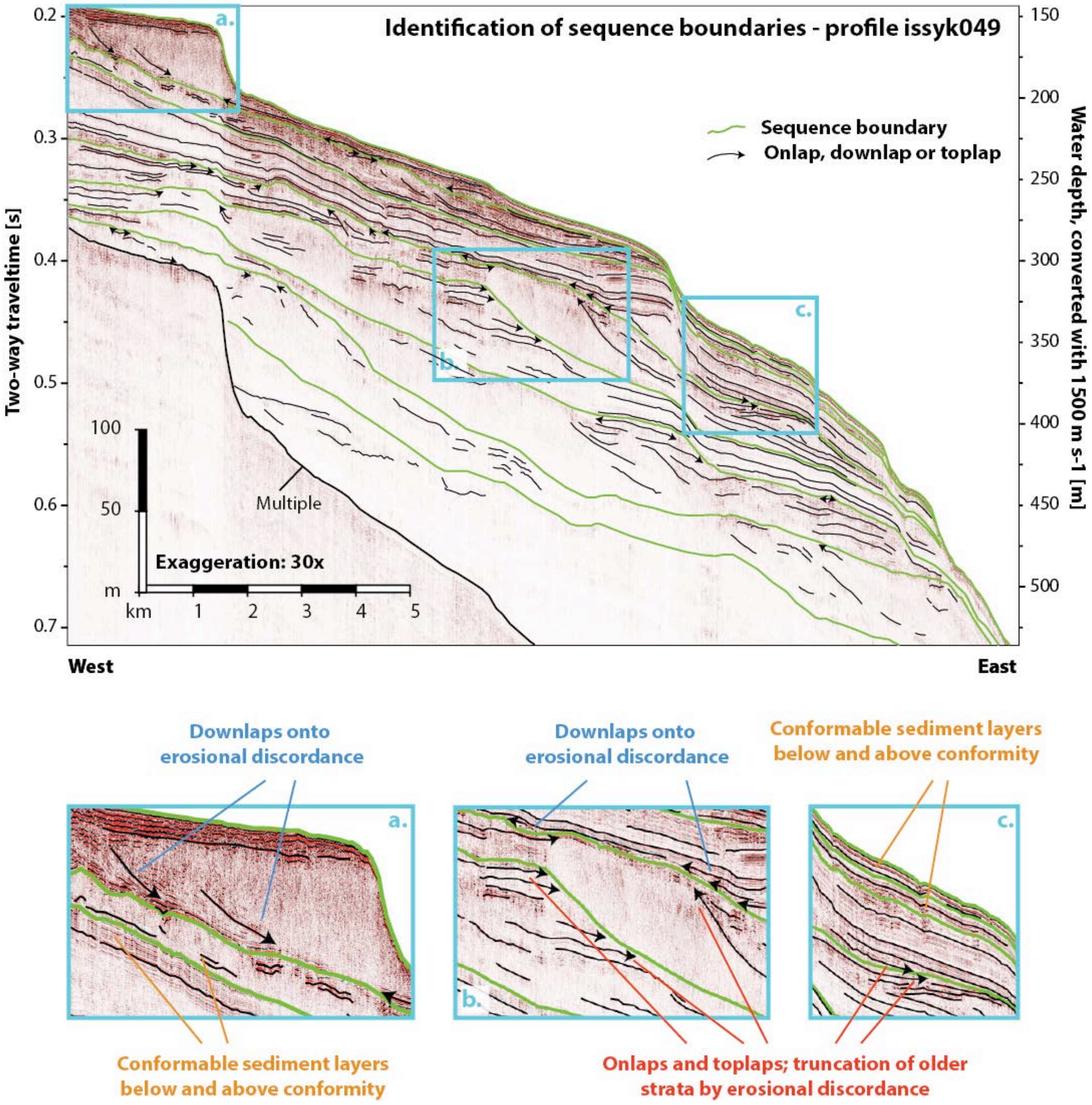


Fig. 3: Identification of sequence boundaries of Lake Issyk-Kul sediments. Sequence boundaries could best be determined in places where underlying strata was truncated by erosion and strata hence form onlaps or toplaps onto the erosional discordance. Also where overlying strata form downlaps or onlaps onto the stratigraphic boundary these were easily identified. Once identified, stratigraphic boundaries could also be traced as distinct reflections into places where they separate the upper and lower stratigraphic sequence as a conformity.

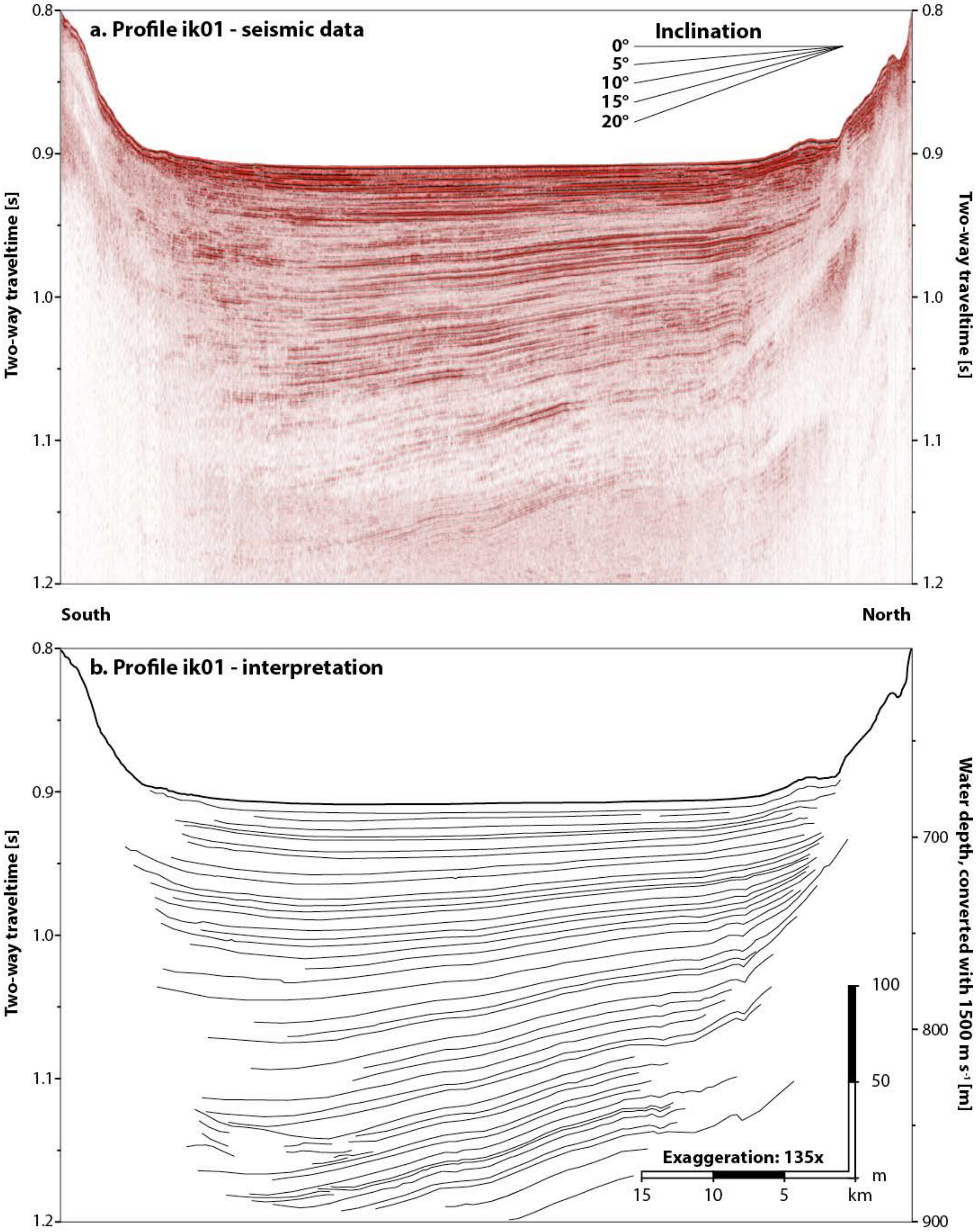


Fig. 4: N-S profile ik01. The asymmetric nature of the lake basin is clearly visible with considerably higher subsidence rates towards South.

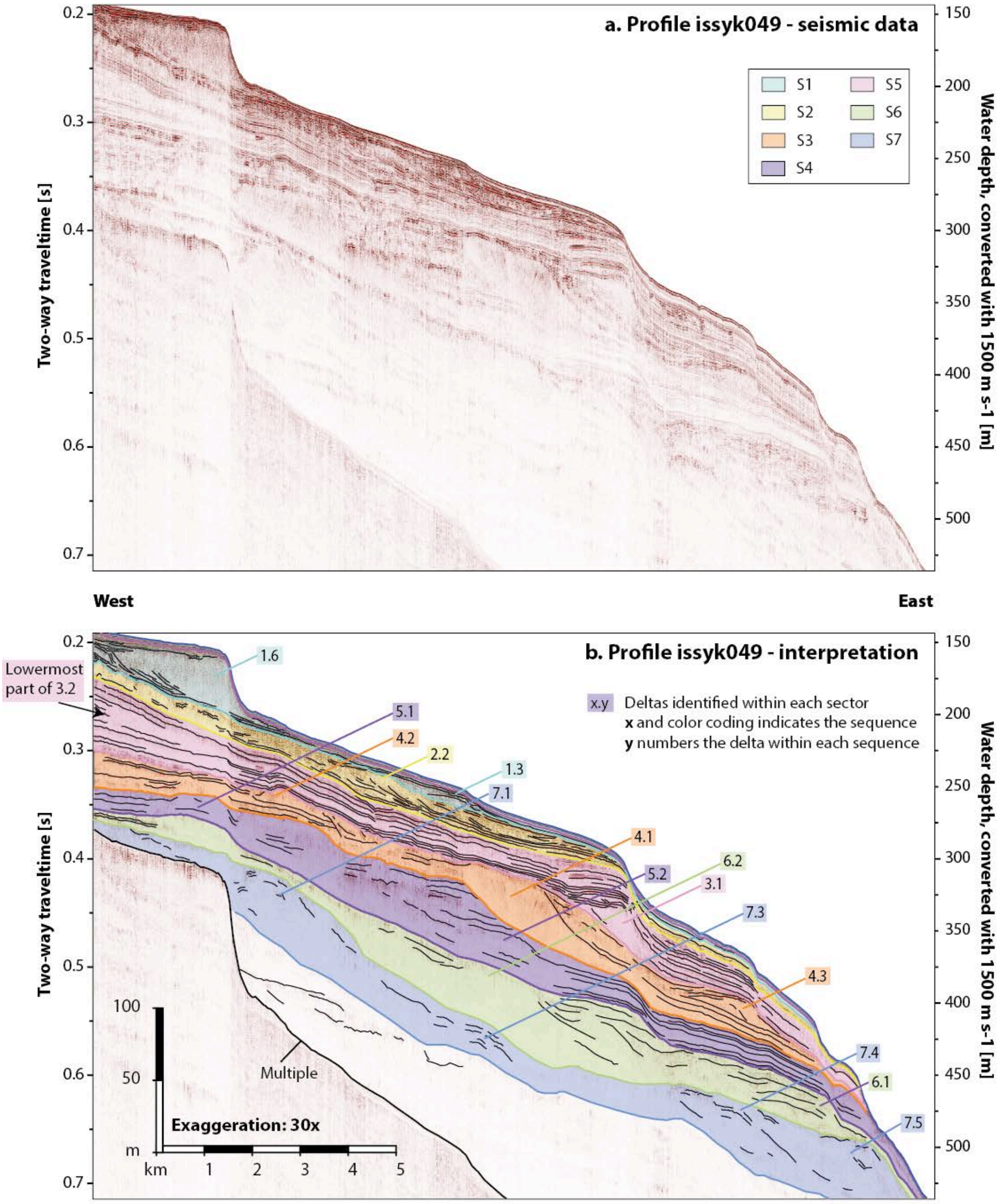


Fig. 5: Seismic profile issyk049. Upper panel: Seismic data. Lower panel: Linedrawing and interpretation of all sequences identified in the profile. All delta lobes identified in issyk049 are indicated. See figure 1 for location of profile issyk049.

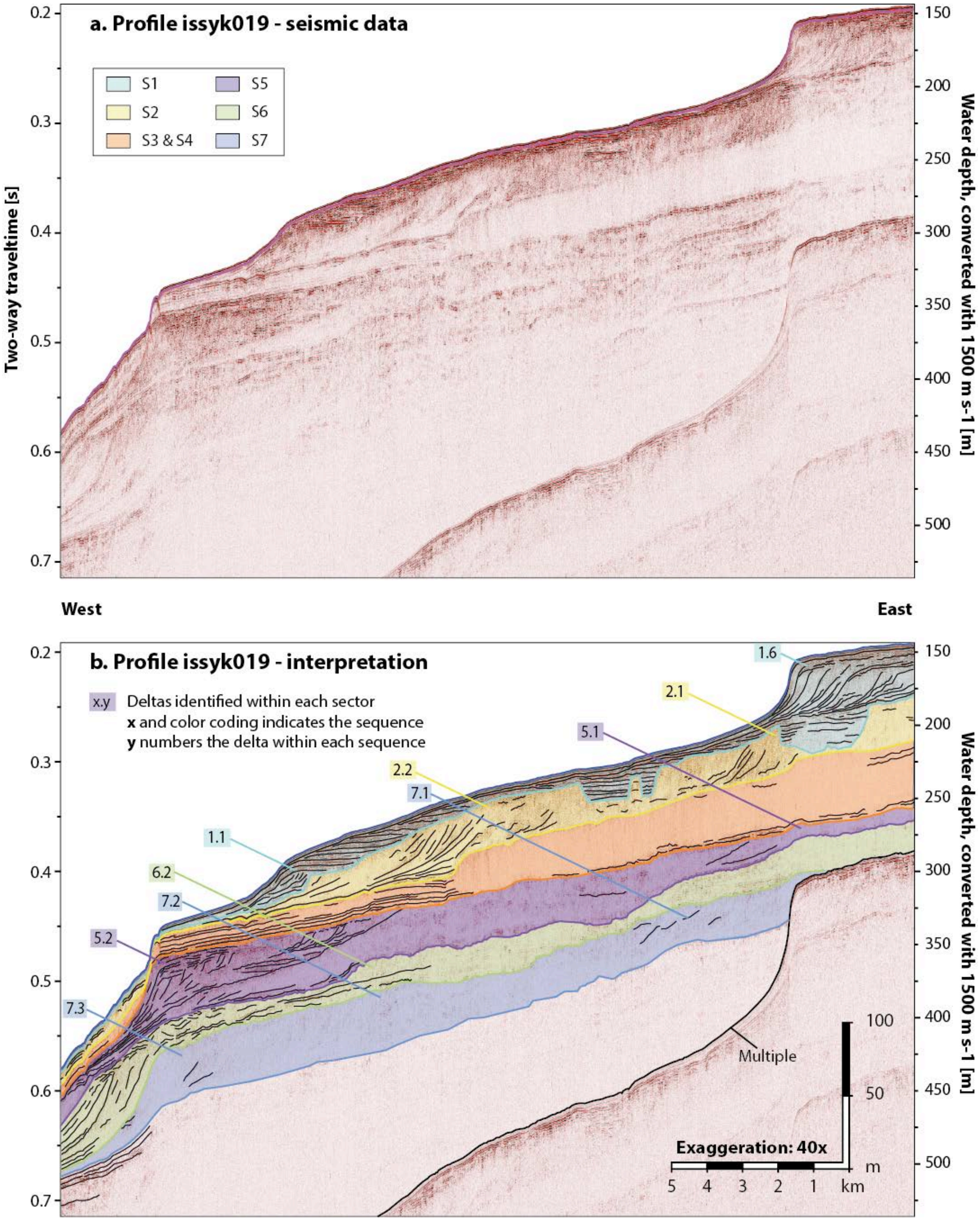


Fig. 6: Seismic profile issyk019. Upper panel: Seismic data. Lower panel: Linedrawing and interpretation of all sequences identified in the profile. All delta lobes identified in issyk019 are indicated. See figure 1 for location of profile issyk019.

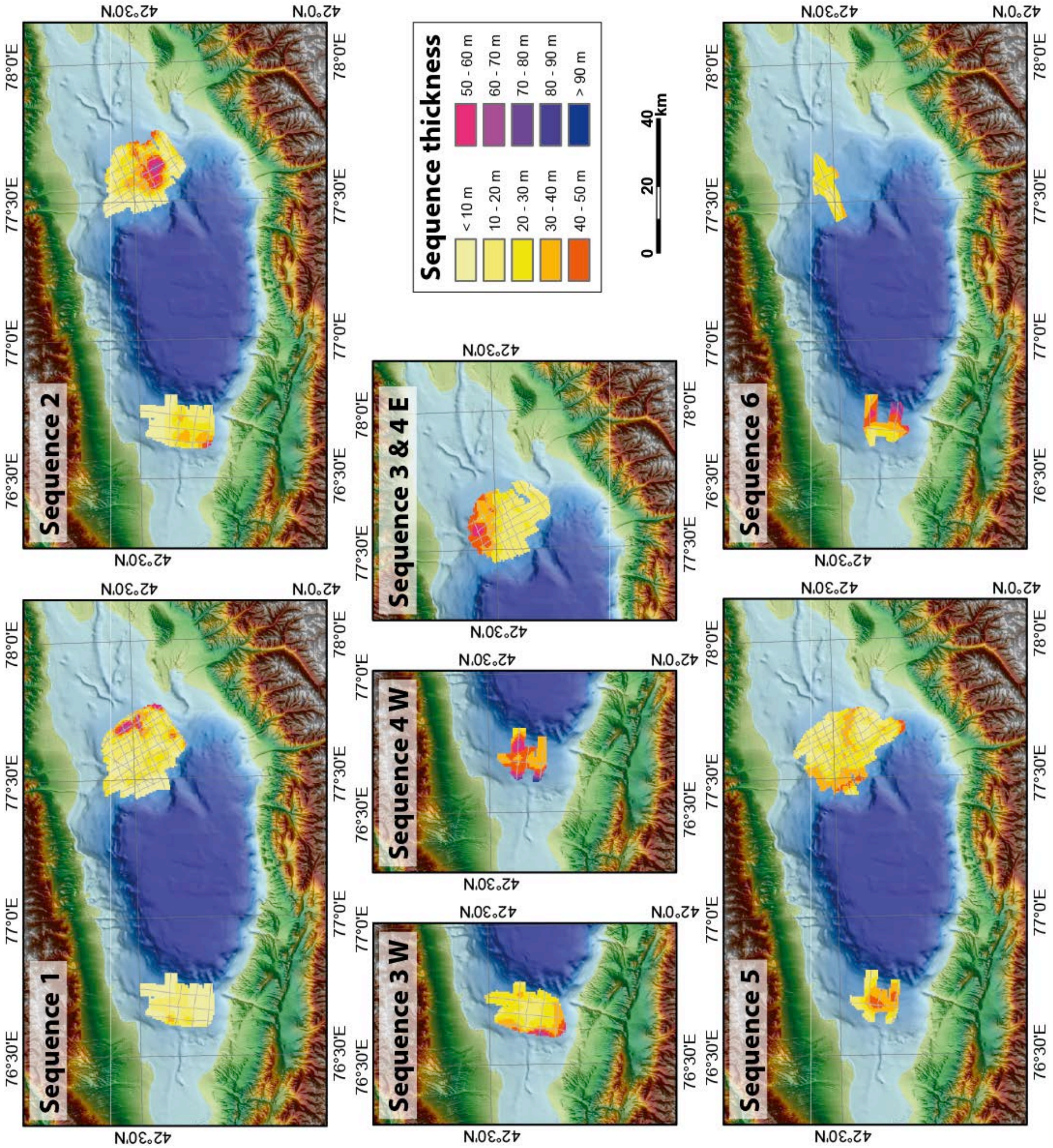


Fig. 7: Minimum thickness of sequences in the western and eastern areas. Thickness is converted from two-way traveltime using a seismic velocity of 1500 m s^{-1}. Thickness color scale is similar for all panels and shown in the figure. Color scales for topography and bathymetry are similar to fig. 1. Grey lines show where data were available for thickness calculation. Note that sequences 3 and 4 could only be distinguished in the western delta, while a combined thickness for sequences 3 & 4 was calculated for the eastern delta.

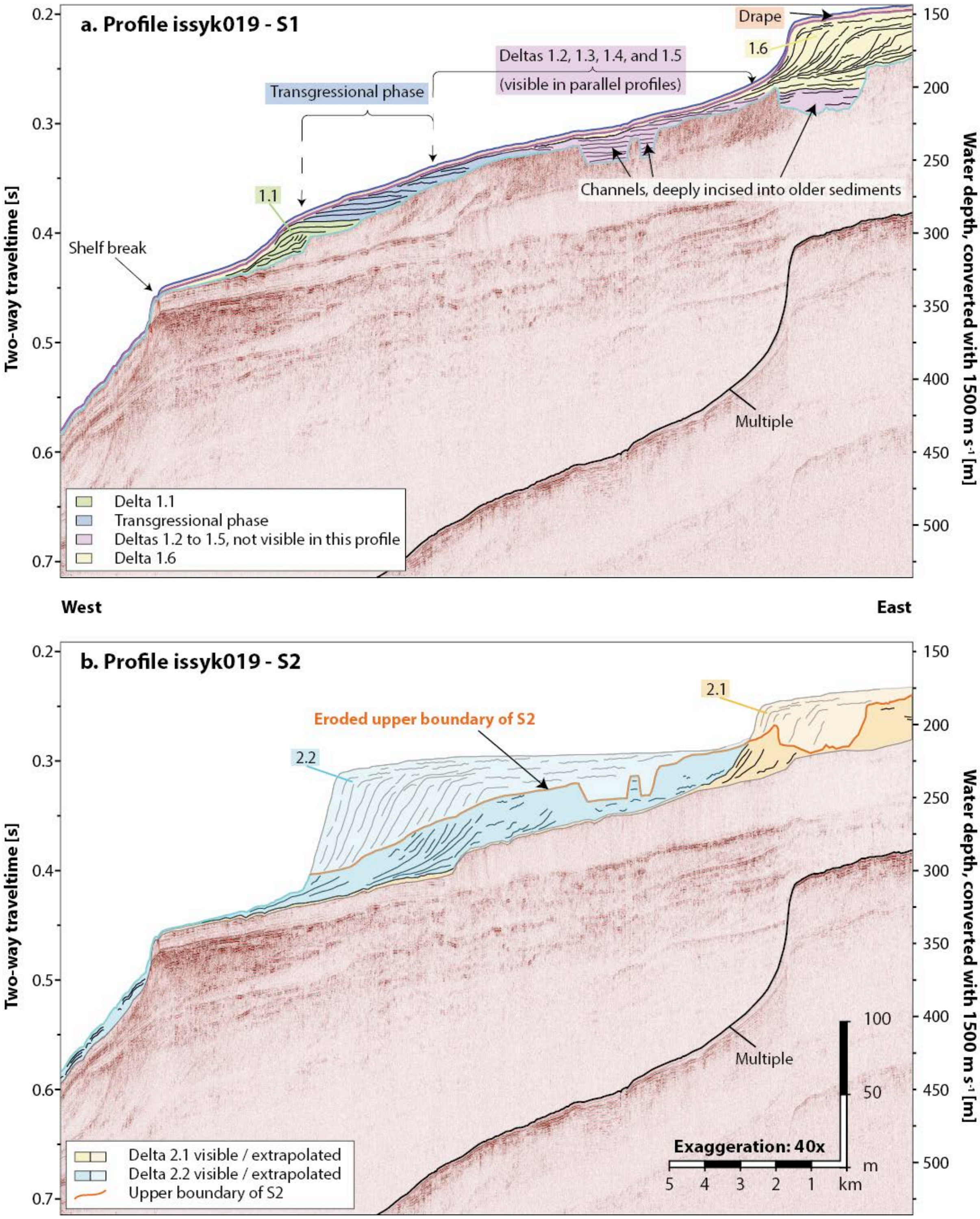


Fig. 8: Sequences 1 and 2 on seismic profile issyk019. Upper panel: Sequence 1 with distinct deltas 1.1 and 1.6 and the transgressional phase. Deltas 1.2 to 1.5 are only visible in parallel profiles, but their relative location is marked. Note that the lower boundary of Sequence 1 is highly erosive with deeply incised channels. Lower panel: Sequence 2. The missing (eroded) parts of deltas 2.1 and 2.2 are tentatively completed in light colors for better visualization. Seismic data overlaying the respective sequences is removed.

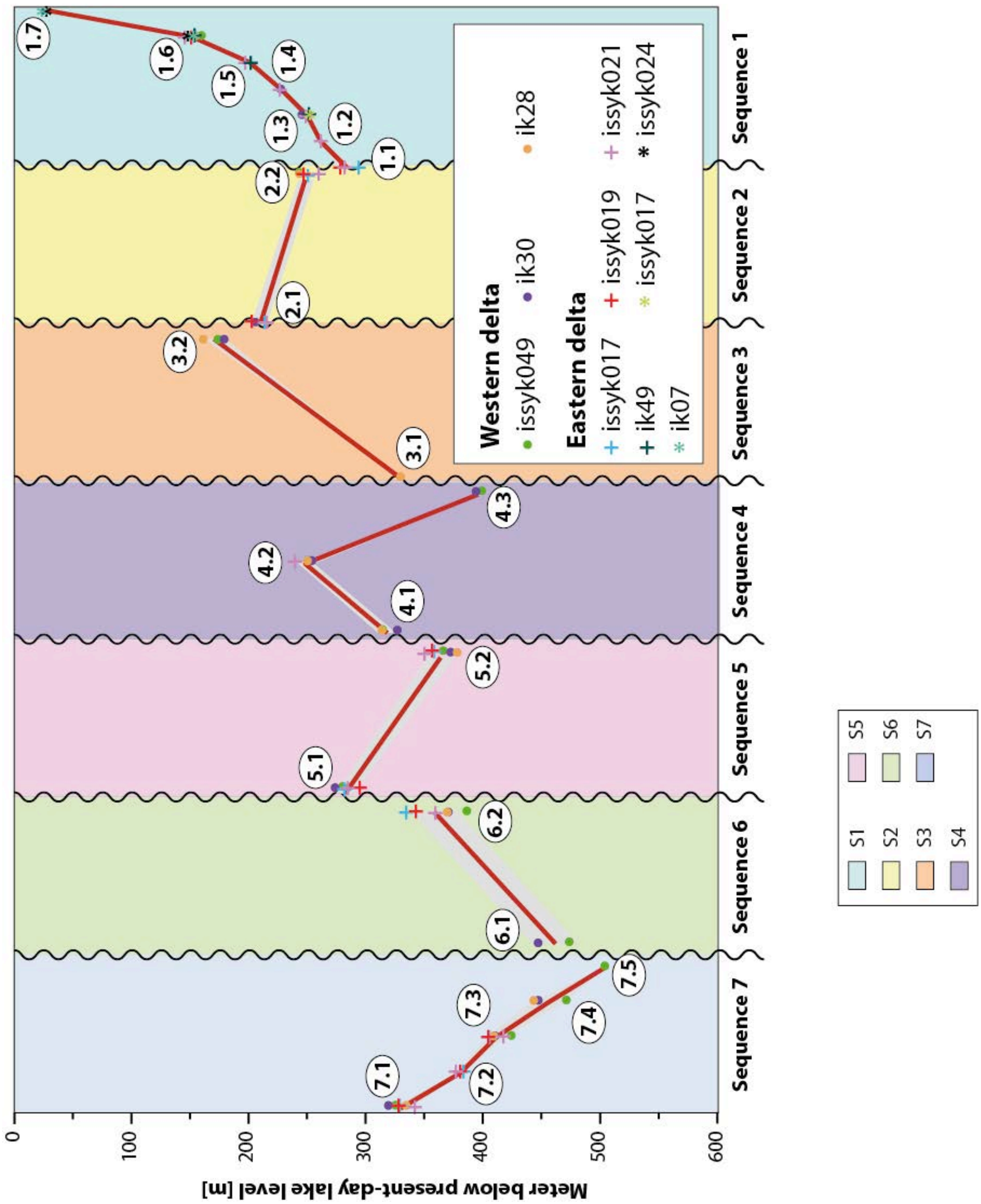


Fig. 9: Lake-level curve of Lake Issyk-Kul. Red line: mean value of delta depths; gray shading: standard deviation of delta depths. Numbers correspond to delta numbers in the text and in table 1. Boundaries in between the different sequences are at least partially erosive.