Response to referees – ESurf-2019-54

Dear Dr. Masteller,

Thank you and the handling editor for the editing advice and to the three reviewers for their time and for the constructive and insightful reviews. We have incorporated many of the suggested changes and modified the manuscript to address the concerns raised, and we are pleased to include the revised manuscript.

Please find below are our replies to different comments by each referee in blue. To summarize, we have made significant changes to the discussion section so it now address the issues raised regarding the calculations of paleo-production rates and the derived erosion rates. We now focus on exposure times comparing between the modern and Miocene cherts, and consider these differences as they pertain to erosion rates. We have also added an additional table (Table 2), which includes exposure times and erosion rates calculated using paleo-elevations that range 500-1000 m.a.s.l in order to make comparison easier for the reader. We hope that the revisions made to the discussion as well as other sections will now make the manuscript clearer and easier to follow.

Please find attached below the revised manuscript with our additions and replacements displayed in tracked changes mode. Page and line numbers refer to the revised version of the manuscript in 'Simple Markup' setting.

We believe that our manuscript is much improved and we hope it is now ready for publication in ESurf. Please contact me for any further questions or information.

Sincerely,

Michal Ben-Israel

Michal Ben-Israel

(on behalf of all the authors)

Response to Reviewer no. 1: Taylor Schildgen

General comments:

Ben-Israel and co-authors analyze stable (21Ne) and unstable (10Be, 26Al) cosmogenic nuclides in detrital Miocene sediments from the NW Arabian plateau to calculate paleo-erosion rates and compare these to "modern" rates obtained from bedrock outcrops. They interpret an approximate 2-fold difference in concentrations to result from erosion rates that were 2x faster during the early-mid Miocene, which could be reasonable considering evidence for a wetter climate in the region at that time. On the positive side, this work illustrates the unique ability of the stable cosmogenic nuclide 21Ne to record erosion rates averaged over relatively short time intervals (if we can consider 100s of kyr short) in ancient, well-shielded sedimentary deposits; such information cannot be obtained with 10Be or 26Al. The authors are careful in their consideration of various potential complications of their data – post-burial deposition, changes in elevation through time, and how different types of detrital material (quartz sand v. chert pebbles) could have experienced very different pathways to the final deposition site. I also really like the use of different types of detrital material to assess the possibility of 21Ne inheritance.

We thank prof. Schieldgen for these comments.

But I see several areas that require improvement. Most concerning for me is the discussion of the uplift-history constraints, which I don't find very convincing, but are critical for the final interpretations, as the difference in measured 21Ne concentrations between modern and mid-Miocene samples can be explained either by a change in elevation through time or a change in erosion rates.

This is a very good point and one that has been similarly made by the other reviewers. While we consider this uncertainty in the original manuscript, we agree that the discussion into the interpreted paleo-erosion rates should have been done more circumspectly. We now include additional discussion into the Miocene paleo-elevation and the calculated production rates. In addition to the stratigraphic and cooling ages evidence we now also calculate the possible elevation using a moderate continental slope. Furthermore, to account for the uncertainty in paleo-elevation as well as basin scaled paleo-production rates, we now consider an elevation uncertainty range of 500-1000 m.a.s.l (see lines 250-289, and table 2).

But even if there has not been a change in elevation, the difference in erosion rates reported (2-4 mm/kyr v. 4-12 mm/kyr) is not huge, and those mid-Miocene rates are still pretty darn slow. Is this really a story about how climate affects erosion rates, or could the conclusion be that it doesn't affect them all that much?

This is a valid point, and while it is true that the differences between modern and paleo-erosion rates calculated are relatively slow, it is important to note that the comparison made is not straighforward. The modern rates represent only erosion from bedrock, while the Miocene erosion rates represent both erosion from bedrock and transport in the Miocene river. There is no way of evaluating what were the actual bedrock erosion rates during the Miocene, only that they must have been faster. This point was is now made more clearly with the comparison between exposure times throughout most of the disscusion with erosion rates mentioned only in the final part of the manuscript. As mentioned, in these (currently) hyper-arid environment, even small changes to erosion rates are significant. See the revised disscusion (lines 333-343) and conclusions (lines 377-381).

I'm also concerned by the small number of samples obtained from the outcrops (only two), and the possibility that the rates reported are not representative of modern rates (often spot samples from outcrops lead to a wide range of erosion-rate estimates). Are there any other modern erosion rates that have been reported that can be used to corroborate the results presented here? Is there a reason a modern erosion-rate estimate wasn't made from modern detrital sands in the region, even if that rate would not be from exactly the same drainage area as the early-mid Miocene samples?

Unfortunately, the area where A. Matmon and Y. Avni collected the modern chert nodules is very difficult to access these days, and it is not possible to collect any more samples. However, as we point to in the manuscript, there has is an extensive body of work looking into rates of erosion of chert and quartzite surfaces in the hyper-arid Negev desert (e.g., Boroda et al., 2014; Fruchter et al., 2011; Matmon et al., 2009; Matmon et al., 2016; Matmon and Zilberman, 2017). We now references rates from these studies (see lines 307-309).

I think the difference between the detrital quartz sand and detrital chert pebbles can be better emphasized in the final interpretations/conclusions of the paper. It seems that the quartz-sand results are not considered in the final interpretations due to the possibility that the quartz experienced multiple periods of deposition and exposure prior to the last deposition, hence it contains inherited 21Ne (if that's the reason that the erosion rates for the quartz samples are not reported, the authors should state that explicitly rather than leaving it for the readers to infer; still I think the erosion rates should be reported). But rather than making it seem as if those samples were just a waste of time, it could be helpful to emphasize how in recycled sediments, inherited 21Ne can be a real problem. I like the approach here of measuring different types of detrital material to assess this possibility! That could be highlighted, rather than hidden.

That was by no means our intention. Inherited cosmogenic 21Ne is one of the disadvantages of using cosmogenic 21Ne and we include this limitation throughout the manuscript and in the conclusion section (see lines 373-376).

Finally, I think the introductory paragraph can be improved; several of my line-specific comments refer to my confusion about where the paper is going just in the first several sentences.

We have now revised the introduction paragraph (see lines 28-54).

Line-specific comments:

l. 36-37: Older landscapes are transient? Odd wording. Also, this sentence doesn't really follow from the previous ones. You've discussed river systems and sediment archives, now we're on to preservation of landscapes themselves? Be more precise and focused.

We have changed the phrasing in this section. See lines 35-46.

l. 38: Okay, so the focus is on quantifying erosion rates from surfaces? This is not easy to follow.

See previous comment.

l. 41: If the focus is on erosion, don't change the terminology here to "surface processes", as that encompasses much more than just erosion.

See previous comment.

l. 43: Now you've explained that the focus is on sedimentary deposits, not slowly eroding surfaces. I suggest rewriting this whole paragraph with a clearer focus on what information you want to give to the reader. What is the main problem, why is it difficult to address, how are you going to do it?

See previous comment.

l. 51: Wouldn't it be the other way around, i.e., the Afar plume leads to magmatic events, and maybe even influenced tectonics?

We have changed the phrasing in this section. See lines 56-65.

l. 67-69: This means that the deposition associated with the river started prior to ca. 20 Ma? Or do you interpret only the upper part of the Hazeva Formation to be associated with the river, meaning that fluvial deposition started after 20 Ma? Please clarify.

The sediments in lower part of the Hazeva formation are local and were not deposited by the Hazeva River (unlike the upper part of the section). We have now clarified this in the text (see lines 79-92).

l. 99-101: How is this history of the quartz sand known? If this history is going to be important for explaining differences between 21Ne measured in quartz vs. chert, then a fuller explanation is needed. One potential worry with quartz sand is that it could be aeolian in origin; can this be ruled out?

The history, provenance and stratigraphy of the Hazeva formation was previously researched and is reported by Calvo and Bartov (2001) and Zilberman and Calvo (2013) and is beyond the scope of this manuscript. While an eolian history cannot be ruled out, it is not likely. There is no reason to assume that sediment eroded from bedrock and deposited in a fluvial environment is of eolian source. We now try to make this clearer in the text (see lines 76-81).

What size fraction of sand was processed?

The grain size fraction analyzed is now reported in lines 134-135.

l. 90-105: I suggest moving this paragraph to the geological setting, as it provides the geological context for the samples collected.

This paragraph has been moved and modified. See lines 75-95.

l. 109: How deeply shielded were the collected samples? Deeply enough to rule out post-depositional 21Ne production?

This question is thoroughly discussed in the discussion section. We now refer to this in the text (see line 116).

l. 113: I suggest “accumulated cosmogenic nuclides only during exhumation”, as the samples that experienced the full sedimentary cycle also accumulated nuclides during exhumation.

We accept this correction. See line 127.

l. 156-157: Is this because you assume the U and Th are equally distributed throughout the rock? Is that a reasonable assumption?

U and Th are most likely found in inclusions within the crystal lattice. The U/Th concentration in the cherts is determined by the age of the rock and the environmental conditions during its formation (or later metamorphosis). It is reasonable to assume that is would the same or similar for all the presented cherts as they all share the same lithology.

l. 212-217: Don’t assume that your readers remember that EJC5 and EJC3 were the surface samples of from the “in situ” outcrops, remind us.

Maybe this comment can be clarified as the first part of the paragraph describes exactly that (see lines 246-259).

l. 214-215: This detail concerning the scaling of production rates belongs in the methods, not the discussion.

We now include these details in the methods section (see section 3.3, lines 152-156).

l. 223-224: I don’t see the added value of reporting equivalent exposure times (if that is what is meant by “simple exposure time”), given that you are mainly interpreting the measured concentrations in terms of erosion rates. Or is the goal to give readers a sense of the averaging timescale of these erosion rates? If the latter, I suggest rewording to make this clear.

The revised manuscript now focuses on exposure times (only later do we discuss the inferred erosion rates). The calculated exposure times are explained in lines 246-249.

l. 224-226: It is important, but why? I can make a guess, but it would better if you explain.

We now explain this, see lines 310-312.

l. 230-231: Could you please briefly remind me what those differences in concentrations are?

This section has now been revised and we no longer discuss 21Ne concentrations but exposure ages, which are reported in lines 291-293 and in Table 2.

l. 237-239: A bigger overview map that includes the Suez rift in addition to the all the other relevant sites mentioned here would be very helpful.

See our revisions to figure 2, and our comments to this there.

l. 237-242: These uplift constraints are crucial for your interpretation of whether or not there the Miocene samples show a faster erosion rate compared to today or reflect a similar erosion rate with a lower nuclide paleo-production rate. Given their importance, some more details on these uplift constraints would be very helpful. Although I have not checked each of the references in detail, I disagree with how you have referenced the Wilson et al. (2014) interpretations. Despite many reasons why these interpretations of uplift histories from river profiles should be considered suspect, their interpretation for your field area is that most of the modern elevation gain occurred since 20 Ma, and it looks like more than half of that is since 10 Ma (see their Fig. 17). For that reason, I don't agree at all with your statement that it is reasonable to presume that the western flank of the Arabian Peninsula (or the NW edge, corresponding to your field area) reached its current elevation prior to the initiation of the Hazeva fluvial system at ca. 18 Ma.

As is mentioned in our answers to the general comments, we agree with this comment. Our discussion regarding the elevation of the Arabian Plateau during the Miocene should have been more thorough. We now provide additional evidence to support our assumption of the paleo-elevation as well as consider a significant uncertainty for this (see lines 250-289). Regarding Wilson et al. (2014), both in figure 17 and in figure 21, the central part of the Arabian plate appears to be stable ~20 Myr ago (unlike the southwestern tip).

l. 255-258: I can guess why you do not mention erosion rates from the quartz sand – because you suspect it has inherited 21Ne – but it seems like an oversight. I suggest to not "hide" those results, but rather emphasize how recycling of quartz sand can lead to incorrect results.

As is mentioned in our answers to the general comments, hiding this aspect was not at all our intention. We refer to the possible inheritance in quartz throughout the manuscript (including the conclusions section). The discussion about the possible effects of it is slightly beyond the scope of this manuscript but is referenced to (see Ben-Israel et al., 2018 for further reading).

l. 281-287: Mostly I've been able to work out myself whether you are referring to surface uplift or rock uplift up until now, but in this section in particular I cannot follow your meaning. In this paragraph, and ideally throughout the manuscript, specify which one you are referring to.

As is mentioned in our answers to the general comments, hiding this aspect was not at all our intention. We refer to the possible inheritance in quartz throughout the manuscript (including the conclusions section). The discussion about the possible effects of it is slightly beyond the scope of this manuscript but is referenced to (see Ben-Israel et al., 2018 for further reading).

l. 285: But this is not an accurate representation of the uplift history for your field area as interpreted by Wilson et al. (2014).

This section has now been revised – see out previous comments and lines 344-351.

l. 288-300: This evidence for a wetter early to mid Miocene climate seems reasonable, and I agree that such a climate would likely erode faster than low-relief, hyperarid landscapes. But the mid-Miocene erosion rates reported here, which might be considered maximum rates given the uncertainty in the paleo-elevation, still seem very slow. How do rates of 4 to 12 mm/kyr compare with erosion rates measured from similar environments today? (Incidentally, I realize I'm assuming that the landscape relief is relatively low, but it would be helpful to actually show a slope/relief map to see whether or not that's the case).

This section has now been revised – see out previous comments and lines 332-343.

Figure 2: As mentioned above, a broader overview map would be very helpful. In 2B, is that a person near the bottom? Highlighting or circling him/her in some way would make it easier to understand the scale of this photo. Likewise, in 2C, is that a dog?

Figure 2 has been revised and now includes a more zoomed overview map with Red Sea marked on it. It additionally now includes clear marking of a human (Dr. Avni) in 2B and dog (Kara) in 2C.

Figure 3: Given the overall focus on erosion rates, I find it odd that the calculated erosion rates are not shown in this figure. Why not use those instead of the effective exposure ages?

With the addition of Table 2, figure 3 no longer includes exposure ages (or erosion rates).

Editorial comments:

l. 35: always specify what you mean after "this“, e.g., this lack of information?

Corrected. See line 38.

l. 64: "comprise" rather than "compose"

Corrected. See line 78.

l. 71: I'd suggest "disruption" rather than "dismantlement"

Corrected. See line 71.

l. 81: What "cycles" are you referring to here? Okay, you clarify it in the next sentence, but please instead clarify at your first instance of using this term.

Corrected. See lines 99-102.

l. 86: This what should hold true?

This section has been revised. See lines 192-202.

l. 96: comprising, not composing.

Corrected. See line 88.

l. 210: Please refer to “denudation” or “erosion” rates throughout, not “rates of surface processes”, which is unnecessarily vague.

We have corrected this in the referenced line (245) and throughout the manuscript.

l. 221: lots of needless words here, please shorten to “erosion rates between 1 and 5 mm/kyr”

This section has been revised. See lines 307-309.

Response to Reviewer no. 2: Anonymous Referee

Ben-Israel et al. present 10 new in situ-produced 21Ne concentrations from quartz and chert material in the pre-Dead Sea rift Hazewa River located in southern Israel. Where possible in situ-produced 10Be and 26Al concentrations are provided for the same sample material. The data from sand, pebbles, and nodules is used to determine Early-mid Miocene erosion rates.

General comments:

The manuscript is generally well written and reads well. However, there are several weak points in the manuscript which need to be clarified and improved:

We thank the reviwer for these comments.

1. The interpretations of the data are relatively strong given the amount of available data. As the manuscript stands right now, it is not clear to me if the given interpretations of the results would stand if more data is available. For instance, the nuclide concentrations of the two chert nodules do not agree with continuous erosion of a landscape. In order to investigate the problem more samples should be analyzed. However, knowing that this is easy to say and that cosmogenic nuclide analysis are expensive, a request for more data is not at the right place. Instead a request to tone down the interpretation is made.

As the first reviewer made a similar point, I include here the answer given there: Unfortunately, the area where A. Matmon and Y. Avni collected the modern chert nodules is very difficult to access these days, and it is not possible to collect any more samples. However, as we point to in the manuscript, there has is an extensive body of work looking into rates of erosion of chert and quartzite surfaces in the hyper-arid Negev desert (e.g., Boroda et al., 2014; Fruchter et al., 2011; Matmon et al., 2009; Matmon et al., 2016; Matmon and Zilberman, 2017). We now references rates from these studies (see lines 307-309).

2. The method section needs to be set-up in a logical and rigorous way (see detailed comments below). The different methods applied need to be described in more detail. The calculations performed and parameters used explained. In general, the order of the presented information could be rearranged to make understanding easier. Concise wording and details in tables and figures are needed (see comments below).

We have somewhat revised the methods section based on comments made here and by the other reviewers. See revisions made to sections 2 and 3.

3. The interpretation of the data needs to be more rigorous. For instance, the nuclide concentrations could be normalized to the same altitude. This would make a comparison more meaningful. A chert nodule at 1000 m above sea level subjected to slow erosion rates is expected to have high nuclide concentrations.

We generally agree with this comment and believe that the data is now presented in a more precise and correct manner. We have now revised the manuscript so we mostly compare exposure times. We still present cosmogenic concentration but solely to examine differences between different samples at the same site (figure 3). Lastly, we present a comparison between exposure times that includes the different possible paleo-erosion rates (see table 2).

Concentrations and erosion rates could also be investigated with “banana plots” for the three different nuclides (e.g., Ivy-Ochs and Kober, 2008). Such plots would help to visualize the data presented in Table 1. In addition, the use of erosion rate in combination with the integration time could be helpful for the reader.

Unfortunately, applying a ‘banana-plot’ type of diagram will not help in investigating the reported data. The Miocene sample presented have been buried for extensive periods and so the measured concentrations of cosmogenic 26Al and 10Be do not represent burial time, as the samples have reached a steady state determined by post-burial (muonic) production. We did include a figure that presents changes in steady state concentration with time (see fig. 4).

Unfortunately, I am not an expert in the measurements of cosmogenic 21Ne. Therefore, the quality and reliability of the presented measurements are not assessed in this review. This is hopefully addressed by another reviewer. For instance, it is not clear to me what happens to 21Ne during sample preparation when leached at 150_C (see line 118-9)? This question comes up as just some lines above (86-9) the closure temperature for 21Ne in quartz is mentioned to be 90 - 100_C. As diffusion is a slow process, the used sample preparation may be valid. Clarification is needed.

As the manuscript suggests, 80-90°C is the closure temperature of Ne in quartz over *geological timescales.* The fractional loss of Ne due to diffusion over a 1.5 hour timeframe is insignificant (<0.1%). Nevertheless, we now include a more rigorous examination of possible diffusion from the samples based on comments made by the third reviewer (see lines 106-112 & 193-203).

Detailed comments:

<u>Abstract</u>

L11-14 The abstract jumps to much into details which are not relevant for the abstract. It would make more sense to give the reader a reason why this study was done and what the goal is.

The abstract has been revised (see lines 25-27). However, we think a short geological background is important for the reader to understand the context of this work and that it is a good starting point.

L15-18 What do you mean by “modern erosion rates”? Do these rates not integrate over hundred thousand of years? Please clarify.

This part has been revised. See lines 14-18.

L16-17 Would it make more sense to first report nuclide concentrations and then move to erosion rates?

This part has been revised. See lines 14-18.

L20-21 Is bedrock erosion equal to modern erosion?

This part has been revised. See lines 21-25.

L21-23 Long sentence not easy to understand. What does the even mean? Are the currently eroding chert nodules not used for the bedrock erosin? Needs clarification.

This part has been revised. See lines 21-25.

L24-25 From what material are the “rates calculated today”? And what does it mean “rates calculated today”? As mentioned in the general comments, it might be better to compare (normalized) concentrations rather than erosion rates.

This part has been revised. See lines 21-25.

1 Introduction

L37-40 This sentence is not easy to understand for a reader not familiar to the technique of in situ-produced cosmogenic nuclides. Can this sentence be extended? What is the limitation of the method due to the half-lives?

The concept of half-lives is well known in the field of Earth Sciences and we feel that further explanation is beyond the scope of this manuscript. Further information can be found in the reference cited (line 44).

L44 “: : :parts of the: : :”

Corrected. See line 48.

L46-48 The introduction comes to a quick end. An outline of the study set-up and a hypothesis to be tested would be helpful for the reader. What kind of samples do you analyze with what method? What are the questions to be answered with this study?

The introduction has been revised. See lines 50-54.

2 Geological Background

L49 This chapter would gain a lot if called “Study Area” and start with a geographic description of today and what deposits are present. Then move over to the geologic background. Changing this order would request to change Fig. 2 to Fig. 1 and vice versa.

Section 2 has been revised (see lines 56-95) and its name was changed to ‘Geological Setting’. However, as we feel that parts of this comment have more to do with writing style choices than substance we choose to keep the name of this section in its current format.

3 Methodology and Analytical Procedures

L76-89 This first section could be labeled 3.1 Cosmogenic method. It could contain the existing information, but also explain the method of catchment-wide erosion rates. In addition, it could contain further explanations of possible problems faced. Not all readers know the caveats of the cosmogenic nuclide methods (e.g., radioactive versus stable nuclides). Would it make sense to discuss here the possible influence of the transport distance and time on radioactive and stable cosmogenic nuclides?

The methods section has been revised (See section 3.3, lines 152-156). Section 3.1 now includes an explanation on Neon-21 accumulation in sedimentary cycles (see lines 98-107). However, as we feel that parts of this comment have more to do with writing style choices than substance we choose to keep the name of this section in its current format.

L90 Now start here: 3.2 Sampling Strategy?

See previous comment.

L134 How is the chemistry blank correction performed? What are the values used for erosion rate calculations?

Blank correction is a commonly performed procedure and further explanation of how exactly it was performed is not in the scope of this manuscript. Regarding erosion rates values see section 3.3, lines 152-156.

4 Results

L143-5 This sentence needs clarification. What is exactly 21Neex?

In addition to the explanation in Table 1, we now include the formula for calculating 21NeEx in the text, see lines 166-167.

L160-1 What is about differences in 21Neex in chert and quartz samples? Could this have an influence on the 21Necos concentration?

We are not sure what the reviewer meant in this comment. However, if the meaning is the differences in cosmogenic 21Ne concentrations (or 21NeEx concentrations) between quartz and chert, those are are presented in Table 1 and explained in the next line below.

L178-9 Difficult sentence to understand. Please clarify.

Al/Be ratios are commonly used for burial ages and as mentioned in the text, this part is thoroughly discussed in the Discussion section and is further explained there.

5 Discussion

L193 What are the parameters used for these calculations?

The parameters are now specified in figure 4 caption and can be found in the referenced sources.

L210 The use of “Modern” is misleading.

This has been revised. See line 245.

L211 On what are the calculations of the erosion rates based? Sea level-high latitude production rate, production rate scaling, etc.? This information should be given in the methods.

We have added the requested details and moved this section to the methods (see section 3.3, lines 152-156).

L215 Are these reported values correct? Please cross-check.

The values used for the calculation were correct, and the mistake made in the text is now corrected (see lines 152-156).

Figures

Fig. S5 - S11: Please label x- and y axes.

Axes labeled. See appendix.

Tables

Table 1: Please cross-check units.

Units have been checked and corrected. See Table 1.

Response to Reviewer no. 3: Marissa Tremblay

In this discussion paper, Ben-Israel et al. present new neon isotope measurements from quartz sand and chert pebbles deposited by the Hazeva River, which drained the Arabian Peninsula during Miocene times, as well as from modern eroding outcrops where the chert pebbles were likely sourced. The authors compare apparent erosion rates calculated from cosmogenic 21Ne concentrations at both sites, and conclude that the erosion rates recorded by the Miocene fluvial deposits are higher than those in the modern. They attribute higher Miocene erosion rates to higher uplift rates and a wetter climate of the Arabian Peninsula at that time.

Major comments:

In general, I think the approach taken in this paper to quantify paleo-erosion rates is exciting.

We thank Dr. Tremblay for this comment.

However, I am concerned that the uncertainties in the paleo-erosion rates the authors calculate are underestimated, and that therefore the conclusions about higher erosion rates during the Miocene are overstated. Specifically, the authors assume that the elevation during Miocene production of cosmogenic 21Ne was 1000 km. It is unclear to me if this is the assumed elevation of the source of the chert pebbles, and that the authors then assume that the majority of cosmogenic 21Ne production occurs prior to sediment transport? Or is 1000 km accounting for sediment transport and meant to be representative of some catchment-integrated value between where the pebbles were sourced and deposited? Furthermore, it appears that the authors do not give this paleo-elevation any uncertainty in their calculation of exposure times or minimum erosion rates. I suspect that if the authors incorporate a reasonable elevation uncertainty of something like ï´C ´s 500 m, that their paleo-erosion rates will overlap entirely with their modern erosion rates. Because the choice of a paleo-elevation has such a large effect on the calculated paleo-erosion rates, there needs to be (1) a more detailed explanation of what the paleo-elevation the authors use represents, and (2) an uncertainty associated with this paleo-elevation incorporated into the calculated paleoerosion rates.

This is a very good point and one that we now incorporate along with other comments regarding paleo-production rates and paleo-elevation of the Miocene sediments. We now consider a range of possible elevations between 500-1000 m.a.s.l and the resulting production rates and exposure times (see Table 2). We have revised the discussion (lines 246-323), conclusions (lines 378-393), and abstract (lines 15-27) accordingly.

I am also wondering if the authors need to be worried about neon diffusion with their analysis chert pebbles. They cite a neon closure temperature for quartz reported by Shuster and Farley (2005), but this was calculated for a 500 micron quartz grain. What is controlling the diffusion lengthscale in these chert pebbles, and what is the typical grain size in the chert pebbles analyzed? If you look at Figure 4 from Shuster and Farley (2005), for a 200 micron-diameter quartz grain (e.g., log radius of -1), you would expect significant diffusive loss of neon on 100 ka timescales and at temperatures of 60-70   certainly be in the range of 60-70   C (e.g., McFadden et al., 2005). Additionally, the fact that the authors observe lower degassing temperatures in the laboratory for the chert samples than they do for the quartz samples suggest that the chert has a lower thermal sensitivity. Altogether, this makes me think that diffusion might be contributing to the observation that the chert pebbles have lower cosmogenic 21Ne concentrations than the quartz sands. Given this, I think a discussion of the potential role of neon diffusion needs to be added to the text. C. These seem like high temperatures, but in the Arabian Peninsula air temperatures regularly exceed 40 C in the summer months and rock temperatures can certainly be in the range of 60-70 C (e.g., McFadden et al., 2005). Additionally, the fact that the authors observe lower degassing temperatures in the laboratory for the chert samples than they do for the quartz samples suggest that the chert has a lower thermal sensitivity. Altogether, this makes me think that diffusion might be contributing to the observation that the chert pebbles have lower cosmogenic 21Ne concentrations than the quartz sands. Given this, I think a discussion of the potential role of neon diffusion needs to be added to the text.

Two very interesting points are made here regarding (1) the 'typical grain size' in the chert pebbles and (2) the temperatures reached in the Negev Desert. We have revised the manuscript to include the possible role of Ne diffusion, and our answers are as follows:

(1) We do not know with certainty whether or by how much the kinetic parameters of chert differ from that of quartz. This uncertainty and its possible implications are now discussed in lines 193-196.

(2) While it is very true that air temperatures get very high in the desert and the temperatures of exposed dark rock (such as cherts) can get up to even higher reaching 60-70°C and very possibly even higher. However, it is crucial to remember that the Miocene samples presented are fluvial samples that are not likely to be exposed to direct solar radiation for extended periods. In support of this claim, the examined chert samples did not exhibit any visible cracking or fractures commonly identified with thermal stresses (see lines 2198-203).

Minor comments:

Figure 1 should have a box indicating the location of figure 2A.

See revisions to figure 2. However, we feel that adding a location box to figure 2 is somewhat redundant, as the major geographical features are marked in both figure 1 and figure 2 so comparison is easy. Furthermore, as the assumed drainage basin of the Hazeva River is marked, it is reasonable not to include additional marking.

Figure 2 should also include field photos of the modern in situ sampling sites of chert nodules.

Unfortunately, these do not exist. While we wish we can go back and take such photos, these sites are no longer accessible.

Lines 204-206: This sentence is awkwardly worded, and I'm not sure I fully understand I follow the logic.

We have rephrased this sentence, hopefully it is now clearer. See lines 238-240.

Lines 255-268: The calculated paleo-erosion rates overlap with the upper end of the modern erosion rates, even without my concerns about the paleo-elevation uncertainty being addressed. This sentence (and similar statements elsewhere) overstates the significance of the authors findings. I think it would be more appropriate to say that the calculated paleo-erosion rates allow for the possibility of higher erosion rates in the Miocene.

This part has been rephrased. See lines 325-335.

Lines 281-283: Here and elsewhere, do you mean rock uplift or surface uplift?

This has been clarified. See lines 345-348.

Supplement: There needs to be some text explaining what is provided in each of the Excel spreadsheet tabs as well as a caption provide for each of the supplemental figures. It’s not obvious to me why you need all of the different neon three isotope plots and why they are in the order that they are presented in. This could be cleaned up by having one three isotope plot for the Miocene samples and one for the modern samples, and using different symbol shapes to represent the different temperature steps.

We have made corrections to the supplement based on these comments. See supplementary data.

The revised manuscript with the author's changes included

Early-mid Miocene erosion rates ~~measured in~~inferred from pre-Dead Sea rift Hazeva River fluvial chert pebbles using cosmogenic ^{21}Ne ~~in fluvial chert pebbles~~

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Abstract. ~~The Miocene Hazeva River was a large fluvial system (estimated catchment size >100,000 km^2) that drained the Arabian Plateau and Sinai Peninsula into the Mediterranean Sea during the Early-Mid Miocene. It was established after rifting of the Red Sea uplifted the Arabian Plateau during the Oligocene. Following late Miocene to early Pliocene subsidence along the Dead Sea Rift, the Hazeva drainage system was abandoned and dissected, resulting in new drainage divides on either side of the rift.~~ In this work, ~~W~~we utilize~~d~~ a novel application of cosmogenic ^{21}Ne measurements in chert to compare exposure times measured in eroding surfaces in the Jordanian Central Plateau~~modern erosion rates~~ with exposure times from ~~Miocene~~ chert pebbles ~~erosion rates that operated~~transported by ~~when~~ the Miocene Hazeva River ~~was active~~. The Miocene Hazeva River was a large fluvial system (estimated catchment size >100,000 km^2) that drained the Arabian Plateau and Sinai Peninsula into the Mediterranean Sea during the ~~E~~early-m~~M~~id Miocene. It was established after the rifting of the Red Sea uplifted the Arabian Plateau during the Oligocene. Following late Miocene to early Pliocene subsidence along the Dead Sea

Rift, the Hazeva drainage system was abandoned and dissected, resulting in new drainage divides on either side of the rift. We find that modern erosion rates derived from cosmogenic ^{21}Ne, ^{26}Al, and ^{10}Be in exposed *in situ* chert nodules to be extremely slow, between 2-4 mm/kyr. Comparison between modern and ~~paleo~~ paleo-erosion rates, measured in chert pebbles, is not straightforward, as cosmogenic ^{21}Ne was acquired partly during bedrock ~~exhumation~~ erosion and partly during transport of these pebbles in the Hazeva River. However, even with bedrock erosion and maintained transport along this big river, ^{21}Ne ~~concentrations~~ exposure times ~~measured~~ calculated in Miocene cherts are generally ~~lower~~ shorter (range between $\mathbf{0^{+59}_{-0}}$~~.66±1.9x10^6~~ and 242±113 kyr~~.97±1.39x10^6 atoms/g SiO$_2$~~) compared to exposure times calculated ~~^{21}Ne concentrations measured~~ in the currently eroding chert nodules presented here (269±49~~.08±1.48x10^6~~ and 378±76~~2.10±2.43x10^6 atoms/g SiO$_2$~~kyr) and other chert surfaces currently eroding in hyperarid environments. Shorter ~~^{21}Ne concentrations~~ exposure times in Miocene cherts correspond to faster ~~minimum~~ paleo-erosion rates, ~~that are at least twice as fast as rates calculated today.~~which w~~W~~e attribute ~~these faster erosion rates~~ to a combination of continuous surface uplift and significantly wetter climatic conditions during the early-mid Miocene.

1. Introduction

Tectonic and climatic conditions control geomorphological processes through surface uplift, rock weathering, and sediment generation and transport (e.g., Allen, 2008; Whipple, 2009; Whittaker, 2012). Fluvial systems and their associated sediment archives respond to and record changes in rates of continental uplift and climatic conditions as rates of erosion influence sediment production, transport, and storage (e.g., DiBiase and Whipple, 2011; Ferrier et al., 2013; Vance et al., 2003). Cosmogenic nuclides, mostly radiogenic ^{26}Al and ^{10}Be, have been used extensively to study weathering and erosion rates in fluvial systems of different scales and ~~in~~at diverse geological settings (e.g., Bierman, 1994; von Blanckenburg, 2005). However, the further back in time we go, the less information there is about rates of surface shaping processes in fluvial environments (e.g., erosion, transport, and deposition), and the harder it becomes to reconstruct the tectonic and climatic conditions that prevailed. This lack of information is mostly due to decreasing preservation ~~potential~~ of older sediments ~~landscapes~~in fluvial systems, as ~~active surface processes~~ these tend to end up either deeply buried at depositional basins or recycled by another erosional process (e.g., Anderson et al., 1996; Guralnik et al., 2011; Schaller et al., 2002). ~~destroy evidence of transient landscapes.Cosmogenic nuclides have long been applied to quantify such rates in diverse geological settings (e.g., Bierman, 1994; von Blanckenburg, 2005).~~ Furthermore, even when geological circumstances do allow for the preservation of ~~slowly eroding surfaces~~older sediments, ~~erosion~~ rates prior to the Pliocene cannot be quantified with the more commonly used cosmogenic radionuclides (^{10}Be and ^{26}Al) due to their half-lives (1.38 Myr and 716 kyr, accordingly; Ivy-Ochs and Kober, 2008). Unlike their radioactive counterparts, s~~S~~table cosmogenic nuclides have the potential to quantify rates of surface processes as far back as Lower Cretaceous ~~of surface processes significantly older than commonly used cosmogenic radionuclides~~ (Balco et al., 2019; Ben-Israel et al., 2018; Dunai et al., 2005; Libarkin et al., 2002; Sinclair et al., 2019). Here, we apply stable cosmogenic ^{21}Ne to sediments deposited during the early-mid Miocene (~18 Ma) by a massive fluvial system that drained parts of the Arabian Peninsula and Sinai into the Mediterranean prior to the subsidence of the Arava Valley along the Dead Sea transform (Garfunkel and Horowitz, 1966; Zilberman and Calvo, 2013). We quantify the time of exposure during erosion and transport of Miocene chert pebbles deposited by the Hazeva River and compare it to exposure times of chert that has been eroding over the recent past (~10^5 yr). Through this comparison, we compare ~~The~~ erosion rates ~~of surface processes deduced from~~during early-mid -Miocene to those measured today in ~~hyper-arid~~hyperarid environments and examine the possible influence of~~river sediments open a window into~~ the tectonic and climatic ~~regimes~~ conditions that ~~dominated~~ operated in the region during this time.

2. Geological ~~Background~~Setting

Following an extended period of transgression that ended in the late Eocene, the Mediterranean Sea retreated to its current location (Garfunkel and Horowitz, 1966). This period of relative tectonic tranquility was followed by a series of tectonic and magmatic events that resulted in ~~The tectonic and magmatic events leading to~~ the rifting of the Red Sea and the Gulf of Aden in the late Eocene to early Oligocene (~35-30 Ma; e.g., Bohannon et al., 1989; Bosworth et al., 2005; Omar and Steckler, 1995). During the last 20-30 Myr, regional doming associated with the emergence of the Afar plume uplifted the Arabian Peninsula ~~has been uplifting~~ from near sea level to its present elevation of ~1km (e.g., Feinstein et al., 2013; Morag et al., 2019; Wilson et al., 2014). As a result of this uplift, widespread ~~erosion~~ denudation followed, and~~following this uplift,~~ a regional truncation surface developed in the northern Red Sea and the southern Levant ~~and~~ exposing~~ed~~ older strata down to Precambrian formations depending on the preexisting structure (Avni et al., 2012). Following these events, ~~D~~during the early-mid Miocene, the uplifted region was drained by a newly established fluvial system, termed the Hazeva River, which flowed northwestward from the ~~uplifted~~ eroded terrains towards the Mediterranean Sea, and drained an estimated area >100,000 km^2 (Garfunkel and Horowitz, 1966; Zilberman and Calvo, 2013; Fig. 1). The Hazeva fluvial system operated until the subsidence of the Dead Sea Rift, during the late Miocene to early Pliocene, brought on a dramatic change in morphology, which led to the disruption of this massive fluvial system, the last of its kind in the region (Garfunkel, 1981). By the early Pliocene, the Hazeva River was abandoned, and new independent drainage systems drained the region toward the Dead Sea Basin (Avni et al., 2001).

At present, the mostly clastic sedimentary Miocene sequence deposited by ~~this~~ the Hazeva ~~fluvial system~~River is preserved mainly in structural lows, karstic systems, and abandoned stream valleys in southern Israel, eastern Sinai, and Jordan (Calvo and Bartov, 2001; Fig. 2). The sediments associated with this Miocene fluvial system ~~compose~~ comprise the upper section of the Hazeva formation in southern Israel. This formation is divided into two major parts, the lower includes autochthonous conglomerates and lacustrine carbonate units, and the upper part is comprised of allochthonous clastic sequences typical to fluvial environments (Calvo, 2002). ~~units, mainly quartz sand and chert pebbles .~~ Here we focus on the allochthonous upper part of the Hazeva formation and examine two different silicate members ~~allochthonous silicate sediments of the upper part.~~ eroded from the uplifted Arabian Plateau and Sinai and deposited simultaneously by the Hazeva River (Zilberman and Calvo, 2013). The first member is sub-rounded monocrystalline quartz-arenite, eroded from Phanerozoic Nubian sandstone, as well as from outcrops of Precambrian crystalline rocks of the Arabian-Nubian shield (Calvo and Bartov, 2001). The second member consists of well-rounded chert pebbles either interbedded with the quartz sand or forming horizons of pebbles in the sandy sequence (Zilberman and Calvo, 2013). The chert comprising these pebbles is sourced only from east of the Dead Sea Rift, and therefore fluvial deposits on the west side containing this "imported chert" (Kolodny, 1965) must have been emplaced prior to rifting. The onset of the Hazeva River is constrained by the Karak dike (~20 Myr) which intrudes the lower section of the Hazeva formation (Calvo and Bartov, 2001). While climatic conditions in the Levant during the Miocene are believed to have been wetter (e.g., Kolodny et al., 2009), currently this region is part of a middle latitude dry warm desert extending from northern Africa to western Asia, with the Negev Desert remaining hyperarid at least since the middle Pleistocene (Amit et al., 2006).The Hazeva fluvial system operated until the subsidence of the Dead Sea Rift during the late Miocene to early Pliocene brought on a dramatic change in morphology, which led to the dismantlement of this massive fluvial system, the last of its kind in the region (Garfunkel, 1981). By the early Pliocene, the Hazeva River was abandoned, and new independent drainage systems drained the region toward the Dead Sea Basin (Avni et al., 2001).

3. Methodology and Analytical Procedures

3.1 Sampling Strategy

Cosmogenic nuclides in sediments accumulate throughout the sedimentary cycle as near-surface material is exposed during weathering and exhumation exposure of the source rock, during transport in a specific drainage system, and to a much lesser degree following burial at some intermediate or final destination. Unlike the more commonly used radioactive cosmogenic nuclides, which may decay substantially or even completely over multiple sedimentary cycles, ^{21}Ne is stable. This means that the concentration of ^{21}Ne measured in the sediment may have accumulated over several sedimentary cycles of exposure and deposition, i.e., after the sediment reaches the depositional basin, it can be re-exhumed and once again exposed and transported in a new sedimentary cycle. Therefore, the concentration of cosmogenic ^{21}Ne measured in sediment represents the total exposure during previous and current sedimentary cycles, unless . This should hold true so long as intermittent burial does not expose the sediment is exposed during transport to temperatures exceeding the geological closure temperature of Ne in quartz (90-100°C; Shuster and Farley, 2005)., The loss of Ne due to diffusion could occur either during burial at depths of corresponding to ~2-3 km burial depth given a geothermal gradient of 30-50°C/km or. if rock temperatures reach high enough temperatures for an extended time, which has been recorded in hot desert environments (e.g., McFadden et al., 2005).

We collected and analyzed ten samples in total. Three samples of quartz sand (MHS1, MHS3, and MHS5), and five individual chert pebbles (MHC2, MHC23, MHC5a MHC2b, and MHC6) were obtained from two Miocene Hazeva ~~deposits~~ exposures (Fig. 2 B-C; Table 1). At both sites, samples were collected from deeply shielded locations to minimize the effects of post-burial production (see section 5.1 for further discussion). The quartz sand and the chert pebbles were both transported by the Miocene Hazeva system and share an overall similar exposure history. However, the quartz sand was exposed in previous sedimentary cycles throughout the Mesozoic and Paleozoic, where it accumulated cosmogenic ^{21}Ne. In contrast, the chert was deposited in the Eocene and then exposed, transported, and buried during the Miocene (Avni et al., 2012). Therefore, while the cosmogenic ^{21}Ne measured in the quartz sand represents multiple sedimentary cycles, the cosmogenic ^{21}Ne measured in the chert pebbles represents erosion and transport during a single sedimentary cycle in the Miocene Hazeva River.

Additionally, ~~T~~two individual samples of *in situ* chert nodules (EJC3 and EJC5) were collected from exposed bedrock outcrops of the Eocene source rock in central Jordan (Fig. 2A). Unlike the Miocene samples, which were exposed during at least one full sedimentary cycle, the Jordanian chert nodules accumulated cosmogenic nuclides only during exhumation to the currently exposed surface. Therefore, the cosmogenic nuclide ~~These~~ concentrations measured in the Jordanian cherts ~~thus~~ represent averaged rates of erosion ~~surface denudation~~ over the last ~10^5 yr ~~time-scales~~.

3.2 Preparation of Chert and Quartz Samples and Analytical Procedures

Chert pebbles (ranging 4-14 cm, b axis) were crushed and both chert and sand samples were sieved to 250-850 µm. Chert and quartz samples were processed to separate clean SiO_2 at the Institute of Earth Sciences Cosmogenic Isotope Laboratory, Hebrew University of Jerusalem, following standard procedures (Hetzel et al., 2002; Kohl and Nishiizumi, 1992). The samples were first leached in HCl/HNO_3 mixture (3:1) at a temperature of 150°C for 1.5h dissolving carbonates and iron oxides. This procedure was followed by Franz magnetic separation to remove magnetic grains, including quartz grains that contain inclusions of magnetic material. Samples were then leached three times in a 1% HF/HNO_3 mixture for 7, 12 and 24h at 70°C, removing the outer rims of the quartz grains. Aliquots of all ten etched samples were then analyzed for Ne isotopes at the Berkeley Geochronology Center. Chert samples were washed with isopropanol to remove fine chert particles attached to the chert grains. Aliquots from samples MCH5A and EJC5 were crushed to compare the degassing results with the uncrushed aliquots. Ca. 70 mg from the chert samples and ca. 150 mg from the quartz samples were encapsulated in a tantalum packet and heated under vacuum using a diode laser micro-furnace at 2-4 heating steps between 450 and 1250°C for 15 minutes at each temperature step. Ne isotope measurements used the BGC "Ohio" system and the procedure described in Balco et al., (2019). 20-30 grams of leached and clean quartz from three quartz samples and three chert samples were processed to separate Be and Al oxides following Kohl and Nishiizumi (1992) and Bierman and Caffee (2001). These were then analyzed for $^{10}Be/^{9}Be$ and $^{26}Al/^{27}Al$ at the Centre for Accelerator Mass Spectrometry, Lawrence Livermore National Laboratory, and calibrated against house standards and blanks.

3.3 Cosmogenic Scaling and Correction Factors

Exposure and burial times and erosion rates were calculated based on Balco (2007) and scaled using time-independent scaling (Stone, 2000) and production mechanisms based on Balco et al. (2008), given sea-level high-latitude production rates of 4.96 atoms/g SiO_2/year for ^{10}Be, 30.6 atoms/g SiO_2/year for ^{26}Al (Balco et al., 2008), and Exposure ages, reported in kyr, are calculated using production rates scaled for latitude and altitude after Stone (2000), using ^{21}Ne production rate of 18.1 atoms/g SiO_2 year (Borchers et al., 2016; Luna et al., 2018).

4. Results

4.1 ^{21}Ne in Quartz Sand and Cherts

For the chert samples, <2% of the total ^{21}Ne and no more than 1% of the total ^{20}Ne measured were released above 950°C (see the Supplementary Tables S1-4). Therefore subsequent analyses were performed at 450, 700, and 950°C heating steps for chert samples and 950 and 1250°C heating steps for quartz samples (Table 1). Of the total ^{21}Ne measured, >85% was released at the low-temperature steps, below the 950°C step in the chert samples and below the 1250°C step in the quartz samples (see Supplementary Tables S1-4). Also, low-temperature $^{21}Ne/^{20}Ne$ and $^{22}Ne/^{20}Ne$ ratios fall on the spallation line, within analytical uncertainty. Therefore, we conclude that excess ^{21}Ne relative to an atmospheric isotopic $^{21}Ne/^{20}Ne$ ratio of 0.002959 ($^{21}Ne_{ex} = {}^{21}Ne/^{20}Ne_{measured} - {}^{21}Ne/^{20}Ne_{air}$) in the low-temperature steps is a good representation for cosmogenic ^{21}Ne ($^{21}Ne_{cos}$; see Supplementary Fig. S8-12). While most samples show some increase in the low-temperature $^{21}Ne_{ex}$, sample MHC2 shows no enrichment in $^{21}Ne/^{20}Ne$ ratio and very little enrichment in $^{22}Ne/^{20}Ne$ ratio compared to atmospheric composition in the low-temperature steps. In the 950°C step, there is enrichment compared to atmospheric values. However, as only ~12% of the total ^{21}Ne was released in the 950°C step, determining the concentration of cosmogenic ^{21}Ne in sample MHC2 is beyond analytical abilities. Therefore, this sample was not considered in further calculations, discussion, and interpretations. It is important to note that even with cosmogenic isotopic values of $^{21}Ne/^{20}Ne$ and $^{22}Ne/^{20}Ne$ ratios at the low-temperature steps, distinguishing the cosmogenic component of $^{21}Ne_{ex}$ from the nucleogenic component, produced by the decay of U and Th within the crystal lattice, is not trivial. Nonetheless, as all chert samples (Eocene chert nodules and Miocene chert pebbles) share the same lithology, any differences in the $^{21}Ne_{ex}$ concentrations must be due to the cosmogenic component.

The chert pebbles and quartz sands sampled at both Miocene Hazeva sites show variable concentrations of $^{21}Ne_{cos}$ ranging between $0.00 \pm 1.88 \cdot 10^6$ and $8.89 \pm 1.83 \cdot 10^6$ atoms/g SiO_2 (Fig. 3). At both Miocene Hazeva sites, the cosmogenic ^{21}Ne concentrations measured in chert pebbles are similar or lower compared to sand samples. These measured concentrations agree with our understanding that the sand samples contain quartz grains that originated from various sandy units that were deposited throughout the Phanerozoic and could have undergone several sedimentary cycles before they were exhumed and transported by the Miocene fluvial system. Alternatively, the sand samples could have higher concentrations of nucleogenic ^{21}Ne as the source rock for this sand is >800 Ma (Kolodner et al., 2009). Conversely, the chert samples are derived from a relatively young, Eocene, source rock and only participated in one sedimentary cycle during the Miocene. Both chert nodule samples collected from *in situ* Eocene outcrops show similar cosmogenic ^{21}Ne concentrations, higher compared to the Miocene chert pebbles (Fig 3).

Diffusion kinetics of Ne in quartz have been examined experimentally and theoretically (Shuster and Farley, 2005; Tremblay et al., 2014) but have yet to be tested on chert samples where it is unclear what is the diffusion length-scale of chert crystals. While diffusion kinetics in chert are likely to be similar to quartz, more work is needed to determine that with certainty. Nevertheless, diffusion is not likely to have been significant over a ~20 Myr timespan in the measured Miocene chert samples. While temperatures in exposed cherts in the Levant region can reach 60-70°C during mid-day in the summertime due to solar heating, it is unlikely that samples that were transported fluvialy were exposed continuously at the surface. In support of this claim, the examined chert samples did not exhibit any visible cracking or fractures commonly identified with thermal stresses, leading us to believe that temperatures were not high enough to cause significant diffusion of Ne out of the chert samples.

4.2 ^{10}Be and ^{26}Al in Quartz Sand and Cherts

^{10}Be and ^{26}Al concentrations were measured in three Miocene sand samples (MHS1, MHS3, and MHS5), the two Eocene chert nodules (EJC3 and EJC5) and two chert pebbles (MHC5b and MHC6). ^{10}Be results for sample MHC5b and ^{26}Al results for sample MHS1 are not available (Table 1). Miocene sand and chert samples show ^{10}Be and ^{26}Al concentrations that are low and consistent with extended periods of burial ($\leq 0.39.\pm 0.03 \cdot 10^5$ atoms/g SiO_2 for ^{10}Be and $\leq 4.33.\pm 0.55 \cdot 10^5$ atoms/g SiO_2 for ^{26}Al). Currently eroding Eocene nodules show higher concentrations of ^{10}Be and ^{26}Al, with sample EJC3 showing ^{26}Al/^{10}Be ratio that is consistent with production at the surface, and sample EJC5 showing a lower ^{26}Al/^{10}Be ratio, suggesting a more complicated exposure history (see Discussion section).

5. Discussion

5.1 Correcting for Post-Burial Muonic Produced Cosmogenic ^{21}Ne

When examining concentrations of cosmogenic nuclides in sediments that have been buried for extended periods, post-burial production needs to be considered. At or near the surface, spallation interactions are the main pathway for *in situ* production of cosmogenic nuclides accounting for >95% for ^{26}Al, ^{10}Be, and ^{21}Ne (Dunai, 2010). However, the relative contribution of production by muon interactions increases with burial depth, and while production rates are relatively low, they can be significant when integrated over long periods of time—especially for stable nuclides. The post-burial component does not represent surface processes, and therefore, it is crucial to account for its contribution to the measured cosmogenic component. For radioactive cosmogenic nuclides, such as ^{10}Be and ^{26}Al, their initial concentrations (acquired during exposure) decrease post burial due to radioactive decay, with ^{26}Al decreasing faster than ^{10}Be according to their corresponding half-lives (e.g., Balco and Rovey, 2008; Granger, 2006; Granger and Muzikar, 2001; Lal, 1991).

We calculated the expected concentrations of cosmogenic ^{26}Al, ^{10}Be, and ^{21}Ne in sediments over a burial period of 18 Myr, the likely age of the fluvial system stabilization (Bar and Zilberman, 2016). We then compared these calculated concentrations to the measured concentrations of ^{26}Al, ^{10}Be, and $^{21}Ne_{cos}$ in Miocene chert and sand samples (Fig. 4). Both ^{10}Be and ^{26}Al measurements are only available for two buried sand samples, one buried chert pebble, and two *in situ* chert nodules (Table 1). The measured ^{10}Be and ^{26}Al concentrations have reached an equilibrium that is consistent with an extended period of burial at depths between 20-120 m (given that overburden consists of clastic sediments with a density of ~2 g/cm^3). The discrepancy between the current burial depth, only tens of meters below the surface, and the deduced burial depth is likely the result of surface erosion that occurred during the last ~2 Myr (Matmon and Zilberman, 2017 and references therein). Additionally, the relatively large uncertainty on muogenic production rates could account for some of this discrepancy (Balco, 2017; Balco et al., 2019). Our calculations show that the cosmogenic ^{21}Ne produced post-burial over 18 Myr of burial at depths between 20-120 m is lower than the $^{21}Ne_{ex}$ measured for in the presented samples (including their uncertainties,). The maximal calculated post-burial cosmogenic ^{21}Ne concentration accountsing for a maximum of ~$1.3 \cdot 10^6$ atoms/g SiO_2,. This which concentration is lower than the analytical uncertainty for all measured Miocene samples except for MHC2, where no cosmogenic ^{21}Ne was measured. However, sample MHC2 is not considered in the interpretations of the results. Therefore, we consider post-burial cosmogenic ^{21}Ne production to be insignificant for the presented Miocene exposure times.

5.2 Calculating Modern and Miocene Exposure TimesRates of Surface Processes

Exposure times Erosion rates calculated for exposure at the surface from cosmogenic ^{21}Ne concentrations measured in modern exposed *in situ* chert nodules from the Jordanian Central Plateau (EJC3 and EJC5) range between a minimum of 193 kyr and a maximum of 454 2-3 mm/kyr (correlating to cosmogenic ^{21}Ne concentrations of $8.08 \pm 1.48 \cdot 10^6$ and $12.10 \pm 2.43 \cdot 10^6$ atoms/g SiO_2).

Erosion rates calculated from ^{10}Be and ^{26}Al concentration measured in sample EJC5 are similar, 2-4 mm/kyr, with production rates scaled for latitude and altitude after Stone (2000), using production rates of 2.62 and 30.26 atoms/g SiO_2 year for ^{10}Be and ^{26}Al, respectively. In contrast, erosion rates calculated from ^{10}Be and ^{26}Al concentrations measured in sample EJC3 are 40-50 mm/kyr, an order of magnitude faster. While we cannot explain this discrepancy, we believe that the representative results are the slower erosion rates. Firstly, the ^{21}Ne calculated erosion rates in sample EJC3 (~2 mm/kyr) agrees with the ^{21}Ne, ^{26}Al, and ^{10}Be calculated erosion rates for sample EJC5. Secondly, modern erosion rates measured in chert bedrock in other hyperarid regions of eastern Mediterranean area also indicate rates of erosion that range between 1-5 mm/kyr . We conclude that ^{21}Ne concentrations in modern Jordanian Central Plateau chert nodules indicate simple exposure times that range between 269±49 and 378±76 kyr, and equivalent erosion rates that range between 2-4 mm/kyr. It is important to note that modern calculated exposure times and erosion rates in the Jordanian cherts represent exhumation only.

In comparison to the Jordanian samples, ~~Q~~quantifying ~~rates of surface processes~~ how long were samples exposed ~~that occurred~~ during the Miocene using cosmogenic ^{21}Ne concentrations is not trivial,~~,~~ most notably due to the challenge in evaluating the local ~~isotope~~ cosmogenic production rates. The production rate of cosmogenic nuclides increases with altitude as the air pressure and shielding effect of the atmosphere decreases (Stone, 2000). While the latitude of the Arabian Peninsula during the early Miocene was similar to today (Meulenkamp and Sissingh, 2003 and references therein), accounting for the elevation of the Miocene samples during production of cosmogenic ^{21}Ne raises two difficulties. Firstly, it is not possible to determine with certainty the elevation of the Jordanian Central Plateau during the Miocene. It is clear that from the Late Cretaceous up until the late Eocene, the Arabian Peninsula was mostly submerged below sea level and that during the Oligocene it was uplifted to a sufficient elevation to allow for significant surface erosion (Garfunkel, 1988). During the early Miocene, broad valleys (500-1000 m wide and ~100 m deep) incised the regional truncation surface that developed in the region, where the Hazeva formation was later deposited (Avni et al., 2012). This timeline of events lead us to believe that significant surface uplift occurred prior to the initiation of the Miocene Hazeva fluvial system at ~18 Ma. Nevertheless, this stratigraphic evidence is not enough to determine whether the Arabian Peninsula reached its current elevation during the early-mid Miocene or whether additional uplift occurred over the past 20 Myr, and if so how significant was it. Studies that focus on exhumation along the eastern flank of the Dead Sea Rift do not provide clear evidence to constrain the timing of surface uplift. Surface uplift histories based on cooling ages (Feinstein et al., 2013), and river profiles (Wilson et al., 2014), conclude that during the last ~30 Myr the western half of the Arabian Peninsula was uplifted to its current elevation. However, in a recent work, Morag et al. (2019) offer that uplift and exhumation along the western side of the Suez Rift flank slowed substantially post ~18 Ma. One more approach to evaluate the paleo-elevation of the Central Jordanian Plateau during the early-mid Miocene is to calculate the elevation given distance and slope. Based on fact that the Hazeva fluvial system drained westward to its base level at the Mediterranean, most likely over a moderate stream gradient, we can use the ~200 km distance between the Mediterranean coast and the current location of exposed chert nodules, with a moderate gradient of ~0.5%, to reach an elevation of ~1 km above sea level. Taking into consideration the different types of evidence reported we believe it is reasonable to presume that the western flank of the Arabian Peninsula reached its current elevation (~1 km) during the early-mid Miocene. However, another difficulty in calculating paleo-production rates is unrelated to the elevation of the Central Jordanian Plateau during the time the Hazeva River operated. The question arises whether it is appropriate to use the elevation of the source rock for production rate calculations or whether a spatially averaged elevation should be used instead. Without any tangible information about the size and steepness of the catchment area of the Hazeva River, we are unable to correct for different elevations and production rates throughout the basin. Although separate, at their core, both possible lower paleo-elevation and a basin-wide integrated elevation add uncertainties that decrease the potential paleo-elevation used for scaling of production rates, resulting in longer calculated exposure times. Therefore, accounting for all uncertainties, we assume an elevation range of 500-1000 meters above sea level, and latitude of 20-30° for the calculated Miocene exposure times.

The calculated exposure times of sediments in the Miocene Hazeva fluvial system are variable, and range between a minimum of $0^{+59}_{-0} - 0^{+86}_{-0}$ kyr measured in sample MHC5b and a maximum of 278±63 – 408±63 kyr measured in sample MHS5 (Table 2). Comparing the two silicate member, concentrations (and exposure times) of the sand samples are overlapping or higher than the chert samples (Fig. 3). This agrees with our understanding that the cosmogenic ^{21}Ne measured in the Miocene chert pebbles represents the total time of exposure during exhumation from bedrock coupled with transport in the Hazeva River, while the sand samples have undergone previous sedimentary cycles and contain inherited cosmogenic ^{21}Ne. Therefore, sand samples cannot be used to calculate the time sediment were exposed during transport in the Hazeva fluvial system or to infer erosion rates.

The cosmogenic ^{21}Ne exposure times calculated from the Jordanian chert samples range 269±63 to 378±76 kyr. Exposure times calculated from ^{10}Be and ^{26}Al concentration measured in sample EJC5 overlap within uncertainty with ^{21}Ne calculated exposure values (Table 2). In contrast, exposure times calculated from ^{10}Be and ^{26}Al concentrations measured in sample EJC3 are much shorter ~13-16 kyr, an order of magnitude difference. While we cannot explain this discrepancy, we believe that the representative results are the longer exposure times. Firstly, the ^{21}Ne calculated exposure time in sample EJC3 agrees with the ^{21}Ne, ^{26}Al, and ^{10}Be calculated exposure times for sample EJC5. Secondly, the timescales of exposure times measured in cherts in eroding surfaces at hyperarid Negev Desert are similar and range from ~2·10^5 to ~2·10^6 yr (Boroda et al., 2014; Fruchter et al., 2011; Matmon et al., 2009). We conclude that exposure times in modern Jordanian

Central Plateau chert nodules range ~300-400 kyr. It is important to note that the calculated exposure times in the Jordanian cherts represent only exposure at the surface, and do not include exposure during transport, in contrast to the Miocene chert pebbles.

Lastly, when examining ancient exposure times, we must first consider the time-scales over which cosmogenic nuclides are averaged. The question arises whether the reported exposure times accurately represent the environmental conditions of a certain period (e.g. the early to mid-Miocene) or if the calculated times are the result of episodic oscillation or catastrophic geomorphic events. For currently exposed *in situ* samples reported here, it is a reasonably simple answer. The modern exposure times are relatively long and so they integrate hundreds of thousands of years over which such oscillations or rare catastrophic events would be averaged. As for the Miocene exposure times, samples were collected from two separate sites and from different depths, so it is unlikely that they all represent the exception. We, therefore, consider the range of times obtained from Miocene samples to be a good representation for Miocene surface processes.

5.3 Modern and Miocene Erosion Rates and the Influence of Climate and Tectonics

The calculated exposure times of the Jordanian chert samples are equivalent to erosion rates of ~4-12 mm/kyr (Table 2), which is consistent with erosion rates measured in the region (Matmon and Zilberman, 2017 and references therein). Calculation of paleo-erosion rates is not as straightforwars, as Miocene samples were sampled post deposition and represnet exposure both during erosion from bedrock and transport in the Hazeva River. However, Miocene exposure times are either shorter or overlap within uncertainty with those of the *in situ* Jordanian chert samples. Thus, the actual bedrock erosion rates during the Miocene must have been faster than modern rates mentioned above.

While we cannot determine how much faster were paleo-erosion during the Miocene, any increase in erosion rates in a hyperarid desert must be~~The increased erosion rates, compared to modern, inferred from Miocene chert pebbles are~~ the consequence of ~~the~~ different environmental conditions that prevailed in the region at that time. An increase in rates of ~~of surface~~ erosion is most commonly attributed to perturbations in fluvial basins in response to tectonic uplift and/or warmer/wetter climatic conditions (e.g., DiBiase and Whipple, 2011; Romans et al., 2016; Schaller and Ehlers, 2006; Val et al., 2016; Willenbring et al., 2013). For example, increased precipitation brings about higher river discharge and enhancement of the stream power available for bedrock erosion and sediment transport. Erosion rates in fluvial systems also respond to tectonically induced changes in base level that increase slope steepness and instability, resulting in higher stream power and more sediment readily available for transport. Here we examine evidence from previous studies of the climatic and tectonic conditions that prevailed in the region during the Miocene, capable of forcing the deduced ~~rapid~~ increase in erosion rates. ~~However, when examining ancient erosion rates, we must first consider the time-scales over which cosmogenic nuclides are averaged. The question arises whether the reported erosion rates accurately represent the environmental conditions of a certain period (e.g. the early to mid-Miocene) or if the calculated rates are the result of episodic oscillation or catastrophic geomorphic events. For the modern erosion rates reported here, it is a reasonably simple answer. The modern erosion rates are relatively slow and so they integrate hundreds of thousands of years over which such oscillations or rare catastrophic events would be averaged. As for the Miocene erosion rates, samples were collected from two separate sites and from different depths, so it is unlikely that they all represent the exception. We, therefore, consider the range of rates obtained from Miocene samples to be a good representation for Miocene surface processes.~~

Many works which quantify the rates and timing of surface uplift related to the rifting of the Red Sea are confined to the edges of the Arabian plate and do not give good constrains for intercontinental uplift (Bar et al., 2016; Morag et al., 2019; Omar et al., 1989; Omar and Steckler, 1995). While s~~Collectively,~~ome of these studies ~~show~~ point to a decrease in exhumation rates during the mid-Miocene (~18 Myr~~).~~; ~~While uplift rates decreased during the Miocene~~Morag et al., 2019), ~~tectonic~~ surface uplift and topographic changes could still drive large-scale landscape response, manifesting as increased erosion rates and the establishment of the Hazeva fluvial system.

Together, the above observations suggest climatic conditions, ~~that~~ which could promote erosion ~~rates which~~rates that are faster than ~~those~~ observed rates in ~~hyperarid~~hyperarid conditions ~~(such as prevail today,)~~ and ~~could~~ that ~~also~~ support ~~and maintain~~ the existence of a great and maintained fluvial system, such as the Hazeva River, during the Miocene.

6. Conclusions

We compared the cosmogenic ^{21}Ne measured in chert pebbles and quartz sand eroded and transported during the mid-Miocene (~18 Myr) by the Hazeva River with the chert source rock (Eocene chert nodules) currently eroding in the Central Jordanian Plateau.

In addition to tectonic forcing, there is ample evidence for a warmer and wetter climate in the region during the Miocene. Locally, the appearance of mammals in the Negev along with arboreal and grassy vegetation during the early-mid Miocene supports a humid environment (Goldsmith et al., 1988; Horowitz, 2002; Tchernov et al., 1987). Tropical to subtropical climate prevailed in the eastern Arabian Peninsula, as indicated by fossilized mangrove roots (Whybrow and McClure, 1980). Locally, Kolodny et al. (2009), interpreted the ^{18}O in lacustrine limestone from the lower part of the Hazeva unit to be deposited by ^{18}O-depleted paleo-meteoric water. They proposed that the presence of a warm ocean to the southeast of the region during the Late Oligocene-Early Miocene resulted in tropical cyclones being more prevalent and increasing rainfall in the region.

We successfully established a novel application for measuring cosmogenic ^{21}Ne in modern and Miocene chert samples, expanding the opportunities and settings in which stable cosmogenic nuclides analysis could be used as a tool to quantify geomorphic processes and ascertaining chert as a viable lithologic target for cosmogenic Ne analysis. In modern samples, measurements of cosmogenic nuclides ^{10}Be and ^{26}Al generally agree with ^{21}Ne results. In the Miocene samples, cosmogenic ^{21}Ne in quartz sand samples is equal or higher compared to Miocene chert pebbles, agreeing with the geologic understanding that sand has experienced several sedimentary cycles where ^{21}Ne was produced, while chert experienced only one such cycle in the Miocene Hazeva fluvial system.

Exposure times calculated from the measured cosmogenic ^{21}Ne concentrations in the Miocene chert pebbles are ~~considerably~~ shorter compared to the chert nodules currently eroding in the Central Jordanian Plateau. While, it is impossible to determine the exact rate of erosion during the Miocene, as cosmogenic ^{21}Ne was produced ~~both~~ during erosion from the bedrock and transport in the river, ~~the~~ shorter exposure times during the Miocene ~~reflect~~ point to rates of ~~faster rates of surface processes that correlate to minimal~~surface erosion being faster ~~erosion rates that are at least twice as fast~~. The cause for increased rates ~~of surface processes~~ during the early-mid Miocene cannot be easily constrained to either tectonic or climatic conditions. The entire region experienced tectonic uplift and exhumation that while possibly decreasing during the m~~M~~id-Miocene, brought on topographic changes that established the Hazeva fluvial system and could have ~~been~~ manifested as faster rates of surface erosion. ~~Furthermore~~In addition, multiple independent proxies presented in previous studies support wetter climatic conditions in the region during the early-mid Miocene. Increased precipitation would explain the faster rates of bedrock erosion deduced as well as the higher water discharge needed to maintain transport along the Hazeva River. Finally, the variability observed in exposure times of Miocene chert pebbles might represent ~~While it is possible that rates of erosion or it~~ a change~~d~~ ~~significantly~~ in rates of erosion throughout the Miocene~~,~~. However, th~~is~~ise variability in ^{21}Ne concentrations ~~measured in Miocene chert samples are~~ is more likely the result of fluvial transport dynamics, temporary storage, and exposure during transport in this large Miocene river.

Data availability

A raw data table including all Ne isotope measurements and three-isotope plots are available in supplement.

Author contribution

MBI and AM designed the study. MBI collected the samples for analysis with assistance from AM and YA. MBI prepared samples for analyses and measured ^{21}Ne/^{20}Ne and ^{22}Ne/^{20}Ne ratios with GB, and AJH measured the ^{10}Be/^{9}Be and ^{26}Al/^{27}Al ratios. MBI analyzed the data, produced the figures, and prepared the manuscript with contributions from all co-authors.

Competing interests

The authors declare that they have no conflict of interest.

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Table 1: Sample Description, Sampling Site Locations and Cosmogenic Nuclide Data

Sample	Sample type	Site	Sampling depth below surface	Location		Elevation	Be Carrier	$^{10}Be/^{9}Be$	[^{10}Be]	$^{26}Al/^{27}Al$	[Al]*	[^{26}Al]	Al/Be	[$^{21}Ne_{cos}$]†
			(m)	Lat (°N)	Long (°E)	(m.a.s.l)	(mg)	(×10^{-13})	(10^{5} atoms/ g SiO_2)		(ppm)	10^{5} atoms/ g SiO_2)		
MHS1	Quartz sand	Paran Valley, Israel	30	30.33296	34.92724	290	176	0.17±0.03	0.14±0.02	NA	104	NA	NA	MHS1
MHS3	Quartz sand	Arad Quarry, Israel	90	31.23372	35.20685	570	171	0.36±0.02	0.29±0.02	0.60±0.08	110	1.33±0.17	4.57±064	MHS3
MHS5	Quartz sand	Arad Quarry, Israel	100	31.23372	35.20685	570	175	0.32±0.02	0.26±0.02	0.35±0.04	114	0.86±0.11	3.25±0.44	MHS5
MHC2	Chert pebble	Paran Valley, Israel	20	30.33296	34.92724	290	NA	NA	NA	NA	NA	NA	NA	MHC2
MHC3	Chert pebble	Arad Quarry, Israel	90	31.23372	35.20685	570	NA	NA	NA	NA	NA	NA	NA	MHC3
MHC5a	Chert pebble	Arad Quarry, Israel	100	31.23372	35.20685	570	NA	NA	NA	NA	NA	NA	NA	MHC5a
MHC5b	Chert pebble	Arad Quarry, Israel	100	31.23372	35.20685	570	172	NA	NA	0.93±0.12	203	4.33±0.55	NA	MHC5b
MHC6	Chert pebble	Paran Valley, Israel	30	30.33296	34.92724	290	170	0.10±0.01	0.39±0.03	0.05±0.02	287	0.32±0.13	0.83±0.35	MHC6
EJC3	In situ chert	Central Jordanian Plateau	Surface	30.97045	36.64469	910	172	0.70±0.03	1.13±0.05	1.50±0.10	230	6.81±0.43	5.11±0.38	EJC3
EJC5	In situ chert	Central Jordanian Plateau	Surface	30.87181	36.52129	1000	178	18.43±0.30	29.75±0.49	11.47±0.25	235	72.96±1.54	2.45±0.07	EJC5

Note: NA – not available. Samples were either not analyzed, or no result was attained.

*Measurement uncertainties are ~5%.

†Cosmogenic ^{21}Ne is the excess of ^{21}Ne concentrations relative to the atmospheric $^{21}Ne/^{20}Ne$ ratio, calculated for the low-temperature steps (<950°C for chert and <1250°C for quartz).

Table 2: Exposure times and erosion rates calculated for the modern and Miocene samples

Sample	Sample type	Location	Exposure time (kyr)	Erosion rate (mm/kyr)
MHS1	Miocene quartz sand	Paran Valley, Southern Negev Desert	114±46 – 166±87	-
MHS3	Miocene quartz sand	Arad Quarry, Northeastern Negev Desert	280±10 – 408±63	-
MHS5	Miocene quartz sand	Arad Quarry, Northeastern Negev Desert	278±17 – 404±83	-
MHC3	Miocene chert pebble	Arad Quarry, Northeastern Negev Desert	167±53 – 242±113	3.0±1.4 – 4.4±1.4
MHC5a	Miocene chert pebble	Arad Quarry, Northeastern Negev Desert	91±46 – 132±78	5.5±3.3 – 8.0±4.7
MHC5b	Miocene chert pebble	Arad Quarry, Northeastern Negev Desert	0^{+59}_{-0} – 0^{+85}_{-0}	>8.6 – >12.4
MHC6	Miocene chert pebble	Paran Valley, Southern Negev Desert	121±59 – 176±102	3.0±1.4 – 4.4±3.5
EJC3*	In situ chert nodule	Central Jordanian Plateau	269±49 / 16±1 / 13±1	2.7±0.5 / 41.7±1.7 / 50.0±3.2
EJC5*	In situ chert nodule	Central Jordanian Plateau	378±76 / 361±6 / 378±3	1.9±0.4 / 1.7±0.0 / 4.4±0.1

Note: Exposure times is the 'simple exposure time' calculated for exposure at the surface, calculated cosmogenic ^{21}Ne production rates ranging 22.2-30 (atoms/g SiO_2 yr), given an elevation of 500 and 1000 meters above sea level. Erosion rates for sand samples were not calculated as the concentration of cosmogenic ^{21}Ne might include inherited cosmogenic ^{21}Ne from previous sedimentary cycles.

*Erosion rates calculated using ^{21}Ne / ^{10}Be / ^{26}Al.

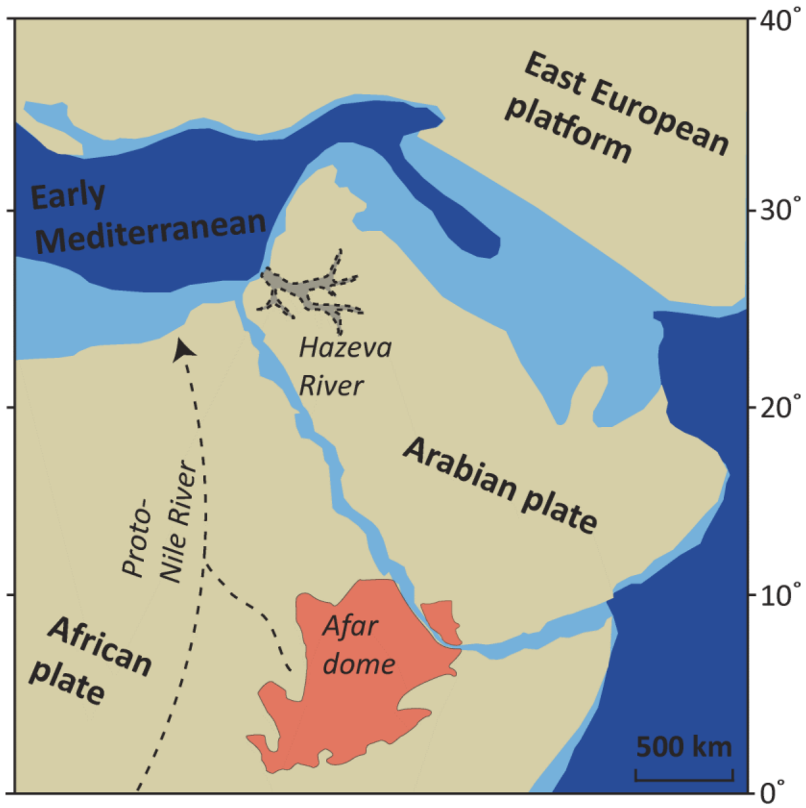

Figure 1. Paleo-geographic map of the eastern Levant during the early Miocene (modified after Meulenkamp and Sissingh, 2003) with the approximated extent of the Hazeva fluvial system (based on Avni et al., 2012; Zilberman and Calvo, 2013).

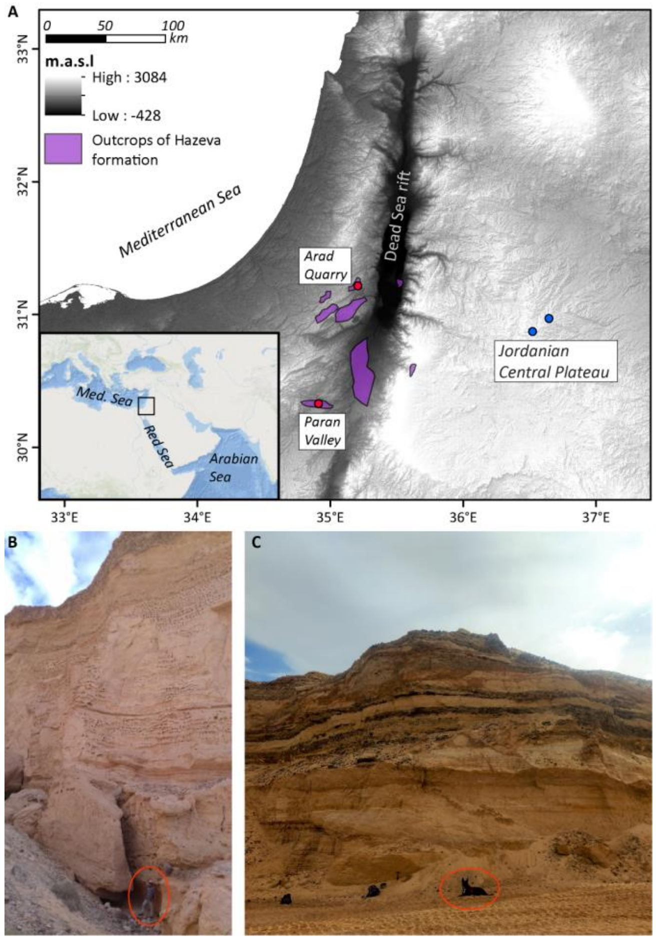

Figure 2. (A) Shaded relief map of the study area with sampling locations of Miocene fluvial sediments sites (red) and in situ Eocene source rock (blue). Hazeva outcrops are after Zilberman and Calvo (2013). Inset map shows regional geographical context. (B) Sampling location at Paran Valley. Sample collected from behind the fallen boulder in a narrow canyon and underneath an overburden of ~50 meters of sand and conglomerate. See person for scale marked at the bottom. (C) Photo of sampling location at Arad Quarry. Samples collected from underneath an overburden of ~100 meters of quartz sand. See dog for scale marked at the bottom.

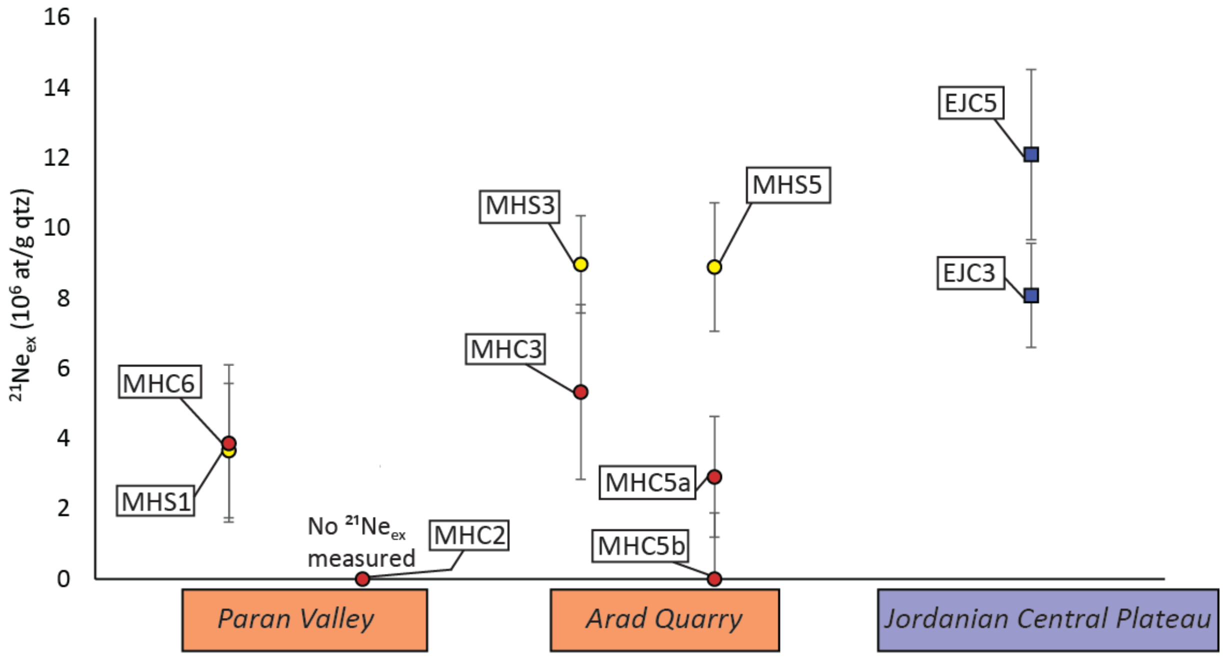

Figure 3. **$^{21}Ne_{cos}$ concentrations in Hazeva sands (yellow), Hazeva chert pebbles (red), and *in situ* Jordanian Central Plateau chert nodules (blue) with respective uncertainties~~. Exposure ages, reported in kyr, are calculated using production rates scaled for latitude and altitude after Stone (2000), using ^{21}Ne production rate of 18.1 atoms/g SiO_2 year (Borchers et al., 2016; Luna et al., 2018)~~.**

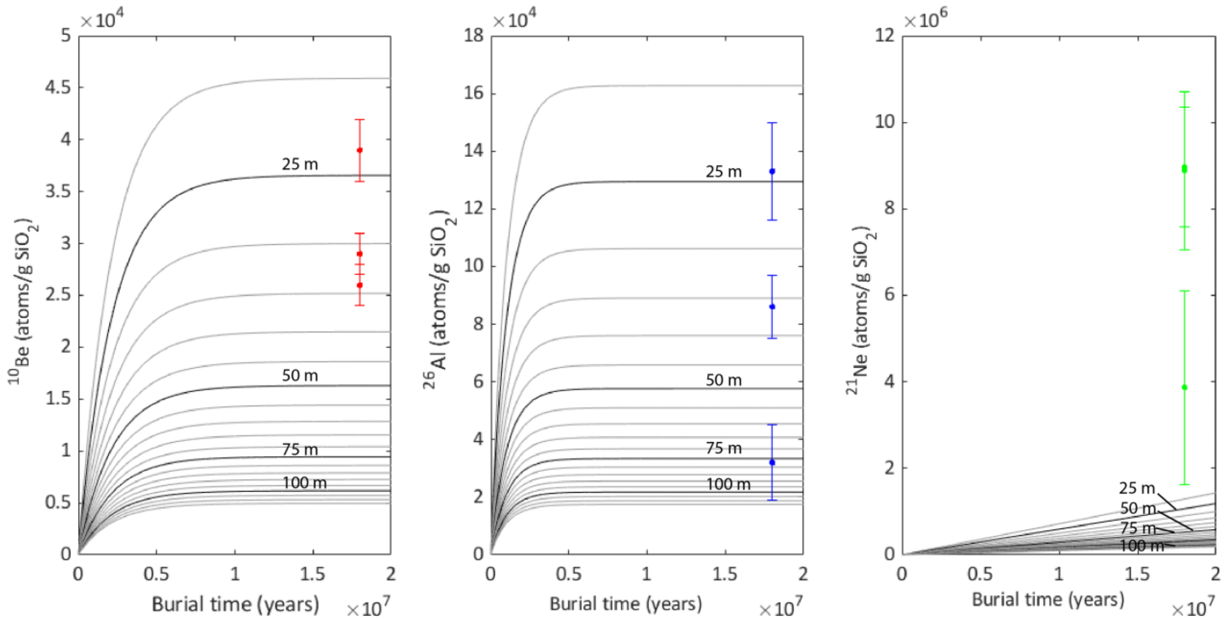

Figure 4. Measured concentrations of ^{10}Be (red), ^{26}Al (blue), and ^{21}Ne (green) in samples MHS3, MHS5, and MHC6. Grey contour lines show changes in nuclide concentrations with time at different depths from 20 to 120 m below the surface in 5m increments. For both sand samples and chert sample, the concentrations of cosmogenic ^{21}Ne are higher than the estimated post burial production. Production by cosmic-ray muons is calculated with schematics presented by Balco (2007). Production rates were calculated at the Arad Quarry site by cosmic-ray muons of ^{10}Be and ^{26}Al are after Balco (2017) and of ^{21}Ne by fast muons is after Balco et al. (2019). This shows that ^{10}Be and ^{26}Al concentrations can be explained by post-burial production, but ^{21}Ne concentrations cannot, so a significant fraction of cosmogenic ^{21}Ne is pre-burial.