



Review Report

Henriquet et al., Unraveling the Kinematics and Morphotectonics of the Petrinja Fault (Croatia), Source of the 2020 M 6.4 Earthquake, TEKTONIKA, 2026.

Table of Contents

1st Round of Revisions	2
Decision Letter.....	2
Comments by Reviewer 1	3
Comments by Reviewer 2	4
Authors' Reply to Reviewer 2	7
2nd Round of Revisions	11
Decision Letter.....	11
Comments by Reviewer 1	13
Comments by Reviewer 2	14
Authors' Reply to Editors	15
Acceptance Letter	16

1st Round of Revisions

Decision Letter

Maxime Henriquet, Lucilla Benedetti, Stéphane Baize, Branko Kordić, Josipa Maslač Soldo, Marianne Métois, Nikola Belić, Marko Špelić, Matija Vukovski, Daniela Pantosti, Francesca Cinti, Stefano Pucci, Alessio Testa, Paolo Boncio, Bruno Pace, Petra Jamšek Rupnik, Adrien Moulin, Riccardo Civico:

We have reached a decision regarding your submission to *tektonika*, "Kinematics and morphotectonics of the Petrinja Fault (Croatia): unraveling the 2020 M 6.4 Earthquake".

Our decision is: Revisions Required

Comments from AE: The comments from two reviewers follow, below. I tend to agree with Reviewer #2, who suggests that the evidence of fault offsets should be presented more clearly and thoroughly, and the interpretation of multiple age populations should be more detailed. This seems like a challenging landscape for morphotectonics. The alluvial surfaces suitable for geochronology seem subtle and discontinuous. I appreciate your effort to describe soil pits to aid in their interpretation. I urge you to consider how to present the evidence for fault offsets in such a way that the reader can assess its quality (perhaps using undecorated lidar figures, as R2 suggests). I'd also suggest to articulate the interpretive relationship between the dated deposit/surface and the piercing line used to measure offset. In Fig 8, for example, the offset seems suspect because I don't believe there is a continuous piercing line across the fault (the alluvial surface is only on one side). Finally, please define an uncertainty for your preferred slip rate (e.g., 0.5 +/-X). At present, I expect that third-party seismic hazard users might adopt a range of rates from 0.5 to 3.9 mm/yr, which seems much too high. I found the work interesting and relevant, and I expect the results will be used in the future.

Comments by Reviewer 1

Dear authors,

This paper is morphotectonic work that analyzes kinematics and geomorphological expressions of Petrinja fault taking consideration of 2020 Mw 6.4 Earthquake. This paper will be of interest to the regional community and wider audience that is interested in quantitative geomorphology, geomorphic mapping of active faults and absolute dating of Quaternary deposits in low stress rate areas and it should be published after minor corrections.

General observations:

Introduction and regional tectonic settings description is properly outlined.

Description of Morhotectonic tracing of Petrinja fault/Cumulative lateral displacement along the PPKF/Quaternary dating of displaced markers: Presented methodology and research results are disclosed in detailed manner, with precise description and illustration.

Discussion follows methodology and results clearly pinpointing tectonic evolution and slip rates associated with PPKF, its importance to seismic sequence occurred in 2020 and correlation of PPKF fault segments with seismic hazard distribution.

Conclusion is in accordance with results and discussion

Supporting materials:

Figure quality in overall is good however they need only a few small correction. See comments outlined.

Paper revision summary:

The presented paper is composed of detailed description and extensive quantitative results so I am in opinion that manuscript require only minor additional work and in this form, after few corrections, is acceptable for publication. I would recommend minor revision. All necessary text corrections, suggestions, and comments are indicated in submitted revised version of submitted manuscript, figures and references.

With best regards,

R1

Comments by Reviewer 2

This manuscript details mapping of the right-lateral/transpressive Petrinja fault (Croatia) using lidar data collected after the 2020 M6.4 earthquake. The authors present detailed descriptions of the fault character, which is largely discontinuous along its relatively short length. The authors also describe several offset features and sampled offset landforms for absolute age control (36Cl and 14C). The resulting lateral slip rates span ~0.5-2+ mm/yr, depending on the age control selected (~early Holocene vs LGM). The minimum slip rate of ~0.5mm/yr is preferred by the authors, as the upper range of the slip rates would indicate this single, short fault consumes about half of the proposed geodetic velocity budget across this region.

Overall, this is a reasonable study (when lower slip rates are preferred) that could be published after major revisions. The manuscript needs much better and clearer figures for the reader to interpret the offsets, which form the backbone of the main results of the paper (slip rates). The figures showing the offsets used in the slip rate study obscure the piercing points/lines themselves. I think the readers need a zoomed in, "plain" (no decorations) topographic map of the piercing lines to assess the offsets. For example, I thought the purple/eastern restoration on figure 10 at site S3 was much too large at 14.4 m, but couldn't honestly assess that from the available figures. Additionally, some topographic profiles across terraces (fault parallel) could help the reader understand and interpret the offsets a bit easier than the current presentation. On the topic of the offset restorations, why are there not minimum and maximum (and, if possible, a preferred) restorations at each location? For example, a restoration of "~14m" at site S1 is incomplete and could be enhanced. At sites S2 and S3, minimum and maximums are presented based on different features, but the min and max values could be enhanced by doing multiple projections of each piercing line (for example, I do not think the piercing line orientation of the upstream extent of the eastern feature in site S3 is the only possible orientation). On a different topic, much more text could be devoted to the difference in age populations (10.3 vs. 19.8 ka). The 10.3 ka age slip rates are very fast, and it seems that the authors prefer using the LGM-ish age of 19.8ka. But, there isn't much discussion about whether or not the incision is related to the post LGM incision event referenced near line 630. It's mentioned that there is widespread incision across Europe and the Mediterranean Sea at that time. However, the slip rates using that age don't produce reasonable slip rates on their own. When did the glaciers recede locally to this fault? Can this be reconciled in the discussion a bit more than current presentation? Also on the topic of geochronology, the spread of radiocarbon ages from the clay unit at sites S2 and S3 was really, really broad. Can this spread be reconciled a bit more, and can the radiocarbon ages help at all? It seems to me that the younger ages could be discarded, but would love to know how the authors would interpret the 14C results a bit more.

I'm currently unable to assess if there are fatal flaws with the observations and interpretations because the figures do not allow for that interpretation. I am taking the author's "word for it" without being able to assess the offsets. Enhanced descriptions in text and figures would strengthen the manuscript. I agree with the author's interpretation that the lower end of the slip rates are (far) more reasonable, and would even suggest further bolstering that finding in the final manuscript. I have some line-by-line comments below.

Alex Hatem, PhD

ahatem@usgs.gov

Figure 3: is the dashed extent on panel a the lidar extent? I didn't see that in the caption

Figure 4: can you show the projected fault on the map (mentioned in the caption in reference to panel g)

Line 247 or so: what figure shows these U vs V shaped valleys?

266-7: can you show simplified lithology on Figure 4 somehow?

Figure 5: panel 5 shows some linear features that strike NE (near the eastern extent of the image), but they are not considered as faults. Can you discuss this more in the text or on the figure?

Figure 7a could be annotated more - the fault is at the very bottom of the image and there's basically no context. What is the goal of this figure/what should I be learning here? I can't see the fault, or at least what is downstream side of the fault.

321: what is meant by "staircase topography"?

Figure 8: why is there an underscore in the site name? remove.

Figure 11: Panel a- what should I be seeing here? I am trusting your interpretation with the arrows, but clearly the fault is obscured by vegetation. A topographic profile should supplement this figure. Panel C could also benefit from a topographic profile - I see the annotations on the map, but really hard to tell what is there besides the annotations.

422 or so: Why not show a topographic profile of the terraces instead of describing the angles in this detail?

600-611: can you show the radiocarbon samples in context on pit walls?

694-6: agreed. If the upper limit is true, than about half of the geodetic budget would fall on this one fault, which doesn't seem reasonable.

717: what do you mean by "segmentation"? this is a loaded term. I do not think you have any evidence of segmentation presented

Authors' Reply to Reviewer 1

Thank you for the positive general comments on this study. We have taken into account the comments made directly on the manuscript and did the modifications requested for the Figure 2. However, we didn't change the notation of the fault geometry on the figure 7, but we added in the caption the convention that is used (strike azimuth, dip angle and dip orientation).

Authors' Reply to Reviewer 2

Thank you for the constructive comments which we hope have greatly improved the paper quality.

We have done major changes concerning the estimation of offsets and we now provide a clear version of the figures showing the topography with and without interpretations (geomorphological mapping + piercing lines) in the Supplementary Figures S1 to S5. We have also added an analysis of the lower fault strand at the Cepeliš site S2 (Figure 9 and S3). Combining the offset from this additional site with the one estimated in the Figure 8 (upper strand) we can then estimate the total slip rate on the fault at the site S2 along the CSPF section. The offset analysis now includes several estimates per site using 2 or 3 sets of piercing lines, and for each we propose a range of minimum and maximum values as well as an estimate of the preferred orientation of the piercing lines to reconstruct the offset.

This new analysis of the piercing lines gives offsets of the same order of the ones presented in the first version of the manuscript. We agree that the lowest estimations of the fault slip rate are more reasonable and should be promoted better in the manuscript. This means that the ages of the corresponding markers cannot date back to the Early Holocene, otherwise the total estimated slip rates are of the order of 2 to 4 mm/yr that would far exceed the potential strain rates detected in the region by geodetic measurements. Therefore, we strengthen in the revised manuscript our hypothesis that most of the analyzed geomorphological markers were shaped during the LGM period. We rely on the fact that some ages obtained in this study are around 19 and 25 ka, and that studies in Slovenia and Albania have shown that the drainage network was marked during the LGM. The radiocarbon ages from the sites S1 and S3 are indeed quite spread, some ages are very young and unlikely to characterize the formation age of terraces (< 1 ka). However, compiling the radiocarbon and cosmogenic ages we find that two age population are represented by the data (lines 972 to 981 ka): 1) the preferred LGM period between 17.3 to 26 ka, and 2) the potential Early to Middle Holocene times (7.2 to 13 ka). Because the piercing lines used to estimate offsets are taken from similar set of terraces along temporary streams, we make the assumption that they formed during the same regional climatic event. Consequently, we now propose two hypotheses concerning the age of formation of the investigated markers (lines 993 to 1016 ka): 1) the preferred LGM period between 17.3 to 26 ka, and 2) the potential Early to Middle Holocene times (7.2 to 13 ka). Based on these two periods, we can estimate slip rates for each site and combining the results together we also probe the total fault slip rate (all the results are summarized in Figure S6 from the Supplementary Information).

We hope that our modifications to the text and the figures make the observations and interpretations clearer to readers, so that they can assess the uncertainties associated

with this approach and the assumptions made in this study to support the conclusions.

Figure 3: is the dashed extent on panel a the lidar extent? I didn't see that in the caption

Indeed, the dashed polygon represents the lidar extent. It is now mentioned in the caption of the Figure 3.

Figure 4: can you show the projected fault on the map (mentioned in the caption in reference to panel g)

We have added the fault trace on the map in panel b.

Line 247 or so: what figure shows these U vs V shaped valleys?

Figure 13 is a good example of these U-shaped and V-shaped valleys downstream and upstream from the fault respectively. Unfortunately, the common practice is to call the figures in the order of appearance, and it would not be relevant to call this figure at this stage of the manuscript. However we have added in the caption of the Figure 13 a sentence referring to these valley shapes.

266-7: can you show simplified lithology on Figure 4 somehow?

We have added the fault trace on the map (4b), but it would be too dense to add the lithology and it would be redundant with the Figure 2. However we have added the main lithological changes (Plio-Quaternary vs Miocene and pre-Miocene basement) along the rivers in the profiles c to f. The lack of correlation between the lithological variations and the river disequilibrium is discussed at line 354-356.

Figure 5: panel 5 shows some linear features that strike NE (near the eastern extent of the image), but they are not considered as faults. Can you discuss this more in the text or on the figure?

These linear features likely correspond to inherited faults and fractures that are exposed and highlighted due to differential erosion. We don't consider these lineaments as active faults because there are no clear offsets of geomorphological markers along these features. But we agree that this trend is eye-catching and we have added a comment to clarify this point (lines 266-2668).

Figure 7a could be annotated more - the fault is at the very bottom of the image and there's basically no context. What is the goal of this figure/what should I be learning here? I can't see the fault, or at least what is downstream side of the fault.

The figure 7a is used to show the alluvial terrace on which the cosmogenic samples (Cep S1 samples 1 to 5) and the radiocarbon ages were extracted. We have annotated the figure accordingly, but the fault trace is unfortunately not visible on the photo, its position is indicative.

321: what is meant by "staircase topography"?

The "staircase topography" refers to relief characterized by steeply sloping hillsides and gently sloping surfaces imitating steps. We have defined what is meant by "staircase" line 450.

Figure 8: why is there an underscore in the site name? remove.

We have removed the underscore in the site name.

Figure 11: Panel a- what should I be seeing here? I am trusting your interpretation with the arrows, but clearly the fault is obscured by vegetation. A topographic profile should supplement this figure. Panel C could also benefit from a topographic profile - I see the annotations on the map, but really hard to tell what is there besides the annotations.

Indeed the fault trace on the ground is masked by forest, as it is usually the case in the area. Although the landscape interpretation is not as straightforward as in desertic region, we still see characteristic features related to the fault activity that will be useful for the community working in such vegetated environment to better recognized evidences of fault activity in the field. For instance, the arrows showing the location of the CMUS and CMLS fault sections outline these low-dipping surfaces found at the foot of the faults along the Hrastovica hill. We kept this panel as we believe it might help the readers not familiar with low deformation rates in vegetated areas.

422 or so: Why not show a topographic profile of the terraces instead of describing the angles in this detail?

We recognize that the level of detail concerning the slopes of the terraces and the riverbed was not useful to support our analysis. We have removed the corresponding sentence.

600-611: can you show the radiocarbon samples in context on pit walls?

Unfortunately, the samples were taken quickly from the pits, and as we were unable to obtain a clean wall and the clay deposits showed no stratification to interpret the depositional context, we have no relevant photos to explain the age dispersion regarding to the depositional context.

694-6: agreed. If the upper limit is true, than about half of the geodetic budget would fall on this one fault, which doesn't seem reasonable.

We have made significant changes in the estimation of slip-rates using multiple offset markers, uncertainties on offset measurements and discussing different hypotheses on the age of formation of the markers. We conclude that given our preferred mean offset measurements and the formation of these markers likely during the LGM period, the slip rates in the central portion of the Petrinja fault fall between 0.9 to 1.6 mm/yr, and around 0.7 to 1.1 mm/yr to the south. Our conclusion is that the Petrinja fault might absorb 1 ± 0.5 mm/yr, which is a significant amount according to the geodetic budget of the area, and at the limit of detection of active faults based on geodetic measurements. Accordingly, the text in the section 6.2 is significantly modified to justify the results in the light of assumptions made.

717: what do you mean by "segmentation"? this is a loaded term. I do not think you have any evidence of segmentation presented in this manuscript.

We are aware that "segmentation" is a term with a heavy meaning. To avoid any confusion we kept the word "complexity" to qualify the fault geometry.

2nd Round of Revisions

Decision Letter

Maxime Henriquet, Lucilla Benedetti, Stéphane Baize, Branko Kordić, Josipa Maslač Soldo, Marianne Métois, Nikola Belić, Marko Špelić, Matija Vukovski, Daniela Pantosti, Francesca Cinti, Stefano Pucci, Alessio Testa, Paolo Boncio, Bruno Pace, Petra Jamšek Rupnik, Adrien Moulin, Riccardo Civico:

We have reached a decision regarding your submission to *tektonika*, "Kinematics and morphotectonics of the Petrinja Fault (Croatia): unraveling the 2020 M 6.4 Earthquake".

Our decision is: Revisions Required

Comments from AE: I have received a second-round review for the manuscript "Unraveling the kinematics and morphotectonics of the Petrinja Fault (Croatia), source of the 2020 M 6.4 earthquake" by Henriquet et al. This review, by the original Reviewer #2, is quite positive. Here it is in full: "I went through the revision this morning. The authors seem to have taken my comments seriously and significantly revised the paper for the better. I'm impressed with the revision and don't have further comments."

I agree that the revised manuscript is much improved. In particular, displacement measurements methods and additional Supplementary Material make the work more robust and reproducible.

I remain concerned with the interpretation of the geochronology. Reading the revised version, it still seems to me that the suite of ages is very inconsistent. I focused on sites Cep S2 (S2b) and Cep S3 (pit1) because the ages at these sites are clearly linked to the offset terraces that are used to calculate displacement. In the manuscript, both offsets have the same preferred age (25 ka), which is derived from an interpretation that climate changes drove terrace formation. However, only one of the nine radiometric ages reported at these two sites is consistent with the preferred age (C-14 at S3). (At other sites, there is similar age scatter, but linking the ages and offsets requires additional interpretations.) Given the amount of scatter, is it possible to rule out the hypothesis that climate-driven terrace abandonment occurred near late MIS 4 as opposed to late MIS 2 (LGM), for example? An age of 50-75 ka seems consistent with 2 of the 3 cosmo ages at S3 (and the third age is older/saturated). I wonder why LGM and early Holocene ages are considered as possibilities, but not older ages, especially since an MIS 4 age would bring the slip rate much closer to prior expectations.

I realize this is a challenging area for slip rate studies, and they are needed in view of the recent earthquake. I'll send this back for revisions to provide an opportunity to consider my concern. I see at least two possible resolutions: (1) adjust your uncertainties to reflect the possibility of older terrace formation and abandonment; and/or (2) make a careful argument that an older age is implausible given the local climatic history (e.g., perhaps there is extensive research showing negligible landscape effects from MIS 4-5?).

Comments by Reviewer 1

I went through the revision this morning. The authors seem to have taken my comments seriously and significantly revised the paper for the better. I'm impressed with the revision and don't have further comments.

Comments by Reviewer 2

N/A – Second round review was not requested

Authors' Reply to Editors

We detail below how we have taken into account the comments and suggestions of the associate editor. Our responses are inserted in blue. Note that in the following, line numbering corresponds to the revised manuscript with track-changes.

Indeed, it was challenging to determine with certainty the timing of terrace abandonment given the scatter in the radiocarbon and cosmogenic ages we obtained. We did not initially consider ages older than the LGM, as only a few data points suggested ages beyond 25 ka, and the literature addressing the geomorphological impact of climatic events prior to the LGM is relatively limited.

However, we agree that the cosmogenic ages from site S3 at Cepeliš are consistent with an older phase of terrace abandonment, around 50–75 ka, corresponding to MIS 4. We acknowledge that there is no strong argument against this interpretation. Therefore, we have incorporated a third hypothesis—referred to as the “MIS 4 hypothesis”—which considers terrace abandonment ages between 50 and 75 ka (see the revisions in Section 6.2, Late-Quaternary chronological constraints).

This addition leads to a third set of slip-rate estimates, with lower values: up to 0.5 mm/yr for individual sites and between 0.2 and 0.7 mm/yr for total slip-rate estimates (see Section 6.3, Late-Quaternary fault slip rates, and Figure 16). These lower values, compared with those derived from the “LGM” or “Early Holocene” hypotheses, are within a plausible range, as they do not exceed the ~1 mm/yr detection limit of geodetic measurements, which have not been found so far on the Petrinja fault, although there is a lack of geodetic studies in the region. No geodetic slip rates have yet been reported for the Petrinja fault, although geodetic data for the region remain scarce.

Acceptance Letter

Maxime Henriquet, Lucilla Benedetti, Stéphane Baize, Branko Kordić, Josipa Maslač Soldo, Marianne Métois, Nikola Belić, Marko Špelić, Matija Vukovski, Daniela Pantosti, Francesca Cinti, Stefano Pucci, Alessio Testa, Paolo Boncio, Bruno Pace, Petra Jamšek Rupnik, Adrien Moulin, Riccardo Civico:

We have reached a decision regarding your submission to *tektonika*, "Kinematics and morphotectonics of the Petrinja Fault (Croatia): unraveling the 2020 M 6.4 Earthquake".

Our decision is: Accept