We thank prof. Stephen Laubach for his thoughtful and constructive feedback. His comments and the suggested references have been of great help in improving the quality of the paper. To address the general comments of prof. Laubach we modified the introduction and conclusions paragraphs, and we propose a new title, to better highlight the scope of the work. In the following, we will address all the comments and explain how we intend to modify the manuscript following the reviewer's suggestions. Reviewer's comments are reported in black and the replies in blue, line numbers refer to the submitted version of the manuscript.

Title. To better describe the scope of the paper, first of all we would like to propose a new title

Original title: **Quantitative parametrization of fracture networks in Digital Outcrop Models: an optimized workflow**

Revised title: **An Integrated Workflow for Parametrization of Fracture Network Geometry in Digital Outcrop Models**

29 The Introduction. Think about creating an opening line that points the reader to the focus of your paper and organizing the elements of the Introduction from general to specific. Line 36 is the most general and ought to be first: 'Fractures exert a fundamental control on mechanical and hydraulic properties of rock' and 'knowledge of fracture attributes has application to many societally important engineering operations' (cite a few references, or put all the references from lines 37-45 in a table. This long text list of applications goes off topic and some of it is repetitive.) Then cover what is important about fractures: 'The effects of fractures on strength and fluid flow depend on several factors, including mode (fault versus opening-mode), mineral fill, orientation, size, and spatial arrangement (some references).' Then focus in on your topic: how fractures are arranged in space. You might want to consider how topic is covered in the 2018 J. Struct. Geol. review of spatial arrangements of faults and opening-mode fractures: 'The arrangement of fractures in space and in relation to one another into networks…' note that size and spatial arrangement are challenging or impossible to document using well data and then go to something specific about what your paper provides. Much of lines 68 to 109 seem distracting for an Introduction. These thoughts may be more effectively explored in the Discussion

Done. We thank the reviewer for the helpful comment. As suggested, we have switched the first and second paragraphs to improve the logical flow. Additionally, we have revised and condensed the paragraph discussing the applications of fracture networks, in order to reduce repetition and enhance clarity:

Original (lines 30-47)

Fracture networks are complex geological objects composed by all the fractures in a rock mass, were “fracture” is used here as a collective term for all the different types of discontinuities that affect rocks, including both primary features (e.g. bedding and foliation) and secondary discontinuities such as faults, shear fractures, joints, veins, stylolites and other dissolution features, deformation and compaction bands, dikes, etc. (Schultz, 2019). Fractures can be classified in sets, i.e. populations of cogenetic discontinuities related to the same deformation phases, kinematics (e.g. joint, normal fault), filling (e.g. quartz vein) and orientation, within statistical variability (Twiss and Moores, 2006; Davis et al., 2012).

Fractures exert a fundamental control on the mechanical and hydraulic properties of rock masses, and their relevance extends to multiple applications, including reservoirs of every kind of geofluid (e.g. Immenhauser et al., 2004; Pringle et al., 2006; Hodgetts, 2013; Wang et al., 2023), nuclear waste repositories (e.g. Follin et al., 2014; Hadgu et al., 2017), geothermal energy (e.g. Kosović et al., 2024), geo-hazard (e.g. Eberhardt et al., 2004; Agliardi et al., 2013; Riva et al., 2018), engineering geology (e.g. Franzosi et al., 2023a, b), seismic swarms migration (e.g. Cox, 2016), hydrothermal mineralization (e.g. Micklethwaite, 2009; Townend et al., 2017), and induced seismicity due to underground fluid injection (e.g. Karvounis and Wiemer, 2022). In recent years, the interest in fractured reservoirs has increased due to the growing number of projects related to decarbonization and the energy transition, such as CUS (Carbon Underground Sequestration; e.g. March et al., 2017, 2018), underground hydrogen storage (e.g. Wallace et al., 2021; Zamehrian and Sedaee, 2022), fractured aquifers and medium/high enthalpy geothermal fields (e.g. Genter et al., 2010), and underground energy storage (e.g. Menéndez et al., 2019). In all these applications, fracture patterns hold great importance as they influence the direction, magnitude, and heterogeneity of fluid flow, and the storage volume of reservoirs.

Revised:

Fractures exert a fundamental control on the mechanical and hydraulic properties of rock masses, and their relevance extends to multiple applications, including reservoirs of every kind of geofluid (March et al., 2017; Wallace et al., 2021; Wang et al., 2022; Forstner et al., 2025), nuclear waste repositories (Follin et al., 2014; Hadgu et al., 2017), geology engineering (Eberhardt et al., 2004; Agliardi et al., 2017; Franzosi et al., 2023) and contaminant transport (Cherubini, 2008; Medici et al., 2024). In all these applications, fracture patterns hold great importance as they influence the direction, magnitude, and heterogeneity of fluid flow, and the storage volume of reservoirs.

Fracture networks are complex geological objects composed by all the fractures in a rock mass, were “fracture” is used here as a collective term for all the different types of discontinuities that affect rocks, including both primary features (e.g. bedding and foliation) and secondary discontinuities such as faults, shear fractures, joints, veins, stylolites and other dissolution features, deformation and compaction bands, dikes, etc. (Schultz, 2019). Fractures can be classified in sets, i.e. populations of cogenetic discontinuities related to the same deformation phases, kinematics (e.g. joint, normal fault), filling (e.g. quartz vein) and orientation, within statistical variability (Twiss and Moores, 2006; Davis et al., 2012).

30 This definition of ‘fracture’ seems overly broad. Useful definitions to some extent depend on the application and how results are going to be used. The Schultz 2019 definitions might be useful in rock mechanics/excavation/engineering setting, but seem to me to be the wrong place to start if your objective is using the outcrop as an analog for the subsurface in the applications that you list next. And there are other uses for outcrop fracture characterization that might use different definitions. For example, for geomorphologic work—which uses many of the same analytic tools of topology, spatial arrangement, and aperture measurement—alternate categories are useful (see for example, the workflow paper by Eppes et al.).

So I suggest you adopt a more structural geologic definition (faults and opening-mode fractures) and mention that for other applications workers may need other terms or definitions.

Not all bedding constitutes discontinuities. And why do you say foliations are a primary feature and fractures secondary? Foliations are certainly in the same ‘secondary’ category as foliations. Later in the text you do not consider bedding to be ‘fractures’ so you don’t seem to be following your own definition.

Done. We thank the reviewer for this comment. We initially thought that a broader definition for the term “fracture” would have been more useful, as the techniques presented are not necessarily related to a fluid flow field of application. It is also true that this workflow was conceptualized to define the input parameters for stochastic DFN models, which are ultimately used to run flow simulations. We agree to remove the distinction between primary and secondary features, that was ill posed. Here is a revised version of the paragraph, trying to account for both the scenarios (fluid flow and other applications):

Original (lines 30-35):

Fracture networks are complex geological objects composed by all the fractures in a rock mass, where “fracture” is used here as a collective term for all the different types of discontinuities that affect rocks, including both primary features (e.g. bedding and foliation) and secondary discontinuities such as faults, shear fractures, joints, veins, stylolites and other dissolution features, deformation and compaction bands, dikes, etc. (Schultz, 2019). Fractures can be classified in sets, i.e. populations of cogenetic discontinuities related to the same deformation phases, kinematics (e.g. joint, normal fault), filling (e.g. quartz vein) and orientation, within statistical variability (Twiss and Moores, 2006; Davis et al., 2012).

Revised:

Fracture networks are complex geological objects composed of all the fractures in a rock mass.

Here, the term “fracture” will be used as a general term including both opening-mode or shear fractures (joints, faults, etc.), filled or not (veins, joints, etc.). Broadening the meaning of “fracture” by including other kind of discontinuities, such as deformation/compaction bands, foliations, bedding, pressure solution seams and stylolites, etc., may be useful in some research field or application, such as engineering rock mechanics, geomorphology or hydrogeology (Schultz, 2019; Eppes et al., 2024).

30 ‘where’?

Done. Thank you, we fixed the typo.

35 for the ‘filling’ aspect these references seem inadequate and moreover, it has already been shown that using mineral deposits alone to help define sets is quite misleading for several reasons. I suggest you call out the Reviews of Geophysics 2019 paper here, which is already in your reference list (line 1185). As for the other citations, I think citing textbooks is not favored. And you already have the Hancock 1985 review in your reference list with its classic summary of fracture set rules.

Done. We fixed the references as the reviewer suggested.

Original (lines 33-35):

Fractures can be classified in sets, i.e. populations of cogenetic discontinuities related to the same deformation phases, kinematics (e.g. joint, normal fault), filling (e.g. quartz vein) and orientation, within statistical variability (Twiss and Moores, 2006; Davis et al., 2012).

Revised:

Fractures can be classified in sets, i.e. populations of cogenetic discontinuities related to the same deformation phases, kinematics (e.g. joint, normal fault), filling (e.g. quartz vein) and orientation, within statistical variability (Hancock, 1985; Laubach et al., 2019).

46 And there are some papers that are examples of extracting fracture information from outcrop specifically for these applications. How does your work differ from or advance from these other studies?

Done. We added two references to complete the paragraph.

Original (lines 46-47):

In all these applications, fracture patterns hold great importance as they influence the direction, magnitude, and heterogeneity of fluid flow, and the storage volume of reservoirs.

Revised:

In all these applications, fracture patterns hold great importance as they influence the direction, magnitude, and heterogeneity of fluid flow, and the storage volume of reservoirs (Davy et al., 2013; Wang et al., 2022).

47 'and rock strength.'

Done. We corrected the typo.

31, 35, 55, 130 A complete description of a fracture network and a method for extrapolation from outcrop to subsurface ought to have a step in it where the diagenetic state of the outcrop host rock and fractures is documented. What is the diagenetic state of the host rock and what kinds, if any, mineral deposits are in the fractures? This is not a hard step to add. There are a number of examples in the literature that describe how to do it. It's just a matter of describing (or even reporting) host rock and fracture properties; and if for some reason this cannot be done (not even one thin section?) then at least the 'complete and rigorous workflow' could mark this as a gap. The paper need not be made much longer by mentioning the need for such a step. The MS already cites one paper that makes this point (Forstner and Laubach 2022) so this is not a matter of adding a citation.

And the case has been made in the literature, and I think it is hard to dispute at this point, that key parameters such as connectivity and length are modified in essential ways by cement deposits. This information, if possible, should be included in the basic network description and the topological formulations. For example, there is a big difference between a network of two orthogonal joints sets, where all fractures are open, and a geometrically identical arrangement where the first set is filled (veins, for example) and the second is open, and a case where all the fractures of both sets are sealed. All of these cases have been found in outcrop. It's not helpful to the modeling or analog user community to report that all with connectivity indices based solely on the trace patterns.

As a brittle structural community and creators and users of fracture outcrop analogs we can't be satisfied with methods that ignore mineral deposits when core data shows that such deposits are a fundamental attribute of most of subsurface fractures that are of interest to practical applications. Moreover, the mineral deposits in fractures are one of the few features that can reliably be measured in both outcrop and subsurface. Such observations can be a useful part of relating outcrops to specific subsurface targets (Ukar et al., 2019; Elliott et al., 2025). Host rock composition and diagenesis is also something that you need to know in comparing mechanical and fracture stratigraphy from analog to target.

Done. Regarding the diagenetic state of the host rock and description (if any) of mineral deposits, we cited previous works in the same quarry focused on microstructural and petrophysical analysis. In this outcrop, veins are almost absent, as well as fibers on small faults. In any case, we feel that this simplification allows concentrating on meso-scale geometry and topology, which are the main purpose of the study. To improve clarity, we highlighted the lack of mineral fillings in the fractures in section 2 -**Selecting an outcrop: the Altamura Limestone at Pontrelli quarry** .

Revised (from line 177):

...Aside from the geometrical characteristics, veins are absent in all of the three fracture sets, as well as fibers on small faults (Set 1 and Set 2).

50 Table and 55-60 Text

This list of fracture properties needed is incomplete.

The table footnotes should do a better job of explaining what you mean by 'static/dynamic'. Overall the table does not seem very clear, and some aspects are questionable. For example, by starring 'network' for 'topology' but not 'sets' you imply that topology can (or should) only be documented for 'networks' but this way of thinking of the issue is limiting. For example, if there is only one set, you could still define the topology (it would be the topology defined by fractures in that set). Core data suggest that 'one set' is common in several basins (see papers by Laubach and by J. Lorenz from the 1990s). If you leave this circumstance out, you may be missing just what the analog is supposed to capture. And in many cases, the network in outcrop in not what you want to describe the subsurface. Instead, it would be better to isolate part of the outcrop network for topology analysis. The literature has plenty of examples of outcrop fracture studies where the first step is figuring out what weathering and other 'near surface' fractures ought to be omitted (or at least accounted for separately in topology analysis). There is a clear example by Lorenz. The studies of fractures in central Texas related to the SSC cite are another. In both of these examples, extracting the meaningful fractures to analyze has major practical implications for the usefulness of the analog study.

On the static versus dynamic, here you must mean ‘on an engineering time scale’, inasmuch as over geologic time scales all of these features are ‘dynamic’ as fractures grow and interact. But even on the engineering time scale how can you be sure that, for example, connectivity and length are static? And there is good evidence that in some reservoirs apertures are not particularly dynamic. So, while the static versus dynamic aspect is useful to think about, it seems like a red herring here where you point is that many of these extended attributes are difficult or impossible to measure in the subsurface with the kinds of probes we have. Do you need the static versus dynamic distinction later? Maybe better to omit and make the table about attributes you desire to measure.

Done. Here we propose to modify Table 1 to better highlight all the parameters needed to fully characterize a fracture network, what parameters can be obtained from DOMs (facets and/or traces) and what parameters we are focusing on. We agree with the reviewer that the Static/Dynamic column can be misleading and it’s not functional for the aims of the study, and we decided to remove it. We removed Static/Dynamic from even from the text.

Original (line 50):

Parameter	Fracture network	Fracture set	Static/Dynamic
Number of sets	*		Static
Orientation		*	Static
Topology	*		Static
Size (length/height)		*	Static
H/L ratio		*	Static
Density/Intensity (1)	*	*	Static
Aperture		*	Dynamic
Spatial organization	*	*	Static
Representative Elementary Volume (2)	*	*	Static

Revised:

Parameter	Fracture network	Fracture set	DOM - Facets	DOM - Traces
Number of sets	*		*	*
Orientation		*	*	
Topology	*	*		
Size (length, height)		*		*
H/L ratio		*		*
Density, Intensity (1)	*	*		*
Aperture		*		
Spatial organization	*	*		*
Representative Elementary Volume, Area (2)	*	*		*

Roughness	*	*
Kinematics	*	
Deformation Mechanism	*	
Filling	*	

Original (line 55-61):

The quantitative characterization of fracture networks requires the determination of several geometrical and topological attributes of fractures and their statistical distributions (Table 1). Some of these attributes apply to the individual fracture set (e.g., orientation, length/height distribution) others to the whole fracture network (e.g., topology). Fracture properties can be static, meaning that they do not change in response to boundary stress field and fluid pressure variations (e.g., number and orientation of fracture sets), or dynamic, meaning that they can change due to variations of mechanical conditions, as for instance does fracture aperture when fluid pressure changes in response to injection of fluids in a reservoir or in the seismic cycle (Gleeson and Ingebritsen, 2012).

Revised:

The quantitative characterization of fracture networks requires the determination of several geometrical and topological attributes of fractures and their statistical distributions (Table 1). Some of these attributes apply to the individual fracture set (e.g., orientation, length/height distribution) others to the whole fracture network (e.g., topology).

64-66 This account of what can and cannot be measured could be more nuanced and do a better job of setting up what your paper contributes. Some aspects of fractures can be measured on the meso scale, like strike and dip, aperture, some aspects of abundance, and if the wells are deviated 1D spatial arrangement. That's not the same as 'cannot be measured'. The elements that can't be measured are length, height, and connectivity.

Done. We changed the text according to the reviewer's suggestions.

Original (lines 64-67):

Fractures in the subsurface (e.g. in reservoirs) cannot be characterized at the mesoscale (meters to tens of meters) using direct techniques. Borehole data (cores and image logs) only provide 1D, very local and sparse information (limited to1D traces in a 3D volume), do not constrain the size of discontinuities, and are affected by important orientation biases (Baecher, 1983).

Revised:

Fractures in the subsurface (e.g. in reservoirs) can only be partially characterized at the mesoscale (meters to tens of meters) using direct techniques. Boreholes provide local information (limited to1D traces in a 3D volume) about the orientation distribution, aperture, fracture abundance (P10, Dershowitz and Herda, 1992) and, if the borehole is properly oriented with respect to the average orientation of a fracture set, 1D spatial arrangement. In contrast, length and height distributions, connectivity and the REA cannot be measured.

68 'fractures are not always...'
86 'fracture state'

Done. We fixed the typos

90-109 This commentary on DFNs seems out of place here. Maybe it belongs in the Discussion. DFN's are something you build once you have information about the fractures (however incomplete) and so topically it seems out of place in a lead up to ways to improve characterization.

Done. We thank the reviewer for the comment. The idea behind the addition of this part of the introduction was to highlight the fact that parameters calculation in this contribution is tuned for the specific purpose of stochastic modelling. We agree that this part of the introduction may be a bit long and too specific. We propose a summarized version of the paragraphs:

Original (lines 91-109):

The impossibility to directly map or image fractures in the subsurface suggested using continuum representations based on some form of upscaling or homogenization, such as the dual porosity model (Warren and Root, 1963). Alternatively, the Discrete Fracture Network (DFN) approach allows generating stochastic simulations where fractures are simplified as planar polygons in 3D or segments in 2D. Generating DFNs requires fracture parameters and a stopping criterion to end the simulation. Standard DFN software (e.g. Move – https://www.petex.com/pe-geology/move-suite/, Petrel – https://www.slb.com/products-and-services/delivering-digital-at-scale/software/petrel-subsurface-software/petrel, FracMan – https://www.wsp.com/en-gl/services/fracman, DFNworks – https://dfnworks.lanl.gov/) are based on a Poisson point process that generates fractures with a random spatial distribution. The geometrical properties of each fracture are drawn from parametric length and orientation distributions, and fracture height is generally controlled by a fixed height/length ratio. The simulator generates fractures until a target fracture intensity $P32$ (Dershowitz and Herda, 1992) is reached in the simulation volume. Connectivity or any other form of spatial organization cannot be taken into account in these models due to limitations of the Poisson distribution, that is specifically based on the assumption of spatial independence between fractures (e.g. Davis, 2002). Modern approaches have been developed in the last years to try and solve this fundamental limitation, for instance controlling clustering of fractures by means of the Ripley's K function (Shakiba et al., 2024), or including attractive vs. repulsive spatial and directional processes controlled by statistical and/or pseudo-mechanical parametrizations (Bonneau 105 et al., 2013; Davy et al., 2013; Bonneau et al., 2016), but a satisfactory solution has yet to be found, especially in 3D. Sometimes also "deterministic" DFNs are used, but the possibility of creating such models is limited to structures that can be imaged in 3D seismics, i.e. meso-scale faults larger than some hundred meters and characterized by an offset that results in a contrast in seismic impedance.

Revised:

The impossibility to directly map or image fractures in the subsurface lead to using continuum representations based on some form of upscaling or homogenization, such as the dual porosity model (Warren and Root, 1963). Alternatively, the Discrete Fracture Network (DFN) approach allows generating stochastic simulations where fractures are simplified as planar polygons in 3D or segments in 2D. In the standard and most widespread approach to stochastic 3D DFNs, the geometrical properties of each fracture are drawn from parametric length and orientation distributions, and fracture height is generally controlled by a fixed height/length ratio. The simulator generates fractures until a target fracture intensity $P32$ (Dershowitz and Herda, 1992) is reached in the simulation volume (e.g. Move – https://www.petex.com/pe-geology/move-suite/, Petrel – https://www.slb.com/products-and-services/delivering-digital-at-scale/software/petrel-subsurface-software/petrel, FracMan – https://www.wsp.com/en-gl/services/fracman, DFNworks – https://dfnworks.lanl.gov/). Fractures are randomly distributed in the simulation volume according to a Poisson point process, therefore connectivity or any other form of spatial organization cannot be reproduced in these models. More sophisticated approaches have been developed in the last years to try and solve this fundamental limitation (Shakiba et al., 2024, Bonneau et al., 2013; Davy et al., 2013; Bonneau et al., 2016), but a satisfactory solution has yet to be found, especially in 3D.

99 Is a fixed height/length ratio realistic? Doubtful.

We agree that a fixed H/L ratio is not realistic, but it's a requirement in most of the stochastic 3D DFN models. This is the reason why the following discussion has been developed.

111 Here and elsewhere where you mention ‘in detail’; note that this is a vague usage. Omit or mention a scale range.

Done. We thank the reviewer for this correction. We followed your suggestion and removed “in detail” where present.

114 For comparing outcrop and subsurface, I don’t think you want to say they ‘underwent the same geologic history’ since outcrops and subsurface targets by definition have different geologic histories, and the differences could have a material effect on what fractures are there. Uplift, contraction, weathering and a bunch of other processes must differ from the target to the outcrop. See English, 2012, Engelder, 1985, and Eppes et al. 2019 for discussions of various aspects of these differences. Peacock 2016 and Elliott et al. 2015 have text that describes how the inevitable differences can be accounted for. The reality is that outcrops and targets will always vary in important ways and one of the steps in a ‘rigorous workflow’ needs to be collecting data that will allow the nature of these differences to be identified. That way, the applicability of the analog can be judged, and, in some cases, the outcrop patterns can be adjusted to match the subsurface situation (as in the example in Forstner and Laubach, 2022, a study you cite).

Done. We thank the reviewer for this suggestion; we changed the text as follows:

Original (lines 113-114):

that underwent the same geological history (Bertrand et al., 2015; Bistacchi et al., 2015; Jacquemyn et al., 2015; Martinelli et al., 2020).

Revised:

that underwent a geological and tectonic evolution that is at least partly comparable. The applicability of an outcrop as an analogue should be evaluated carefully, and some assumptions should be eventually made (Forstner and Laubach, 2022)

116-118 This is vague. I’m not sure what you mean. What are ‘traditional, direct…’ surveys? Outcrop fracture trace maps via surveying instruments and film have been acquired since at least the 1980s and although those methods are certainly slower than DOMs they may not be less accurate. Are you trying to say that previous studies of fracture statistics from outcrop that don’t use your method are unreliable? If this is your point, then the comments belong in the Discussion after you have demonstrated this.

116 I don’t know what you mean by the phrase ‘unavoidable as it is limiting’ and how does the ‘traditional direct geological and structural field survey’ differ materially from flying the outcrop with a drone? In any case, relative chronology’ if you mean crossing and abutting relations can be estimated from images and ‘mineralization/filling’ is best done in the

laboratory with a thin section. And if by 'geometrical datasets with traditional techniques' you mean fracture trace maps, this was accomplished in the past for large outcrops without drones or digital outcrop models (see Barton from the late 1980s) although no doubt current technology makes collecting such information easier. So these sentences need adjustment so as not to be misleading.

Either way, access to advanced image collection methods do not solve two big limitations the use of outcrop fracture tracer mapping: the finite size of most outcrops and the potential for fractures in outcrops to be unrelated to the subsurface. These caveats ought to be mentioned.

Provide a definition of what you mean by 'traditional direct geological and structural field survey'.

132 Define the 'traditional direct field…'

Done. These three comments are addressed together given that they are about the same topic. We agree with the reviewer that "traditional" might deliver a misleading significance, and we decided to remove the term. At the same time, we want to clarify that in the paper it is nowhere stated that other methods are considered unreliable. We agree that fracture network properties such as mineralization and filling are best characterized in laboratory. Even if we agree that trace mapping and data collection in general can be accomplished without the support of digital outcrop models, we think that this statement is limited to horizontal outcrops. Vertical walls or gorges that are more than 50 m in height, common occurrence in the Alps for example, cannot be characterized without a digital model, given safety and accessibility restrictions. Certainly, DOMs don't inherently solve certain problems like the cited finite size of the outcrop or potential fractures unrelated to subsurface, but these limitations appliy to any data acquisition method. DOMs are a mean for data collection, which does not imply any kind of interpretation. In this paper we present a statistical approach, based on data collected from DOMs, to address the finite size of an outcrop, at least for the length/height distribution calculation, while detecting fractures not related to the subsurface is out of the scope of this contribution.

Original (lines 115-119):

In this regard, the traditional direct geological and structural field survey is as unavoidable as it is limiting, in the sense that parameters such as kinematics, roughness, relative chronology and mineralization/filling of structures can only be gathered during fieldwork (e.g. Hancock, 1985), but on the other hand limited accessibility and logistical limitations prevent the collection of extensive geometrical datasets with traditional techniques (e.g. McCaffrey et al., 2005)

Revised:

In this regard, field survey, intended as physically inspecting and collecting data from outcrops, is a fundamental step in the process of fracture network characterization, because features such as kinematics, roughness, relative chronology and mineralization/filling can only be gathered during fieldwork. At the same time, even if it is possible, manually collecting massive amounts of data is time consuming on horizontal outcrops, and very difficult in vertical outcrops, where the accessibility is limited (data can only be collected in the portion of the outcrop reachable by the geologist) and depending on the conditions, safety is not guaranteed (e.g. rocks falling from the top of the cliff).

130 The actual scope of the paper needs to be clarified here. And mention what parameters you are leaving out.

Done. Here is a revised version of the last two paragraphs:

Original (lines 130-144):

In this paper we present a workflow that combines new and existing methodologies to quantitatively characterize all the parameters of a fracture network, with a particular focus on obtaining robust statistical distributions to be used as input in stochastic DFN models. The analysis is based on both traditional direct field observations and photogrammetric DOM analysis. The integrated workflow is aimed at maximizing the structural information that can be obtained from different types of DOMs, including orientation distributions, topological relationships, length and height distributions and fracture intensity. Some of these parameters (i.e. topology) are not direct inputs to DFN models, yet they represent a fundamental control on the quality of the generated model itself.

The workflow, rooted in a rigorous statistical background, attempts at minimizing the assumptions made at every step, for example during the choice of the orientation distribution, or the length and height distribution. The methodologies proposed to estimate each parameter can be applied independently, subject to the type and quality of the outcrop. The complete workflow (Figure 1), combining both facet and trace data, includes two separate processing pipelines: (i) semi-automated fracture orientation analysis carried out on point cloud DOMs (Sect.4.4); and (ii) fracture trace analysis carried out on orthomosaics, allowing to measure topological relationships, length and/or height distributions, $P21$, and to estimate (subject to assumptions) the H/L ratio distribution (Sect. 5 to 8). The two pipelines are integrated to achieve a complete 3D parametrization of the fracture network (Sect. 9 and following).

Revised:

The scope of this paper is to present a workflow based on statistically rigorous methodologies to characterize a fracture network from the geometrical point of view. The result of such workflow provides a suite of parametrical distributions to be used as input in current stochastic 3D DFN models. The parameters considered here are: The orientation distribution, the length/height distributions, the topological parameters, the fracture areal intensity (P21) and the H/L ratio. We aim at integrating 2D and 3D data sources (point clouds, orthomosaics, DEMs), vertical and horizontal outcrops and facets and traces data to achieve a 3D geometrical parametrization of the fracture network (Sect. 9 and following). The methodologies proposed to estimate each parameter can be applied independently, subject to the type and quality of the outcrop.

The first part of the paper is dedicated to best practices about data acquisition (both ground-based and UAV-based), pre-processing, reconstruction and quality assessment of a photogrammetric model (Sect. 3). Then two separate processing pipelines are presented, depending on the DOM type: (i) semi-automated fracture orientation analysis carried out on point cloud DOMs (Sect. 4.4); and (ii) fracture trace analysis carried out on orthomosaics, allowing to measure topological relationships, length and/or height distributions, $P21$, and to estimate (subject to assumptions) the H/L ratio distribution (Sect. 5 to 8).

135 Is it really correct that factors such as connectivity are not incorporated in DFNs? Some DFNs can incorporated aperture size variation. See papers by Sweeney et al, for example, 2023.

Yes, topology is never taken into account as an explicit parameter in DFN models, for example including a P20 specific for X nodes or Y nodes. The starting point is the standard stochastic 3D DFN model, based on Poisson point process, where the connectivity is achieved randomly and only by means of X nodes (Y nodes are high unlikely). Advancements have been made by different approaches (Davy et al., 2013; Bonneau et al., 2016), where a higher degree of connectivity is achieved by integrating geo mechanical principles in the stochastic generation of fractures. Recently, FRACMAN software integrated a new approach in which fracture set are generated in different steps depending on the relative chronology, and the connectivity is managed by a “termination chance” parameter. This is the reason why we wrote that connectivity represents a fundamental quality check.

137 Awkward wording: ‘minimizes assumptions at each step’.

Done. Thank you for the correction. This phrase was deleted in the revised version of the introduction.

138-146 This would be more compelling if you could state your specifics claims: 'here we show that...'

This comment falls in the revised version of the paper proposed in a comment above (line 130)

163, 425, 638 Describing and classifying height patterns should be a step in outcrop network description. There is a useful height classification in Hooker et al. (2013. J. Struct. Geol.)

This comment, and the others related to height patterns will be answered at line 605

175 What do you mean by 'distinctly younger'? This makes it seem like you can detect a gradation in age, but all you have is an abutting relation but no information about how much younger. Geomechanical modeling shows that such relations can arise in a single deformation sequence or can reflect much longer times. Check the text and remove such unjustified qualifiers.

Done. We agree to remove "distinctly", the time gap could be very small or very large actually, but abutting relationships are systematic and point to two different events, with the exception of ca. 4% of D1 fractures that might have been reactivated in a later stage.

Original (lines 174-175):

However, structures belonging to Set 2 always abut on those belonging to Set 1, showing that Set 2 is distinctly younger (Table 2).

Revised:

However, structures belonging to Set 2 always abut on those belonging to Set 1, showing that Set 2 is younger (Table 2).

181 Forstner et al. 2025 GSL Energy Geoscience Conference Series, v. 1 explicitly investigates the effects of such patches on length distribution statistics. A good workflow needs to establish and describe how continuity across these features is treated.

This comment will be addressed at line 680

183 'drowned by artificial fractures' is causal and vague. Can you restate this?

Done.

Original (lines 181-183):

Other zones distributed across the pavement are partially affected by non-natural, quarrying-related fractures, but with a careful analysis it is still possible to detect Set 1, while Set 2 and especially Set 3, being characterized by smaller fractures, are drowned by artificial fractures.

Revised:

Other zones distributed across the pavement are partially affected by non-natural, quarrying-related fractures, but with a careful analysis it is still possible to detect Set 1, while Set 2 and especially Set 3, being composed of smaller fractures, are more difficult to interpret and separate from the ones related to quarrying.

249 I think the text here could be confusing. You mean the best parameter to extract information from your image, but the way you put it ('most important parameter for applications in structural geology') it sounds like a geologic or fracture parameter and the reader asks The most important parameter for what? Most important probably depends. Is this qualifier even needed here? The remark seems more appropriate for the Discussion, where it can be defended.

This sentence for definition of 'surface density' could be clearer. I take it that this is an imaging parameter but it could be read as a fracture abundance measure. If what you mean by this is 'where the most fractures are' at least in terms of fluid flow there are examples in the literature where production data shows that numerous fractures does not correlated with, for example, high fluid flow (Wang et al. 2023, Marine & Petroleum Geology).

Done. We thank the reviewer for the comment. The surface density parameter in this paragraph doesn't refer to the areal fracture density as defined by Dershowitz and Herda, 1992, but it is a parameter specific to point clouds and refer to the number of points inside a sphere of arbitrary radius. The higher the point surface density, the easier it will be to detect geological features on the cloud surface. Following the suggestions of the reviewer here is a new version of the paragraph:

Original (line 249):

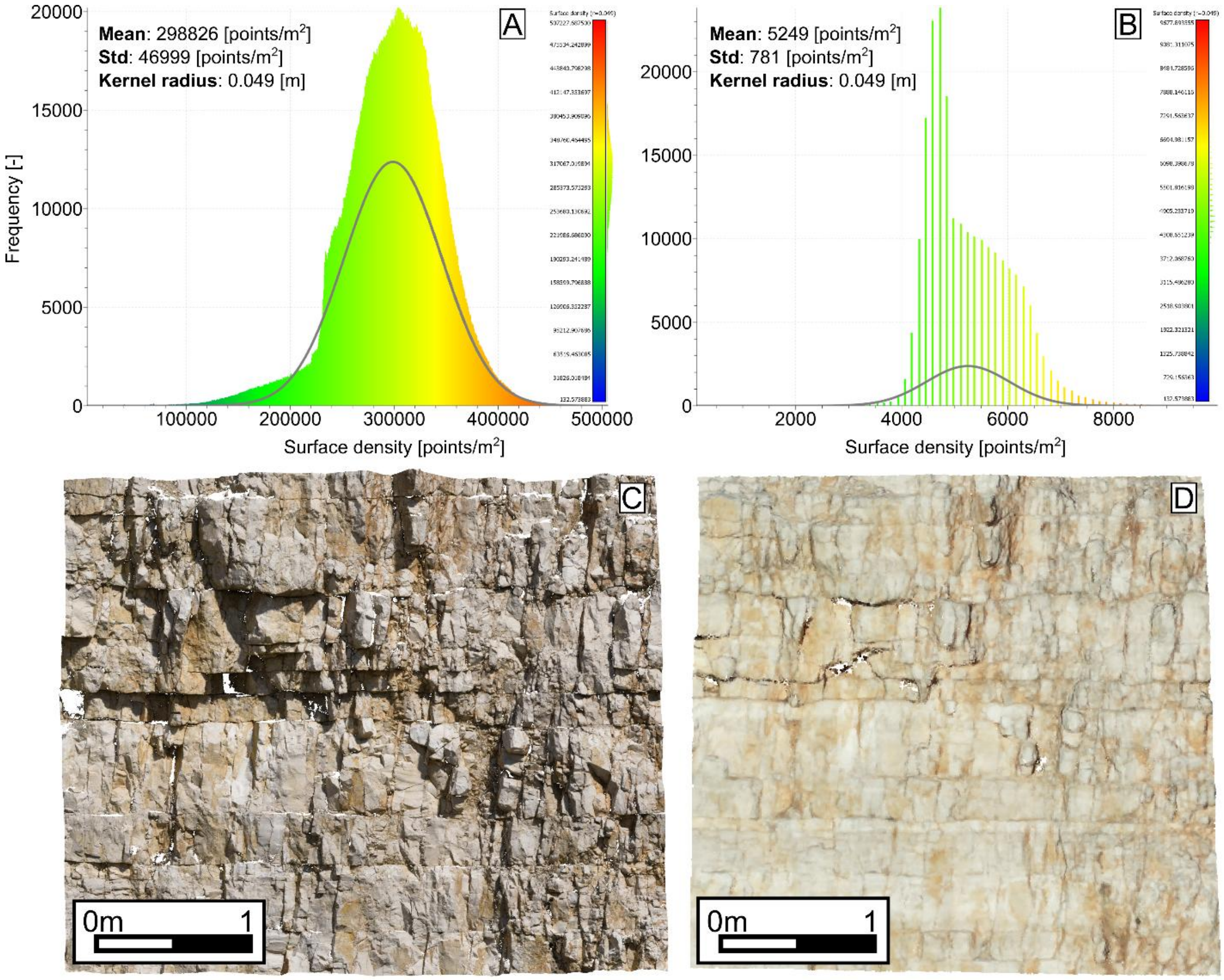
We believe that the most important parameter for applications in structural geology is surface density.

Revised:

We believe that the most important parameter to evaluate the quality of a photogrammetric model for applications in structural geology is the point cloud surface density (SD).

270 Add graphic bar scales to the outcrop images.

Done, we modified the figure as suggested.



503 ‘trace connectivity’ and their possible effects on ‘fluid flow’ are two different things and ought to be more carefully separated in your description. Fully connected traces may not imply any enhancement in flow (for example, if the traces are faults or sealed fractures); disconnected open fractures can enhance flow if the host rock is permeable. Please be more careful in how these parameters are portrayed.

Done. We thank the reviewer for this correction. We acknowledge that connectivity and fluid flow are two different things, and we decided to remove “fluid flow” from the sentence.

Original (lines 501-503):

Even under this limitation, topology is a fundamental component of fracture network analysis because it is directly related to connectivity and fluid flow, as demonstrated by Sanderson and Nixon (2015).

Revised:

Even under this limitation, topology is a fundamental component of fracture network analysis because it is directly related to connectivity, as demonstrated by Sanderson and Nixon (2015).

510 Include contingent nodes in nodes list. These kinds of nodes go back to at least Barton and Hsieh.

Done. We added C nodes to the list as the reviewer suggested. We strongly believe that the detailed analysis presented in the suggested paper is a key step in implementing representative fluid flow models. Using C nodes implies that the geologist must take a decision about their nature, since "activated" C nodes become V nodes, and "not activated" C nodes become I nodes. This decision heavily impacts all the statistical parameters calculated downstream (length and height parameters, H/L ratio). We therefore believe that making a decision about the nature of C nodes should be undertaken before standard topological analysis, and it is beyond the scope of this contribution. At the same time, the non-uniqueness of the definition criterion makes the implementation in a standardized library complex.

Original (lines 508-516):

According to Benedetti et al. (2025), four main nodes categories can be found in a fracture network (Figure 8):

- I nodes: fracture trace true tip points;
- Y nodes: abutting relationship;
- X nodes: crosscutting relationship;
- V nodes: perfect coincidence of two tip points belonging to two different fractures - these are theoretically possible, but extremely unlikely;
- B nodes: boundary nodes, where a fracture trace terminates at the interpretation boundary.

Revised:

Six main nodes categories can be found in a fracture network (Benedetti et al., 2024; Forstner and Laubach, 2022; Nyberg et al., 2018, Figure 8):

- I nodes: fracture trace true tip points;
- Y nodes: abutting relationship;
- X nodes: crosscutting relationship;
- V nodes: perfect coincidence of two tip points belonging to two different fractures - these are theoretically possible, but extremely unlikely;
- B nodes: boundary nodes, where a fracture trace terminates at the interpretation boundary.
- C nodes: Contingent nodes that can be enabled or not, generating different fracture network configurations, depending on configuration rules defined according to the study objectives and sometimes micro-scale observations (Forstner & Laubach, 2022).

515. I think you mean ‘hard to recognize’. Since many fracture arrays grow by linkage such connections my be common; and in fact, most opening mode fracture traces have evidence at a range of scale that they are made up of end-to-end links. See papers by Olson and Pollard and Lamarche et al. If you increase the image resolution, single traces bounded by I-nodes may reveal numerous low angle Y nodes (see Forstner et al. 2025, their figure 6c.

Done. We fixed the phrase in accordance with the reviewer’s suggestions.

Original (lines 514-515):

V nodes: perfect coincidence of two tip points belonging to two different fractures - these are theoretically possible, but extremely unlikely;

Revised:

V nodes: perfect coincidence of two tip points belonging to two different fractures - these are theoretically possible, but hard to recognize at the interpretation scale.

516 ‘C-nodes’, which you mention later, ought to be listed here. They certainly reflect the same level of abstraction as these other node types.

Done.

Original (lines 517-519):

The nature of I, Y, X and V nodes is related to the processes that generate the fractures in the first place, but an additional consideration pertains to B nodes (Nyberg et al., 2018, Benedetti et al., 2025), which result from the interaction between the fracture network and external processes.

Revised:

The nature of I, Y, X, V and C nodes is related to the processes that generate the fractures in the first place, but an additional consideration pertains to B nodes (Nyberg et al., 2018, Benedetti et al., 2025), which result from the interaction between the fracture network and external processes.

Original (lines 522-525):

Nodes classification is based on their topological value (Sanderson et al., 2019), representing the number of branches connected to each node. Specifically, I nodes have a topological value of 1, V nodes have a value of 2, Y nodes have a value of 3, and X nodes have a value of 4. B nodes can be categorized as nodes with a topological value of 3, but one branch originates from the fracture trace while the others come from the interpretation boundary.

Revised:

Nodes classification is based on their topological value (Sanderson et al., 2019), representing the number of branches connected to each node. Specifically, I nodes have a topological value of 1, V nodes have a value of 2, Y nodes have a value of 3, and X nodes have a value of 4. B nodes can be categorized as nodes with a topological value of 3, but one branch originates from the fracture trace while the others come from the interpretation boundary. C nodes assume a different topological value depending on the chosen configuration. If they are enabled, the topological value will be equal to 2 (V node), if they are not enabled, topological value will be equal to 1, and one C node generates two I nodes. This choice heavily impacts length and height distribution calculation as it is connected to topological analysis. Therefore, the decision about connecting or not fractures through C nodes should be made before running the topological classification.

519 By 'external processes' do you mean 'the size and shape of the outcrop'? Why not just say that? It's less obscure.

Done. We fixed the phrase in accordance with the reviewer's suggestions.

Original (lines 517-519):

The nature of I, Y, X and V nodes is related to the processes that generate the fractures in the first place, but an additional consideration pertains to B nodes (Nyberg et al., 2018, Benedetti et al., 2025), which result from the interaction between the fracture network and external processes.

Revised:

The nature of I, Y, X and V nodes is related to the processes that generate the fractures in the first place, but an additional consideration pertains to B nodes (Nyberg et al., 2018, Benedetti et al., 2025), which result from the interaction between the fracture network and the size and shape of the outcrop.

540 This assumes that all the fractures are open. It's one thing to talk about traces and how connected thy may be, but it's quite a jump to assume 'percolation'.

Done. We agree with the reviewer, in fact, the cited paper is based on synthetic models and considers all the fractures as open. We will specify this assumption in the text.

Original (540-543):

Backbone extraction solves this problem, highlighting the more numerous connected cluster, and also represents a graphical solution to the percolation threshold problem, since if the backbone touches two opposite sides of the interpretation boundary, this means that a giant connected component exists, and a thoroughgoing flow can be established (Haridy et al., 2020). As shown in Figure 9, the backbone is marked by a significant increase in the CI value.

Revised:

Backbone extraction addresses this problem by highlighting the most extensively connected cluster. Under the assumption that all fractures are open, it also provides a graphical solution to the percolation threshold problem. Specifically, if the backbone spans two opposite sides of the interpretation boundary, it indicates the presence of a giant connected component, allowing for the establishment of a continuous flow (Haridy et al., 2020). As illustrated in Figure 9, the backbone is characterized by a notable increase in the CI value.

594 Omit 'very' as vague. This interpretation of relative ages by abutting and crossing is confusing. Crossing relations and abutting relations amongst have the same implication for relative timing: the abutted fracture is older and the crossed fracture is older.

Done. Thanks for the correction, we omitted "very" as suggested. It is true that both crosscutting and abutting relationships have the same implications when it comes to relative timing. At a certain point in time a fracture of a hypothetical "set 2" crosscut a fracture of another hypothetical "set 1", meaning that "set 2 is younger". The same line of thought can be applied to abutting relationships. In absence of distinctive differences between the two fracture sets, the systematically abutting set is interpreted as "younger". At the same time defining relative ages between two mutually crosscutting sets is more difficult.

Original (lines 594-595):

100% of abutting nodes is an asymptotic value, very difficult to reach in a natural context, but nonetheless revealing a tendency in this direction would be interesting.

Revised:

100% of abutting nodes is an asymptotic value, difficult to reach in a natural context, but nonetheless revealing a tendency in this direction would be interesting.

605 Where do these patterns fall on a height classification scheme?

Done. We thank the reviewer for providing this reference. The height classification scheme defined by Hooker et al. 2013 provides a visual way to classify the height patterns on a vertical outcrop. The application of FBI index quantifies the percentage of fractures that abut on the bedding but does not provide an interpretation or a binding with aperture measurement as Hooker et al. 2013 does. We believe that the two methods are complementary, and we decided to associate the proposed height classification scheme with the FBI in the results.

Revised (from lines 818 and 835):

818 In relation to classical height pattern classification schemes (Hooker et al., 2013), Set 1 falls between the perfectly bed bounded and the top bounded class, given that even if the major part of the fracture about on the bedding, some fractures (33% of the complete fractures) end between two bedding surfaces.

835 In particular, almost all the Set 2 fractures abut on the bedding surfaces, identifying it a perfectly bed bound fracture set in the height classification scheme (Hooker et al., 2013).

641 ‘rely’?

Corrected

641-642 Hel the reader by succinctly defining what these distinctions mean

Done. We modified the text as reported below.

Original (639-641):

Defining an unbiased trace length distribution has always been one of the main challenges in rock mass and fracture network characterization. When calculating or estimating trace length parameters it is possible to distinguish between distribution-dependent and distribution-free methods (Mauldon, 1998).

Revised:

Defining an unbiased trace length distribution has always been one of the main challenges in rock mass and fracture network characterization. When calculating or estimating trace length parameters it is possible to distinguish between distribution-dependent (assume a specific probability distribution) and distribution-free methods (population parameters not linked to any specific probability distribution, Mauldon, 1998).

562-564 This section of text could use some clarification.

Done. Here is a revised version of the paragraph:

Original (lines 561-565):

This kind of information can be obtained with what we call "directional topology", where every node not only includes information about its type (I, Y, X and B), but also about its "origin" or "direction", i.e. from which sets a Y node is generated and if it is the first fracture set that abuts on the second or vice versa. The same line of thought can be applied to X and I nodes but to a shallower level, given that in a crosscutting relationship it is not possible to define, just with topological information, which fracture is older or younger, and for I nodes it is only possible to identify the origin set.

Revised:

This kind of information can be obtained using what we call "directional topology." In standard topological analysis, nodes store only the topological value. In contrast, in directional topology nodes also contain information about the fracture set (in the case of I-nodes) or sets (in the case of Y- and X-nodes) from which the connected branches originate. This enables a more detailed topological characterization: I-nodes are classified by set, X-nodes are described by the intersecting sets (e.g., an X-node between Set 1 and Set 2), and for Y-nodes, it is possible to determine whether they are generated by Set 1 abutting on Set 2 or vice versa, by counting the number of branches (Fig. 10).

650-655 The data sets are still constrained by the size of the outcrops. Some early studies captured complete fracture inventories within large and clean outcrops (e.g., Barton, others). So these claims about 'massive' data sets seem like they are missing key elements of the problem.

Done. We were not able to find the cited paper and therefore making a proper confrontation between the size of the cited outcrop and our case study. A significant amount of data is fundamental in this kind of analysis, and DOMs are an aid in this regard. Nonetheless we agree that the phrase can be made clearer, in particular we would like to specify that computational power is another key element that the previous author did not have at their disposal. For example, Baecher, (1980), was only able to correct for censoring the exponential distribution, thanks to its closed form solution.

Original (lines 652-655):

Digital outcrops make it possible to overcome with huge datasets some problems that previous authors could only consider theoretically from a mathematical and stereological point of view. With these new techniques it is possible to acquire massive datasets on very large sampling windows and successfully tackle the different biases that can be present on an outcrop.

Revised:

Digital outcrops and the increasing computational power make it possible to overcome some problems that previous authors could only consider theoretically from a mathematical and stereological point of view. On one hand, these new techniques facilitate the acquisition of massive datasets on very large sampling windows and successfully tackle the different biases that can be present on an outcrop. On the other hand, the increased computational power makes it possible to calculate the solution to mathematical problems that previously could not be solved due to the lack of a closed form solution (Baecher, 1980).

660-663 But this does not solve the conceptual problems of measuring lengths as laid out for example in Ortega and Marrett 2000.

Done. We thank the reviewer for this comment. It is true that we didn't consider the problem from this point of view. Adding to the problem highlighted in the cited paper, a potential fracture set parallel to the outcrop mean plane would be undetected. We think that this problem can be partially solved by associating the vertical and horizontal sides of the outcrop. The vertical side acts as a window on the 3D geometry of the network in which it is possible to check the presence/absence of a fracture set parallel to the horizontal side surface and if fractures are under-sampled on the bedding interface. If present, how to address this underestimation is beyond the scope of this paper and should be evaluated on a case-by-case basis. Regarding our case study, we observed that the number of Set 1 fractures on the vertical outcrop roughly matches the number of fractures in the adjacent part of the horizontal outcrop. For Set 2 fractures, as written in the discussion, we can measure them on the vertical side but are drowned by artificial fractures related to quarrying activities on the horizontal side. The doubt remains for Set 3, that is sub parallel to the vertical outcrop and therefore we cannot measure fracture traces. We propose to modify the introduction, adding this bias in the paragraph starting at line 75, and modifying the current paragraph reporting what was mentioned in this reply:

Original (lines 82-83):

82 The size bias states that larger fractures (i.e. fracture surfaces with a larger area) have a greater probability to intersect the outcrop surface and to be sampled.

Revised:

The size bias states that larger fractures (i.e. fracture surfaces with a larger area) have a greater probability to intersect the outcrop surface and to be sampled. Another bias, related to layered media, is the under-sampling of fractures shorter than the bed thickness (Ortega and Marrett, 2000). This bias changes the shape of the length distribution, given that only the fracture high enough to about or crosscut the bedding interface can be systematically sampled.

Original (lines 660-663):

The size bias applies to 1D sampling methodologies (scanlines) where longer fractures have a higher probability of being sampled, but this bias does not apply to areal sampling strategies where everything inside the interpretation boundary is sampled. Even fractures much longer than the interpretation boundary are sampled and classified as censored fractures (see below).

Revised:

The size bias applies to 1D sampling methodologies (scanlines) where longer fractures have a higher probability of being sampled, but this bias does not apply to areal sampling strategies where everything inside the interpretation boundary is sampled. Even fractures much longer than the interpretation boundary are sampled and classified as censored fractures (see below). Areal sampling alone, however, does not account for the possibility of fractures parallel to the outcrop mean plane, and for the under-sampling of fractures shorter than the bed thickness (Ortega and Marrett, 2000). The association between the vertical and horizontal side of the outcrop can partially solve this bias. On the vertical side it is possible to check the presence/absence of a fracture set parallel to the horizontal outcrop surface and the relationship between fractures and the bedding interface. The problem remains for fracture sets parallel to the vertical outcrop mean plane, as the orientation bias hinders the trace mapping. Regarding our case study, we observed that the number of Set 1 fractures on the vertical outcrop roughly matches the number of fractures in the adjacent part of the horizontal outcrop. For Set 2 fractures, we can measure them on the vertical side but they are hidden by artificial fractures related to quarrying activities on the horizontal side. Set 3 is almost parallel to the vertical outcrop configuring the situation in which this bias cannot be evaluated.

666 These size/resolution issues can affect length distributions. This is obvious when you collect fracture information at different scales, and it follows from the segmented character of most fractures and the tendency for fracture length to grow by linkage. See the example in Forstner et al. 2025 where drone, hand held LiDar, and scanline datasets cover the same fracture array.

In any case, saying that you know where your data are truncated is not the same as being able to claim that it can be safely assumed that truncation bias is not affecting the dataset.

Done. We thank the reviewer for this specification. It is true that at a fixed scale, fracture smaller than the DOM resolution are lost. It is also true that it is always possible to miss some fractures during the digitalization and among them there may be a fracture smaller than the one we have identified as the limit for truncation bias. We modified the text to account for this suggestion.

Original (lines 664-666):

Working with DOMs, the truncation bias applies to small fractures that can be truncated by limited DOM resolution. In our case, the resolution of the TS-DOM is around 4 mm/pixel and the smallest digitized fracture is 57 cm. This means that there is an order of magnitude between the two and it can be safely assumed that truncation bias is not affecting the dataset.

Revised:

Working with DOMs, the truncation bias applies to small fractures that can be truncated by limited DOM resolution. In our case, the resolution of the TS-DOM is around 4 mm/pixel and the smallest digitized fracture is 57 cm. Although the possibility remains that some fractures were missed during the digitization process — including potentially fractures smaller than the identified truncation threshold — the order of magnitude difference between the resolution of the DOM and the smallest recognized fracture is expected to mitigate truncation bias at a fixed scale.

672 It might be random censoring. But it's useful to wonder whether where you have continuous outcrop and where not is likely to be random, given that in many environments plants (and cover) may be localized in fractures (or in one case I know of, where the wide fractures are). It's a geomorphology and vegetation issue that should not be lost sight of in fracture trace collection; see the comments in Eppes et al.

The assumption of independence implies that the mechanism responsible for fracture generation operates independently from the censoring process; that is, the processes leading to fracture formation and those causing censoring are distinct and unrelated (Benedetti et al., 2025). For example, tectonic activity that induces fracturing is independent from post-fracture processes such as vegetation growth, which may obscure or censor the observable record.

680 See the Discussion in Forstner et al. 2025 of this problem. If what you are doing is just connecting traces that look coplanar across outcrop gaps, that is problematic.

Done. We have better clarified how no-data zones are treated in the caption of figure 12:

Original (lines 678-680):

Figure 12 Different cases of censoring in a natural outcrop. The presence of information gaps affects trace length measurements. Double censored fractures are considered a single censored fractures with one of the end nodes coinciding with the interpretation boundary.

Revised:

Figure 12 Different cases of censoring in a natural outcrop. The presence of information gaps affects trace length measurements. Double censored fractures are considered as a single censored fracture with one of the end nodes coinciding with the interpretation boundary. Fractures that look coplanar across an information gap are considered two separate censored fractures.

737 Here and elsewhere you can omit 'very'; it is vague and not needed.

Done. Thanks for the correction, also following the comment above we will omit 'very'.

835 'implies'

Done. We fixed the typo.

849 The true scope of the workflow needs to be stated here and in the Introduction. What you are describing is really only part of a comprehensive workflow for describing fractures.

Done. We modified this paragraph following the revised version of the introduction:

Original (lines 849-851):

This contribution proposes a workflow with quantitative methodologies to address the parametrization of fracture networks aimed, for instance, to the generation of stochastic models that are more realistic under the geological and structural point of view.

Revised:

This contribution is focused on the geometrical characterization of fracture networks and in particular on the input parameters necessary to generate stochastic DFN models. The main goal of the paper is to provide quantitative methodologies that limit the user choices as much as possible through the implementation of statistical tests (e.g. orientation distribution). If statistical tests are not viable due to the violation of the underlying assumptions, other statistical parameters (P21 REA) or statistical distances from a non-parametrical estimator (length and height distribution) are provided. The presented methodologies are based on data collected from DOMs, both point clouds and orthomosaics. In the context of upscaling geometrical parameters, DOMs are a convenient framework when it comes to collecting data on wide outcrops, decreasing the time for the acquisition process, allowing data collection in areas inaccessible due to practical or safety reasons, and opening to the possibility of implementing automatic feature extraction methods or automatic classification methods (topology). For a complete characterization of the fracture network, especially when targeted to fluid flow simulations, the geometrical parameters included in this contribution have to be integrated with further analysis, to characterize filling, mineralization and other characteristics of the network (e.g., microscale connectivity) that can be assessed with other type of techniques and at a smaller scale (Forstner et al., 2025).

855-858 So how did you accomplish this filtering? This is a general problem, and not just restricted to outcrops in quarries. Spurious near surface fractures can be in regular sets. See the protocols in Eppes et al. and in the older literature.

Done. Regarding this comment, we used the word “filtering” but probably is not appropriate for what we did in this paper. We didn’t write it explicitly (it is explained in the result section), but in areas affected by noise related to quarrying activities we digitalized only Set 1 fractures that were clearly recognizable due to orientation, length, and presence of centimetric displacement. We know that the other fracture sets are present, because we can measure them on the adjacent wall, but we were not able to digitalize them on the pavement. We modified the text to better explain the digitalization procedure.

Original (855-858):

Filtering noise and associating a genetic signature to each fracture set is an obvious concern in a quarry, where some fractures were generated during quarrying operations, but is of the outmost importance also in an outcrop analogue modelling perspective, if for instance we want to filter out fractures generated during exhumation, that might not be present in a reservoir still buried at depth.

Revised:

In quarries some fractures are generated during excavation. It is thus of the utmost importance, for both genetic reconstructions and analogue modelling, to exclude fractures that are related to anthropogenic surface processes. In our case study, the measured fracture sets are in accordance with the existing literature on the area (Sec. 2). In the outcrop pavement are present no data zones, characterized by debris accumulations, where no fracture set can be detected. Other parts of the pavement are affected by quarrying activities, resulting in zones "saturated" by fractures with random orientations or distributed following a radial pattern (related to explosions). In these areas only Set 1 is clearly detectable, given the constant spacing and orientation, an average length higher than the other fractures and the centimetrical displacement. Set 2 and Set 3 are drowned by these artificial fractures and even if present it is difficult to reliably isolate and digitalize them.

865 The claim 'complete characterization…' of 'fracture network parameters' seems overstated and vague. What parameters? Do you mean 'heights and correlated lengths' and associated connectivity patterns? In sedimentary rocks the bed-normal patterns of heights are commonly quite different from length patterns. Heights may or may not be correlated with stratigraphic features that (depending on depositional environment, etc) may be on a meter or less scale, whereas sedimentary boundaries have been shown to affect length patterns but on a longer scale (again depending on the scale of the sedimentary features). An outcrop trace pattern example of the later is in Geol. Mag. 2016, v 108., p. 135, their fig. 2. This is one reason why classifying height patterns (i.e., height relative to stratigraphic features) should precede drawing conclusions about height/length relations.

Done. We thank the reviewer for the comment. Following the suggestions provided in other comments we have modified the sentence to make it clearer:

Original (lines 865-866):

The integration of facets and traces (collected both on horizontal and vertical outcrops) allows a complete characterization of fracture network parameters…

Revised:

The integration of facets and traces (collected both on horizontal and vertical outcrops) allows a complete characterization of the parameters listed in Table 1…

866 'only one of these two data sets' is confusing. It's not clear what 'datasets' in the cited references that you mean. Do you mean 'that rely on data collected on either bed-parallel outcrops or in cross section'?

Done. We have changed the phrase to make it clearer:

Original (lines 866-867):

unlike other approaches that rely on the analysis of only one of these two datasets (e.g. Ortega et al., 2006; Boro et al., 2014; Martinelli et al., 2020; Smeraglia et al., 2021).

Revised:

unlike other approaches that rely on facets or traces only (e.g. Ortega et al., 2006; Boro et al., 2014; Martinelli et al., 2020; Smeraglia et al., 2021).

859 ‘very high quality’ is vague; omit ‘very’; and ‘perfectly exposed’ seems to contradict your Conclusion, where you note that there are gas in the outcrop. Even the best outcrops have covered areas and exposure gaps, although there are some that are quite large and clean.

Done. We modified the text as follows:

Original (lines 859-863):

The very high quality of our outcrop, with perfectly exposed horizontal and vertical surfaces, was instrumental in testing techniques that represent, in our opinion, a step forward in collecting rich quantitative datasets and developing rigorous statistical treatments for many parameters of a fracture network (Table 1). On the other hand, we must also recall that for some parameters there are still limitations in data collection and analysis. Both these points are discussed in the following sub-sections.

Revised:

The high quality of our outcrop, with adjacent horizontal and vertical surfaces, was instrumental in testing techniques that represent, in our opinion, a step forward in collecting rich quantitative datasets and developing rigorous statistical treatments for many parameters of a fracture network (Table 1). On the other hand, we must also recall that for some parameters there are still limitations in data collection and analysis. Both these points are discussed in the following sub-sections.

872 Is this typically done? I don’t think this is the protocol in Healy et al.

Yes, we confirm that Fracpaq considers B nodes as if they are I nodes.

874 Awkward. ‘…huge areal extension…’ > ‘xxxx m2 extent’ (provide an area rather than the vague ‘huge’ and it’s ‘extent’ not ‘extension’

Done. We modified the text as suggested:

Original (lines 874-875):

$P21$ is calculated on the pavement TS-DOM where the huge areal extension enables to define a sufficient number of scan areas to detect the REA lower threshold.

Revised:

$P21$ is calculated on the pavement TS-DOM where the huge areal extension (≈ 18.000 m^2) enables to define a sufficient number of scan areas to detect the REA lower threshold.

866 On the other hand, some of these techniques provide information on key parameters that you do not address. Ortega et al. for example, provide aperture data over wide size ranges, but you apparently do not collect any width information so how can your technique be portrayed as 'a complete characterization of fracture network parameters'. Your contribution can stand on its own without overselling it

Done. We agree with the reviewer. We adjusted the scope of the paper in the comment above by removing "complete characterization" and limiting it to the parameter addressed in this contribution. (lines 865-866)

870 But you ought to note the limitations; for example, your DOM is all at one scale. What happens if you collect fracture data over a range of scales and resolutions (e,g,. Forstner et al. 2025; Elliott et al. 2025).

Done. We thank the reviewer for the comment. We brought an example where data has been collected at a fixed scale. The presented methodologies for analyzing fracture traces can be applied to data collected at different scales. It is more difficult to collect facets data at the thin section or at satellite scale but nonetheless clustering and goodness-of-fit tests can be applied to every dip/dip direction datasets regardless of the scale or technique used to collect them.

Original (lines 870-873):

TS-DOMs allow the digitalization of fracture traces and of the interpretation boundary both on horizontal and vertical outcrops. The integration between fracture traces and the interpretation boundary is fundamental to avoid underestimating the connectivity index by misinterpreting B-nodes as I-nodes and provides a fundamental input to identify censored fractures.

Revised:

TS-DOMs allow the digitalization of fracture traces and of the interpretation boundary both on horizontal and vertical outcrops. TS-DOM allows the digitalization of fracture traces at a fixed scale, corresponding to the resolution at which they were collected. Nonetheless, the proposed methodologies can be applied to different scales, from thin sections to satellite images, provided that data are organized as digitized fracture traces combined with the interpretation boundary. The integration between fracture traces and the interpretation boundary is fundamental to avoid underestimating the connectivity index by misinterpreting B-nodes as I-nodes and provides a fundamental input to identify censored fractures.

911 The criterial is scale and diagenetic considerations. The latter point relates to whether the fractures are open.

Done. We want to apologize for the misinterpretation. We fixed the text:

Original (lines 909-911):

From an almost opposite perspective, other authors (Forstner and Laubach, 2022) suggest considering also contingent nodes (C nodes) that would allow merging individual small branches to form larger traces, based on genetic or hydraulic considerations.

Revised:

From an almost opposite perspective, other authors (Forstner and Laubach, 2022) suggest considering also contingent nodes (C nodes) that would allow merging individual small branches to form larger traces, based on the considered scale and/or diagenetic consideration.

906 It's not clear what your point is here. The text needs to be thought through a bit more. The contrast you draw between Sanderson and Nixon and Forstner and Laubach I think is ill posed. The problem of open fracture continuity for opening mode fractures identified by Forstner and Laubach would be equally valid if you could somehow see the 3d shape of fractures; this is not an artifact of looking at a 2D surface. The issues you need to address are on the most general level, that fractures intersecting a 2D surface (or fractures in 3D) may or may not be open. In other words, the fracture maps (and all the parameters derived from them) may be unrelated to fluid flow (or strength). Consequently, the only way to go from the outcrop analog fracture map to any kind of fluid flow estimation needs to account for whether the fractures are open. This can be done by simply assuming they are all open, as is usually done. Such an approach can lead to insights, but it contradicts geologic observations to say that the maps and derived parameters are all you need to estimate flow. Other geologic evidence can and should be brough to bear. The geologic evidence shows that what fractures (or parts of fractures) are open depends on scale (fracture width) so some fractures (or parts of fractures) may be sealed, so this information can be used to make trace maps more informative for flow parameters. Other geologic elements could be in play. For example, the 'network' might be a mixture of opening-mode fractures and faults.

Done. We thank the reviewer for the comment. We want to apologize as the comparison between the two approaches is indeed ill posed. We removed "From an almost opposite perspective" from the revised version. Fractures that should or should not be considered in topological analysis, and more generally in the orientation, length and height parameters calculation, depend on the scope of the work. How length, orientation and topological relationship are measured is independent of the type of fracture or discontinuity we are considering (open fracture, veins, stylolites etc.).

Original (lines 909-911):

From an almost opposite perspective, other authors (Forstner and Laubach, 2022) suggest considering also contingent nodes (C nodes) that would allow merging individual small branches to form larger traces, based on genetic or hydraulic considerations.

Revised:

Other authors (Forstner and Laubach, 2022) suggest considering also contingent nodes (C nodes) that would allow merging individual small branches to form larger traces, based on genetic or hydraulic considerations.

943 On the other hand, Forstner et al. 2025 make the case that outcrop trace maps, however collected, always overestimate length.

We think that the digitalization scale and the underestimation of fracture mean trace length are two separate problems. Underestimation of fracture length comes from the presence of censored fractures, while overestimation depends on the scale and additional considerations as well explained in Forstner and Laubach 2025. For example, consider a one-meter-long censored fracture (one of the two terminations touches the interpretation boundary). If further analysis reveals that this fracture actually consists of ten individual fractures, each approximately 10 cm in length, the one intersecting the interpretation boundary remains censored, resulting in an underestimation of the length distribution parameters.

962 Awkward. 'allowing to define' > 'defining'

Done. Thank you for the correction.

966 The text starting "For these reasons a step behind…" is confusing. Clarify what you mean.

Done. We modified the text accordingly.

Original (lines 966-969):

For these reasons a step behind has been taken with respect to the application of formal statistical tests in the definition of REA (Martinelli et al., 2020), adopting a more qualitative approach which, however, does not require such stringent assumptions as the tests used by (Martinelli et al., 2020).

Revised:

For these reasons a quantitative approach based on formal statistical tests cannot be safely applied. Adopting a more qualitative approach will result in a less significant result, which partially depends on the interpreter choice, however, it does not require such stringent assumptions as the tests used by (Martinelli et al., 2020).

981 ‘every relevant parameter’ is overstating this case, as you have not characterized the distributed aperture distribution or where the fractures are open versus not open.

984-988 Are these major conclusions? The first bullet item is no news to anyone who has measured fractures in outcrop and if this is a conclusion, the Introduction does not do a good job of setting up or prefiguring this point. Also, if this is an issue why not discuss the solution for describing and dealing with incomplete outcrop patches suggested by Forstner et al. 2025?

986-988 This statement does not seem to be posed as a Conclusion.

991 Where was ‘tectonic related fracture’ sets introduced? Why not stick to descriptive terms? How do you know that any of the sets are related to tectonics? I don’t see anything in the MS that demonstrates when and why these fracture sets formed (and is it even relevant to a characterization workflow?).

Done. We have decided to revise the conclusions with a stronger emphasis on the methodologies presented, while leaving out the geological interpretations regarding the nature of the fracture sets.

Revised:
In conclusion, this paper presented a series of quantitative methodologies to characterize fracture network geometry from Digital Outcrop Models (DOMs). Among all the parameters required to fully characterize a fracture network, we focused on those required to generate 3D stochastic DFN models, that are: orientation parameters, topological relationships, length and height distribution parameters, H/L ratio and P21:

- Orientation data are collected through a semi-automatic workflow, clustered with k-medoids, and tested for the goodness-of-fit to a Fisher distribution. Alternatively, the Kent distribution parameters are also provided. This procedure allows subjectivity to be removed from the assignment of dip/dip direction data to a specific fracture set and supports the choice of meaningful orientation parameters through the implementation of statistical tests.

- Topological relationships are calculated including the interpretation boundary, this allows to: (i) to define B nodes and exclude them from the connectivity index (CI) calculation (ii) to identify censored fractures in an automatic way. Backbone extraction highlights the presence of large, connected clusters in the network. Crosscutting and abutting relationships between different fracture sets are quantified through directional topology.
- The approach developed to deal with censoring bias provides as a result a set of fully specified distributions (all parameters are explicit) corrected for censoring. The best model among the initial selection is defined through a graphical approach and a series of statistical distances.
- We demonstrate that estimating H/L is not possible without introducing some assumption, even for the best exposed set and in the presence of both horizontal and vertical exposures. Therefore, we opted to make our assumption as transparent as possible, and we tested it with regression analysis.
- P21REA is calculated with a qualitative approach to avoid violating the underlying assumption of more formal statistical tests.

1255/1260 Why are the article titles formatted differently? Make these uniform.

Done. Thank you for the correction, we did not notice the difference in format.

1265 Check the author's name.

Done. Thank you for the correction.