Fault Fictions: Systematic biases in the conceptualization of fault zone architecture

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Abstract:

Mental models are a human's internal representation of the real world and have an important role in the way a human understands and reasons about uncertainties, explores potential options, and makes decisions. However, they are susceptible to biases. Issues associated with mental models have not yet received much attention in geosciences, yet systematic biases can affect the scientific process of any geological investigation; from the inception of how the problem is viewed, through selection of appropriate hypotheses and data collection/processing methods, to the conceptualisation and communication of results. This article draws on findings from cognitive science and system dynamics, with knowledge and experiences of field geology, to consider the limitations and biases presented by mental models in geoscience, and their effect on predictions of the physical properties of faults in particular. We highlight a number of biases specific to geological investigations and propose strategies for debiasing. Doing so will enhance how multiple data sources can be brought together, and minimise controllable geological uncertainty to develop more robust geological models. Critically, we argue that there is a need for standardised procedures that guard against biases, permitting data from multiple studies to be combined and communication of assumptions to be made. While we use faults to illustrate potential biases in mental models and the implications of these biases, our findings can be applied across the geoscience discipline.

What do you think of when you think of a geologist? In a study of the representations of scientists in 222 Hollywood films, Weingart *et al.* (2003) found that scientists were predominantly white (96%), male (82%), American (49%), and middle aged (40% between 35 and 49 years old). They found interesting variations in the characters of scientists based on discipline. Medical researchers, physicists, chemists, and psychologists were most likely to be portrayed as 'mad scientists', whereas anthropologists, astronomers, zoologists, and geologists were more likely to be depicted as 'good' or 'benevolent'. Further, 'benevolent' scientists were often portrayed as naïve!

The stereotypical portrayal of scientists in movies is an example of analogous thinking; that is, people's 'mental models', which are internal representations of something in the real world (Johnson-Laird 1983). Such analogous thinking helps people to interact with and make sense of a (complex) external reality, often by allowing them to solve problems or make judgments quickly and efficiently. However, mental models are developed from biased input information and are thus inherently limited. This can be both beneficial and problematic.

Every model is a simplification of reality and therefore every model is wrong (Sterman 2002; Poeter 2007). Increasing the complexity of a mental model does not necessarily make the model more useful, however overly simplified models can omit key factors. For humans, models are the foundation of decision making, and so these models need to be useful – i.e. they must be a sufficient approximation to reality, striking a balance between simple and complex (Pidd 2009).

Geological rock formations and the processes that happen to them are the result of complex dynamic systems that vary in space and time, and are formed over time frames that can range from tens of millions of years to essentially instantaneous events. Therefore, constructing a mental model of any geological process is challenging, particularly if we cannot observe that process in situ. This is due in part to difficulties traditionally encountered by individuals in trying to understand dynamic systems (Sterman 2008). It is compounded by the super-human timeframes separating geological processes of interest and human observations of them. Additionally, exposures are often limited to the near surface of the Earth and data often have to be extrapolated from a small sample. Geologists in the field are physically embedded within their research context, and as such geologists' perception and understanding are often tied in with sensorimotor experiences (Raab & Frodeman 2002; Petcovic & Libarkin 2007). Further, geologists must often combine multiple studies, with differing perspectives and approaches, to create a fuller picture of geological processes that can advance geological understanding and result in robust, unified models. To do so successfully, the thinking, methodology, and critically the assumptions underpinning each model must be explicated, and the input and output information organised in a way that allows for model interconnectivity (Loudon 2012). This process should include recognising and accounting for different biases in each approach, since these biases will introduce artificial variation into the studies.

In this paper, we draw on cognitive science and system dynamics research, and reflect on research and experiences within field geology, to highlight common biases that geologists and geological data may be subjected to, and how this may influence geological models of fault systems. First, we review the literature regarding mental models which are typically understood as internal representations of external events. We then consider key systematic biases in geological thinking, how the resulting uncertainties may be processed, and the impact on model outcomes. We do not intend to test or validate the existence of these biases but rather, in the context of this special issue, we wish to explore biases that are relevant to the interpretation of geological data and therefore the development of models of the hydraulic and/or mechanical behaviour of fault zones. We close by recommending ways to manage these biases, and so to improve geological understanding and modelling of complex processes, such as fault seals. Faults and fault properties are an ideal topic to explore because faults are nearly ubiquitous in the Earth's upper crust, have numerous impacts on the formation and utilisation of natural resources and are important controls on a number of natural hazards, yet they are complex, their exposures are limited, and there is a myriad of different approaches taken for gathering data on faults to elucidate and quantify their physical properties.

Mental models and their application to Geosciences

The construction and use of mental models is a psychological process that humans use to support decision making (Jones *et al.* 2011). In essence, a mental model internally represents 'real-world' events or processes; it replicates an event of interest, allowing one to make sense of it and to try out various scenarios (Craik, 1943). The model is a product of what an *individual* has experienced up until that point, but it is updated with new information and use (Jones *et al.* 2011). Like any model, mental models are simplified representations of some external event. Limitations of human's cognitive ability (Pracht 1990) restrict their complexity. The nature of experiences, including those experienced in person and/or second hand, (e.g. read about in academic journals) will govern the variables in the model, their relationships, and the boundaries of the model (i.e. what is included or excluded, what is implicit or explicitly assumed). Thus, mental models are inherently limited in scope, which is not necessarily a problem for their application. Mental models are specifically what is held in the mind and so they cannot be reviewed by others (Jones *et al.*, 2011). Doyle & Ford (1998) find that within the published literature the definition of mental models is contradictory and simplistic in nature and generally there are disagreements on whether mental models are: static or dynamic; held within the working memory or long-term memory; complex or highly simple. However, two types of mental models are widely accepted: *logical* or *structural* mental models represent the components of a problem or system and how they interact, whereas *causal* models represent the reasoning or rationale that underpin knowledge or theory (Johnson-Laird 1983, 2005; Markman & Gentner 2001; Callahan 2013). Within a mental model, the logical model identifies a systems' components and the causal model explains the function of these components (Tversky 2005). Causal mental models therefore represent an individual's understanding about how the components of a system or problem interact.

The construction of a person's mental model is influenced by their educational and professional 'culture' (Sterman 2002). This observation is an important one for the study of faults. Fault models are applied by geoscientists with a range of backgrounds and training, for example a structural geologist may consider fault analyses quite differently to a geophysicist or a reservoir engineer. The variables included in their mental models could be very different if they hold different views of the problem. An 'us-versus-them' perspective, in that one training or approach is better than another, can develop and foster a problematic divide between disciplines and professionals (Sterman 2002). This divide then serves to encourage the belief that one's own practices are better than that of someone outside their group. These beliefs are critical to what is selected and placed in a mental model and how model components are derived. Further issues of academic and professional boundaries are the assumptions and omissions that individuals implicitly make (Sterman 2002), in that a person may have automated the process to the degree that they are unaware of their own procedure. The variation in approaches by different individuals is a source of artificial variation.

To construct certain mental models, and particularly scientific mental models, quantitative input values are required. However, selecting quantitative values is not necessarily straightforward; probabilistic assessments and handling uncertainty are particularly challenging. As such, quantitative assessment is prone to cognitive biases or 'heuristics' (mental shortcuts). Tversky & Kahneman's research on judgement and decision making under uncertainty (see Kahneman & Tversky 1972; Kahneman & Tversky 1973; Tversky & Kahneman 1973; Tversky & Kahneman 1974 for more detail) identifies three systematic biases or shortcuts employed by individuals when providing probabilistic assessments: an availability heuristic, an anchoring and adjustment heuristic and a representative heuristic (Tversky & Kahneman 1974). Subsequently, many more biases have been identified, including an overconfidence effect (Lichtenstein & Fischhoff 1977) and a confirmation bias (Nickerson 1998). As such, not only will heuristics influence and systematically bias the construction of the mental model, they will bias how information will be interpreted, and thus how the mental model evolves.

See Table 1 for definitions and geoscience examples of these biases. A full list of known biases can be found in Montibeller & von Winterfeldt (2015).

Given that mental models are limited (being finite in size and incomplete, subject to biases, bounded by culture, and limited by how complexity and uncertainty is handled by the brain), it is crucial that when they are externally represented, the associated documentation and reporting allows for scrutiny, interrogation and appropriate use by others (Sterman 2002) (i.e. biases are recognised and, where possible, accounted for in data analysis or data transfer). Generally, humans are not consciously aware of the mental processes that underlie their experience of the world (Bargh & Morsella 2008), and thus extracting mental models, particularly without affecting them, is impossible. Lessons can be drawn from system dynamics, where research has found that when eliciting mental models from experts or laypersons it is best to follow a structured process that is designed to limit common or known biases (Vennix *et al.* 1992; Hall *et al.* 1994; Ford & Sterman 1998).

In geosciences, mental models have been used to examine decision making associated with risk, risk communication and education (Gibson *et al.*, 2016 and references therein). Geological hazards including flash floods and landslides (Wagner 2007; Morss *et al.* 2015; Lazrus *et al.* 2016), subsurface geological engineering hazards (Gibson *et al.* 2016), radon gas hazard (Atman *et al.* 1994), sea-level change (Thomas *et al.* 2015) and broader issues of climate change (Bostrom *et al.* 1994; Read *et al*. 1994; Leiserowitz 2006; Sterman & Sweeney 2007; Sterman 2008) are all examples of the application of mental models in assessing geological risks. In particular, mental models have been used to inform risk communication, often by eliciting and identifying inconsistencies between mental models of risk held by experts (or scientific literature) and publics, for examples see Morgan *et al*. 1992, Thomas *et al*. (2015) and Wagner (2007). Pedagogical studies have examined differences in how novices and experts create geological maps and the cognitive processes involved, and find that experts develop and test mental models of the subsurface much more rapidly, and naïve mental models can interfere with the ability to reason (e.g. Petcovic & Libarkin 2007; Petcovic *et al*. 2009; Bond *et al*. 2011). However, to date, the approach has not been applied to highlight uncertainties of data collection, synthesis and communication within the geoscience discipline, nor for geologists to gain introspective insight so as to improve their most important tool – their mind.

Systematic biases in models of fault architecture

Fault zones are composed of many heterogeneously distributed deformation-related elements. Low permeability features include regions of intense grain-size reduction, pressure solution features, neomineralization due to hydrothermal interactions, cementation and shale smears. High permeability elements are open fractures and breccias. The highly variable nature of (1) the architecture of faults and (2) the properties of deformation-related elements, demonstrates that there are complex controls on the physical, chemical, and thermal evolution of fault zones. There is no simple way of deterministically predicting the bulk hydraulic and mechanical properties of faults. Field observations of fault zones are essential to understand fault growth processes and to make predictions of fault zone mechanical and hydraulic properties at depth. Mapping of fault structure and observation of deformation features is important to unravel geological and tectonic histories, and understanding the internal architecture of faults is important for a wide variety of applications (refer to papers in this volume). Bond *et al*. (2007) and Torvela & Bond (2011) discussed uncertainties in interpreting fault and basin models, and Polson *et al*. (2012) discuss uncertainties in identifying locations of faults at depth within seismic data. Here we are particularly concerned with how geologists develop mental models of fault architecture, and the role of field observations in developing these models.

Models of fault architecture are important to make process-based predictions of fault properties at depth, such as the sealing or mechanical properties of the fault. The properties of faults that control fluid flow are key in applications such as hydrocarbon exploration and production, waste water disposal, geological storage of CO_2, the occurrence of groundwater, geothermal resources, and radioactive waste disposal. Faults and fault systems also serve as the locus of several important mineral deposit types. Similarly, predictions of the mechanical properties of faults are key for understanding induced and triggered seismicity, mining-induced rock bursts and the properties of earthquake ruptures. Such models are routinely applied within industry and academic research by end-users who are not either the originators of the data or the originators of the models of fault architecture: for instance, a reservoir engineer may be relying on the observations of years of field geology by multiple geoscientists, to develop simplified models that predict fault hydraulic properties (refer to papers in this volume). In a similar way, a mining engineer trying to predict rockburst or slope failure in a mine, will do so by constructing models based on structural data gathered from the mine tunnel, and, where available, results from rock deformation experiments. Such models can be updated with results from *in situ* stress monitoring, passive seismic or CO_2-CH_4 monitoring. These data may be collected by different subcontractors, and results must be communicated to the mining engineer to inform models of rock stability.

Integrating datasets from multiple studies and sites is required for robust understanding of fault zone properties and processes. However, these datasets contain important biases, which affect our ability to combine them effectively. In the following section we outline potential sampling and cognitive biases that must be considered when (a) gathering and interpreting data and (b) translating mental models into predictive models.

Outcrop scale vs human scale

A typical human has a volume of 66.4 L (0.066 m^3). A geologist trying to understand the processes that have developed our planet is trying to understand something 10^{23} larger in volume than themselves[1]. The limitation of our size means that we are generally restricted to making field observations at length scales of millimetres to tens of meters, which are then aggregated via maps to larger length scales. Air photos, remote sensing (e.g. LiDAR), and more recently remotely controlled drones (Jordan 2015) and reprocessing of seismic data (see Ross *et al.* 2019 for a beautiful example), have allowed us to examine geology from a greater distance, thereby sampling the Earth's heterogeneity at longer length scales, albeit often at lower resolution. However, field studies of fault zones, and therefore our mental models, may still be biased towards features that are both exposed and visible at a scale that humans can realistically observe and measure.

Studies of fault architecture are significantly biased towards normal faults (Childs *et al*. 2006). Even a simple search using Google Scholar[2] finds at least twice, and up to ten times as many, papers on the architecture, hydrology, and petrophysics of normal faults compared with strike-slip and reverse faults. This reporting bias probably occurs because fault offset is one of the key determinants of fault architecture and so studies tend to focus on faults where the offset can be quantified. To quantify offset, markers must be exposed or visible. It therefore tends to be more difficult to determine offset for strike-slip faults and low angle faults - i.e. the majority of thrust faults - because a large horizontal section needs to be exposed to be able to make correlations across the fault (unless the strike slip

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[1]Assuming that a geologist represents a typical human.

[2]Google Scholar search (excluding patents) using terms: "fault zone" + [term] + [type]. Where term = architecture, properties, or mechanics; type = normal, strike slip, reverse, or thrust. July 2018.

fault is in a deformed basin, or cuts steeply dipping dykes, so that markers are not sub-horizontal). Similarly, our human size limitations also likely favour smaller faults where cross-fault stratigraphic correlations can be more easily made from limited outcrop.

Fault architecture has repeatedly been shown to be highly variable along strike (see Caine and Minor, 2009; Sosio de Rosa *et al.*, 2018 and references therein). However, the tendency to examine a limited number of relatively small outcrops of a fault risks biasing the mental models that can be developed from those exposures. In particular, if there exist relatively infrequent types of fault rock, these will rarely be sampled by typical human-scale exposures such as road or stream cuts. Sosio de Rosa examined a 100m long section of the Jalan Mukah fault (Malaysia) exposed in a platform of rock that had been cleared for the building of a water tank. While 96.5% of the fault was characterised by the type of fault rocks that were very well recorded in neighbouring (and commonly visited) road cuts (Urai & van der Zee, 2005), 3.5% of the fault was characterised by a type of fault rock that had not previously been reported by any geologist working in this very commonly visited area. Fault rocks that are rare along-strike may have unique properties that change the fault behaviour; in the case of the Jalan Mukah fault, the rare fault rocks that Sosio de Rosa identified represented areas of relatively high permeability in an otherwise sealing fault. Similarly, differences in strength between rare and common fault rocks could cause heterogeneities that affect how an earthquake rupture propagates.

Field geoscientists are limited to studying the outcrops that have been made available by nature (stream sections, beach sections, recently de-glaciated pavements) and human-made exposures such as road cuts and tunnels. This leads to a form of selection bias: partly the result of human choices but largely the result of geological and geomorphological processes that have eroded and preserved the rocks that are available for study. Both natural and human-made exposures create a bias.

Faults are often characterised by grain size reduction, increased fracture density and chemical alteration that commonly, but not always, makes them weaker than the rocks that surround them; i.e. unless artificially exposed, faults tend to be preferentially eroded out or obscured. Indeed, it is common practice to use fault 'gullies' or alignments of vegetation, to map faults in air photos (e.g. Schneeberger *et al*. 2016). As such, where faults are exposed and observable via natural processes, it is interesting to consider if these exposures are representative of 'typical' fault rocks. Even in human-made exposures, the geotechnical instability represented by faults means that faulted rocks more often have to be supported by shotcrete or other slope stability measures than non-faulted rocks (e.g. Barton *et al*. 2017), meaning that they also are not accessible for study.

Figure 1 shows several natural and human-made exposures of faults cutting granite gneiss at Grimselpass in the Swiss Alps. At this location faults are typically localised along mafic dykes (Schneeberger *et al*. 2016, 2017), and can be traced across the landscape in air photos for 4.6 km (Belgrano *et al*. 2016). Figure 1a & b show two contrasting ways that the faults are exposed depending on the slope that they cut. In Figure 1c we see a very rare example of an exposure of fault rock: in two days of fieldwork explicitly looking for fault exposures, only this example was recorded, and the rocks were only exposed due to human-made excavation (a section of footpath had been carved into the mountainside by blasting). A far better place to observe the faults is within the network of tunnels drilled by NAGRA for the Grimsel Test Site (Fig. 1. d&e). The tunnels were cut by a tunnel boring machine and are therefore almost completely cylindrical and smooth walled. One of the principal fault strands has been entirely shotcreted for stability, but the others are exposed in the surface of the tunnel walls. Figure 1d shows a photomontage of the tunnel wall that has been 'unwrapped' in much the same way as a borehole image log, showing the exceptional level of detail that can be gleaned about fault architecture from these tunnel exposures. Without these human-made exposures, very little would be known about the Grimsel Faults. It is also interesting to note that the fabric of the ductiley-deformed dykes that are overprinted by the brittle deformation is almost impossible to pick out in the tunnel walls (though it can be observed in thin section; Schneeberger *et al*. 2016), but is beautifully picked out in the blasted and weathered footpath section. Observable features are hence also biased by the nature of the exposure.

In a study of a fault that had hosted reservoir-induced seismicity in Brazil, Kirkpatrick *et al*. (2013) and Soden *et al*. (2014) examined along-strike exposures of a fault cutting Archaean gneiss in a river section. The fault runs at least 150 km along the base of the Rio Piranhas valley which is filled by the reservoir at its northern end. The Jucurutu River flows to the south from the reservoir and follows the base of the valley. The river has an unusually straight trace in the same orientation as the fault, suggesting that the river has been 'captured' by the fault, presumably because the fault rock is weaker than the surrounding rocks. The fault is therefore not exposed in the valley. However, at one location (-6.074756, -37.064272) the river takes a bend and the fault zone is exposed, allowing the fault to be mapped in detail by Kirkpatrick *et al*. (2013) and Soden *et al*. (2014). But why is there a bend in the river at this location? Are the fault rocks at the bend locally harder than the rest of the fault? And so how representative of the whole fault is this single, unique, exposure?

What are the data for?

Generally speaking, when studying fault rocks and rock deformation processes, geologists tend to be interested in the subsurface, and so consider the implications of their surface observations for rock properties and behaviour in the subsurface. Indeed, geologists are trained to 'look beneath' the effects of erosion, weathering or excavation on a given outcrop. Anyone who has taught geology students in the field will recall patiently encouraging students to ignore uplift-related joints in order to see the layers of bedding or structures that they cut. However, a professional hydrogeologist visiting the same outcrop and wishing to study modern fracture-controlled groundwater flow in the shallow subsurface would focus preferentially on the joint networks. The purpose of the study, therefore, affects the features observed and the data collected. While it is necessary, particularly in the interests of efficiency, to limit the scope of field studies, this introduces a form of selection bias that can lead to scientifically important features being scoped out of the complex information that can be gleaned, even from a single outcrop. This is different from motivational bias (in which judgments are influenced by the desirability of events, consequences, outcomes, or choices), because in this case it is the *observations* of geological features that are biased by the geologist's interests, rather than the findings or results. In many cases, the application of the study will also bias the data gathered, for example, data on features deemed to be relevant to the petroleum industry will be preferentially collected over other features.

As an example, McCay *et al*. (2019) found that a fluid flow network within low permeability shales was facilitated by a combination of bedding-orthogonal fractures and very thin sandstone beds. A structural study could easily have considered only the fractures in the shale, disregarding the small sedimentological features which McCay finds to significantly affect the fluid flow network. Similarly, at a study of CO_2 seepage from sandstones and shales in Victoria (Australia) Roberts *et al*. (2019) found that at the Earth's surface, the fissile and fractured shales were more permeable to CO_2 flow than the cohesive sandstones that the shale was interbedded between. Though the shales are less permeable than the sandstones at depth, the response of the shale rock to unloading significantly enhances its permeability. Results from McCay and Roberts have implications for risk management of engineered geological stores, such as for CO_2 storage or radioactive waste disposal. For example, if it was assumed that CO_2 leakage through low permeability rocks such as shales would only occur via connected fractures, a shale rock close to the surface might erroneously be deemed to be sealing. Likewise, if it was assumed that CO_2 leakage to surface would not occur through shales, the monitoring strategy would focus on non-shale rocks and would not detect CO_2 degassing from shales.

This selection bias can also affect the features that are reported. For example, a series of papers in the mid 2000's discussed the apparent rarity of pseudotachylytes and the implications for the physics of earthquake slip (Sibson & Toy 2006; Kirkpatrick *et al*. 2009). When one of the authors discussed this issue with an experienced field geologist specialising in Archean tectonics, with long experience of working at the margins of the Antarctic ice sheet, he replied that in his experience pseudotachylytes were really quite common in these rocks, but that he had not explicitly recorded them because he was busy looking at other aspects of the geology (S. Harley pers. comm., 2018).

Bias occurs even when different geologists are looking at a single fault, but with different motivations. The well-documented exposure at the entrance to Arches National Park (Fig. 2a) has been visited by hundreds of geologists on university and industry fieldtrips, as the fault is considered a classic example of a fault analogous to those in hydrocarbon reservoirs. Figure 2b-e shows four interpretations of the exposure shown in Fig 2a, all made by experienced field geologists interested in examining fault architecture. These four studies (Davatzes and Aydin, 2005; Jolley *et al*. 2007; Foxford *et al*. 1998; Kremer *et al* (in press)) are very different, not only in scale of observation, but also in the geological processes and features they focus on.

Davatzes and Aydin (2005) aim to identify the key geological processes responsible for the formation of fault rocks and fault architecture along the Moab fault (Fig. 2b). Consequently, they highlight multiple short, and unconnected slip surfaces within the fine-grained fault rocks, and discuss the rock mechanics processes responsible for such fault architecture. In contrast, Jolley *et al*. (2007) report the outcrop as one of three examples of a shale smear, and annotate a photograph of the outcrop (Fig. 2c). Interestingly, nowhere in Jolley *et al.* (2007) does it explain what the white dotted lines in Figure 2c are picking out, but we interpret that they are intended to pick out the fabric in the fault zone. Foxford *et al*. (1998) examine along-strike variations in fault architecture to test existing industry algorithms for the prediction of fault seal. They present 32 simplified cross sections across the fault at 15 different locations, including that reproduced in Figure 2d. Kremer *et al*.'s (in press) study (Fig. 2e) is motivated by understanding the hydraulic properties of the fault zone and consequently, concentrates on mapping areas of the fault deemed most likely to affect fluid flow (e.g. shale smears as barriers, slip surfaces as pathways). The four studies present distinctly different maps (models) of fault architecture that depend in part on the assumptions that were made about what 'mattered' to the authors of the maps, and any preconceived ideas that they hold. This, and the fieldwork budget, weather and other external conditions, will influence the time spent at the outcrop, and what was being focussed on. Consequently, each study highlights very different features of the same fault outcrop. Logged transects of the Moab fault from Foxford *et al*. (1998) were later used by Yielding *et al*. (2002) to calibrate their shale gouge ratio against field data. If observations from all four studies were used, the differences in the field sketches/maps would result in variable upscaled shale gouge ratio (Kremer *et al*. (in press).

The words and classification systems we use

Geoscientists have developed a specific language, methodologies, and techniques to describe and represent fault zones (e.g., Childs *et al*. 2004) and spatial and temporal relationships within them (Shipley *et al*. 2013). However, the terms we use to describe observations and processes can lead to ambiguities and uncertainties. Ideally the language we use to report our field observations *descriptively* should not imply a genetic origin. We should also use terms to describe things that can be distinguished in the field – i.e. *without* lab-based observations. However, many phrases imply a specific conceptual model or process, or have slightly misleading meanings. 'Melange' originated from the French word 'to mix' to describe a rock unit, but now the term melange implies specific geological processes and tectonic settings (Festa *et al*. 2010). Further, a number of phrases in geology that refer to mixing, such as melange or fault mixed zones (Rawling & Goodwin 2006), describe simply the presence of multiple features (e.g. rocks, minerals, fabrics); they do not necessarily imply the degree to which the components are mixed, nor whether the components are chaotic or ordered. In some cases, the term origin becomes outdated; for instance, mylonites are now known to be formed by solid-state crystal-plastic deformation mechanisms, but the Greek root of the word (mylon = mill) suggests clastic milling and comminution (Higgins 1971; Wise *et al*. 1984). Some geological words that do not explicitly have genetic origins can be loaded with implicit origins (Schmid & Handy 1991). For instance, the word ultramafic describes the chemical composition (low silica, high magnesium and iron) of an igneous rock. However, as the Earth's mantle is composed of ultramafic rocks, they are mostly preserved or exposed as a result of processes such as orogenic and ophiolite emplacement. As such the term ‘ultramafic’ is implicitly tied to the processes that generate or expose those rocks, and will affect the mental models of the rocks being studied. In fault studies there are two distinct usages of the term membrane seal: some authors use it to mean a fault rock that seals due to capillary forces, others to refer to any sealing fault that seals due to a process other than juxtaposition. Table 2 presents 20 publications from a simple Google Scholar query for journal publications and book chapters that use the term “membrane seal” grouped by their definition of membrane seal. Historically, where terms are known to be ambiguous or are commonly used wrongly, there have been efforts to define their usage (e.g. Wise *et al*. 1984; Wang & Dixon 2004; Childs *et al*. 2009), but many issues of ambiguity and misuse remain.

Other examples of the challenges that language presents are the different approaches to classifying fault rocks (e.g. Sibson 1966; Schmid and Handy 1991; Woodcock and Mort 2008). There is a similar variation in the terms used to describe fault structure (Caine et al 1996; Childs et al. 2009). It could be argued that the Caine et al 1996 model (Figure 3a) is the most useful when you start at outcrop scale and work upwards – i.e. concentrating on what’s inside a fault strand – whereas the Childs et al model (Figure 3b) is what you get when you start from the seismic scale and work downwards – concentrating on the architecture of multiple fault strands in a zone. Ambiguities in the definition of terms such as ‘fault width’ summarised in Bond *et al*. (2007), affect our understanding of the relationship between fault width and displacement (Figure 3c).

Ultimately, ambiguous terminology or classification bias not only affects the mental models of fault processes, it also affects how data are communicated and represented. Particular problems related to data description and terminology biases will arise when end users of field structural geology data or literature try to apply models to general cases, without understanding that the results of field data collection (field maps, cross sections, notebooks) are simplified models. Examples are, a simplified geological section (like the one in Chester and Logan 1986) gets projected infinitely into the third dimension to define the structure along a fault the scale of the San Andreas, or Shale Gouge Ratios are applied to an Allen diagram without recognising that sub-seismic scale relays may provide "hidden" juxtapositions that cause fluids to bypass low permeability fault cores. All too often end users use phrases like “low-permeability fault core and high-permeability damage zone” without fully appreciating complex along-strike relationships, or the likelihood of temporal variations in fault hydraulic properties. Indeed, even though fault classifications (be they of Caine *et al*. 1996 or Childs *et al*. 2006) do not exclude such heterogeneity, they may implicitly simplify or homogenise the fault zone, so that the mental model that the user constructs is simplistic.

Ambiguous or misleading terminology can impede the development and use of conceptual models (Ilgen *et al*. 2017), and make it challenging to compile and compare data, for example to compile studies of fault zone thickness (Shipton *et al*. 2006). In the modern world of data repositories, archives and data sharing these issues become particularly relevant. Appropriate documentation of how data are collected and processed is important to enable data combination or metadata production (Bond *et al*. 2007). As articulated by Loudon (2012) with regards to systems geology, effective data pooling or metadata compilation requires an overall review of the geological thinking and methodology, and an organised, interconnected set of widely accepted geological concepts. Recognising this, a particularly comprehensive catalogue of recent definitions can be found in a recent IEAGHG report on faults (2016).

Expertise – being a geologist

Most geological knowledge, and the suite of skills developed, is held unrecorded in the collective human memory as background acquired by training, education and experience (Loudon 2012). This knowledge sets geologists apart from non-specialists, and affects the mental models that geologists construct and use (Agnew *et al.* 1994). The knowledge obtained is more than simply domain-specific knowledge, that is, the specific content knowledge of experts beyond common geoscience concepts such as Earth materials, Earth processes, and Earth history (Petcovic & Libarkin 2007). One can be extremely knowledgeable about a subject without wide ranging experience. Instead, the knowledge and skills gained through experience develops a more nuanced form of expertise. First, geological training transforms the mental models in the brain, or how the mental models are used by the brain. For example, when constructing mental models of complex systems, long time delays between cause and effect tend to prove challenging for the human brain, and lead to key cause-effect relationships being omitted (Sterman 2002). However, geologists grow into to thinking over particularly long and abstract time periods, and to thinking of low-frequency, high-impact events (Kastens *et al*. 2009). Structural geology in particular requires particularly intensive spatial and temporal thinking and, through experience, geologists learn to organize spatial problems in ways that allow optimal processing (Shipley *et al*. 2013). Research indicates how the brain gathers and collates data, as well as how these data are used, changes with experience (Chase & Simon 1973). Indeed, experienced geologists approach outcrops differently to novices (Callahan *et al*. 2010; Baker & Petcovic 2016), and Petcovic *et al*. (2009) and Bond *et al*. (2011) find that expert geologists develop and test mental models of the subsurface much more rapidly than novices.

While expertise clearly brings advantages, it may also bring limitations. Experts are not immune to cognitive biases (Phillips 2011), and indeed can be more prone to some biases than non-experts. It is well documented that when required to make an assessment, experts may make different prior assumptions resulting in radically different assessments. These assumptions can be tested using, for example, structured elicitation (O'Hagan *et al.* 2006), but otherwise it is possible that in real-life interpretations, assumptions and misunderstandings commonly occur in expert judgements but remain undetected (Polson & Curtis 2010).

For example structural geologists can use many different methods to gather fracture data, each of which has its own advantages and disadvantages (Watkins *et al*. 2015). Some schools of geology favour particular mapping techniques over others, but ultimately decisions about what approach to apply are aided by experience. It is not always clear how data collected by novices and experienced geologists compare for the same sampling area and approach. Andrews *et al*. (2019) find no systematic differences in the fracture data collected by geologists with varying levels of experience, but do find clear evidence that individuals express consistent subjective biases that affect the data that are collected, mostly regarding smaller-scale features. Raab and Frodeman (2002) point out that geologic methods, much as any intellectual labour, tend to be become intuitive and automatic (and therefore less 'visible' to our awareness) with growing expertise, much like driving a car. This could make experienced geologists more susceptible to the bias, particularly if they may have developed their own mental shortcuts (Sterman 2002). Further, with experience, geologists may become more aware of, or more comfortable with, the subjective aspects of field sciences – with positive or negative implications. For example, decisions such as selecting the 'appropriate' specimen or approach for gathering certain structural data, or how to determine fracture aperture, which are highly subjective, can lead to uncertainty, and ultimately can bias the resultant models of the field area. An experienced geologist may approach an outcrop 'how they always have' because 'everyone knows' 'that's how to do it', and so may lack the awareness to prevent bias from affecting the mental models they develop. In fact, they may simply be adapting a pre-existing mental model of one fault zone to another, and in doing so omit key and unique fault properties such as the rare fault rocks reported by Sosio de Rosa *et al.* (2018). Alternatively, their experiences may aid their decision making, and prevent the mind from jumping to conclusions (which we often have to coax geology students away from) and becoming vulnerable to anchoring bias. Indeed, Callahan *et al*. (2013) found that, while undertaking a mapping exercise, more experienced geologists pay more attention to uncertainty and how to test their mental models than novices (students). Similarly, Bond *et al*. (2011) found that more experienced geologists are more comfortable with interpretative reasoning and hypothesis-testing than novices interpreting a seismic dataset.

Finally, regarding personal differences in data collection, Andrews *et al.* (2019) propose that indivduals, whether expert of novice, will consciously or subconsciously construct their own personal data collection protocols around how data should be collected, and what features should or should not be included. These protocols will not only be shaped by their cognitive biases such as personality, interest, or expertise bias. There will also be practical and physical factors at play beyond the exposure bias, which may include eyesight quality, ease of manoeuvrability (whether or not it is easy for them to repeatedly crouch down to get a closer view and stand up to move around), and their spatial co-ordination.

On a side note, an experienced field geologist will know that field conditions (e.g. poor weather, difficult terrain, lighting), personal circumstances (e.g. hunger, extreme cold or heat) and the fieldwork timeframe (a couple of very focussed days, or several weeks) hugely influences the the field approach, the quality and quantity of the data they collect, and the quality of their notebook reporting and metadata. They will have learnt first hand of the difficulties that arise when, back in the office, they must attempt to use data from, or revisit, a poor quality field notebook. In short, their experience will have made them better field geologists, both in terms of the data they collect and its useability. These attributes have important implications for recent use of digital data collection devices and the kinds of biases that may become incorporated into field data collection and its compilation once back at the office.

Discussion

Geological interpretation is by nature uncertain: geologists strive to reconstruct the most probable sequence of events producing features that are currently exposed at the Earth's surface with limited exposure and time indicators. Biases in the mental models of fault zones, and the limitations that arise from this with regards to how data are gathered, interpreted and used, lead to uncertainty or errors in the understanding of fault zone processes that these data inform. Further, an incorrect mental model can interfere with an individual's ability to reason, or to respond to new information or data (Petcovic & Libarkin 2007).

Observation-based field research often relies on geological outcrops. The availability and accessibility of outcrop, and what they can tell us are affected by how the rock was exposed/the outcrop orientation, and the size of the outcrop versus the size of the process being studied. How we approach an outcrop, the data we gather and the approaches we use to collect it will be affected by (i) what processes we are most interested in or are the focus of the study and (ii) what we are familiar with. The latter is a product of how we were trained, who we have worked with in the field, and where and how long we have worked.

How the data are described and communicated (terminology/data description bias) will affect how the data are then used, and how well the data outcomes can be pooled or compared with other works. Experienced field geologists are comfortable knowing that if they walk along strike or up dip of a fault zone they will find variations in fault rock type, number and orientations of slip surfaces, variations in fracture density, relays, asperities, variable juxtaposition relationships etc. The user of the fault model does not necessarily know this.

Given the breadth of the geoscience discipline, our mental models of fault zones will be influenced by many other factors than those we identify here, which are science-focused and systematic. However, Schein (1984) argues that the selection processes that contribute to what we perceive are also highly influenced by highly individual factors regarding our social, cultural, and spiritual environment. Therefore, these factors will not systematically affect the mental models of fault zones, but may significantly affect individuals' mental models and their decision-making process. However, for the least biased science, the systematic biases that we identify must be reduced or minimised where possible.

Research has been conducted by decision and risk analysts to reduce or eliminate (debias) results, for example Fischhoff (1982) and Montibeller & von Winterfeldt (2015). How a bias is identified, managed and reduced depends on the type of bias that it is, and some biases are more difficult to correct than others. We know from substantial published research on how to tackle unconscious bias that the starting point is to simply raise awareness of the presence of, and effect of, these biases. Indeed, for some biases, just explaining potential bias to individuals, thereby raising their awareness of bias into conscious thought, can reduce that bias, though may not remove it entirely (Atewologun et al., 2018). For example, for previously documented biases (Table 1) Polson *et al.* (2010) report that motivational bias could be overcome by stressing the importance of unbiased results, and that availability bias is harder to reduce, but directing experts to think of all relevant similar situations throughout their career, rather than focusing on the most memorable or recent example, can reduce its impact.

Acknowledging that these biases exist is the first step to reducing them among Earth scientists and in Earth Science. For each of the biases we identify in this work, we propose a number of additional approaches to reduce or eliminate them, summarised in Table 3, depending on whether the bias is caused by nature, is a conscious cognitive bias, or is a subconscious cognitive- bias. The approaches in Table 3 are adapted from the debiasing literature but there is significant scope for further work to test and refine them in the geoscience context.

We argue that the field geology community needs to consider ways to (a) communicate our uncertainties better to users and (b) make sure that we educate end-users to consider appropriate and cautious approaches to make best use of the data we provide, and gain an appreciation of the uncertainties inherent in our limited ability to characterize 4D, largely inaccessible tectonic structures, at the same time as understanding the value of carefully collected and representative field data.

Ultimately, we challenge the adage that ‘the best geologist is the one who has seen the most rocks’ and instead argue that ‘the best geologist is the one who is the most prepared to challenge their own biases’, but this is much harder to measure or brag about! Really, the best geologist is a member of a team, with mixed skills and experience, who are open to scrutinising one another’s thought processes (Andrews *et al.,* 2019). They are someone who has the ability to think over long time periods to understand the potential processes that could have caused the geological feature being studied, who follows a standardised, yet flexible and open minded procedure to avoid common biases, who thinks broadly and is willing to look to other facets of geology to understand and explain the object of study (i.e. does not overly narrow the bounds of their mental and/or conceptual models), who maintains integrity in not being driven to produce results motivated by publishing or client goals, and who thoroughly documents their modelling process to allow interrogation/inspection/reproducibility from other geologists.

Finally, the workflow for geologists collecting geological data, or users of geological data, can be interrupted or manipulated to improve the geologist’s performance. For example, Macrae *et al*. (2016) found that when data users interpreting 2D seismic sections were explicitly asked to consider the temporal sequence of events, their interpretation quality was statistically significantly improved. There is great scope to introduce such processes to improve how geologists operate in the field. We recommend that further work should aim to investigate similar approaches to de-biasing field observations and the transfer of field observations into models.

Conclusion

A mental model is a person’s internal representation of an external system, and is the basis for how a conceptual or numerical model of a system is defined and parameterised. Mental models are constructed on the basis of a person’s experience of the external system, and that experience is by its very nature incomplete and partial when compared to the complexity in the real world. The mental model, and biases in the input data to these models, will be specific to the individual, and will affect how data are collected, analysed, represented and communicated. These biases need to be acknowledged to improve the predictive capability of such models and guide future research to fill gaps. Faults and fault zones are specifically addressed here, but the concepts presented apply to many other Earth structures and features. 'End-users' of fault-related information, such as petroleum reservoir engineers, mining engineers, and seismologists of course have their own mental models of what a fault looks like and how its physical properties affect Earth processes. Arguments over the details of terminology baffle the 'end users' of fault studies and can dilute the importance of the research.

We articulate several systematic biases introduced by geologists that may affect the quality of field investigations, how the data are reported, and how the data are used, using fault zones as a case study. Some of these biases are physical, and others are a product of how we were trained, who we have worked with in the field, and where we have worked.

We build on research by decision and risk analysts to reduce or eliminate (debias) bias in results and we suggest approaches to reduce bias in geological field data collection and communication. The first step is acknowledging which biases may be affecting your work. Once potential biases are identified, steps can then be taken to de-bias the work; i.e. to guide the rational development of our mental models. These include working in groups in which individuals are encouraged to break down the rationale for their judgement, since by explicating their thought process, their results and their mental model is less likely to be affected by bias. Following from this, clearly outlining the process, the rationale and the scope of the work (that is, what is and isn't being noted) are important steps to aid end users, and the move towards open data, data archiving, and data collection method files, encourage such reporting. Finally, there is scope to introduce processes to improve how geologists validate their models in the field, and this is an important subject for future interdisciplinary work in the Earth sciences and beyond.

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Tables

Table 1. *Key biases made by individuals during probabilistic assessments*

	Bias	Definition/Example
Cognitive Bias	Availability bias	A short cut that humans use to assess the probability of an event. Events are perceived as more likely to occur if they are memorable to the individual and less likely to occur if the event is difficult to remember (i.e. people tend to use ease of recollection as a short-hand for frequency) (Montibeller & von Winterfeldt 2015). For example, it has been found that individuals overestimate the probability of an airplane crash and underestimate the probability of a car crash. *Example*: A basin analyst who has recently been working on a series of normal fault systems may be more likely to interpret normal faults from a new seismic section than a different fault type.
	Anchoring / adjustment bias	This is the tendency for individuals to 'anchor' on an initial numerical judgement. The anchor value is insufficiently adjusted for the specific event of interest (Montibeller & von Winterfeldt 2015). For example, when given new information, the individual then adjusts this starting value, but does not update their judgement sufficiently. This leads to a systematic bias towards the initial value (Tversky &Kahneman 1974). *Example*: From their background reading, a geologist knows that the X Formation is approx. 20 meters thick. Later, when making a field sketch a cliff section in which the X Formation is exposed, they judge that the unit is ~20 meters thick, and use this for scale. The unit is in fact 40 m thick at the cliff outcrop.
	Representative bias	The tendency for individuals to predict the outcome which is most similar to that described (Kahneman & Tversky 1973). *Example*: A field geologist observes an apparently fine-grained rock within a fault zone partially obscured by moss. They describe it in their field notebook it as a fault gouge even though they have no hand specimen to observe grain size to justify this interpretation.
	Overconfidence bias	The tendency for individuals to be overconfident in their judgements when compared to the objective reality. Experts often exhibit an overconfidence bias, which means that when asked to provide probabilistic judgements, the confidence bounds that they provide are too narrow and fail to appropriately account for uncertainty or their estimate is greater than in actuality (Montibeller & von Winterfeldt 2015). *Example*: A geologist states 90% confidence that an earthquake above magnitude 7 will occur on the X Fault within the next 2 years, even though they have comparatively little data for this fault and they know that predicting earthquakes is highly uncertain.

Motivational	Motivational bias	The tendency for an individual's judgement to be influenced by some conflict of interest. *Example*: Not wanting to come across as undecided or uncertain to their boss, a junior geologist looks briefly at a fine-grained grey limestone and states with confidence that the rock is a volcanic sill.
	Confirmation bias	The tendency for an individual to more readily reject information that does not support their belief or hypothesis, and more readily accept information that does (Montibeller & von Winterfeldt 2015). *Example*: A geologist believes that small faults should have a narrow cross-fault thickness. To back up this thesis, they spend a lot of time in the field trying to show that the Wherever Fault, previously described as having a thickness of 5 m and an offset of only 10 m, is in fact a series of small thin faults, or that the offset is much larger than originally thought.
Physical bias	Selection bias	A range of biases introduced by the available data or the data selected for study. *Example*: Geophysicists wrongly interpret the topography of the core due to bias resulting from the non-random spatial distribution of seismic stations, which are mostly located on continents (Mulgaria, 2001).

Table 2. *Examples of different usages for one geological term: membrane seal*

Seal controlled by capillary entry pressure	Seal formed by properties of fault rock in contrast to juxtaposition	Text fitting both interpretations
Bretan, Yielding, Jones (2003)	Childs *et al.* (1997; 2009)	Hesthammer & Fossen (2000)
Brown (2003)	Doughty (2003)	Manzocchi (1999)
Cerveny *et al.* (2004)	Faerseth (2006); Faerseth et al. (2007)	
Eichubl (2005)	Foxford et al. (1998)	
Fisher & Knipe (1998)	Grant (2016)	
Fristad (1997)	Jones & Hillis (2003)	
Gibson (1994)	Manzocchi, Childs and Walsh (2010)	
Unterschultz (2007)		
Watts (1987)		
Yielding *et al.* (1997)		

Table 3. *List of geological biases and proposed means for debiasing*

Bias	Approach to remove/reduce bias
Physical selection biases (i.e. nature)	The nature and extent of rock outcrops is difficult to change without involving a lot of heavy engineering (!). However, by being aware of potential sources of bias, field geologists can train themselves to interrupt and revise the mental models they form. The geologist must be aware of, and account for, how factors such as the physical property of what they are trying to measure might be correlated to limitations on the outcrops available for study. For instance softer fault rocks are less likely to be preserved for study, rare fault rock types are less likely to be sampled. Ideally such potential correlations should be captured and communicated to the end-user of the data. They must also consider that the sample size is constrained by outcrop size/frequency/distribution and so on, and the geologists' own abilities to access difficult outcrops (e.g. a kayaker will be able to better access coastal outcrops; a capable climber might safely access a greater range of outcrops with the aid of ropes than someone with a fear of heights). This will also be constrained by the field budget, field conditions, and health and safety (e.g. long periods of detailed fracture mapping may be unsafe in cold wet conditions). The geologist should seek to remediate these biases by seeking out different types of exposure of the same rock, e.g. natural and man-made, and also by recognising, and being open minded about what might be 'inside' the outcrop – consciously avoid infinite projections into the rock face. The study of fault zones can also be complemented by non-field geological techniques. Indeed, remote imaging is a large and highly used field of research, particularly in Earth science because so little of the Earth is exposed/visible or can be studied by eye. Therefore, data pooling is an important tool for reducing physical selection biases, but we do note that this is challenged by and susceptible to biases of language and classification, and so requires clear communication of the key assumptions and the data collection and analysis process (Scheiber et al., 2015).
Conscious cognitive biases	
Selection bias	We can't, and do not want to, eliminate cognitive selection bias. If a client is interested in shallow hydrogeology there is no point recording the mid-crustal mylonite fabrics that are cut by the open fracture networks hosting flow. However there may be merit in ensuring that it is standard practice to state what geological features are *not* being recorded as well as what *is* being recorded. The introduction of field work methodology papers in the published literature could facilitate this. Data pooling and compiling metadata from the same area would reduce interest bias. There is great merit in this work, although unfortunately working with secondary data are not currently deemed to be 'high impact', thus there may be a pressure for academics and students to steer clear of this approach.

<table>
<tr><td>Language and communication</td><td>Clearly define any terms that used. Use existing terms consistently, and acknowledge where there might be conflict in the chosen terminology.</td></tr>
<tr><td></td><td>Biases affect the data collected and therefore the data that is communicated to a data user. Biases arising from language and communication can therefore be minimised by the suggested approaches above, and by …better communication! That is, by clearly outlining the process, rationale, the scope of the work (that is, what is and isn’t being noted). This is routine, for example, in the publication of the results of medical trials.

As with selection bias, the rise in open data, data archiving, and methods files may to some extent reduce these communication biases, as details about the fieldwork are provided outside of the generally length-limited peer reviewed publication of the results of the work.</td></tr>
<tr><td colspan="2">Unconscious cognitive biases</td></tr>
<tr><td colspan="2">Some biases may be alleviated, or exacerbated, by collective or group working. Geologist bias should be the former, and so reduced by working in groups, particularly groups with different disciplines and training, or that know the limits of each other’s’ knowledge, and where the geologists are encouraged to question and challenge each other. As long as the group operates supportively, such that emotional factors such as personality and seniority do not inhibit communication.

Actively encouraging multiple working hypotheses was first suggested by Chamberlin in 1890, where he stated that “with this method the dangers of parental affection for a favourite theory can be circumvented”. While Chamberlin later revised his article to be specific to geology, in his 1890 article he finished by stating that he believed “that one of the greatest moral reforms that lies immediately before us consists in the general introduction into social and civic life of that habit of mental procedure which is known in investigation as the method of multiple working hypotheses”.

Structured intervention by logic and decomposition are a common way to eliminate correctable biases; i.e. by encouraging the individual to break down the rationale for their judgement, their thought process (or mental model) is less likely to be affected by bias (Montibeller & von Winterfeld 2015). The rationale is that the articulation of a thought process allows for interrogation of a thought process (Macrae et al. 2016). Such intervention could be an effective measure for geologist bias, and particularly experience bias. Geologists are trained to make a note of their thought processes and rationale in their field notebooks in addition to collecting quantitative data or observations. However, even if this practice is performed routinely, a geologist doing it alone may not be challenged to think alternatively. Working together or alone, geologists should be encouraged to ‘think out loud’, which forces articulation and thus introspection of one’s own thought process.</td></tr>
</table>

Figure captions

Fig. 1. Exposure of fault zones at Grimselpass, Swiss Alps. (**a**) Typical vegetated fault gully on a mountain ridge. Note the gullies can be traced across the valley and into the hillside in the far distance. (**b**) Typical deeply eroded exposure of a fault on the mountain flank viewed up a steep slope. (**c**) Rare exposure of fault rocks along a footpath that had been blasted with explosives. (**d**) 'unwrapped' photomontage of a typical fault cutting the tunnels. The tape measure is 7 m long. (**e**) Image of the tunnel drilled by NAGRA at the Grimsel Test Site. Photos taken by Shipton and Kremer.

Fig 2. Four interpretations of the same exposure of the Moab fault, Utah. (**a**) Outcrop photograph with the outlines of the different maps in blue. (**b**) shows a map of part of the exposed fault zone by Davatzes and Aydin (2005), (**c**) shows an annotated photo from Jolley et al. (2007), (**d**) shows a structural log of the outcrop modified from Foxford et al (1998) and (**e**) shows a map of the full width of the fault zone by Kremer et al. (in press).

Fig 3. Models of fault architecture. (**a**) Fault architecture model reproduced after Caine et al. (1996). This model divides faults into zones with different hydrological properties: fault core, damage zone and the surrounding protolith. (**b**) Fault architecture model from Childs et al. (2009), highlighting the large scale structure of fault planes in the fault zone. (**c**): Figure from Bond et al. (2007), each panel shows a schematic fault zone, and different ways in that the fault architecture might be described using fault core/damage zone approach. Without common criteria for property measurements, or appropriate documentation of the field observations, data description bias will become problematic when compiling or comparing data with other studies or sites.