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The importance of structural model availability on seismic interpretation

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ABSTRACT

Interpretation of faults in seismic images is central to the creation of geological models of the subsurface. The use of prior knowledge acquired through learning allows interpreters to move from singular observations to reasoned interpretations based on the conceptual models available to them. The amount and variety of fault examples available in textbooks, articles and training exercises is therefore likely to be a determinant factor in the interpreters' ability to interpret realistic fault geometries in seismic data. We analysed the differences in fault type and geometry interpreted in seismic data by students before and after completing a masters module in structural geology, and compared them to the characteristics of faults represented in the module and textbooks. We propose that the observed over-representation of normal-planar faults in early teaching materials influences the interpretation of data, making this fault type and geometry dominant in the pre-module interpretations. However, when the students were exposed to a greater range in fault models in the module, the range of fault type and geometry increased. This work explores the role of model availability in interpretation and advocates for the use of realistic fault models in training materials.

1. Introduction

Reflection seismic imaging is a fundamental tool for understanding the structure of the Earth's crust. Despite the importance of seismic interpretation to subsurface geoscience, there are remarkably few studies of how interpretations themselves are performed – in marked contrast to the numerous technical studies of how the images themselves are created (e.g., Juhlin, 1995; Yilmaz, 2001; Campbell et al., 2010; Alcalde et al., 2013). The interpretation of seismic reflection data is the fundamental method for determining the geometry and displacement of faults in the subsurface at lithospheric to reservoir scales (e.g., Yielding et al., 1991; Tari et al., 1992; Underhill and Paterson, 1998; Simancas et al., 2003; Faulkner et al., 2010). The aim of this paper is to examine the role of advanced (graduate) training on seismic interpretation with specific reference to faults. Faults were chosen because they play a major influence in the seismo-mechanical properties of the crust, the migration and trapping of fluids and the shaping of the Earth's surface (e.g., Handy et al., 2007; Wibberley et al., 2008).

Interpretation of seismic image data involves a certain degree of knowledge in structural geology, stratigraphy and tectonic settings, as well as an understanding of the physics behind the creation of a seismic image. Interpreters must use knowledge and understanding to produce a consistent solution that satisfies not only all available data, but also conforms to expectation (Frodeman, 1995; Rankey and Mitchell, 2003; Bond et al., 2011). Knowledge is acquired from new information by developing new or modifying existing schemas (models) (Piaget, 1983; Kastens and Ishikawa, 2006). This learning process usually relies on the observation of multiple examples of the structures to be processed

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(or interpreted) in different contexts. These examples provide a source of prior knowledge which will help to tie observations to known models during the interpretation stage. In geosciences, this issue is often epitomised in the maxim "the best geologist is the one who has seen the most rocks", attributed to Read (1957). A successful learning process, however, requires that the studied examples are assimilated through use, forming a deeper understanding of the problem (Chi et al., 1989). This understanding process allows experts to move quickly from small-scale, scattered, singular observations, to reasoned, more coherent and larger-scale combined interpretation (Larkin et al., 1980; Baker et al., 2012). Teaching materials (e.g., lecture notes, textbooks, atlases and practical exercises) usually include abundant examples of faults from different tectonic settings, with geometric variety and complexity. These examples constitute a major source of generation or modification of existing fault models for students. Therefore, the relative proportion of different fault representations in training material is likely to influence the models available to students: a potential source of bias for certain fault types. This bias occurs when models that are easier to recall are more commonly used, and it is known as "availability bias" (Tversky and Kahneman, 1973, 1974).

In a seismic interpretation experiment by Macrae et al. (2016), geologists with greater experience in structural geology, that had interpreted seismic image data frequently, and had worked at the greatest number of structural styles, achieved significantly better interpretation results than those with less experience. The learning process, including training, is an important aspect of model assimilation. It is assumed that geoscientists with the most training and practical experience will achieve better results than those with less experience. For example, Bond et al. (2012) observed a correlation between seismic interpretation accuracy and education level in an experiment completed by 184 participants: more "correct" interpretations were achieved by interpreters with masters and PhD degrees. The same relationship between experience and interpretation accuracy was observed in a subsequent interpretation experiment with borehole data (Bond et al., 2015). A positive correlation between interpretation success and training illustrates that interpreters use different approaches when facing interpretation problems according to their different expertise levels.

Masters degree programmes focusing on petroleum geoscience are an integral part of many geoscientists' professional development, and are increasingly demanded by the oil industry (Heath, 2000, 2003). Such courses often represent a student's first opportunity to learn 'the art' of seismic interpretation in more detail. In bespoke modules on stratigraphy or structural geology, elements of seismic interpretation are often taught as part of the course. These modules encompass the learning and application of stratigraphic or structural principles together with conceptual models of different tectonic settings that influence the interpretation of a seismic image. The interpretation of faults and the correlation of stratigraphic horizons across them are central to the interpretation of a seismic image and are of significant relevance to petroleum geoscience (e.g., Gartrell et al., 2004; Løseth et al., 2009; Richards et al., 2015; Yielding, 2015). Such interpretation forms the basis of a geological or structural framework model.

This paper investigates the influence of available fault examples in training material on the acquisition of interpretational skills by petroleum geoscience masters students taking a module in structural geology. We analyse the results from an interpretation experiment (Alcalde et al., 2017) carried out before and after the students completed the module. Rather than examining whether students perform better or not after completing the module, as this would be subjective, our analysis focuses on differences in fault geometries. Interpreted fault geometries Pre- and Post-module are compared to those presented during the module and representations in common textbooks. This comparison allows us to investigate the potential influence of available fault models in textbooks and presented in the module teaching. This contribution aims to identify potential sources of availability biases in the seismic interpretation of faults.

2. Interpretation experiment

The interpretation experiment was taken by c. 70 masters students before and after completing a training module on structural geology for petroleum exploration (referred to in the text from herein as Pre-module and Post-module). The training, delivered by a highly experienced industry professional, included abundant examples and interpretation exercises of seismic image data. At the start of the experiment, the participants were given a seismic section either in two-way travel time (TWT) or in depth (Fig. 1). The participants were asked to interpret the seismic section, paying special attention to a major fault located near the middle of the section.

The students were also asked to complete an anonymous questionnaire designed to elicit background, training and knowledge in structural geology and experience in seismic interpretation, before and after completing the module (Fig. 2). Over 90% of the participants in the experiment had a background in geology, with 60% having no industry experience in geology or geophysics. Only 7% of the students interpreted seismic more frequently than monthly. Their experience in seismic interpretation and in structural geology ranged chiefly from basic to good, none of the students considering themselves experts in either discipline.

3. Masters module in structural geology

The interpretation experiment was completed by students studying on the Integrated Petroleum Geoscience Master of Science degree at the University of Aberdeen, UK. The experiment was run twice, in 2015 and 2016, with different student groups but with the same training element delivered by the same tutor using the same material and practical exercises.

The two-week long intensive module (72 h in total) entitled "Structural Geology for Petroleum Exploration", consisted of a series of lectures and practical exercises intended to provide a comprehensive knowledge of structural models relevant to petroleum exploration and structural styles employed in the interpretation of seismic image data. The learning outcomes of the module were to: (i) improve participants' seismic interpretation skills by developing an understanding of structural geometry and the application of appropriate structural models in different tectonic settings; (ii) provide a toolkit for making more robust, viable and quick interpretations at regional, prospect and reservoir scales, or for very quick assessment of an existing interpretation; and (iii) provide some common concepts and language to facilitate team technical discussions.

The module contents included an overview of the fundamentals of structural geology applied to seismic interpretation, together with specific lessons on the different tectonic settings (i.e., extensional, compressional, strike-slip, inversion and salt tectonics). Module materials include multiple diagrammatic and real case examples of seismic interpretations from different tectonic settings. Due to their importance in petroleum geology, a particular emphasis was placed on fault characteristics, including fault geometry, displacement and recognition strategies. A specific lesson, entitled "Fault analysis techniques", addressed 2D/3D correlation, fault displacement and trapping assessment. The module also

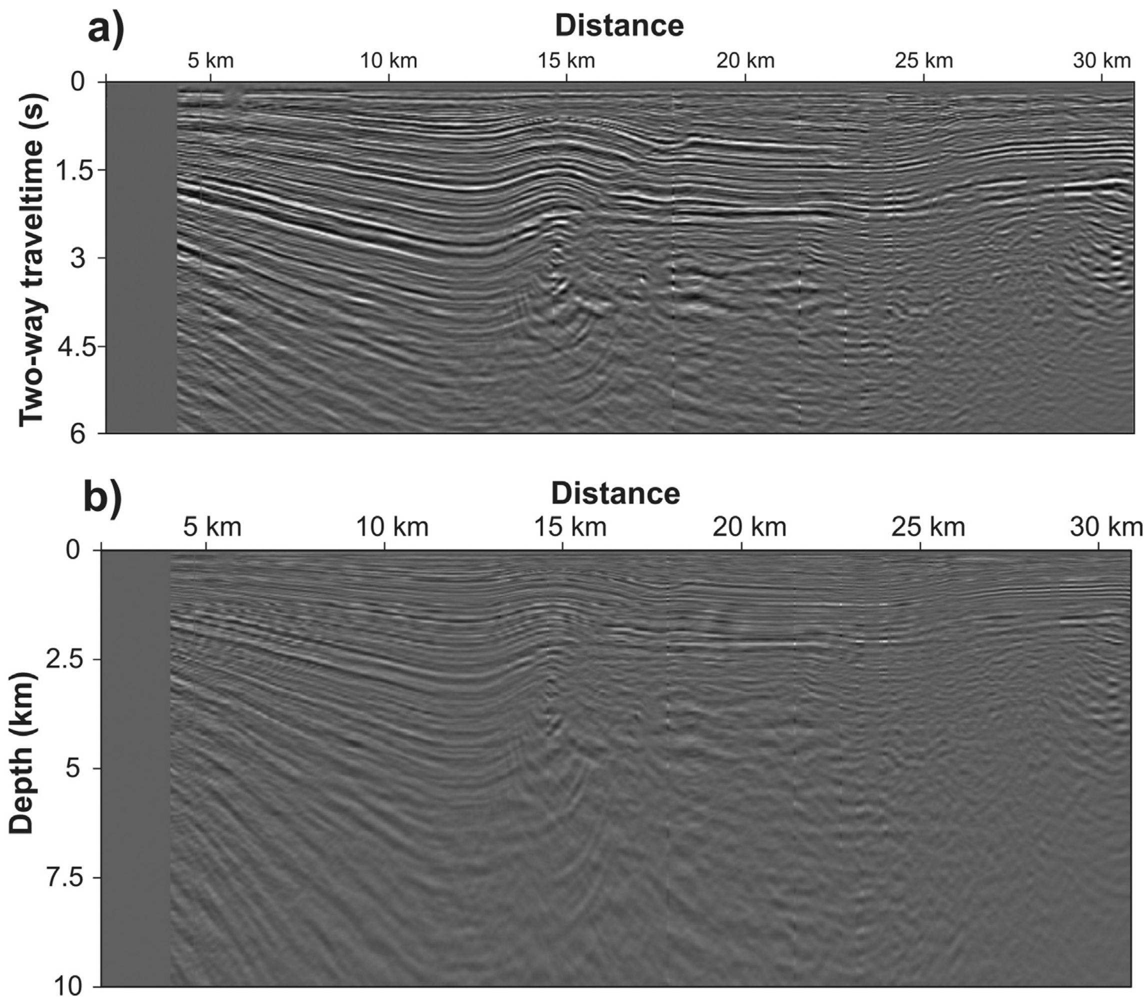

Fig. 1. Seismic images used in the interpretation exercise (a) in two-way travel time (TWT), and (b) in depth domain.

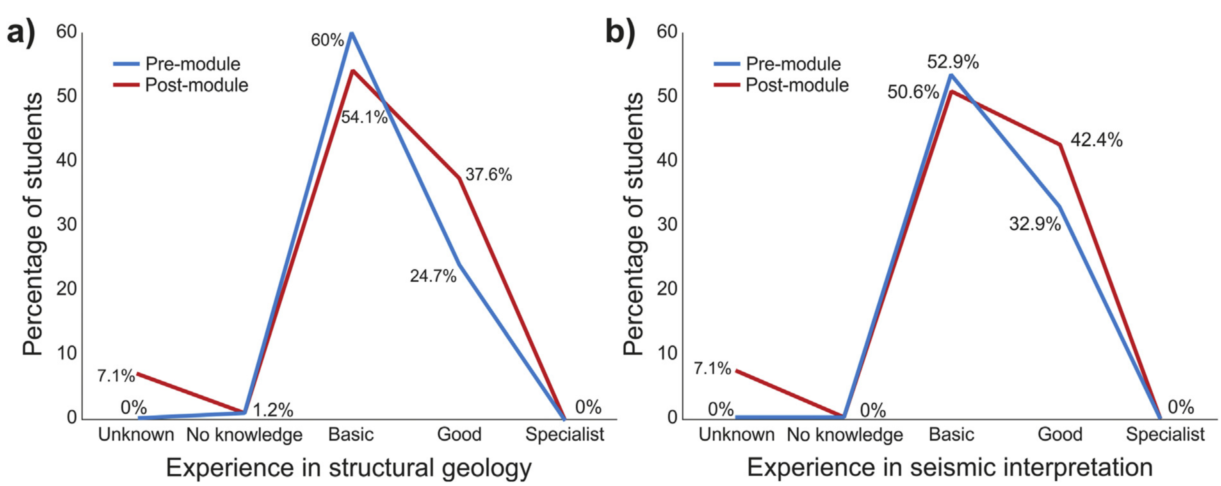

Fig. 2. Self assessed by students of their experience in (a) structural geology and (b) seismic interpretation, for Pre- (in blue) and Post-module (in red). Six Post-module students (7.1%) left the questionnaire blank. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

provided a number of heuristic tools commonly used in structural seismic interpretation. These tools included map-based mechanisms to determine extent and displacement direction (e.g., “the bow-and-arrow rule”; Elliot, 1976) as well as elements for fault analysis in 2D sections, such as the concept of regional elevation to distinguish extensional from compressional settings (Cooper et al., 1989) and the relationships between fault and hanging wall geometries (White et al., 1986).

4. Analysis of the interpretation results

The Pre- and Post-module experiment results contain a similar number of interpretations (73 Pre-module and 85 Post-module), a total of 158 interpretations. These have been sub-divided by the domain in which they were interpreted - TWT or depth (Fig. 3a and b, respectively). An almost equal number of interpretations were undertaken in each domain, both Pre-module (36 in TWT and 37 in depth) and Post-module (43 in TWT and 42 in depth). This allows assessment of any effect the interpretation domain may have had on the experiment outcome. The interpretations in TWT were also converted to depth using the approach described in Alcalde et al. (2017), in order to merge the Pre- and Post-module datasets.

The results of the interpretation experiment were analysed in terms of four different elements, for both the Pre- and Post-module results: (1) geometry and placement of the fault(s); (2) analysis of fault curvature; (3) the number of faults and horizons interpreted with depth; and (4) fault type.

The variability in interpreted fault placement was computed at nine depths in each interpreted seismic image (markers from 1 to 9 km, every km) (Fig. 3). At each depth marker, the 1st and 3rd quartile positions (in horizontal distance) for the fault interpretation populations were calculated. The distance between quartile 1 and quartile 3 (i.e., the inter-quartile fault placement range), provides a good estimation of the fault placement spread at a given depth (blue lines for Pre- and red lines for Post-module quartiles in Fig. 4a). The difference between Pre- and Post-module inter-quartile ranges (ΔIQ) is also calculated (Fig. 4a). The fault placement spread in the Post-module results is generally greater (ΔIQ of 85 m on average), with the maximum difference located at the bottom of the section ($\Delta IQ = 320$ m). Only at 5 and 7 km depth is the fault spread larger in the Pre-module set, with differences at these depths of 33 and 67 m, respectively. The Post-module interpretations are offset to the left at depths below 4 km in comparison to the Pre-module interpretations (Fig. 4a).

In this work, we define curved faults as any non-planar fault, i.e., faults that change in dip along their length. The upper part of the images (i.e., depths ranging from 0 to 3 km and times from 0 to 2.5 s TWT) show similar interpretations of fault geometry. An analysis of the geometry of the interpreted faults was undertaken using curvature analysis, to act as a proxy for the curved nature of the interpreted faults. Curvature is calculated for each point on a curve, with equation $y = f(x)$, the tangent line of which turns at a certain rate. The curvature k is a measurement of the rate of

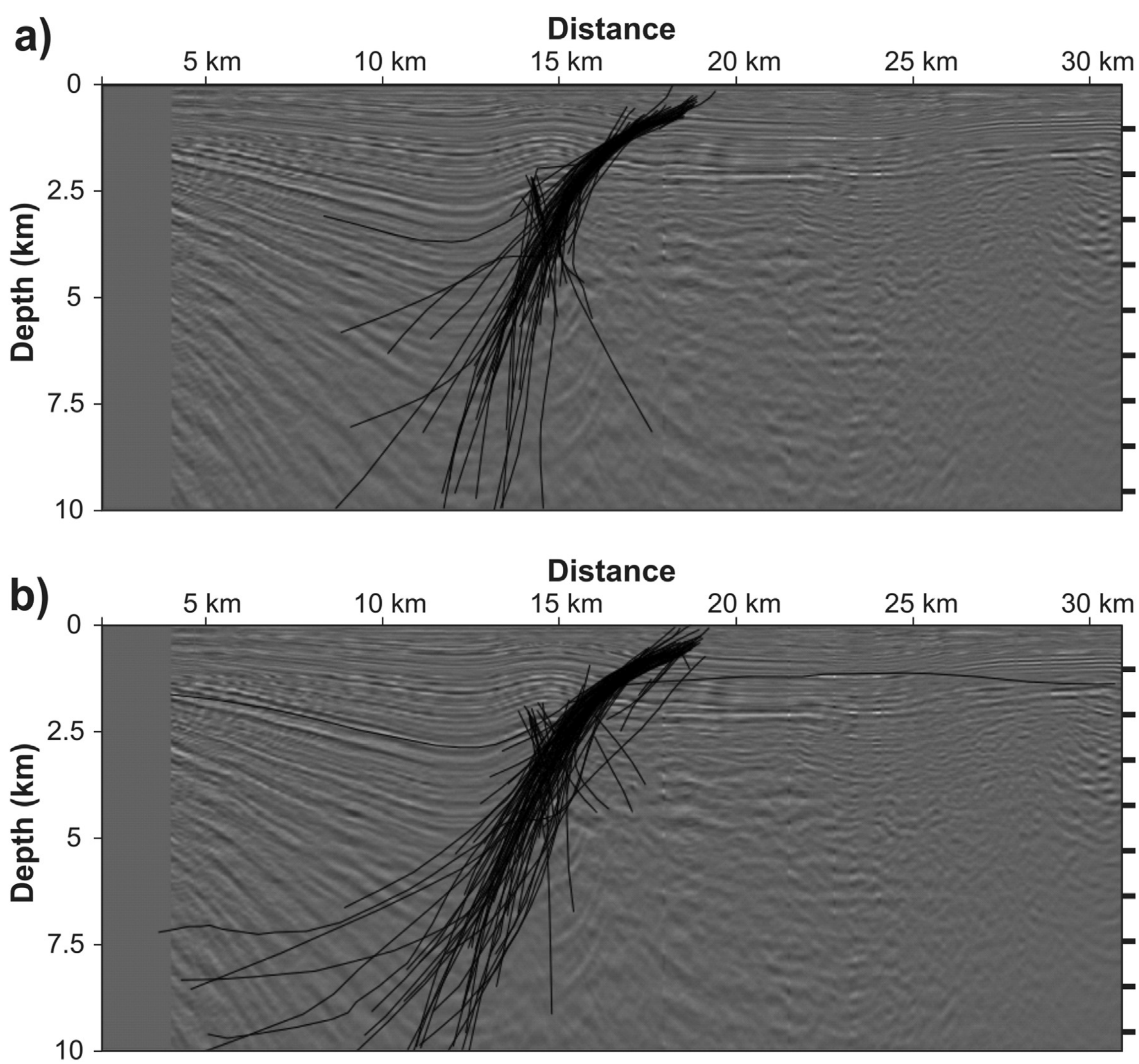

Fig. 3. Stacked results of the interpreted faults by students (a) Pre-module and (b) Post-module. Note that the results in TWT were converted to depth, for comparison of interpretations in the two domains. The black lines at the right side of the images mark the nine depths at which the analyses of the fault and horizon interpretations were made.

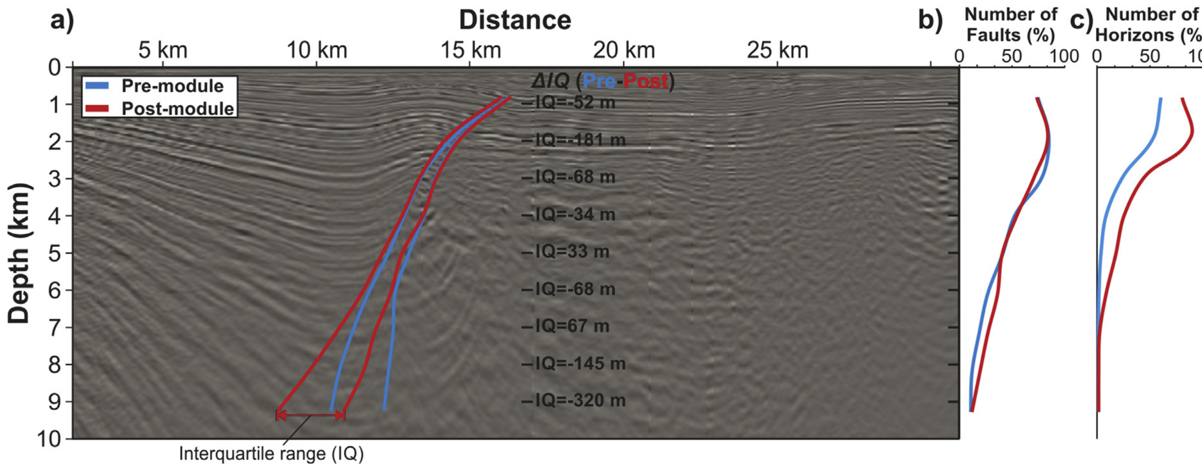

Fig. 4. Analysis of the fault placement spread (a), and count of the number of faults (b) and horizons (c) in percentage with depth normalised to the number of interpretations in each set. The fault placement spread is represented by the 1st and 3rd quartiles in horizontal position of the interpretations shown in Fig. 3, blue for Pre-module and red for Post-module. The numbers at the depth markers show the difference in the interquartile range between Pre- and Post-cases (ΔIQ), with positive values indicating a smaller interquartile range Post-module. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

turning of this tangent:

$$k = \left| \frac{f''(x)}{\left(1 + [f'(x)]^2\right)^{3/2}} \right|$$

where $f'(x)$ and $f''(x)$ are the first and second derivatives of the curve. Curvature values were calculated for all the faults at the fault nodes, the points on the digitised faults connecting two segments of different dip. The absence of change in dip between two segments (i.e., a flat segment) results in curvature zero, whereas the higher the curvature value, the greater the change in dip between the two segments. Computation of the curvature values from the nodes of the Pre- and Post-module fault interpretations allows a quantitative comparison of the geometry of the interpreted faults in the two datasets (Fig. 5). At the top of the profile, Pre-module faults have a greater curvature than the Post-module ones down to 1.5 km depth, a depth from which the median curvature values of both datasets decrease at a similar rate. This decrease occurs irrespective of the domain (TWT or depth) in which the seismic image was interpreted. At 6.5 km depth, the Post-module curvature values start increasing again whereas the Pre-module ones decrease, reaching two orders of magnitude difference at 8 km depth. The mean curvature values converge at the bottom of the section.

The number of faults and horizons interpreted at different depths were counted at the 9 depth markers and normalised against the total number of each subset (Fig. 4b and c). The interpreted fault count shows a similar amount of faults in the shallow part of the section down to 5 km (1% more faults in the Pre-module results on average); at this depth and greater, Post-module fault interpretations exceed the Pre-module horizon interpretations (7% more on average, Fig. 4b). The Post-module interpretations had a greater number of horizon interpretations at the different depths, resulting in 25% more horizons interpreted on average at each depth marker than the Pre-module interpretations (Fig. 4c).

Finally, the type of faults interpreted in the two datasets was also analysed (Fig. 6). The fault types identified comprised, in order of occurrence magnitude: normal, inversion, reverse and undefined. Normal faults are the most dominant fault type interpreted in both datasets, with 49.3% and 42.4% of the Pre- and Post-module fault interpretations, respectively. In the Pre-module data set, reverse and inverted faults were interpreted with a similar frequency (26% and 23.3%, respectively). The Post-module results show a greater number of inversion interpretations (38.8%, c. 15% more than the pre-module fault interpretations), and a smaller number of reverse fault interpretations (11.8%, 14.2% less than the pre-module fault interpretations).

5. Fault illustrations in textbooks and teaching material

Beyond the answers to the questionnaire (Fig. 2), it is difficult to assess the backgrounds of interpreters to determine effectively their exposure to different fault models in their early-years training. Here, we assess the representation of faults in textbooks as a proxy. A count of fault type and style was carried out in ten textbooks commonly used in structural geology teaching (Table 1). The publications were chosen to represent the range in fault models available to geology students in textbooks. The ten textbooks include European and US publications, ranging in publication date from 1987 to 2013. Fault representations in figures were counted and grouped based on their slip motion: normal, reverse (thrust), inversion and strike-slip. The faults were also classified as planar (e.g., Fig. 7a and b) or curved if they showed changes in dip (e.g., Fig. 7c and d). The fault count was carried out observing the following guidelines: (i) each sub-figure was counted as one fault, no matter how many faults were represented (e.g., Fig. 7c and d counted as one curved fault each); (ii) block diagrams only counted as faults if they showed displacement (e.g., Fig. 7e); (iii) oblique faults counted as both strike-slip and the corresponding dip-slip (Fig. 7f). Faults with unclear or absent slip motion, faults in outcrop photographs or maps, shear fractures, joints etc. were excluded from the fault count. The fault count was done by eye, and therefore faults with subtle or imperceptible changes in dip may have been assigned to the planar set unintentionally.

The result of the fault count show a dominance of normal (429 faults) and reverse (380) fault types compared to strike-slip (126) and reactivated (inverted) faults (11) (Table 1). Together, normal and reverse faults represent more than 86% of the faults found in the textbooks (Fig. 8a). The geometry of the faults was also addressed in the fault count (Fig. 9). In total, the number of curved faults (523) is higher than the number of planar faults (423). Curved faults are dominant in all the fault types except in strike-slip faults, where planar faults are twice as prevalent as curved faults (90 vs 36 faults, respectively).

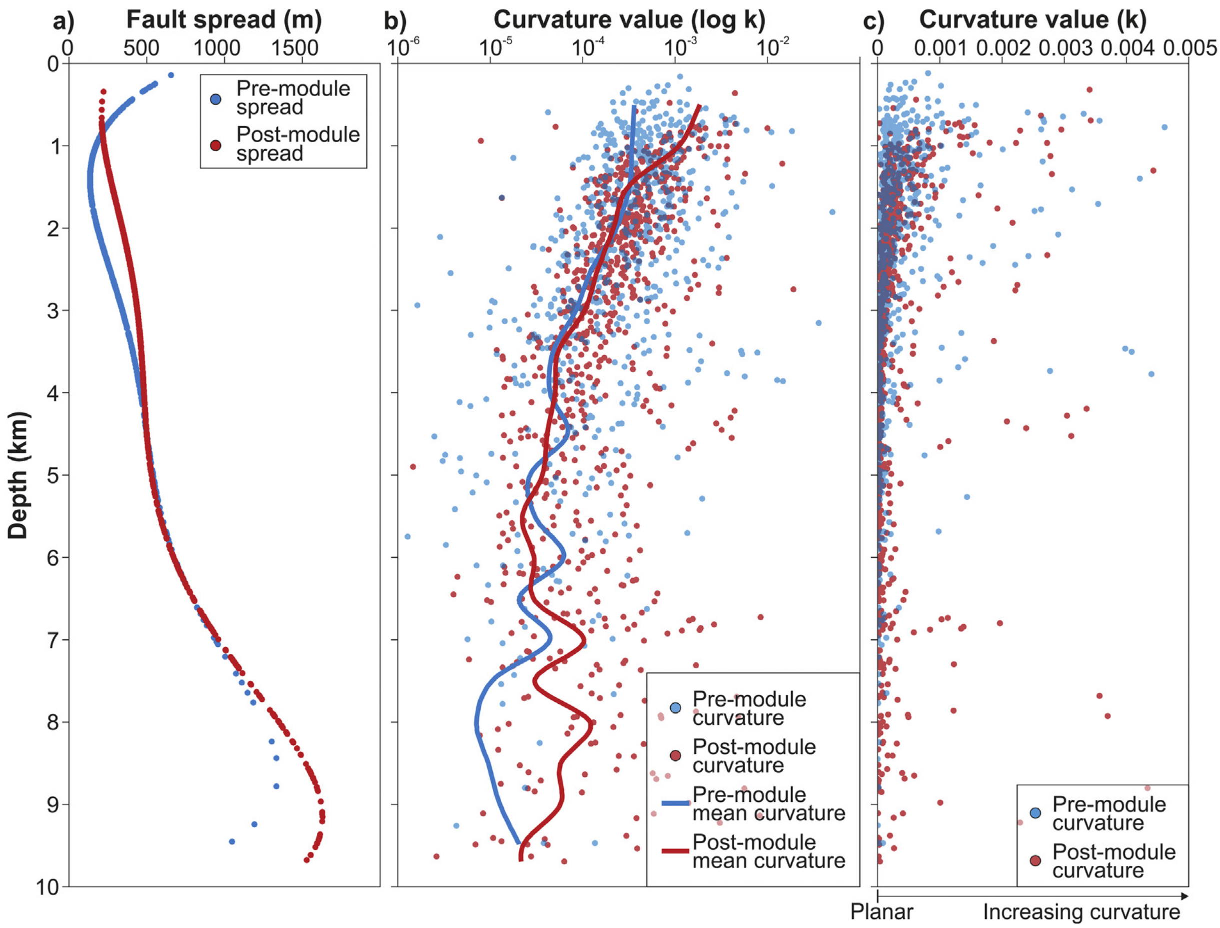

Fig. 5. Calculated fault spread (a) and calculation of the curvature values with depth in logarithmic (b) and linear (c) scale, for all the fault nodes. The spread of the nodes corresponds to the values illustrated in Fig. 4 a. The continuous lines in the curvature graph represent the median values calculated from the curvature analysis. For display purposes, 6 and 4 outliers were not shown in the curvature graphs b and c, respectively.

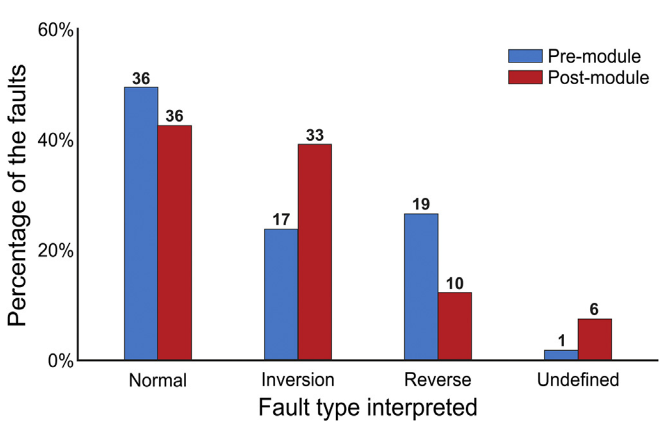

Fig. 6. Percentage of faults interpreted as normal, inversion, reverse or undefined in the students' interpretations. Pre-module (in blue) and Post-module (in red). The numbers at the top of the bars indicate the number of interpreted faults of each tectonic setting. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The fault count was further divided into examples from introductory textbook chapters and those from more advanced chapters (Table 1, Fig. 10). We define introductory chapters as those including the fundamentals of faults (i.e., nomenclature, classification and basic concepts) commonly describing Andersonian mechanisms (Anderson, 1950, 1951), and usually in the form of block diagrams or conceptual models. In contrast, advanced chapters usually include more detailed description of faults, with specific examples, usually from real settings. This subdivision of fault count shows that fault appearances in introductory chapters are dominated by planar faults (75% appearances on average, excluding inversion), whereas curved faults dominate in advanced chapters (73% on average), except in strike-slip fault types (Fig. 10).

Numerous fault examples, both conceptual (e.g., block diagrams) and real, were presented in the masters module teaching material. A fault count, similar to the textbooks, was carried out of faults represented in the teaching material, module lectures and practical exercises (Table 2). The fault type count in the module's lectures and exercises show a similar distribution to the count in textbooks (Fig. 8): normal faults (164 in lectures and 8 in exercises) and reverse (96 and 7, respectively) are the most observed types, whilst strike-slip (14 and 2, respectively) and inverted faults (19 and 5, respectively) are less prevalent. Whilst fewer in number (22) the faults counted in the module exercises, however, show a more distributed representation compared to the other two counts. The fault geometries in the module materials (both lectures and exercises) also show the same distribution between planar (37% of the total) and normal faults observed in the textbooks (63%) (Fig. 9).

Table 1
Count of fault types and geometries in illustrations in ten commonly used structural geology textbooks. The table differentiates between introductory chapters and advanced chapters in the textbooks. Introductory chapters involve conceptual descriptions of the mechanisms, geometries and motion of faults, whereas advanced chapters include more realistic geometries and real examples. The chapters were divided as follows in the textbook sources (introductory chapters, "int"; advanced chapters "adv"): Dennis (1987); Twiss and Moores (1992) (int: 4; adv: 5 to 20); Hatcher, (1995) (int: 8 to 10; adv: 11 to 13); Van der Pluijm and Marshak (2003) (int: 6 and 8; adv: 14 to 22); Price and Cosgrove (2005) (int: 5 to 8; adv: 9 to 18); Ragan (2009); Fossen (2010) (int: 8 and 9; adv: 16 to 21); Grotzinger and Jordan (2010); Davis et al. (2012); McClay (2013).

Textbook	Fault type count															
	Introductory chapters								Advanced chapters							
	Normal		Inversion		Reverse (thrust)		Strike-slip		Normal		Inversion		Reverse (thrust)		Strike-slip	
	Planar	Curved	Planar	Curved	Planar	Curved	Planar	Curved	Planar	Curved	Planar	Curved	Planar	Curved	Planar	Curved
Dennis (1987)	7	12			12	18	1	2								
Twiss and Moores (1992)	9	4			4	2	7	1	12	31			21	31	11	5
Hatcher (1995)	12	3			7	2	5		13	26		6	3	38	1	2
Van der Pluijm and Marshak (2003)	19	3			11	6	9	4	1	57		1	19	57	7	12
Price and Cosgrove (2005)	12	11			13	20	6		7				2	7		
Ragan (2009)	8	8			2	3	3									
Fossen (2010)	40	7			8		6		21	63		4	21	22	12	6
Grotzinger and Jordan (2010)	3	1			6	3	5									
Davis et al. (2012)	13	14			14	14	9	4								
McClay (2013)	6	6			7	7	8									

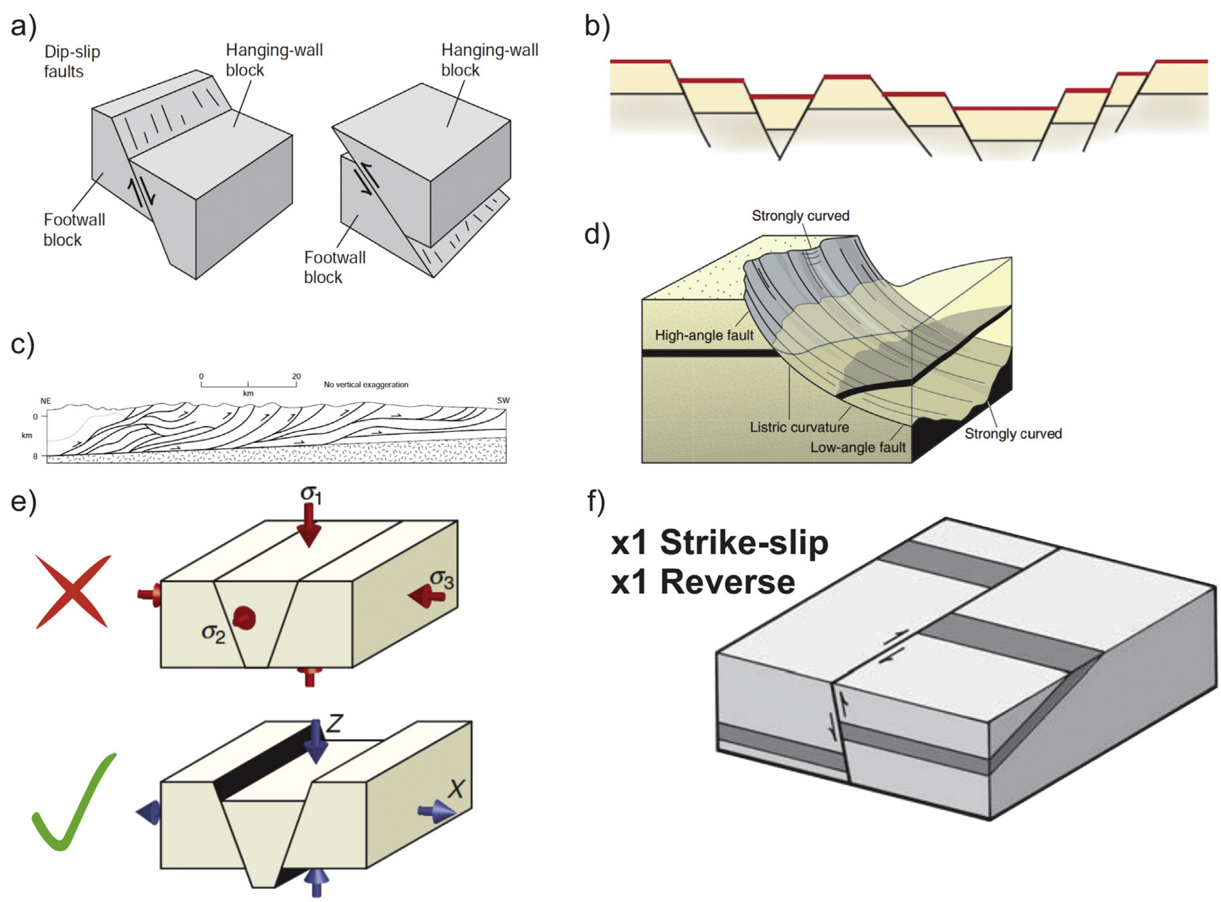

Fig. 7. Examples of faults counted in the textbooks. Faults included planar (a and b) and curved (c and d) geometries. Block diagrams were only counted if they showed any displacement (e). Transpressional or transtensional faults were counted as both strike-slip and reverse or normal slip senses (f). Modified from Van der Pluijm and Marshak (2003) (a and c); Fossen (2010) (b, d and e); and Davis et al. (2012) (f).

6. Discussion

6.1. Variation in fault placement and extent

In seismic image data, faults are commonly interpreted as 2D surfaces linking stratal terminations (e.g., Bahorich and Farmer, 1995). However, faults are frequently at the limit of the vertical and horizontal resolution of the seismic data, permitting multiple valid interpretations of the same dataset and hence carry interpretation uncertainty (Botter et al., 2014). The Inter-quartile range of fault placement can be used as an indicator of fault placement uncertainty for each seismic image, where larger inter-quartile

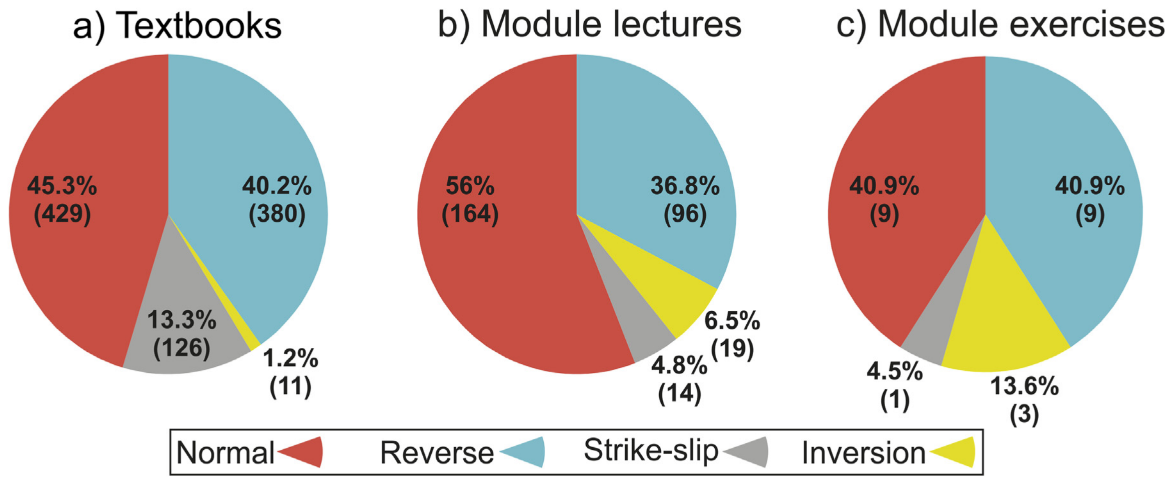

Fig. 8. Percentage of appearances of each fault types in (a) the textbooks; (b) in the masters module lecture materials; and (c) in the masters module exercises (bulk numbers in brackets). Sources in Tables 1 and 2.

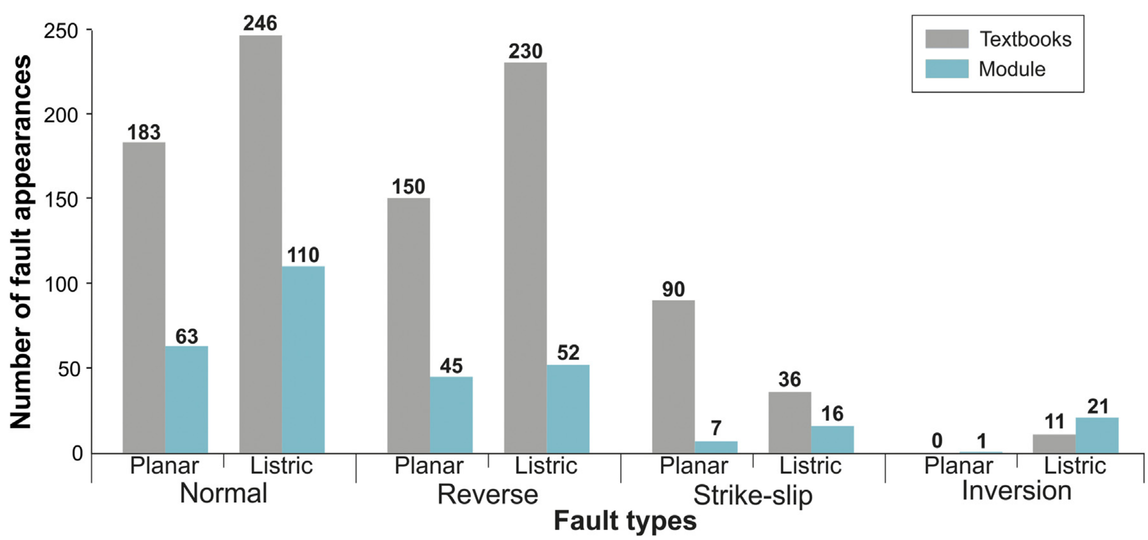

Fig. 9. Fault geometry appearances in textbooks (blue) and masters module materials (combining lectures and exercises; orange). Textbook sources in Table 1. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

ranges correspond to higher uncertainty (Alcalde et al., 2017). The experiment results show a greater spread in placement of the Post-module interpreted faults across the majority of the seismic section (Fig. 5a). As the students were interpreting the same images, Pre- and Post-module data uncertainty does not change. Thus, we infer that the difference in interquartile range relates to differences in the Pre- and Post-module interpretation process by the student cohorts.

Both Pre-module and Post-module interpretation results attest to a dramatic reduction in the number of horizon interpretations at c. 3 km depth (Fig. 4c). Alcalde et al. (2017) identified this boundary as a threshold depth separating the upper-part of the seismic section, with high seismic reflectivity and coherence and hence greater data constraint, to the lower part, showing lower seismic reflectivity and relatively incoherent reflections with greater interpretational subjectivity. This boundary also corresponds to a change in the number of faults interpreted at depth (Fig. 4b). Overall, the number of fault interpretations decreases below the boundary in both sets of interpretations. However, the number of fault interpretations is greater in the Post-module interpretations, particularly at increasing depths (Fig. 4b) when compared to the Pre-module interpretations. The effect of data quality on the number of faults interpreted at depth is more gradual than that observed for horizon interpretations. There are 178 fewer horizon than fault interpretations below 3 km (47 horizons vs. 225 faults). This may be because: 1) the fault geometry at depth can be projected from the upper-part of the seismic image into the lower more subjective data; or 2) simply an artefact of interpretation of sub-vertical features as compared to sub-horizontal horizons. It would be expected that more experienced interpreters use information from the data-constrained upper-section to project their interpretations in the deeper parts. In this respect, Shipley et al. (2013) hypothesised that experts are more capable to associate different spatial observations into a single entity. In these less data-constrained areas, conceptual models play a greater role in the interpretation of the seismic image (Bond, 2015). This inference is supported by the greater number of horizons interpreted and the more sustained fault interpretations to greater depths in the Post-module dataset.

We suggest that, following the Structural Geology for Petroleum

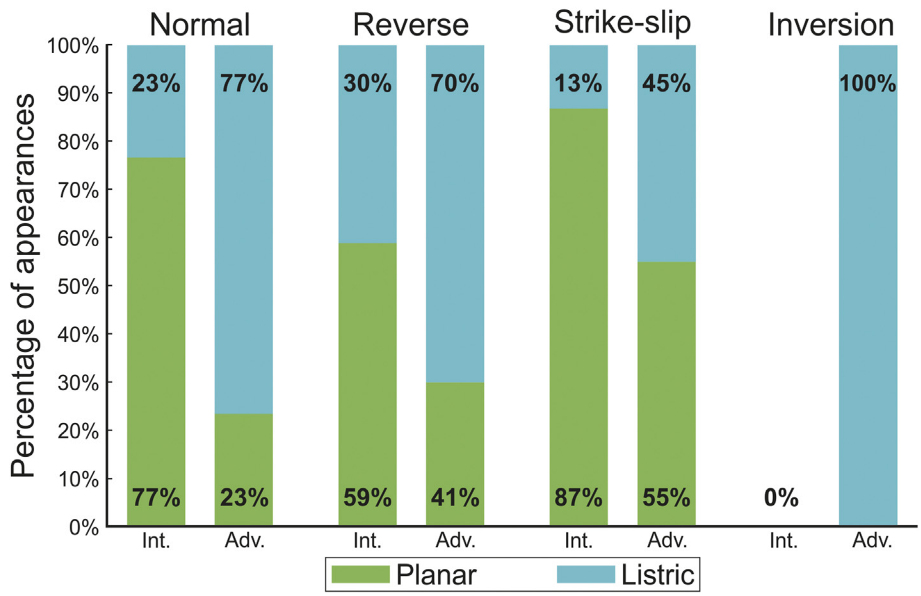

Fig. 10. Percentage of appearances of planar (yellow) and curved (blue) faults in introductory ("Int.") and advanced ("Adv.") chapters in the ten textbooks analysed, for each fault type. Textbook sources in Table 1. Only the textbooks containing both introductory and advanced chapters were included. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 2
Count of fault types and geometries in illustrations in the masters module lectures and exercises.

Teaching material	Fault type count								
	Normal		Inversion		Reverse (thrust)		Strike-slip		Total
	Planar	Curved	Planar	Curved	Planar	Curved	Planar	Curved	
Masters module lectures	63	101	1	18	45	51	7	7	293
Masters module exercises	2	7	1	8		1		3	22
Total	65	108	2	26	45	52	7	10	315

Exploration module, the students were more confident drawing the fault to depth into areas of poor-quality seismic image. This increased confidence in their interpretation abilities is supported by the student responses in the questionnaire (Fig. 2). We propose that the Post-module students were more confident in their interpretation of the seismic image, making their interpretations less restricted, leading to the interpretation of more variable fault geometries and to the subsequent increase in fault placement range (i.e., the calculated inter-quartile range), creating coherent holistic interpretations. Comparable increases in confidence relating to the amount of training for interpreters were also observed in a similar experiment carried out by Bond et al. (2011).

6.2. Interpretation of fault type and geometry

The nature of the seismic image used in the experiment is such that correlating horizons across the fault to determine fault type (e.g., normal, reverse/thrust, inversion or strike-slip) and displacement is not straightforward. Consequently, the experiments generated a range of interpreted fault types (Fig. 8) in both Pre- and Post-module cohorts. Interpretations are dominated by normal faults, perhaps reflecting their prevalence in introductory structural geology textbooks (Fig. 6 and Table 1). The Post-module interpretations were slightly less dominated by normal fault interpretations, perhaps reflecting the greater diversity in interpretation exercises of different fault types completed as part of the module, despite similar representation to textbooks of fault types in the taught (lecture) component of the module (Fig. 8). A greater influence on model availability would be expected from practical interpretation exercises in which learning is reinforced by engagement, rather than pure observation (Anzai and Simon, 1979).

Another characteristic observed in the Post-module interpretations is the increase in curved fault interpretations in the deeper part of the seismic section (depths >2.5 km) (Fig. 4 a and Fig. 5b and c). This increase suggests a greater appreciation in Post-module students for a range of fault models extending beyond planar fault geometries to encompass more complex geometries, including curved fault planes. Planar fault geometries are extensively used in training material for illustration purposes: as an example, the fault count carried out in structural geology textbooks revealed a relatively similar proportion of planar and curved faults (Table 1; Fig. 9). Planar faults are frequently used to illustrate the fundamental notions of faulting in the form of block diagrams (e.g., Fig. 7a and b). The fault geometries counted in undergraduate textbooks shows that curved faults appear more often (56.5%) than planar faults (43.5%) (Fig. 9). A similar proportion is observed in the masters module materials, where curved faults account for 60% of the faults interpreted and planar faults 40%. However, planar fault representations appear mainly in introductory chapters (Fig. 10), and may be more available than later models to interpreters.

6.3. Availability of fault models

When interpreting data, students learn how to discriminate different properties of the subject in order to match them with their own mental models. Since the learning process of these models is deeply dependent on the observation of analogue examples (Bond et al., 2007), careful selection of these examples is of great importance. Experiments in image interpretation suggest that better results are achieved when training includes difficult exemplars from the beginning (Donnelly et al., 2006). Therefore, the use of a greater range of fault geometries that better represent nature in introductory teaching materials is strongly encouraged. Similar observations in two experiments testing the readiness of fold models document the tendency of geologists to conceptualise folds as anticlines (as opposed to synclines), and to focus on certain properties of the folds (e.g., hinges instead of limbs) (Chadwick, 1975; Cowan, 2016). These studies also considered experts and non-experts in geology in their experiments, observing that the tendency to interpret folds as anticlines is irrespective of the level of expertise. Cowan (2016) hypothesises that "the antiform bias seen in the results from the geological community is due to subliminal conditioning caused by the geological education process". We propose a similar effect caused by availability bias (Tversky and Kahneman, 1973, 1974) of fault models; textbook and teaching illustrations of faults dominate conceptualisation of a fault type and geometry, in this case biasing the interpretations towards normal planar faults. By providing the students with a greater range of fault models that were readily available to them, we were able to influence interpretation outcome for the same seismic image. Nevertheless, many questions remain to be explored regarding the longevity of this effect, how training builds expertise over time, and what the impact is, on availability bias, of the interplay between a wealth of knowledge built up through time, examples that are more recent, and material exposed to early in knowledge acquisition.

7. Conclusions

We have examined the role of training in the interpretation of faults on a 2D seismic reflection profile using cohorts of graduate students before and after a module in structural geology. There are quantified differences in the students' interpretations in fault type, geometry, placement and extent, before and after this training. Normal faults chiefly of planar form dominate Pre-module interpretations. A greater range in fault type and geometry is represented in Post-module interpretations. These observations suggest that more experienced interpreters (i.e., Post-module students) use a greater range of fault models. They are also more likely to extend interpretations (faults and horizons) into regions of the seismic data of poorer image-quality. This behaviour may reflect an increased confidence on the part of the interpreters, as suggested by the questionnaire returns.

Analysis of training material (textbooks and lecture slides) suggest that normal faults are dominant, and planar fault geometries are over-represented with respect to more complex fault patterns in introductory materials. We propose that this unrepresentative dominance of normal-planar faults in introductory chapters of textbooks influences the conceptual fault models available to geologists for interpretation of data. Hence we recommend that both educators and applied geoscientists recognise the potential of available fault models to bias interpretation and attempt to minimise its effects by exposing students and professionals to as wide a set of fault analogues as possible. A move away from simplistic fault models to more representative fault types and geometries at all learning levels should create more effective seismic interpreters. We suggest that the impact of such a move will increase the range in fault geometries interpreted mostly for early career geologists who have likely been exposed to a smaller range in fault analogues and may have fewer models readily available. Perhaps the maxim "the best geologist is the one who has seen the most rocks" (Read, 1957) is not just a cliché, but the diversity and examples of the observed rocks seems to be as important as the quantity.

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