Continent-Ocean Transition or Boundary? Crowd-sourced seismic interpretations of the East-India Passive Margin

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Key Points:

- Passive margin models are conventionally interpreted as abrupt continent-ocean boundaries or diffuse transitions
- We run a group experiment to explore the range and variability in interpretations of a seismic section from the Eastern India margin
- Expert elicitation and crowd-sourced experiments are helpful to identify areas of uncertainty within passive margin model building

Abstract

On the edge of our continents, oceanic crust meets continental crust. At passive margins, those where there is no active tectonics, subduction or transform faulting, these crustal types are connected as sharp continent-ocean boundaries (COB) or as diffuse continent-ocean transition (COT) zones. Passive margins are hard to explore and consequently relatively little is known about their morphology or the geological processes of their formation. Here we elicit and analyse seismic image interpretations of the passive margin offshore East India conducted by 17 groups of geoscientists to better understand the differences, or lack therein, of COB or COT interpretations of the margin. The group interpretations provide a wide range of margin models, five of which are abrupt COB based and 11 which are diffuse COT based. However, interpretations within the COB set vary in the placement of the boundary line between continental and oceanic crust, the boundary placement lying within the range of interpreted COT zones, with the average COB location falling in the centre of the interpreted COT zones. These crowd-sourced results are then compared with ten published interpretations across the margin, which show COB and COT zones falling in the same area. These findings raise questions as to the real differences in COB and COT models and the geological processes involved in their formation. Considering this, we discuss the implications for passive margin models and the use of Wisdom of Crowds-type approaches in reflecting on both the range of interpretation-based models and in the value of determining 'average' model approaches.

1 Introduction

Passive margins are present along the coasts of all continents. Their total length exceeds 105,000 km of the coasts of all continents, constituting the longest tectonic feature and covering circa 7% of the Earth's surface (Bradley, 2008; Brune et al., 2016). They also host the thickest accumulations of offshore sediments (Straume et al., 2019) and contain large amounts of energy resources (Berndt, 2005; Zhixin et al., 2016), making them important research targets. In spite of their importance, questions about their constituent form remain.

Passive margins are formed by juxtaposed continent and oceanic lithosphere, whether in the form of sharp or abrupt limits (continent-ocean boundaries, COB) or as more diffuse transition zones (continent-ocean transitions - COT). These coupling parts of the margins have always attracted interest; not least because of their implications for rifting and crustal processes (Chian and Louden, 1994; Blaich et al. 2011; Franke et al. 2011; Peron-Pinvidic et al., 2013), but also because of how they are used to determine palinspastic reconstructions (Keen and De Voogd, 1988; Seton et al. 2012; Eagles et al. 2015). As Eagles et al. (2015) cover in their comprehensive review, the definition and demarcation of continent-ocean margins are not well defined, and scientists frequently propose different margin models for the same area, often even using the same datasets. It is generally recognised that, in its simplest form, a COB (where continental crust changes to oceanic crust defined as a linear boundary or line on a map) is a simplification; whereas as a COT allows for a 'mix' of crustal types across a transition zone (an area, or polygon on a map), and although a range of crustal processes are implied in this transition zone (e.g. Lavier and Manatschal, 2006; Pindell et al. 2014) they are not necessarily delineated. This raises issues for palinspastic reconstructions and broader questions on rifting processes that rely on these margin models. Yet these two conceptual models (COB and COT) continue to be used and mapped across a range of continent-ocean margins.

To truly confirm abrupt COB or diffuse COT zones and the different process-based interpretations, sampling is required in often very deep, inaccessible or expensive and difficult-to-drill locations (e.g. Sibuet et al., 2007). Therefore, in reality, interpretations and their associated conceptual models are mainly reliant on interpretations of geophysical data: seismic (reflection and refraction), magnetic and gravity data (e.g. Minshull, 2009; Franke, 2013). Interpretations of geophysical data, reflection seismic images in particular, are well documented as being inherently uncertain (e.g. Bond et al., 2007; Alcalde et al. 2017a, 2019; 2022; Pérez-Díaz et al., 2020; Alcalde and Bond, 2022). This uncertainty can create unwanted outcomes, e.g. flawed horizon (Rankey and Mitchell, 2003) and fault (Faleide et al., 2021) interpretations or imprecise interpretation of break-up markers (Causer et al., 2020), that can ultimately lead to inaccurate (COB or COT) margin models.

The uncertainty in the interpretation of geophysical data across the continental rift zone of the East-India margin is the focus of this work. This area has been interpreted as both an abrupt COB and diffuse COT margin, which purport, or suggest the possibility of, exhumed mantle at the COB or in the COT zones (Eagles et al., 2015). As well as the difference in the interpretations, it is clear that the mechanisms that underpin the formation of this and other rifted continental margins are still a subject of debate.

Previous interpretation experiments have investigated the value of aggregate individual interpretations to determine an optimal solution(s) (e.g., Bond et al., 2009; 2015; Macrae et al., 2016; Alcalde et al., 2019; Schaaf & Bond, 2019). Instead, here we use a collective of experts' interpretation approach to address this question, a combined "Wisdom of Crowds" and group expert elicitation. The Wisdom of Crowds approach relies on different mechanisms to turn the judgements into a collective outcome or decision (Surowiecki, 2004), i.e., diversity of opinion and experience from the participants involved, independence of ideas, a decentralized approach in which participants draw on their own specialist knowledge, and make an effective aggregation of the results. We draw on these aspects, but our crowd are experts (geoscientists) and perform the interpretation in small groups.

In this work, we explore the range in interpretations of a single 2D regional seismic dataset from the East-India margin by several groups of geoscientists. The experiment presented in this work originated from multiple interpretations of this seismic dataset, providing an excellent example through which to test the variety in interpretations and the competing hypotheses on which they are based. It also allows the question to be posed of if the different interpretations can, or cannot, be used collectively to determine broad model suites. The aim of the experiment was to explore the range in interpretations to a single dataset, to understand which parts of the data yield similar interpretations and which are more contested. The use of a single 2D seismic image allows us to better constrain the range in interpretations, without the additional uncertainty associated with different input datasets that Eagles et al. (2015) recognise as a likely factor in their review of interpretations across the East Indian margin. We observe a range in interpretations across our participant groups, to quantify the difference in abrupt COB and diffuse COT interpretations and to see if the average COB and COT interpretations (i.e. the Wisdom of the Crowd) could be thought of as representative of the interpretation set(s) and if they are geologically reasonable.

2 The East-India margin

The East-India passive margin formed as a result of the breakup between Antarctica and the Indian subcontinent during Early Cretaceous time (Powell et al., 1988; Haupert et al., 2016). The subsurface of the East-India margin is well imaged by seismic data, and has been the focus of numerous interpretations. Several of these interpretations (Powell et al. 1988; Rao et al. 1997; Bouysse et al, 2009; Krishna et al., 2009; Veevers, 2009; Bastia et al. 2010; Sinha et al. 2010; Seton et al. 2012; Gibbons et al. 2013; Nemčok et al. 2013) are included in the overview of Eagles et al. (2015; their figure 10); redrawn here (Figure **1a**) to show the range of interpretations for the margin. Note that papers published in 2014 and onwards are not included in the overview of Eagles et al. (2015). Eagles et al. (2015) calculate a mean width of the COB of 184 km, standard deviation of 79 km, measured along 16 equally spaced transects.

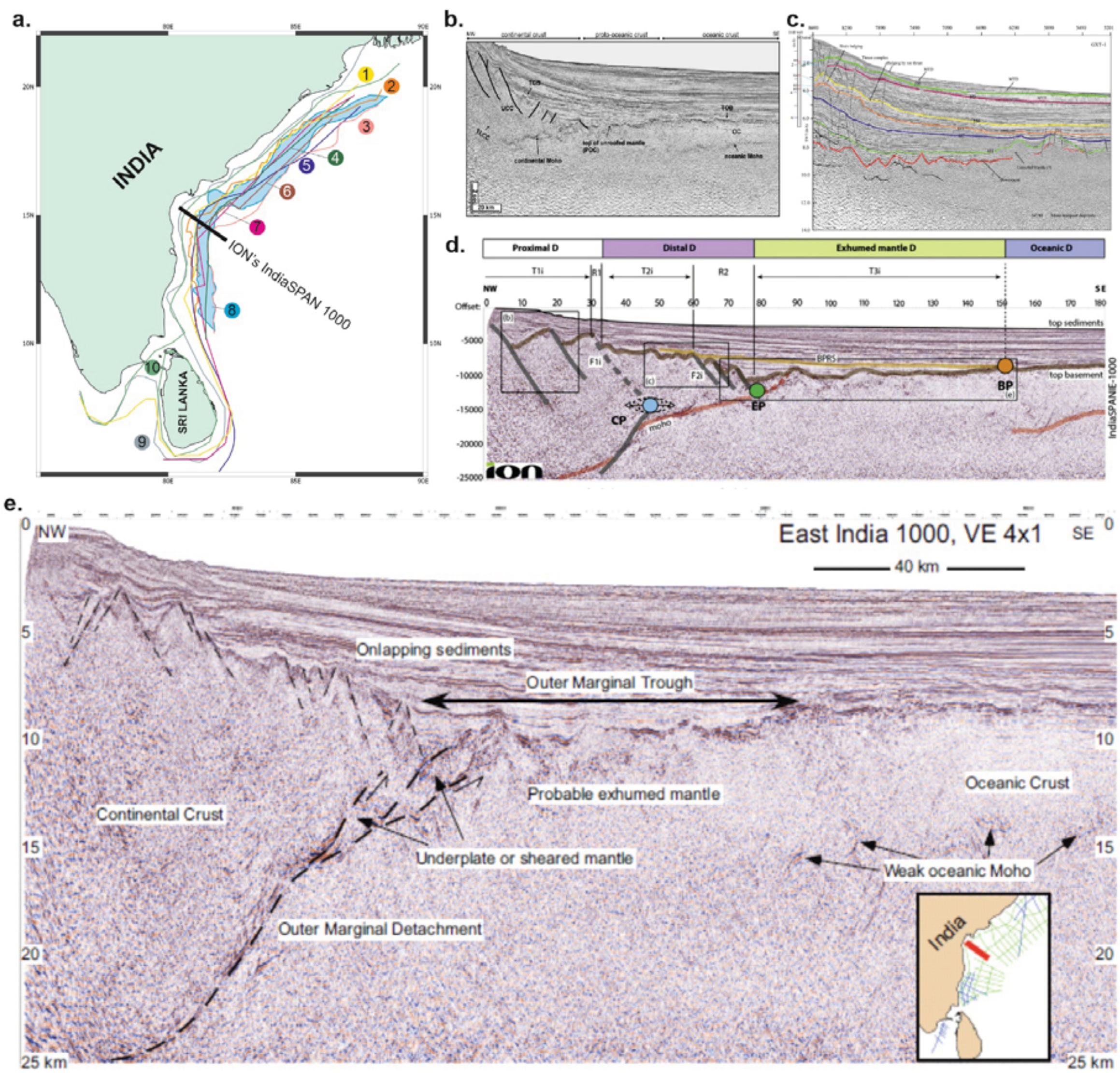

Figure 1. Location map and seismic section used in this experiment. a) The East Indian margin with the location of the ION's IndiaSPAN 1000 marked, and data showing the location of COB and COT interpretations redrawn from Eagles et al. (2015). The numbers indicate the interpretation sources as follow: 1 – Bouysse et al., (2009); 2 – Bastia et al. (2010); 3 - Sinha (2010); 4 - Rao et al. (1997); 5 - Krishna et al. (2009); 6 – Veevers (2009); 7 – Powell et al. (1988); 8 - Nemčok et al. (2013); 9 – Gibbons et al. (2013); 10 – Seton et al. (2012). b), c), d) and e) The Ion East India 1-1000 seismic section interpreted by Nemčok et al., (2013), Haupert et al. 2016, Mangipudi et al., (2014) and Pindell et al. (2014), respectively. Note that the numbers in a) do not correspond to the number codes in Eagles et al (2015).

This study focuses on the interpretation of the ION's IndiaSPAN-1000 2D regional seismic line. This seismic dataset comes from the offshore Andhra Pradesh part of the margin and extends over 200 kms (Figure 1a). This line has been interpreted in five recent papers (Sinha et al., 2010; Nemčock et al., 2013; Pindell et al. 2014, Mangipudi et al. 2014, Haupert et al. 2016) (Figure **1b-e**). Sinha et al. (2010) and Nemčock et al., (2013) define a COT zone as a "proto-oceanic crust", featuring c. 50 km of "exhumed" and "unroofed" mantle, respectively. Mangipudi et al. (2014) also describe an area akin to unroofed mantle, reported in similar areas with interpreted proto-oceanic crust. For Haupert et al. (2016) the exhumed mantle is extensive and indicative of hyperextension processes (Lavier and Manatschal, 2006). For Pindell et al. (2014) exhumed mantle is "possible" and they suggest an additional primary stage in passive margin formation, 'outer marginal collapse' occurring after the traditional rift stage and before the thermal subsidence stage that they describe as encompassing the collective processes that form COT zones. Nemcok et al. (2013) provide the only COT interpretation of this dataset, with a 20-100 km transition zone interpreted along the margin.

3 Group interpretation experiment

Interpretation of the ION's IndiaSPAN-1000 2D regional seismic line (like that shown in Figures 1c and 1e but uninterpreted and unannotated) was conducted during the 17th International SEISMIX Conference, held in May 2016 in Aviemore, Scotland. The participants were geoscientists (chiefly geophysicists and geologists with expertise in seismology) attending the conference. Interpretation of the seismic line was conducted through a facilitated workshop. Participants self-assigned themselves into groups of three to five people, with 17 groups completing the interpretation in total. Each group was given a deep seismic profile provided by Ion, that had been migrated and depth converted. The seismic profile was presented as a hard copy print in colour with vertical and horizontal scales equal, shown in km at a scale of 1:1. The only annotation on the image were the scale. The participants were not told where the seismic profile was from, nor were there presentations (oral or poster) before the experiment that discussed the image or the tectonics of continental rifting. The India-SPAN-1000 2D seismic line has a high quality and therefore provides the best opportunity to minimise interpretational uncertainty associated with image quality (Alcalde et al. 2017b; Alcalde et al., 2017c). Confidentiality reasons mean we cannot share this image with readers, but images of the line (with different display characteristics) have been published (Figure **1**). A printed instruction

sheet that explained the exercise and asked the participants as a group to interpret the image. The instructions included a preamble to explain the scope of the experiment, general information about the seismic line and about the author's commitment to keep the results anonymised.
To ease comparison between the different interpretations, the groups were asked to identify the following four features: (i) different crust (basement) types – i.e., continent vs oceanic crust; (ii) different sedimentary units – e.g. pre-, syn- and post-tectonic units; (iii) the Moho – under the continent, the ocean and whether/how these connect; and (iv) the presence of faults. The full set of instructions are available in the supplementary material.
Each group were also asked in the instructions to complete a questionnaire. The questionnaire was designed to elicit the groups' knowledge of the specific seismic image they were being asked to interpret, as well as of rifted margins more generally and the groups experience in seismic interpretation. The collated information is summarised in **Annex 1**. The groups consisted of individuals with a range of seismic interpretation expertise and backgrounds in rifted margins. Importantly, none of the groups had worked on, or recalled having seen the seismic image previously. This means that comparison between the different groups' interpretations is more robust, with no individual or group carrying a specific bias or expectation from having seen or worked on the data previously. The participants were encouraged to be proactive and cooperative within the interpretation exercise.

4 The Wisdom of Crowds approach

The Wisdom of Crowds (Surowiecki, 2004) builds on the hypothesis that the combination of multiple judgements outperforms individual assessments (Budescu & Chen, 2015). A highly successful example of Wisdom of Crowds is Wikipedia, which has substituted traditional encyclopaedias thanks to its open access, collaborative approach (Kittur and Kraut, 2008). Surowiecki (2004) outlined four key criteria for a successful Wisdom of Crowds approach, namely diversity, independence, decentralization and aggregation approach. Below is a description of these four elements and their fit in our interpretation experiment.
i) **Diversity** in opinion and expertise. Each participant should add their own point of view to the interpretation, as it is well accepted that diversity in expertise and viewpoints enhances creativity and problem solving (e.g. Kelley and Tibaut, 1954; Hoffman and Maier, 1961; Larson Jr, 2007). By running our seismic interpretation experiment at the international SEISMIX conference, we aimed to ensure a diverse mix of individuals with different backgrounds and experience. Across the groups there were some "super experts" (i.e., had completed research in these settings), whilst others had less experience. Collectively, the experts in this experiment could be described as seismologists with a range of expertise in application, from signal and data processing relating to various seismic techniques through to geological interpretation of seismic (chiefly reflection) imagery. Each participant could contribute to the interpretation based on their different expertise.

ii) **Independence**, so that individuals' opinions are formed independently. Participants should be able to provide their opinions without being conditioned by the opinions of the rest of the members of the group. In other words, care must be taken so that the Wisdom of the Crowd prevails over herding bias (Larrick et al., 2012). For this element, we did not follow a Wisdom of Crowds approach and the experiment was undertaken as a group exercise, and we acknowledge that within any individual group, the opinions of individuals will have been tempered by others and the group view. However, we ensured that the 17 groups operated independently with interpretation sharing and discussion only after completion of the interpretation. We used the collective interpretation of each group as a data point or set (e.g. as though created by an individual); although we recognise that dominance of specific individuals, and personality traits within the groups will likely affect the collective outcome (see Polson and Curtis, (2010), for a geoscience example of group decision making dynamics). The collective experience of each group can be seen in Annex 1.

iii) **Decentralization**, where people draw on their own specialist knowledge. By running the experiment at SEISMIX individuals were free from the normal constraints of their working practices and colleagues. This decentralized approach would likely result in greater diversity than for example running the exercise with a group of geoscientists from the same company in their usual working environment. Although groupings were self-assigned the experiment coordinators encouraged participants to form groups with people they did not know or with which they did not commonly collaborate, to enhance diversity, independence and decentralization within the groups.

iv) **Aggregation**, an effective mechanism to turn the judgements into a collective decision. As the majority of the information, we collected is geo-spatial we used a simple image stacking approach in order to determine the range in interpretations, and the mean response. This process is outlined further in the results section.

Our experiment differs from that of a classic Wisdom of Crowds approaches is that in the traditional examples (e.g. estimating the weight of a Bull at an agricultural fair) there is a single unequivocal answer to the question posed. In our interpretation example there is not a single deterministic solution and indeed two independent conceptual models dominate known thoughts. So here we use the wisdom of the collective-experts slightly differently, not to determine the solution to a simple question with a singular answer, but to address three important questions: (i) to see if the experts wisdom represents the two known dominating models; (ii) to investigate how independent these two models actually are in practice; and (iii) to assess the use the collective wisdom of the experts to determine an optimal interpretation solution or solutions for the interpretation of this seismic dataset. In summary, we are using a Wisdom of Collective Experts approach to explore the diversity in interpretation and what that means for the conceptual models of an abrupt COB or a diffuse COT zone.

5 Interpretation results

The collated interpretations were initially assessed for the four different features that the groups had been asked to identify in the interpretation instructions (i.e. the Moho, the basement, the faults and the different types of crust) (Table 1). All groups identified the Moho, all but one group had interpreted faults in the sedimentary cover sequence and similarly crustal types. Two groups chose not to identify pre-, syn-, and post-rift mega sequences, see summary of identified features in Table 1. Using the key features identified in the interpretation instructions, and other commonly identified elements (e.g. exhumed mantle, thinned or hyper extended continental crust, continent-ocean transition zones, see Table 1 for the full list) the interpretations were divided into the binary 'model types' an abrupt relationship – COB or a diffuse one (COT). Figure 2 shows examples of the group interpretations. Of the 17 group interpretations, 11 groups (65%) explicitly defined a continent ocean transition (COT) zone. For the five groups that made a COB interpretation (29%), two of the groups marked a boundary, whilst in the other three cases continental crust was identified distinctly from oceanic crust, so the COB categorisation and boundary is implicit from the joining point rather than explicitly identified. Only one group did not provide enough evidence for categorisation into either of the binary model types.

	Specifically requested in the instructions								Other features interpreted							
						Sedimentary units										
Group	C-O margin	Moho	Number of faults	Faults	Crust types	Pre-rift	Syn-rift	Post-rift	Thinned or hyperextended Continental Crust	Exhumed mantle	Serpentinised Mantle	Underplating	Intrusions	Salt	Subduction	Data Artefact
JJ	COT	Y	10	Y	Y	Y	Y	Y	N	N	N	N	N	N	N	N
JK	COT	Y	14	Y	Y	Y	Y	N	Y	N	N	N	N	N	N	N
JL	?	Y	6	Y	N	N	N	N	N	N	N	N	N	N	N	N
JM	COB	Y	10	Y	Y	N	Y	Y	N	N	N	N	N	N	N	Y
JN	COT	Y	11	Y	Y	Y	Y	Y	N	Y	Y	N	N	N	N	Y
JP	COT	Y	6	Y	Y	N	N	N	N	N	N	N	N	Y	Y	N
JQ	COT	Y	33	Y	Y	N	Y	Y	Y	N	N	N	N	N	N	Y
JR	COB	Y	12	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	N	N	Y
JS	COT	Y	1	Y	Y	N	N	Y	Y	Y	Y	N	N	N	N	N
JT	COT	Y	12	Y	Y	N	Y	Y	Y	N	N	N	N	N	N	Y
KJ	COT	Y	-	N	Y	Y	Y	N	Y	N	N	N	N	N	Y	N
KK	COB	Y	10	Y	Y	N	Y	Y	N	N	N	N	N	N	N	N
KL	COT	Y	8	Y	Y	N	Y	N	N	N	N	N	N	N	N	N
KM	COT	Y	10	Y	Y	N	Y	Y	N	Y	Y	Y	N	N	N	N
KN	COB	Y	14	Y	Y	N	N	N	N	N	N	Y	Y	N	N	N
KQ	COB	Y	6	Y	Y	Y	Y	Y	Y	Y	N	N	N	N	N	N
KR	COB	Y	20	Y	Y	N	Y	Y	N	N	N	Y	N	N	N	N
Percentage of Y		100%	-	94%	94%	35%	76%	65%	41%	29%	24%	18%	12%	6%	12%	29%

Table 1. A summary of the features interpreted by the 17 different groups. The table is divided into those features specifically requested in the interpretation instructions and other features interpreted by the groups (column 1) that have been used to define the 'binary' model type (COB or COT) interpreted (column 2); Y=yes interpreted, N=Not interpreted.

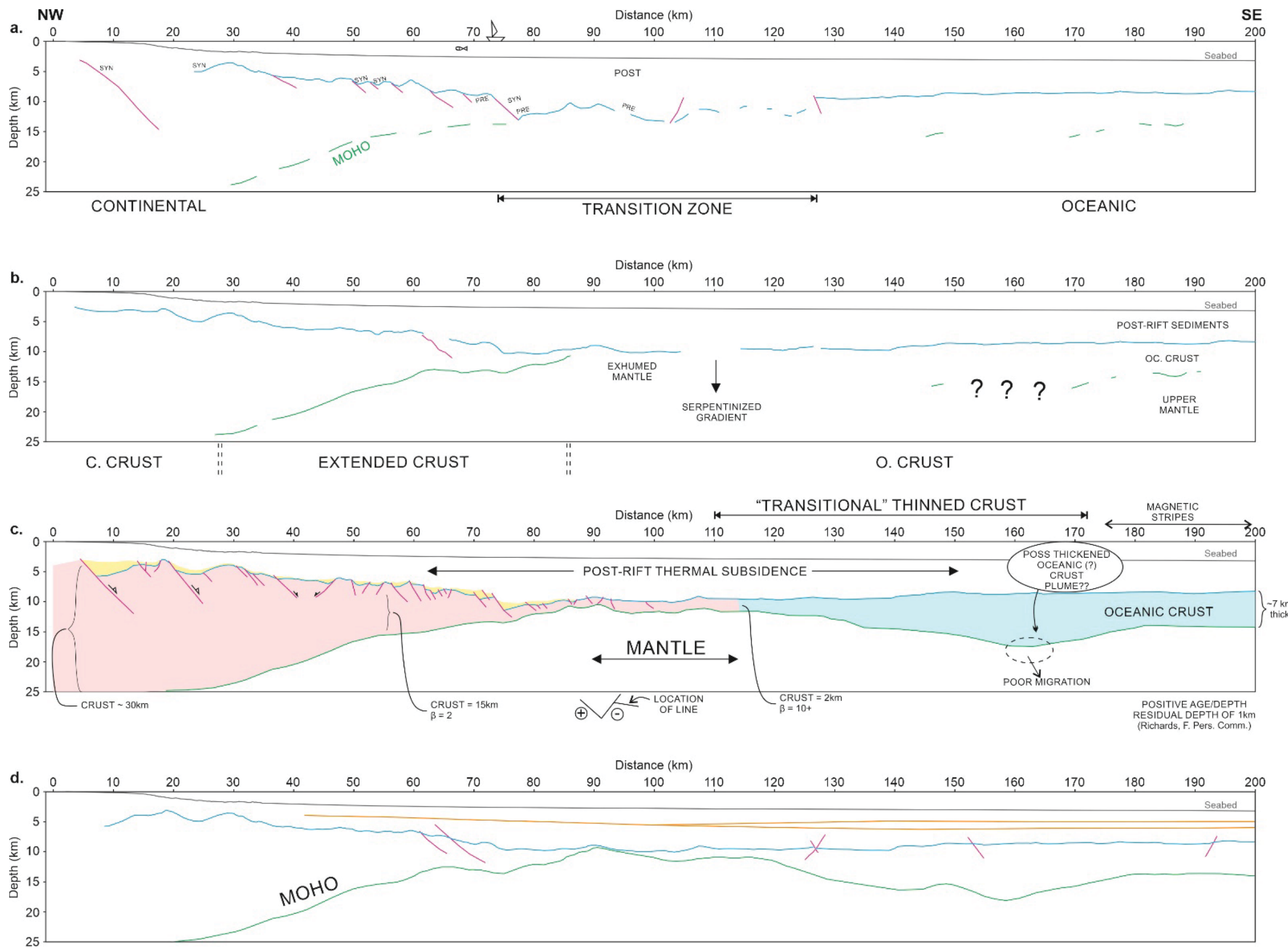

Figure 2. Digitised examples of the different group interpretations. a) COT interpretation (group - JJ), with the extent of the transition zone marked by an arrowed section. The Moho is partially interpreted, as is the top of the Basement. b) COB interpretation (group - JS). This interpretation has the extended crust annotated, as well as exhumed mantle. The Moho is partially interpreted and uncertainty in its position is marked by question marks. c) COT interpretation (group - JQ). The interpretation uses annotation to show the extent of 'transitional' thinned crust; the thickness of the continental crust and the oceanic crust and associated ß - stretching factors, as well as other features. d) The one interpretation (group – JL) that could not be categorised. The interpretation shows the Moho, Top Basement, Faults and sediment fill; but with no identification of oceanic or continental crust, a boundary or a transition zone.

After categorisation into abrupt COB interpretations or diffuse COT, we measured the distance of the boundary or transition from the beginning of the seismic section. Note that all distances are measured left-right (i.e. NW-SE) from the continental crust end of the section. For the group interpretations categorised as COB, the interpreted end of the continental crust and the start of the oceanic crust ranged in location from 75 km-142 km along the section, with a mean value of 101 km and a median of 93 km (Table **2a**). For the group interpretations categorised as having COT zones, calculations were made of the extent of the transition zone that had either been indicated directly, or that could be inferred from the marked extents of the continental and oceanic crust in each interpretation (Table **2b**). For the COT interpretations, the length of the transition zone ranged from 24 km-84 km, with a mean value of 44 km and a median of 38 km. The interpreted position of the start of the transition or end of the continental crust along the 200 km long seismic section ranged from 43 km-110 km with the oceanic crust or end of the transition zone starting between 67 km-172 km.

a.	Group/reference	COB (distance in km)	Method
Group COB Interpretations	JM	75	Re
	JS	86	Re
	KQ	86	Re
	KR	127	Re
	KN	142	Re
Literature COB Interpretations	9	11	G
	10	28	G
	2	59	G
	1	70	U
	5	82	G
	6	103	Ra
	7	123	Ra
	4	127	G,M,Re
	3	135	U

b.	Group/reference	COT (distance in km)			Method
		length	start	end	
Group COT Interpretations	KL	24	43	67	Re
	KJ	84	51	135	Re
	JJ	53	74	127	Re
	JP	65	76	141	Re
	JT	38	76	114	Re
	JN	47	80	127	Re
	JK	58	83	141	Re
	KM	38	85	123	Re
	KK	30	87	117	Re
	JR	14	109	123	Re
	JQ	62	110	172	Re
Literature COT Interpretations	8	76	62	138	G, Re

Table 2. The interpreted positions of the COB and COT zone along the seismic section. a) Interpreted positions of the COB from groups in this study and from the literature measured along the seismic section. b) The interpreted length and start and end points of the COT zone from groups in this study and the literature, along the seismic section. The distances refer to the position with respect to the beginning (i.e. NW, left handside of the seismic image) of the Ion IndiaSPAN 1000 seismic line. See Figure 1 for literature reference numbers. The "Method" column indicates the method used to estimate the COB or COT in the literature interpretations, as reported in Eagles et al (2015): G – gravity data; M – magnetic data; Ra – refraction seismic data; Re – reflection seismic data; U – unknown source.

For each groups' interpretation three elements were manually digitised: the Moho, Top Basement and any interpreted Faults. The digitisation provided a suite of interpretations that are easily compared in standard software graphics packages. We used the software Corel Draw (www.coreldraw.com) to stack the interpretations (Figure 3b) for comparison. This initial stacking allowed a precis of the range in the 17 different group interpretations, including assessment of evidence for differences in interpretation of these three specific elements. We were particularly interested in differences in interpretations between the two categorisations (COB and COT) of interpretations (Figure 3a and c); and how interpretation inference, and annotations, of the crustal processes are reflected in the interpretation of these elements. We also generated heat maps of interpretation intensity (Figure **4**), using the software Image J (Schneider et al. 2012). In these maps, areas with great number of overlapping interpretations (or greater interpretation intensity) are highlighted over a white background of no interpretations. This way we can use these heat maps to identify areas where participants interpreted the same (i.e. high intensity) or different (low intensity) features. Using these two methods, we consider each of the interpreted elements in turn.

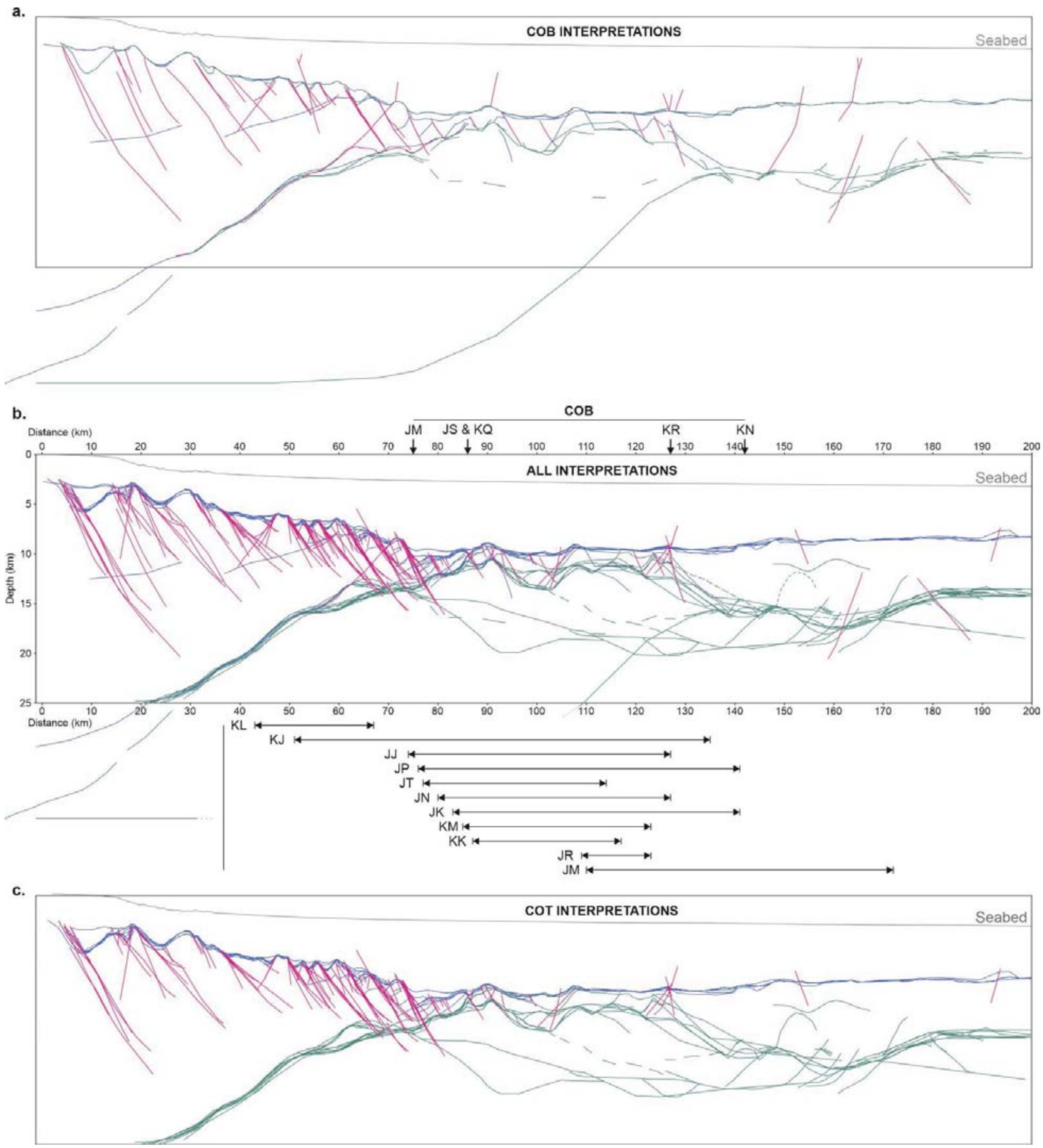

Figure 3. Digitised and stacked group interpretations. a) The five COB interpretations stacked. b) All 17 group interpretations stacked. The position of the COB as identified by the five groups is annotated above the stacked interpretations, and the extent of the COT zone for the 11 COT group interpretations is shown below the stacked interpretations. c) The 11 COT interpretations stacked. In each subfigure the Moho is green, Top Basement is blue and Faults are magenta.

The Moho

Interpretation of the Moho (green lines in Figure 3, and as a heat map Figure 4a and 4b), shows consistency in interpretation in all groups, bar two, under the continental crust at the start of the section. The two groups with differing interpretations are both abrupt COB interpretations, one shows the Moho starting to deepen from c.140 km toward the continental crust end of the section, the other shows the Moho deeper than other interpretations at the continental end of the section (0 km). There is also relatively good correlation of Moho interpretations under the oceanic crust at the far end of the section. These areas are less equivocal than the central part of the section where the continental crust 'joins' the oceanic crust. None of the COB interpretations show the Moho reaching the Top Basement, indicating that mantle has not been fully exhumed and therefore do not support a fully hyper-extended rifting model that brings mantle to the surface. In contrast, several of the diffuse COT interpretations show this to be the case with mantle being exhumed to the surface covered only by syn- and post-rift basin fill. In all the interpretations the Moho is relatively shallow, resulting in a significantly thinned crust even where mantle is not exhumed.

Top Basement

Variation in the interpretation of Top Basement is limited (Figure **4c** and **4d**), although two interpretations have a much deeper Top Basement than the others. These two groups (JM and KN) are both abrupt COB interpretations (Figure 4c) and also interpreted a deeper Moho than other groups (Figure 4a). Bar these two groups, most of the group interpretations conform with minor discrepancies in areas where basement faulting has or has not been interpreted. This is particularly evident between 60 and 90 km on the seismic line. This is around the point where interpretations mark the start of a transition zone or the edge of continental crust (Figure 3b).

Faults

Fault interpretations were mainly concentrated in the continental crust (Figure **3**). The majority of the interpreted faults dip basin-wards accommodating extension during rifting. Fault interpretation in the central and farthest (i.e. ocean-ward) part of the section is varied, with examples of faults dipping both towards and away from the continental margin. Where the crust is interpreted by all group to be its thinnest faulting is not ubiquitous or dominant and the mechanism for crustal thinning in this zone is therefore unclear. The lack of fault interpretations in this zone maybe because the resolution and clarity of imaging in this part of the seismic is not as clear as elsewhere (see Figure 1e), and/or due to the short extent of any possible faults so that the groups did not bother to interpret them. Fault dip measurements of 143 interpreted faults (including antithetic faults) in the continental crust ranged from 15-90^{o} with a mean fault dip of 38^{o}, lying within the expected value range for normal fault dips accommodating rifting. There is no change in the fault dip of those faults that were interpreted where the crust is at its thinnest and where the abrupt COB and diffuse COT zone interpretations fall.

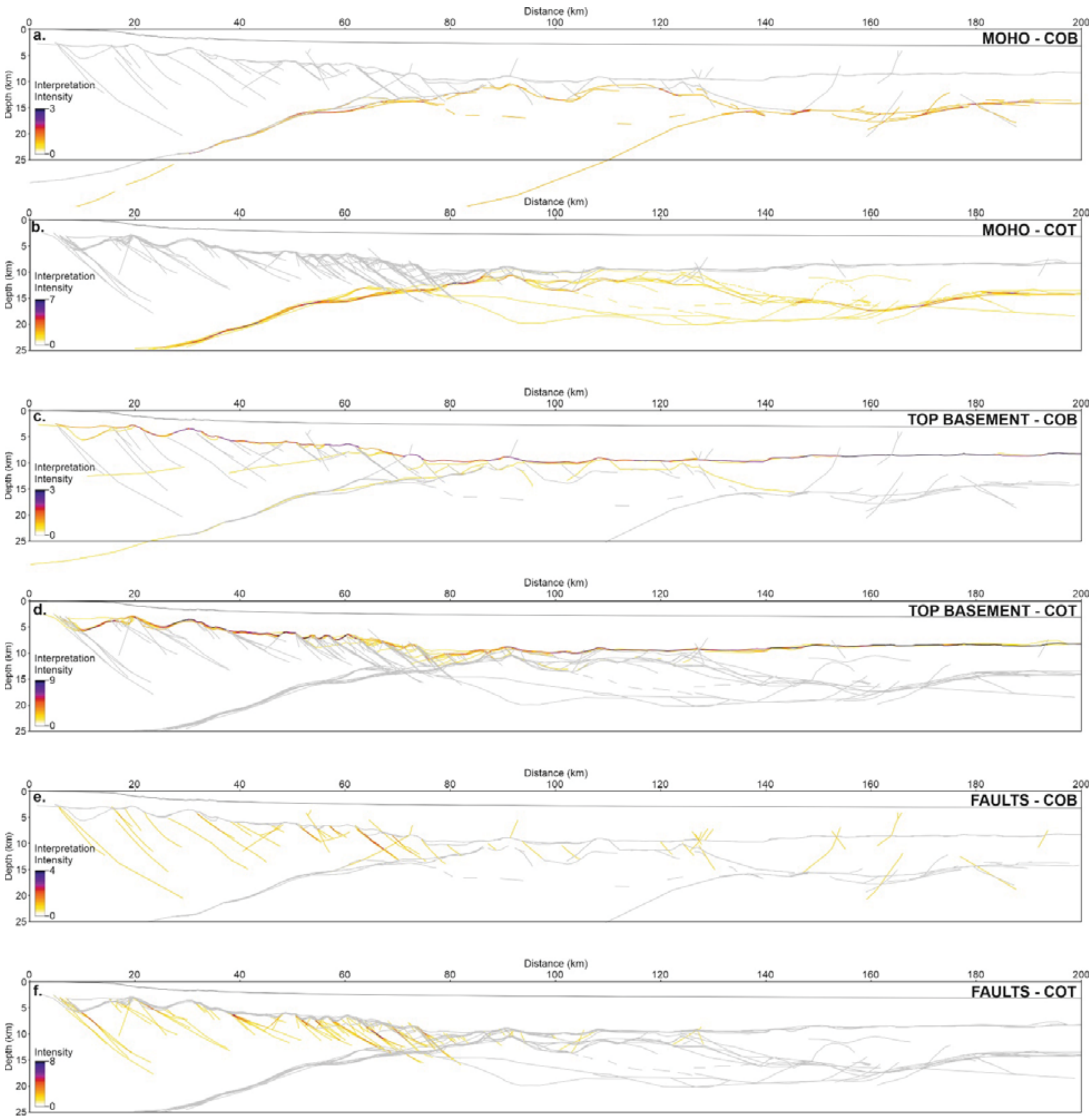

Figure 4. Heat maps of the three elements (Moho, Top Basement and Faults) that the groups were requested to interpret, split by abrupt COB and diffuse COT model types. Moho heat maps of the COB (a) and COT (b) interpretations. Top Basement heat maps of the COB (c) and COT (d) interpretations. Fault heat maps of the COB (e) and COT (f) interpretations. In all images, the heat map intensity colour bar is scaled to the maximum number of overlapping interpretations in

the set for the element of interest. In each instance the other elements interpreted as well as the seabed are shown in pale grey.

6 Crustal tinning calculations

For all fourteen interpretations with Top Basement and Moho interpreted, a crustal thickness value was calculated. This calculation was completed in Move software by unfolding the Moho to a horizontal template line using a vertical simple shear algorithm and passively unfolding Top Basement to create a thickness profile. The combined thickness profiles for the 14 interpretations are shown in Figure 5, split by COB and COT margin types. The interpreted crustal thickness ranges from 30 km at the continental end of the section to zero in the COB/COT zone, with a range of oceanic crust thickness of 5.5–10.5 km, and an average of 6 km. The five COB interpretations range from 30 km (continental crust) through a minimum crustal thickness of 0 km and have an average oceanic crustal thickness of 5.7 km; whilst the nine COT interpretations range from a maximum 22 km thickness for the continental crust (note that there are few full interpretations at the left hand-end, continental crust, of the section) through a minimum continental crustal thickness of 16.3 km and an average oceanic crustal thickness of 6.9 km.

Apart from at the left-hand end of the section, where only one interpretation of each margin type are available, the abrupt COB and diffuse COT interpretations give very similar average crustal thickness. These averages always lie within the range of both the COB and the COT based interpretations (blue and red envelopes, respectively, Figure 5). The interpreted continental crustal thickness decreases rapidly, from an interpreted maximum of c. 30 km to less than 5 km over 70 kms, through a combination of fault-based rifting and crustal thinning. The range in the crustal thicknesses calculated from the interpretations gives an indication of the uncertainty in the groups' interpretations for the Top Basement and Moho. Diffuse COT interpretations show a greater range in interpretations of thickness for the oceanic crust than the abrupt COB interpretations, presumably resulting from differences in interpretations of the extent of the transition zone and the associated underpinning processes. In the area defined by the range in COB interpretation points (c.75-140 km) and the average COT transition (c.80-130 km) (Figure 6), the envelopes of both the abrupt COB and diffuse COT crustal thickness interpretations show a spread indicative of uncertainty in crustal thickness of up to 10 km.

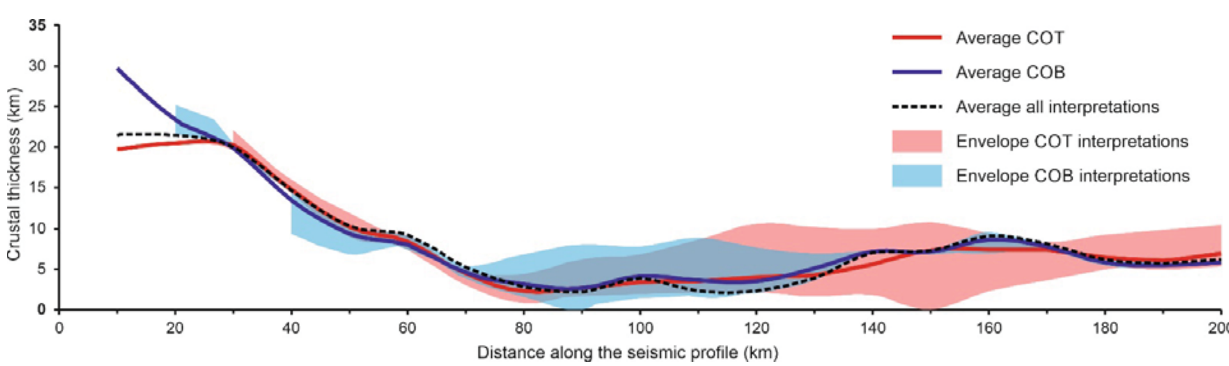

Figure 5. Average crustal thickness interpreted across the section showing the average for all interpretations (dashed line), the average for the diffuse COT (red line) and abrupt COB interpretations (blue line) separately, and the envelopes of the range in thickness interpreted. Crustal thicknesses were calculated every 10 km along the seismic section for each interpretation.

7 The crowd-sourced interpretations

An overall *'average'* interpretation was created from all 17 interpretations, as well as *averages* for the abrupt COB and diffuse COT interpretations separately (Figure 6). These averaged interpretations were created by picking the highest intensity trace of each of the three elements (Moho, Top Basement and faults) from the heat maps (Figure 5). Thus, they are not averages in the true sense of the word, but frequency derived, and hence modes or modal interpretations. Modal interpretations can only be created if two or more interpretations overlap. Modal interpretations of the Moho and Top Basement across the seismic image were created without issue, but the number of faults and their placement on the section line by each group varied. In total, 143 faults were interpreted across the seismic section by all groups, many of which were only interpreted by one group; the resulting fault modal model only contains those interpreted by two or more groups.

The modal interpretations result in a model where the crust in the central section of the interpretation is significantly thinned. This corresponds with the average extent of the transition zone across all of the COT interpretations, extending from 80-125 km along the section (Figure 6b). In this zone, the average crustal thickness is fairly constant, with a range of 2.2 – 3.8 km and an average of 2.7 km. The middle point of this transition zone falls approximately at the point of the average placement of the continent ocean boundary in the abrupt COB models (Figure 6a), the middle of the seismic profile. The geometries of the Moho and Top Basement are generally similar, including the broadly stepped profile observed in the Moho. The major difference is observed at the start of the thickening of the oceanic crust, which is gentler in the modal COB model and steeper in the modal COT model and coincident with the end of the transition zone. The modal COT interpretation has a greater number of faults interpreted than the modal COB interpretation. This is probably partly due to the greater number of diffuse COT than abrupt COB interpretations in the dataset.

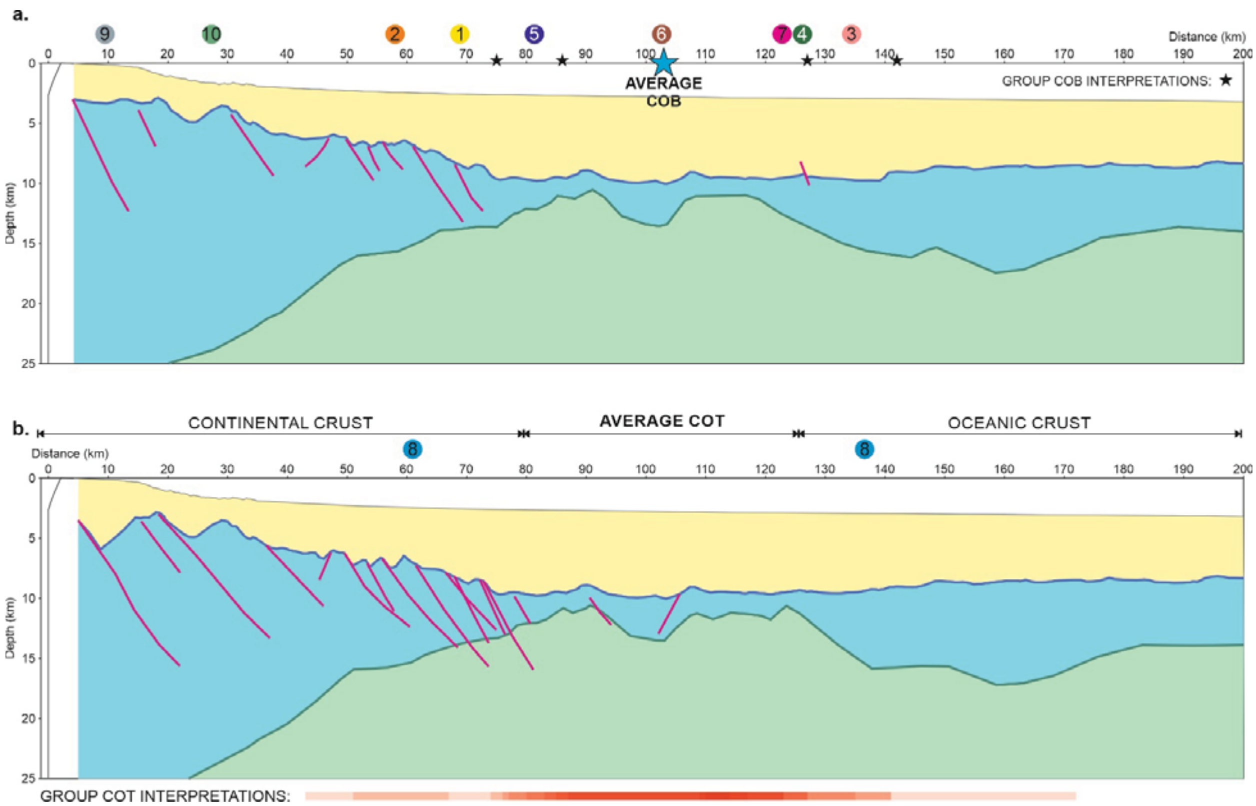

Figure 6. Modal interpretations calculated from all groups for abrupt COB and diffuse COT models, including the sedimentary units (yellow), the basement (blue) and the upper mantle (green). a) Modal interpretation calculated from the five COB model interpretations. The position of the average COB is shown with a blue star, individual COB position interpretations are marked with smaller black stars (see also Figure 3b). b) Modal interpretation calculated from the eleven COT model interpretations (calculated as the average start and average end of the COT interpretations). The extent and position of group interpretations of the COT zone are represented below the section as an intensity colour bar, the higher the colour intensity (red) the more groups interpreted a transition zone in that portion of the seismic section (see Figure 3b for individual group transition zone extents). Interpretation colours follow previous figures: Moho – green, Top Basement – blue, Faults - magenta. The coloured numbers represent the placement of COB and COT interpretations across the East Indian Margin from the published studies outlined in Eagles et al. (2015) and summarised in Figure 1.

We also compare the group interpretations elicited in this study with those previously published for the margin, as summarised in Figure 1. Figure 7 shows this comparison in a schematic map view. Eight of the published interpretations lie within the range of the 17 group interpretations elicited for this study. They also span (symmetrically) the average COB and COT range (calculated as the average start and average end of the COT interpretations) and, if included in our analysis, they would not significantly modify these averages. Two of the published interpretations, those reported in Gibbons et al. (2013) and Seton et al. (2012), are located closer to the coast of India, outside the range of COT interpretations (interpretations 9 and 10 in Figure 7).

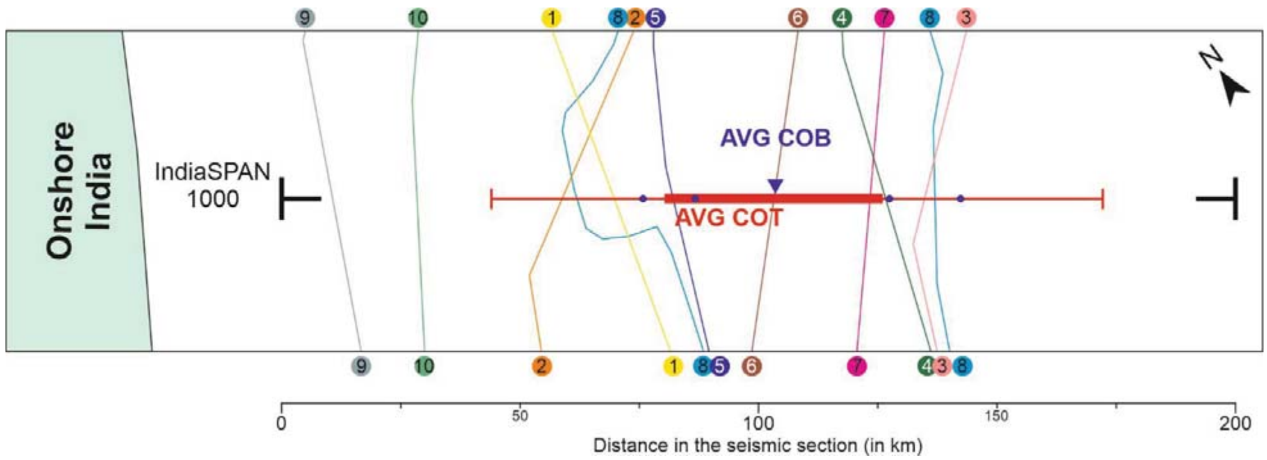

Figure 7. Schematic map view of the placement of abrupt COB and diffuse COT interpretations across the East Indian Margin from the published studies outlined in Eagles et al. (2015) and summarised in Figure 1. Numbers refer to the different publications (see Figure 1 caption). Analysis of the 17 group interpretations elicited in this study are represented by an average COB mark (blue triangle), the positions of the COB interpretations (blue circles), the average COT range (calculated as the average start and average end of the COT interpretations, thick red line) and the range of COT interpretations (red whiskers).

8 Discussion and conclusions

From our analysis, the areas of greatest interpretation diversity (which we equate with the areas of greatest uncertainty in interpretation) are located in the middle of the seismic section, where the continent-ocean boundary or transition takes place. Here the interpretation focus is on the placement of the Moho and Top Basement and their relationship to each other. This is emphasised by the range across all groups in thickness interpretations of the crust through this central part of the seismic section. This zone of greatest uncertainty lies within the average COT zone of the interpretations and the range of COBs identified. This uncertainty is also emphasised by the other interpreted elements that lie within this zone including exhumed mantle and serpentinised crust. Here we discuss what this means for the different model concepts and a Wisdom of Crowds type approach to interpretation of Continent-Ocean margins.

The features that we requested the groups to interpret (Top Basement, Moho, Faults) are relatively consistent in their placement irrespective of the underlying conceptual abrupt COB or diffuse COT model evoked in the interpretation. A similar range of crustal thicknesses and the average COB boundary falling in the centre of the average COT transition zone interpreted implies a unity in observation and interpretation of key elements. Two interpretations stand out from the others; the first, in which interpretation of the Moho is deeper beneath the continent than in the other interpretations; and the second, in which the crust does not have a significant extent of thinned section and the change from apparent continental crust to oceanic crust is relatively abrupt. However, these two groups did interpret the COB within the range of other interpretations. In summary, differences in interpretations appear to be the result of other factors and are not related to the abrupt COB or diffuse COT margin model implied.

Although the interpretations of the two model concepts, COB and COT, differ in how they deal with the uncertainty in interpreting the margin area, what is striking about the comparative analysis of multiple interpretations of this single dataset are the similarities. If we consider the two modal interpretations in Figure 6, the similarities between them are most apparent, with little divergence in the interpretation of the Moho and Top Basement. Yet, the placement of the COB and the demarcation of the COT zone are quite distinct. The COB interpretations span a range from 75 km to just over 140 km along the seismic section, and the average COT zone ranges from 80 km to just under 130 km. If we consider the COT zone interpretations in more detail (Figure 3c), the 11 interpretations appear to fall into three sets: (a) those that have the COT zone starting at a point (40-50 km along the section), where the continental crust can be considered as definitely thinned (average thickness of 10-15 km). (b) Those that interpret the start of the COT zone where the crust is significantly thinned to 2-3 km thick, between 75 - 85 km. And (c) those that start the transition between 108-110 km in the middle of the significantly thinned section of crust. Of these transition zone starting points, only the second group (i.e. starting between 75 and 85 km) coincide with three of the interpreted continent-ocean boundary points (Figure 3a). This area is located at the approximate end of the deepening of the basement and encompass the greatest number of interpretations (three COB and seven COT interpretations). Krishna et al. (2009) also identified the COB in this area, based on gravity data (Figure 6a).

The extent or end point of the interpreted COT zones also differ, but are mostly concentrated between 110 and 145 km (nine COT and the remaining two COB interpretations) (Figure 3b). This zone (110-145 km) also include three of the published abrupt COB interpretations (i.e. Powell et al., 1988, Rao et al., 1997, Sinha et al., 2010) as well as the end point of the diffuse COT interpretation by Nemčok et al. (2013). Despite the broad coincidence in starting and ending positions of abrupt COB and diffuse COT interpretations, the variability is too high to tie these interpretations to single identifiable geological features in the Moho or the Top Basement. This interpretational variability is also evident in published interpretations of COB and COT for the East India passive margin (Table 2). These published interpretations use a range of data (gravity, magnetic, refraction and reflection seismic data) to support the interpretation of COB and COT locations and are thus not due to the methods used to identify the different components of the passive margin. What becomes apparent is that not only are we uncertain about the underpinning processes of continent-ocean margin rifting and development, but in how we define COB and COT zones and their location.

As purported by Eagles et al. (2015), the terms and the ‘competing’ conceptual models are perhaps not useful given the uncertainty in what is happening in these zones to the crust and therefore in how we define and interpret these binary model concepts. From our analysis of interpretations of a single 2D seismic section through the East Indian Margin, we can infer that abrupt COB and diffuse COT models are not single deterministic model concepts, but that a range of possible models exists within them. In our opinion, the terms are useful in describing end-member concepts, but not in applying them in a binary nature. To understand tectonics requires consideration of the uncertainty or range of possible interpretations of images and data types, and the reduction of the debate to binary choices is unhelpful.

The paper is framed around the potential of using a combined Wisdom of Crowds and expert elicitation approach to determine an optimal interpretation, or interpretations for the two (COB and COT) model concepts. The conventional Wisdom of Crowds approach (Surowiecky, 2005) was not perfectly applicable here because of the nature of the research question; the data that can be interpreted using different model concepts and therefore there is not a single deterministic solution, or answer, to the question posed. We also employed groups of experts to complete the interpretations rather than individuals, so in fact the experiment results feature a double crowd-sourcing: from individuals to their groups, and from groups to the abrupt COB and diffuse COT modal interpretations. However, we believe that the range in interpretations is representative of the community as supported by comparison of our data with existing published interpretations through the margin (Figure 7). Eight of the ten published interpretations are located within the interpretation range resulting from our experiment, and, perhaps anecdotally, the published COB interpretation by Veevers et al (line 6 in Figure 7) lies almost at the exact position of the average location of the COB groups (blue star in Figure 7). The average COT zone gives a good representation of the likely range in continent-ocean crust change, and the average COB interpretation falling in the middle of this range supports that the resulting average models are, at the very least, geologically plausible. However, in our opinion our results do not imply a greater probability of actually being in the middle of this range, or that the COB/COT locations follow a symmetrical bell-shaped probability distribution. As is the case with many expert elicitation exercises of this sort (see for example Polson and Curtis, 2010), the value of the exercise is more in understanding expert interpretation processes the and range of opinion and possible interpretations, rather than producing any aggregated solution.

In summary, the interpretations highlight to us the uncertainties in using seismic image data to determine processes operating at continent-ocean margins, that multiple interpretations can be used to determine the extent of the possible continent-ocean crust change, and that the current 'competing' model concepts of an abrupt COB or diffuse COT are helpful in thinking about processes of continental rifting but that constraining interpretation of continental margins into binary choices is not useful. Our experiment highlights the range of possible interpretations within each concept and the range of interpretations and potential continental rifting processes.

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Open Research

The IndiaSPAN-1000 2D regional seismic line used in this experiment is not available, but images of the line (with different display characteristics) have been published in the following articles:

Haupert, I., Manatschal, G., Decarlis, A. and Unternehr, P., 2016. Upper-plate magma-poor rifted margins: Stratigraphic architecture and structural evolution. Marine and Petroleum Geology, 69, pp. 241-261. url: https://www.sciencedirect.com/science/article/abs/pii/S0264817215301215 (last accessed: 03/10/2022).

Mangipudi, V.R., Goli, A., Desa, M., Tammisetti, R. and Dewangan, P., 2014. Synthesis of deep multichannel seismic and high resolution sparker data: Implications for the geological environment of the Krishna–Godavari offshore, Eastern Continental Margin of India. Marine and petroleum geology, 58, pp. 339-355. url: https://www.sciencedirect.com/science/article/abs/pii/S0264817214002621 (last accessed: 03/10/2022).

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Figure 1.

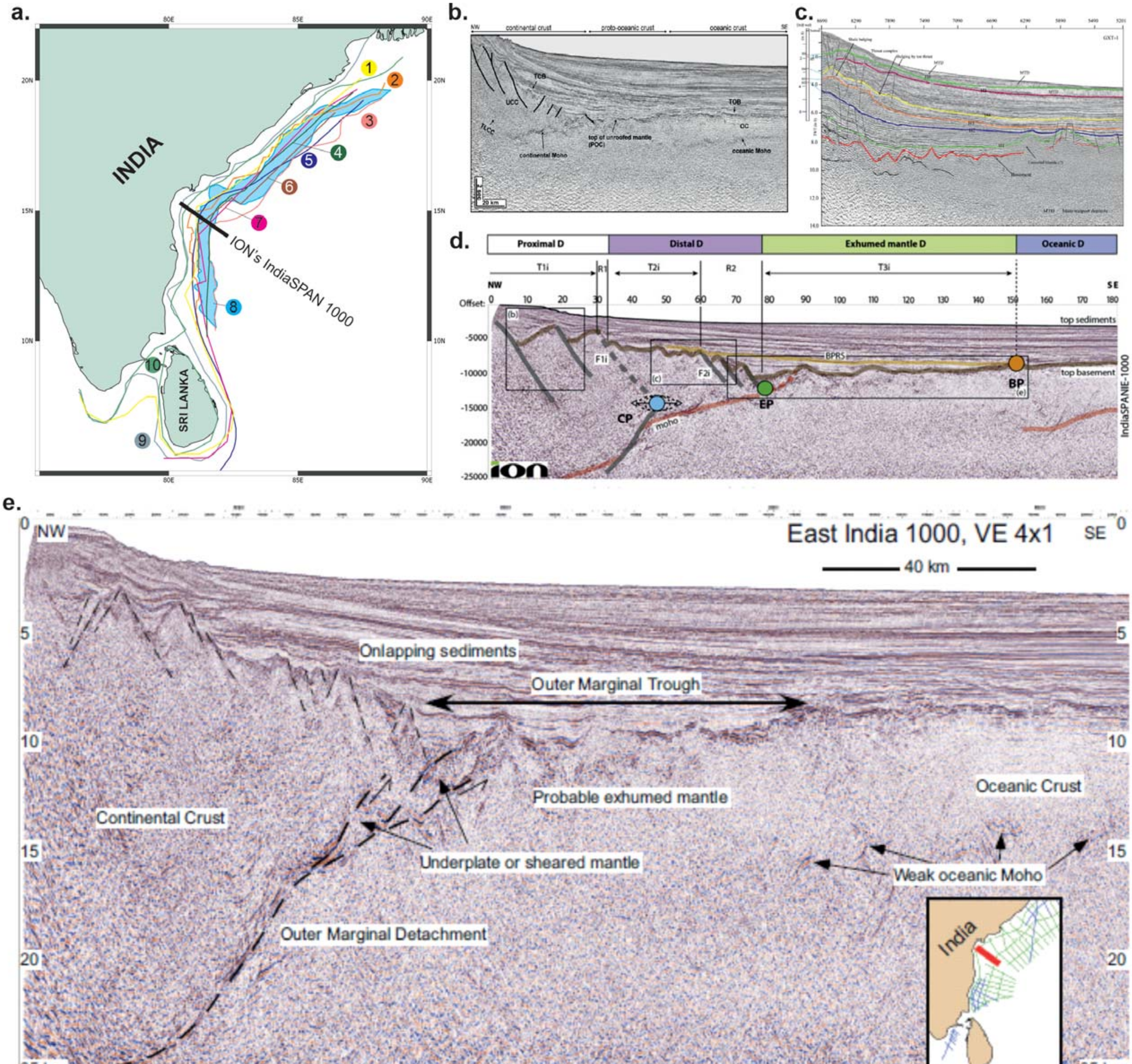
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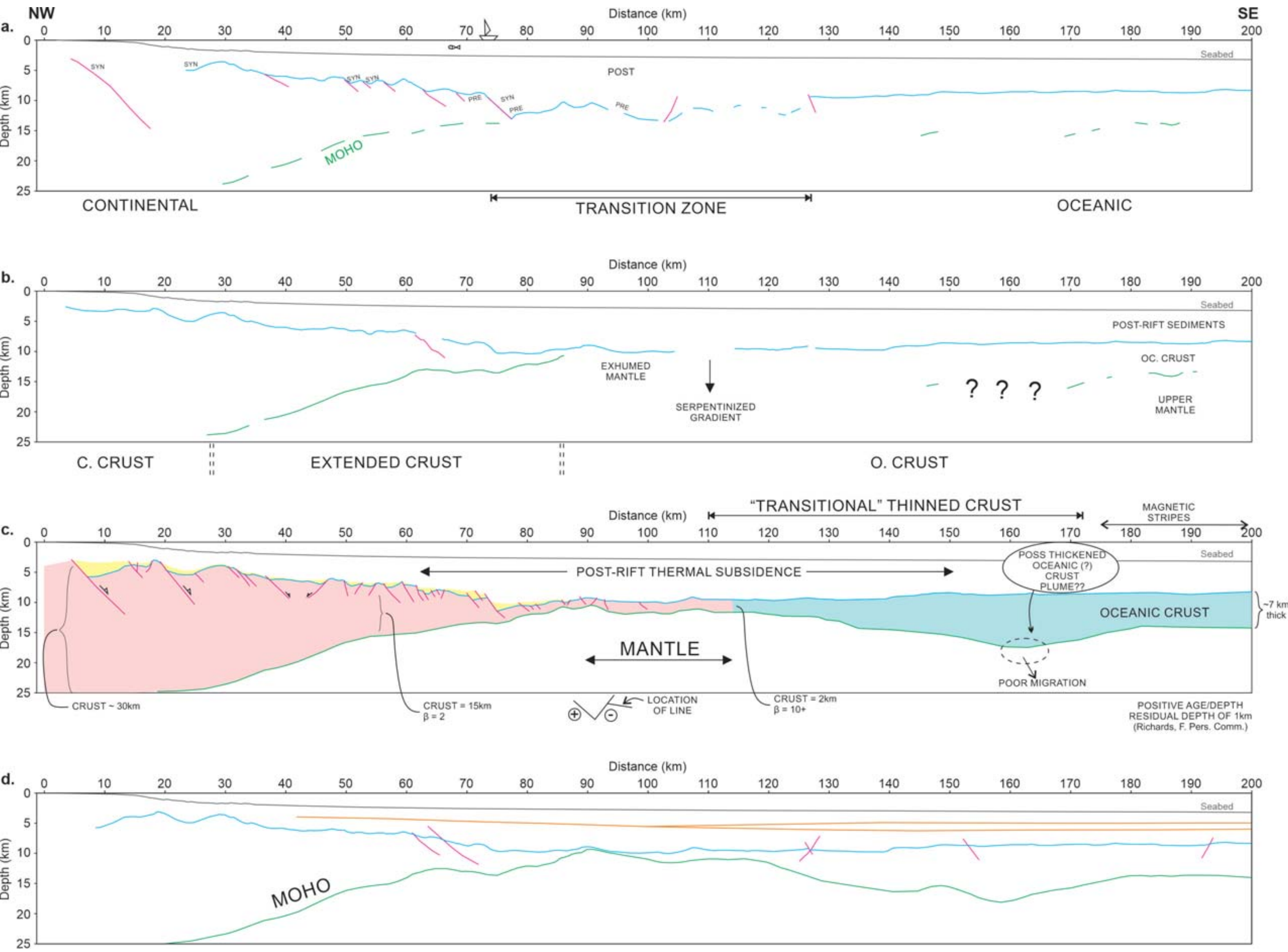
Figure 2.



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CONTINENTAL
TRANSITION ZONE
OCEANIC
b.
Distance (km)
Depth (km)
Seabed
POST-RIFT SEDIMENTS
EXHUMED MANTLE
OC. CRUST
SERPENTINIZED GRADIENT
? ? ?
UPPER MANTLE
C. CRUST
EXTENDED CRUST
O. CRUST
c.
Distance (km)
"TRANSITIONAL" THINNED CRUST
MAGNETIC STRIPES
Seabed
POST-RIFT THERMAL SUBSIDENCE
POSS THICKENED OCEANIC (?) CRUST PLUME??
OCEANIC CRUST
~7 km thick
MANTLE
POOR MIGRATION
CRUST ~ 30km
CRUST = 15km
β = 2
LOCATION OF LINE
CRUST = 2km
β = 10+
POSITIVE AGE/DEPTH RESIDUAL DEPTH OF 1km (Richards, F. Pers. Comm.)
d.
Distance (km)
Depth (km)
Seabed
MOHO

Figure 3.

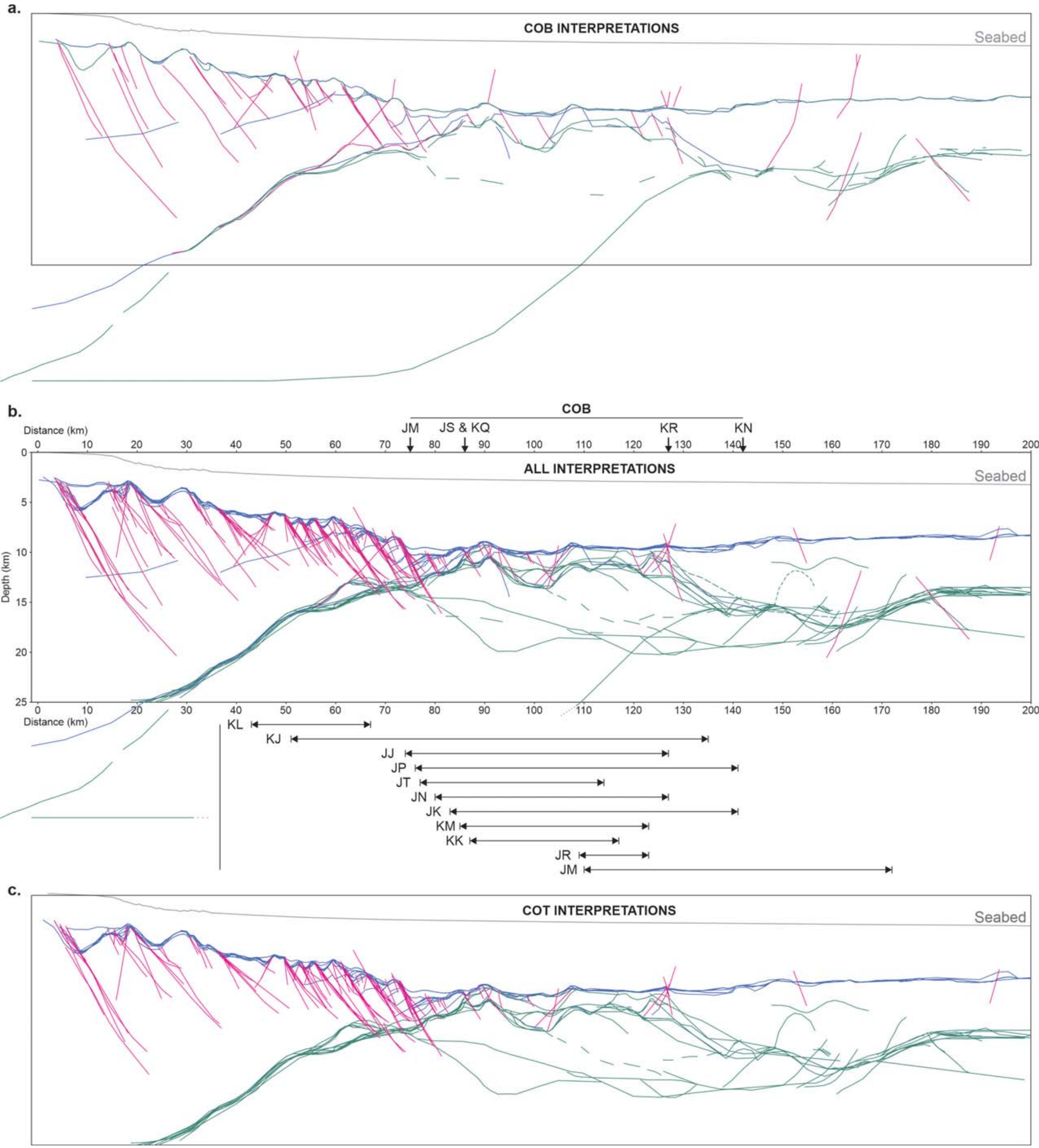
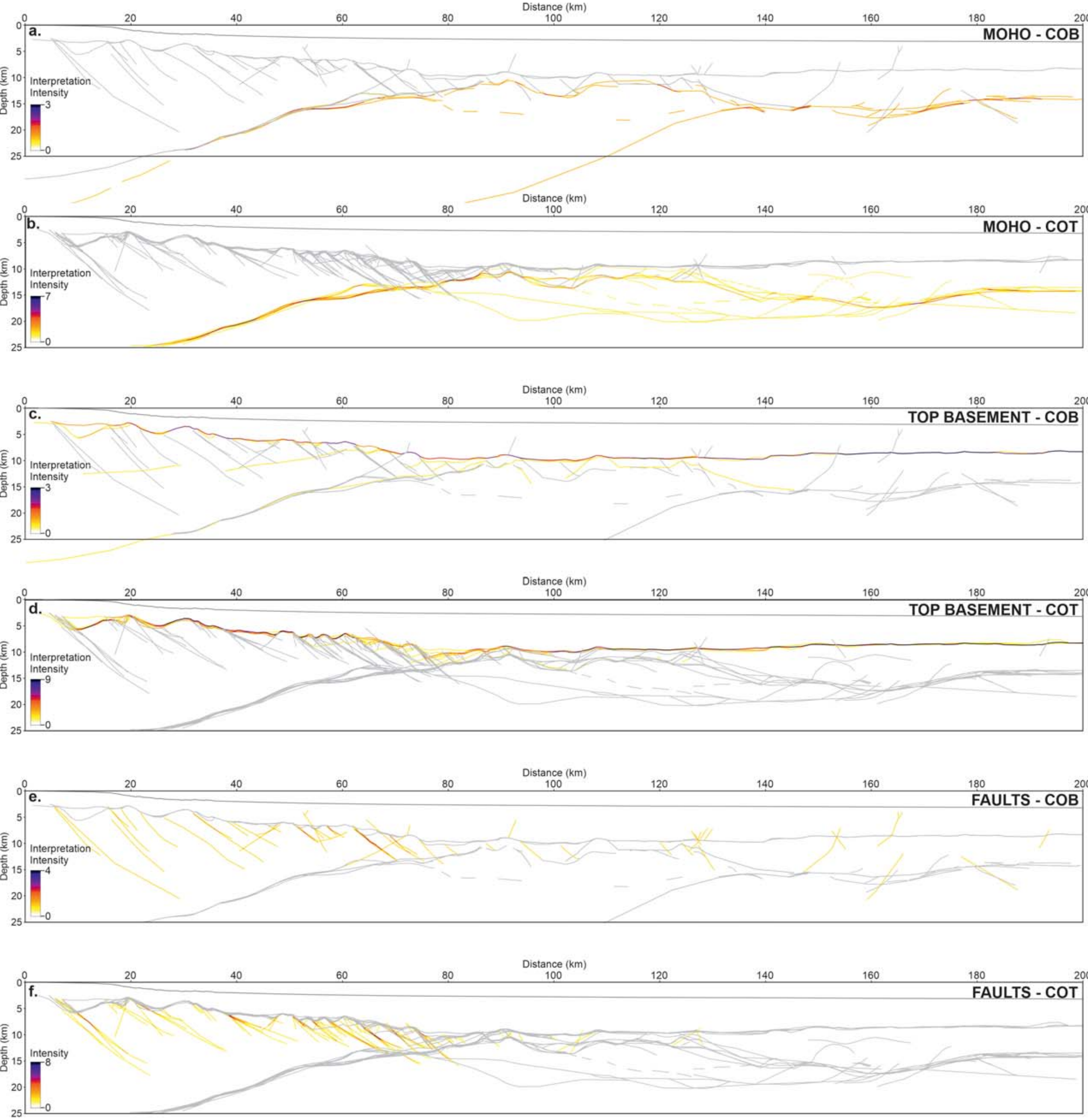
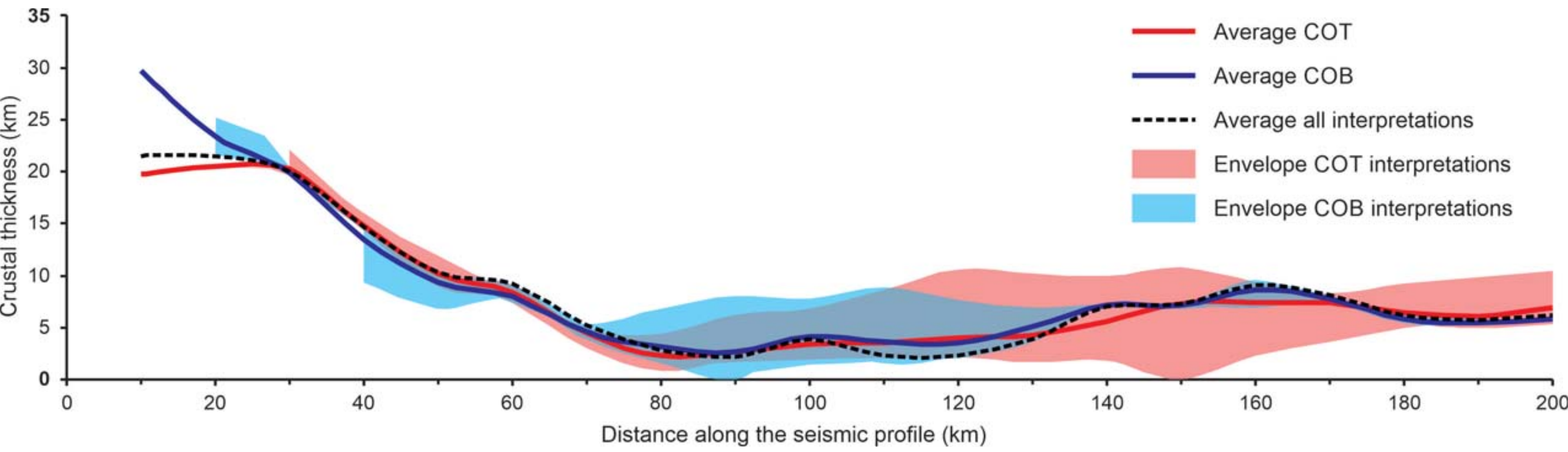

a.
COB INTERPRETATIONS
Seabed
b.
COB
Distance (km)
JM
JS & KQ
KR
KN
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180 190 200
ALL INTERPRETATIONS
Seabed
Depth (km)
0 5 10 15 20 25
Distance (km)
KL
KJ
JJ
JP
JT
JN
JK
KM
KK
JR
JM
c.
COT INTERPRETATIONS
Seabed

Figure 4.



Distance (km)
Depth (km)
a.
MOHO - COB
b.
MOHO - COT
c.
TOP BASEMENT - COB
d.
TOP BASEMENT - COT
e.
FAULTS - COB
f.
FAULTS - COT
Interpretation Intensity
Intensity

Figure 5.



Average COT
Average COB
Average all interpretations
Envelope COT interpretations
Envelope COB interpretations
Crustal thickness (km)
Distance along the seismic profile (km)
35
30
25
20
15
10
5
0
0
20
40
60
80
100
120
140
160
180
200

Figure 6.

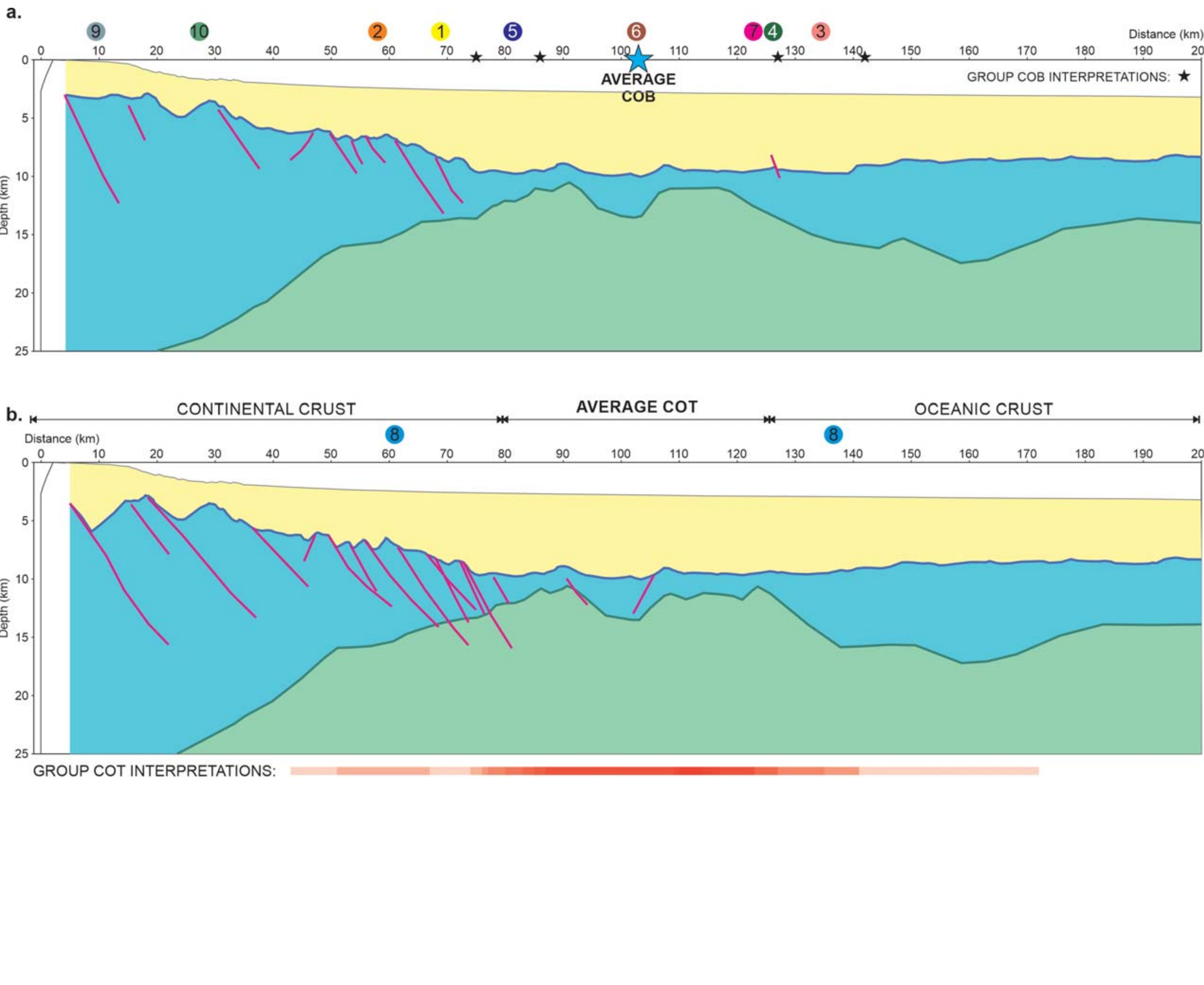
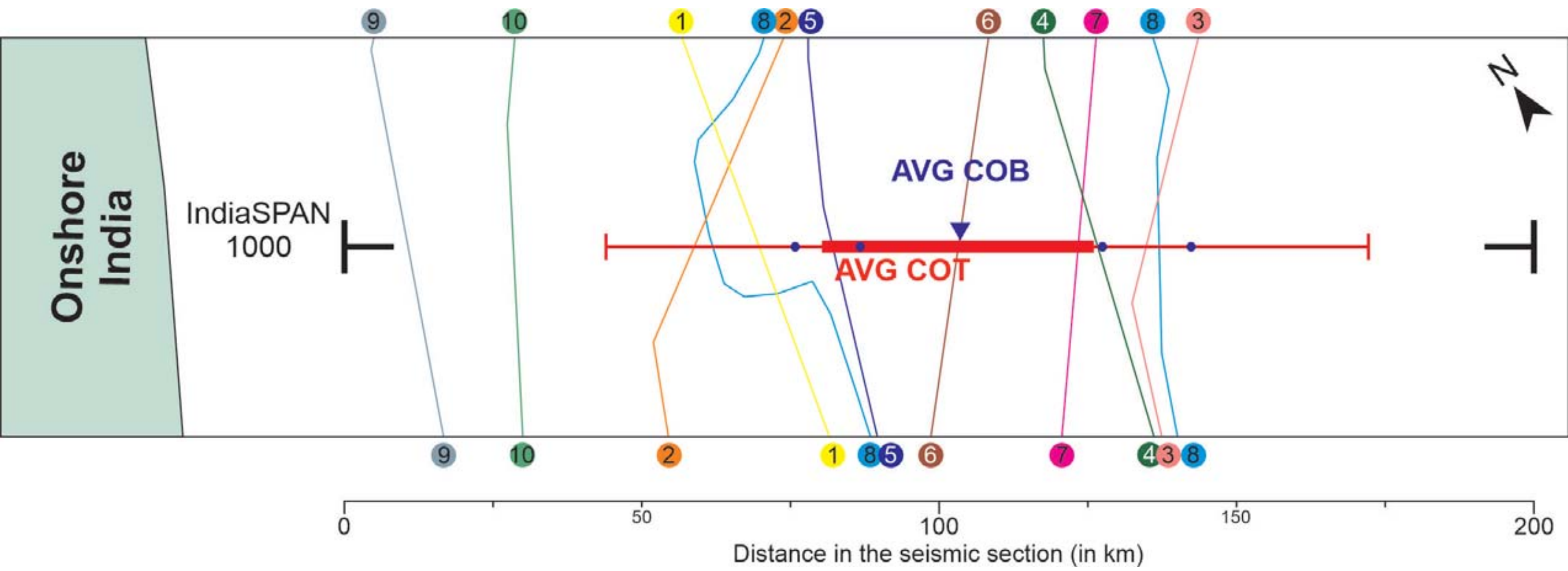

a.
9
10
2
1
5
6
7
4
3
Distance (km)
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200
AVERAGE COB
GROUP COB INTERPRETATIONS: ★
Depth (km)
5
10
15
20
25
b.
CONTINENTAL CRUST
AVERAGE COT
OCEANIC CRUST
8
8
GROUP COT INTERPRETATIONS:

Figure 7.


Onshore India
IndiaSPAN 1000
AVG COB
AVG COT
N
0
50
100
150
200
Distance in the seismic section (in km)