PETROLEUM PROSPECTIVITY IN VOLCANIC BASINS: AN OVERVIEW ON UNDERSTANDING VOLCANIC FACIES RELATIONSHIPS AND ROCK PROPERTIES IN VOLCANIC MARGINS

Dougal A. Jerram[*1,2], John Millett[3,4], Sverre Planke[3,1]

1: CEED, University of Oslo. Norway: dougal@dougalearth.com; planke@vbpr.no

2: DougalEARTH Ltd., Solihull. UK: dougal@dougalearth.com

3: Volcanic Basin Petroleum Research (VBPR), Oslo. Norway: john.millett@vbpr.no; planke@vbpr.no

4: Department of Geology and Geophysics, University of Aberdeen. UK: john.millett@vbpr.no

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RESUMEN

Las rocas volcánicas intrusivas y extrusivas se presentan en una variedad de facies que reflejan su composición, modo de emplazamiento e interacción con su entorno. Las unidades volcánicas resultantes, a su vez, comprenden propiedades altamente variables, que determinan las características potenciales del yacimiento y la influencia de éstas rocas desde una perspectiva petrolera. Cuando examinamos el subsuelo, vemos una expresión de estas propiedades físicas asociadas en lugar de las facies en sí, y donde existen facies volcánicas, a menudo podemos enfrentarnos a una serie de problemas al interpretar lo que vemos, o en algunos casos no ver nada. En este sentido, podemos hacernos la pregunta: ¿cuáles son las facies volcánicas clave, cuáles son sus propiedades físicas y cómo se distribuyen espacialmente estas propiedades? Los buenos análogos de afloramiento proporcionan un método integral para investigar estas propiedades y heterogeneidades de las rocas de una manera que nos ayude a informarnos sobre su probable comportamiento en el subsuelo. Utilizamos un enfoque integrado para registrar los tipos de facies volcánicas y las variaciones dentro de las facies que se observan en afloramientos 3D, testigos coronas, registros de imágenes de pozos, registros con cable, *cutting* y datos geofísicos remotos de alta resolución. Este enfoque integrado nos permite comprender mejor sus impactos en el sistema petrolero y ayudar a evaluar la prospectividad del petróleo dentro de las cuencas volcánicas.

INTRODUCTION

Intrusive and extrusive volcanic rocks occur in a variety of facies that reflect their composition, mode of emplacement, and interaction with their environment. The resulting volcanic units, in turn, have highly variable properties, which determine their potential characteristics in the subsurface as potential reservoirs or seals, and their influence on petroleum systems like maturation

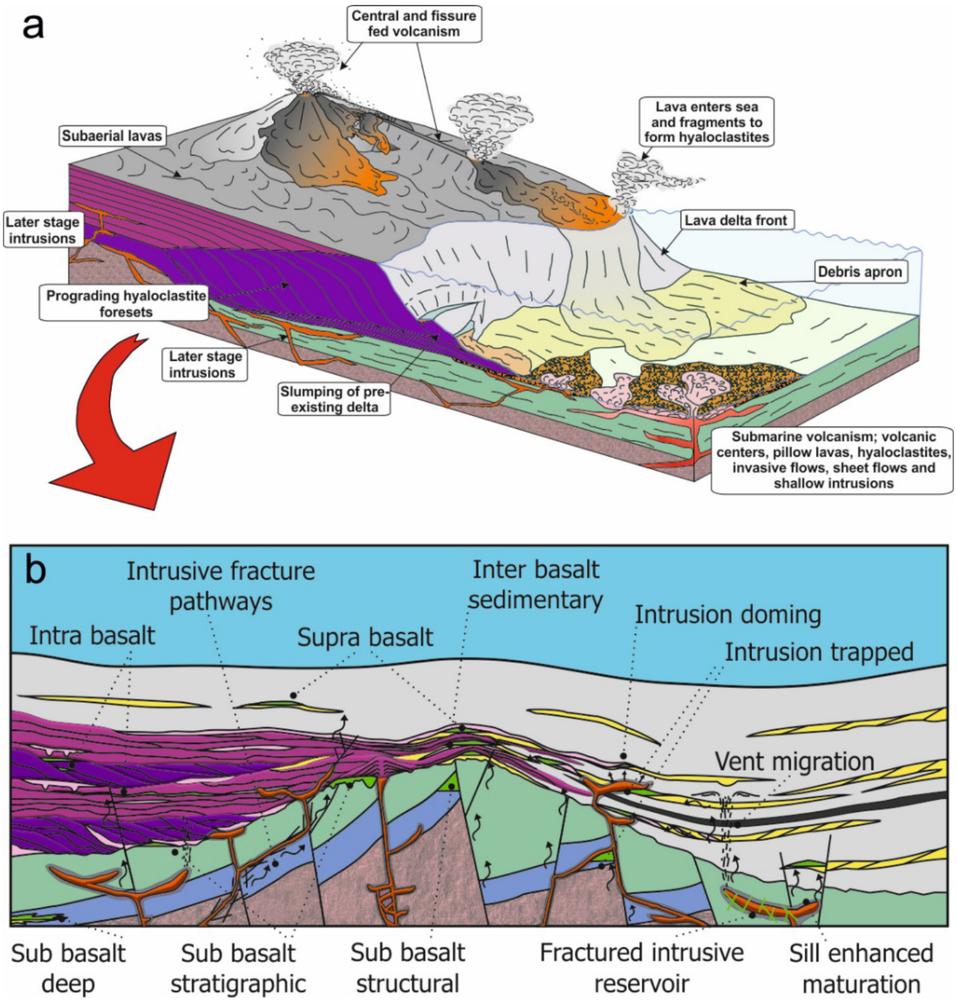

Figure 1. Models of the types and distribution of volcanic facies in a typical volcanic rifted margin. A) A schematic snapshot of the different volcanic and intrusive elements at play during the evolution of a volcanic margin. B) A model of the volcanic facies distribution seen in a classic volcanic margin profile. (Adapted from; Jerram 2015; Abdelmalak *et al.* 2016: Senger *et al.* 2017).

and fluid migration. In order to address the nature of volcanic rocks in volcanic rifted margins and basins influenced by volcanics, we need to define the types and nature of the key volcanic facies and how they are manifest at different scales, how they affect rock properties and how they are spatially distributed. We use an integrated approach to record volcanic facies types and variations within facies observed in 3D outcrops, core sections, image logs, electrical logs, cross-sections, and remote high-resolution geophysical data. This ultimately leads to the development of volcanic facies models that can be applied to better understand the subsurface and how to aid the petroleum prospectivity within volcanic basins and margins.

The structure of this short summary contribution is the following:

- First the scales of facies variations seen within volcanic units from outcrops to seismic scale are defined;

- Then the typical facies variations that we see in many volcanic successions are introduced and some details on their rock properties presented;
- Volcanic facies at the seismic scale are outlined using seismic volcanic stratigraphy and seismic geomorphology;
- Finally, we present a conceptual volcanic evolution model for the types and styles of volcanism that develops along a typical volcanic rifted margin.

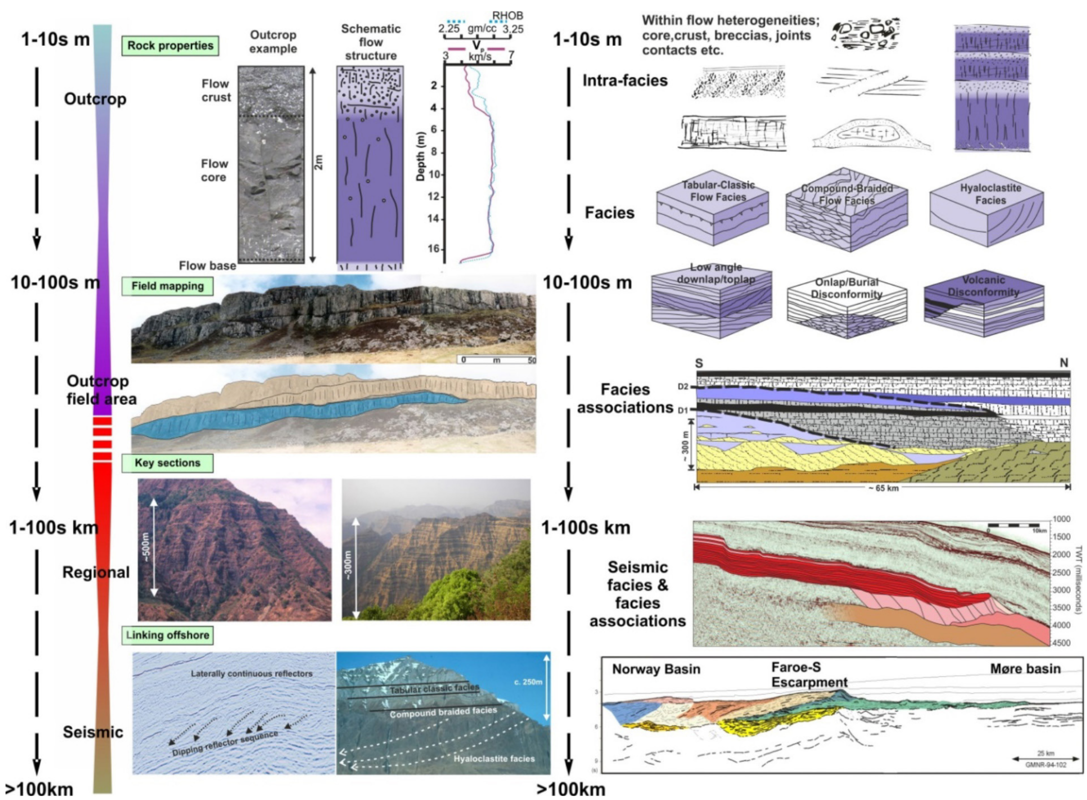

Figure 2. The scales of variation seen with volcanic successions from within volcanic 'intra-facies, through facies types and associations and to seismic scale in volcanic basins and margins (examples adapted from Planke *et al.* 2000; Jerram 2002; Nelson *et al.* 2009; Jerram and Widdowson 2005; Jerram et al 2009; Wright *et al.* 2012, see text for details).

SCALES OF FACIES VARIATIONS AND ASSOCIATIONS

The role of interpreting the subsurface is to realise the best geological models that we can define to best explain the data that we are presented with. With volcanic rifted margins and volcanic basins we are often faced with a variety of volcanic settings, from both sub-aerial to sub-aqueous, as well as the spatial and temporal evolution of the margin (e.g. Planke *et al.* 2000; Jerram 2002; Bischoff *et al.* 2021; Millett *et al.* 2021a; Planke *et al.* 2022). As the margin or basin develops, the volcanic style may change and be modified, the places where sediments and volcanics interact will change, and their influence on the basin and any future petroleum system will vary accordingly.

Therefore a detailed understanding and development of a good working model is a vital first step (Figure1) (Jerram 2015; Abdelmalak *et al.* 2016; Senger *et al.* 2017).

With this in mind, we are often faced with looking at basins and rifted margins where there are a variety of volcanic rocks present, this brings two main issues at hand. Firstly volcanic rocks have a wide variety of scales of preservation, from thin ash horizons to lava flows and pyroclastic rocks of varying thickness and lateral distribution. This is the most widely observed in volcanic lifted margins and their associated flood basalt provinces, where the overall amount of volcanic material can be vast and laterally extensive and yet made up of individual flow packages (e.g. Planke *et al.* 2000; Jerram and Widdowson 2005; Bryan *et al.* 2010; Nelson *et al.* 2011; Millett *et al.* 2021a). Secondly, the nature of volcanic rocks means that they have a wide range of rock properties even within individual flows and facies (Planke *et al.* 1994; Nelson *et al.* 2009; Millett *et al.* 2021a & b). These internal variations that can be found in individual volcanic facies, highlighting the wide variation of heterogeneity in properties such as velocity and density, which mark internal facies which have been termed intra-facies (e.g. Single and Jerram 2004).

A good way to conceptualise the above issues is to look at the different scales of observation that we need to make in order to characterise our volcanic parts of the basin as shown in Figure 2. We can understand and observe volcanic units and the internal properties (intra-facies) at the outcrops scale (1-10s m), and then start to build on an understanding of how the individual units stack together within the outcrop to field scale (10s – 100s m). Key lithological sections and how they link up on the regional scale (e.g. 1-100 km), provided a link between the outcrop observations and the features that we can see at the seismic, and even margin scale (1 - >100s km) (Figure 2 - observations). We can therefore define and interpret the main facies types and their internal intra-facies variations (e.g. Single and Jerram 2004; Jerram 2002), and then look at how these variations create facies association's at the larger scale (Jerram and Widdowson 2005). Finally, we can start to map out the facies and facies associations at the seismic scale (Planke *et al.* 2000) (Figure 1 – interpretations). In order to achieve this last step we use the concepts of seismic volcanostratigraphy in 2D and igneous geomorphology in 3D (Planke *et al.* 2000; Planke *et al.* 2017), which will be summarised later.

This recognition of facies and facies associations, and an understanding of the wide variety and heterogeneity of rock properties both laterally and vertically within volcanic successions, is key to being able to understand their role within the Petroleum System. Volcanic rocks and associated intrusions can be both advantageous and disadvantageous in the context of a working petroleum system, and can act as seals, reservoirs, and conduits to fluid flow, as well as influencing the maturation of the source rocks. Next we will take a brief look at how volcanic rock properties are linked to their facies types.

LINKING FACIES TYPES AND ROCK PROPERTIES

It has been introduced above that an important first step in looking at volcanic units is to start to define the key types of volcanic facies, scales and facies associations. At the outcrop scale the individual facies types can be defined and also key contact and internal variations can also be introduced. A number of volcanic facies can be defined (e.g. Figure 2) such as different lava flow types (e.g. Tabular, compound and ponded), volcanics erupting into water (e.g. Hyaloclastites), as well as the internal intra-facies variations and the contact variations with volcanics and sediment units (e.g. Jerram 2002; Single and Jerram., 2004; Nelson *et al.* 2009; Famelli *et al.* 2021). A key observation is that volcanic units vary significantly in type and geometries as well as the units clearly contain internal and contact variations that will result in a wide variety of rock properties. These marked heterogeneities with volcanic successions will in turn affect how the volcanic rock units behave in the subsurface.

The next step then is to investigate the distribution of rock properties within these facies types. The importance of this is highlighted in figure 3. The scale of rock property variation between different types of unit is remarkable (e.g. Figure 3a). Even when we consider an individual lava flow (e.g. Figure 3b), we can see that the distribution of fractures and vesicles within the flow is manifest through a dramatic variation in properties (such as density and velocity). Also it can be shown that these variations change with the scale of the lava flow. By linking these internal facies, the 'intra-facies' variations, we can help to better define the distribution of the rock properties within the volcanic stratigraphy (e.g. Single and Jerram. 2004; Nelson *et al.* 2009; Nelson et al; 2011; Rossetti *et al.* 2019; Greenfield *et al.* 2020). An example of the application of the rock property variations to a 3D outcrop model is highlighted in Figure 3C (adapted from Greenfield *et al.* 2020), and shows the potential power of the combination of rock properties and volcanic facies mapping. Recent studies have also been looking at rock property variations with intrusions such as fracture distribution and host rock interactions (e.g. Galland *et al.* 2019 and 2022; Rabbel *et al.* 2021; Spacapan *et al.* 2018). Clearly, with a good understanding of the variations of rock properties in volcanic units we can start to address issues such as; borehole identification (e.g. Nelson *et al.* 2009; Jerram *et al.* 2019), volcanic reservoir characteristics (e.g. Millet *et al.* 2021 b & b; Marins *et al.* 2022), drilling (e.g. Millett *et al.* 2016), carbon sequestration (e.g. Planke *et al.* 2021), and better linking outcrops to seismic (e.g. Jerram *et al.* 2009; Planke *et al.* 2017; Angkasa *et al.* 2017; Rabbel *et al.* 2018), as well as many other factors to better understand the role of volcanic rocks within a rifted margin and basin.

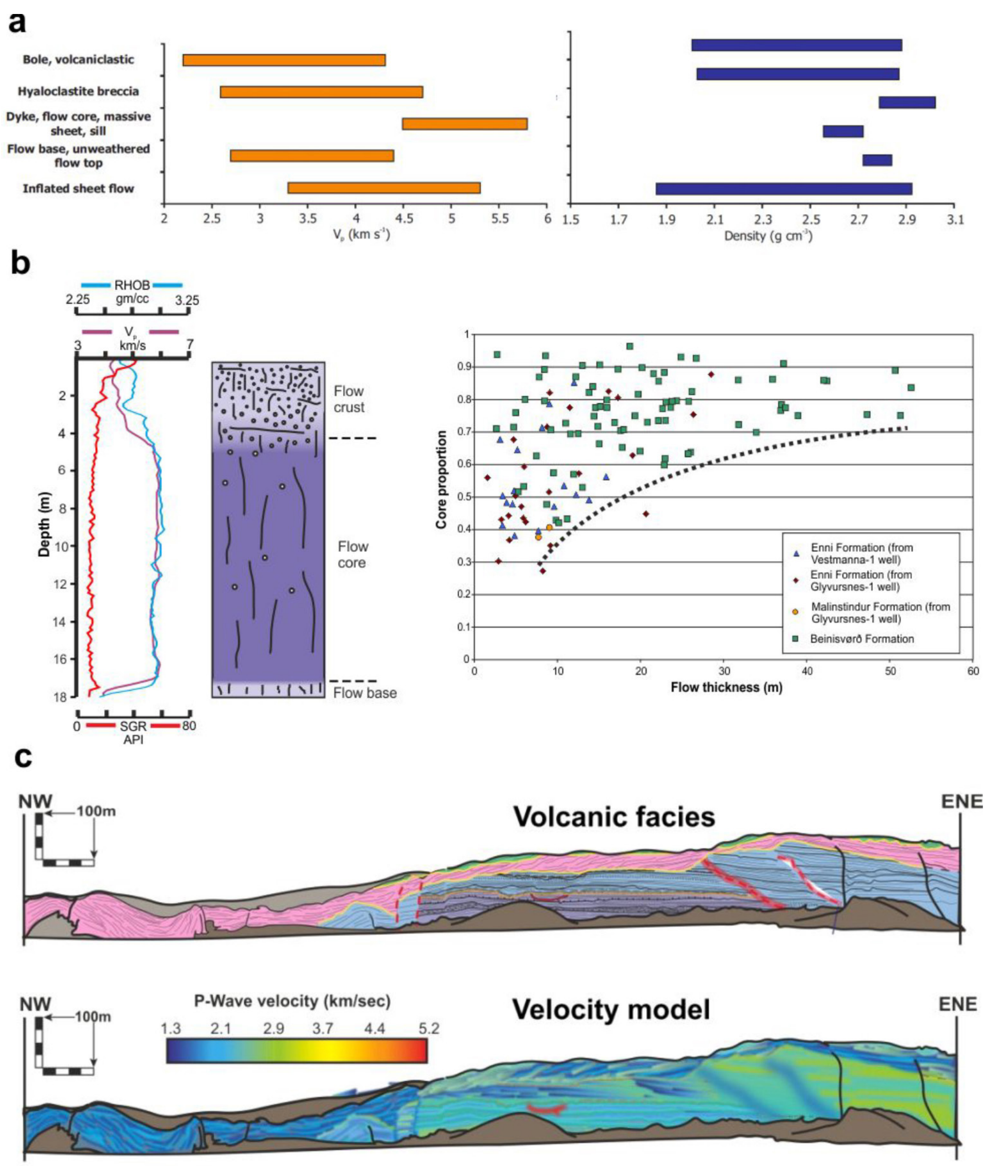

Figure 3. Rock property heterogeneity in volcanic rocks. A) the variation of velocity and density as seen within different types of volcanic facies. B) Within flow Intra-Facies variations and the effect on rock properties. C) A 3D outcrop of Hyaloclastites from Iceland showing how the volcanic facies variations look in terms of the equivalent velocities. (Adapted from Nelson *et al.* 2009 and Greenfield *et al.* 2020).

VOLCANIC FACIES AT SEISMIC SCALE

Having looked at the volcanic facies types and associations that can be defined in outcrop scale studies, we now turn our attention to what we can interpret at the seismic scale. In the first instance we are often faced with 2D seismic through our volcanic margins, and as such a scheme of key volcanic-seismic facies has been developed, termed ‘seismic solcanostratigraphy’. This was pioneered in the 1990s-2000s with interpretations of key section along the Norwegian Margin (e.g. Planke *et al.* 1999; Planke *et al.* 2000). In seismic data where we are faced with extrusive lava sequences, the normal sequence stratigraphic principles are applied in conjunction with seismic facies analysis to achieve a seismic volcanostratigraphy interpretation. The key types of seismic volcanostratigraphy are presented in Figure 4, the key features of the facies types are defined (Figure 4a), with the classic interpretive model (Figure 4B), and and example of some interpreted facies along a classic profile (Planke 2000; Abdelmalak *et al.* 2016). A major component of the development of the seismic volcanostratigraphy approach has been the lining of the seismic observations with good onshore volcanic analogues to help refine the seismic interpretation (Planke *et al.* 2000; Planke *et al.* 2017).

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Seismic facies unit	Reflections characteristics			Volcanic facies	Depositional environment
	Shape	Boundaries	Internal		
Inner Flows	Sheet	Top: high amplitude, disrupted, rough being onlapped or concordant. Base: negative polarity often obscured	Chaotic sheet-like body of very disrupted or hummocky reflections	Massive and fragmented flows, volcanoclastics and hyaloclastics	hallow marine deposited in broad basin
Lava Delta	Bank	Top: high amplitude or reflection truncation. Base Reflection truncation or termination	Progradational reflection configuration	Massive and fragmented basalts and volcanoclastics	Coastal
Landward Flows	Sheet	Top: high amplitude, smooth being onlapped or concordant. Base: law amplitude, disrupted	Parallel to subparallel. High-amplitude disrupted	Flood basalts	Subaerial or shallow marine flood basalts deposited on a plain or in broad basin
Inner SDR	Wedge	Top: intermediate to high amplitude, smooth with pseudoescarpment. Base: seldom defined	Divergent arcuate or sometimes a divergent-planar pattern	Flood basalts	Subaerial flood basalts deposited in subsiding structure
Outer High	Mound	Top: high amplitude, disrupted and rough. Base: not visible	Chaotic	Hyaloclastic flows and volcanoclastics	Shallow marine environment
Outer SDR	Wedge	Top: Intermediate to high amplitude, smooth with pseudoescarpment. Base: seldom defined	Divergent arcuate internal reflectors, lower amplitude than the Inner SDR	Flood basalts mixed with pillow basalts sediments and sills	deep marine depositional environment
Lava Flows	Sheet	Top: high amplitude with pseudoescarpment. Base: not visible	Chaotic	Flood basalts	Subaerial to shallow submarine depositional environment

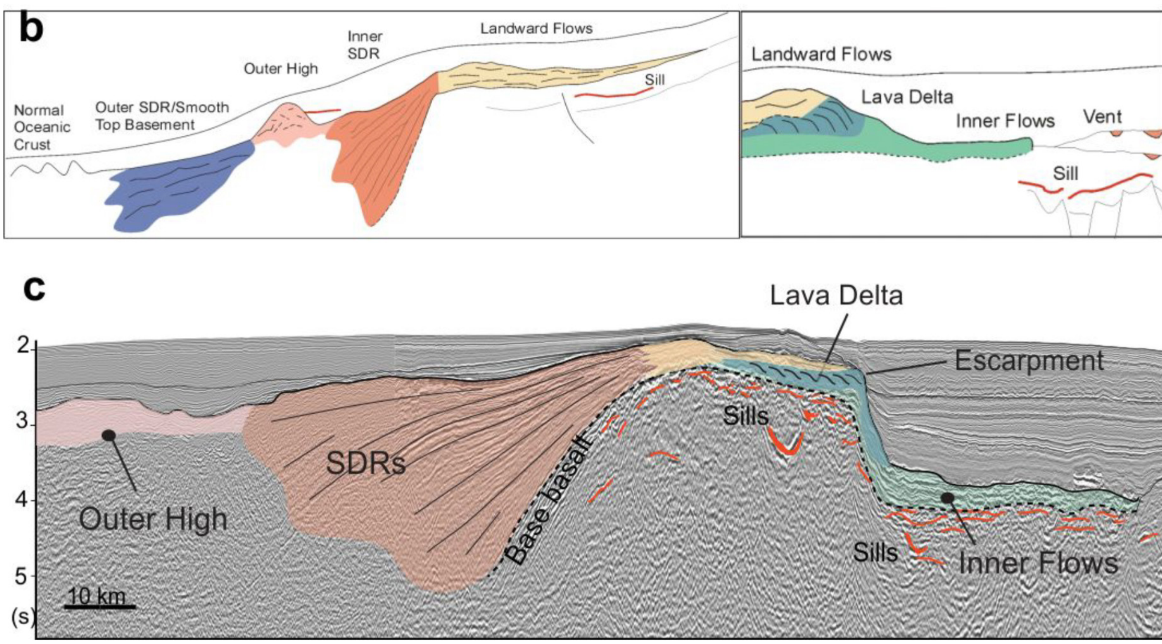

Figure 4. Seismic volcanostratigraphy. A) the definitions of some of the key seismic volcanostratigraphic facies and how they relate to the volcanic facies and depositional environment. B) The classic interpretation of the Norwegian Margin from continental to Ocean transition. C) A summary seismic volcanostratigraphic interpretation of a classic line along the Norwegian Margin. (Adapted from Planke *et al.* 2000 and Abdelmalak *et al.* 2016).

In more recent years there have been a larger number of 3D seismic data sets available (Planke *et al.* 2017; Walker *et al.* 2020; Bishoff *et al.* 2021). With good 3D data we have the potential to fully map out our volcanic facies, and realise their true spatial and temporal distribution. This expansion in 3D data over significant volcanic deposits resulted in the development 'igneous seismic geomorphology' (e.g. Planke *et al.* 2017). Igneous seismic geomorphology is the study of igneous systems (deposits and processes) using 3D seismic images in map view, linking the resultant observation to modern and ancient 3D analogue examples (Figure 5) It can be shown that using the approach of Igneous seismic geomorphology, used in conjunction with seismic volcanostratigraphy in cross section, represents the state of the art approach to extracting volcanological insights from 3D seismic data (Planke *et al.* 2017; Bischoff *et al.* 2021). As more 3D seismic datasets become available to fully interprets the volcanic sequences, more spectacular examples of preserved volcanic features in the subsurface will be realised (e.g. Walker *et al.* 2020; Bischoff *et al.* 2021).

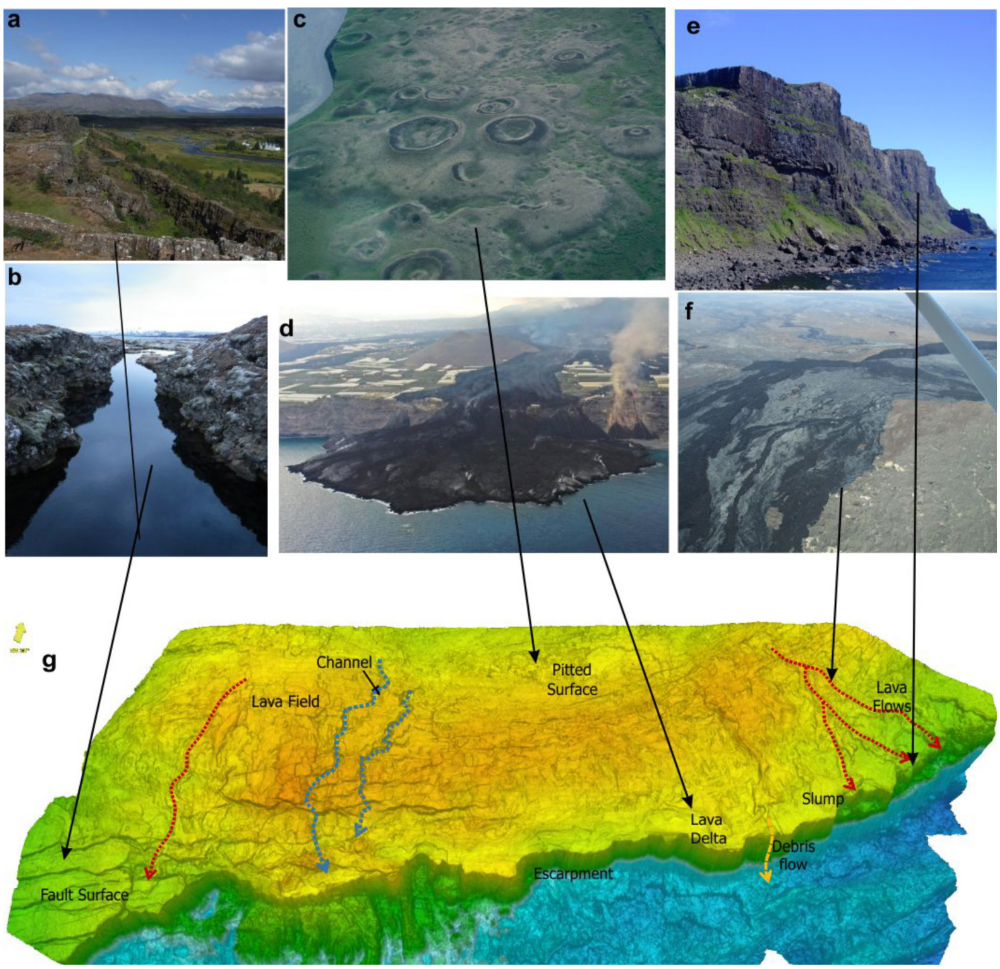

Figure 5. Igneous seismic geomorphology - Linking the 3D igneous seismic geomorphology to well constrained modern and ancient analogues. a-b) rift faults in Iceland, c) rootless cones in Iceland, d) Lava delta from La Palma, e) volcanic cliffs in Scotland, f) lava flows in Ethiopia, g) the 3D top volcanic surface from seismic data offshore Norway (adapted from Planke *et al.* 2017).

TOWARDS A VOLCANIC MARGIN EVOLUTION MODEL

With a better understanding of the volcanic facies types and facies associations within volcanic margins and volcanic basins we can start to converge on evolution models for how the system develops through time. Here we introduce a simplified evolution model for a volcanic rifted margin. By considering the evolution of a volcanic margin through time, as highlighted in Figure 7, from onset of initial volcanism to the final rifting phases, we can start to see how the main volcanic facies are related, providing a concep-tual model of the evolution of a volcanic margin which contains the main geometries observed in the subsurface data, and its relation to subaerial, coastal, and marine settings.

Initial volcanism commonly occurs in a basin-environment as either subaqueous or sub¬aerial (e.g. stages 0 and 1). This can form shallow in¬trusions, peperites, hyaloclastite depos¬its generated by magma-wet sediment interaction in marine/lacustrine environments or effusive, subaer¬ial volcanism where the volcanics are erupted on land. At the onset of volcanism, lavas will in-fill and pond in topographic lows and basins, which will affect the geometry and properties of the base basalt transition. If lava reaches the shoreline it will fragment in contact with water, commonly constructing a foreset bedded pro¬grading lava delta consisting of hyaloclastites such as lava delta facies, which are common along vast areas in volcanic margins (e.g. Wright *et al.* 2012; Abdelmalak *et al.* 2016). The low strength of these de¬posits and the high-energy coastal environment lead to

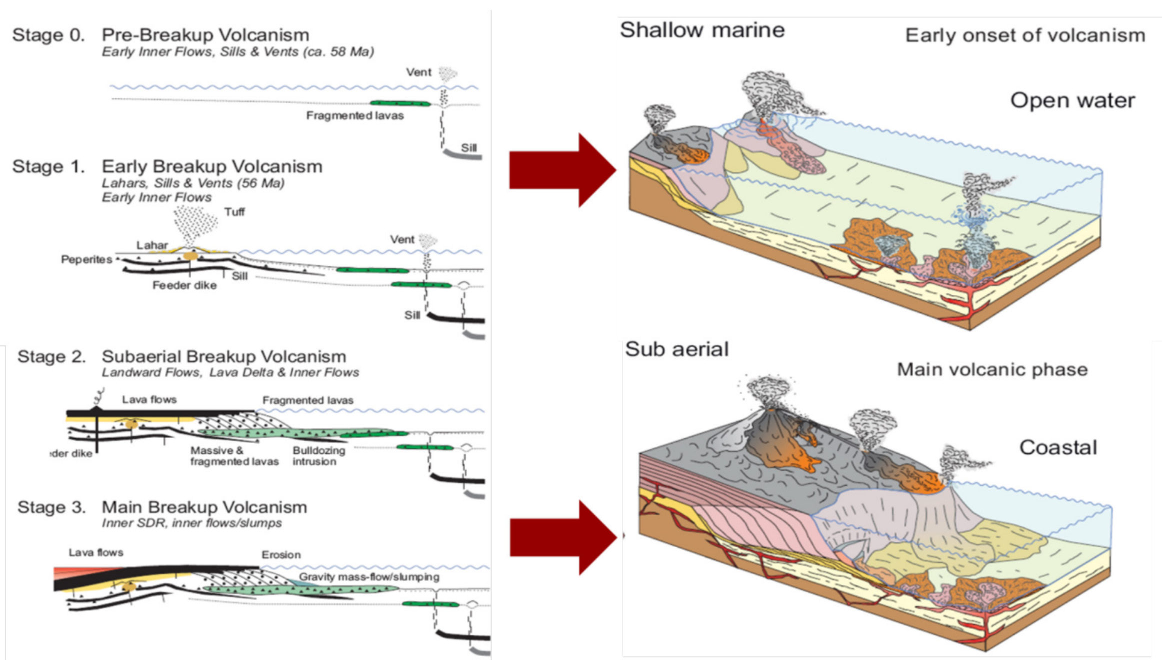

Figure 6. Linking a conceptual 2D evolution model of a volcanic margin (adapted from Planke *et al.* 2000) with 3D palaeo-environment evolution models. This builds an understanding of the 3D architecture of the system through time. Scenarios like this can be envisaged for certain stages of development in other volcanic margins and basins, and the model can be adapted to suit the particular case in mind.

extensive erosion, formation of regional escarpments, and deposition of volcaniclastic sediments by gravity mass flows which can make up part of the inner flows facies, as well as further sub-aqueous eruptions. There is further development of the intrusive plumbing system and a general increase of the extent and distribution of sub-aerial flows, fissures and volcanic centres mark the main phase of volcanism (Stage 2) which eventually leads to the main break-up phase (stage 3) and the development of seaward dipping reflector SDR facies and outer volcanic highs before the full break-up of the margin (e.g. Planke 2000). This sequence of events produces the classic profiles that we see in parts of the North and South Atlantic margins (e.g. Figure 4).

CONCLUDING REMARKS

This short overview has focused on the recent developments in our understanding of volcanic facies, facies associations and their link to the scales of observation and to the rock properties of the volcanic units. It is clear that in order to assess the role of volcanics within a basin and its potential role in the context of e petroleum system, the scales of observation are vitally important. The ability to recognise the different facies types, and to map them and their facies associations at the larger scale, helps to constrain the likely distribution of the volcanic rock types and also their likely rock property variations. Ideally this leads to better interpreted seismic sections where volcanic and intrusive units are present and can help allow the construction of 3D geological models. We can also start to develop good conceptual models as to how margins and basins develop from a volcanic perspective, which in turn help us to inform our interpretation of the subsurface (e.g. Figure 6).

Understanding the differences in volcanic rock properties is also quite revealing and help provide a good understanding of the way in which the different volcanic units affect the distribution of vesicles and fractures etc., which in turn have dramatic effects on their physical properties (porosity, permeability, density etc.). Additionally, examples of the facies types from core plugs can start to be used to start build porosity with depth curves for volcanic rocks, which are currently poorly understood (e.g. Millett *et al.* 2016). It can be shown that common volcanic units such as; Lava flows, hyaloclastites and intrusions, contain key internal rock property variations (intra-facies) that can be mapped out in 3D in good onshore analogues (Nelson *et al.* 2009; Nelson *et al.* 2011; Watton *et al.* 2013; Greenfield *et al. et al.* 2020). These key facies can be used to help understand reservoir characteristics showing how properties such as velocity, porosity and permeability are distributed, and may also be linked with core and with remote data such as wireline logs, cuttings and ultimately seismic (e.g. Jerram *et al.* 2019; Millett *et al.* 2020; Millet *et al.* 2021 a & b; Marins *et al.* 2022), providing a vital link from the seismic to sub-seismic scale. By building up a volcanic facies model that looks at the types and styles of volcanism from sub-aerial through coastal to submarine, as well as the styles of intrusions and the processes occurring in their contact aureoles, we can start to define the framework for looking at volcanic basins in the subsurface (Senger *et al.* 2017; Millet *et al.* 2000; Bischoff *et al.* 2021; Planke *et al.* 2022). Such models can be constrained using a wealth of onshore analogues from many localities around the world (including Namibia, Angola, Brazil, South Africa, Greenland, UK, Iceland, Siberia, Hawaii, India, etc.), and can also be linked to data-sets gathered from a number of important subsurface examples (e.g. Jerram *et al.* 2019, Millett *et al.* 2021 a&b).

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