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Seismic volcanostratigraphy of large-volume basaltic extrusive complexes on rifted margins

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Abstract. Large-volume extrusive basaltic constructions have distinct morphologies and seismic properties depending on the eruption and emplacement environments. The presence and amount of water is of main importance, while local rift basin configuration, erosion, and resedimentation determine the overall geometry of the volcanic constructions. We have developed the concept of seismic volcanostratigraphy, a subset of seismic stratigraphy, to analyze volcanic deposits imaged on seismic reflection data. The method places special focus on identification and mapping of seismic facies units and the volcanological interpretation of these units. Interpretation of seismic reflection data along the Atlantic and Western Australia rifted margins reveals six characteristic volcanic seismic facies units named (1) Landward Flows, (2) Lava Delta, (3) Inner Flows, (4) Inner Seaward Dipping Reflectors (Inner SDR), (5) Outer High, and (6) Outer SDR. These units are interpreted in terms of a five-stage tectonomagmatic volcanic margin evolution model comprising (1) explosive volcanism in a wet sediment, broad basin setting, (2) subaerial effusive volcanism forming Gilbert-type lava deltas along paleoshorelines, (3) subaerial effusive volcanism infilling a fairly narrow rift basin, (4) shallow marine explosive volcanism as the injection axis is submerged below sea level, and finally (5) deep marine sheet flow or pillow-basalt volcanism. Further, erosion and resedimentation processes are particularly important during the shallow marine stages. Seismic volcanostratigraphy provides important constraints on rifted-margin development, in particular, on the prevolcanic basin configuration, relative timing of tectonomagmatic events, total amount of volcanic rocks, location of paleoshorelines, and margin subsidence history. These parameters give key boundary conditions for understanding the processes forming volcanic margins and other large-volume basaltic provinces.

1. Introduction

Continental breakup is commonly associated with massive, transient volcanism, forming volcanic rifted margins (Figure 1). These margins are normally classified on the basis of observation of (1) prominent wedges of seaward dipping reflections, commonly called seaward dipping reflectors (SDR), near the continent-ocean transition and (2) high P wave velocity bodies, $V_p > 7$ km/s, in the lower crust [*Eldholm et al.*, 1995]. Deep sea drilling in the northeast Atlantic has confirmed that the SDR consist of stacks of subaerially emplaced flood basalts [*Roberts et al.*, 1984; *Eldholm et al.*, 1987; *Larsen et al.*, 1994]. The high-velocity bodies are normally interpreted as magmatic underplated material below extended continental crust and as the lower part of thick oceanic crust seaward of the continent-ocean boundary [for example, *Furlong and Fountain*, 1986; *White and McKenzie*, 1989; *Eldholm et al.*, 1995].

The increased availability of high-quality seismic data and reinterpretation of old data on rifted margins show that breakup volcanism is common, although its intensity and character may vary significantly along a margin and between margins. Typical volcanic and nonvolcanic rifted margins, such as the northeast Atlantic and Iberia margins, respectively, appear to be end-member cases [*Eldholm et al.*, 1995]. On transitional-type volcanic margins, such as the Western Australia margin, the characteristic SDR are regionally absent or poorly developed [*Symonds et al.*, 1998]. The presence of voluminous basaltic breakup complexes can here be inferred from well and dredge data combined with interpretation of characteristic seismic reflection configurations other than the SDR.

Our ability to identify the presence of volcanic constructions on rifted margins on the basis of interpretation of seismic reflection data is important in order to understand the causes and effects of continental breakup magmatism. Aspects of seismic stratigraphy have previously been used for studies of volcanic constructions, for example, in the Faeroe-

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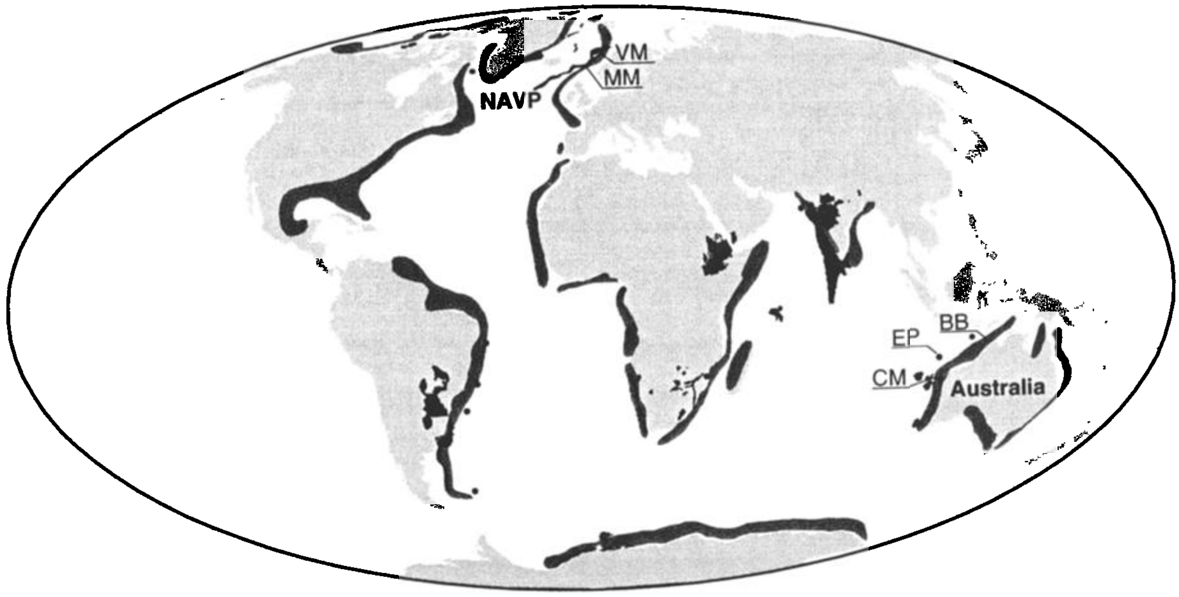

Figure 1. Worldwide distribution of passive continental margin sedimentary basins (dark gray) and continental margin breakup-related large igneous provinces (black and black dots). BB, Browse Basin; CM, Cuvier Margin; EP, Exmouth Plateau; MM, Møre Margin; NAVP, northeast Atlantic Volcanic Province; VM, Vøring Margin. Based on *Kulke* [1994] and *T. P. Gladzcenko* (personal communication, 1997).

Rockall Plateau region [*Gatliff et al.*, 1984; *Wood et al.*, 1988; *Boldreel and Andersen*, 1994], on the east Greenland [*Larsen and Jakobsdottir*, 1988] and the U.S. East Coast [*Lizarralde and Holbrook*, 1997] margins, in the Columbian Basin [*Bowland and Rosencrantz*, 1988], and by mapping zones of characteristic basement reflections on the mid-Norway volcanic margin [*Talwani et al.*, 1983; *Skogseid and Eldholm*, 1987]. However, the interpretation methods and terminology are generally defined briefly and used inconsistently, making it difficult to compare results from different margins and find consistent criteria for identification of volcanic constructions on seismic data. In particular, the terminology related to the characteristic seaward dipping reflections (for example, seaward dipping reflectors, seaward dipping wedge, seaward dipping reflector sequence, seaward dipping reflector sequences, and feather-edge of seaward dipping reflector sequences) is poorly defined or used inconsistently in the literature.

Our interpretations of new high-quality seismic reflection data and well data on rifted margins suggest that it is necessary to refine the seismic interpretation procedure used to identify and map volcanic constructions. In this paper we adopt the concept of seismic stratigraphy [*Payton*, 1977] to analyze voluminous extrusive basaltic constructions, placing particular emphasis on seismic facies analysis. The seismic volcanostratigraphic method is developed on the basis of interpretation of more than 50 industry-standard regional seismic profiles collected during the last decade and numerous older profiles across the northeast Atlantic (Møre, Vøring, and east Greenland margins), southeast Atlantic (Namibian Margin), and western Australian margins. The focus of this paper is on (1) describing and documenting type-examples of characteristic volcanic seismic facies units, (2) documenting typical seismic and petrophysical properties of the volcanic units, and (3) proposing constructional processes of the volcanic seismic facies units by integrating results from the seismic interpretation with outcrop data and models for the formation of modern and ancient large-volume basalt provinces. The regional tectonic and volcanological aspects of the interpreted seismic data are addressed elsewhere [*Symonds et al.*, 1998; *Planke and Alvestad*, 1999; *Frey et al.*, 1998; *Alvestad*, 1997].

2. Seismic Volcanostratigraphy

Seismic volcanostratigraphy is the study of the nature and geologic history of volcanic rocks and their emplacement environment from seismic data. The method relies on seismic sequence analysis and seismic facies analysis as described by *Vail and Mitchum* [1977]. A sequence is normally defined as a depositional unit of genetically related strata bounded by unconformities or their correlative conformities, whereas a seismic sequence is a depositional unit identified on seismic data [*Mitchum et al.*, 1977].

Sequence stratigraphy is used mostly to study siliciclastic systems in marine basins but can also be used to study terrestrial and nonsiliciclastic systems such as carbonate and volcanic deposits. Eustatic sea level changes are traditionally regarded as the key sequence-forming process [*Haq et al.*, 1987]. However, changes in relative sea level and accommodation space related to tectonism and variations in sediment supply are also important elements [*Galloway*, 1989; *Helland-Hansen et al.*, 1997]. There are further controversies about how sequence boundaries are identified and the processes responsible for forming these boundaries [*Embry*, 1995; *Emery and Myers*, 1996]. In basaltic volcanic systems the depositional response of relative changes in sea level, accommodation space, and supply of material is clearly different from that of a siliciclastic system. On volcanic margins the supply of material is irregular, occurring mainly during volcanic eruptions. Further, lava flows may be deposited entirely above sea level or burrow into soft sediments, forming sills and dikes.

A seismic sequence may consist of several mappable seismic facies units, which are "... groups of seismic reflections whose parameters such as reflection configuration, continuity, amplitude, frequency, or interval velocity, differ from adjacent facies units" [*Mitchum,* 1977, p. 210]. Seismic sequence stratigraphy relies on a time-stratigraphic and process-dependent framework [*Helland-Hansen et al.,* 1997]. In contrast, interpretation of seismic facies units represents a relatively objective way to classify observable seismic parameters by a method that does not rely on geological models or concepts.

Seismic volcanostratigraphy relies mainly on seismic facies analysis, that is, the mapping and geological interpretation of seismic facies units. Volcanic deposits are commonly difficult to image by seismic reflection data as they are seismically very heterogeneous where intrabasement reflections primarily are interference phenomena or coherent noise such as converted waves and short multiples [for example, *Planke and Eldholm,* 1994]. It is therefore difficult to interpret intrabasement reflections directly in terms of geology. However, the reflection configuration of seismic facies units might provide insight into the geological nature of the imaged deposits.

Seismic volcanostratigraphy requires knowledge of the seismic response of different volcanic deposits. This might be obtained by drilling of characteristic seismic facies units. However, only very few drill holes penetrate the volcanic seismic facies units identified on rifted margins [*Planke and Alvestad,* 1999]. It is therefore essential to utilize results from studies of volcanic processes and outcrops to improve the volcanological interpretation of the imaged units.

3. Voluminous Basaltic Constructions

Basaltic volcanic rocks express a wide range of morphologies, depending on feeder system geometry, discharge rate and volume, topography, presence of water, cooling rate, and magma properties such as rheology, temperature, and volatile content [for example, *Basaltic Volcanism Study Project,* 1981; *Walker,* 1993; *Hon et al.,* 1994; *Gregg and Fink,* 1995]. The bulk part of the volcanic margin volcanic rocks appears to be fairly homogenous tholeiitic basalts erupted at high discharge rate from large fissures [*Macdougall,* 1988b; *Self et al.,* 1997]. The most important factors determining the facies of voluminous basaltic deposits are related to the presence of water and the water depth during eruption and emplacement of the lava, and the local topography.

3.1. Subaerial Effusive Eruptions

3.1.1. Subaerial deposits. The most voluminous historic flood basalt eruption was the 15-km^3 1783-1785 Laki eruption on Iceland [*Thordason and Self,* 1993]. Many flood basalt emplacement processes are well described by the Laki eruption. However, this was a relatively small eruption compared with lava flows with volume up to 2000 km^3 in the Columbia River flood basalts province [*Tolan et al.,* 1989]. The 30-km-long Laki eruption fissure is located in a valley in the highlands of southern Iceland. During the eruption the lava filled up the valley to the spill point and started flowing down one and, somewhat later, down a second river gorge. When the lava entered the flat-lying flood plains below, it spread out as a lobe being extended and inflated during four or five main surges within a 5-month period, finally reaching a mean thickness of 21 m.

Many ancient subaerially flood basalt constructions, such as the Deccan Traps in India and the Columbia River flood basalt province in the northwestern United States, are well studied [*Macdougall,* 1988a; *Reidel and Hooper,* 1989; *Mahoney and Coffin,* 1997]. The flood basalts are dominantly fissure-erupted lavas which have flowed downhill for several hundred kilometers (a >750-km-long flow is documented in the Columbia River flood basalt province [*Tolan et al.,* 1989]) by thermally insulated flowage in lava tubes or sheets [*Self et al.,* 1997]. The lavas are compound pahoehoe sheets thickened by lava rise and endogenous growth mechanisms, and deposit or pond in structural lows until the spill point is reached [*Hon et al.,* 1994; *Self et al.,* 1996, 1997]. Individual sheet lobes have a characteristic three-part internal structure with a vesicular upper crust, a regularly jointed lava core, and a thin glass-rich (hypohyaline) lava base (Figure 2) [*Self et al.,* 1997].

3.1.2. Coastal processes. Lava deltas are constructed by explosive and nonexplosive interaction of magma and water

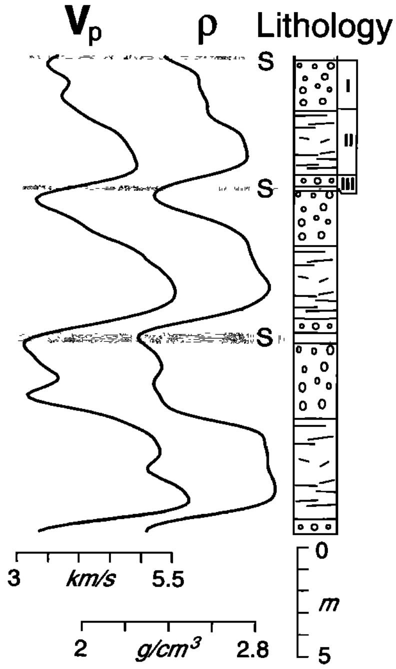

Figure 2. Characteristic internal structure and variations in seismic P wave velocity V_p and density ρ in subaerial flood basalts. Smoothed downhole logs were recorded in Ocean Drilling Program Hole 642E [*Planke,* 1994]. Note the asymmetric, cyclic character of the logs, with gentle increase in the vesicular flow top (zone I), high velocity and density in the massive lava interior (zone II), and steep decreases near, or just below, the base of each unit (zone III). A similar tripartite division has recently been identified by field studies of inflated pahoehoe flood basalts [*Self et al.,* 1997]. Large impedance contrasts are mainly a function of intrabasalt physical property variations, not the presence of thin interbedded sediments *S*. The low velocity of flow tops is related to high porosity and extensive alteration of the basalt to smectite clays and iron hydroxsides [*Planke et al.,* 1999].

by basalt quenching and fragmentation when subaerially erupted lavas flow into the sea [*Fischer and Schmincke*, 1994]. This process has been observed in detail on Kilauea, Hawaii [for example, *Moore et al.*, 1973; *Hon et al.*, 1993], where subaerial lavas were emplaced on top of shallow marine, foreset-bedded hyaloclastites of volcanic sand and rubble. Additional fragmentation is caused by wave action, forming volcaniclastic conglomerates and sandstones, and by catastrophic collapses of unstable lava deltas [*Kauahikaua et al.*, 1993]. Lava tubes are occasionally formed across the surf zone in periods with high magmatic flow rate, enabling the lava to flow down the lava delta foreset construct massive basaltic tongues.

The internal structure and depositional processes of basaltic lava deltas can be compared with coarse-grained alluvial Gilbert-type deltas [*Porebski and Gradzinski*, 1990]. Schematically, a Gilbert-type delta has a tripartite depositional geometry, forming a subhorizontal topset, a steep, prograding foreset (up to 35° dip), and a gentle-dipping aggradational bottomset [*Nemec*, 1990]. Resedimentation processes by gravitational mass transport dominate the foreset, commonly by avalanches, transporting coarse material to the deep-sea environment. Alluvial deltas have a fairly constant annual input of erosional material. In time, the sediment source will become more distal, causing deposition of finer-grained material as the delta builds out. In contrast, lava deltas have a supply of proximal, very coarse-grained sediments during each eruption as the lava fragmentation occurs in the coastal environment. The structure of the lava delta is further influenced by relative sea level changes [*Lipman and Moore*, 1996], the type of wave-energy environment, and the basin geometry. The time span between lava emplacement episodes away from the eruption center can be fairly long (for example, about 20,000 years in the Tertiary lava pile on Iceland; G. Fitton, personal communication, 1997), providing ample time to rework and redeposit the volcanic rocks by sedimentological processes. Coastal erosion and resedimentation dominate the final phase of a lava delta development. This occurs as the supply of magmatic material vanishes because of changes in eruption style and basin configuration. It can lead to development of an erosional escarpment and to modification of the shape of the lava delta as, for example, observed along the southern coast of Iceland.

Volcanic margin lava deltas are exposed in the Tertiary flood basalt provinces in eastern and western Greenland. *Pedersen et al.* [1993, 1996] have mapped subaerial lava flows and foreset bedded hyaloclastite units on Nuussuaq on western Greenland. These deltas were deposited in a low-energy lake environment, and the foreset beds consist of both hyaloclastite and resedimented basaltic conglomerate, locally interbedded with massive basalt.

3.1.3. Deep water processes. Gravity mass-transport processes are responsible for construction of the volcanic aprons around islands such as Hawaii and the Canary Islands (Figure 3) [*Schmincke et al.*, 1995]. These processes are similar to those forming aggradational bottomset beds in clastic environments where reworked sediments are transported to the deep-sea environment by debris flows and turbidite currents [*Nemec*, 1990]. Fine-grained volcaniclastic sediments have been transported several hundred kilometers offshore the Canary Islands, and such distal, resedimented volcaniclastic rocks tend to be fairly well stratified and are easily mapped by seismic data [*Schmincke et al.*, 1995]. However, massive basalt flows may also be deposited interfingered with the

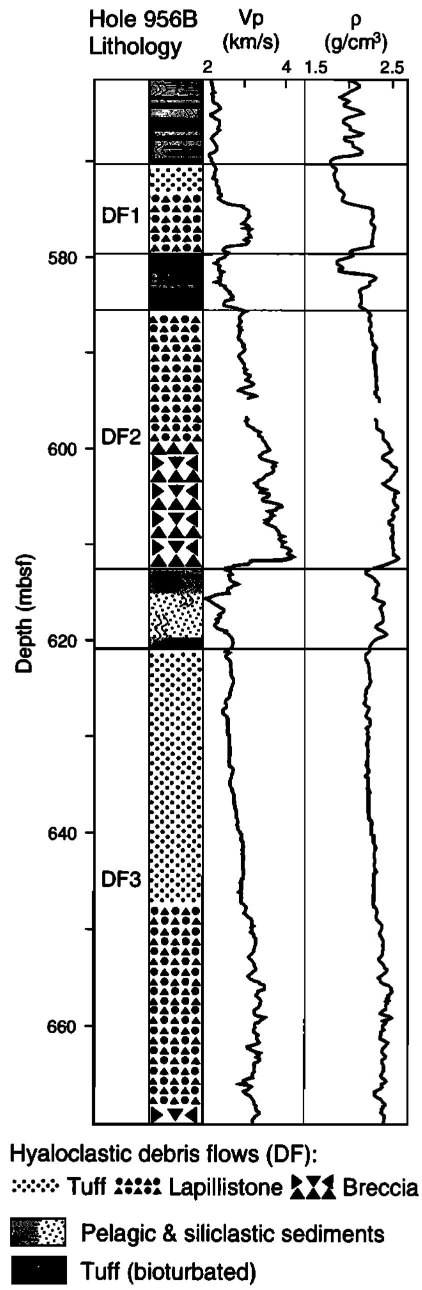

Figure 3. Characteristic internal structure and P wave velocity V_p and density ρ variations in volcaniclastic sediments drilled in ODP Hole 956B off the Canary Islands. Large velocity and density variations are observed within individual hyaloclastite debris flows. Also note high ρ in pelagic and siliciclastic sediments compared with the tuff intervals, which do not correspond to similar changes in V_p. The downhole lithology is based on core and log data from *Schmincke et al.* [1995] but has been reinterpreted on the basis of the wireline log and reprocessed formation-microscanner (FMS) data.

volcaniclastic sediments near the eruption vent. Degassed lavas with high volumetric flow rate may obtain coherence across the surf zone and flow down the foreset in lava tubes and sheets [*Moore et al.*, 1973], providing a mechanism for transport of basaltic melt into the basin. On the more flat-lying basin floor the lavas will spread out as lobes, forming massive sheet flows in proximal regions with high volumetric flow rates and pillow basalts in distal regions as the flow rate decreases outward in the lobe [*Griffiths and Fink*, 1992]. In places the lava may bulldoze into soft, low-density sediments, forming shallow sills or pond in local depressions forming lava lakes [see *Pedersen et al.*, 1993]. Volcaniclastic sedimentation dominates the periods between eruptions, leading to the formation of a heterogeneous, layered lava-sediment complex.

3.2. Shallow Marine Eruptions

Spectacular explosive-type eruptions result when the ejection center is in a shallow marine environment. The explosive nature of the eruption is largely controlled by degassing of the magma, though fragmentation is also facilitated by rapid cooling due to entrenchment of sea water within the magma [*Kokelaar*, 1986]. The maximum depth of explosive Surtseyan-type volcanism is typically 100-200 m for tholeiitic melts but depends on a number of parameters and processes, such as magma volatile content and effusion rate [*Allen*, 1980; *Kokelaar*, 1986]. Few examples of large-volume, shallow water, fissure-type basalt eruptions are documented. One exception is a thick Pleistocene unit on southern Iceland consisting of mixed massive basalt and hyaloclastite erupted from a source near the Laki fissure [*Bergh and Sigvaldason*, 1991]. A typical hyaloclastite flow consists of a lower regularly jointed massive basalt, followed by cube-jointed or pillow basalt, then hyaloclastic breccia with isolated pillows, and finally bedded hyaloclastite (Figure 4). Large lateral variations in thickness and internal structure are found in the hyaloclastite flow units. The average hyaloclastite flow thickness is 35-135 m, or 5-15 times thicker than the subaerial Laki flow of similar total volume, showing that the lava pile will thicken more rapidly during the shallow marine stage.

The shallow marine explosive eruption may occasionally build a volcano reaching above the sea level. The eruption will then enter into an effusive subaerial phase. This change in eruption style is well documented from studies of the table mountains on Iceland. These mountains were formed by emergence of central-vent subglacial volcanoes, having a hyaloclastite core formed during the aquatic eruption stage and a massive lava cap emplaced during the subsequent subaerial eruption stage [e.g., *Allen et al.*, 1982]. Similarly, during the Surtsey eruption, explosive volcanism continued until the vents were completely enclosed from the ocean, in which case the magmatic activity changed to Hawaiian-type fountaining [*Kokelaar*, 1986].

The large production of volcaniclastic sediments during shallow marine explosive eruptions suggests that sedimentary processes can be important for deposition of volcanic material. The Surtla eruption south of Surtsey never broke the sea level, and only a few tephra-laden jets broke the sea surface when the cone was at 5-m depth. This volcano was rapidly eroded by wave action down to 45-m depth, showing the low erosional strength of the hyaloclastite deposits [*Bergh and Sigvaldason*, 1991; *Kokelaar*, 1986].

3.3. Deep Marine Eruptions

Deep marine eruptions give rise to a range of basalt morphologies such as pillow basalts and various sheet flows [*Gregg and Fink*, 1995]. Laboratory wax experiments suggest that the volumetric flow rate is the primary parameter determining the basalt morphology for such eruptions [*Griffiths and Fink*, 1992]. Pillow basalts form at a wide range of flow rates, whereas submarine sheet flows and lava lakes are expected for increasingly higher flow rates. The thermally efficient flowage in lava tubes may allow the lava to flow for at least 100 kilometers in a subaqueous environment, as documented off Hawaii [*Holcomb et al.*, 1988]. However, magma is mainly emplaced as sill intrusions in a narrow rift basin environment with a high sedimentation rate [*Einsele*, 1985].

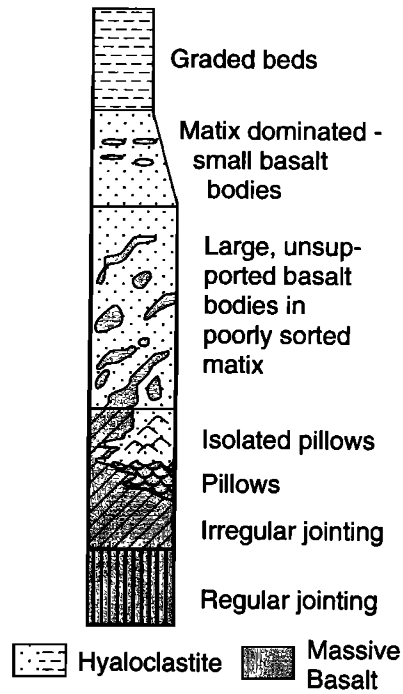

Figure 4. Schematic internal structure of a shallow marine basaltic hyaloclastite flow unit in southern Iceland [*Bergh and Sigvaldason*, 1991]. Note the chaotic interior, consisting of mixed fractured, massive basalt, and hyaloclastite.

3.4. Magma-Sediment Interaction

Volcanic eruptions in a sedimentary basin environment may involve explosive interaction of wet sediments and magma forming internally chaotic volcanic-sedimentary complexes. The important factors determining the nature of these deposits are the type and depth of aquifers, lithology and strength of country rocks, and magma properties [*Busby-Spera and White*, 1987; *Sohn*, 1996]. As an example, the Kirkpatric flood basalts in Antarctica were preceded by voluminous basaltic eruption in a wet basin setting, forming more than 400-m-thick pyroclastic air-fall and lahar deposits and peperitic basalt intrusive rocks [*Hanson and Elliot*, 1996].

3.5. Tephra Deposits

Two main phases of explosive magma-water interaction are identified during the development of a volcanic margin: (1) magma-wet sediment or water interaction during the early phase of volcanism and (2) shallow marine volcanism as the injection axis subsides below the sea level. A massive amount of ash is formed during explosive magma-water interaction [e.g., *Fischer and Schmincke*, 1994]. In contrast, fairly small amounts of tephra are formed during the subaerial eruption stage. *Thordarson and Self* [1993] have estimated that during the Laki 1783-1785 eruption only about 2.6% of the erupted magma formed tephra and that main environmental hazards were related to acid haze of sulfur and sulfur dioxide.

The presence of late Paleocene and early Eocene tuff layers is well documented in northwest Europe. The early Eocene Balder Formation in the North Sea is a rapidly deposited tuffaceous mudstone (30-60 m thick in the central North Sea, increasing to >270 m westward, being deposited in circa 0.7 m.y.) [*Mudge and Bujak,* 1996]. Similarly, several hundred tephra layers are identified in the lowest Eocene mo-clay formation in northern Denmark [*Pedersen et al.,* 1975; *Pedersen and Jørgensen,* 1981]. Here, individual tephra layers are up to 19 cm thick with volumes exceeding 4 km^3. Initially, the volcanism was bimodal, with tholeiitic to rhyolitic composition, while the dominantly late stage tephras are monotonous basalts formed by ultraexplosive, shallow marine Surtseyan eruptions [*Pedersen and Jørgensen,* 1981].

4. Volcanic Seismic Sequence Analysis

A volcanic construction can be divided into a hierarchy of sequences depending on the resolution of the data and the nature of the problem being studied. On the smallest scale a subaerial basalt flow may be regarded as a sequence bounded by an erosional unconformity at the top and base. However, individual lava flows are generally too thin to be resolved on seismic data [*Planke and Eldholm,* 1994]. On the largest scale the entire basaltic extrusive complex may be treated as one sequence consisting of genetically related strata. This sequence is very voluminous and rapidly deposited on most rifted volcanic margins, for example, about 1.8×10^6 km^3 of flood basalts were deposited in a ~3 m.y. period during the opening of the northeast Atlantic [*Eldholm and Grue,* 1994]. Intermediate-scale sequences may further be mappable within the lava pile because of temporal variations in eruption frequency and volume, tectonism, and relative changes in sea or lake water level.

We have found it most appropriate to interpret the entire extrusive complex as one seismic sequence for regional seismic volcanostratigraphic studies on rifted margins. Seismic reflection data are commonly of poor quality in volcanic terrains, and seismic modeling suggests that reflection terminations are largely due to interference phenomena [*Planke and Eldholm,* 1994]. This makes it generally difficult to interpret internal seismic sequence boundaries with high confidence.

The regional extent of the extrusive breakup complex is interpreted on seismic reflection data primarily on the basis of the nature of its top reflection (Figures 5-9). This reflection is normally a high-amplitude, positive event that can be correlated with the top-basement reflection on normal oceanic crust and landward with the rift or breakup unconformity. The overlying sedimentary reflections are dominantly onlapping, but locally also concordant. The top reflection of the volcanic sequence is often smooth but may locally be planated or irregular or include pseudoescarpments [e.g., *Larsen and Jakobsdottir,* 1988]. Variations in the reflection strength depend on factors such as lithology and thickness of overlying strata, volcanic facies, average lava flow thickness, total thickness of the volcanic pile, the presence of interlava sediments, and seismic acquisition and processing parameters. Interpretational difficulties are common in regions where the volcanic sequence pinches out or if the volcanic rocks are deeply buried. The volcanic rocks are normally high-velocity units but may locally correspond to a low-velocity layer (Figure 8).

The basal sequence boundary is frequently difficult or impossible to identify (Figure 6). This is often due to imaging problems related to the seismic properties of basaltic constructions. In particular, irregular, high impedance contrasts at the top of and within the lava pile give rise to mode conversion, ringing, and scattering of the seismic energy [*Pujol et al.,* 1989; *Planke and Eldholm,* 1994]. In addition, the lower boundary of the volcanic extrusive complex may be poorly defined, as it can consist of a transition zone of sequentially deposited extrusive volcanic rocks mixed with subsequently intruded magmatic rocks.

5. Volcanic Seismic Facies Analysis

5.1. Seismic Facies Units

Seismic facies analysis is the main component of seismic volcanostratigraphy. We have identified four characteristic seismic facies units within the extrusive breakup sequence on

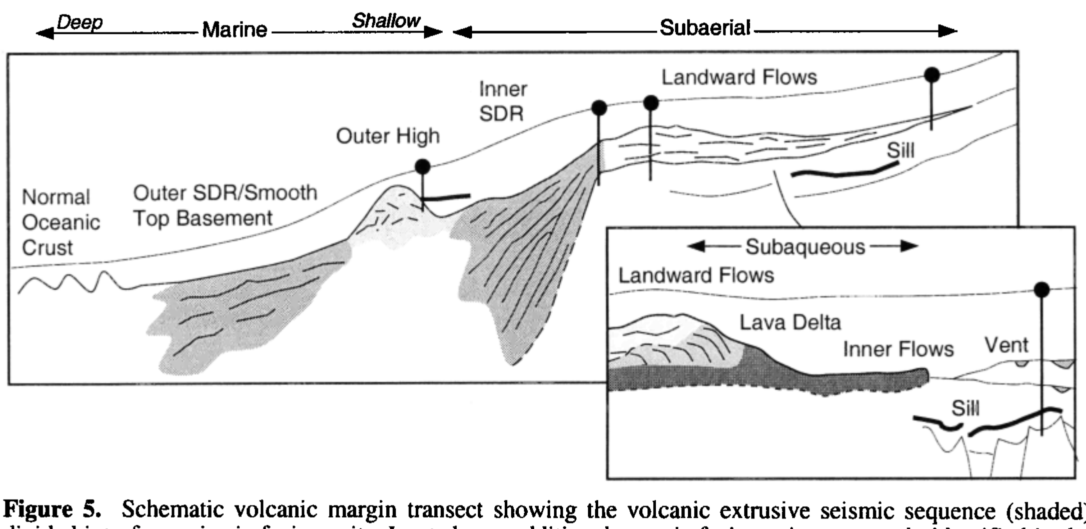

Figure 5. Schematic volcanic margin transect showing the volcanic extrusive seismic sequence (shaded) divided into four seismic facies units. Inset shows additional seismic facies units commonly identified in the northeast Atlantic. Proposed emplacement environment is shown by arrows. Wells (solid circle with vertical line) schematically located where drill holes penetrate corresponding seismic facies unit. SDR, seaward dipping reflectors.

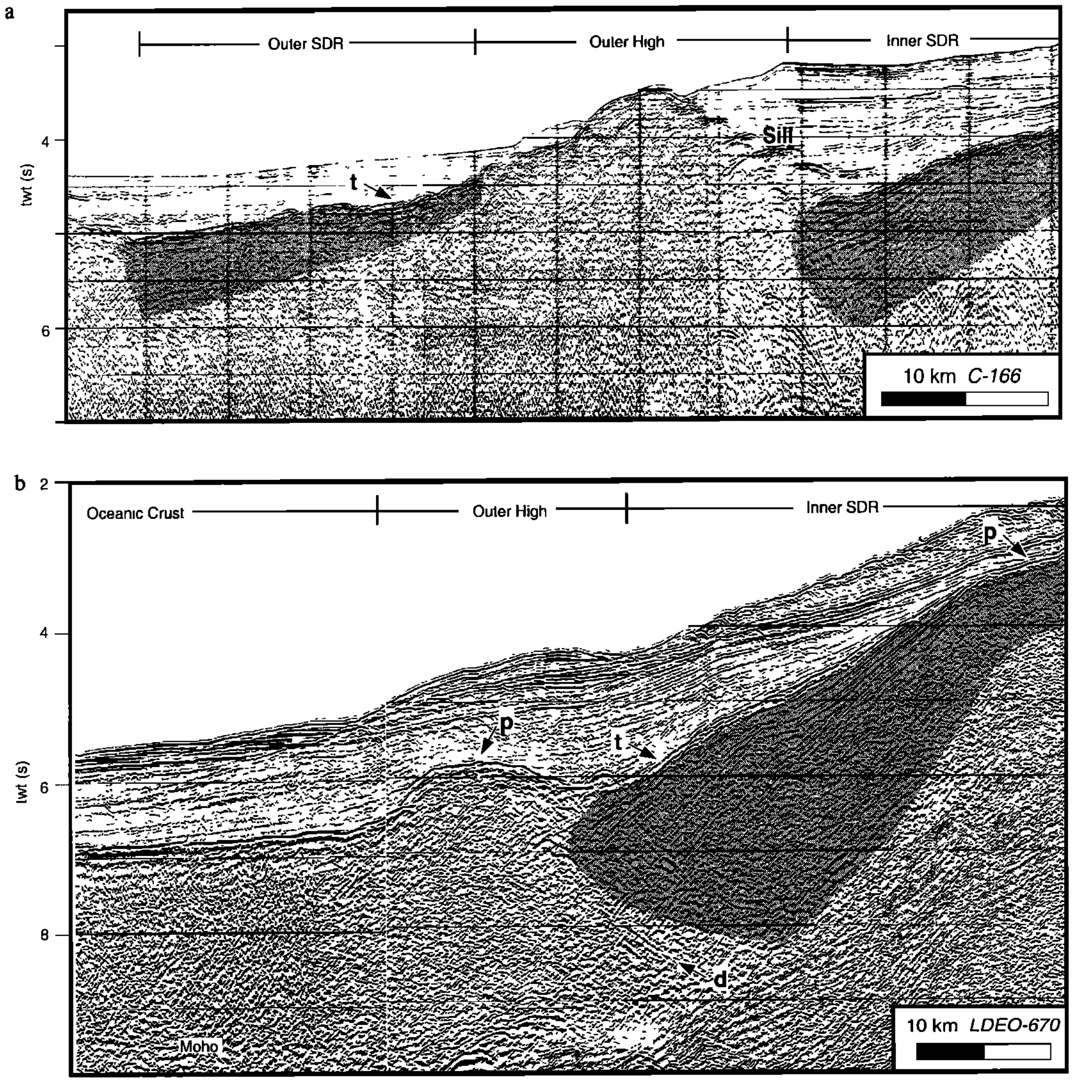

Figure 6. Volcanic margin transects showing changing seismic expressions from Inner SDR to oceanic crust: (a) Profile across the central Vøring Margin (Figure 1) showing the Inner and Outer SDR separated by a large mound, the Outer High, and (b) profile across the north-central Cuvier Margin (Figure 1) [*Hopper et al.*, 1992] showing the Inner SDR terminated by a wide mound, the Outer High, merging with about 10-km-thick oceanic crust [*Hopper et al.*, 1992] with a very smooth top-basement reflection. Landward dipping reflection segments below the termination of the Inner SDR are interpreted as intruded faults and feeder dikes. Here t, top of volcanic sequence; p, planated top-basement reflection; d, landward dipping reflection.

the basis of published data and interpretation of numerous seismic reflection profiles in the northeast Atlantic, off Western Australia and in the south Atlantic. These units are named (1) Outer SDR, (2) Outer High, (3) Inner SDR, and (4) Landward Flows (Figure 5; Table 1). Commonly, two additional facies units are identified: (5) Lava Delta and (6) Inner Flows. However, all units are not always present on a single margin transect. Further, note that we use our definition of the seismic facies units when discussing previously published seismic data. We start to describe the three seismic facies units located landward of the continent-ocean boundary, then continuing in an oceanward direction.

5.1.1. Landward Flows. The Landward Flows unit is commonly identified on seismic profiles landward and below the Inner SDR (Figures 5, 7, and 8). The top reflection is a strong, fairly smooth event. The external shape is sheet-like, whereas internal reflections are disrupted or hummocky and subparallel. The basal boundary may be identified as a negative-polarity reflection on high-quality multichannel seismic reflection data. Deeper reflections are low-amplitude, discontinuous events, but frequently no reflections are identified below the Landward Flows.

The Landward Flows unit frequently wedges out in a landward direction, for example, on the Namibian margin [*Gladczenko et al.*, 1997], the southeast Greenland margin [*Larsen*, 1990], and the Western Australia margin [*Symonds et al.*, 1998]. Along the European northeast Atlantic margin the unit frequently terminates at a regional escarpment or merges with prograding reflections (Figure 7).

5.1.2. Lava Delta. The Lava Delta has an internal progradational reflection configuration. The upper unit boundary is determined by reflection terminations or a change in reflection geometry from fairly flat-laying to disrupted, arcute events (Figure 7). The lower unit boundary is interpreted as a

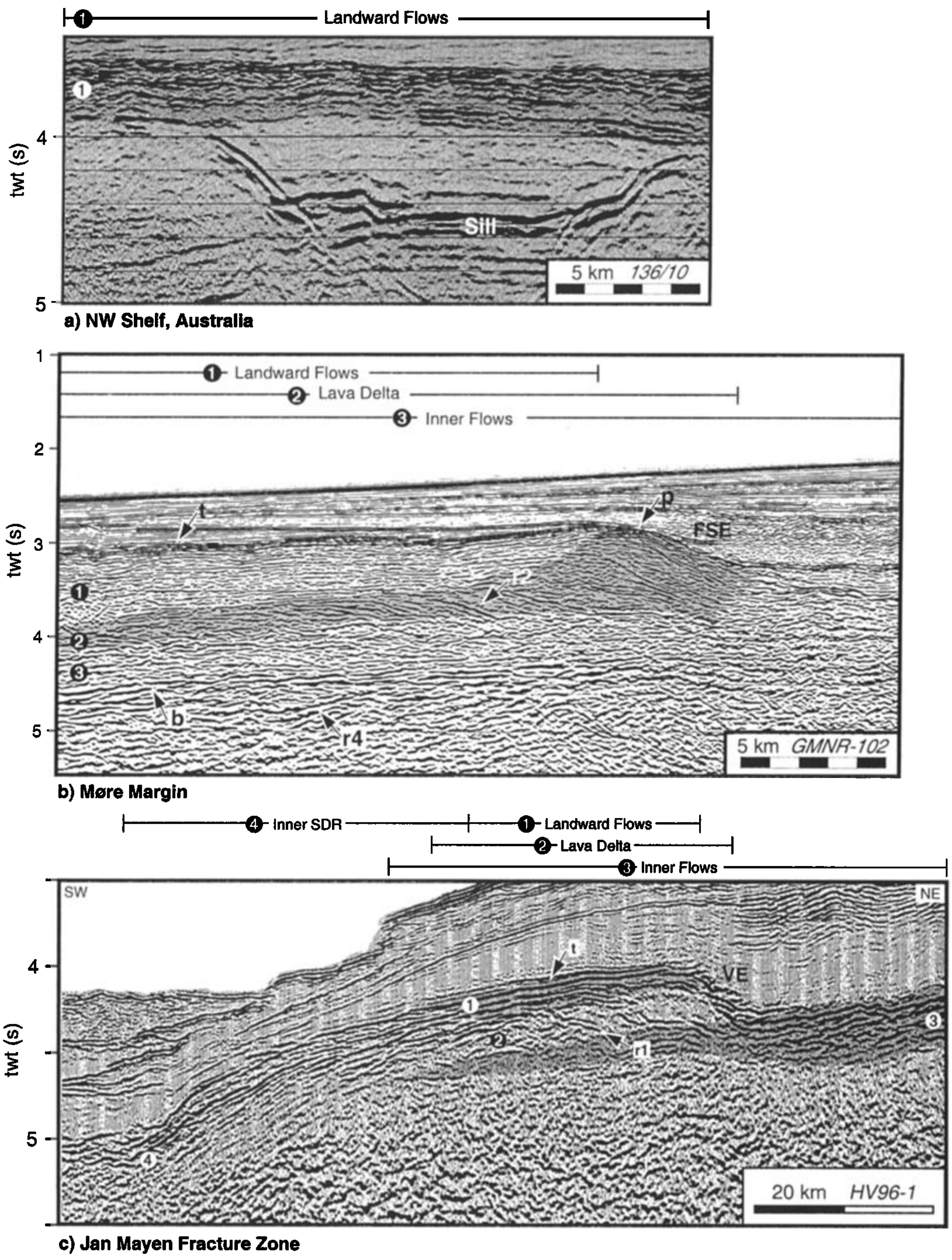

Figure 7. Seismic examples of the inner and central part of the extrusive seismic sequence (shaded). (a) Browse Basin (Figure 1) profile showing Landward Flows characterized by (1) a high-amplitude, smooth top reflection; (2) high-amplitude, subhorizontal, disruptive internal reflections; and (3) a negative-polarity, segmented base reflection. The unit is ~0.4 s thick, with stacking-derived interval velocities of 3.6-4.0 km/s. It is interpreted as a subaerial basalt complex on the basis of seismic characteristics and well-ties. The high-amplitude, saucer-shaped reflection below is interpreted as a magmatic intrusion on the basis of its seismic characteristics. (b) Møre Margin (Figure 1) profile showing Landward Flows overlying a progradational Lava Delta facies unit and the disrupted Inner Flows facies unit. Note the smooth, high-amplitude top Landward Flows reflection (t), interfingering of the base Landward Flows and top Lava Delta, well-defined prograding reflections (r2), and the band of low-frequency, high-amplitude reflections below the outer part of the base Inner Flows (r4). (c) Vøring Margin profile located perpendicular to the margin strike across the Jan Mayen Fracture Zone. Note the presence of Inner SDR, the well-defined prograding reflections (r1) in the Lava Delta, and high-amplitude, disruptive reflections in the Inner Flows. FSE, Faeroe-Shetland Escarpment; VE, Vøring Escarpment. t, top of volcanic sequence; p, planated top-basement reflection.

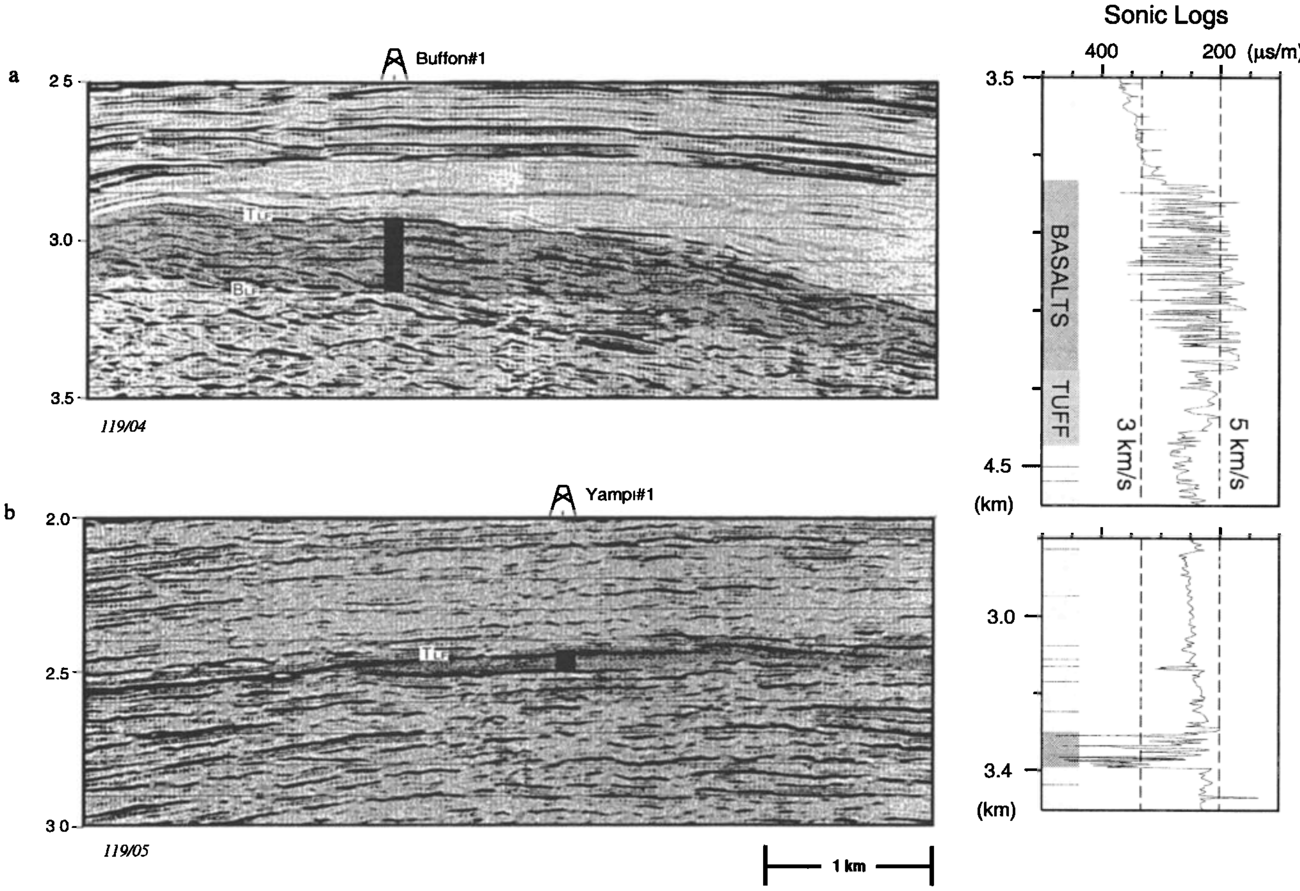

Figure 8. Seismic examples of Landward Flows drilled in the Browse Basin (Figure 1). In Buffon-1 (Figure 8a) the basalts represent a high-velocity unit, with P wave velocity varying from 3 to 5.5 km/s and an average check shot velocity of about 4 km/s. In contradiction, the volcanics in Yampi-1 (Figure 8b) constitutes a low-velocity interval. T_{LF}, top lava flow; B_{LF}, base lava flow. Well interpretations and data are from *Wilmot et al.* [1993] and well-completion reports.

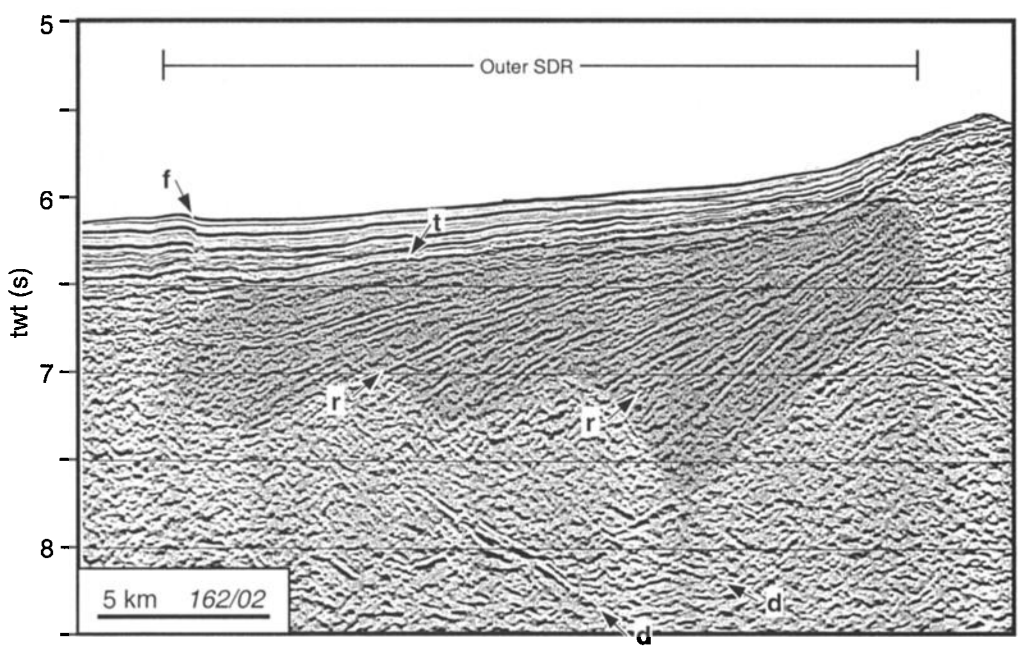

Figure 9. Seismic example of the Outer SDR off the southwest corner of the Exmouth Plateau (Figure 1) showing a smooth top-basement reflection and well-defined, diverging internal reflections. Here t, top of volcanic sequence; r, prominent reflections dividing the Outer SDR into sub-units; d, landward dipping reflections interpreted as intruded faults; f, fault.

Table 1. Dominant Characteristics of the Main Volcanic Extrusive Seismic Facies Units on Rifted Volcanic Margins

Seismic Facies Unit	Reflection Characteristics			Selected References*
	Shape	Boundaries	Internal	
Outer SDR	wedge	Top: high-amplitude, smooth or with pseudoescarpments. Overlying: onlap or concordant. Base: seldom defined.	Divergent-arcute or -planar. Disrupted, nonsystematic truncations.	*Skogseid and Eldholm* [1987]; *White et al.* [1987]
Outer High	mound	Top: high-amplitude, disrupted or planated. Overlying: distinct onlap. No base.	Chaotic.	*Roberts et al.* [1984]
Inner SDR	wedge	Top: high-amplitude, smooth or with pseudoescarpments. Overlying: onlap or concordant. Base: seldom defined.	Divergent-arcute. Disrupted, nonsystematic truncations.	*Hinz* [1981]; *Mutter et al.* [1982]; *Talwani et al.* [1983]; *Larsen and Jakobsdottir* [1988]; *Keen and Potter* [1995]; *Barton and White* [1997]; *Lizarralde and Holbrook* [1997]
Landward Flows	sheet	Top: high-amplitude, smooth. Overlying: conform or onlap. Base: low-amplitude, disrupted.	Parallel to subparallel. High-amplitude, disrupted.	*Talwani et al.* [1983]; *Boldreel and Andersen* [1994]
Lava Delta	bank	Top: high-amplitude, or reflection truncation. Base: reflection truncation.	Prograding clinoform. Disrupted.	*Wood et al.* [1988]; *Boldreel and Andersen* [1994]
Inner Flows	sheet	Top: high-amplitude, disrupted, Overlying: conform or onlap. Base: negative polarity, but often obscured.	Chaotic or disrupted, subparallel.	*Talwani et al.* [1983]; *Wood et al.* [1988]; *Skogseid et al* [1992]; *Boldreel and Andersen* [1994]

*References are to publications with original seismic profile reproduced Interpretation of seismic facies units may differ from those in the publications.

surface connecting the lower termination of the prograding reflections but is often more difficult to identify. In the northeast Atlantic the unit is associated with the landward facing Vøring and Faeroe-Shetland escarpments on the central Norwegian and northern United Kingdom margins [*Smythe et al.*, 1983], although significant variations in reflection characteristics are found along strike of the escarpments [e.g., *Blystad et al.*, 1995].

5.1.3. Inner Flows. The Inner Flows is a sheet-like body of very disrupted or hummocky reflections located landward and below the Lava Delta (Figures 5 and 7). The top reflection is a high-amplitude, disrupted event. Internal reflection configuration is chaotic. The base is a weak negative-polarity reflection but is often difficult to identify. The unit is up to ~60 km wide on the central Norwegian margin [*Blystad et al.*, 1995] and is typically several hundred meters thick. Overlying reflections are dominantly sub-parallel, whereas deeper reflections are frequently masked.

5.1.4. Inner SDR. The Inner SDR top-basement reflection is typically a strong, continuous, smooth or wavy event, and toplap is commonly observed (Figure 6). Locally, the reflection is planated or includes small escarpments [e.g., *Larsen*, 1990]. Intrabasement reflections are fairly weak, discontinuous segments with a divergent-arcuate or sometimes a divergent-planar pattern [*Parson et al.*, 1988]. The unit is wedge-shaped. Reflection terminations are common within the SDR. These are mostly nonsystematic but do sometimes define boundaries dividing the SDR into subunits [*Planke and Eldholm*, 1994; *Lizarralde and Holbrook*, 1997]. A base reflection is rarely identified, partly because of masking by strong sea floor multiples. A notable exception is the intrabasaltic K reflection on the south-central Vøring Plateau [*Hinz*, 1981; *Skogseid and Eldholm*, 1987]. The Inner SDR units are typically 15-50 km wide with a maximum thickness of 6 km [*Eldholm and Grue*, 1994; *Keen and Potter*, 1995]. Internal reflections are <10-15 km long, with a general dip of <15°. Much wider SDR are imaged near hot-spot trails [e.g., *Larsen*, 1990]. The presence of an Inner SDR unit is regarded as a sufficient, but not necessary, condition for the definition of a volcanic margin (Figure 1) [*Eldholm et al.*, 1995].

5.1.5. Outer High. The Outer High is a mounded feature characterized by a fairly strong top reflection, chaotic internal reflection configuration, and a location near the seaward termination of the Inner SDR (Figures 5 and 6). The mounds are up to 1.5 km high and 15-20 km wide and are locally continuous along strike. The unit has been mapped along the western margin of the Rockall Plateau near Anomaly 24B [*Roberts et al.*, 1979] and for >150 km on the Cuvier Margin [*Symonds et al.*, 1998]. The relief of the mound varies along strike but is commonly flat-topped. Different type of outer highs are observed on nonvolcanic rifted margins near the continent-ocean boundary [e.g., *Shipboard Scientific Party*, 1984]. These outer highs have different seismic characteristics and are interpreted as rotated fault blocks or basement highs.

5.1.6. Outer SDR. Two sets of SDR units are observed on many volcanic margins, for example, on the Vøring Margin [*Skogseid and Eldholm*, 1987] and the Rockall/Hatton Bank Margin [*Roberts et al.*, 1984; *White et al.*, 1987; *Barton and White*, 1995]. Overall, the seismic characteristics of both SDR units are similar. However, the Outer SDR is smaller, with weaker, less prominent internal reflections (Figures 6a and 9). The Outer SDR are located seaward of the Outer High at greater water depths than the Inner SDR. It has a smooth top-basement reflection and a gradual transition to a normal, hummocky-type or smooth top oceanic basement reflection.

5.1.7. Other characteristic features. A range of other extrusive and shallow intrusive volcanic features has been identified on seismic data. These features include shield volcanoes [*Boldreel and Andersen,* 1994], plugs and plutons [*Gatliff et al.,* 1984], dikes [*Jenyon,* 1987], and vents [*Skogseid and Eldholm,* 1989]. Furthermore, the tuffaceous Balder Formation in the North Sea corresponds to a prominent base-Eocene reflection in the North Sea [*Wood et al.,* 1988]. Sill and dike intrusions are commonly found in sedimentary basins on volcanic margins, imaged typically as high-amplitude, climbing reflections (Figure 5a) [*Joppen and White,* 1990; *Larsen and Marcussen,* 1992; *Conceicao et al.,* 1993]. These volcanic features frequently have diagnostic seismic expressions and may thus be important in evaluating and corroborating the existence and nature of breakup volcanic complexes.

The seismic characteristics and thickness of oceanic crust adjacent to rifted margins further provide constraints on the breakup-related magmatism. On volcanic margins the top-basement reflection is often a high-amplitude, very smooth event seaward of the Outer High. Here, the crustal thickness is up to 10 km (Figure 6b) [*Hopper et al.,* 1992]. Further seaward, low-angle, ridgeward dipping intrabasement reflections in the oceanic domain are interpreted to reflect episodes of high magmatic productivity [*Eldholm et al.,* 1995]. Such reflection units are identified in a number of ocean basins in the vicinity of volcanic margins and often in areas with a smooth top-basement reflection [*Symonds et al.,* 1998]. However, the intrabasement reflections should be interpreted with caution in these areas, as they locally appear to be peg-leg multiples in the overlying sediment package. In contrast, normal oceanic crust is, on average, 6 km thick [*White et al.,* 1992] and frequently has a hummocky or rough high-amplitude top-basement reflection with little subhorizontal or shallow dipping intrabasement reflections.

5.2. Volcanic Facies and Emplacement Environment

The nature of the characteristic seismic facies units identified within the volcanic seismic sequence may be related to variations in volcanic morphology and emplacement conditions. A volcanological interpretation of the seismic facies units requires an integrated approach combining well data, outcrop studies, petrophysical data, and seismic wave propagation theory.

5.2.1. Landward Flows. The Landward Flows unit has been drilled at a number of margins, for example, off Western Australia (e.g., Buffon-1, Figure 8a) and in the northeast Atlantic (e.g., ODP Sites 642 and 917 near the boundary of the Inner SDR and the Landward Flows [*Eldholm et al.,* 1989; *Larsen et al.,* 1994]). The drilled intervals consist of subaerially erupted and emplaced flood basalts, with no or thin inter-basalt sediment layers.

The internal lava-flow structure and variations in petrophysical properties can be obtained from borehole cores and log measurements. The P wave velocity in subaerial basalts shows systematic variations from 2-3 km/s in the top to 5.5-6 km/s in the interior in >5-m-thick units (Figure 2). These large velocity variations are primarily caused by changes in porosity, pore aspect ratio, and alteration [*Wilkens et al.,* 1991; *Planke,* 1994; *Planke et al.,* 1999]. The average velocity in the lava pile is largely dependent on the average lava flow thickness, being ~4 km/s for lava piles with average thickness of 6 m [*Planke and Cambray,* 1998]. Seismic reflections in the Landward Flows are mainly interference phenomena of thin flows due to large, systematic variations in physical properties within individual lava units but may also represent thick, ponded lavas from voluminous eruptions [*Planke and Eldholm,* 1994; *Smallwood et al.,* 1998]. The systematic changes in P wave velocity in layered basalts suggest that such constructions are anisotropic, estimated to be 10-20% from combined vertical seismic profiles (VSP) and refraction measurements on Iceland and synthetic seismogram modeling [*Planke and Flóvenz,* 1996].

Near-vertical feeder dikes are difficult to image on seismic data. The source region for the Landward Flows unit is therefore poorly constrained. Because subaerial flood basalts may flow for several hundred kilometers, a fairly narrow zone along the incipient breakup axis can supply basalt to the Landward Flows complexes. The overall sheet-like shape and the pinch out and onlap on deeper reflections in a landward direction suggest the unit is constructed by infilling of a broad basin.

5.2.2. Lava Delta. In places, the Landward Flows unit does not pinch out but merges with the Lava Delta seismic facies unit (Figure 7). The Lava Delta unit has not been drilled, but a combined interpretation of the well-defined seismic reflection configuration compared with modern and ancient analogues suggests that this unit can be interpreted as the foreset of a lava delta.

Velocity measurements of fragmented basalts are scarce. Downhole P wave velocities of basaltic breccia, lapillistone, and hyaloclastite in ODP Holes 953C and 956B off the Canary Islands vary from 2.5 to 4 km/s (Figure 3). Core measurements are systematically higher because of biased sampling of more massive parts, and the P wave velocities of individual clasts are up to 6 km/s. Volcaniclastic rocks drilled below flood basalts in Buffon-1 off Western Australia have sonic P wave velocities of 3.5 to 5 km/s with an average of 4.4 km/s (Figure 8a). The seismic properties of the Lava Delta are likely related to the strongly varying velocities in the hyaloclastic breccias. Locally, massive flows may constitute high-velocity units, while volcaniclastic sands are low-velocity units. The reflections will vary from well-developed prograding events in bedded volcaniclastics, or between main depositional units, to a chaotic character in basaltic breccias.

The seismic data suggest that the Lava Delta is building outward in front of the growing Landward Flows. Thus, the eruption fissure of the Lava Delta and Landward Flows units is in the same region.

5.2.3. Inner Flows. The Inner Flows unit is identified landward, and sometimes below, the Lava Delta and Landward Flows. The facies unit has not been drilled, and the emplacement model is thus based on seismic characteristics and the setting in relation to other facies units. In our model the Inner Flows correspond to the bottomset in a Gilbert-type delta. The Inner Flows has a chaotic internal reflection pattern, frequently inhibiting imaging of deeper basin structures (Figure 7). We interpret these seismic characteristics to reflect a chaotic internal and external structure of a unit consisting of a mixture of massive and fragmented basalt and volcaniclastic rocks. We suggest that the main source of the Inner Flows are fissures along the region of continental breakup, as the unit is interpreted to have formed simultaneously with the Landward Flows and Lava Delta.

5.2.4. Inner SDR. Scientific drilling has confirmed that the top of the Inner SDR seismic facies unit consists of subaerially emplaced flood basalts with minor interflow sediments [e.g., *Larsen et al.*, 1998]. The basalts in both the Inner SDR and Landward Flows units are subaerially emplaced lavas with similar petrophysical properties (Figure 2). However, the reflection pattern of the Inner SDR and the Landward Flows differs, as the Inner SDR shows a diverging, arcute pattern, while the Landward Flows has a subparallel, subhorizontal internal reflection configuration. We relate these differences in seismic facies to differences in basin geometries. The Landward Flows were deposited on a plain or in a broad basinal depression. In contrast, the Inner SDR are either formed during a phase of subaerial seafloor-spreading [*Mutter et al.*, 1982] or by syntectonic infilling of a rift basin [*Hinz*, 1981].

Pálmason [1981] developed a kinematic model for the generation of ridge-axis dipping lavas in a steady state subaerial seafloor-spreading system on the basis of observations of dipping lavas in the Tertiary basalt pile on Iceland. This model has later been used as a basis to explain the construction of SDR on rifted margins [e.g., *Mutter et al.*, 1982; *Larsen and Saunders*, 1998]. Both seismic data and drilling results show that the Inner SDR is at least partly underlain by extended continental crust [*Eldholm et al.*, 1989]. Figure 7c shows that SDR also can be formed perpendicular to fracture zones on volcanic margins, clearly not deposited in a seafloor-spreading environment. The steady state assumption in Pálmason's model is therefore likely not obtained during the construction of the Inner SDR. Its formation is rather a response to the interplay between tectonic and magmatic processes involving rapid subsidence of extended continental crust and newly formed basaltic crust.

Normal faults have not been clearly imaged within the SDR, though it has been speculated that the SDR are fault-bounded [e.g., *Eldholm et al.*, 1989; *Barton and White*, 1997]. Normal faults were further penetrated at Site 917 on the southeast Greenland margin [*Larsen et al.*, 1994]. Landward dipping reflections within the lower part of the Inner SDR may be interpreted as intruded faults (Figure 6b). The seismic expression of sediment infill in active-fault bounded basins is dependent on the rate of fault movement and the rate of sediment flux [*Prosser*, 1993]. In a nonvolcanic setting the rift climax stage is likely to be characterized by sediment starvation, and postrift sediments make up a large proportion of the basin fill [*Prosser*, 1993]. In contrast, on a volcanic margin, large volumes of magma are erupted near breakup time, and the basins are likely not starved. The lava flows may therefore infill any depression to its spill point. However, the basin geometries may be complex, as documented by the absence of SDR on seismic profiles nearby reflection profiles with well-developed SDR [*Alvestad*, 1997; *Larsen*, 1990]. The arcute, diverging reflection pattern in the Inner SDR is related to more numerous and thicker lava flows toward the rift axis where the largest accommodation space was created. Hypothetically, the reflections may locally represent fragmented basalt units formed by lava-water interaction. Presently, no drill holes have penetrated a major reflection within the SDR, and the nature of the reflections is thus not well constrained [*Planke and Alvestad*, 1999].

Short, segmented landward dipping reflections are frequently identified within the lower, seaward part of the Inner SDR (Figure 6b). These events are nearly perpendicular to the SDR. We interpret them as feeder dikes possibly intruding along faults. The dikes may initially have been emplaced as near-vertical sheets, having acquired their dip by subsequent basin subsidence.

5.2.5. Outer High. The Outer High is commonly located near the seaward termination of the Inner SDR. The primary target of Deep Sea Drilling Project Site 554 was to investigate the nature of the Outer High on the Rockall Plateau. Hole 554A drilled ~82 m into basement, recovering volcaniclastic conglomerates and sandstones, interbedded with basalt lava flows [*Shipboard Scientific Party*, 1984]. The core recovery was poor, only 16%, because of very difficult drilling conditions. The core analysis suggests that the drilled unit is totally derived from submarine basalt flows, consisting of both primary emplaced basalt flows and volcanogenic sediments eroded by wave action and deposited just below wave base [*Shipboard Scientific Party*, 1984].

The construction of the Outer High is related to shallow marine volcanism occurring when the spreading center is submerged [*Planke et al.*, 1995]. A shallow marine fissure environment may explain the location, geometry, and lateral continuity of the Outer High units. The internal chaotic reflection pattern is related to interference of energy reflected from laterally rough, high-impedance boundaries between massive and fragmented basalt within individual hyaloclastite flows. Large volumes of tuffs are formed during explosive shallow marine eruptions [*Fischer and Schmincke*, 1994], and the tuffs may be wind-transported far away from the source region. Volcaniclastic and volcanogenic sediments formed during shallow marine eruptions and subsequent coastal erosion may rapidly infill local basins landward of the Outer High (Figure 6a). Strong, horizontal reflections within these basins are interpreted as energy reflected from either massive flows or shallow sill intrusions, both being evidence of rapid sedimentation.

5.2.6. Outer SDR. The Outer SDR have never been sampled by drilling but are interpreted as deep marine sheet flow constructions [*Planke et al.*, 1995]. Voluminous volcanism with high volumetric flow rates is expected during the early drift phase, resulting in basaltic sheet flows emplaced by similar processes as subaerial flood basalts [*Holcomb et al.*, 1988; *Hon et al.*, 1994]. The petrophysical properties of subaerial and deep marine flood basalts are quite similar, with low-velocity flow tops and high-velocity flow interiors (for example, ODP Site 642 and DSDP Site 462; Figure 2 and *Shipboard Scientific Party* [1986], respectively). The infilling of a deep marine basin by sheet flows may therefore result in a seismic image similar to that observed in the Inner SDR. The continuity of reflections is poorer for deep marine lava complexes than for its subaerial equivalent, as the dominant deep marine emplacement mode changes from massive to pillow basalts as the volumetric flow rate decreases away from the eruption fissure. Furthermore, interbedded sediments may be more common in a narrow, submarine basin, giving rise to seismic ringing and poorer reflection images.

Multiple SDR units may be constructed by ridge jumps or in multiple prebreakup rift basins separated by basement highs (e.g., on the mid-Norwegian margin and southern Cuvier Margin [*Skogseid and Eldholm*, 1987; *Symonds et al.*, 1998; *Alvestad*, 1997]). Both SDR units may in these provinces be subaerial constructions. Deep marine SDR may be distinguished from subaerial SDR on the basis of observations of (1) smooth top-basement reflection continuos between SDR and normal oceanic crust and (2) SDR located seaward of an Outer High.

Figure 9 shows a well-imaged Outer SDR unit. The interpretation of this unit is based on its position seaward of the continent-ocean boundary, its location in deep water (~4.5 km), and the smooth continuation of its top reflection to normal oceanic crust. Deeper landward dipping events are interpreted as intruded faults. Displacement of the sea floor reflection shows that movement has occurred on the fault up to recent times. These observations suggest that the Outer SDR is formed by similar processes as the Inner SDR, that is, by volcanic infilling of a rift basin.

Intrabasement reflections are often not imaged seaward of the Outer High (Figure 6b). The top-basement reflection is typically smooth in these regions, suggesting high magmatic productivity. The reflection may represent the top of a massive flow complex [*Macdonald et al.*, 1989], or, alternatively, it may be related to sill intrusions [*Abrams et al.*, 1993]. Sills are commonly drilled near the continent-ocean transition (e.g., ODP Hole 766 on the Western Australian margin [*Gradstein et al.*, 1992]), and sill intrusions are the favored magma emplacement mode in narrow ocean basins with high sedimentation rate [*Einsele*, 1985].

5.3. Magma-Sediment Interaction

The initial stage of flood basalt volcanism commonly occurs in a rift basin setting, having undergone lithospheric extension prior to the initiation of volcanism. On the Vøring Margin, extension started in Late Cretaceous, about 13 m.a. before the first flood basalt volcanism in the northeast Atlantic [*Skogseid et al.*, 1992]. Similarly, the flood basalts on east and west Greenland regionally overlie Cretaceous and Tertiary sedimentary basins [*Watt et al.*, 1986; *Pedersen et al.*, 1996]. Recently, *Hanson and Elliot* [1996] showed that the Antarctic Kirkpatrick flood basalts emplaced during the Jurassic Gondwana breakup were preceded by extensional tectonics.

Explosive eruptions of magma in a wet sedimentary basin may have formed the sequences below the Inner Flows. Figure 7b shows a seismic facies unit that is interpreted as a mixed sedimentary and volcanic complex. However, this unit has not been included in the general seismic facies description, as we have few well-documented seismic examples of it. Locally, explosive eruptions may also have produced deposits forming parts of the Inner Flows.

5.4. Tephra Formation

The explosive volcanic stages have not received much attention in volcanic margin studies. The potentially large volumes of ash and volcanogenic sediments that are formed should be considered when estimating extrusive volumes and climatic effects of large igneous provinces. We propose that tephras in the Balder and the mo-clay formations are mainly formed during the postbreakup, shallow marine volcanic stage. The presence of extensive, voluminous tephras in Denmark, more than 1000 km from the breakup axis, shows that the ash has been deposited over a large region in northwestern Europe. Tephras will easily erode, become resedimented, and alter to clay minerals [*Fischer and Schminke*, 1994]. Large parts of the Eocene and Paleocene sediments in the North Sea and on the central Norwegian margin are smectite-rich clays with distinct petrophysical properties [*Jordt et al.*, 2000]. Smectites are typical alteration products of basaltic tuffs [*Thyberg et al.*, 2000], and we suggest that the Tertiary North Sea smectites largely represent resedimented, altered tuffs formed during the shallow marine volcanic stage.

6. Emplacement Model

The results of the seismic volcanostratigraphy on rifted margins are summarized in Table 2. This table shows the interpreted volcanic facies and emplacement environment for the main seismic facies units. A five-stage schematic two-dimensional emplacement model is proposed based on the analysis. The prevolcanic rift setting, total magma production, and extent of erosion will determine the significance or presence of each depositional unit and evolutionary stage. Deviations from the model are therefore expected between various margins and margin segments.

The five volcanic stages (Figure 10) represent (1) initial explosive volcanism in an aquatic or wet sediment environment forming basalt-sediment complexes poorly imaged on the seismic data; (2) effusive subaerial volcanism, including coastal hydrovolcanic and sedimentary processes, forming the deposits imaged as the Inner Flows, Lava Delta and Landward Flows seismic facies units; (3) continuing effusive subaerial volcanism as the rift narrows, infilling the rapidly subsiding rift basins along the breakup axis forming the deposits imaged as the Inner SDR; (4) explosive shallow marine volcanism forming deposits imaged as the Outer High; and (5) voluminous, effusive deep marine volcanism forming deposits imaged as the Outer SDR.

The location of the feeder systems is relatively poorly constrained. Steep landward dipping reflection segments are

Table 2. Seismic Facies Analysis

Seismic Facies Unit	Volcanic Facies	Emplacement Environment	Well Calibration*
Outer SDR	flood basalts mixed with pillow basalts, sediments, and sills	deep marine	
Outer High	hyaloclastic flows and volcaniclastics	shallow marine	DSDP 554
Inner SDR	flood basalts	subaerial	DSDP 553, ODP 918
Landward Flows	flood basalts	subaerial	DSDP 552, ODP 642, 915, 916, 917, 988, 989, 990 Buffon-1; Yampi-1†
Lava Delta	massive and fragmented basalts; volcaniclastics	coastal	
Inner Flows	massive and fragmented basalts; volcaniclastics	subaqueous	

*From *Planke and Alvestad* [1999].
†See Figure 8.

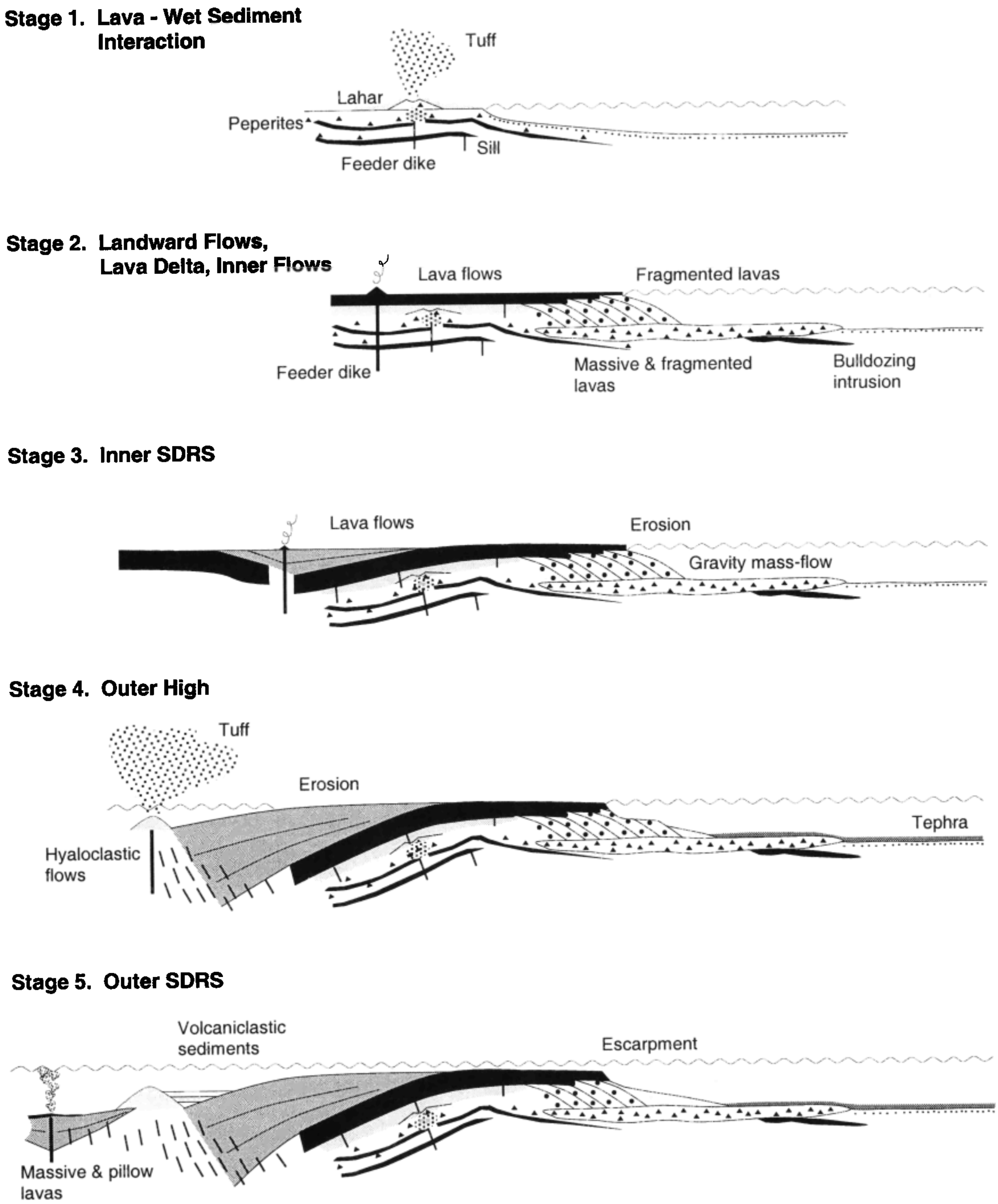

Figure 10. Schematic emplacement model for the major extrusive seismic facies units on volcanic margins divided into five main stages. See Table 2 and text for further discussion.

sometimes identified below the seaward part of the Inner SDR (Figures 6b and 9) and have been interpreted as feeder dikes on the Jan Mayen Ridge [*S. Gudlagsson*, personal communication, 1997]. Mounded features may in places be interpreted as volcanoes but are seldom identified except as the linear Outer High. There is a spatial correlation between the lower crustal high-velocity bodies interpreted as magmatic underplated material and the upper crustal extrusive and intrusive complexes on volcanic margins (e.g., the Vøring Margin [*Skogseid et al.*, 1992]). This correlation suggests that the upper crustal volcanic deposits are partly fed directly from below. However, the interpretation is hard to document from the available seismic data. In our model we have therefore emphasized volcanic feeders along the well-documented source region along the incipient breakup and subsequent seafloor-spreading axis.

7. Conclusions

Basaltic volcanic complexes on rifted margins often have distinct seismic expressions. We have developed the concept of seismic volcanostratigraphy, a subset of seismic stratigraphy [*Payton*, 1977], to study volcanic extrusive complexes on volcanic margins. The method can provide constraints on the prevolcanic basin setting, the nature and relative timing of volcanic and tectonic events, and the location of paleoshorelines. Only one volcanic seismic sequence is interpreted in regional studies. However, seismic volcanostratigraphy emphasizes the seismic facies analysis, in particular, identification and mapping of seismic facies units. Six well-defined seismic facies units are commonly present on volcanic rifted margins. These are the Inner Flows, the Lava Delta, the Landward Flows, the Inner SDR, the Outer High, and the Outer SDR (Table 1).

The seismic facies units are interpreted in terms of volcanic eruption and emplacement processes (Table 2). Volcanic margin studies often focus on the subaerial seafloor-spreading processes [*Mutter et al.*, 1982]. Our new data document the importance of tectonism, water-magma interaction, and resedimentation processes for understanding the nature of the volcanic breakup complex. Landward dipping reflection segments interpreted as intruded faults show that the Inner and Outer SDR are often fault-bounded. Moreover, the presence of SDR on a profile perpendicular to the Jan Mayen Fracture Zone corroborates the tectonic control on the geometry of the SDR. Coastal processes are also important because they form characteristic Gilbert-type deltas, with an aggradational subaerial basalt topset, a shallow marine progradational foreset, and a mixed volcaniclastic-massive basalt aggradational bottomset.

The explosive, shallow marine eruption stage forms the characteristic mounded Outer High and voluminous volcaniclastic sediments and tuffs being deposited in nearby basins. The extensive tuff formation during this eruptive stage may further be responsible for regional environmental changes. Resedimentation and alteration of the tuffs may yield smectite-rich clay units with distinct petrophysical and geotechnical properties. Voluminous deep marine sheet flow deposits are further suggested to be imaged as the Outer SDR, being formed in a similar manner as the subaerial Inner SDR. The deep marine nature of the Outer SDR unit is not constrained by borehole data but is an easily accessible target for scientific drilling.

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