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Influence of rift jump and excess loading on the structural evolution of northern Iceland

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[1] New structural data combined with published structural and geochronological data allow reconstruction of the structural evolution that followed the last rift jump across northern Iceland. Tertiary lava flows erupted along the Skagafjördur paleo-rift have been down-bent under the weight of, and in the direction of, Plio-Pleistocene lava flows emitted from the Northern Volcanic Zone and the central part of Iceland. This down-bending process involved development of local flexure zones and a flexural extension along the resulting monoclines. This structural reorganization explains the existence of the Húnaflói-Skagi synform without need for a paleo-rift axis along it, in agreement with previous radiometric dating. The large amount of Plio-Pleistocene lava flows erupted in Central Iceland may have been enhanced by ice cap loading.

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1. Introduction

[2] Iceland is an emerged ridge that results from the interaction between the Mid-Atlantic Ridge (MAR) and the Icelandic hot spot. The apex of hot mantle upwelling is localized beneath the Vatnajökull ice cap [*Tryggvason et al.*, 1983] (Figure 1). As the North American-Eurasian plate boundary, marked by the MAR, migrates westward relative to the Icelandic hot spot [*Burke et al.*, 1973], eastward rift jumps bring the volcanic zones of Iceland back to the centre of the hot spot [*Saemundsson*, 1974; *Ward*, 1971]. Such a phenomenon has been documented on mid-oceanic ridges [*Brozena and White*, 1990; *Krishna and Rao*, 2000; *Small*, 1995; *Vogt and Jung*, 2004; *Wilson and Hey*, 1995], but generally remains difficult to analyze because the corresponding evidences for plume-ridge interaction are underwater. Iceland, as an emerged part of the MAR, offers the opportunity to study precisely structural consequences of such rift jumps.

[3] Recent dating led to reconsider both the chronology and the locus of the last rift jump in Northern Iceland. *Garcia et al.* [2003] thus demonstrated that the North Volcanic Zone (NVZ) of Iceland (NVZ in Figure 1) initiated about 8-8.5 Ma on the eastern flank of the recently defined Skagafjördur paleo-rift (SPRA) (SPRA in Figure 1) and that this paleo-rift became extinct around 3 Ma. The new location of the paleo-rift axis appears to be 60 km east of the previously proposed position for a paleo-rift axis (Húnaflói-Skagi synform (HSS) in Figure 1) [*Saemundsson*, 1974].

[4] In the active Icelandic rift, lava flows usually dip in direction of the rift axis and thus define a synform-like structure. By analogy with this particular geometry, the paleo-rift zones in Iceland are classically defined as synform-like structures. The previous location of the paleo-rift axis in Northern Iceland (HSS in Figure 1) had been proposed to fit such a structure [*Saemundsson*, 1974]. In contrast, no similar structure has been described along the paleo-rift axis proposed by *Garcia et al.* [2003] based on magmatic ages. Such discrepancies between structural and dating evidences reveal the complexity of the relationships between lava flow dips and rift positions. The following question thus needs to be addressed: why does the Skagafjördur paleo-rift location ascertained by radiometric dating so markedly differ from that of the Húnaflói-Skagi synform previously considered as paleo-rift evidence?

[5] In this paper, a new model for the structural evolution of Northern Iceland is presented, based on a compilation of newly acquired structural data as well as published ones (lava dips, dike orientations, and fault measurements). This new model aims at reconciling structural data in Northern Iceland with both the location and the age of extinct or active rift structures revealed by geochronology [*Garcia et al.*, 2003]. The structural evolution of Northern Iceland appears mainly related to the rift jump process. However, our structural analysis leads us to highlight the key role played by the accumulation of Plio-Pleistocene to Holocene lavas from the Central part of Iceland (Figure 1), which partly controlled the later structural evolution of Northern Iceland. Besides presenting a coherent frame for the structural evolution of Northern Iceland, this paper also provides

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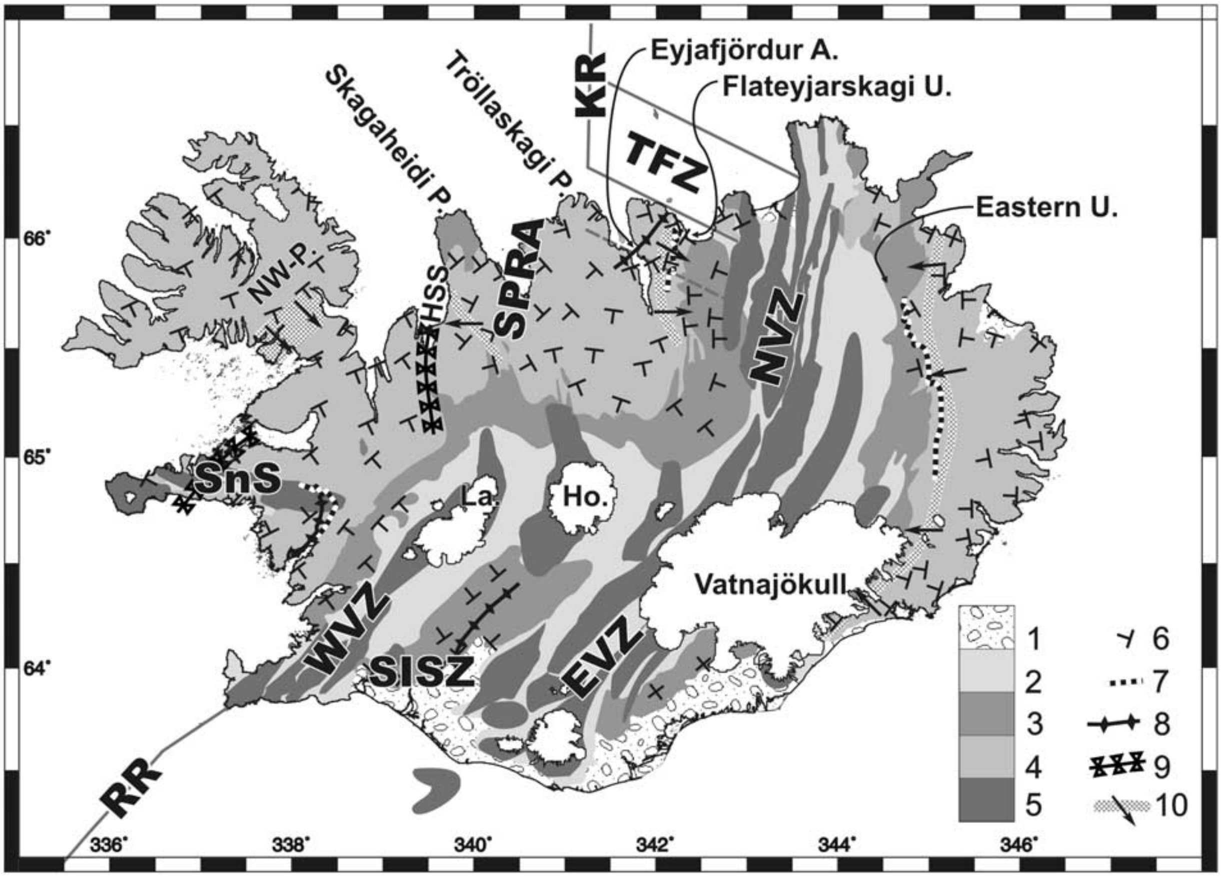


Figure 1. Structural map of Iceland: main active structures or structures resulting from rift jump process. Details, numbered in key, are as follows: 1, Holocene sediments; 2, upper Pleistocene–Holocene lava flows (<0.8 Ma); 3, Plio-Pleistocene lava flows (<3.3 Ma and >0.8 Ma); 4, Tertiary lava flows (>3.3 Ma); 5, active volcanic system; 6, dip of lava flows; 7, angular unconformity; 8, axis of antiform-like structure; 9, axis of synform-like structure; 10, flexure zone with sense of lava flows dip. Abbreviations are as follows: A, Antiform; EVZ, Eastern Volcanic Zone; Ho., Hofsjökull; HSS, Húnaflói-Skagi Synform; KR, Kolbeinsey Ridge; La., Langjökull; NVZ, Northern Volcanic Zone; P, Peninsula; RR, Reykjanes Ridge; SISZ, South Iceland Seismic Zone; SnS, Snaefellsnes; SPRA, Skagafjördur Paleo-Rift Axis; TFZ, Tjörnes Fracture Zone; U, Unconformity; WVZ, Western Volcanic Zone. Modified from *Johannesson and Saemundsson* [1998] and *Kristjansson et al.* [1992].

a general model of structural reorganization related to rift jump processes in hot spot setting.

2. Structural Geology of Northern Iceland

[6] The localization of the Skagafjördur paleo-rift proposed by *Garcia et al.* [2003] is based on geochronological data. It corresponds to the youngest domain (outside of the present active rift) in an age-versus-distance profile that trends parallel to the divergent plate motion in Northern Iceland [see *Garcia et al.*, 2003, Figure 5]. In this section, we present and describe new structural data from Northern Iceland in order to compare the results with the spatial and temporal frame proposed by *Garcia et al.* [2003]. We chose to combine our new data with the pre-existing ones as our data complete and confirm the structural scheme of Northern Iceland.

2.1. Strikes and Dips of Lava Flows

[7] The attitude of 200 lava flow piles were measured across Northern Iceland [*Garcia*, 2003]. However, in order to produce a more comprehensive and statistically valid map of lava flows attitude (Figures 2 and 3), our data are compiled together with data available from the literature [*Gudmundsson*, 1995; *Johannesson and Saemundsson*, 1998; *Kristjansson et al.*, 1992; *Saemundsson*, 1974, 1979; *Young et al.*, 1985]. It is worth noting that because of the fluidity of basaltic lavas the initial dips of these lava flows can be ignored with respect to the subsequent tilt angles at all places where the present-day dip is significantly steeper than that of most post-glacial lava flows in Iceland, for which the post-flow tilting effect is negligible. Except for local slopes, this dip is generally shallower than 2 degrees, which imply that dips of 4 degrees or more over large areas significantly reveal tilting. For shallower dips,

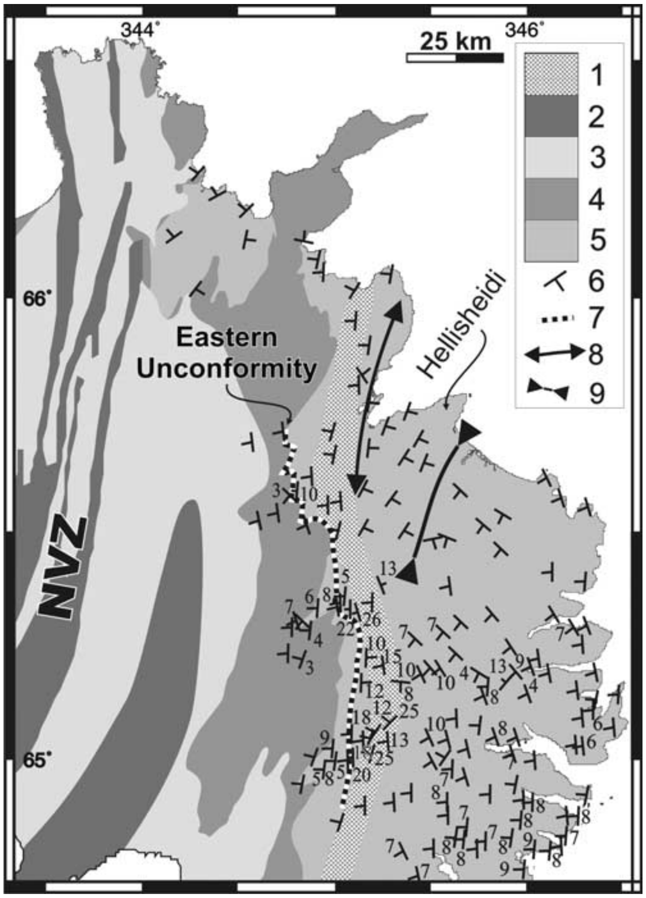


Figure 2. Lava dips and structures resulting from rift jump in Eastern Iceland. Details, numbered in key, are as follows: 1, flexure zone; 2, active volcanic system; 3, upper Pleistocene–Holocene lava flows (<0.8 Ma); 4, Plio-Pleistocene lava flows (<3.3 Ma and >0.8 Ma); 5, Tertiary lava flows (>3.3 Ma); 6, dip of lava flows; 7, angular unconformity; 8, axis of antiform-like structure; 9, axis of synform-like structure. NVZ: Northern Volcanic Zone. Newly acquired data are compiled together with published data from *Johannesson and Saemundsson* [1998], *Saemundsson* [1979], and *Walker* [1964].

further consideration of the initial flow direction brings additional constraints where the present-day dip direction markedly differs from the downstream direction of the lava flow. Note also that we only measured strikes and dips that affect large portions of lava piles with regular stratification at scales of several hectometers (horizontally) and decameters (vertically) or larger. This restriction allows us to avoid local effects that result from initial irregularities in lava flow or from late local faulting.

[8] Lava flows from the NVZ reach a maximum age of 8–8.5 Ma old [*Garcia et al.*, 2003]. Along both the eastern and western margins of the NVZ, lava flows unconformably overlie, and consequently are clearly distinct from, the older lava flows from the Skagafjördur paleo-rift [*Saemundsson*, 1979; *Walker*, 1964] (Figures 1, 2, and 3). The western and eastern angular unconformities are named Flateyjarskagi Unconformity (Figure 4) and Eastern Unconformity, respectively. Along both margins of the NVZ, lava flows dip by similar, low angles (3°–10°) toward the centre of the rift (Figures 2 and 3), defining a typical synform-like structure, which is more or less symmetrical with respect to the active central axis of the NVZ.

[9] East of the Eastern Unconformity, most of the 9–14 Ma old lava flows [*Bagdasaryan et al.*, 1976; *McDougall et al.*, 1976; *Moorbath et al.*, 1968; *Musset et al.*, 1980], emplaced within the Skagafjördur paleo-rift, dip 6°–10°W to SW [*Walker*, 1964], that is toward the present rift zone (Figure 2). They locally define a flexure zone with westward dips increasing to as much as 15°–18° along the Eastern Unconformity [*Walker*, 1964] (Figure 2). Some discrepancies exist within this frame: for instance, eastward dipping lava flows have been mapped, mainly along the extension of the Hellisheidi peninsula (Figure 2).

[10] The dip distribution of paleo-rift lava flows west of the Flateyjarskagi Unconformity is more complicated (Figure 3). As a whole it defines a synform-like structure centered on the Húnaflói-Skagi axis [*Johannesson and Saemundsson*, 1998; *Kristjansson et al.*, 1992; *Saemundsson*, 1974, 1979] (Figure 3). Along this synform-like structure, the dip of the lava flows rarely exceeds a few degrees (3°–10°) (Figure 3).

[11] West of the Húnaflói-Skagi synform axis, lava flows ages decrease from 15.05 ± 0.08 Ma to 8 ± 0.3 Ma old south-eastward along the NW-Peninsula [*Bagdasaryan et al.*, 1976; *McDougall et al.*, 1984; *Moorbath et al.*, 1968]. Most of these lava flows are dipping in direction of the Húnaflói-Skagi synform axis, i.e., to the E-ESE (Figure 3), with a locally deviating S-SSE dip direction within the area of Dala (Figure 3).

[12] East of the Húnaflói-Skagi synform axis, most lava flows dip to the W-WSW, with some easterly dip directions on the eastern part of the Skagaheidi Peninsula, giving rise to the so-called Skagaheidi antiform-like structure (Figure 3) [*Kristjansson et al.*, 1992]. It is important to note that this antiform-like structure parallels a synform-like structure along the Skagafjördur fjord (Figure 3) [*Kristjansson et al.*, 1992], along which *Garcia et al.* [2003] localized their Skagafjördur paleo-rift axis (SPRA in Figure 3).

[13] East of the Skagafjördur synform-like axis, most lava flows are gently dipping W-SW (Figure 3), with some E-SE dipping lavas in the eastern and south-eastern parts of the Flateyjarskagi Peninsula (Figure 3) [*Young et al.*, 1985]. Thus the lava flows emplaced within the Skagafjördur paleo-rift define a broad antiform-like structure (the Eyjafjördur Antiform) between the Húnaflói-Skagi synform and the Flateyjarskagi Unconformity (Figure 3) [*Young et al.*, 1985], which strikes approximately NE-SW through the Flateyjarskagi Peninsula (Figure 3). Moreover, lava flow dip directions rotate toward S-SSE in the southern and south-eastern parts of the Tröllaskagi Peninsula (Figure 3). We consequently propose that the Eyjafjördur Antiform ends in the Tröllaskagi Peninsula as a wide antiform termination (Figure 3). The axis of the Eyjafjördur Antiform can hardly be defined across the fjord of Eyjafjördur (Figure 3). We

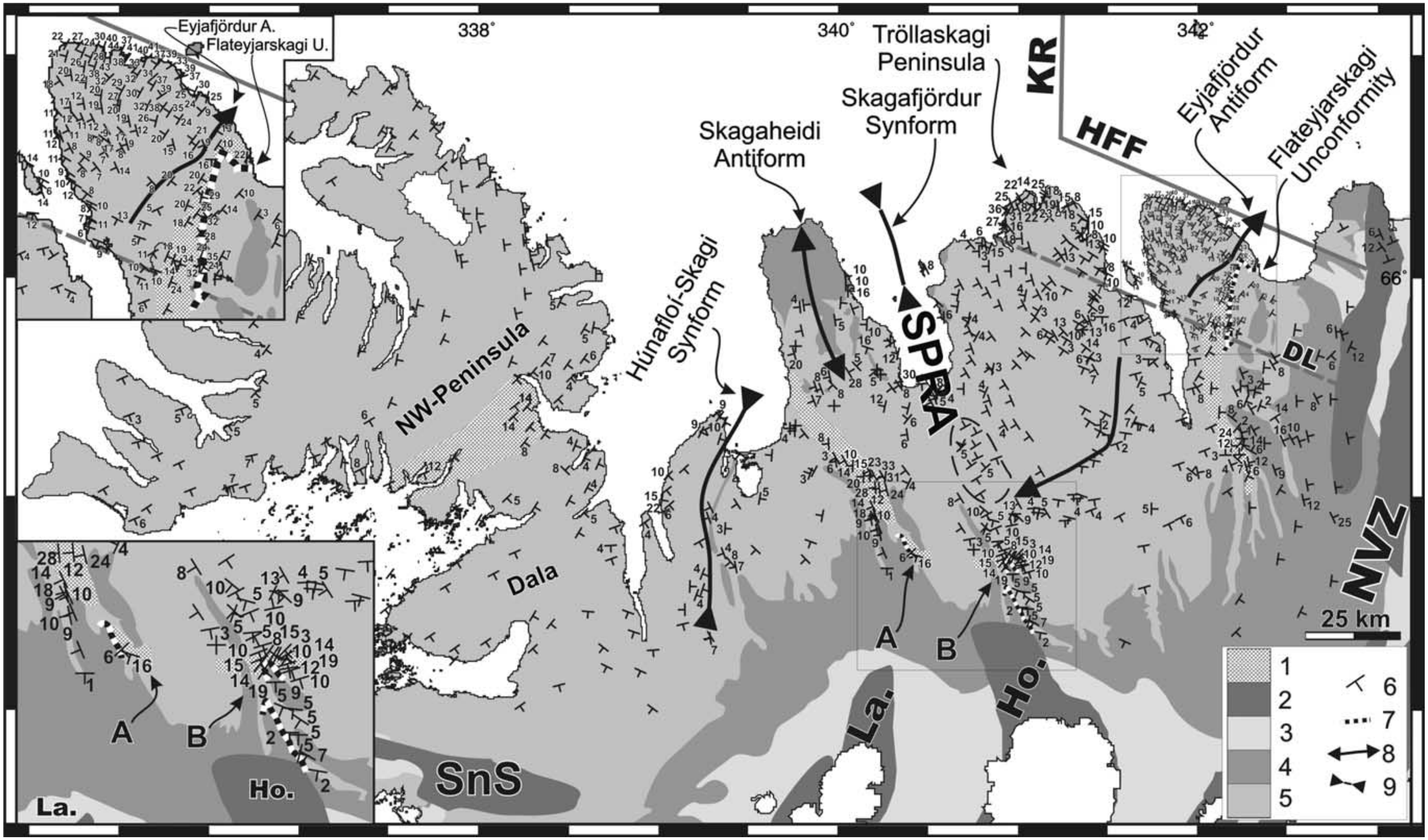


Figure 3. Lava dips and structures resulting from rift jump in Northern Iceland. Details, numbered in key, are as follows: 1, flexure zone; 2, active volcanic system; 3, upper Pleistocene–Holocene lava flows (<0.8 Ma); 4, Plio-Pleistocene lava flows (<3.3 Ma and >0.8 Ma); 5, Tertiary lava flows (>3.3 Ma); 6, dip of lava flows; 7, angular unconformity; 8, axis of antiform-like structure; 9, axis of synform-like structure. Abbreviations are as follows: DL, Dalvík lineament; HFF, Húsavík-Flatey Fault; La., Langjökull; Ho., Hofsjökull; KR, Kolbeinsey Ridge; NVZ, Northern Volcanic Zone; SnS, Snaefellsnes; SPRA, Skagafjördur Paleo-Rift Axis. Newly acquired data are compiled together with published data from *Gudmundsson* [1995], *Johannesson and Saemundsson* [1998], *Kristjansson et al.* [1992], *Saemundsson* [1974, 1979], *Saemundsson et al.* [1980], and *Young et al.* [1985].

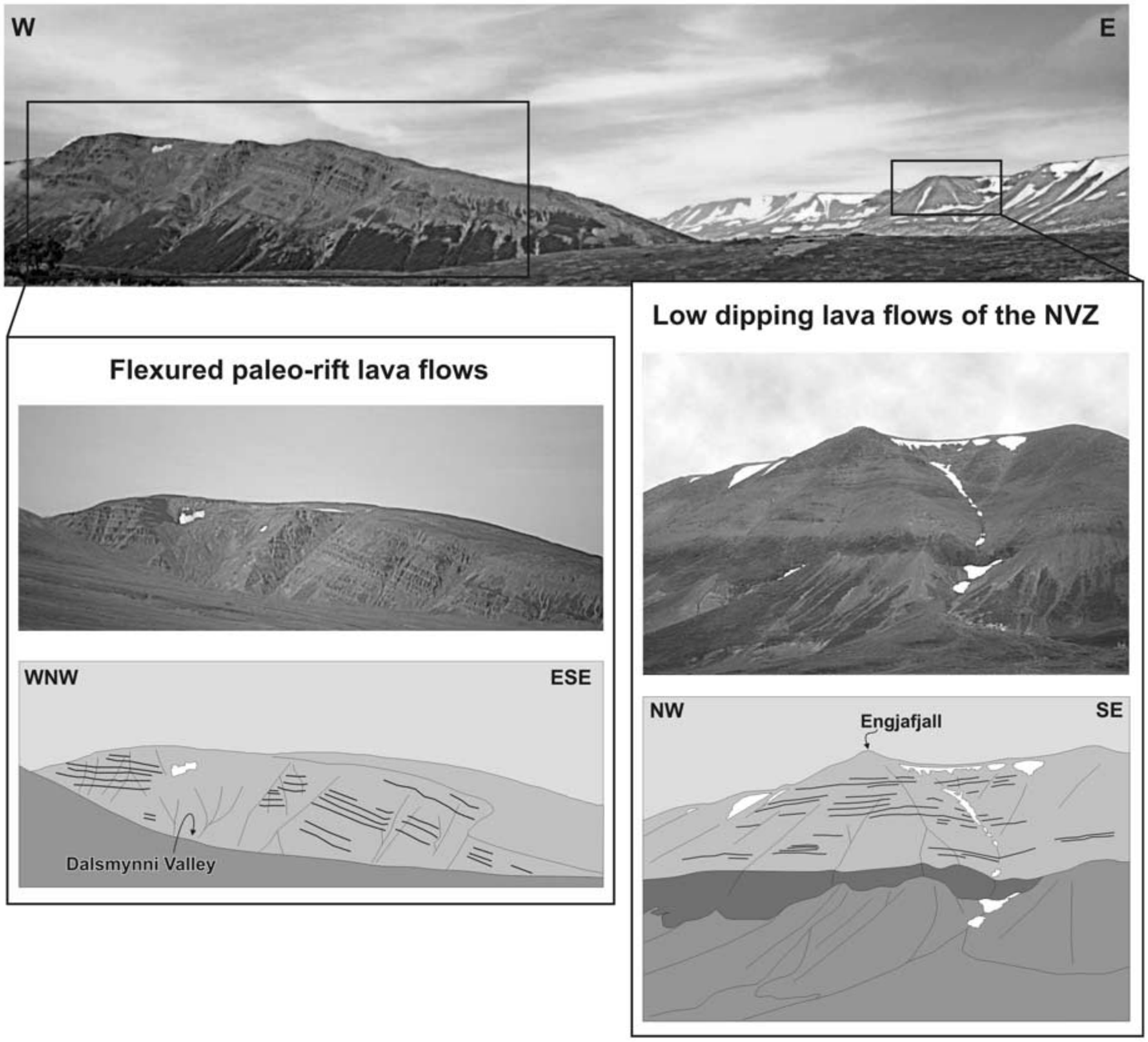


Figure 4. Flateyjarskagi angular unconformity and flexured zone. See Figure 1 for a localization of the angular unconformity and flexured zone.

suspect that the Dalvík lineament, the southernmost structure of the Tjörnes Fracture Zone (TFZ), a wide transform zone between the active NVZ and Kolbeinsey Ridge (Figures 1 and 3) [e.g., *Bergerat et al.*, 1992; Langbacka and *Gudmundsson*, 1995; *Rögnvaldsson et al.*, 1998] is responsible of these local heterogeneities of dip.

[14] In a symmetrical position relative to the eastern edge of the NVZ, the paleo-rift lava flows situated along the Flateyjarskagi Unconformity exhibit local eastward dips as steep as 20°E–25°E [*Young et al.*, 1985] (Figures 3 and 4). The dip distribution of paleo-rift lava flows thus defines a N-S trending flexure zone (Figure 3). Other flexures zones, with dips steeper than 30°, have been mapped in the paleo-rift lava flows on the southern part of the NW-Peninsula [*McDougall et al.*, 1984] and of the Skagaheidi Peninsula [*Johannesson and Saemundsson*, 1998; *Kristjansson et al.*, 1992] (Figure 3). Moreover, we have locally observed Tertiary lava flows with steep southern dips (or flexure zones) south of the Tröllaskagi and Skagaheidi Peninsulas (indicated by letters A and B in Figure 3). Also, lava flows are dipping NW to SW with dips locally reaching 45° along the northern coasts of Flateyjarskagi and Tröllaskagi Peninsulas (Figure 3) [*Bergerat et al.*, 2000; *Fjäder et al.*, 1994; *Langbacka and Gudmundsson*, 1995; *Young et al.*, 1985]. These relatively steep dips along the northern coasts of Flateyjarskagi and Tröllaskagi Peninsulas are due to the Húsavík-Flatey Fault, a major transform fault of the TFZ, (Figures 1 and 3) [*Bergerat et al.*, 2000; *Fjäder et al.*, 1994; *Langbacka and Gudmundsson*, 1995; *Young et al.*, 1985].

[15] The Flateyjarskagi Unconformity is not the unique unconformity restricted to the west of the NVZ, as we observe Plio-Pleistocene lava flows unconformably overlying the Tertiary lava flows in several places south of the

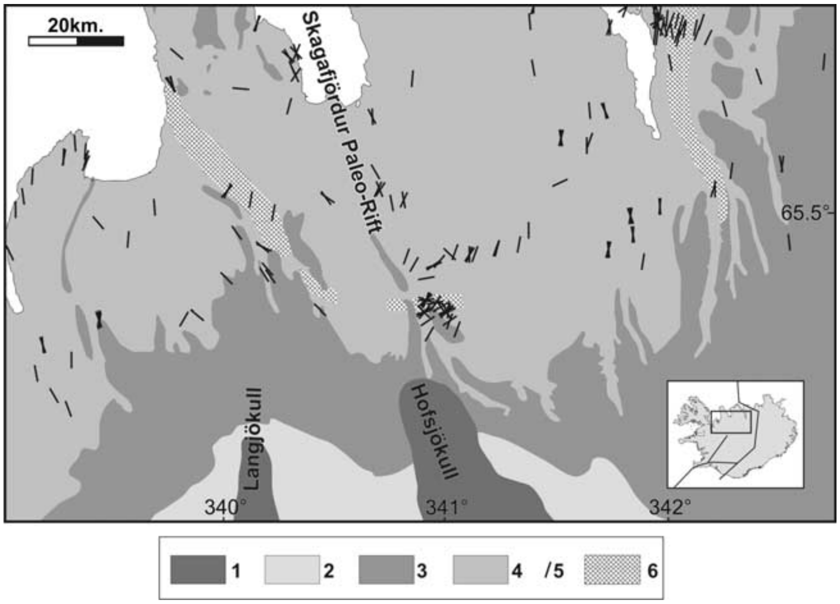


Figure 5. Dykes directions in Northern Iceland. Details, numbered in key, are as follows: 1, active volcanic system; 2, upper Pleistocene–Holocene lava flows (<0.8 Ma); 3, Plio-Pleistocene lava flows (<3.3 Ma and >0.8 Ma); 4, Tertiary lava flows (>3.3 Ma); 5, dyke direction; 6, angular unconformity. Newly acquired data are compiled together with published data from *Young et al.* [1985]. The area covered by Figure 5 is indicated in the inset.

Tröllaskagi and Skagaheidi Peninsulas (A and B in Figure 3). At one of these localities, 15°S–20°S dipping Tertiary lava flows are capped by Plio-Pleistocene lavas that dip only 5°S. Similarly, Plio-Pleistocene lava flows overlie deeply eroded Tertiary lava flows along the Húnaflói-Skagi synform and the Skagaheidi Peninsula [*Saemundsson*, 1974] (Figure 3).

2.2. Dykes, Faults Orientations, and Inversion of Fault Slip Data in Northern Iceland

[16] The measured trends of more than 150 dykes and more than 50 large normal faults [*Garcia*, 2003] are compiled in Figures 5 and 6 respectively, together with data available from the literature [*Johannesson and Saemundsson*, 1989, 1998; *Young et al.*, 1985]. Thirty paleostress tensors resulting from inversion [*Angelier*, 1990] of fault slip data [*Garcia*, 2003] are also shown in Figure 6. In some areas, the collected data showed unacceptable mechanical inconsistency when determining a single stress tensor, indicating polyphase deformation resulting from two or more distinct tectonic regimes. In such cases, the relative chronology between the different tectonic regimes could sometimes be established from the superposition of fault striae on reactivated faults, crosscutting relationships between faults or dykes and geometrical relation to block tilting.

[17] Many of the mapped dykes and faults strike N-S to NNE-SSW (Figures 5 and 6), consistent with the E-W to ESE-WNW directions of the minimum principal stress axis (σ_3) derived from our inversions (Figure 6). They were observed in the NVZ lavas flows as well as in the Skagafjördur paleo-rift lavas, both in the Tertiary and in the Plio-Pleistocene lavas (Figures 5 and 6). They are roughly parallel to the regionally N-S to NNE-SSW trending active structures of the NVZ [*Johannesson and Saemundsson*, 1998] and to the N106°E direction of plate divergence in Northern Iceland [*DeMets et al.*, 1990, 1994]. However, the general trend of dykes and faults is approximately N-S to NNW-SSE west of the Skagafjördur paleo-rift axis (Figures 5 and 6), where accordingly the inversion revealed E-W to ENE-WSW directions of the σ_3 axis (Figure 6). Further structural complexity is found north of Langjökull and Hofsjökull (Figures 5 and 6), where fault and dyke trends define a wide array from NE-SW to SE-NW, reliable to a NW-SE to NE-SW directed σ_3 axes (Figure 6). Most of this structural complexity is located in, or at the vicinity of, the previously mentioned flexure zones (see section 2.1). Where a chronology could be established, the fault striae providing this state of stress systematically postdated the striae conforming to the regionally dominating E-W to ESE-WNW directed σ_3 axes.

3. Structural Evolution Due to the Last Rift Jump in Northern Iceland

[18] Lava flows dipping toward the rift axis is a typical regional feature of Icelandic volcanic systems. These regional dips vary with stratigraphical depth, from nearly horizontal at the present mountain summits (i.e., around 1000 m above sea level) to 5°–10° at sea level [*Kristjansson et al.*, 1995; *Saemundsson et al.*, 1980; *Walker*, 1964]. The increase in dip is matched by thickening of the stratigraphical

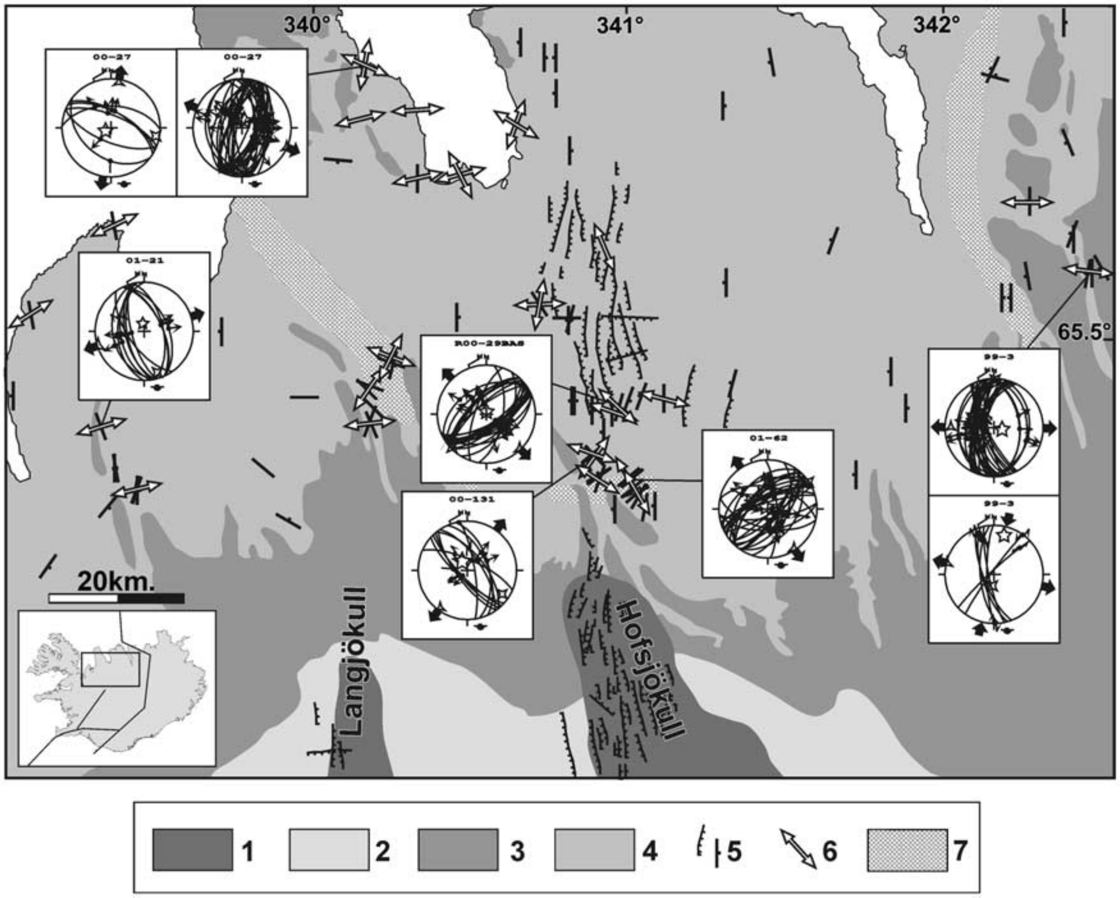


Figure 6. Normal faults and associated stress tensors in Northern Iceland. Details, numbered in key, are as follows: 1, active volcanic system; 2, upper Pleistocene–Holocene lava flows (<0.8 Ma); 3, Plio-Pleistocene lava flows (<3.3 Ma and >0.8 Ma); 4, Tertiary lava flows (>3.3 Ma); 5, normal fault (with barbs: active fault from *Johanesson and Saemundsson* [1989, 1998], with single dip indicator: inactive fault); 6, direction of extension deduced from fault slip data inversion; 7, angular unconformity. Diagrams are in lower hemisphere and equal area projection. Faults are as thin lines, slickenside lineations as dots with single (centrifugal-normal) or double (left or right lateral) arrows. Maximum (σ_1), intermediate (σ_2) and minimal (σ_3) stress axes are as five, -four-, and three-branched stars, respectively. Direction of extension or compression is represented as large black arrows. N denotes geographic north, M denotes magnetic north. The area covered by Figure 6 is indicated in the inset.

units of the pile when traced down the direction of dip. The tilt of the lavas has been related to the growth of the lava pile in a stationary volcanic zone where lateral migration and subsidence occurred as a result of crustal extension and loading due to the growing thickness of the pile on top of a visco-elastic body [*Bodvarsson and Walker*, 1964; *Daignières et al.*, 1975; *Menke and Sparks*, 1995; *Palmason*, 1973, 1980, 1981]. Combined, an opposite set of inwardly dipping lava flows define a symmetrical synform-like cross-sectional structure, which may be considered as (paleo-) rift reference structures in Iceland.

[19] A superimposed rift jump is expected to generate a cross-sectional geometry through the upper crustal lava pile as schematically illustrated in Figure 7 [*Bodvarsson and Walker*, 1964; *Daignières et al.*, 1975; *Palmason*, 1980]. This schematic profile roughly represents an E-W section across the regionally N-S to NNE-SSW trending active structures of the NVZ [*Johannesson and Saemundsson*, 1998] and roughly parallel to the N106°E direction of plate divergence in Northern Iceland [*DeMets et al.*, 1990, 1994]. Prior to the rift jump (Figure 7a), the lavas erupting along the Skagafjördur rift (i.e., the present paleo-rift) became gently tilted toward the accretion axis and thereby produced the Skagafjördur synform-like structure (Figures 3 and 7). Following the eastward rift jump that initiated the presently active NVZ, another similar synform-like structure of younger (i.e., younger than 8–8.5 Ma) erupting lavas was superimposed on the eastern flank of the paleo-rift (Figure 7b). Consequently, these lava flows unconformably overlie lava

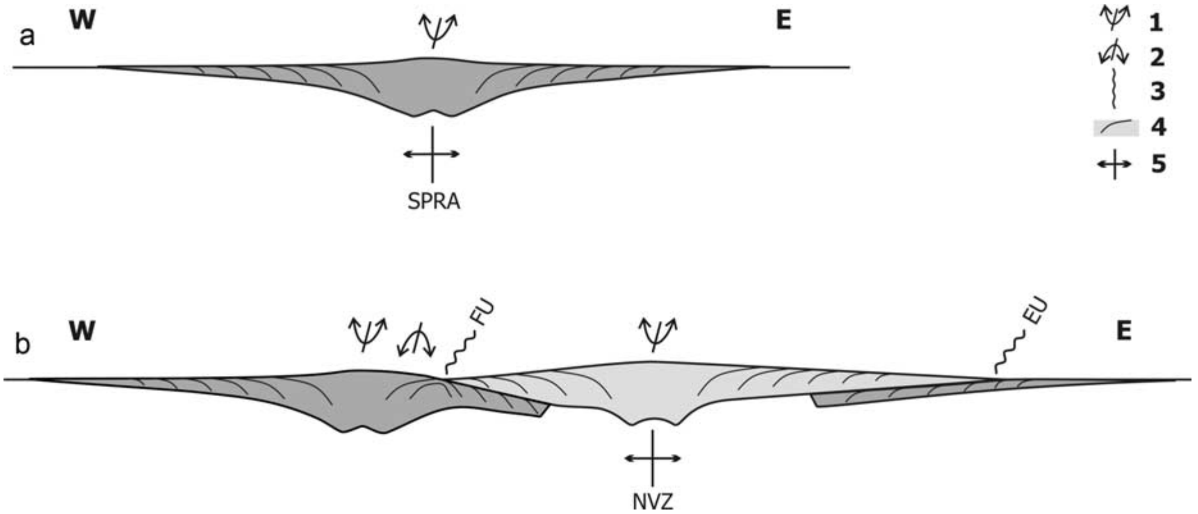


Figure 7. Schematic model of rift jump and associated flexure process in Iceland for (a) Paleo-rift functioning time and (b) New rift functioning time. Structures, numbered in key, are as follows: 1, synform-like structure axis; 2, antiform-like structure axis; 3, angular unconformity; 4, lava flow dip; 5, active rift. Abbreviations are as follows: EU, Eastern Unconformity; FU, Flateyjarskagi Unconformity; NVZ, Northern Volcanic Zone; SPRA, Skagafjördur Paleo-Rift Axis. Note dip variations in flexure zones. Modified from *Bodvarsson and Walker* [1964], *Daignières et al.* [1975], *Helgason* [1984], and *Palmason* [1980].

flows from the paleo-rift, corresponding to the present Flateyjarskagi and Eastern Unconformities.

[20] As an intricate feature of this rift jump, owing to the excess loading from the capping NVZ lava pile, the lava flows from the paleo-rift underwent further flexuring. This flexure process clearly occurred late and was not related to the initial, syn-rift distribution of the lava flows. The resulting structure is variable as a function of the superimposed dip distributions: along the Eastern Unconformity, the superimposed loading by the NVZ simply resulted in an increasing westward dip of the underlying lava pile, resulting in a well-marked flexure. In contrast, the flexure along the Flateyjarskagi Unconformity was produced from back-tilting of the old westward dipping lava pile issued from the Skagafjördur paleo-rift, resulting in a present dip to the east (Figure 7). As a consequence, the lava flows produced by the paleo-rift now define an antiform-like structure along the Flateyjarskagi Unconformity (the Eyjafjördur Antiform, Figure 7). This back-tilting of the paleo-rift lava pile along the Flateyjarskagi Unconformity was first suggested by *Saemundsson* [1974].

4. Is It Necessary to Consider An Additional Down-Bending Process?

[21] Eleven noticeable discrepancies appear while comparing the general scheme presented in section 3 with the structural data detailed in section 2, even considering the local dip perturbations related to central volcanoes [*Walker*, 1975b]. One generally expects N-S trending synforms, antiforms and flexure zones and E or W dipping lava flows in Northern Iceland. However, we note that (1) the paleo-rift lava flows are dipping to the S-SSE rather than to the W-SW or E-SE (depending on the considered flanks of the Eyjafjördur Antiform) and thereby producing a wide termination of the Eyjafjördur Antiform in the southern and south-eastern Tröllaskagi Peninsula (Figure 3); (2) no synform-like structure exists in the southern emerged part of the Skagafjördur paleo-rift (Figure 3); and (3) paleo-rift lava flows are on average southward dipping in the Dala area (at the base of the NW-Peninsula), rather than dipping to the W-SW (Figure 3).

[22] We also describe some structures that were unexpected and/or are presently unexplained like (4) the Húnaflói-Skagi synform-like structure (Figure 3), (5) the Skagaheidi antiform-like structure (Figure 3), (6) the regional flexure zones mapped at the base of the NW- and Skagaheidi Peninsulas, and the shorter ones observed south of the Tröllaskagi and Skagaheidi Peninsulas (Figure 3), (7) the NE-SW to SE-NW trending faults and dykes mapped north of Langjökull and Hofsjökull area in the paleo-rift lava flows, and the related NW-SE to NE-SW trending σ_3 axis (Figures 5 and 6), (8) the N-S to NNW-SSE general trend of dykes and faults in the Skagafjördur paleo-rift area, and the related E-W to WSW-ENE directions of σ_3 axis (Figure 3), (9) some Tertiary lava flows dips along the Skagafjördur paleo-rift axis (delimited by a dashed line in Figure 3), (10) the Plio-Pleistocene lava flows that unconformably overlie the deeply eroded Tertiary lava flows south of Tröllaskagi and Skagaheidi Peninsulas and along the Húnaflói-Skagi synform (the Skagafjördur paleo-rift axis was extinct at this time) (Figure 3), and (11) the antiform-synform system induced by the eastward dipping lava flows mapped along

the extension of the Hellisheidi peninsula (Eastern Iceland) (Figure 2).

[23] The generally accepted model prior to the present study considers a paleo-rift axis localized along the Húnaflói-Skagi synform-like axis [*Saemundsson*, 1974; *Ward*, 1971]. As mentioned before, the main argument that supports this model is the coincidence of the synform-like structure in the Húnaflói-Skagi area. One may consider that a paleo-rift was functioning along the Húnaflói-Skagi synform-like axis before the Skagafjördur paleo-rift axis was active. However, there is no radiometric dating supporting this hypothesis and no angular unconformities exists near the two flexure zones mapped at the base of the NW- and Tröllaskagi Peninsulas, like those observed on both sides of the NVZ. Note that there is no significant age discontinuity from the Húnaflói-Skagi synform toward the Skagaheidi Peninsula [*Garcia et al.*, 2003] or the NW-Peninsula [*Bagdasaryan et al.*, 1976; *McDougall et al.*, 1984; *Moorbath et al.*, 1968] when crossing over the corresponding flexure zones. Moreover, such a multiple paleo-rift model would not explain some of the previously listed incompatibilities, like the termination of the Eyjafjördur Antiform, and the NE-SW to SE-NW trending faults and dykes mapped north of Langjökull and Hofsjökull area.

[24] For comparison, few data are available about the one known paleo-rift predating the Skagafjördur paleo-rift [*McDougall et al.*, 1984]. The axis of this earlier rift is assumed to lie offshore, along the western coast of the NW Peninsula. Along this coast, southeastward dipping lava flows, related to the Skagafjördur paleo-rift, unconformably overlie northwestward dipping lava flows. Sedimentary layers, composed of laterite and lignite, underline this angular unconformity. Available ages on both sides of this unconformity do not provide a coherent temporal frame for the rift jump [*Bagdasaryan et al.*, 1976; *McDougall et al.*, 1984; *Moorbath et al.*, 1968]. Ar/Ar results from *Hardarson et al.* [1997] indicate a 14.85 ± 0.12 Ma age below the unconformity and a 15.05 ± 0.08 M1 age above the unconformity, respectively, indicating that the volcanic hiatus associated with this unconformity was brief.

5. Structural Evolution Posterior to the Last Rift Jump in Northern Iceland

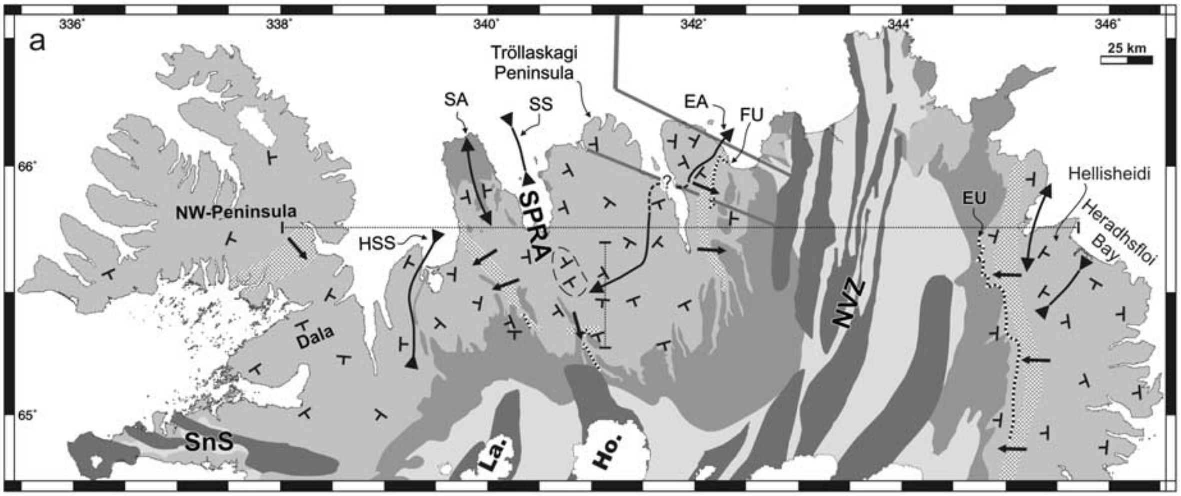
5.1. Influence of an Excess Loading From the Central Part of Iceland

[25] In order to explain most of the discrepancies listed previously (section 4), we assume that excess loading centered in the Langjökull-Hofsjökull area induced southward down-bending of the Tertiary lava flows. In this respect, we assume the classical down-bending process as used to explain the cross-sectional geometry of the Skagafjördur paleo-rift lava flows, which underwent down-bending under the weight of the lava flows coming from the NVZ (Figures 7 and 8b). Schematic cross-sections containing the main described structures in Northern Iceland and illustrating the down-bending process under the weight of excess loading centered in the Langjökull-Hofsjökull area are presented in Figure 8.

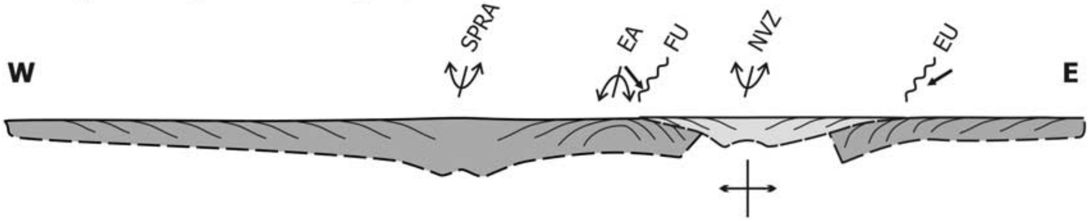
[26] This excess loading area extends to the south of the NW-, Tröllaskagi and Skagaheidi Peninsulas and along the Húnaflói-Skagi area (Figure 8a). The excess loading to the south of the NW-, Tröllaskagi and Skagaheidi Peninsulas are responsible for (point 1 in section 4) the down-bending to the S-SSE of the Tröllaskagi lava flows (the wide Eyjafjördur Antiform termination) (Figures 8a and 8d), (point 2) the southward down-bending of the southern part of the Skagafjördur paleo-rift axis and the consecutive partial disappearing of the associated synform-like structure (Figure 8a), and (point 3) the down-bending to the south observed in the Dala area (Figure 8a). At the same time, a northward propagation of this excess loading along the Húnaflói-Skagi area was responsible for the development of the corresponding synform-like structure (point 4) (Figures 8a and 8c). According to this interpretation, the Skagaheidi antiform (point 5) simply results from the down-bending of the paleo-rift lava flows located on the western part of the Skagaheidi Peninsula, evolving from an initial eastward dip to a final westward dip (i.e., in direction of the Húnaflói-Skagi synform-like structure) (Figures 8a and 8c).

[27] This down-bending process can lead to the development of local flexure zones in the paleo-rift lava flows, as those observed at the base of the NW- and Skagaheidi Peninsulas and south of the Tröllaskagi Peninsula (point 6) (Figures 8a, 8c, and 8d). Present field observations do not permit us to combine the local flexure zones into a continuous structure that extends from the base of the Skagaheidi Peninsula to the south of the Tröllaskagi Peninsula, or to consider that they develop only in areas where the excess loading was sufficient. Nevertheless, the flexure process explains the NE-SW to SE-NW trending faults and dykes mapped north of Langjökull and Hofsjökull area in the paleo-rift lava flows, and the associated NW-SE to NE-SW trending σ_3 axis (point 7). These structures are incompatible with the rifting process, but may be induced by flexural extension along the convex side of the produced monocline (Figure 8d). The fact that most of these structures have been mapped at the vicinity of the different observed flexure zones (Figures 5 and 6) reinforces this interpretation. Similar extension but along N-S trending normal faults with major easterly downthrows and minor westerly downthrows has been recognized along the N-S trending flexure zone located along the Flateyjarskagi Peninsula. They have been related to the flexure process due to the initiation of the NVZ [*Jancin et al.*, 1985]. *Klausen* [2006] showed how an excess loading may increase in its periphery (i.e., in the flexure zone) an extensive stress. The dispersion in azimuth of these structures can result from the non-linear geometry of the excess loading zone. According to *Klausen* [2006], the dyke trends may vary in relation with local loading variations. Thus we conclude that the present structural pattern of Northern Iceland results from the superimposed effects of the rift jump and the excess loading from the Central part of Iceland.

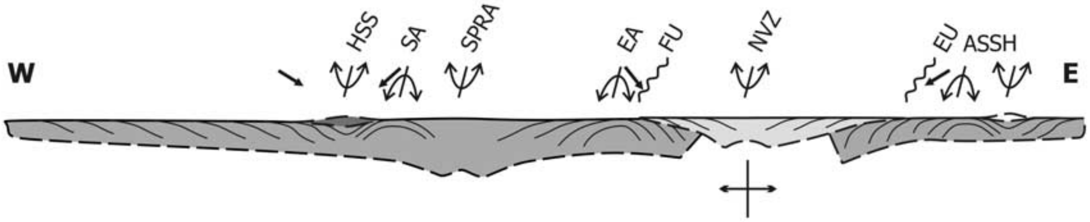
[28] Some of the discrepancies listed in section 4 do not result from, or cannot be explained by, the last rift jump in



b- Flexuring resulting from the rift jump



c- Flexuring resulting from excess loading coming from the south



d- Flexuring resulting from excess loading located in the south

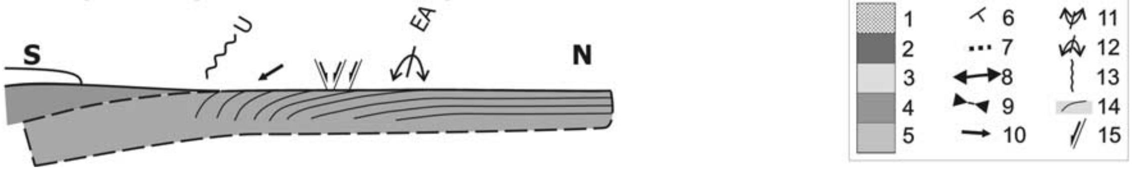


Figure 8. Synthetic map of structural discrepancies in Northern Iceland and schematic cross sections illustrating the different flexure processes. Details, numbered in key, are as follows: 1, flexure zone; 2, active volcanic system; 3, upper Pleistocene–Holocene lava flows (<0.8 Ma); 4, Plio-Pleistocene lava flows (<3.3 Ma and >0.8 Ma); 5, Tertiary lava flows (>3.3 Ma); 6, dip of lava flows; 7, angular unconformity; 8, axis of antiform-like structure; 9, axis of synform-like structure; 10, sense of dip in flexure zone; 11, synform-like structure axis; 12, antiform-like structure axis; 13, angular unconformity; 14, lava flow dip (in cross view); (15), flexural extension. Abbreviations are as follows: ASSH, Antiform-Synform System of Hellisheidi; EA, Eyjafjördur Antiform; EU, Eastern Unconformity; FU, Flateyjarskagi Unconformity; Ho., Hofsjökull; HSS, Húnaflói-Skagi Synform; La., Langjökull; NVZ, Northern Volcanic Zone; SA, Skagaheidi Antiform, SnS, Snaefellsnes; SPRA, Skagafjördur Paleo-Rift Axis; SS, Skagafjördur Synform; U, Unconformity. Note dip variations in flexure zones. Indicative positions for cross sections are indicated by dotted lines. Construction of schematic cross sections is adapted from *Bodvarsson and Walker* [1964], *Daignières et al.* [1975], *Helgason* [1984], and *Palmason* [1980].

Northern Iceland or the excess loading centered in the Langjökull-Hofsjökull area. The N-S to NNW-SSE general trend of dykes and faults in the Skagafjördur paleo-rift area, and the associated E-W to ENE-WSW directions of the σ_3 axis (point 8) are not compatible with a N-S to NNW-SSE trending paleo-rift axis (i.e., parallel to the active NVZ). This structural trend may reflect a different trend for the Skagafjördur paleo-rift axis, as compared with the general trend of the NVZ. Block rotations during rift propagation and/or retreat [e.g., *Rusby and Searle*, 1995] can also be considered to explain these trend differences. However, no reliable information (such as paleomagnetic data) is presently available to quantify such possible rotations. Last, some dip data located along the Skagafjördur paleo-rift axis (point 9) remain unexplained. The dip of these Tertiary lava flows may be related to a local perturbation, although no clear structure (such as a central volcano) has been mapped nearby. Whatever, we consider that this local discrepancy do not cast doubt on our overall model.

5.2. Origin of the Excess Loading

[29] A large volume of Plio-Pleistocene and Upper Pleistocene - Holocene lava flows has erupted, covering a large mapped surface in the Central part of Iceland (Figures 1 and 8). Icelandic Plio-Pleistocene lava flows are between 3.3 and 0.8 Ma old and Upper Pleistocene–Holocene lava flows are younger than 0.8 Ma old [*Saemundsson*, 1979]. Outliers of Plio-Pleistocene lava flows have also been mapped along the Húnaflói-Skagi synform axis (Figure 8). They have 1–2.5 Ma old [*Everts et al.*, 1972]. They are considered as outliers of distal lava flows [*Saemundsson*, 1974] even if their source is still controversial [*Schilling et al.*, 1978; *Sigurdsson et al.*, 1978]. They may correspond to glacial relics of much wider Plio-Pleistocene lava flows, later largely removed by glacial erosion. *Bourgeois et al.* [1998] showed that major Quaternary ice flows have run along, and thus dug out, this topographic depression.

[30] These relics of a wide surface of Plio-Pleistocene lava flows implies a major volcanic activity from the southern part of the Skagafjördur paleo-rift before its extinction time and/or strong volcanic activity from the Central part of Iceland after the extinction of the Skagafjördur paleo-rift (Figure 1). On the other hand, the Skagafjördur paleo-rift became extinct around 3 Ma [*Garcia et al.*, 2003] and we observe that Plio-Pleistocene lava flows unconformably overlie the Tertiary lava flows in many places (point 10 in section 4). We deduce from these observations that most of these Plio-Pleistocene lava flows have not been emitted by the Skagafjördur paleo-rift but rather from the Central part of Iceland after the extinction of the Skagafjördur paleo-rift. The reactivation of the Snaefellsnes Volcanic Zone since the Plio-Pleistocene [*Bagdasaryan et al.*, 1976; *McDougall et al.*, 1977; *Moorbath et al.*, 1968; *Smith*, 1967] may also be partly responsible for this large amount of lava flows in Central Iceland. Thus we propose that the weight of the large amount of accumulating lava flows, emitted since the Plio-Pleistocene in the Langjökull-Hofsjökull area, accounts for the excess loading responsible for the superimposed down-bending process observed in Northern Iceland.

[31] Few data are available in the literature concerning the geology of major volcanic systems well represented by the presently active Langjökull and Hofsjökull volcanoes. The Langjökull volcano marks the northern termination of the Western Volcanic Zone (Figures 1 and 3). The central volcano is associated with a fissure swarm made of normal faults and tension fractures, trending NW-SE and N-S to the south and the north of the central volcano, respectively (Figures 1 and 6) [*Johannesson and Saemundsson*, 1989]. Its activity during the Holocene time was minor. The Hofsjökull volcanic system is composed of two volcanoes, one of them being a large central volcano (diameter of 25–30 km). An important NNW-SSE Holocene fissure swarm departing from the volcano toward the northern coast has been recognized and mapped without any further constrains concerning its initiation time and present-day activity (Figure 6) [*Johannesson and Saemundsson*, 1989]. Moreover, in the central icecap region, the fault patterns consists of NE-SW and NNW-SSE fractures [*Saemundsson*, 1978] and a few faults and eruptive fissures, generally trending E-W, join the Langjökull volcano and the Snaefellsnes Volcanic Zone [*Johannesson and Saemundsson*, 1998; *Khodayar and Einarsson*, 2002; *McDougall et al.*, 1977; *Walker*, 1975a].

[32] At the same time, ice caps may also be considered as a factor increasing the loading process. The present Langjökull, Hofsjökull and Vatnajökull ice caps (Figure 1) are relics of a much wider ice cap which has covered by interval the major part of Iceland during the last 2–2.5 Ma [*Geirsdottir and Eiriksson*, 1994]. It is considered that the ice thickness reached a maximum of 1000–1500 m in Central Iceland while only 300–500 m along the present coastlines [*Einarsson and Albertsson*, 1988; *Kjartansson*, 1966; *Norddahl*, 1990, 1991; *Walker*, 1965]. The supplementary loading due to this ice cap is not negligible, especially in the Central part of Iceland. Indeed, 1000 meters of ice weights as 350 m of lavas, considering their respective density, whereas the load of a 1000-m-high lava pile increases of 5–10° the tilt of lavas at the base of the lava pile. This glacial loading may also explain the antiform–synform system observed along the extension of the Hellisheidi peninsula (point 11 in section 4) (Figures 8a and 8c). Indeed, an important glacial stream ending in the Heradhsfloi Bay bound this lava flows area (Figure 8a) [*Bourgeois et al.*, 1998].

[33] It is worth noting that, because of the weakness of the Icelandic lithosphere underlain by the mantle plume [*Pollitz and Sacks*, 1996; *Sigmundsson*, 1991], several authors have proposed that this Plio-Pleistocene glacial loading and unloading might have caused, among others features, increased magmatic production [*Gudmundsson*, 1986; *Jull and McKenzie*, 1996; *Sigvaldason et al.*, 1992]. According to this hypothesis, the ice cap, increasing the overall loading, would have also induced an increase in magmatic activity during the Plio-Pleistocene, an effect that would have increased the overall loading in return. This increasing of the magmatic production rate may be accompanied by a widening of the active rift zone and multipli-

cation of the number of active fissure swarms during glacial times [*Bourgeois et al.*, 1998] and/or a more localized subglacial magmatism along the peripheral margin of the igneous centers [*Klausen*, 2006].

6. Conclusion

[34] The present structural pattern of Northern Iceland mainly results from tectonic reorganization consecutive to the last rift jump. The present dip of Tertiary lava flows erupted along the Skagafjördur paleo-rift is mainly a consequence of their bending under the weight of, and in direction of, younger lava flows emitted from the N-S trending NVZ. However, in the southern half-part of Northern Iceland, the Tertiary lava flows have been down-bent southward by lava flows emitted since the Plio-Pleistocene (i.e., after the extinction of the Skagafjördur paleo-rift) from the Central part of Iceland. The major Plio-Pleistocene magmatic activity in this part of Iceland and the resulting overall loading in this area have been enhanced by the Plio-Pleistocene ice cap loading.

[35] This southward down-bending of the Tertiary lava flows explains the present geometry of the Eyjafjördur Antiform in the Tröllaskagi Peninsula and the absence of a synform-like structure in the southern emerged part of the Skagafjördur paleo-rift. Furthermore, the weight of this extended Plio-Pleistocene lava flows cover (nowadays, important glacial erosion has reduced its extension) is responsible for the development of the Húnaflói-Skagi synform and, consequently, of the Skagaheidi Antiform. The resulting flexure zones are observed around the Skagaheidi and Tröllaskagi Peninsulas. Roughly flexure-parallel normal faults and dykes suggest that local flexural extension was associated with this post-rift down-bending. Finally, this important structural reorganization explains the presence of the Húnaflói-Skagi synform, without the need for a paleo-rift axis along the Húnaflói-Skagi synform.

[36] We thus conclude that the reconstruction of paleo-rift axes based on structural considerations should take into careful account a variety of phenomena that postdate rifting and may markedly affect the distribution of lava pile attitudes. As suggested in the present paper, these phenomena may include important magmatic production in out-of-rift volcanic zones (e.g., in the central part of Iceland) and influence of ice cap on magmatism in Iceland.

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