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H$_2$O : A FUNCTIONAL ANALOGUE FOR
CONTINENTAL MARGIN RIFT TECTONICS?

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H$_2$O: A FUNCTIONAL ANALOGUE FOR CONTINENTAL MARGIN RIFT TECTONICS?

by

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ABSTRACT

Rifted continental margins are an important facet of craton development and evolution. Two relatively well-studied rifts, the Palaeoproterozoic Huronian rift (Canada), and the Jurassic Lebombo rift (South Africa) are summarized to demonstrate both the insights and limitations of our understanding of rift evolution, particularly in terms of magmatic evolution. The use of Icelandic glacial outbursts (jökulhlaups) as an analogue model provides a fresh perspective on crustal extension and associated magmatic development. Specifically, the nature of stress development, fracture propagation and dyke, pluton and extrusive development may be examined in the light of an ice-water analogue, where existing geochemical models and geochronology are insufficient to provide unambiguous solutions.

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H$_2$O: A FUNCTIONAL ANALOGUE FOR CONTINENTAL MARGIN RIFT TECTONICS?

INTRODUCTION

The scope of geological processes ranges from the planetary to the sub-microscopic; many of these can be modelled in a wide variety of ways. Although we can observe geological phenomena at the present time, frozen in various stages of transformation, data such as stresses, rates of process, and chronological sequence must be inferred from resultant phenomena, such as strains, or quantitative evaluation of individual aspects of each "frozen stage". In general it is with some difficulty that we can reproduce the physical processes taking place (or analogues thereof) and thus derive information directly rather than inferring it.

In order to model tectonic processes, an environment is needed in which a rigid, brittle crust overlies more buoyant liquid of the same average composition, but where the interactions occur on a time scale conducive to study, rather than that of thousands to millions of years. This environment exists in the case of ice layers underlain by heat sources, providing us with a natural analogue model for silicate crust. Molten ice (i.e., water) is generated and infused with effectively buoyant tendencies relative to the ice above, such that the brittle ice sheet provides downward thrust, by gravity, onto incompressible liquid trapped below. The liquid source region remains in a mobile, uncrystallized state as long as the heat source remains active (in contrast to a purely glacial system, where the liquid component is generated only above the ice). This circumstance exists on Iceland where long-lived glacial ice sheets are underlain by magmatic heat sources (a spreading ridge and a hotspot, in this case). Other circumstances can be envisioned in which this arrangement can exist, such as inboard regions of subduction zones, such as the Basin and Range domains of the United States, where high collision-induced elevations suitable for permanent (non-seasonal) ice might coincide with magmatic heating below (hot springs). Iceland provides a geologically stable (from an investigative sense) and well-studied example.

In this study, the behaviour of ice sheets above upwelling water is examined, and compared with the behaviour of equivalent silicate systems in the form of continental rift zones. One ancient and one recent example are presented; the Palaeoproterozoic Huronian rift in Canada, and the Jurassic Lebombo rift in South Africa, respectively.

MODELLING

Physical models can be described in terms of a gradational spectrum (e.g., Peakall et al., 1996), defined at one end by scale models, wherein all key parameters are represented in the model in order to replicate the natural environment, as reflected by a single or specific prototype case. Typically this is impractical, and compromises must be reached by compensating 'realistic' values of some key parameters by varying others. At a point where realistic end results are achieved by combinations which include patently unrealistically scaled values for some variables, this is referred to as a 'distorted' model. Ultimately, models which obey 'similarity of process', but are not based on a specific physical prototype and are therefore not quantitatively constrained in terms of process, are referred to as 'analogue' models (Peakall et al., 1996).

In structural analogues, process rate information can be sacrificed for mineral structural data by substituting elements with similar ionic behaviour, but different (i.e., faster) geochemical

reactivity rates than their equivalent in the geological environment of interest. For example, the use of germanium as an analogue for silica (forming tetrahedra of GeF_4 instead of SiO_4) in crystallochemical studies provides a higher volatility, but structurally equivalent compound whose growth can be evaluated in conditions where silicate growth rates would preclude practical study. Similarly, substitution of elements with like ionic behaviour (applying Goldschmidt's rules, in general) in order to derive behavioural data on elements of interest, which would otherwise form compounds which are less stable, toxic, or otherwise inconvenient, could be described as a chemical analogue.

In terms of material interaction, geological materials have been successfully modelled as liquids by using immiscible low viscosity liquids as analogues for high viscosity geological materials. For example, different organic liquids (such as alcohols) or solutions of differing salinities provide sufficient initial density and/or viscosity contrast to experimentally model processes such as convection in the earth's mantle or in mafic intrusions, plumes in the mantle, and fine-scale phenomena such as magmatic boundary-layer behaviour. Interactions between liquids and solids can be simulated on a small scale in the case of sedimentary environments, such as using flumes for fluvial-related clastic sedimentary processes. The effectiveness of this modelling is constrained by the size of the system being modelled, such that aspects of deltaic systems can be modelled with some success, but not, for example deep-water depositional environments. Tectonic processes such as extension and faulting can be effectively modelled using layers composed of constituents such as sand (brittle layers) and silicon putty (more ductile) to represent heterogeneous crust (e.g., Watkeys and Sokoutis, 1998) in a three-dimensional 'sandbox' (Mandl, 1988). Mathematical modelling of liquid-solid mixtures can be effected to an extent, without the upper size limitation, through the device of treating solids as extremely viscous liquids. By varying the Rayleigh and Prantl numbers of a liquid, materials equivalent to liquid-solid mixtures or solids can be modelled, albeit not readily simulated.

Mathematically derived modelling can be extremely effective and allows us to examine environments, which are completely untestable or even entirely hypothetical. However, the models are still ultimately dependent on the assumptions and physical criteria which underpin them, which, in geology, are provided by accurate observation of natural phenomena, and for which appropriate boundary conditions are not easily set in complex systems. Paola (2000), in an evaluation of sedimentary basin modelling, described some of the conceptual issues and problems in designing accurate models for natural systems in terms of three non-exclusive categories of model. These consist of geometric versus dynamic models, one- versus two- versus three-dimensional models, and rule-based versus deductive models.

Geological activity associated with tectonic processes in particular, such as orogenies, involve large time scales, on the order of tens of millions of years, large energies, and large volumes of material. These processes are most effectively modelled using largely extrapolated data; geochemical construction of the crust based on petrological observations from surface and xenolithic material, supported by experimental petrology, and physical properties inferred from seismic and gravity properties. This provides us with reasonable behavioural models for crustal interactions on the large scale, which detailed mathematical extrapolations can break down for us at progressively smaller scales. However, this involves the collection and application of immense amounts of data from disparate sources in order to provide meaningful models. Ultimately, analogue modelling of geological processes can allow us to bypass many of these shortcomings.

RIFTING OF CONTINENTAL CRUST

For the purposes of this study, the characteristics of the sequences, which allow them to be described as rift-induced assemblages are presented, and subsequently the chronological sequence and genetic relationship of the components described to the best of present understanding. It is not intended to critically examine the interpretation of various workers on the rift zones, but to provide a context for subsequent comparison using lithological assemblages, which can be described as rifts without undue controversy.

Ancient rifting: *c*. 2500 Ma Huronian volcanism, magmatism and sedimentation, Canada

The Huronian sequence represents the southern boundary of the Archaean Superior Province, a set of Meso- to Neoarchaean granite-greenstone and metasedimentary belts in Ontario and Quebec, central Canada (Fig. 1). The Huronian comprises most of what is referred to as the Southern Province, distinguishing it from the Superior Province to the north, and the Grenville Province to the south, which consists of high-grade reworked Palaeo- to Mesoproterozoic gneisses. The Southern Province includes a thick (up to 1 km in places) sequence of continental flood basalts, associated with lesser rhyolitic lavas and tuffs. Both subaqueous and subaerial deposition are indicated. The volcanics are spatially associated with a suite of leucogabbroic
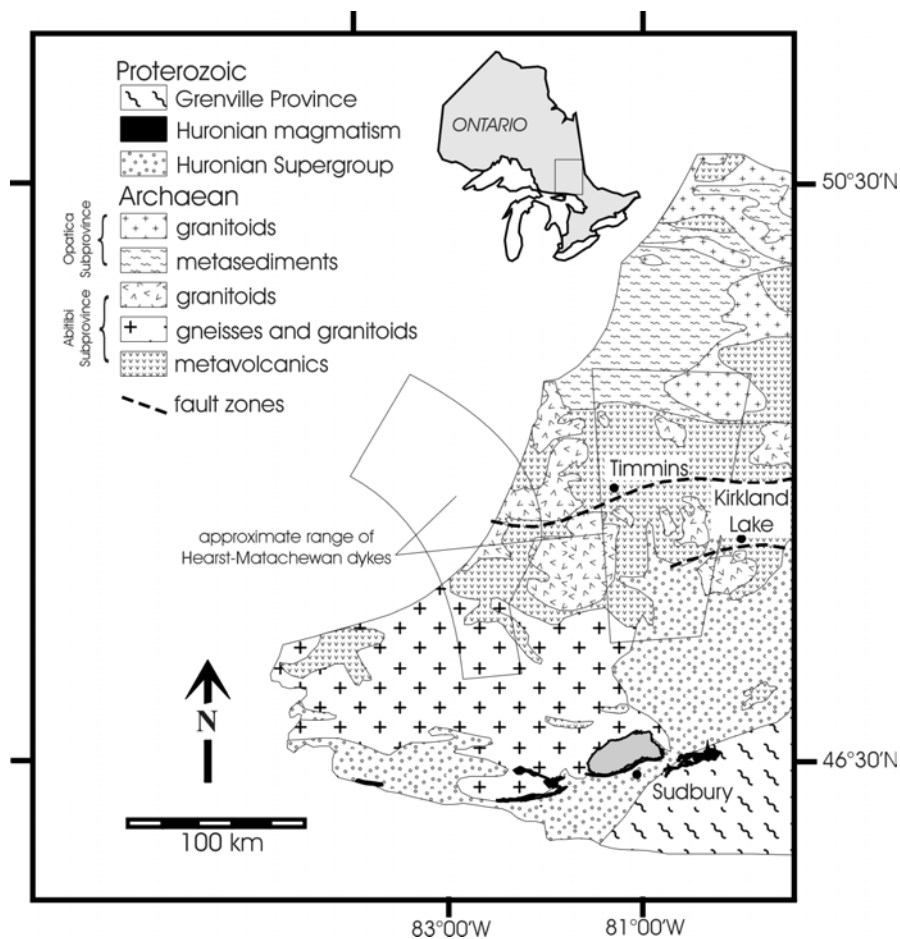

Figure 1: *Geology of the Huronian rift environment, showing major terranes and rift-related units.*

plutons and sills, and with granitic plutons, locally. Ultramafic rocks are essentially absent. The magmatic rocks are interbedded with and overlain by a thick sequence of cyclic, glacially deposited clastic sediments, comprising the Huronian Supergroup (e.g., Card et al., 1977). This sequence is crosscut by a volumetrically significant swarm of doleritic-to-gabbroic dykes and sills, referred to in the literature as Nipissing Diabase. The emplacement of this dyke swarm represents the end of the Huronian sequence, and the magmatic components of this sequence are known as the Huron-Nipissing Magmatic Belt (e.g., Peck et al., 1995). The Nipissing, which runs parallel to the rift, may be related to activity along the rift (closure or other reactivation) after Huronian Supergroup deposition, or alternatively may be an extension of the Preissac/Senneterre dyke swarm, 1000 km to the northeast (Ernst and Buchan, 1997). The sequence is interpreted as a rift zone resulting from doming and rifting, such that a radiating dyke swarm to the north (500 km), the Hearst-Matachewan dykes, may represent the aulacogenic failed north-south arm of the rift (Fahrig, 1987). Bimodal continental volcanism and magmatism, shallow-water clastic sediment deposition and the linear geometry are consistent with a rifting interpretation.

Field relationships could not clearly distinguish an unambiguous chronological relationship between the Superior Province granites and greenstones, the Huronian basalts, and the leucogabbroic plutons (e.g., Collins, 1936; Moore and Armstrong, 1945; Card, 1965). Although there has been extensive petrogenetic study of the volcanic rocks (e.g., Jolly et al, 1992; Tomlinson, 1996), the mafic dykes (Nelson et al., 1990) and the mafic intrusions (e.g., Peck et al., 1995), the precise relationship between these rocks remains a matter of debate. Syn-emplacement crustal assimilation by the dykes (Nelson et al., 1990) and basal volcanics (Jolly et al., 1992) complicates their petrogenesis. Attempts made to relate these bodies by isotopic correspondence and geochemical modelling, for example (Prevec, 1993), suggest that a tholeiitic bulk composition like that of the least-evolved gabbroic sills (Vogel et al., 1998) could provide a parent composition for the plutons which is comparable to that of least-contaminated tholeiites. Through fractionation and minor upper-crustal contamination, most of the magmatic units can be related. However, to date there are no unique solutions which unambiguously relate these bodies.

The onset of HNMB magmatism is constrained in time by U-Pb zircon and badelleyite age ranges of *c.* 2470 to 2490 Ma for three of the leucogabbroic intrusions (Krogh et al., 1984; Heaman, 1995), and *c.* 2450 to 2470 Ma for the Hearst-Matachewan dykes (Heaman, 1995). Associated felsic magmatism consists of the Copper Cliff Rhyolite and the Creighton and Murray Granites, the latter intrusions being coeval with the mafic rocks at 2477 ± 9 Ma (Krogh et al., 1995), and a minimum age for the Huronian basalts from an age of 2450 +25/-10 from the former, the rhyolitic upper member of the volcanics (Krogh et al., 1984). Finally, a cluster of ages between 2210 and 2220 Ma for the Nipissing Diabase represents the end of the HNMB (Corfu and Andrews, 1986; Krogh et al., 1987; Noble and Lightfoot, 1992; Buchan et al., 1993). The HNMB is thought to be largely contemporaneous with deposition of the Huronian Supergroup (e.g., Bennett et al., 1991).

Juvenile rifting: *c.* 200 Ma Karoo sedimentation, volcanism and magmatism, South Africa

The Lebombo 'monocline' represents the eastern boundary of the Karoo province of sediments, volcanics, and intrusive dykes. It extends for about 900 km in a north-south direction along the border of South Africa with Mozambique (Fig. 2), part of an 1100 km long exposure of early

Jurassic bimodal volcanic rocks (e.g., Eales et al., 1984). Watkeys and Sokoutis (1998) pointed out that the term monocline is actually a misnomer for what is, in fact, a zone of complex faulting and block tilting. As in the Huronian example, the magmatic and volcanic rocks are associated with the aulacogenic side of the rift, but in this case, the sedimentary rift sequence, the rift itself, in effect, is incomplete, as it would have been outboard of the African continent, and removed by post-Gondwanaland breakup, of which the rifting event is implicitly a part. The extensive Karoo volcano-sedimentary sequence to the west predates the rifting and is not rift-related, except as host rock.
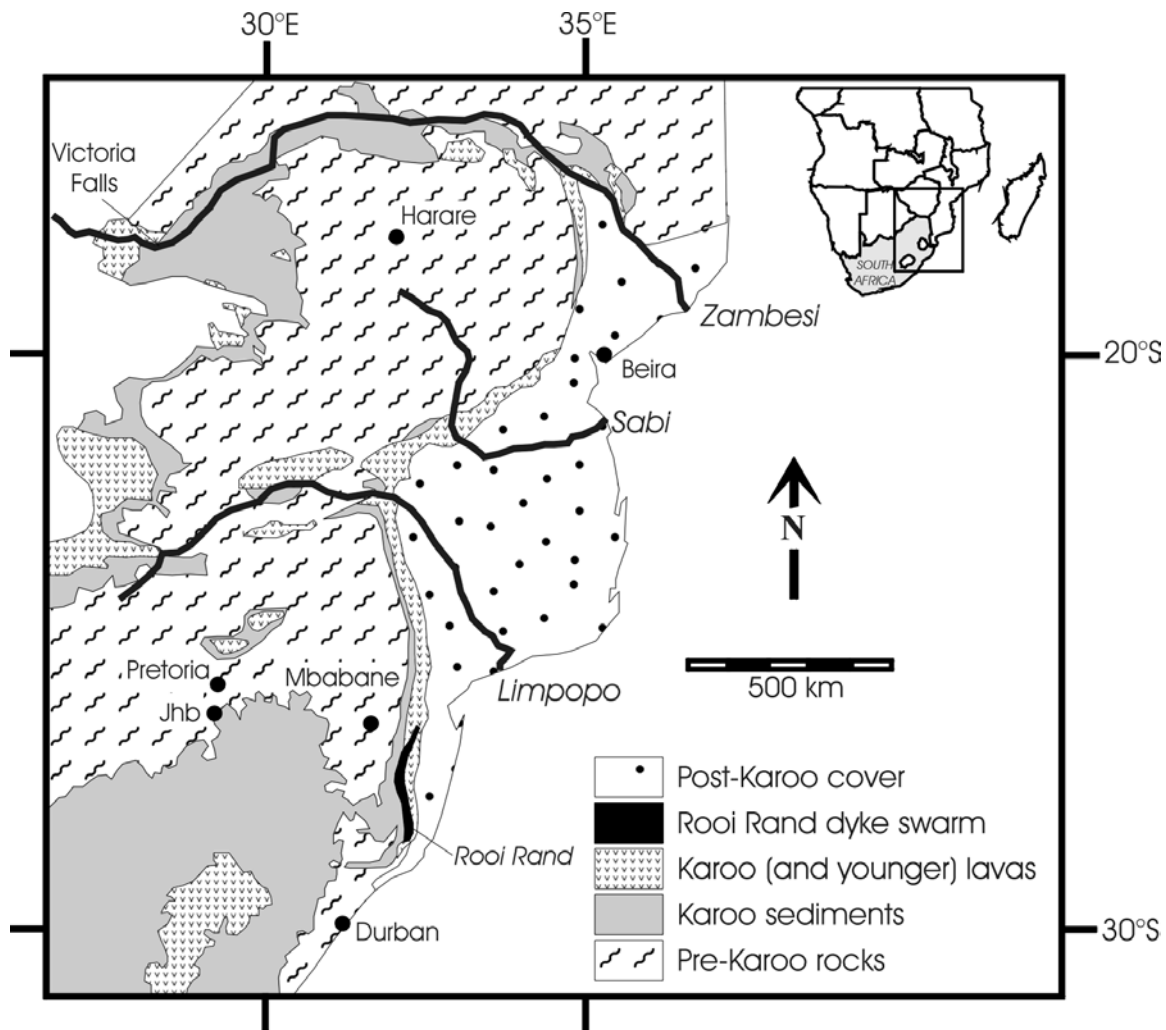

Figure 2: *Geology of the Lebombo rift environment, showing major terranes and rift-related units (after Armstrong, 1984, and others in the same volume).*

The existing 'monocline' then consists of a bimodal volcanic sequence, comprising mainly picritic to tholeiitic basaltic and rhyolitic rocks, with minor volumes of nephelinitic rocks present (e.g., Bristow and Cox, 1984). There are minor gabbroic rocks intrusive into the basaltic pile. The Karoo host rocks and the volcanic sequence are cross cut by a locally volumetrically significant set of dolerite dykes known as the Rooi Rand Dyke Swarm (Armstrong et al., 1984). Another set of dykes further to the west (about 300 km), the Oliphants River Dyke Swarm, also run parallel to the rift.

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Investigation of the magmatic rocks of the Lebombo has provided genetic models for each component based on fractionation of distinct mantle sources and subsequent minor syn-emplacement fractionation and contamination. The basaltic rocks have been interpreted as the products of minor mantle metasomatism followed by fractional melting of picritic and gabbroic sources (Cox and Bristow, 1984). The nephelinites are spatially associated with the picritic basalts, but geochemical modelling suggests that the two rock types are not related by a common source, and that the nephelinites are, instead, related to carbonatitic volcanism associated with early stages of intraplate rifting (Bristow, 1984a). The picritic basalts themselves have been interpreted as peak-rifting products, probably from magnesium-rich parental magmas (Bristow, 1984b), distinct, however, from the suggested metasomatised peridotites from which the nephelinite was derived (Bristow, 1984a). The thick sequence (5 km) of rhyolites has been interpreted as the product of about 10% partial melting of Karoo basaltic crustal rocks (Cleverly et al., 1984). The late Rooi Rand dykes are interpreted as products of within-crust fractionation from a gabbroic source (Armstrong et al., 1984).

Existing age constraints on this sequence are limited to Rb-Sr whole-rock dates. The Lebombo rhyolites include an age range from between 200 to about 170 Ma, with a distinctly younger age for one rhyolite (the Kuleni) at 145 ± 3 Ma (Allsopp et al., 1984a). Age constraints on gabbroic complexes intrusive into the basalts range between about 230 and 540 Ma for the Komatipoort Complex (centred in two clusters around 450 and 250 Ma), an unhelpful scatter attributed (in large part because they pre-date the apparent host rock ages) to crustal contamination and mixing (Allsopp et al., 1984b). The Bombani Complex was dated at 133 ± 4 Ma (Allsopp et al., 1984a) and at 141 ± 1.4 Ma (Armstong, unpublished data, pers. comm. 03/2002), significantly postdating most of the volcanic activity (except the Kulani Rhyolites, which are only slightly post-dated). The late Rooi Rand dykes were dated at 188 ± 5 Ma by K-Ar (Cleverly, 1977), inconsistent with apparently younger ages for many of their host rocks. The Rooi Rand and the Oliphants River swarms may represent the rift-parallel dykes associated with syn-rifting volcanism (Uken and Watkeys, 1997), features rarely preserved in Precambrian equivalents.

RIFTING OF ICE SHEETS

The tectonic behaviour of ice has been studied in a variety of disparate contexts. In terrestrial environments, this consists mainly of glacial studies, where the ice is, by definition, effectively permanent (in terms of the duration of study, at least). Typically, these investigations focus on the behaviour of ice mechanics during 'normal' transgressive or regressive phases (e.g., Branney, 1985; Sharp et al., 1988). Alternatively, as in the case of Icelandic glaciers, localised transformations (melting, fracturing, migration) result from intraglacial flooding, with more catastrophic resultant processes (e.g., Roberts et al., 2000, 2001; Waller et al., 2001). Croot (1987) has suggested a direct analogy between glacial tectonics and thin-skinned thrust sheets from Icelandic glaciers as a consequence of an investigation into glacial compression response. There have been studies of extraterrestrial environments, such as the identification of apparent active tectonic processes on Jupiter's moon Europa, such as doming, volcanism, diapirism, partial melting, folding and triple junctions (e.g., Head III, 2000; Pappalardo, 2000; Pappalardo and Prockter, 2000). Frank (1973) discussed the isostatic equivalence between silicate continental crust and glacial ice. In these cases silicate tectonics are being applied as analogues for ice tectonics, rather than the reverse, but the same mechanical and chemical analogies are being drawn.

Ice fracturing during glacial outburst floods, or jökulhlaups, provide well-studied examples of extensional environments near the margins of thick sheets of ice, underlain (at least at the time of extension) by upwelling, low viscosity compositional equivalents (i.e., water). Hydraulic pressure is built up beneath the glacier by flooding, definable as the appearance of volumes of water greater than the normal carrying capacity of the glacier's sub- and intraglacial channels. The flooding itself can come from a wide variety of sources or causes, including excessive rainfall on the glacier surface, rapidly channelled into the interior, rapid melting induced by subglacial heating (geothermal heat carried by magmas or water), overspill of ice-dammed lakes, and a variety of others, summarised in Tweed and Russell (1999). Water can subsequently extrude via two mechanisms. First, water will traverse the bedslope, or the base of the glacier, and eventually extrude along a linear fracture system parallel to the glacier margin (Fig. 3). Secondly, water can ascend existing fractures or create new ones (hydrofractures) and extrude as non-linear (at surface), localised outbursts. Depending on the angle and speed (and therefore depressurisation potential) of ascent, the water in the fractures may be supercooled (e.g., Roberts et al., 2001).
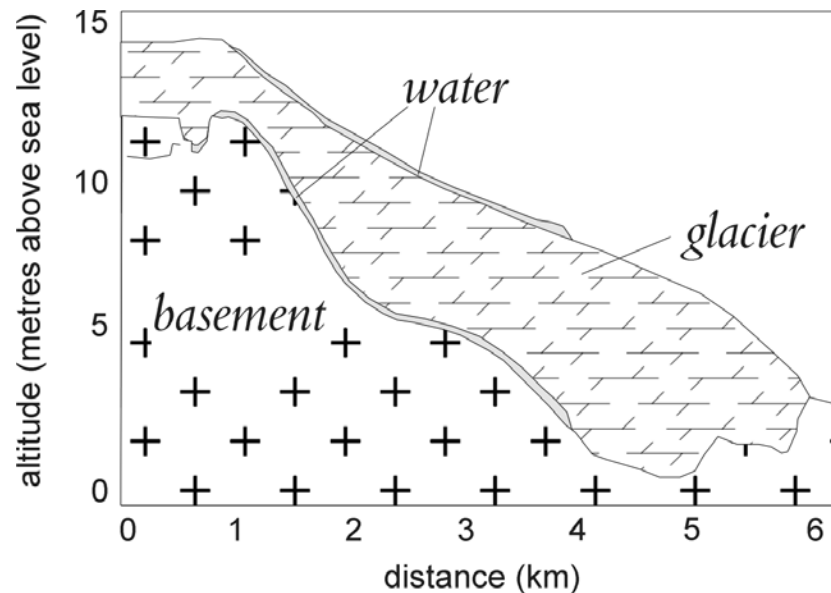

Figure 3: *Cross-sectional cartoon of a glacier, showing drainage pathways (modified after Jóhannesson, 2002).*

Discharge or extrusion rates can be quite variable, depending on the nature of the flooding. Typical flood hydrographs (showing discharge volumes against elapsed time) display fundamentally Gaussian "normal" distributions modified by negative kurtoses before and after the peak. This reflects an exponential increase in water discharge up to the peak, followed by a comparable exponential decrease as flow diminishes. By contrast, flood hydrographs for jökulhlaups can show strongly negatively skewed frequency distributions (e.g., Roberts et al., 2000, as shown in Fig.4), with a weak positive kurtosis on the pre-peak curve, such that a significantly larger component of the discharge occurs in the first half of the total discharge time.
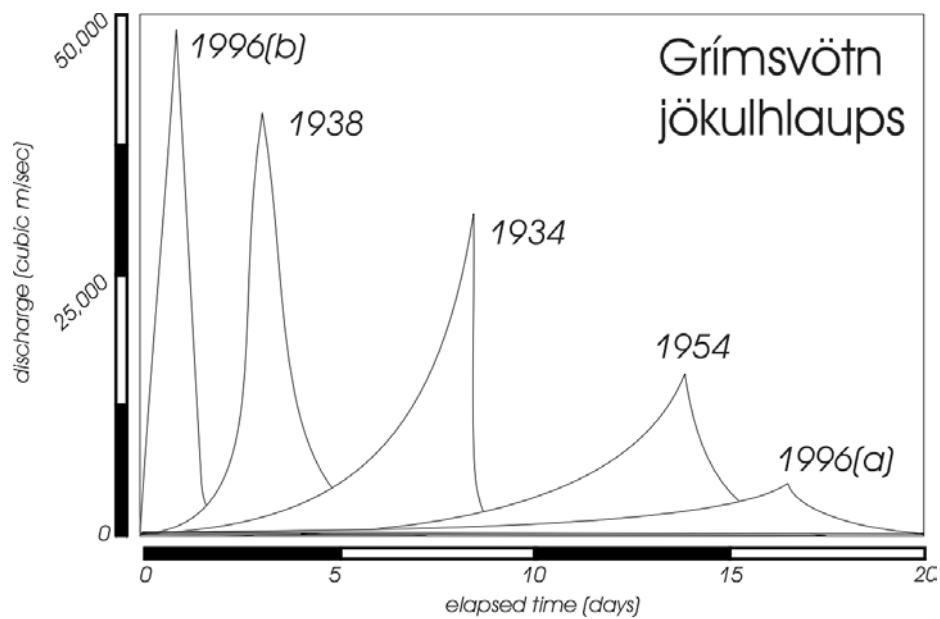
Figure 4: *Characteristic hydrograph patterns for jökulhlaups, after Roberts et al. (2000).*

The implication of this with regard to ice fracturing is that in normal flooding, water ascends and extrudes the glacier through glacial bedflow and through pre-existing channels (e.g., Nye, 1976). In the case of jökulhlaups, where the flooding rate results in near instantaneous rise to peak discharge rates and very rapid filling of the intraglacial channels, fluid overpressure occurs (as reflected by internal pore pressure), exceeding the tensile strength of the overlying ice. This condition allows for the induction of new ascending fractures by hydraulic fracturing, and consequent new supraglacial extrusion channels (Roberts et al., 2002).

On the basis of sediments deposited by ascending water dykes, Waller et al. (2001) identified two discrete stages of extrusion. First, there is an early low-energy, steady, laminar flow phase, associated with irregular fracture pathways. This is followed, and crosscut, by a more active, high flow, actively erosional (and therefore probably turbulent) phase, directed through major, linear channels, and containing xenoliths from the glacier bed. This appears to represent the main phase of eruption, prior to a further, discrete waning phase of duration approximately equal to that of the preceding stages combined.

Roberts et al. (2000, 2001) studied englacial sediment deposition associated with volcanically induced jökulhlaups (Tweed and Russell, 1999) at Skeiđarárjökull and Sólheimajökull glaciers in southern Iceland, displaying multiple supraglacial and ice-marginal outbursts, occurring on November 5, 1996, and July 18, 1999, respectively (Fig. 5). Roberts et al. (2000) depicted various manifestations of characteristic supraglacial fracture patterns from water extrusion, including features analogous to doming (albeit by reverse faulting as opposed to ductile uplift), caldera collapse (brittle, as normal-faulted gräbens, as well as more ductile sinking), normal-faulted half-gräbens, and chaotic fracturing from a single feeder outlet ascending into a veined network.
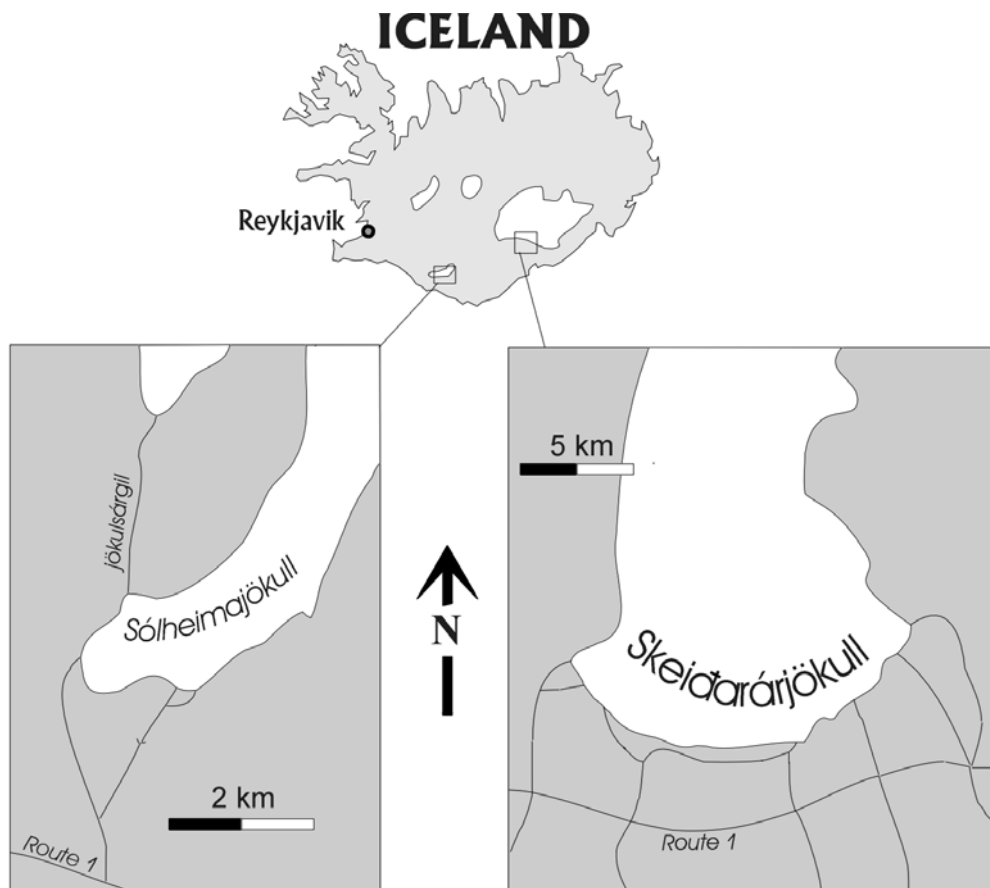
Figure 5: *Location and distribution of Skeiðarárjökull and Sólheimajökull glaciers in southern Iceland (after Roberts et al, 2000).*

DISCUSSION

Elucidating rift environments

Multi-component magmatic suites are relatively complex systems. The components of these suites, consisting of dykes, sills, stocks, and flows, are each complicated by local assimilation of host rocks, resultant different crystallisation histories, depending on local conditions such as geochemical and fluid composition of assimilant and thermal regime, for example, and degree of preservation through subsequent metamorphism, alteration, and weathering. Identifications of primary or parental compositions and resultant magmatic reconstructions are, as a result, potentially very model-dependent and subjective. Similarly, chronological sequences in continental rift magmatism are often difficult to elucidate as they consist predominantly of mafic rocks, which are less conducive to high-precision geochronology. The felsic components are volumetrically less, and consist largely (if not exclusively) of remelted pre-rifted crust, leading to large inherited contributions.

In spite of the fact that the HNMB clearly represents one of the best-dated rift sequences in the world, the imprecision on the zircon ages, the absence of datable material in the mafic volcanics, and the conceptual difficulty in establishing ages of sedimentation (as opposed to provenance) for the rift-infilling sequence results in fairly precise control on the time span of the sequence, but relatively poor control on the relationships therein. The age dates and stratigraphic sequence suggest a sequence beginning with the mafic and granitic plutonism, simultaneous with and followed by volcanism and sedimentation. The mafic dykes and felsic volcanics represent the final stages of rift magmatism, with the Nipissing diabases, about 250 million years later, finally

post-dating the deposition of the rift sediments. The data for the Huronian example suggest, then, about 40 million years of mafic and felsic magmatism, and associated sedimentation into the rift zone, continuing for more than 40 and less than 250 million years.

The Lebombo 'monocline' has been the subject of detailed geochemical evaluation of its magmatic components, although a coherent unifying magmatic model appears to be elusive. This is, in part, the result of inadequate geochronological constraints, which do not allow for the generalisation of the magmatic sequence into a strict chronology for the belt. While this may be largely attributed to the techniques applied (K-Ar and Rb-Sr, as opposed to U-Pb zircon), the precisions on individual ages are relatively high. The same limitations apply here as they did in the Huronian case, such that the bulk of the magmatism is not readily dateable, being mafic volcanism. Environments involving rifting also invite interaction between relatively wet sedimentary rocks and hot magmatic rocks, which may often lead to enhanced crust-magma assimilation and upsetting of isotopic systems such as Rb-Sr, as noted by Allsopp et al. (1984b). The apparent duration of bimodal volcanism and related mafic intrusions is approximately 70 Ma in this case, with no constraints on the duration of related sedimentation. Although there are differences in style between the two environments, such as the presence of more olivine-rich and of undersaturated rocks in the Lebombo, and the paucity of early intrusive rocks, the duration of magmatism is on the same order of magnitude as the apparent duration of the Huronian rift magmatic episode.

Ice-silicate equivalence

The ascent mechanisms involved in hydraulic fracturing, whether applied to ice (e.g., Roberts et al., 2000), sediment-hosted petroleum-based studies (e.g., Mandl and Harkness, 1987), or studies of silicate dyke propagation mechanisms (e.g., Pollard, 1987; Turcotte et al., 1987), are based on the same precepts of propagating fractures through an elastic medium. The conditions for inducing and maintaining (i.e., keeping them from being squeezed closed after formation) new fractures along or across bedding by hydraulic fracturing are discussed by Mandl and Harkness (1987) in an evaluation of hydrocarbon movement, and are constrained by the compressional stress from the overlying impermeable layer (cap-rock; crust or glacier), competing with the upwards pressure of the fluid (or gas). The upward pressure is largely (exclusively?) a function of buoyancy, in the case of trapped hydrocarbons and molten silicates, whereas in the case of subglacial flooding there is a hydraulic head acquired at the source of the flooding, upglacier, which ultimately provides an upward pressure in the waters downglacier (e.g., Jóhannesson, 2002). The upwards pressure is competing with the compressional stress of the overlying load, and the upwards pressure can be further negated if the overlying rocks are sufficiently permeable to allow dissipation of the pressure by absorption of fluid. This is reflected by a rise in pore pressure and is a transient effect, controlled by the drainage properties of the wall rock, such as permeability, bed thickness, fracture spacing and bed surface conditions (Mandl and Harkness, 1987). In the case of ice and silicate crust, the permeability is derived from pre-existing fractures, rather than porosity. In ice and in crust (continental and oceanic), as in sedimentary basins, there is horizontally stratiform structure with compositional and structural competency variations, which can be treated in similar ways, mechanically.

Once the ponding liquid has filled its available local reservoirs (subglacial or subcrustal channels) it can subsequently exceed the fracture resistance of the overlying layer, comprising components of the bedding-parallel tensile strength and the pre-pressurization bedding-parallel

normal stress. It should be noted that hydraulic fracturing may occur whether the overlying crust is under extension or compression (Mandl and Harkness, 1987), so an extensional regime does not appear to be a prerequisite for fracturing or dyke emplacement. The most direct mechanism for effecting this process would be a rapid build up of pressure, such as by very rapid glacial flooding or (geologically) rapid and localised subcrustal ponding of magma, such as produced by a mantle plume or by subduction-induced asthenospheric melting. However, equivalent fracturing can also be achieved by unloading the overlying layer while maintaining the upwards fluid pressure (Mandl, 1988). Unloading could occur as a response to rapid erosion; climatically driven melting of a glacier, or topographically driven erosion of a crustal terrane margin, or rapid excavation (as a response to large meteorite impacts).

It has been described earlier how 'normal' flooding, and perhaps even most jökulhlaups, do not build subglacial pressure sufficiently rapidly to necessitate hydraulic fracturing. This is because, in part, subglacial waters have other avenues of release such as bed flow and through existing ascending channels, which may be bypassed or complemented by hydraulic fracturing when the pressure build up is sufficiently rapid. In the magmatic equivalent, our understanding of the 'drainage' systems at the base of the crust are limited by the relative lack of exposure thereof. Sigurdsson (1987) summarizes observations of subvolcanic chamber behaviour under Icelandic and Hawaiian volcanic calderas, and associated intrusive mafic dyke swarms in the former example, where expansion and contraction of the magma chamber can be monitored by topographic and seismic variations. Magma influx into the chambers is described as steady-state, although the reported rates for Iceland vary by up to about half an order of magnitude (less for Kilauea, Hawaii). This may suggest that the occurrence of hydraulic fracturing in crustal environments is less dependent on short-lived surges in magma production than is the case for glaciers.

It has been observed that in some cases water will create or exploit ascendant channels by thermal and mechanical erosion, as opposed to (or perhaps complementing) hydraulic fracturing. In the glacial analogue, Jóhannesson (2002) described evidence for supercooled water (deposits reflecting a high component of suspended mushy, or frazil, ice, and frozen sedimentary deposits with ice matrices) from floodwaters and from crevasses (respectively) in the terminus of the Skeiðarárjökull Glacier. This required very rapid transmission of the heated water from a high-pressure subglacial environment to low-pressure extrusive environment, in order for the water to remain supercooled. Jóhannesson (2002) identified a canyon near the ice cap as the conduit for this very rapid escape; the canyon, 1 km wide, 100 m deep and 6 km long, extends from the flooded lake (Lake Grimsvötn) through the ice cap (contrasting with the 50 km total floodpath for the bulk of the jökulhlaup). The mechanism for the canyon formation was provided by the thermal energy of water at 8°C, which melted 0.3 km^3 of ice. The implications of this to jökulhlaup discharge models is primarily the speed of discharge of both water and of heat to the surface, an order of magnitude or two faster than previously thought (Jóhannesson, 2002).
From the perspective of crustal analogues, this might be equated (in terms of process) to komatiite emplacement, where unusually hot, low viscosity ultramafic magmas ascend rapidly through the crust, showing evidence of high assimilation rates. This has been attributed both to turbulent flow during ascent (e.g., Nisbet, 1982), a relatively high temperature of formation and extrusion, and to a relatively corrosive (low silica, high magnesium) bulk composition (promoting assimilation of wall rock during both ascent and emplacement) (e.g., Huppert and Sparks, 1985). Komatiitic lavas also provide a rapid (localised) mechanism for transferring heat from the mantle to the earth's surface.

These two examples both relate to the nature of the fluid discharge at given points in an extrusive episode. In both cases, these turbulent flows are part of a continuum. In the glacial case, the turbulent regime reflects peak discharge behaviour, when feeder channels are well developed and well fed, and is preceded and succeeded by laminar regimes which are, in the former circumstance, the products of poor (immature) fracture development, but motivated by a strong pressure head, and in the latter, a well-developed drainage system with a waning, weak pressure head. In the case of komatiitic lavas, these represent an early phase of a magmatic continuum progressing to more siliceous basaltic komatiites, komatiitic-to-tholeiitic basalts, and subsequently intermediate and evolved lava compositions (although not necessarily all proceeding from the same source). In this case, the largely bimodal tholeiitic-to-rhyolitic sequence, which overlies komatiites, is less commonly associated with turbulent flow during ascent, a limitation of viscosity. Turcotte et al. (1987) pointed out that for basaltic dyke emplacement, the rate of progress is limited more by internal viscosity drag than by fracture propagation efficiency (i.e., flow resistance in the crack >> fracture resistance of the elastic medium), although both laminar and turbulent regimes may be represented.

Regardless of the causes of pressure buildup and fracturing, the consequent nature of the fracturing processes can be compared. Most of the supraglacial fracturing occurs along a zone running parallel to the margin of the glacial advancing front, or tongue. In the glacial case, the tongue is not the thinnest part of the glacier (in fact, based on Jóhannesson [2002], as shown in Fig. 3, the tongue is actually about the thickest section), but this is the area of maximum upwelling fluid pressure. In the case of rifted silicate crust, a passive, rifted crust, domed over a hotspot, would not necessarily be thinner, while an extensionally thinned crust might be thinner near the rift zone (by definition). The fracture orientations themselves are either tangential or normal (much less commonly) to the front. Figure 6 (a) shows fracture orientations from Skeiðarárjökull based on jökulhlaup outlets, after Roberts et al. (2000). Most of the fracturing depicted is tangential to the front. This can be compared with the expected distribution of mafic dykes associated with rifting, spreading, and collision (Fig. 6b, after Fahrig, 1987). The initial fracturing and dyke emplacement here is also mainly tangential to the initial rifting. Often, as a result of aulacogen formation, and opening and closing of the rift, the distribution pattern preserved ultimately by the dyke swarm is that of a radial fan propagating away from the successful rift (the aulacogen being largely obliterated, meanwhile).

An ice-based model for rifts

A sequence may be envisioned in which mantle melting produces a buoyant reservoir of magma, pooling at the base of the crust and underplating it as fluid pressure builds (depending on the rate of liquid accumulation). Hydraulic theory suggests that either doming induced by magmatic pressure from below, or basin formation and (or by) crustal thinning by extension (or erosion of
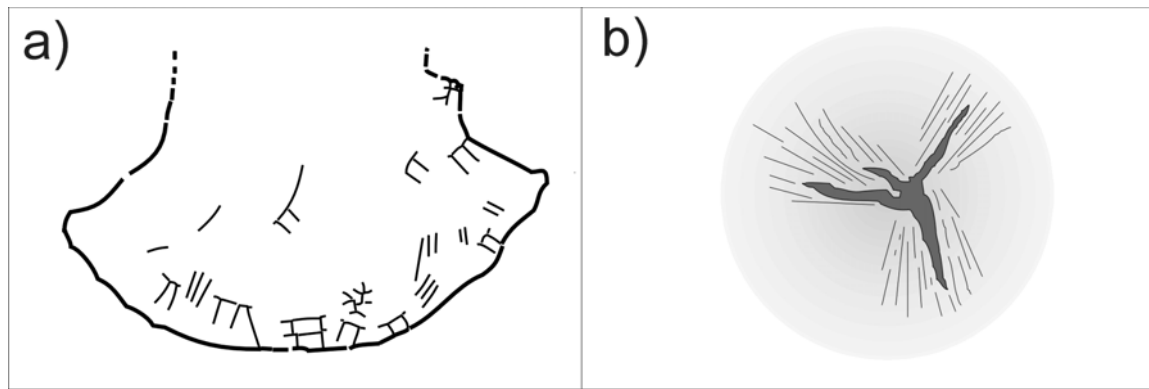
Figure 6: *Fracture patterns in glacier ice and in rifted silicate crust.*

excavation) could create supra-critical fracturing conditions. Ascent of the magma into brittle, elastic crust exploits existing zones of weakness where possible, and where it does not, creates new ones by hydraulic fracturing. Random networks of 'dry' fractures propagating ahead of the advancing dyke tips could ultimately provide reservoirs for magma chambers. The chambers would be both fed by and crosscut, after 'freezing', by ascending dykes. This is post-dated by extrusion of liquid being fed by the magma source, with changes in source, assimilant content and composition and (partial) remelting contributions being dictated by the flow style as buoyant pressure (periodically) waxes and wanes.

If this emplacement process is applied to Huronian rifting, implications for the magmatic relationships and timing of fracturing may be examined. Initial ascent of basaltic magma would proceed along pre-existing faults as well as, or perhaps subsequently, by hydraulic fracturing of adjacent crust. The string of plutonic sills were emplaced in an area of prior weakness, fed by a progression of dykes emplaced in quick succession, prior to solidification of their predecessors (e.g., Cawthorn, 1999). In the Huronian example, the East Bull Lake-type intrusives were emplaced along the Murray fault system. In the Lebombo example, the 'monocline' was likely the pre-existing boundary during Gondwana assembly, and a prominent crustal lineament (e.g., Storey and Kyle, 1997). Simultaneous and subsequent emplacement of basaltic extrusives would have occurred, along with remelting of the crust (even more analogous to the glacial process) to produce early granitic intrusions. Sedimentation and deposition off the rifted craton into the off-cratonic rifted basin was in progress by the time the extrusives appeared, but largely postdated this magmatism. In both of the rift environments described, the principal associated dyke swarms (i.e., as opposed to locally distributed and undated dykes associated with individual plutons) post-date (in the case of the syn-Huronian Matachewan-Hearst dykes) or crosscut (in the case of the Rooi Rand dykes) the rift sequences. This is inconsistent with early dyke emplacement as a consequence of crustal extension induced by proto-rift doming, but is consistent with hydraulic fracturing of a crust already structurally weakened and thinned by ongoing rifting.

CONCLUSIONS

Our grasp of even well-studied rift systems is limited by restrictions of preservation, exposure, scale, and methodological criteria. While the application of fluid dynamic theory and fracture propagation to interacting liquids and solids is well developed in geology, glacial ice tectonic

analogues evolve rapidly and cause and effect are more readily apparent. Aspects of crustal behaviour such as fracturing, faulting, and thrusting have been the subject of past studies, but growing knowledge about processes active in and below Icelandic glaciers may have implications for processes such as crustal underplating and rift-induced sedimentation. Meteorite impact phenomena and continent-continent collisions are also areas of potential benefit, perhaps more from ice sheets than glaciers. It is likely that a great deal of complementary and perhaps new information may be derived by further examination of ice and silicate analogues.

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