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Will Present Day Glacier Retreat Increase Volcanic Activity?

Stress induced by Recent Glacier Retreat and its Effect on Magmatism at the Vatnajökull ice cap, Iceland

Carolina Pagli[1,2] and Freysteinn Sigmundsson[3]

[1]Faculty of Sciences, Technology and Communication, University of Luxembourg, Luxembourg

[2]Now at School of Earth and Environment, University of Leeds, UK

[3]Nordic Volcanological Center, Institute of Earth Sciences, University of Iceland, Iceland

Abstract. Global warming causes retreat of ice caps and ice sheets. Can melting glaciers trigger increased volcanic activity? Since 1890 the largest ice cap of Iceland, Vatnajökull, with an area of ~8000 km^2, has been continuously retreating losing about 10% of its mass during last century. Present-day uplift around the ice cap is as high as 25 mm/yr. We evaluate interactions between ongoing glacio-isostasy and current changes to mantle melting and crustal stresses at volcanoes underneath Vatnajökull. The modeling indicates that a substantial volume of new magma, ~0.014 km^3/yr, is produced under Vatnajökull in response to current ice thinning. Ice retreat also induces significant stress changes in the elastic crust that may contribute to high seismicity, unusual focal mechanisms, and unusual magma movements in NW-Vatnajökull.

1. Introduction

Climate warming is causing retreat of ice caps and the solid Earth is deforming in response to these load changes, as observed e.g. at Glacier Bay, Alaska [*Larsen et al.*, 2005] and at the Vatnajökull ice cap, Iceland [*Pagli et al.*, 2007a] (Fig. 1), where mass balance measurements indicate concentrated thinning at the edges of the ice cap and a total volume of ice loss of ~435 km^3 in 1890-2003 [*Helgi Björnsson*, personal communication, 2007; see also *Pagli et al*., 2007a and references therein]. GPS measurements of glacio-isostatic deformation in the area have been used to evaluate the underlying Earth structure [*Pagli et al*., 2007a]. An axisymmetric finite element Earth model with an elastic plate over an isotropic, incompressible Maxwell viscoelastic half-space with Vatnajökull modeled as a circular ice cap explains the observations well [*Pagli et al.*, 2007a]. The ice retreat history assumes isostatic equilibrium in 1890 and gradual thinning of the ice cap between 1890 and 2003. A viscosity of 8×10^{18} Pa s, assuming an elastic plate thickness of 10 km, gives a best fit to the data (Fig. 2). Using this model, we have calculated the stress tensor due to glacio-isostasy at Vatnajökull, and evaluated its consequences. The tensor is taken as positive in tension and the pressure, *P*, is obtained as the mean of the normal stresses:

$$P = -\frac{1}{3}(\sigma_{rr} + \sigma_{\theta\theta} + \sigma_{zz}) \qquad (1)$$

where the stress components are given in a cylindrical coordinate system with origin at the center of Vatnajökull (Fig. 1).

The Mid-Atlantic Ridge passes through Iceland and is segmented into zones of rifting and volcanism, and transforms (Fig. 1). Vatnajökull overlies the eastern segment of the Mid-Atlantic plate boundary in Iceland, partly above the inferred center of the Iceland mantle plume [*Sigmundsson*, 2006]. Plate spreading and hot spot volcanism is associated with an underlying zone of mantle upwelling, creating new magma through decompression melting. As the Vatnajökull ice cap retreats over the Mid-Atlantic Ridge, the effect of material upwelling at the spreading ridge and ice thinning combine to produce decompression. *Jull and McKenzie* [1996] have shown that during the deglaciation of Iceland removal of an ice sheet the size of the country decreased the pressure in the mantle and increased melt production by a factor of about 30. Additionally, flexure of the elastic crust during glacio-isostatic movements may influence volcanism, as it induces stress changes near magma chambers, eventually enhancing or inhibiting eruptive activity [*Sigvaldasson*, 2002]. Today Vatnajökull is experiencing less ice thinning (~0.5 m/yr) than during the deglaciation of Iceland (~2 m/yr) and the area covered by the ice cap is smaller (~50 km radius) than during the last glacial period (~180 km radius). Accordingly a smaller effect on melt production is to be expected.

2. Stress changes in the mantle

We calculate the rate of change of pressure decrease in the mantle due to the present thinning of Vatnajökull (Fig. 3a). The largest rate of pressure decrease is 1700 Pa/yr beneath the ice cap. It is an order of magnitude smaller than the inferred pressure decrease during the deglaciation of Iceland at the Pleistocene-Holocene boundary, that was up to 19000 Pa/yr [*Jull and McKenzie*, 1996]. A pressure change of 1700 Pa in the mantle corresponds to pressure change due to removal of 17 cm of water, or removal of about 5 cm of rock. The influence of present ice thinning produces therefore decompression equivalent to material upwelling of up to 5 cm/yr. This may result in significant change in mantle melting, as it is comparable to mantle upwelling rates of 1-10 cm/yr inferred under Iceland [*Ito*, 2001].

The amount of melt generated by the ice unloading decompression can be evaluated from the knowledge of the pressure change, if the relation between pressure change and melt fraction is known. For isentropic decompression melting, as appropriate for a spreading ridge, the substantive derivative of melt fraction by weight, *X*, relates to pressure, *P*, by [*Jull and McKenzie*, 1996]:

$$\frac{DX}{Dt} = \left(\frac{\partial X}{\partial P}\right)_S \left(\frac{DP}{Dt} + \overline{\mathbf{V}} \cdot \nabla P\right) \tag{2}$$

where $\overline{\mathbf{V}}$ is the velocity of the solid. The partial derivative of melt fraction with respect to pressure for constant entropy, $(\partial X/\partial P)_S$, can be evaluated by numerical integration from a relation between *X*, *P* and temperature, *T*, e.g. from laboratory measurements, as demonstrated by McKenzie [1984]. We integrated his equations (D7) and (D8) of *McKenzie* [1984], using a fourth order Runge-Kutta scheme, starting on the solidus (*X*=0) at a temperature of 1500 °C. $(\partial X/\partial P)_S$ is then about constant, taking the value of 8.7×10^{-11} Pa^{-1}. Multiplication of pressure change with this factor gives the melt fraction produced per year (Fig. 3b). This is true only within the melting region – pressure change in areas outside the pre-existing upwelling region does not lead to melting. The total integrated melt volume created by the ice decompression can be inferred by specifying where the melting region is. We follow *Jull and McKenzie* [1996] and assume that melting is confined to a triangular melting region centered at the ridge axis (Fig. 3b), between the base of the crust and the solidus depth at 112 km estimated from petrological data. *Allen et al* [2002] indicate that crustal thickness in Iceland varies from 15 to 46 km. We use an average thickness of the crust of 25 km. We also assume the melting is restricted to the area underneath the Vatnajökull ice cap, where ice thinning influences the melting regime.

With this model, we find that since 1890 the average melt production rate due to glacio-isostatic decompression is about 0.014 km^3/yr.

3. Stress changes in the elastic crust

The seismicity of the Vatnajökull region (Fig. 1) is mainly confined to the plate boundary where a group of volcanic systems are situated (Bárdarbunga, Grímsvötn and Kverkfjöll) [*Jakobsdóttir et al.*, 2002]. The most seismically active of them has been Bárdarbunga and a sequence of ten earthquakes magnitude ~5 were recorded between 1974 and 1996 [*Einarsson*, 1987 and 1991; *Nettles and Ekström*, 1998]. The earthquake focal mechanisms indicate reverse faulting which is unusual for a volcano located at a spreading center. *Einarsson* [1987 and 1991] interpreted the seismicity as a result of pressure decrease in a magma chamber leading to reverse faulting in the chamber roof. *Nettles and Ekström* [1998] found non-double-couple focal mechanisms for the earthquakes, interpreted as thrust motion on an outward dipping cone-shaped ring fault beneath the Bárdarbunga caldera. In either case the earthquakes are consistent with horizontal compression and vertical tension axis. The sequence of earthquakes culminated in 1996 when a M_w 5.6 earthquake occurred at Bárdarbunga leading to the Gjálp eruption. The eruption occurred on an unusual place, midway between the Bárdarbunga and Grímsvötn volcanoes. We explore whether interaction between glacio-isostatic stresses in the crust and tectonic and volcanic stresses can influence seismic and volcanic activity in this area.

We calculated normal stresses associated with glacio-isostasy over 113 years, from 1890 to 2003, assuming a 10 km elastic thickness of. The stresses are concentrated near the outer areas of Vatnajökull, at 30-50 km distance from the ice cap center (Fig. 4). No major glacio-isostatic crustal stress changes occur at Grímsvötn, as the volcano is situated near the ice cap center. On the other hand, the Bárdarbunga and Kverkfjöll volcanoes are significantly affected. Bárdarbunga is close to the central rift axis and thus it is subject to higher build up of tectonic stresses than Kverkfjöll. Furthermore, at Bárdarbunga the tectonic stress and the radial glacio-isostatic stress (Fig. 4b and Fig 1) are almost parallel and their contributions add, while at Kverkfjöll the two stresses are almost perpendicular. Therefore, Bárdarbunga is the volcano most affected by crustal glacio-isostatic stress changes. Figure 4b shows that the inferred glacio-isostatic radial stress, σ_{rr}, at the ice cap edge is positive (tension) between 0-5 km, reaching a maximum value of 1.3 MPa over 113 years, or ~0.01 MPa/yr. On the contrary, σ_{rr} is negative (compression) between 5-10 km depth, reaching about -0.9 MPa over 113 years, or about -0.008 MPa/yr. In addition, the normal vertical stress, σ_{zz}, (Fig. 4a) is always tensional, causing vertical stretching of the crust. At each location, the $\sigma_{\theta\theta}$ stress component has the same sign as σ_{rr}, but is smaller. Thus, between 5-10 km depth, the crust is subject to horizontal compression and vertical tension, consistent with reverse faulting. Fig. 4d shows that the difference between the vertical and the radial stresses, $\sigma_{zz} - \sigma_{rr}$, is on the order of 1 MPa between 5-10 km depth. This is assuming a uniform crustal layer, but stresses are expected to increase around areas mechanically weak within a stronger crust, such as magma chambers.

4. Discussion and Conclusions

Our model indicates that recent retreat of Vatnajökull can cause increased mantle melting at a rate of about 0.014 km^3/yr. The steady-state melting rate under Iceland can be inferred from the fact that the melt extracted at the plate boundary forms the crust. In order to generate ~30 km thick crust over the 300-km north-south length of Iceland spreading at 1.9 cm/year, a magma generation of ~0.17 km^3/yr is required. Thus our inferred magma volume increase of 0.014 km^3/yr corresponds to ~10% increase in magma production. This percentage would be larger if the melt generated by glacial retreat would be compared to the melting under Vatnajökull only, but not the whole of Iceland.

Our magma production increase of ~1.4 km^3 per century can be compared to the estimated mean volcanic production at Vatnajökull in historical times (~last 1000 years), ~2 km^3 per century [Thordarson and Larsen, 2007]. This estimate is, however, uncertain as a large part of eruptive products accumulate sub-glacially, and volumes of sub-aerially deposited tephra are not well known. The most recent relatively large eruption underneath Vatnajökull occurred at Gjálp in 1996 [*Gudmundsson* et al., 2004; *Pagli et al.*, 2007b], when 0.45 km^3 of magma erupted. Our inferred melt rate is comparable with such an eruption every 30 years, if all the melt produced is erupted. In any case, our model indicates that a significant volume of additional magma, as high as 1.4 km^3, could be produced every century under Vatnajökull due to present day glacial retreat, suggesting that increased volcanic activity may be expected in the future.

Our inferred melting rate due to present day glacial thinning is over 2 orders of magnitude smaller than the inferred melt production rate during deglaciation [*Jull and McKenzie*, 1996], that was about 3.5 km^3/yr over an unloading interval of 1 kyr. The areal extent of the ice sheet and the ice thinning rate were much larger during deglaciation than currently at Vatnajökull, causing the large difference in mantle melting rates. Also Vatnajökull only partly overlies the plate boundary, thus a fraction of the total glacio-isostatic stress changes are induced within the melting region and lead to increased mantle melting (Fig. 3b), while the ice fully covered the country during deglaciation.

The surface influence of the increase in mantle melting will depend on how much magma will reach the surface, and how much will be intruded in the crust. It is inferred that during the 1975–1984 Krafla rifting episode about a quarter of ~1 km^3 of magma erupted and the rest was emplaced as dikes [*e.g.*, Sigmundsson, 2006]. Most of the lava flowed in the later half of the rifting episode after tensional stress had been relieved by diking in the earlier half of the rifting episode. If the melt increase due to glacial thinning is excessive, and the background melt generation will relieve the tensional stress at the plate boundary by diking, then a large part of the produced magma can be expected to reach the surface. When this happens is uncertain. A time lag between melt generation at depth and the eventual eruption of that magma is anticipated, depending on the vertical velocity of the melt. Based on the variation of eruptive activity and lava composition after deglaciation, the vertical ascent velocity of melt in Iceland is inferred to be > 50 m/yr, without a well defined upper limit [*Maclennan et al.*, 2002].

The plate spreading rate across the plate boundary in central Iceland is about 20 mm/yr [*LaFemina et al.*, 2005], with spreading accommodated over a deformation zone about 80 km wide. The continuous stretching causes a tectonic stresses build up of ~0.01 MPa/yr [*Sigmundsson*, 2006]. Our analysis indicates that glacio-isostatic stress changes in the crust at Bárdarbunga are tensional between 0-5 km depth, about 0.01 MPa/yr, but compressional between 5-10 km depth, about -0.008 MPa/yr. Given that tectonic and glacio-isostatic stresses add at Bárdarbunga, this scenario corresponds approximately to doubling the stress rates in the uppermost crust (0-5 km) and reducing them to a large extent at depth (5-10 km). We suggest that coupling of glacio-isostatic and tectonic stresses contributes to the high seismic activity in NW-Vatnajökull. Furthermore, the glacio-isostatic stress favors reverse faulting at 5-10 km depth. Glacio-isostasy may thus have facilitated or triggered the anomalous sequence of reverse faulting earthquakes from 1974 to 1996 at Bárdarbunga, although a prior event at the volcano may have been the original source of a compressive stress field. The difference between the vertical and the radial stresses of about 1 MPa, generated over a century, is one order of magnitude larger than the static stress changes caused by the M_w 6.5 earthquake in South Iceland in 2000, which appears to have promoted failure on a second fault [*Árnadóttir et al.*, 2003].

The compressive glacio-isostatic stress at 5-10 km depth may further inhibit magma movements at this depth, perturbing magmatic systems. We suggest that magma may deflect laterally away from areas of increased horizontal compressional stresses (Fig. 4). Magma would eventually reach the surface closer to the central part of the ice cap, at a distance of about 30 km from the center, or outside the ice cap. We suggest tha this mechanism contributes to the unusual location, and unusal strike, of the Gjálp eruptive fissure, which occurred between the Bárdarbunga and Grímsvötn volcanoes, in fact at a distance of about 30 km from the ice cap center. Seismicity preceding this eruption originated at Bárdarbunga, and propagated towards the Gjálp site. Furthermore, a recent InSAR study by *Pagli et al.* [2007b] shows that an inferred 10 km deep magma chamber under Bárdarbunga deflated during the second half of the Gjálp eruption. This is interpreted as a clear indication of a pressure connection between the Gjálp eruptive site and the Bárdarbunga volcano, although the connection may be complex as the deflation only occurred after the initial half of the eruption.

Jellinek et al. [2004] suggest that volcanism is influenced by the growth and retreat of glaciers. The processes described here have broad relevance as global warming causes extensive world-wide ice retreat. Modification of mantle melting by ice retreat requires relative large ice caps whereas important changes in crustal stresses due to ice retreat may be more widespread at ice-capped stratovolcanoes. Areas affected may be locations such as Mount Erebus, Antarctica, the Aleutian Islands volcanoes, Alaska and in the volcanic zone of southern Patagonia.

Figure captions

Fig. 1 Map of the Vatnajökull region. The main figure shows the Vatnajökull ice cap (white) in the Eastern Volcanic Zone. Fissure swarms (shaded), central volcanoes (solid outlines), and calderas (dashed lines) after Einarsson and Saemundsson [1987]. The Gjálp eruptive fissure is marked by 'Gj'. The black circle gives the outline of the Vatnajökull model and its center marks the origin of the coordinate system. Black points are earthquake epicenter locations recorded by the Icelandic Meteorological Office seismic system between 1994 and 2003, excluding the seismicity during two eruptions, in October 1996 and December 1998. The inset shows the Mid-Atlantic plate boundary in Iceland and the location of the study area.

Fig. 2 Modeled velocities (lines) and observed GPS velocities (crosses) at Vatnajökull [*Pagli et al.*, 2007a]. Black crosses are the vertical and grey crosses are the radial GPS velocities. The black line is the vertical and the grey line is the radial modeled velocity, using an ice cap radius of 50 km, an elastic thickness of 10 km and a viscosity of the viscoelastic medium of 8×10^{18} Pa s.

Fig. 3 Pressure change and corresponding melt production in the mantle. **a**, Pressure change per year (Pa/yr). The thick black line represents the diameter of Vatnajökull, 100 km. **b**, melt fraction by weight per year (yr^{-1}). The black lines represent a triangular melting region centered at the ridge axis under western Vatnajökull.

Fig. 4 Stress changes in the elastic crust**.** **a**, vertical stress, σ_{zz}. The black thick line represents the radius of Vatnajökull, 50 km. Color scale bar in panel **a** applies to all panels. **b**, radial stress, σ_{rr}. **c**, tangential stress, $\sigma_{\theta\theta}$. **d**, difference between vertical and radial stress, $\sigma_{zz} - \sigma_{rr}$.

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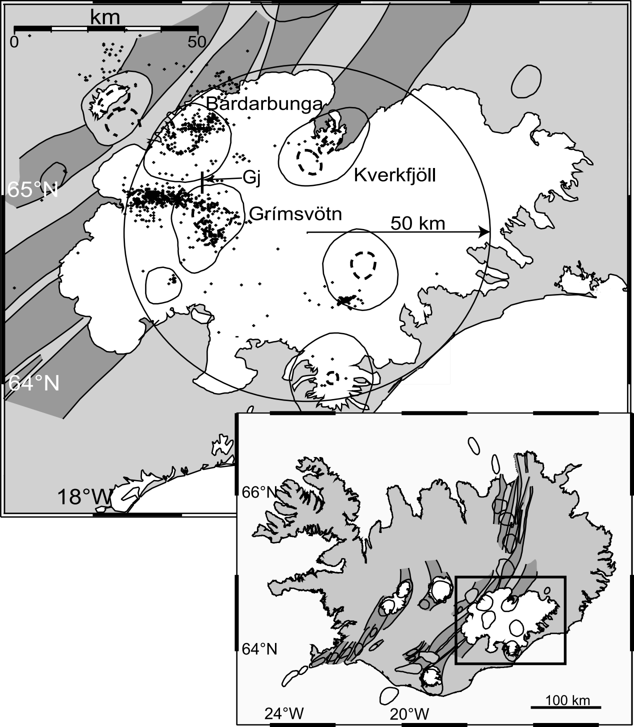
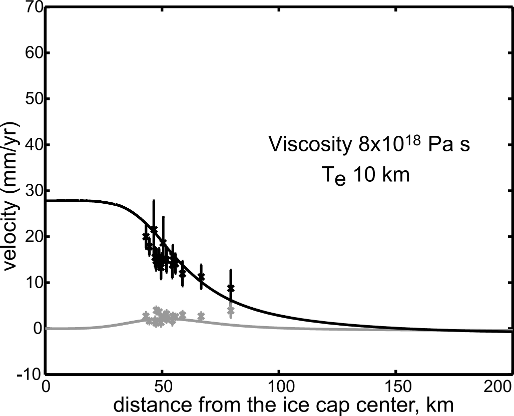
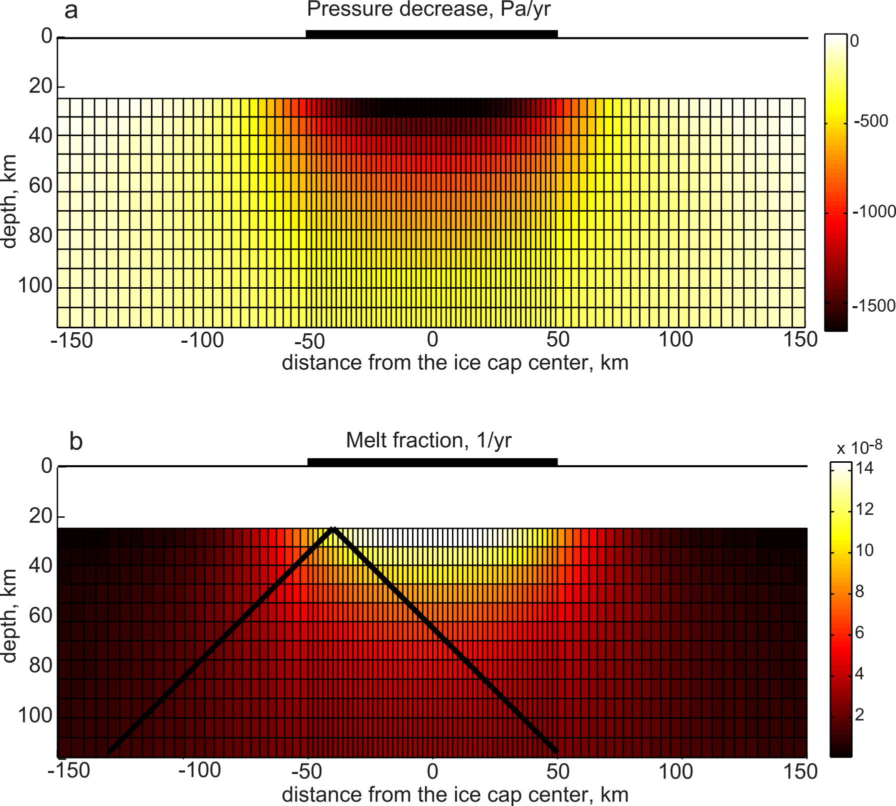
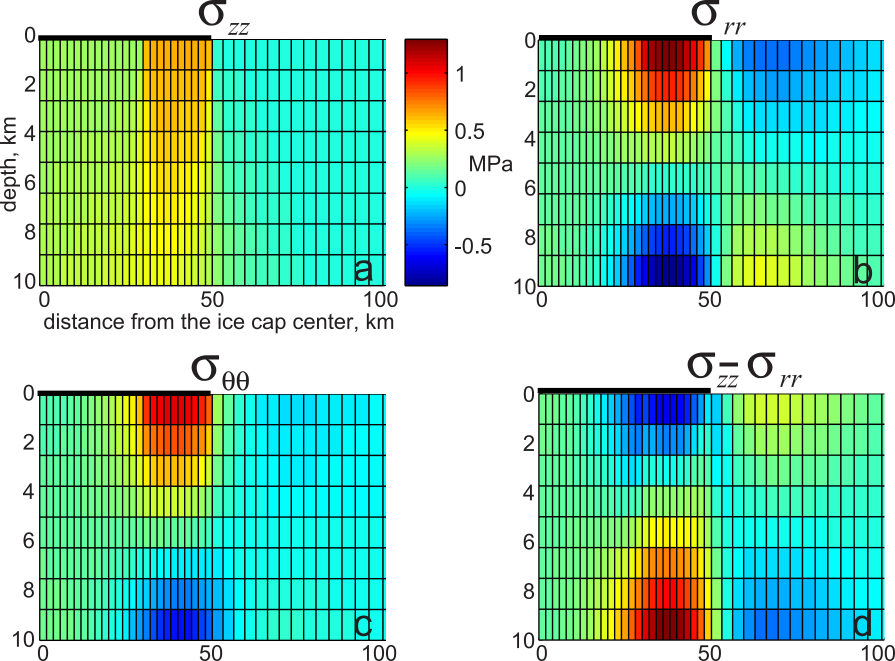


km
0
50
Bárdarbunga
Gj
Kverkfjöll
65°N
Grímsvötn
50 km
64°N
18°W
66°N
64°N
24°W
20°W
100 km



Viscosity 8x10^{18} Pa s
T_e 10 km
velocity (mm/yr)
distance from the ice cap center, km
70
60
50
40
30
20
10
0
-10
0
50
100
150
200


a
Pressure decrease, Pa/yr
0
20
40
60
80
100
depth, km
-150
-100
-50
0
50
100
150
distance from the ice cap center, km
0
-500
-1000
-1500
b
Melt fraction, 1/yr
0
20
40
60
80
100
depth, km
-150
-100
-50
0
50
100
150
distance from the ice cap center, km
x 10-8
14
12
10
8
6
4
2



σzz
σrr
σθθ
σzz–σrr
MPa
1
0.5
0
-0.5
depth, km
distance from the ice cap center, km
0
2
4
6
8
10
0
50
100
a
b
c
d