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**Glacial-isostatic adjustment and sea-level change  
near Berkner Island, Antarctica**

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## Introduction

On 13 January 2005, an ice core from the summit of the Thyssenhöhe on Berkner Island, Ronne Ice Shelf, Antarctica (314.30°E, -79.57°N; see [Figure 1.1](#)) was retrieved. At the final coring depth of 948 m below the surface, the ice core contained significant amounts of yellow sediments. The shape and size of the grains suggest an aeolian origin. The location of the sediments is  $\sim 62$  m below the present-day sea level ([Twickler & Mulvaney, 2005 \[online\]](#)).

At the location of the core, relative sea-level (RSL) height has varied mainly as a consequence of two counteracting processes. First, the global eustatic sea-level change associated with the global ice-mass changes (mainly in the northern hemisphere), and, second, the deformation of the earth's surface due to the glacial history in the vicinity of the location, *i. e.* the glacial-isostatic adjustment (GIA).

The objective of this study is to calculate the RSL height at the location of the Berkner Island ice core during the last glacial cycle using a viscoelastic earth model and several glacial histories. Earlier glacial cycles are not considered, the basic assumption being that the sediments were deposited during the last glacial cycle. However, to some extent the results can be extrapolated further back into the past. The results impose a constraint on the time of deposition of the sediments. Conversely, if the time of deposition is determined, *e. g.* by luminescence dating, this study provides a constraint on the glacial history of the Ronne Ice Shelf.

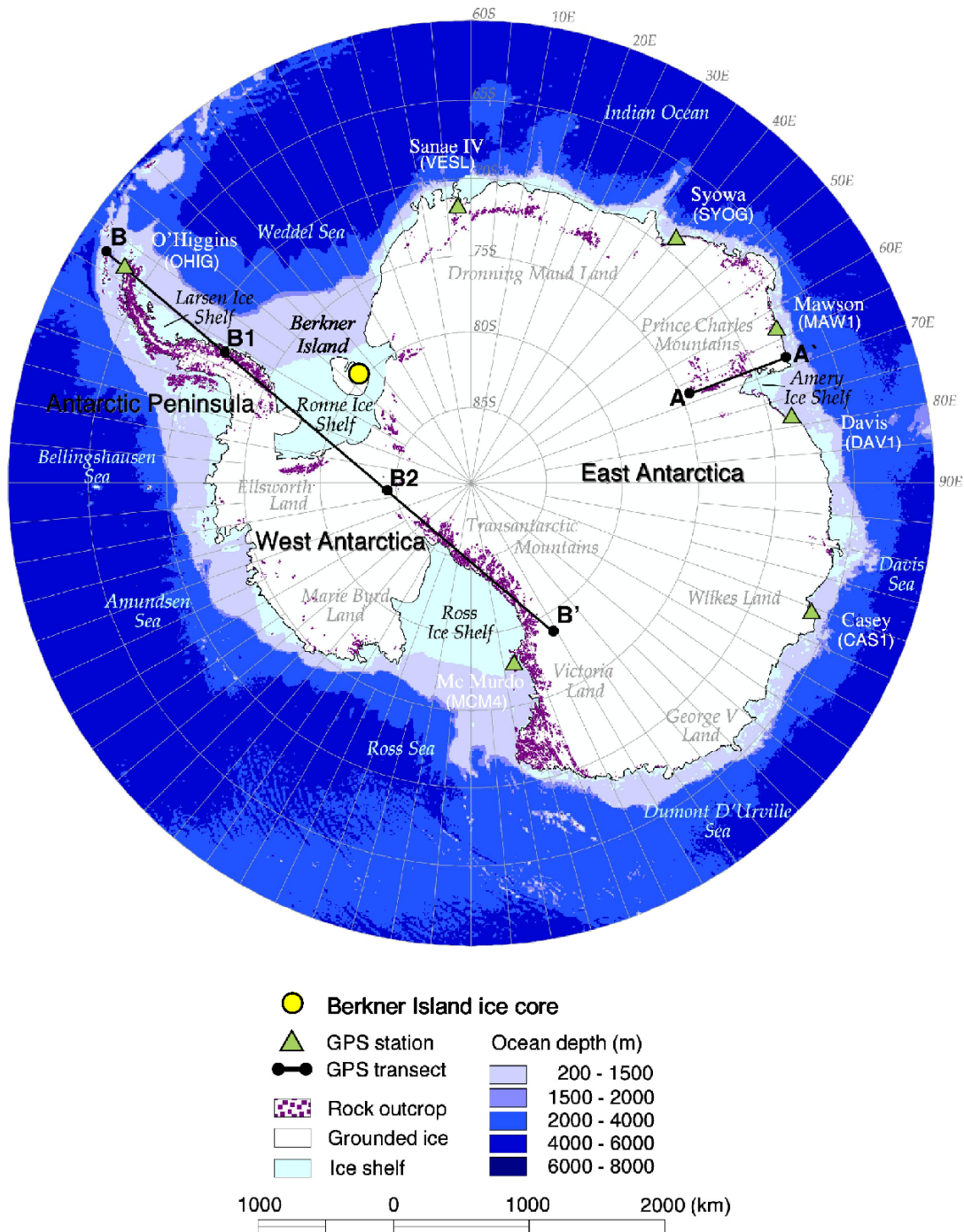


Figure 1.1: Map of Antarctica based on the Antarctica Digital Database (ADD Consortium, 2000 [\[online\]](#)), the Digital Chart of the World (ESRI, 2003 [\[online\]](#)) and the BEDMAP – bed topography of the Antarctic (Lythe *et al.*, 2000 [\[online\]](#)). The toponomy follows the Composite Gazetteer of Antarctica (Cervellati & Geoscience Standing Scientific Group (GSSG), 2003 [\[online\]](#)). This and all following maps of Antarctica are in the polar stereographic projection with 0°E central longitude and 90°S true-scale latitude.

## Method

Glacial changes redistribute water between the continents and the oceans and induce a viscoelastic response of the earth. This response is calculated by solving the field equations for a self-gravitating Maxwell-viscoelastic continuum subject to interface and boundary conditions, as imposed by the ice- and water loads. Here, the predicted quantities of interest are the radial displacement and the RSL height.

The temporal variation of the ice distribution is prescribed by the load models (see [Section 4](#)), whereas the distribution of the associated melt water is governed by the sea-level equation (e.g. [Johnston, 1993](#)). The numerical code used is based on the spectral finite-element approach described by [Martinec \(2000\)](#) and provides a resolution up to spherical-harmonic degree 340. The sea-level equation is implemented according to [Hagedoorn \(2005\)](#).

The retreat of an ice sheet has various implications for the RSL height in its vicinity. First, the load of the ice sheet causes land subsidence, which rebounds by viscoelastic relaxation after the retreat of the ice sheet. This causes a decrease of the RSL height. However, this is counteracted by melt water entering the oceans, which increases the RSL height. In addition, the melt water also represents a load, which causes land subsidence and an increase of the RSL height. Thus, it is necessary to consider the changes in the ice–ocean system on a global scale. Furthermore, the influx of mantle material towards the uplifting area increases the RSL height due to the associated rise of the geoid. In contrast to this, the missing attraction of the former ice masses causes a decrease of the RSL height due to the fall of the geoid.

The load models used in this study only consider changes relative to the contemporary load distributions, which implies that no load is present today. The radial displacement is given relative to the initial state of the earth defined by the isostatic equilibrium due to the self gravitation of the earth's body. The RSL height is referred to the contemporary sea-level height, *i. e.* compared to today, where positive values indicate a higher, negative values a lower sea level.

## Earth models

The GIA of the earth is mainly influenced by its radial viscosity distribution. The viscoelastic earth model used here is discretized in three layers of uniform viscosity, *i. e.* the lithosphere, the upper mantle and the lower mantle, as well as a liquid core. The upper and lower-mantle viscosities are assumed to be free parameters. The radial distribution of the elastic parameters is taken from PREM (Dziewonski & Anderson, 1981). The lithosphere is modelled as a layer of very high viscosity such that it behaves effectively elastic on the time scale considered. Its thickness controls the magnitude of its flexure when a load is applied. The boundary between the upper and lower mantle is assumed at the depth of 670 km.

Two viscoelastic earth models are employed: the standard-viscosity model (SVM) and the low-viscosity model (LVM). The viscosity values of SVM (after Wiczerkowski *et al.*, 1999; Martinec & Wolf, 2005) are based on the analysis of GIA in Fennoscandia. The values of LVM represent an arbitrarily chosen lower bound on the mantle viscosity beneath West Antarctica, which allows us to assess the sensitivity of the results to the viscosity assumed. Additionally, compared to LVM, SVM has a thinner lithosphere. Table 3.1 lists the parameters used for the viscoelastic earth models.

Model	Lithosphere thickness (km)	Viscosity		Elasticity
		Upper mantle (Pa s)	Lower mantle (Pa s)	
SVM	100	$5.2 \times 10^{20}$	$5.9 \times 10^{21}$	PREM
LVM	50	$2.0 \times 10^{20}$	$2.0 \times 10^{21}$	PREM

Table 3.1: Parameters of the viscoelastic earth models SVM and LVM.



## Load models

Two types of load model are used to describe the glacial changes with the largest influence on the RSL height near Berkner Island.

Load model BICE describes the contemporary ice thickness over Berkner Island and considers no realistic time evolution. The load is applied until the earth reaches isostatic equilibrium. The calculated displacement represents the maximum depression of the lithosphere caused by the contemporary ice load, which, in turn, is equivalent to the maximum uplift that occurs for ice-free conditions on Berkner Island.

The Pleistocene load models NAWI-A1 and NAWI-A2 describe the global ice-thickness change from 180 ka before present (BP) until today. They are used to compute the viscoelastic response of the earth to ice-thickness changes in Antarctica and the global melt water contribution.

### 4.1 Load model BICE

[Figure 4.1](#) shows the present-day ice thickness over Berkner Island described by load model BICE. The load is axisymmetric with a radius of 55 km. The maximum ice thickness of 1000 m decreases radially outward according to an elliptical function. It is known that the flexure of the lithosphere strongly depends on its thickness. Thus, load model BICE is used in conjunction with earth models SVM and LVM.

### 4.2 Load models NAWI-A1 and NAWI-A2

Load models NAWI-A1 and NAWI-A2 describe the global glaciation history. They are constructed from glaciological models for the northern hemisphere ([Zweck & Huybrechts, 2005](#)) and the southern hemisphere ([Huybrechts, 2002](#)). The latter models the Antarctic ice sheet (AIS) and is modified such that the additional volume of the ice sheet compared to present day is 12 m equivalent sea level (ESL). Here, ESL is a measure defined as the water volume equivalent to the ice mass under consideration divided by the global ocean area, fixed to  $362 \times 10^6 \text{ km}^2$ . The time interval considered for the northern hemisphere is 120 ka BP to present. For the southern hemisphere, the interval is extended to 180 ka BP in order to model also the viscoelastic response associated with the previous glacial cycle in Antarctica. This approach is sufficient since the most important contribution of the northern hemisphere to the RSL height around Antarctica is due to the instantaneous melt-water induced changes of the global mean sea level.

The difference between load models NAWI-A1 and NAWI-A2 lies in the initiation of the glaciation in Antarctica. For load model NAWI-A1, the volume of the AIS

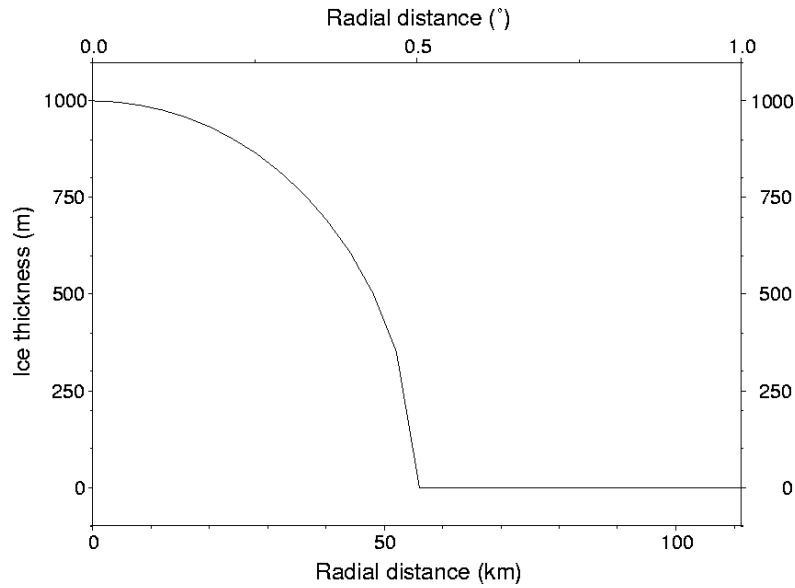


Figure 4.1: Present-day ice thickness on Berkner Island for load model BICE.

increases linearly from 120 ka BP to 15 ka BP; for load model NAWI-A2, the glaciation extends from 50 ka BP to 15 ka BP. The contribution to the global mean sea-level change associated with either glacial history is shown in [Figure 4.2](#). Although NAWI-A2 contradicts the widely accepted synchronous glaciation of the northern and southern hemispheres, it is used to assess the influence of an independent glaciation history for the Ronne Ice Shelf.

The spatial distribution of the ice-thickness change in Antarctica since the last glacial maximum (LGM) for load models NAWI-A1 and NAWI-A2 is shown in [Figure 4.3](#). For these models, [Figure 4.4](#) depicts the ice-thickness change since the LGM along 314.30°E, which intersects with the location of the Berkner Island ice core.

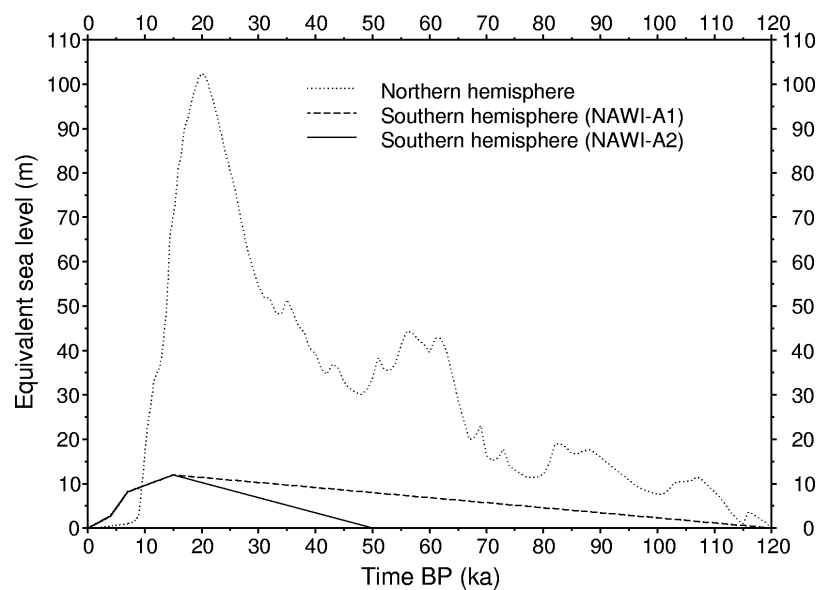


Figure 4.2: Total ice-mass change for the Pleistocene load models NAWI-A1 and NAWI-A2. The northern hemisphere contributes 120 m ESL, the southern hemisphere (*i. e.* the AIS) 12 m ESL to the global mean sea-level change since the LGM. The northern-hemisphere glaciation starts at 120 ka BP, reaches its maximum at 20 ka BP and is identical for both load models. The last glaciation of the southern hemisphere starts at 120 ka BP (NAWI-A1) or 50 ka BP (NAWI-A2) and reaches its maximum at 15 ka BP. The previous glacial cycle (only modeled for the southern hemisphere) has the same temporal evolution and terminates at 120 ka BP (not shown).

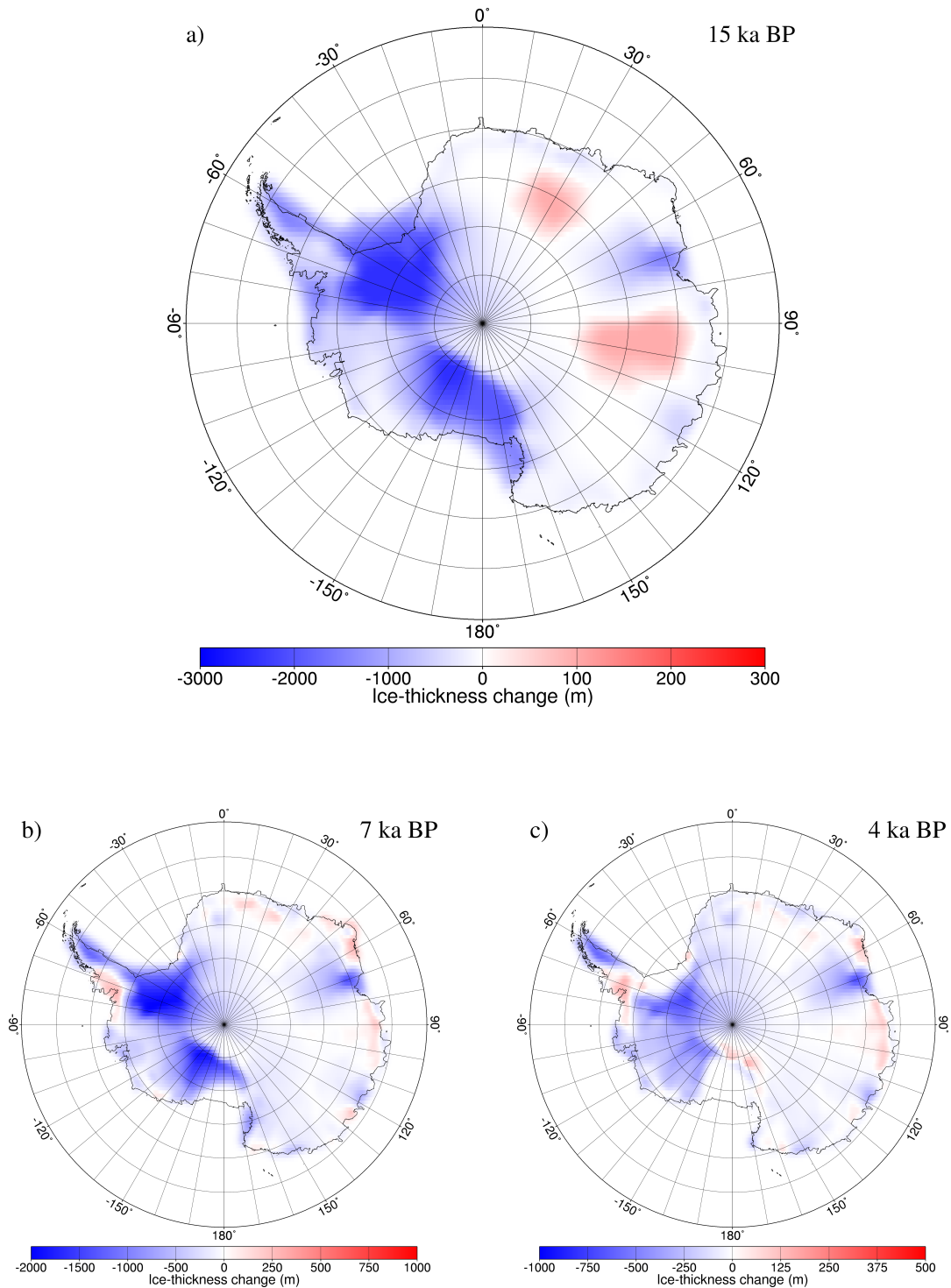


Figure 4.3: Ice-thickness change since 15, 7 and 4 ka BP in Antarctica for load models NAWI-A1 and NAWI-A2. (a) 15 ka BP: Large decreases occur at the Ross, Ronne, Larsen and Amery Ice Shelves; central parts of East Antarctica show a slight increase of ice. (b) 7 ka BP: Grounded ice has largely retreated from today's Ross Ice Shelf. (c) 4 ka BP: The deglaciation of the Ronne Ice Shelf continues. The discretization is  $0.25^\circ \times 0.25^\circ$ .

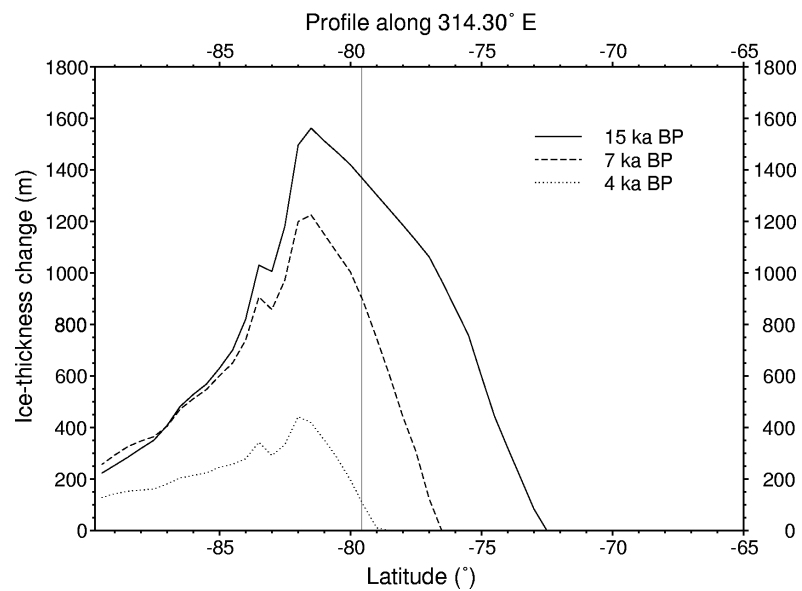


Figure 4.4: Ice-thickness change along 314.30°E for load models NAWI-A1 and NAWI-A2. The location of the Berkner Island ice core is indicated by the vertical line. At the LGM, the grounding line was ~700 km north of Berkner Island. At that time, a 1400 m thick layer of additional ice was present on Berkner Island.

## Results

This section presents the results for the radial displacement and RSL height at the location of the Berkner Island ice core, Ronne Ice Shelf, Antarctica. The calculations apply to earth models SVM and LVM forced by load models BICE and NAWI-A1 or NAWI-A2. First, we present the radial displacement calculated for the present-day load model BICE (Section 5.1). Then, we address the radial displacement and the RSL height due to the Pleistocene load models NAWI-A1 and NAWI-A2 (Section 5.2). We regard load model NAWI-A1 to represent the more realistic glaciation history of the AIS. The results for load model NAWI-A2 allow us to assess the sensitivity of the results to an independent glaciation history of the Ronne Ice Shelf.

### 5.1 Load model BICE

Load model BICE produces a maximum depression of the lithosphere of 10.8 m (SVM) or 25.8 m (LVM) (Figure 5.1). The magnitude of the displacement is controlled by the lithosphere thickness and is rather small compared to the maximum load thickness of 1000 m. This is due to the small radius of the load, causing much of it to be supported by the lithosphere.

The results show that the radial displacement associated with the complete deglaciation of the island is not sufficient to raise the location of the sedimentary horizon to  $\sim -62$  m above present-day sea level. This indicates that the earth has not regained isostatic equilibrium since the last deglaciation in the region of the Ronne Ice Shelf. The values calculated are used to reduce the RSL indicated by the sediment assuming ice-free conditions at the time of deposition.

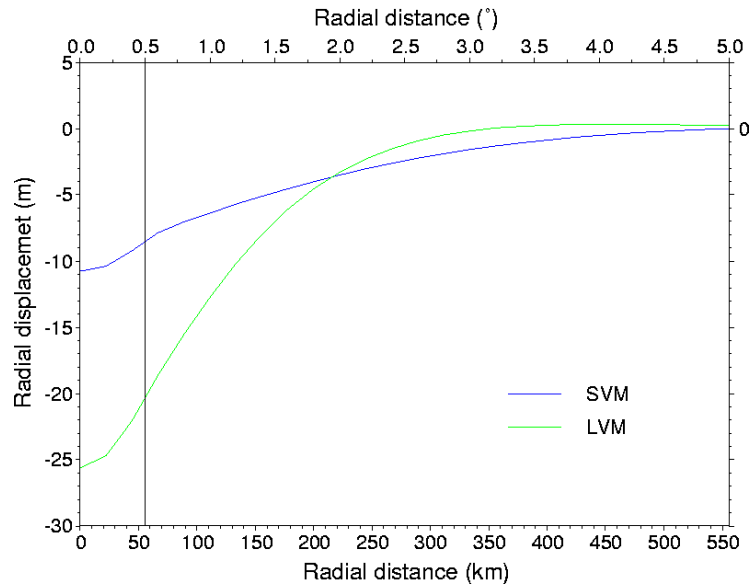


Figure 5.1: Radial displacement for load model BICE and earth models SVM and LVM. The ice extent is indicated by the vertical line.

## 5.2 Load models NAWI-A1 and NAWI-A2

Earth model	Load model	Time BP	
		Start (ka)	End (ka)
SVM	NAWI-A1	114.5	92.2
LVM	NAWI-A1	–	–
SVM	NAWI-A2	114.3	35.5
LVM	NAWI-A2	115.5	44.1

Table 5.1: Time interval of potential sediment deposition for the earth and load models employed.

This section presents the results for the radial displacement and RSL height for load models NAWI-A1 and NAWI-A2 in combination with earth models SVM and LVM.

The RSL height indicated by the sediments ( $-62$  m relative to today's sea level) is reduced by the radial displacement resulting from load model BICE (Section 4.1). This correction is necessary since it is assumed that Berkner Island was largely ice free at the time of deposition. The value of this correction depends on the earth model chosen and amounts to  $-51.2$  m (SVM) or  $-36.2$  m (LVM). In the following, we refer to the reduced value as the indicated RSL height (horizontal line in Figures 5.2, 5.3, 5.4 and 5.5).

### Radial displacement for load model NAWI-A1

Independent of the earth model, the radial displacement induced by load model NAWI-A1 (Figures 5.2 and 5.3, dashed lines) is mainly due to the glaciation history in the vicinity of Berkner Island. However, the radial displacement lags the load changes

due to the viscoelastic properties of the underlying mantle. The earth model with higher viscosity values (SVM) responds slower, such that the time of the maximum displacement is later (108 ka BP for SVM, 114 ka BP for LVM). However, due to the gradual increase of the ice thickness in the load model, both earth models produce the minimum of the radial displacement ( $-304$  m for SVM,  $-358$  m for LVM) at approximately the same time ( $\sim 15$  ka BP). The present-day radial displacement is  $-103$  m (SVM) or  $-43$  m (LVM).

#### **RSL height for load model NAWI-A1**

The RSL height for load model NAWI-A1 (Figures 5.2 and 5.3, solid lines) is mainly reflected by the radial displacement, however, with opposite sign. The change of the global mean sea level due to the glaciation history of the northern hemisphere is smaller in magnitude. Nevertheless, this effect reduces the RSL height near Berkner Island and partially compensates the changes of the RSL height induced by the radial displacement. The minimum of the RSL height is reached at 107 ka BP (SVM,  $-77.5$  m) or 112 ka BP (LVM,  $-32.6$  m).

#### **Radial displacement for load model NAWI-A2**

For load model NAWI-A2 describing the late glaciation of the AIS, the magnitude of the displacement is small until  $\sim 50$  ka BP (Figures 5.4 and 5.5, dashed lines). For the earth model SVM, the minimum of the radial displacement induced by this load model amounts to  $-289$  m, which differs from the value obtained for load model NAWI-A1 ( $-304$  m). For the earth model LVM, the minimum displacement of  $-352$  m is close to the value produced by load model NAWI-A1. The values for the present-day radial displacement are  $-101$  m (SVM) or  $-46$  m (LVM).

#### **RSL height for load model NAWI-A2**

The RSL height resulting from load model NAWI-A2 (Figures 5.4 and 5.5, solid lines) mainly decreases until 100 ka BP (SVM) or 110 ka BP (LVM) due to the viscoelastic relaxation following the previous deglaciation. Then, a further decrease is also caused by the glaciation of the northern hemisphere and the associated global sea-level fall. After 50 ka BP, the changes of the RSL height are dominated by the radial displacement induced by the increase of the ice load near Berkner Island. The minimum of the RSL height is reached at 56 ka BP (SVM,  $-141.4$  m) or 51 ka BP (LVM,  $-80.9$  m).

#### **Time of sediment deposition**

According to the results described above, Table 5.1 summarizes the time intervals in which the computed RSL height allows the deposition of aeolian sediments on Berkner Island. The intervals lie between the intersection points of the curve of the calculated RSL height with the height of the sedimentary horizon for each combination of earth and load model (Figures 5.2, 5.3, Figure 5.4 and 5.5, marked in red). For the modelling scenario considered to be most realistic (earth model SVM and load model NAWI-A1), the time interval is 22.3 ka. For the late glaciation of the Ronne Ice Shelf (load model NAWI-A2), the time interval increases to 78.8 ka (earth model SVM) and 71.4 ka (earth model LVM). For load model NAWI-A1 and the low-viscosity earth model LVM, the calculated RSL height is always above the height of the sedimentary horizon, which contradicts the geological evidence represented by the sediments.



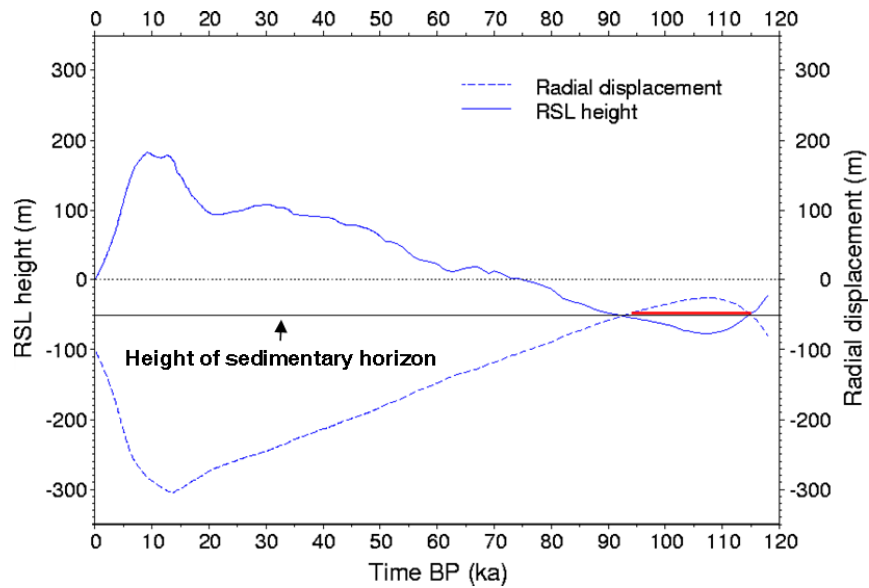


Figure 5.2: Radial displacement and RSL height for load model NAWI-A1 and earth model SVM.

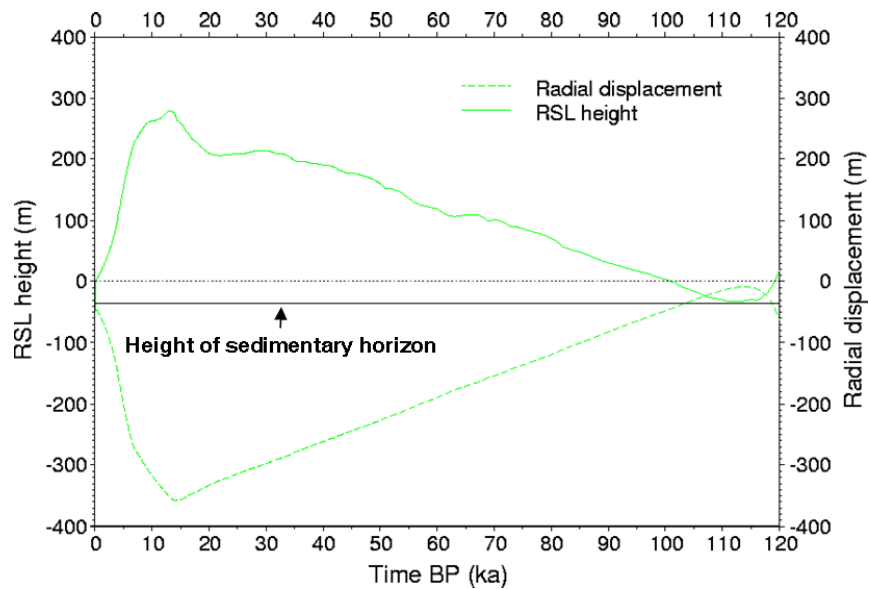


Figure 5.3: Radial displacement and RSL height for load model NAWI-A1 and earth model LVM.

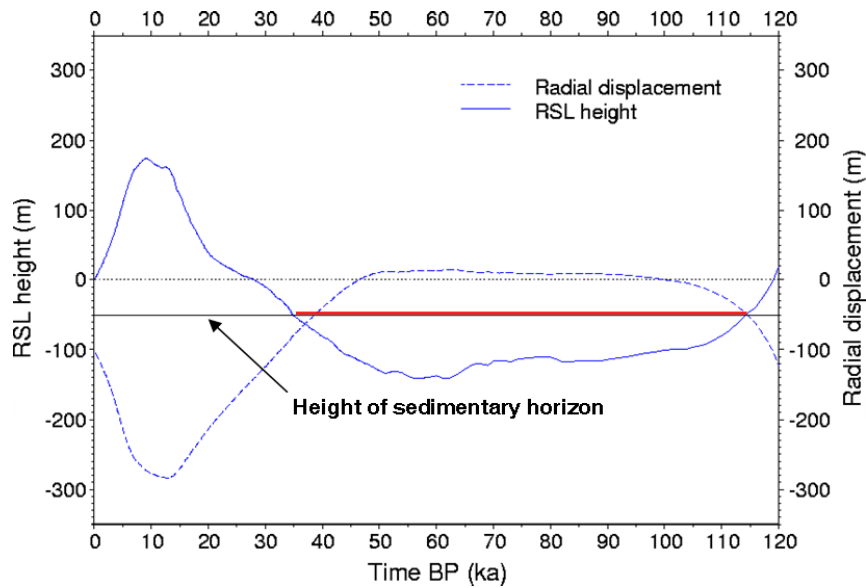


Figure 5.4: Radial displacement and RSL height for load model NAWI-A2 and earth model SVM.

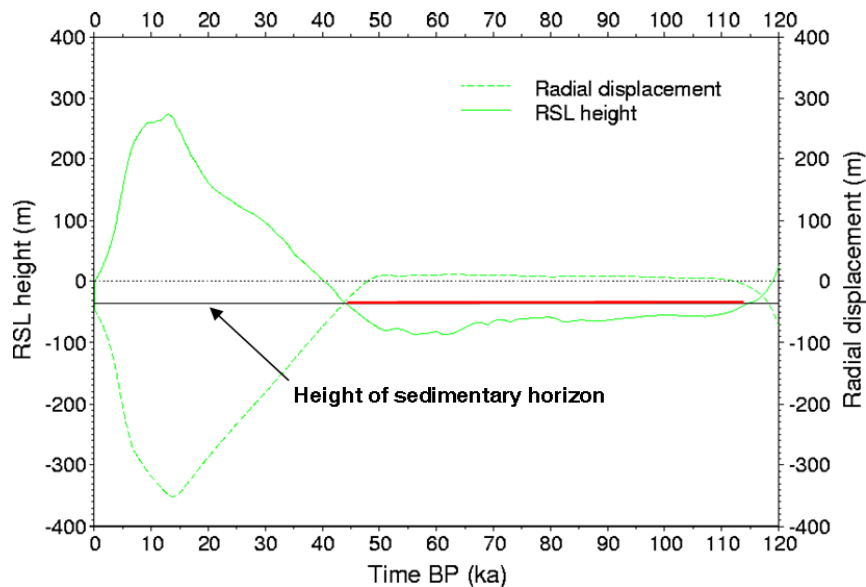


Figure 5.5: Radial displacement and RSL height for load model NAWI-A2 and earth model LVM.

## Conclusion

The objective of this study is to explain the occurrence of aeolian sediments on Berkner Island, Ronne Ice Shelf, Antarctica. The sediments were retrieved from near the base of the Berkner Island ice core,  $\sim 62$  m below the present-day sea level. We have calculated the variation of the RSL height at the location of the Berkner Island ice core during the last glacial cycle using a viscoelastic earth model and several glacial histories. The results show that:

1) The present-day ice cover on Berkner Island causes 10.8 to 25.8 m of land subsidence. Conversely, the land uplift associated with a complete removal of this ice cover is not sufficient to raise the location of the sedimentary horizon above the present-day sea level.

2) The variation of the RSL height near Berkner Island is dominated by the land uplift/subsidence associated with the earth's viscoelastic response to the history of the Ronne Ice Shelf. The melt water contribution of the northern hemisphere is smaller.

3) The most realistic combination of viscoelastic earth and glacial history (SVM and NAWI-A1) allows aeolian sediment deposition from 114.5 to 92.2 ka BP.

4) If the sediments were deposited the last 120 ka BP, the height of the sedimentary horizon represents a constraint on the mantle viscosity and the glacial history of the Ronne Ice Shelf.

In future, it will be possible to extend and refine this study by

- the consideration of dated sea-level indicators located in the near-field with respect to the Berkner Island ice core.
- the adoption of a refined resolution of Antarctica's glacial history, *i. e.* based on climatological proxies.
- the improvement of the glacial history in the area of the Ronne Ice Shelf by considering geomorphological constraints.

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# Abbreviations

## 1. Earth models

<i>Abbreviation</i>	<i>Page</i>	<i>Description</i>
LVM	<a href="#">5</a>	low-viscosity model
SVM	<a href="#">5</a>	standard-viscosity model

## 2. Load models

<i>Abbreviation</i>	<i>Page</i>	<i>Description</i>
BICE	<a href="#">6</a>	present-day load model for the Berkner Island ice cover
NAWI-A1 -A2	<a href="#">6</a>	Pleistocene deglaciation models based on numerical modelling

## 3. Text tokens

<i>Abbreviation</i>	<i>Page</i>	<i>Description</i>
AIS	<a href="#">2</a>	Antarctic ice sheet
BP	<a href="#">2</a>	before present
ESL	<a href="#">6</a>	equivalent sea level
GIA	<a href="#">2</a>	glacial-isostatic adjustment
LGM	<a href="#">6</a>	last glacial maximum
PREM	<a href="#">5</a>	Preliminary Reference Earth Model
RSL	<a href="#">2</a>	relative sea level

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