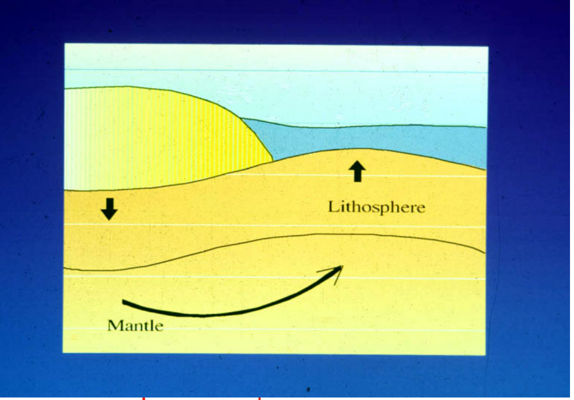
GIA signals in Geodetic Reference Frames

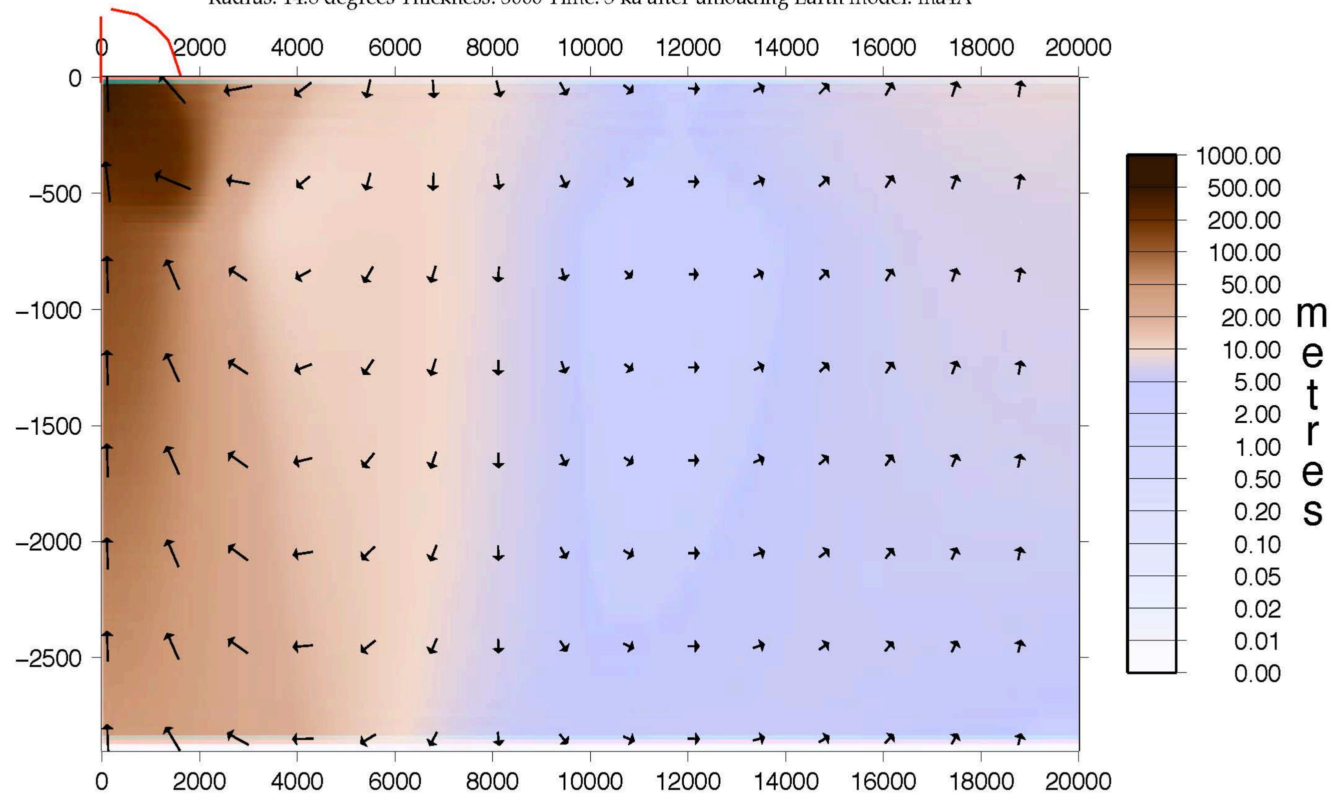
Kurt Lambeck, Anthony Purcell and Hélène Rouby



symmetric
parabolic
ice
load

Deformation due to an axisymmetric parabolic Heaviside load

Radius: 14.8 degrees Thickness: 3000 Time: 5 ka after unloading Earth model: ma4A



(i) The deformation of the solid Earth in response to a single ice load change, is global.

(ii) There is the associated water load change and changes in inertia tensor

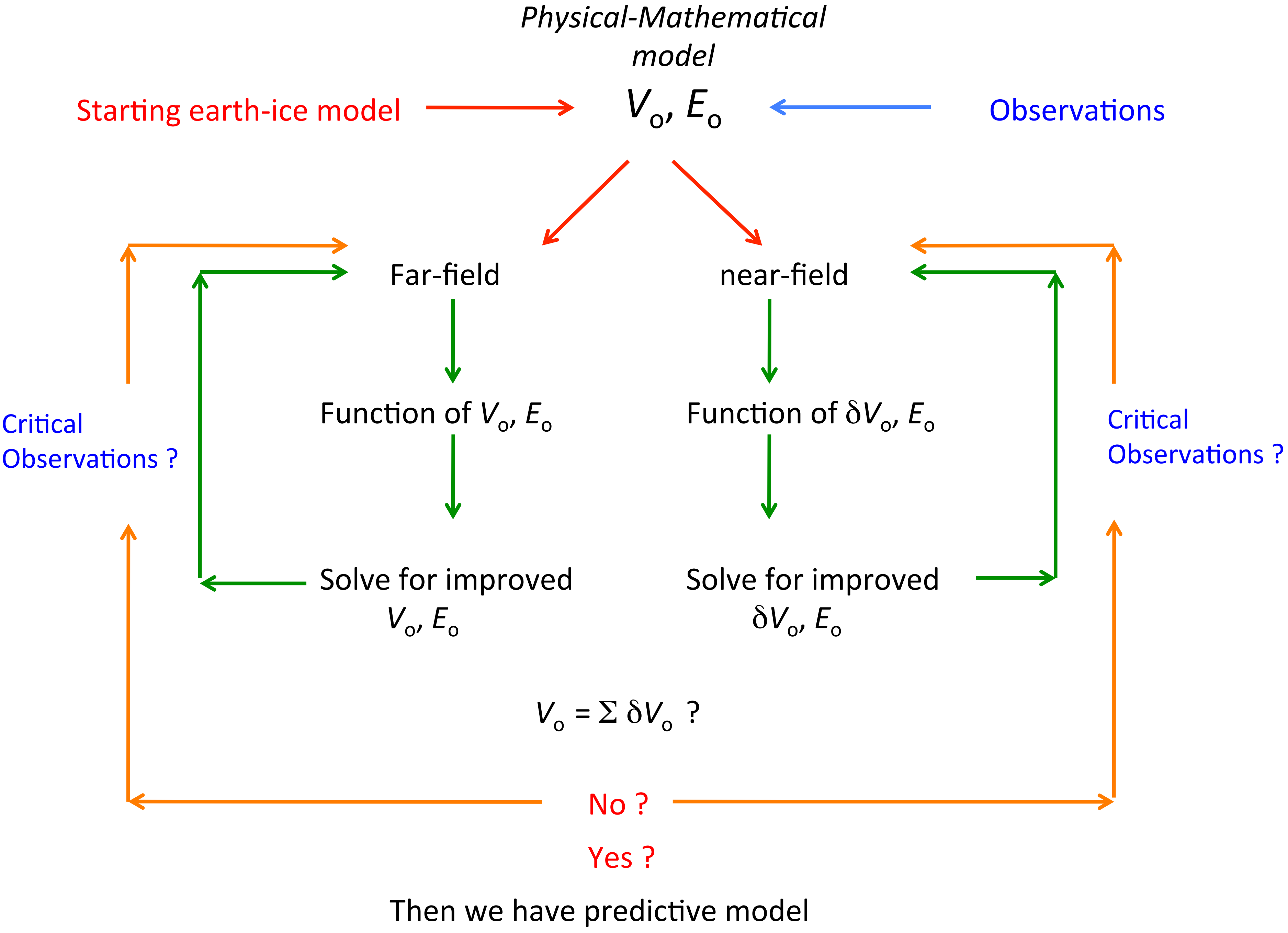
(iii) It is ongoing for > 10^3 years after the ice load is stabilized

(iv) The signals will be indistinguishable form recent or present-day deglaciation from areas that also contributed to the past deglaciation.

(v) To have effective predictive models we need to know the Earth rheology. Maxwell rheology? Internal phase boundaries? Lateral variability in viscosity and lithospheric thickness?

(vi) Need the ice load history back to the LGM and beyond,

(vii)) Need high resolution models for the ocean bathymetry, particularly for former and present ice shelves.



Physical-Mathematical model

Starting earth-ice model → V_o, E_o ← Observations

Far-field

Function of V_o, E_o

Solve for improved V_o, E_o

near-field

Function of δV_o, E_o

Solve for improved δV_o, E_o

Critical Observations ?

Critical Observations ?

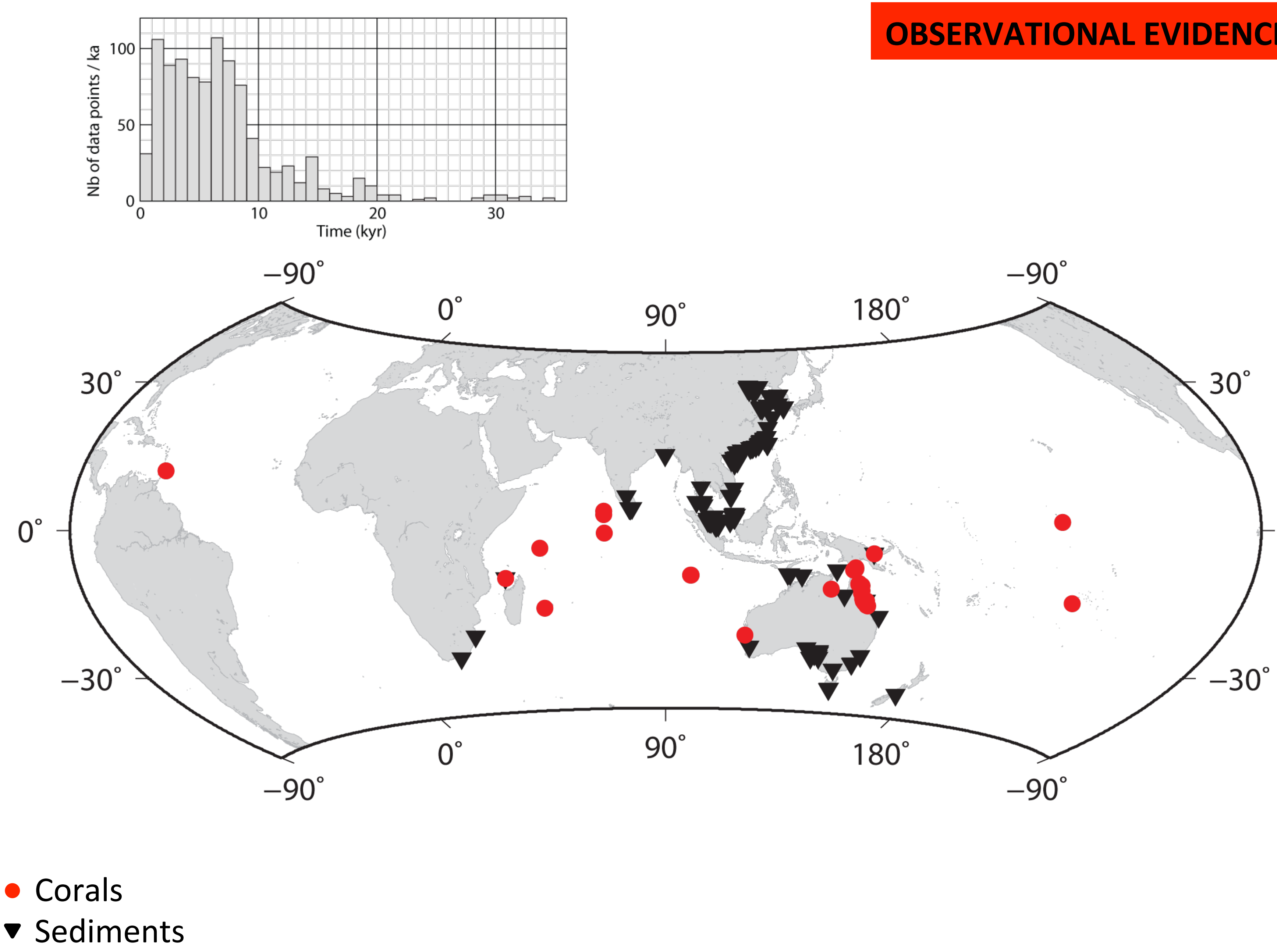
$V_o = \Sigma\, \delta V_o$?

No ?

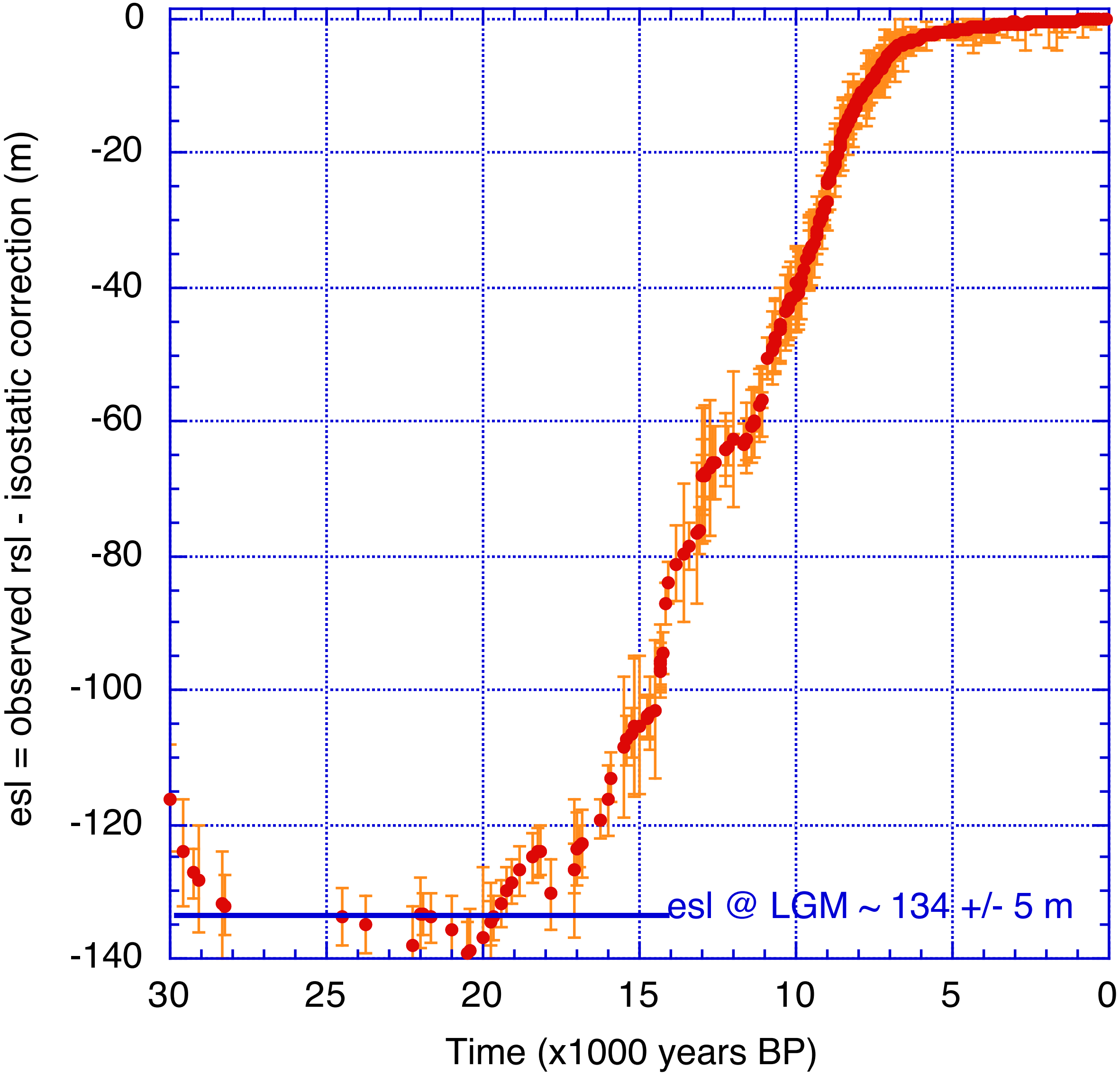
Yes ?

Then we have predictive model

OBSERVATIONAL EVIDENCE



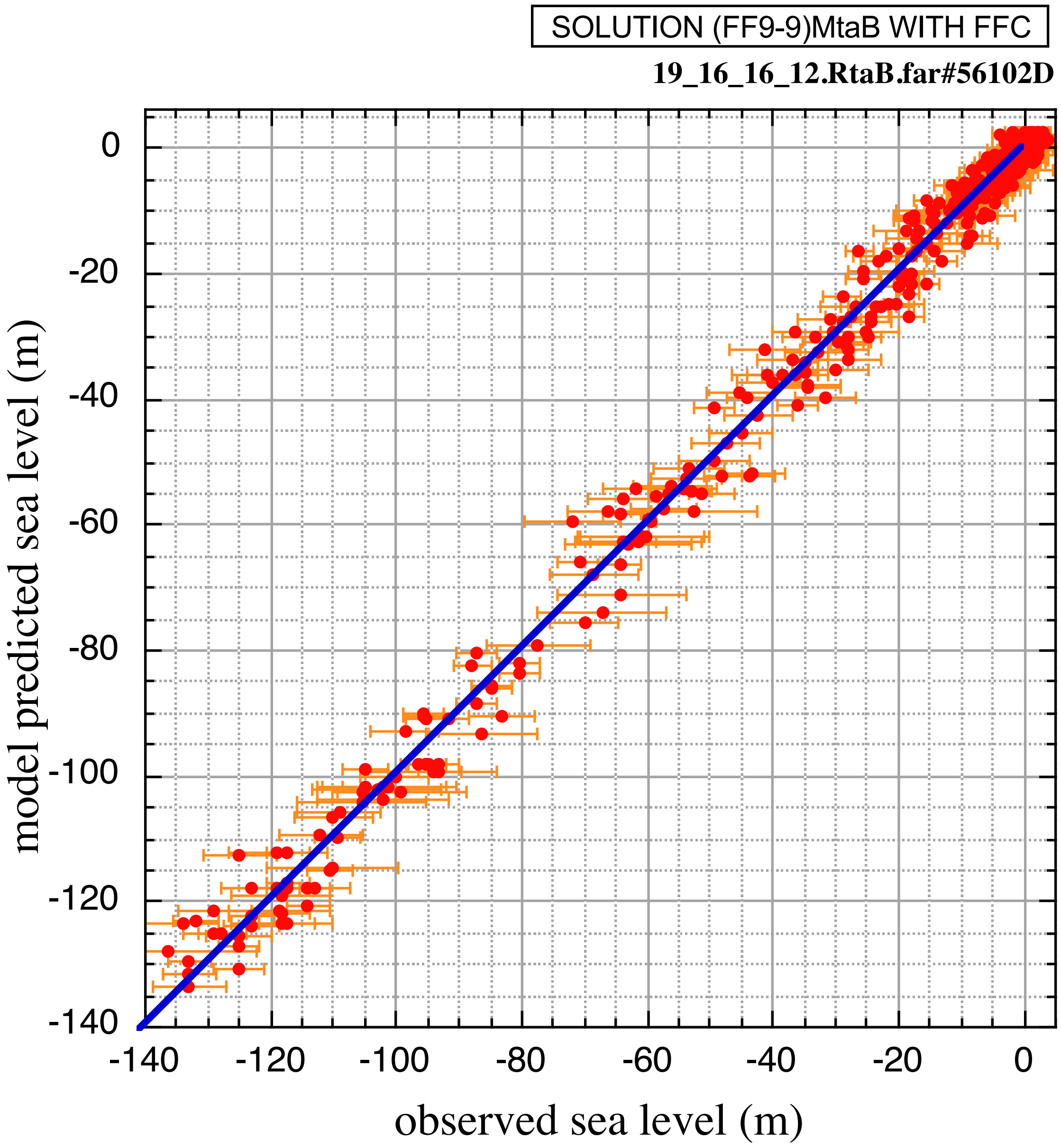
Esl = ice volume equivalent sea level



$$\Delta\zeta_{esl}(t) = -\frac{\rho_i}{\rho_o}\int_t \frac{1}{A_o(t)}\frac{dV_i\,dt}{dt}$$

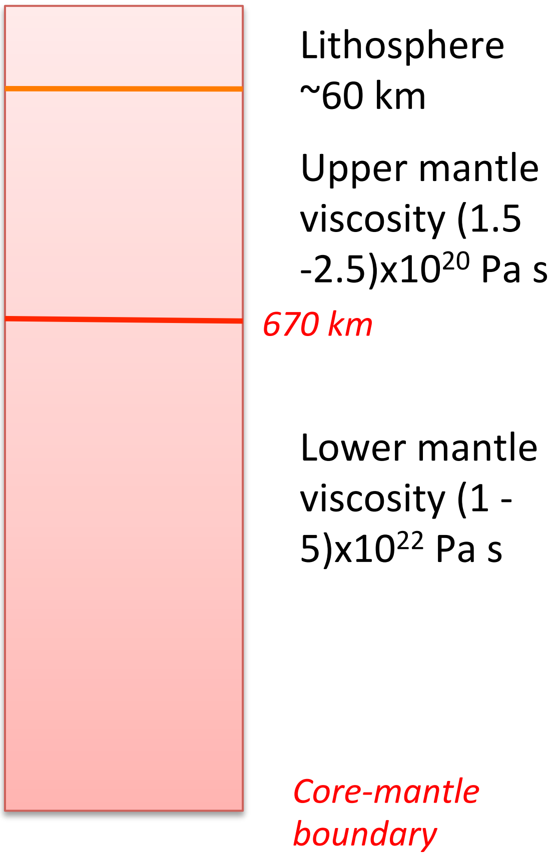
$$\Delta\zeta_{esl} = \Delta\zeta_{obs} - (\Delta\zeta_I + \Delta\zeta_T)$$

134 m esl = 52x10^6 km^3 grounded ice



SOLUTION (FF9-9)MtaB WITH FFC

19_16_16_12.RtaB.far#56102D



Lithosphere
~60 km

Upper mantle
viscosity (1.5
-2.5)x10^{20} Pa s

670 km

Lower mantle
viscosity (1 -
5)x10^{22} Pa s

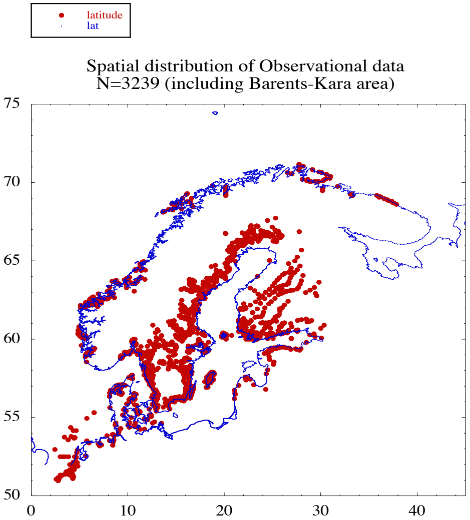
*Core-mantle
boundary*

Earth response parameters for Fennoscandinavia

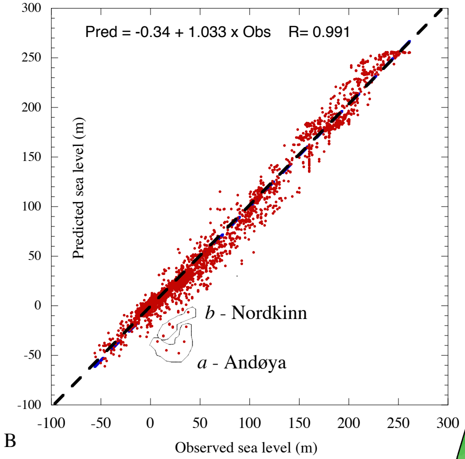
Litho-sphere *80 km*	*Upper mantle* *(3-4)x10^{20} Pa s*	*Lower mantle* *(5-20)x10^{22} Pa s*

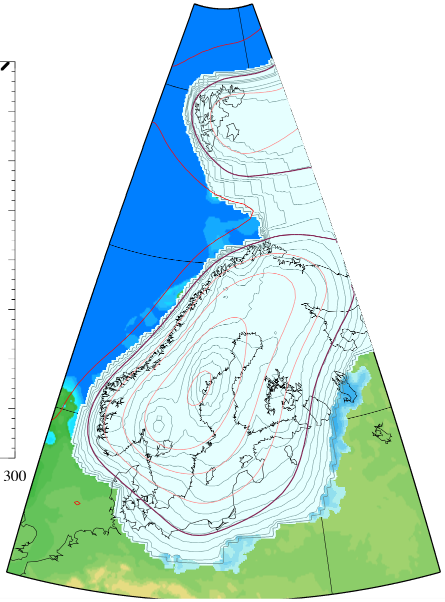
	H (km)	η_{um} (x10^{20} Pa s)	η_{lm} (x10^{21} Pa s)
Geological data[1,2]	80-90	3.0-4.0	7-30
Tide gauge data[1,3]	80-100	4.0-4.5	≥10
GPS data[4]	93-110	3.4-5.0	7-13

[1] Lambeck and Purcell (2003); [2] Lambeck et al., (2008); [3] Lambeck and Ekman (1998); [4] Zhao et al. (2012).

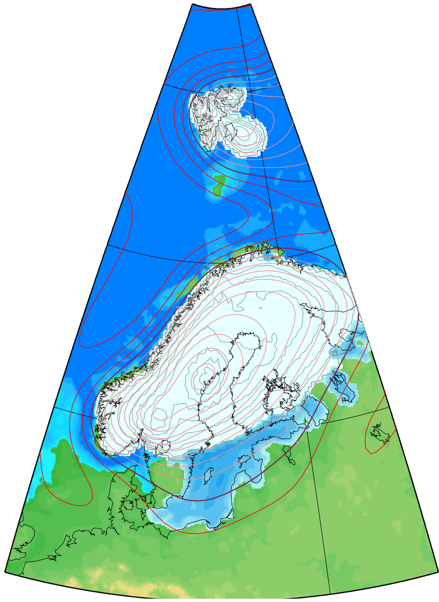


Spatial distribution of Observational data
N=3239 (including Barents-Kara area)

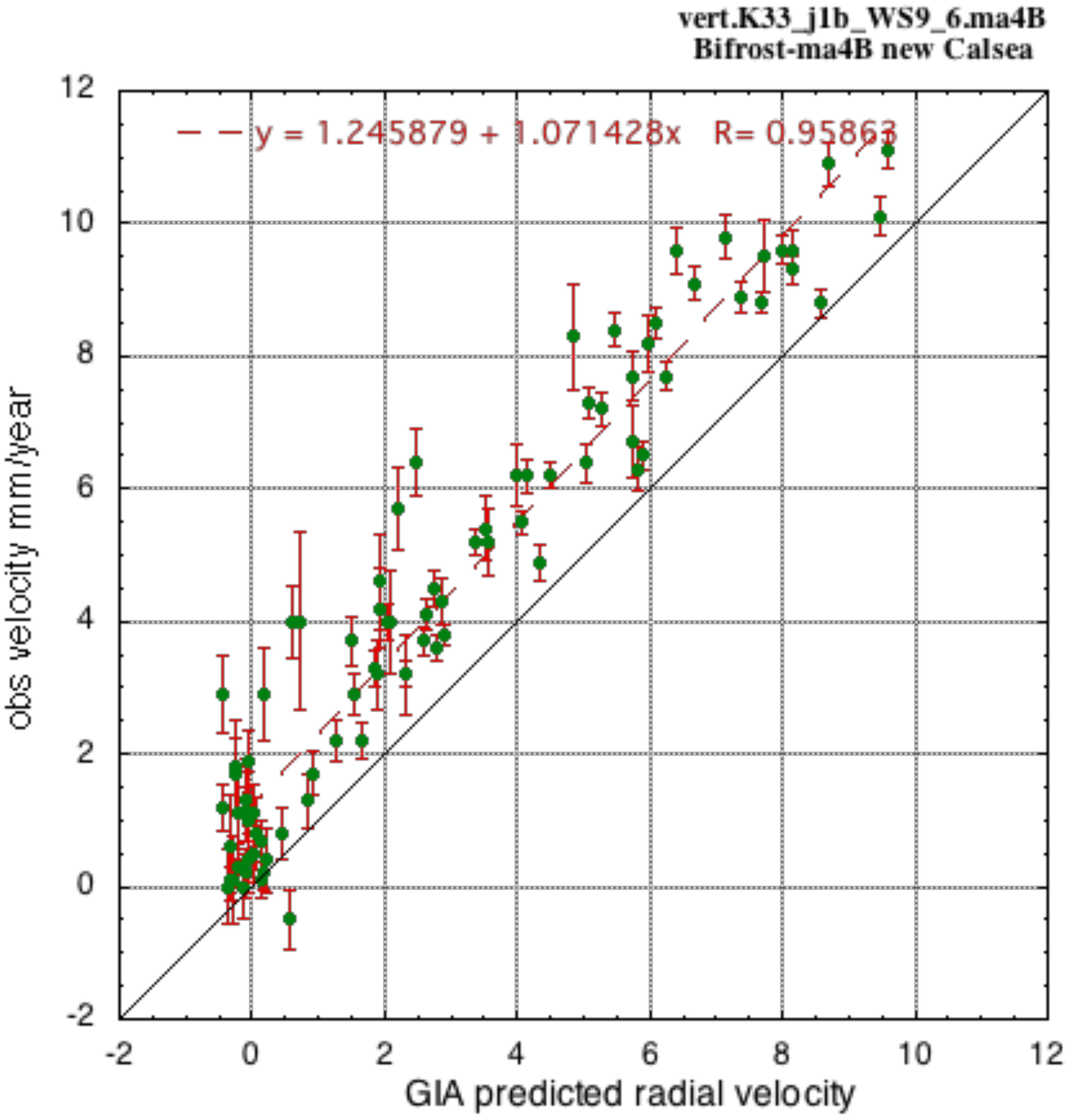




21,000 years ago



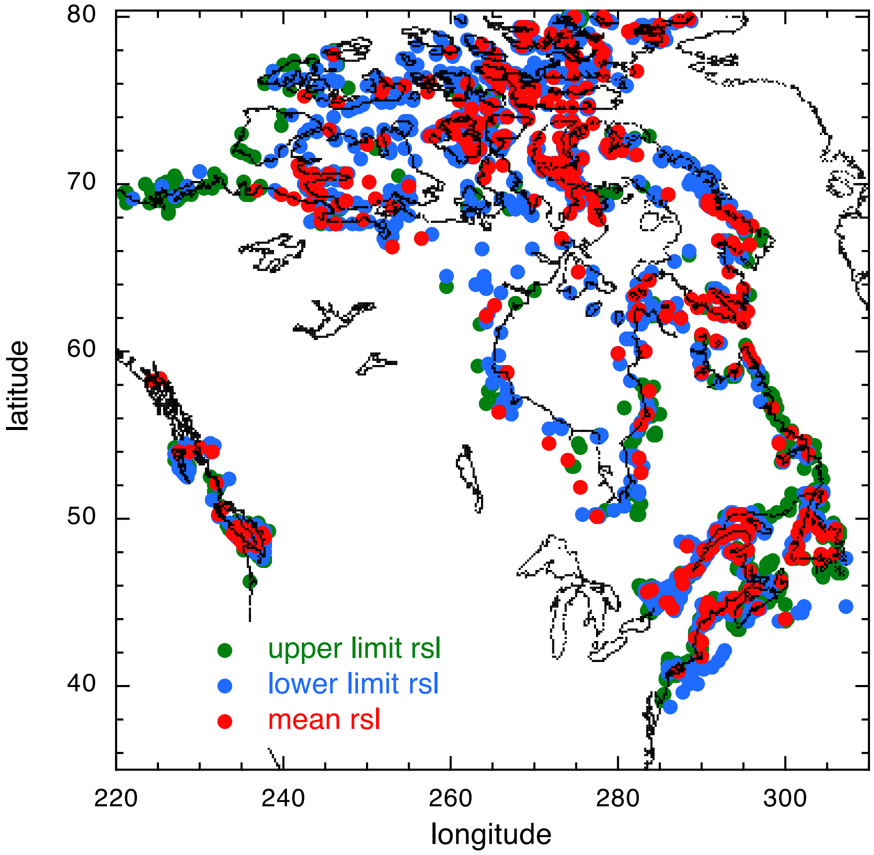
12,500 years ago

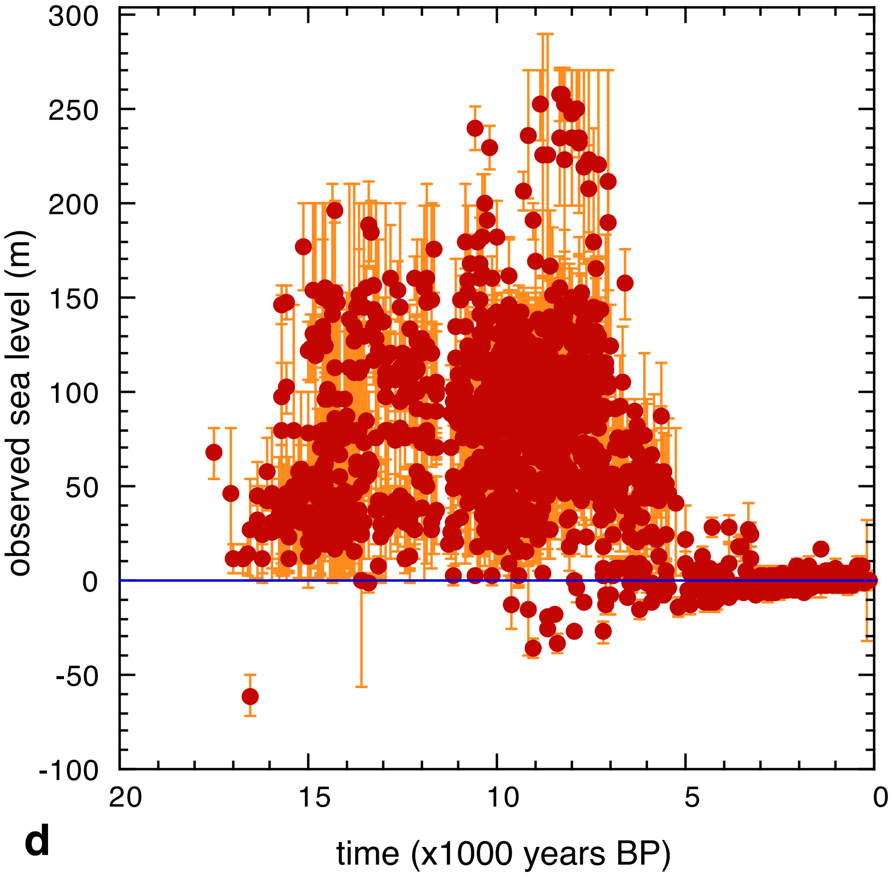


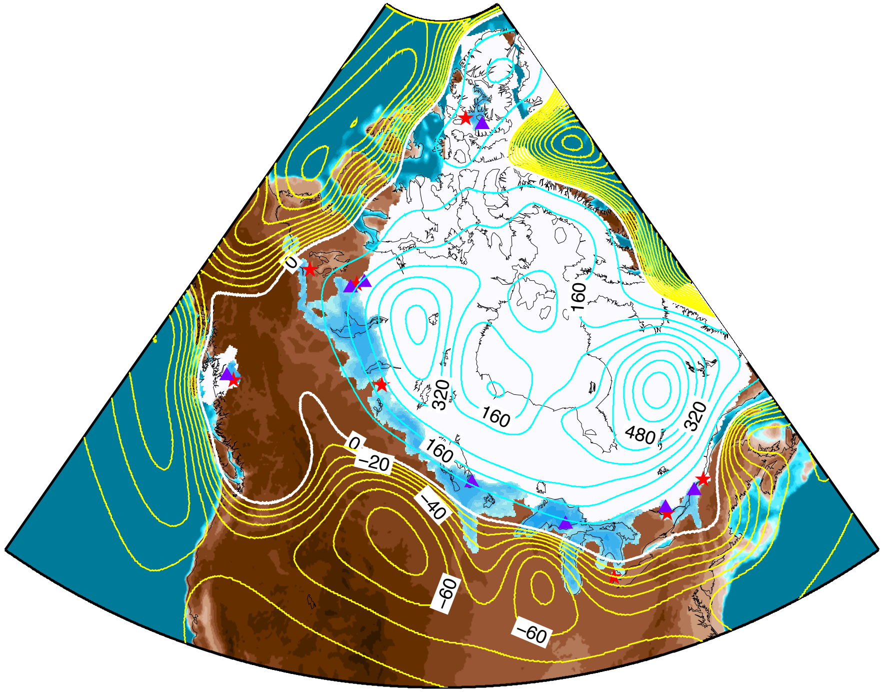
Observed radial velocity:
Lidberg 2009. (ITRF 2005)

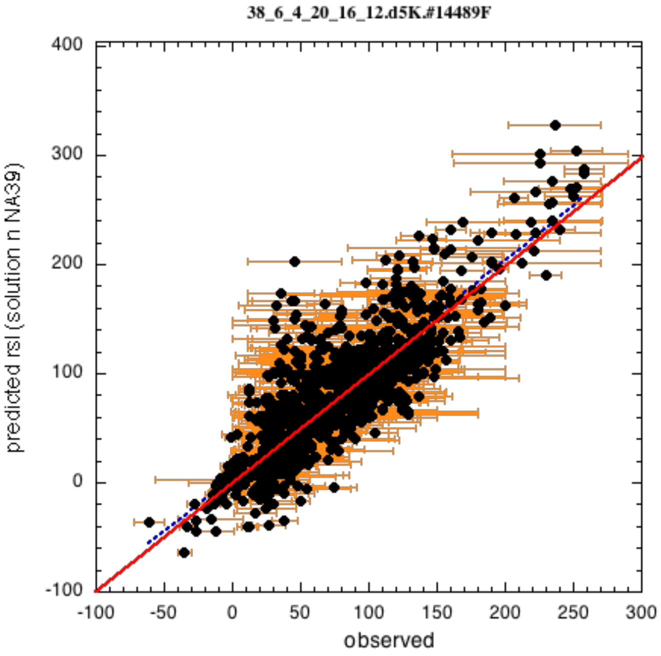
Predicted radial velocity:
GIA model Lambeck et al. 2010

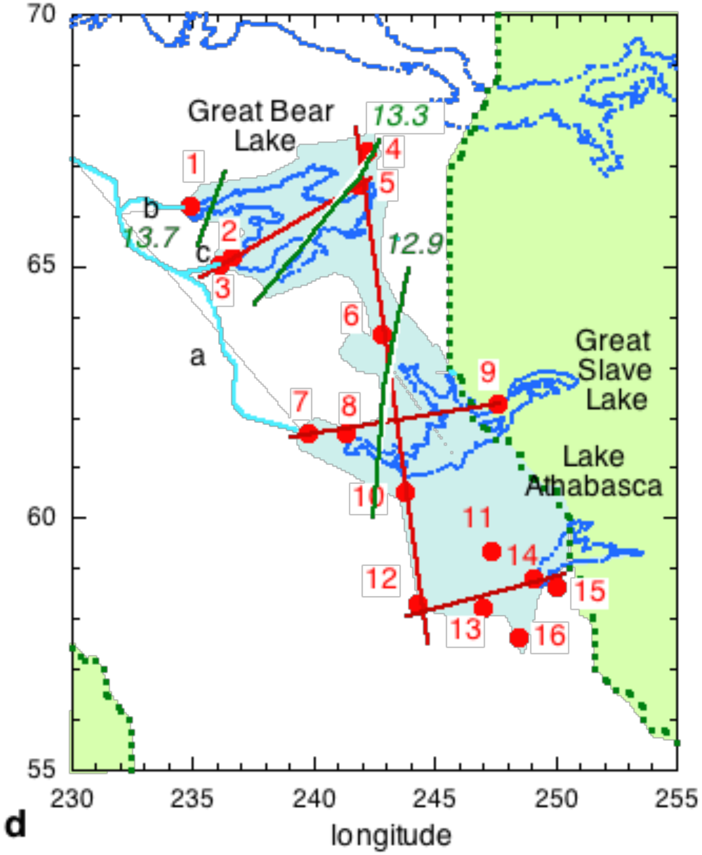
Noted a systematic offset with observed rates > predicted rates.


80
70
60
50
40
latitude
220
240
260
280
300
longitude
upper limit rsl
lower limit rsl
mean rsl

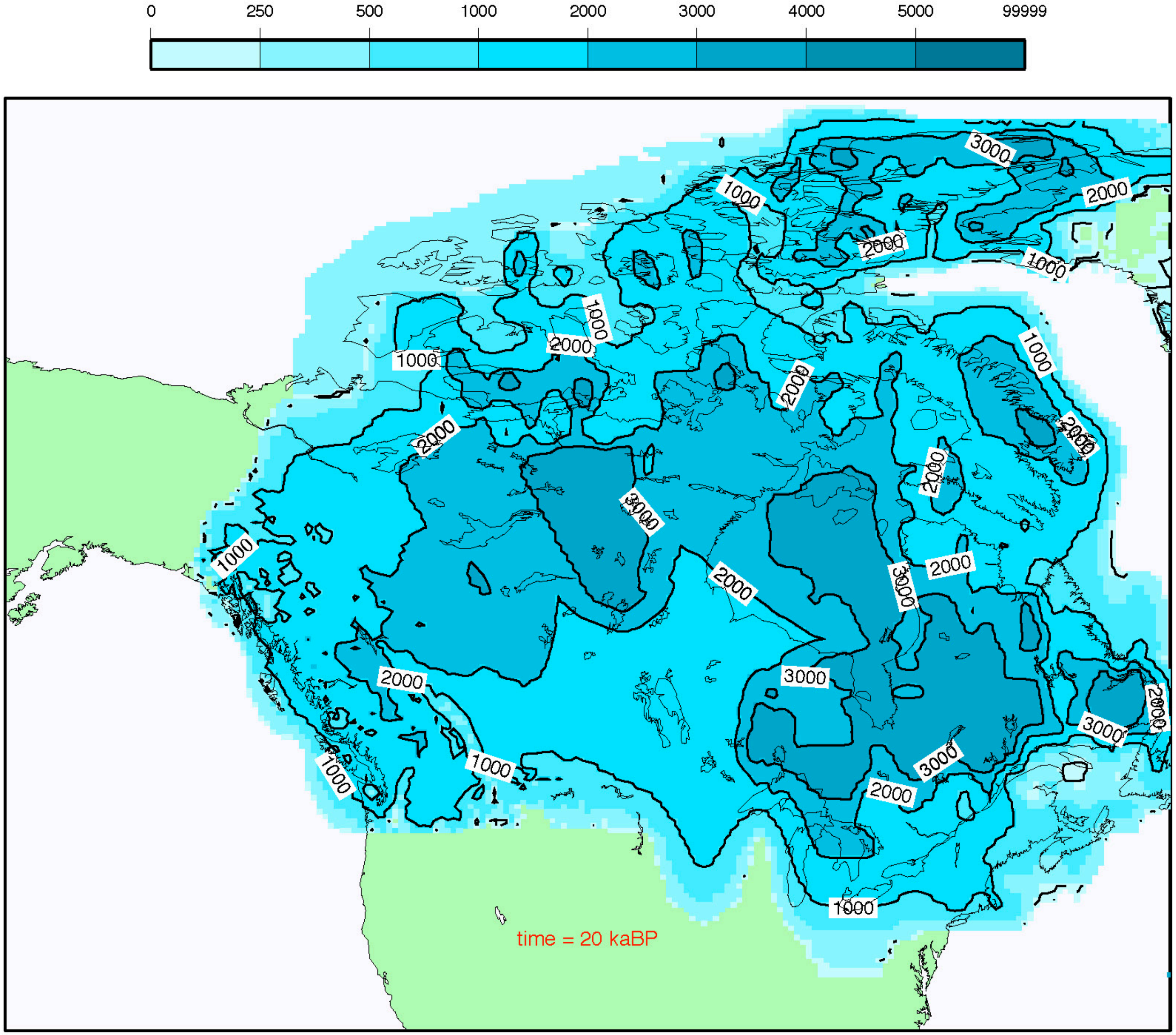

300
250
200
150
100
50
0
-50
-100
observed sea level (m)
20
15
10
5
0
time (x1000 years BP)
d



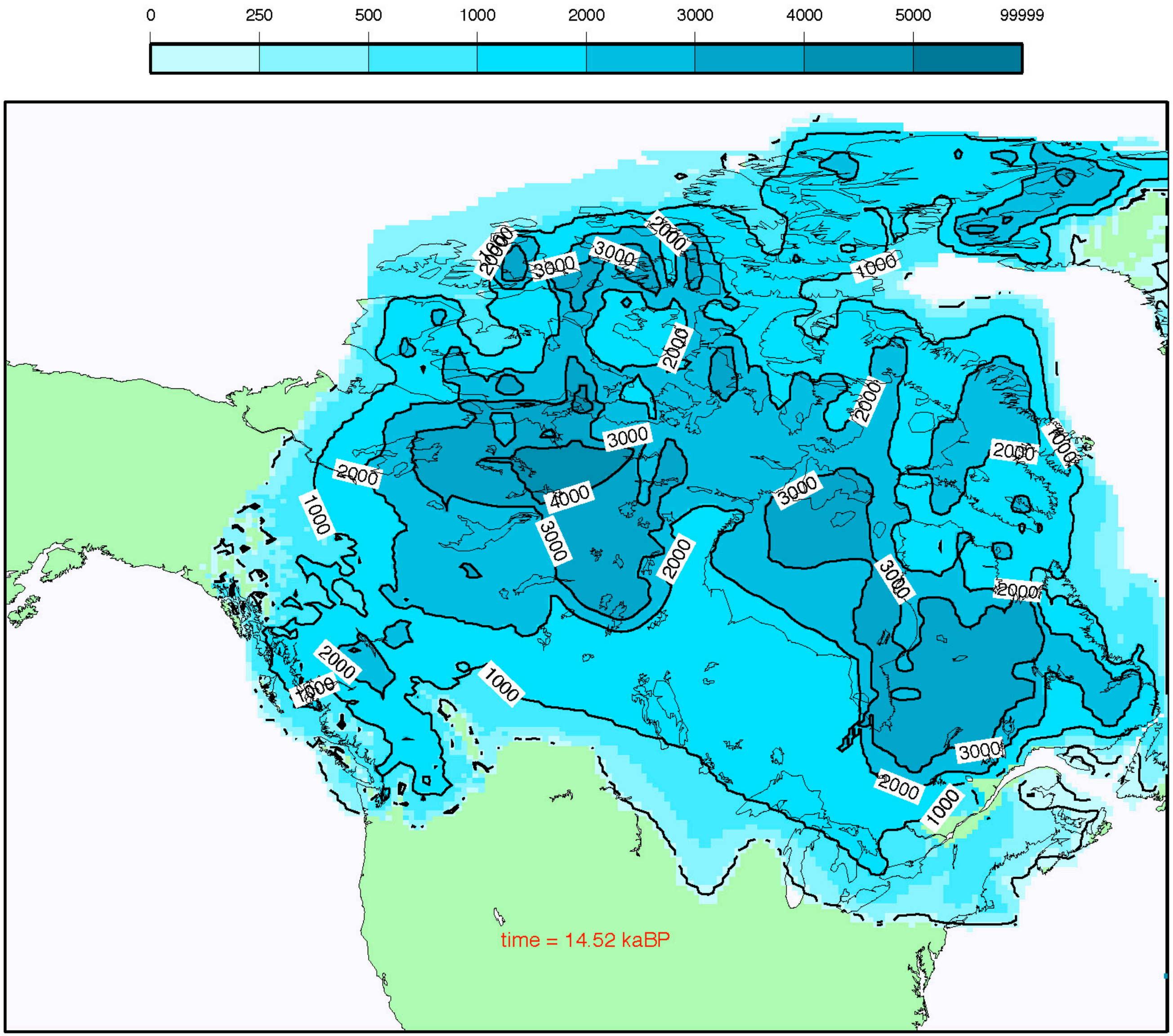




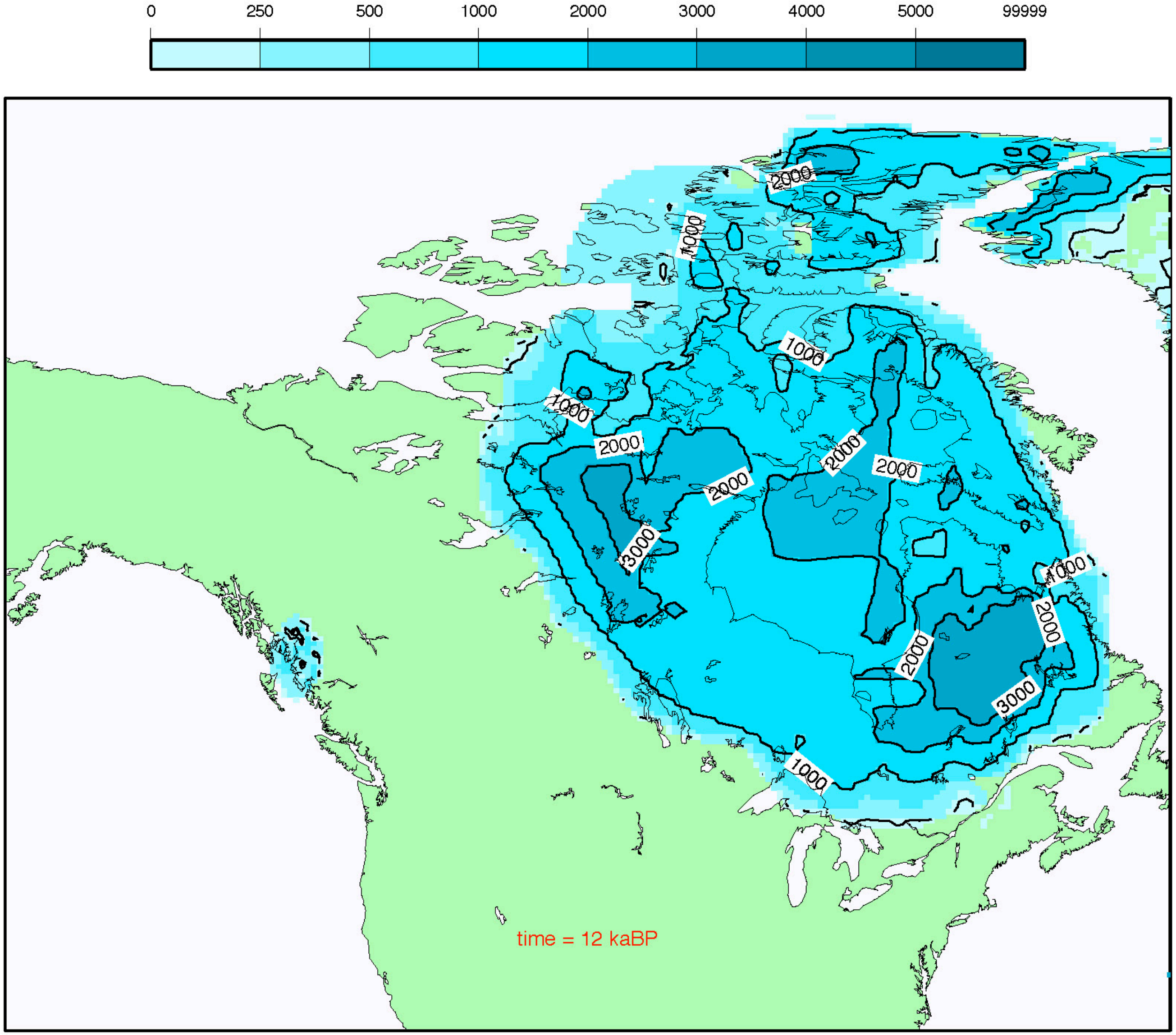
Litho-sphere 80 km	*Upper mantle $(4\text{-}5)x10^{20}$ Pa s*	*Lower mantle $(5\text{-}20)x10^{22}$ Pa s*


0
250
500
1000
2000
3000
4000
5000
99999
1000
2000
3000
time = 20 kaBP

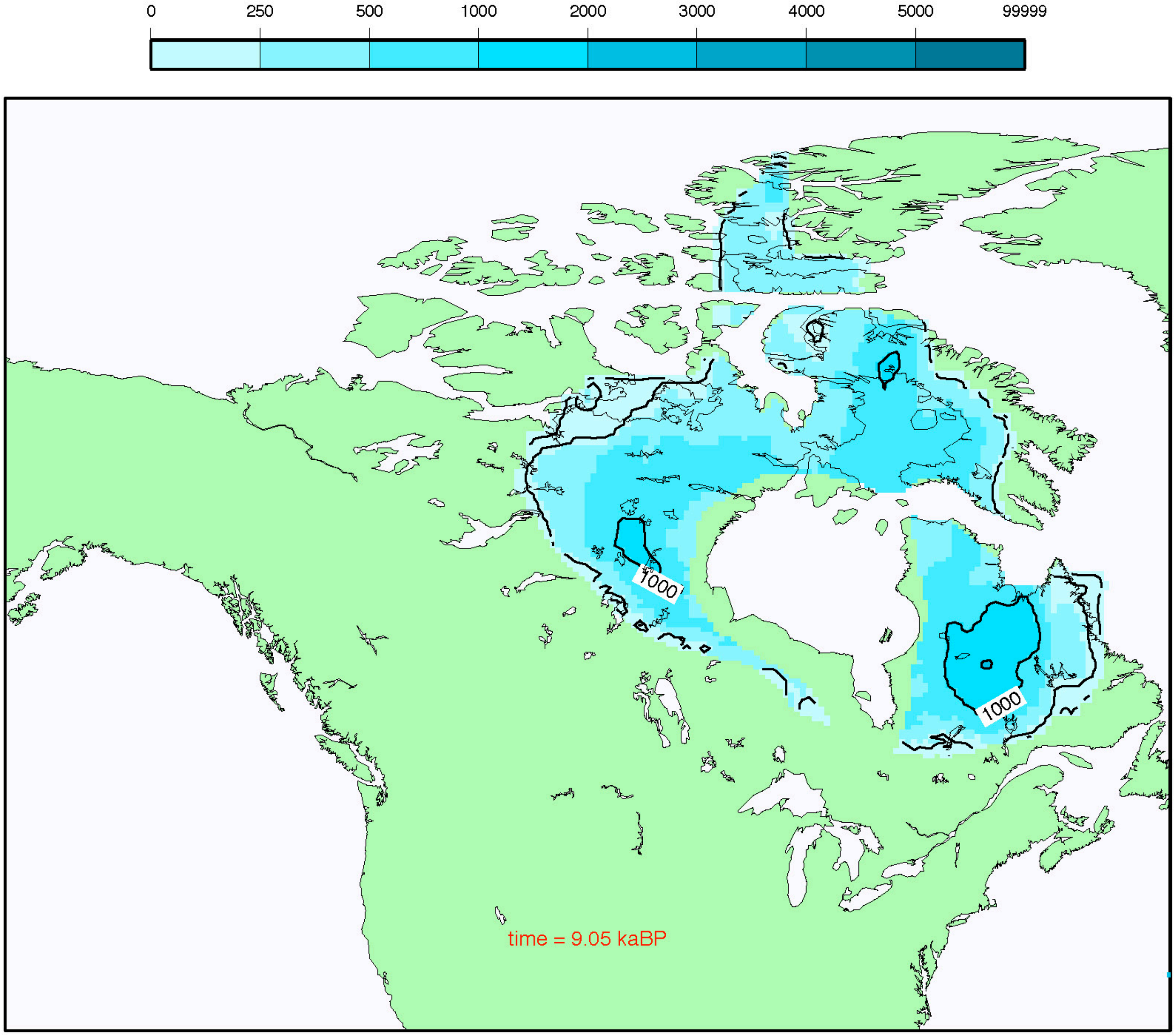
LGM 20 ka



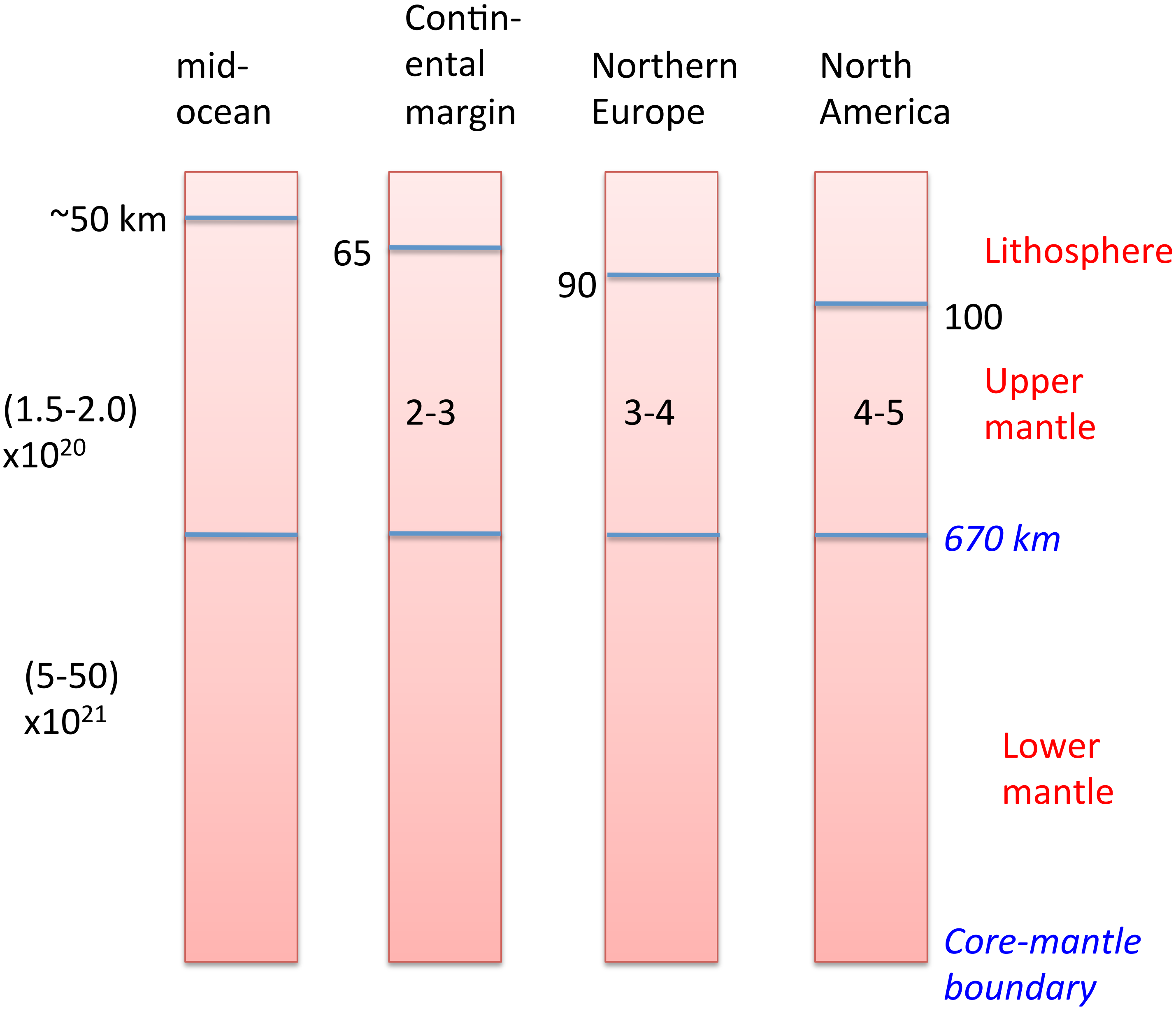
Onset of BA
14.5 ka


0
250
500
1000
2000
3000
4000
5000
99999
1000
2000
3000
time = 12 kaBP

YD 12ka


0
250
500
1000
2000
3000
4000
5000
99999
1000
1000
time = 9.05 kaBP

9.0 ka



mid-ocean

Continental margin

Northern Europe

North America

~50 km

65

90

100

Lithosphere

(1.5-2.0) x10^{20}

2-3

3-4

4-5

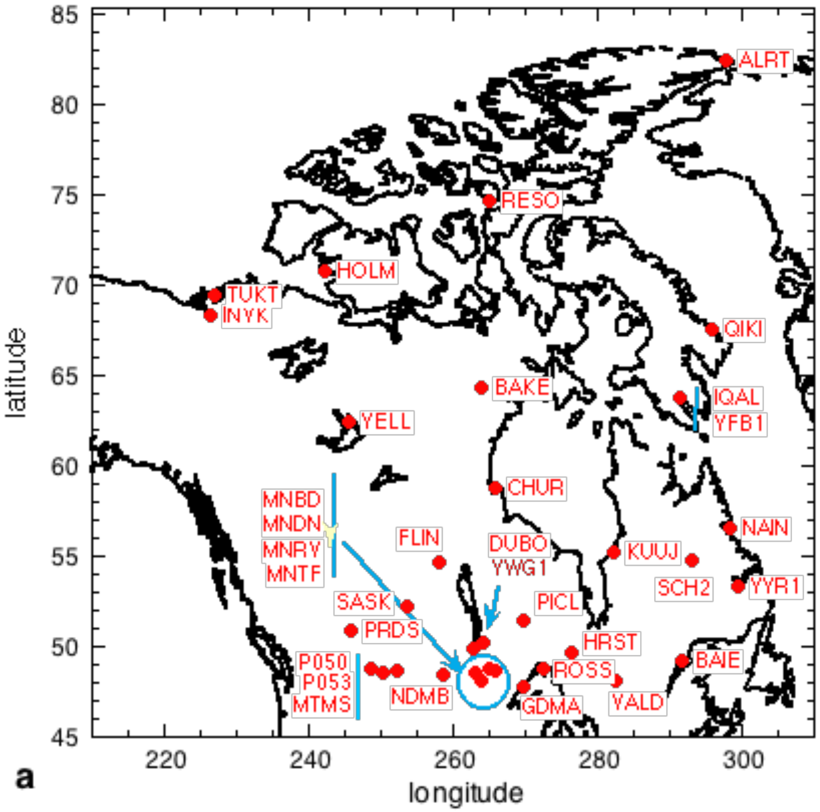
Upper mantle

670 km

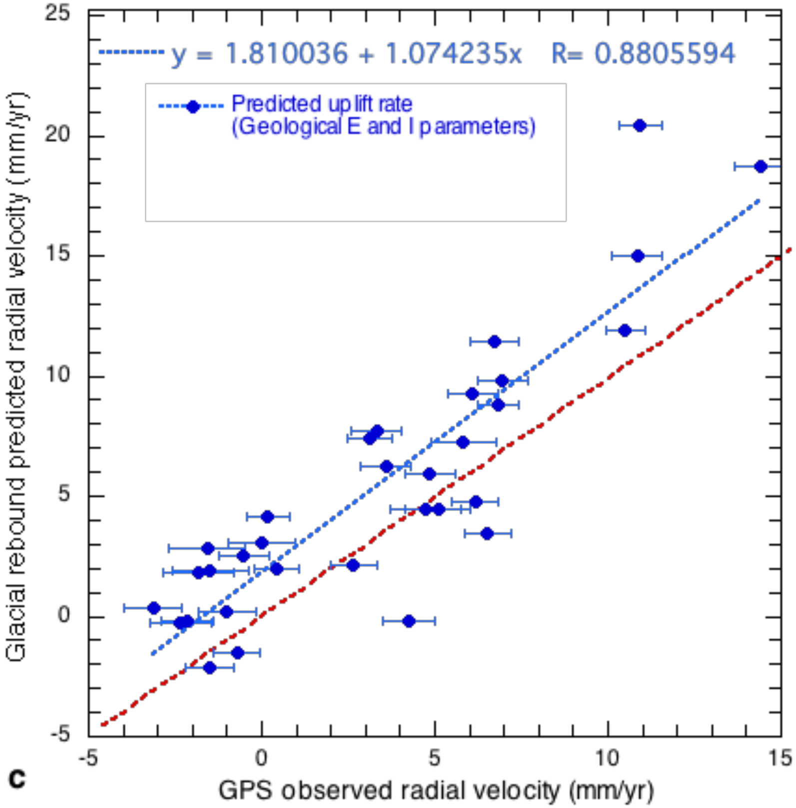
(5-50) x10^{21}

Lower mantle

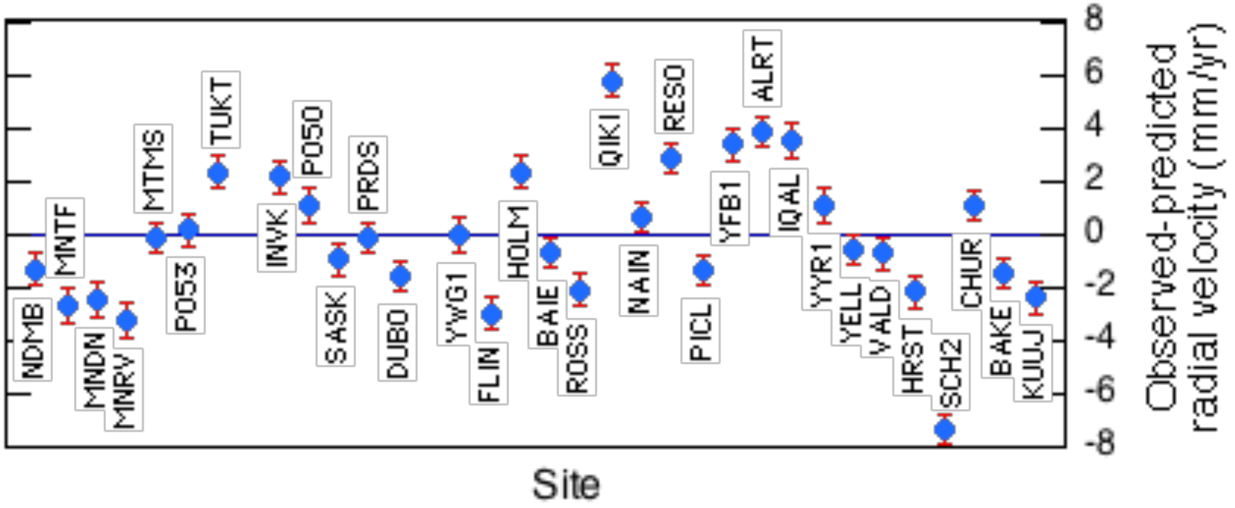
Core-mantle boundary


ALRT
RESO
HOLM
TUKT
INVK
QIKI
BAKE
IQAL
YFB1
YELL
CHUR
MNBD
MNDN
MNRY
MNTF
FLIN
DUBO
YWG1
NAIN
KUUJ
SCH2
YYR1
SASK
PICL
PRDS
HRST
P050
P053
MTMS
NDMB
ROSS
BAIE
GDMA
VALD
85
80
75
70
65
60
55
50
45
220
240
260
280
300
latitude
longitude

a


y = 1.810036 + 1.074235x R= 0.8805594
Predicted uplift rate
(Geological E and I parameters)
Glacial rebound predicted radial velocity (mm/yr)
GPS observed radial velocity (mm/yr)
25
20
15
10
5
0
-5
-5
0
5
10
15

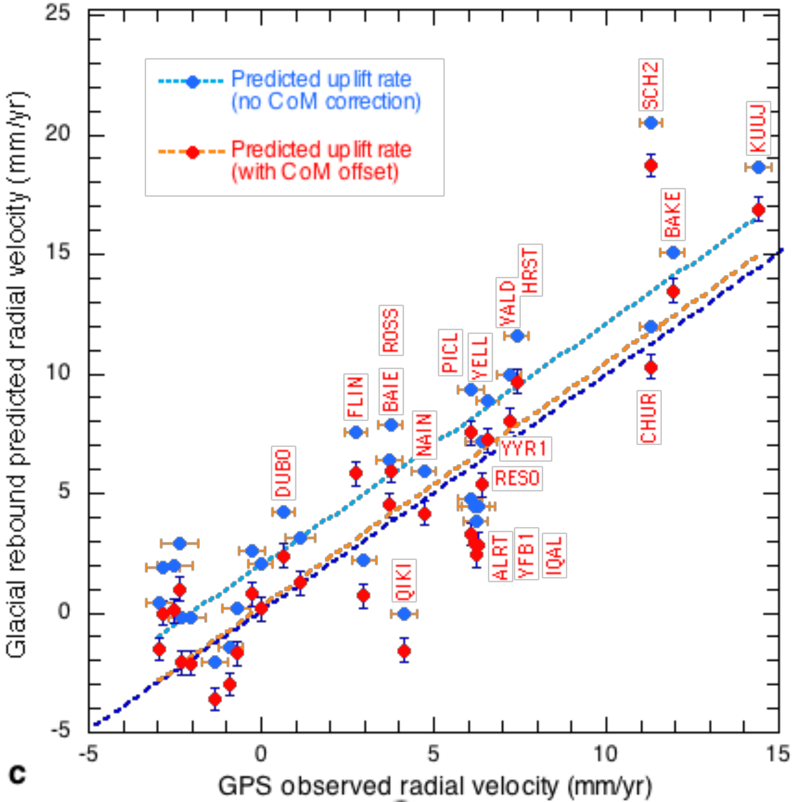
c


NDMB
MNTF
MNDN
MNRV
MTMS
P053
TUKT
INVK
P050
SASK
PRDS
DUBO
YWG1
FLIN
HOLM
BAIE
ROSS
QIKI
NAIN
RESO
PICL
YFB1
ALRT
IQAL
YYR1
YELL
VALD
HRST
SCH2
CHUR
BAKE
KUUJ
8
6
4
2
0
-2
-4
-6
-8
Observed-predicted
radial velocity (mm/yr)
Site

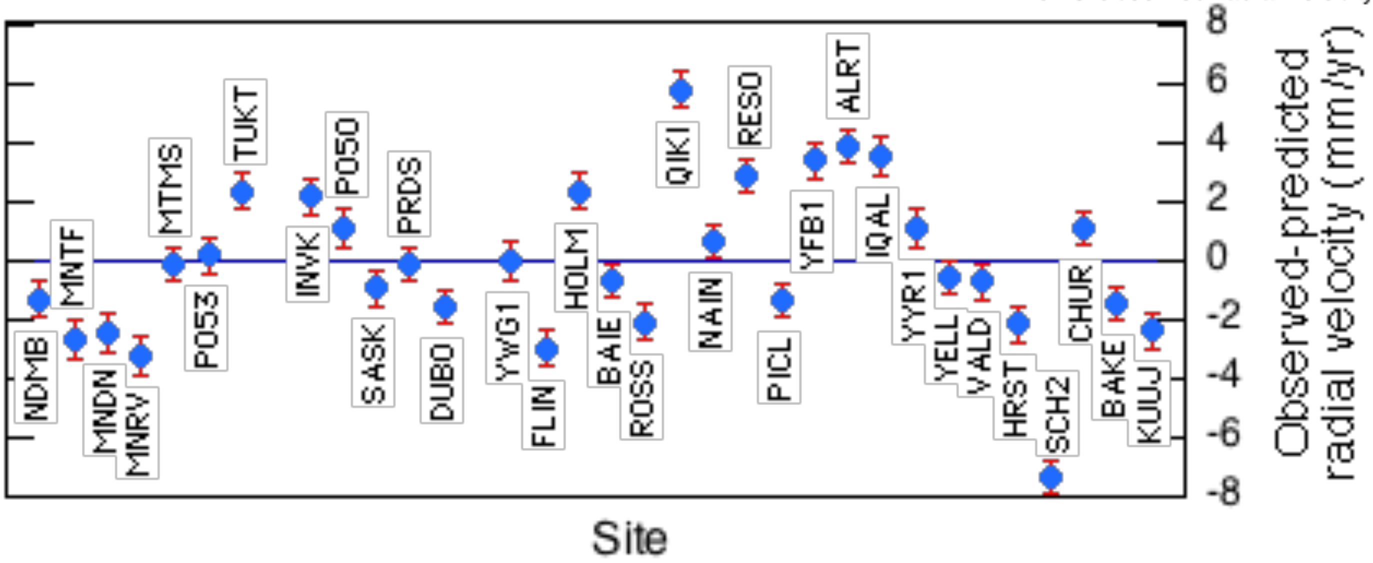
e

$$U_z = \langle (u^i_{obs} - u^i_{iso\text{-}pred}) \sin \phi^i \rangle_W$$

$$= -1.62 \pm 0.51 \text{ mm/year}$$



c



e

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North America		88 m
Scandinavia, including Barents Sea		19 m
Greenland		3 m
British Isles		1 m
Alpine glaciers		4 m
– Alaska	0.8 m	
– South America	0.9 m	
– Sub-Antarctic Islands	0.15 m	
– Alps	0.07m	
– Northern Asia (Taymyr, Putorama, Severnaya Z)	1.9 m	
– Tibet and other mountain glaciers	1.0 m	
Total		115 m
Observed		134 m
‘Missing Ice’		19 m