Using radar layers to infer migration of WAIS Divide

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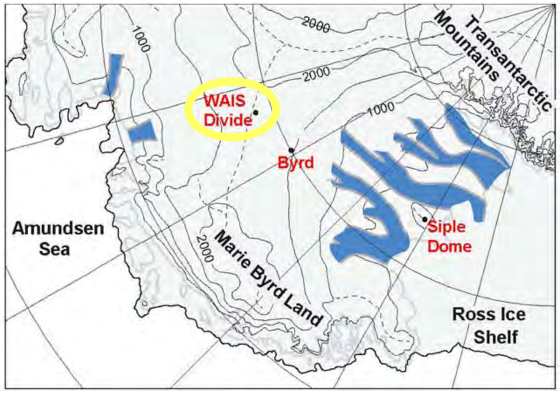
Background / Motivation



1. WAIS Divide ice core drilled to ~3331 m

- Ice at depth is younger than expected – thick layers at depth
- Ice at depth may be colder than expected

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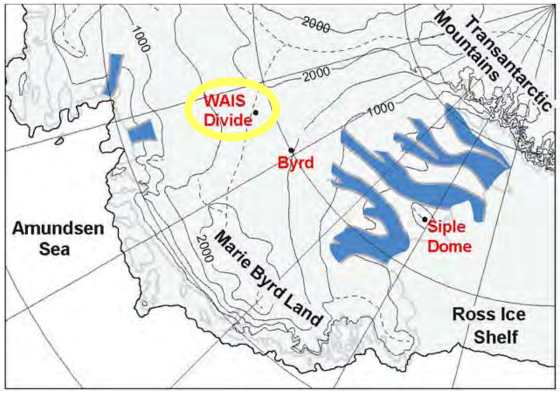

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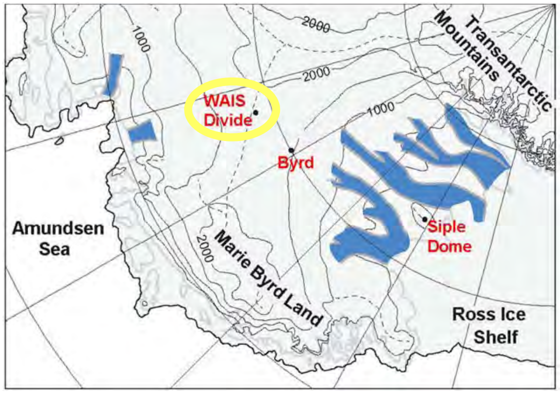
   - Ice at depth may be colder than expected

2. WAIS divide is migrating and thinning today (Conway and Rasmussen, 2009)

   - Migrating toward Ross Sea at ~10 m/yr and thinning ~8 cm/yr *(1000 years at this rate gives 10 km migration and 80 m thinning)*

   - Ice-divide position and interior ice thickness likely controlled by ice dynamics

Background / Motivation



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- Migrating toward Ross Sea at ~10 m/yr and thinning ~8 cm/yr

3. *History* of ice-divide position is unknown

- Need to inform ice-core interpretation

Objectives

1. **Compare 2-D ice-sheet model realizations to ice-sheet data:**

    - Ice-core depth-age scale

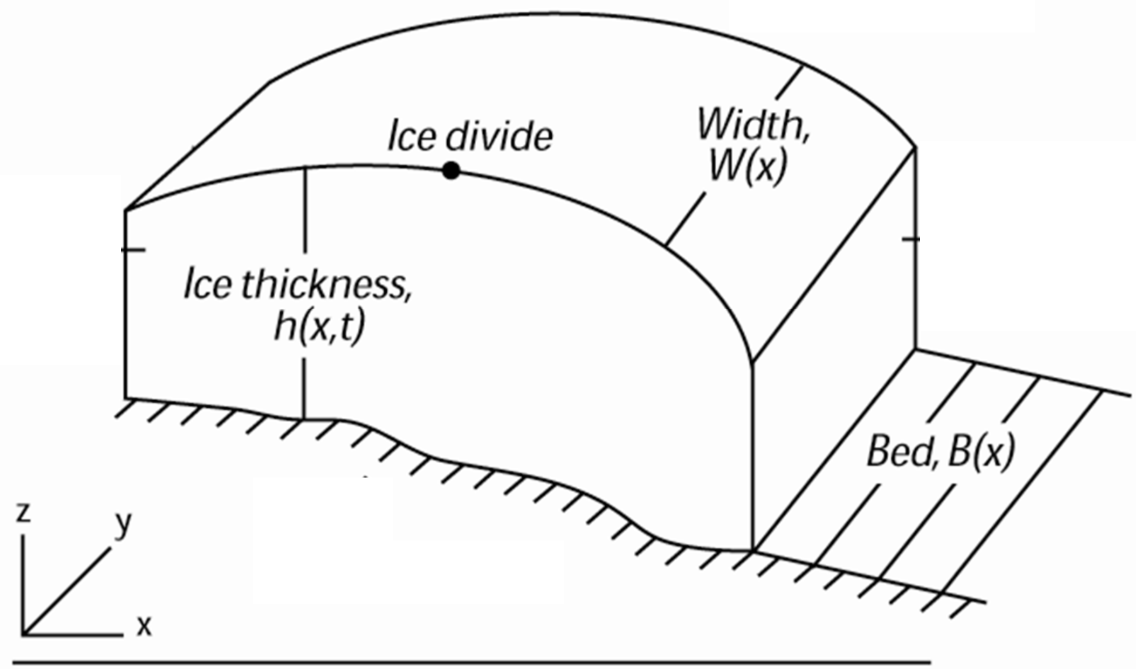
    - Ice-temperature profile

    - Surface-velocity measurements

    - Modern ice-surface profile

    - Internal-layer shapes

2.5-D Ice-sheet flowband model



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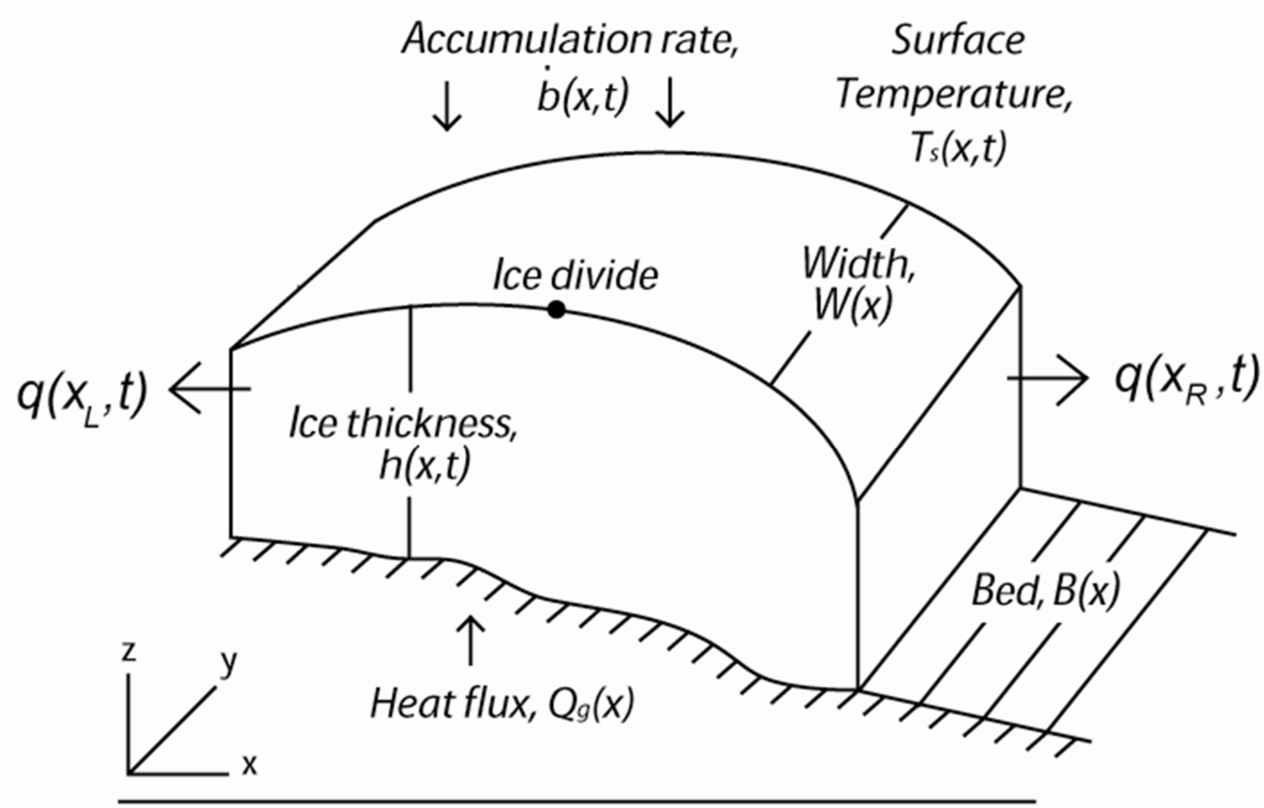

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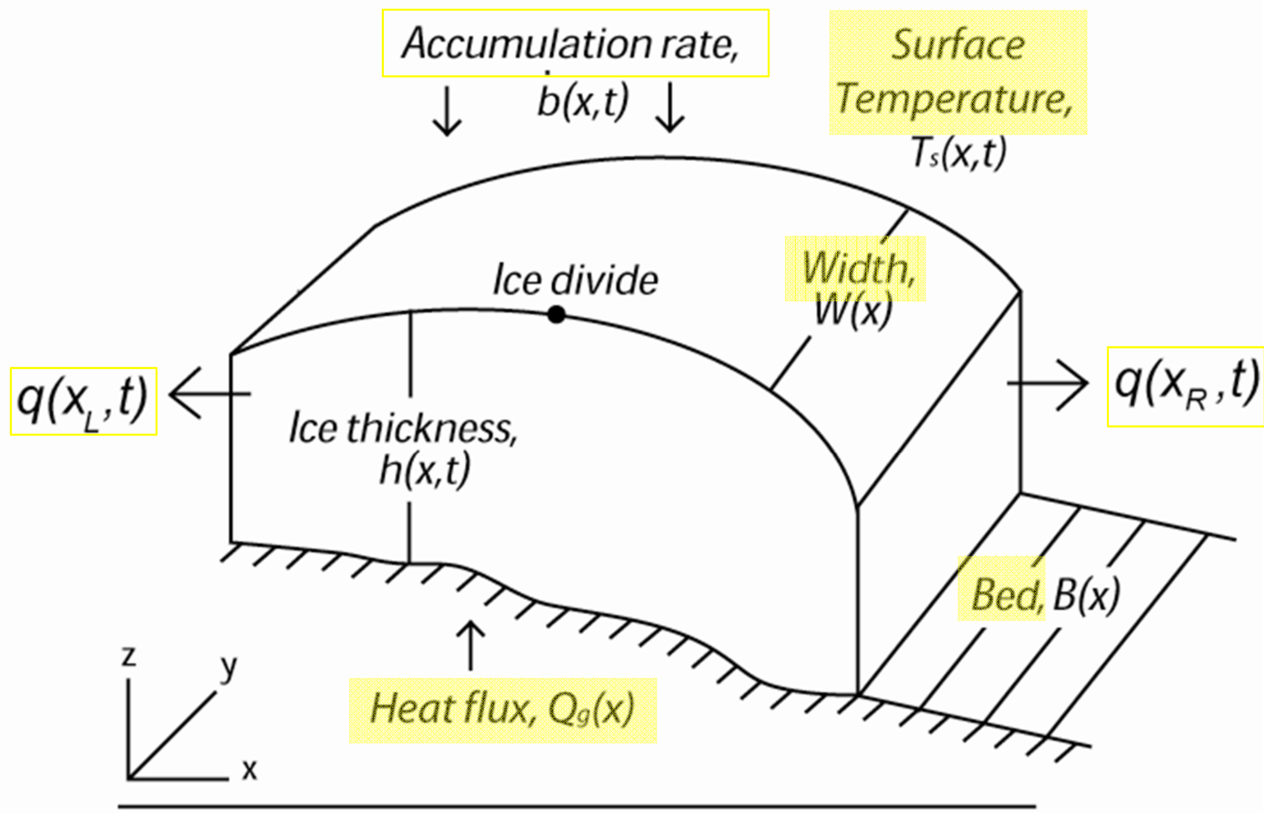
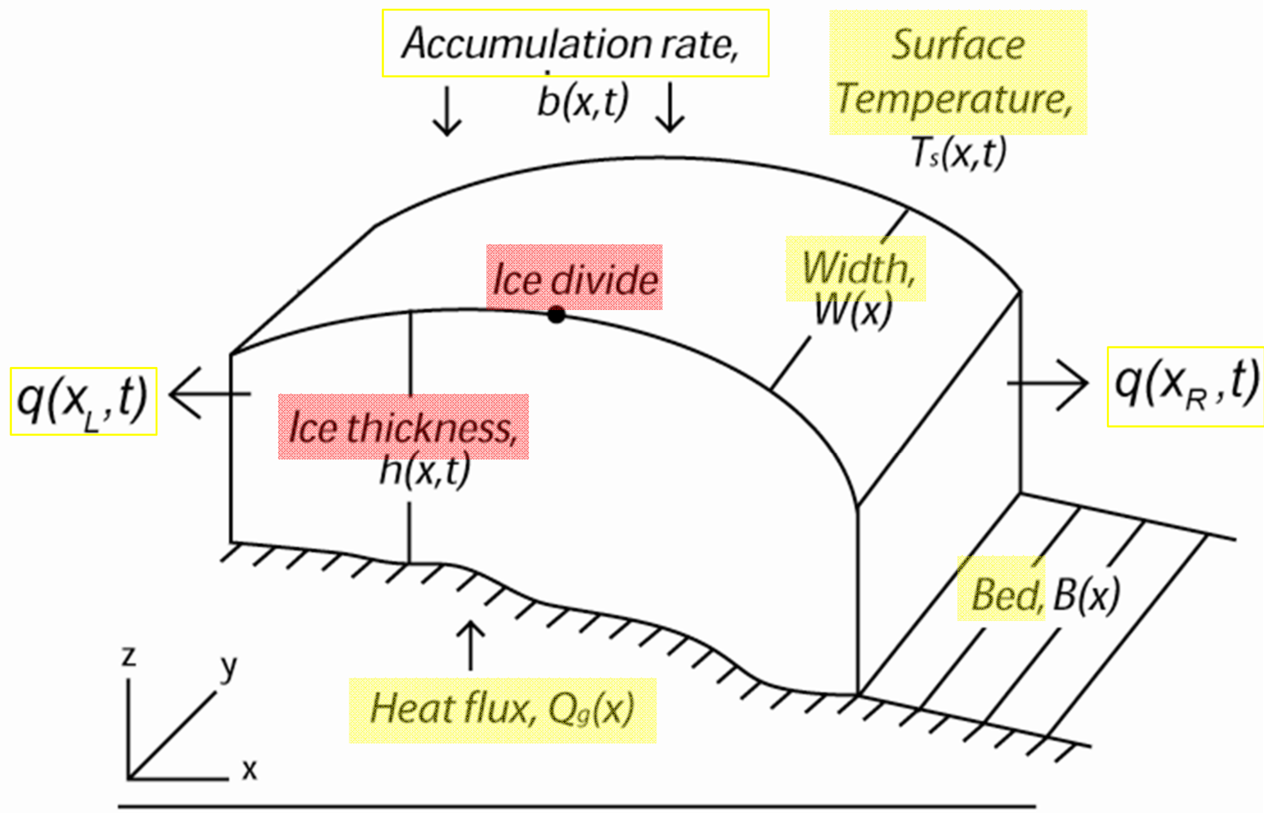


= *Prescribed*

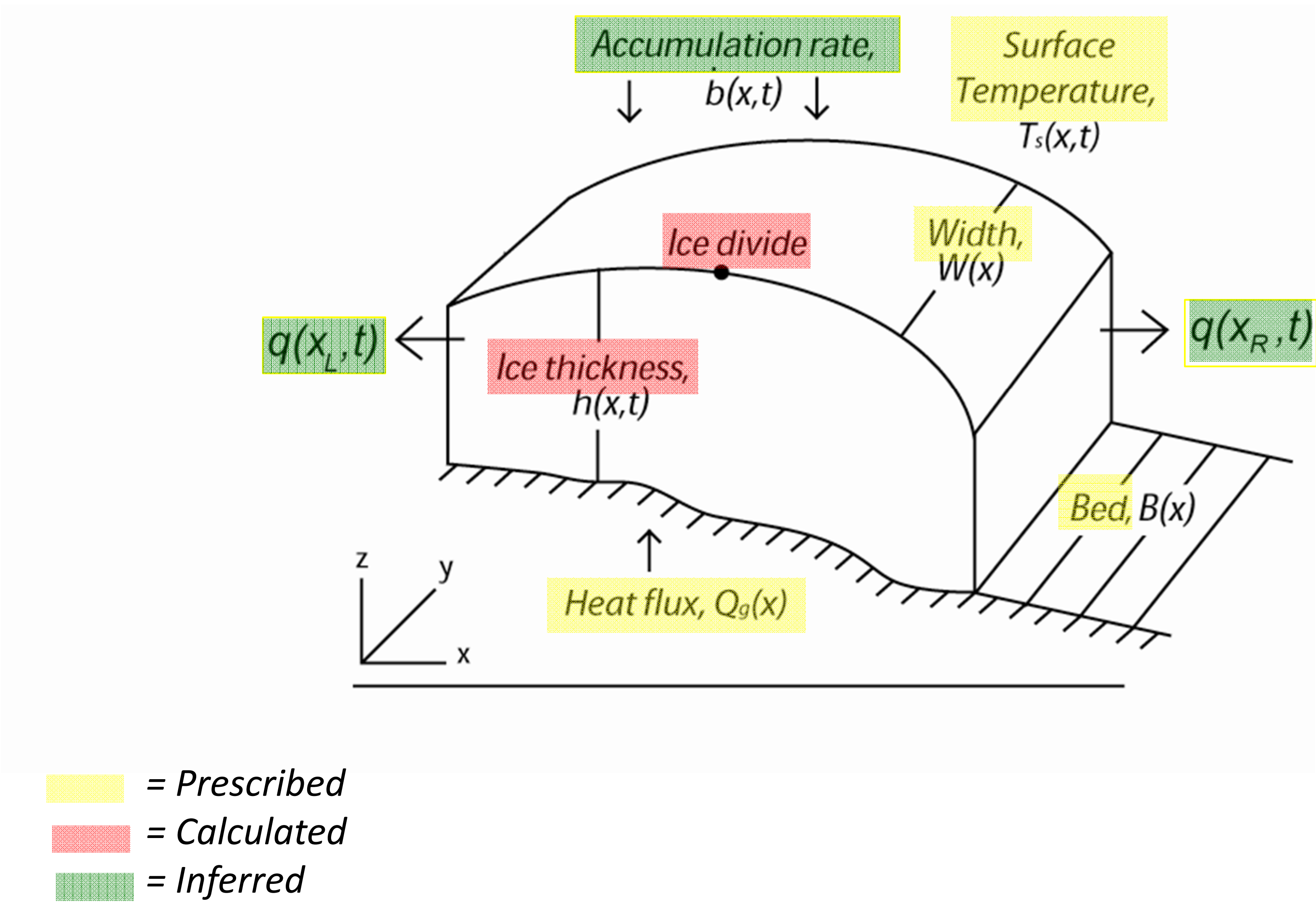
2.5-D Ice-sheet flowband model



= *Prescribed*

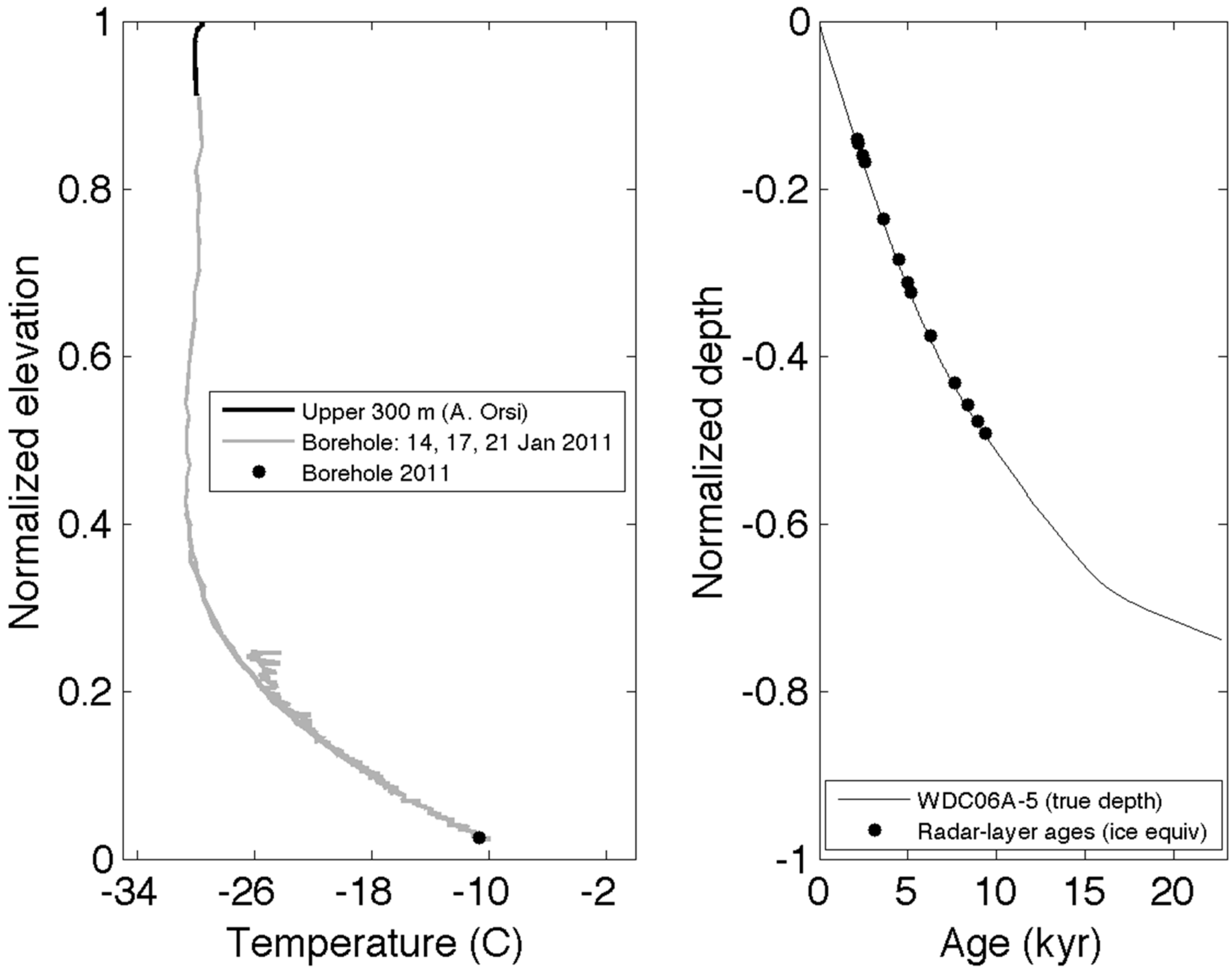
= *Calculated*

2.5-D Ice-sheet flowband model

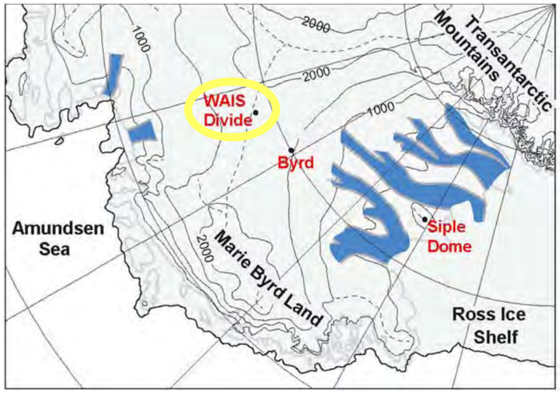


Ice temperature and **depth-age scale**

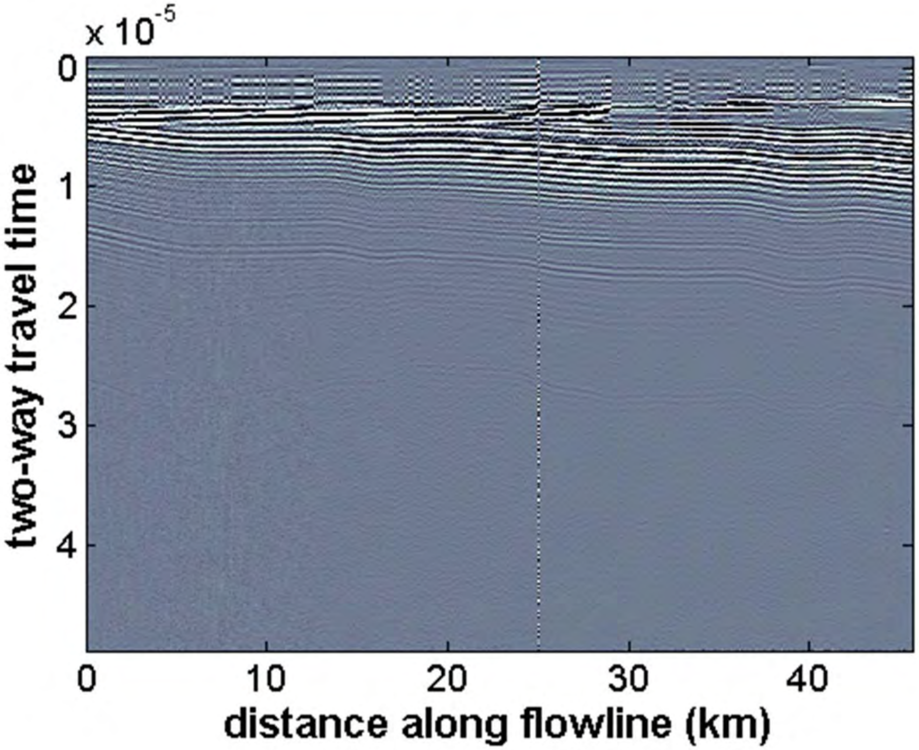
Data from WAIS Divide Science Team



Internal layers

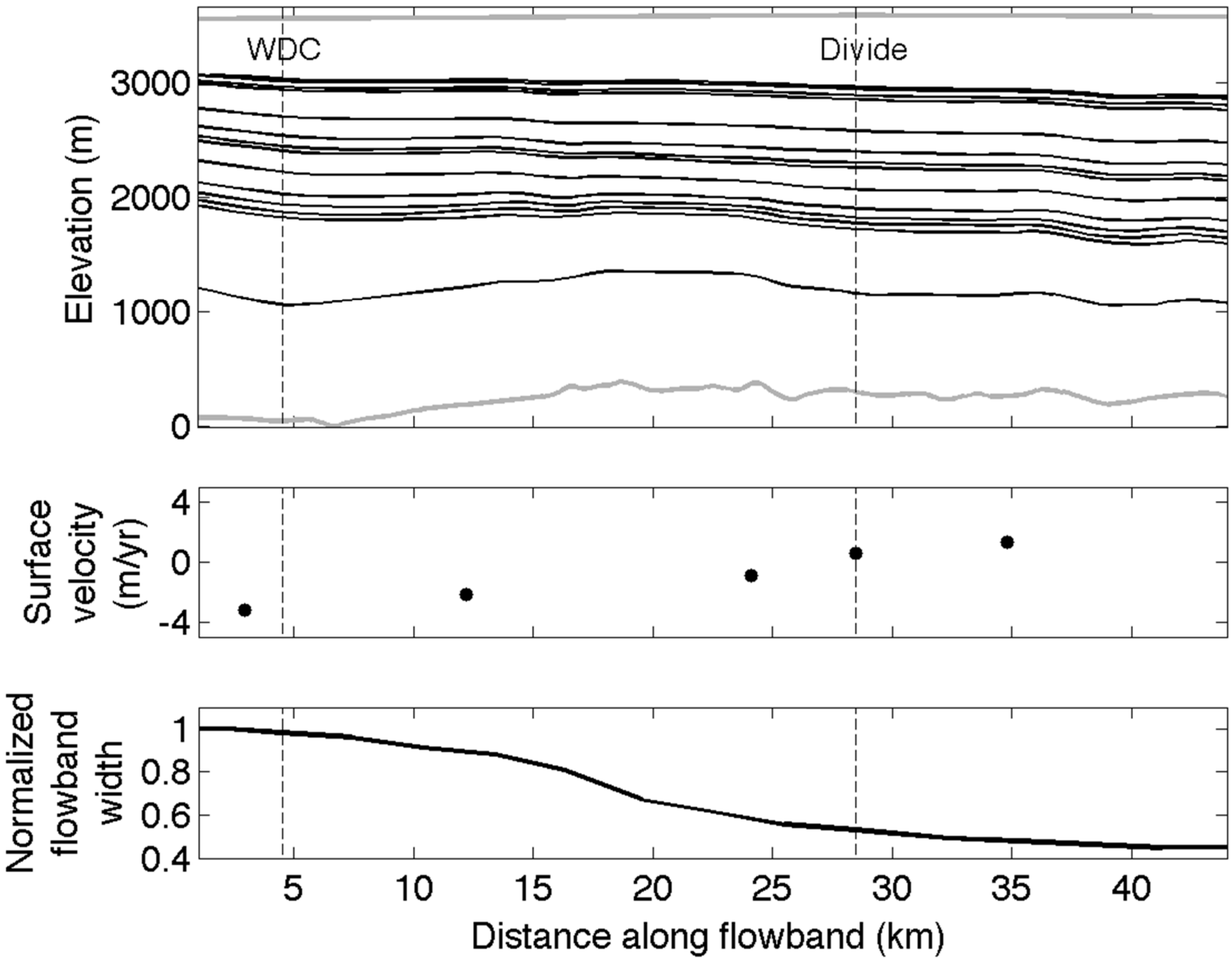


Ross Sea *Amundsen Sea*



+ *(additional radar data?)*

← *Ross Sea* *Amundsen Sea* →

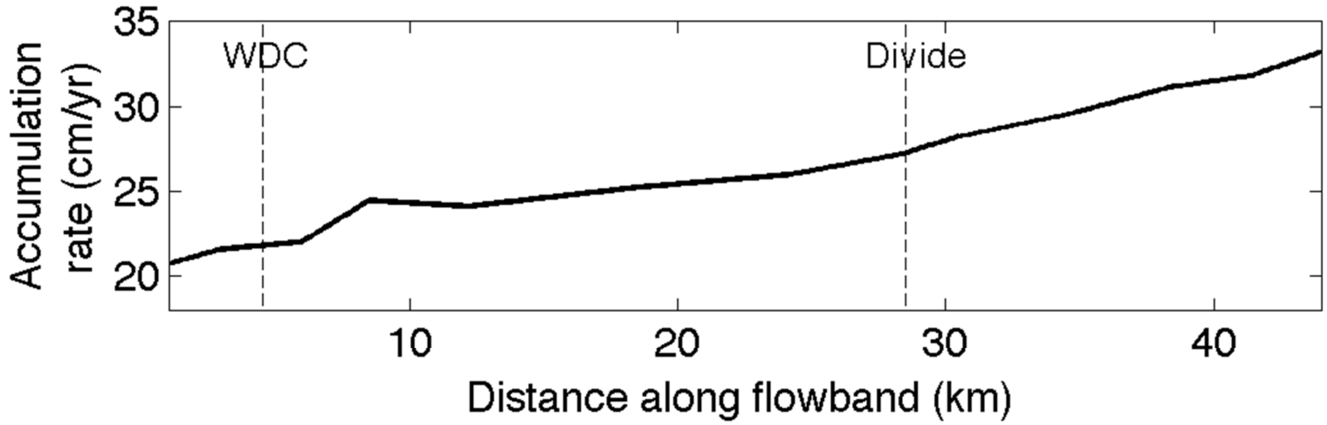


(e.g. *Neumann et al., 2008*)

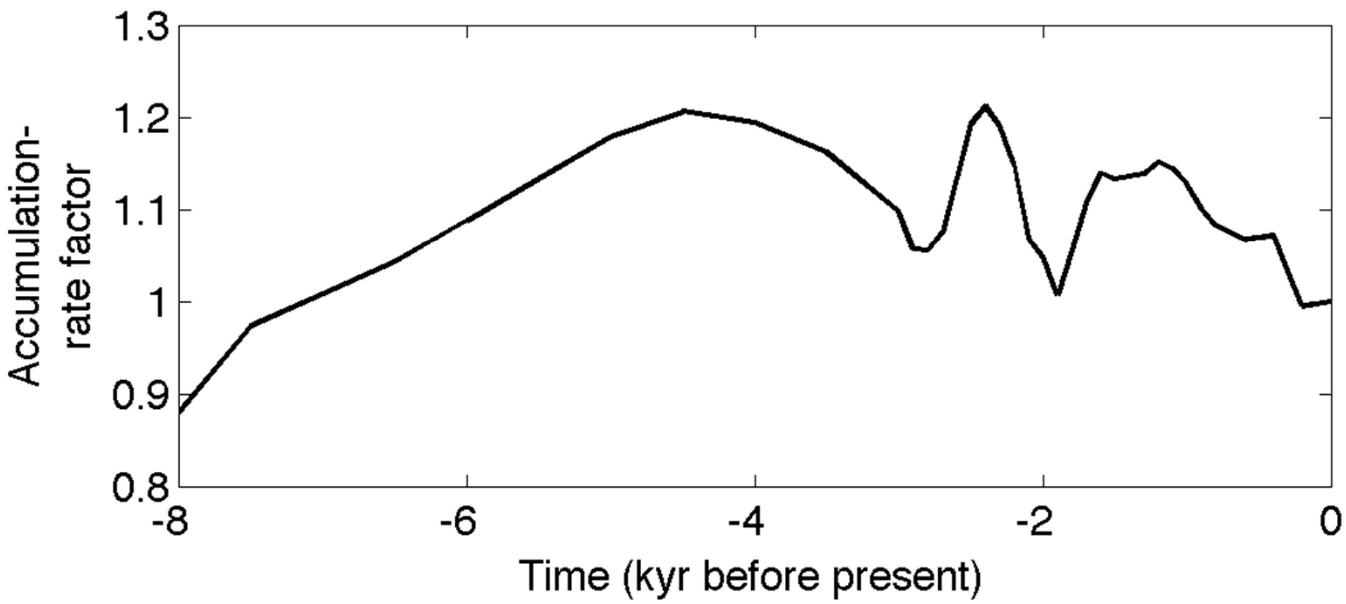
(*Conway and Rasmussen, 2009*)

(*Neumann and Price, unpublished*)

← *Ross Sea* *Amundsen Sea* →



(*Neumann et al., 2008*)



(*Neumann, Price, McConnell, 2010*)

Objectives

1. **Compare 2-D ice-sheet model realizations to ice-sheet data:**

   - Ice-core depth-age scale
   - Ice-temperature profile
   - Surface-velocity measurements
   - Modern ice-surface profile
   - Internal-layer shapes

Preliminary analysis in preparation for the inverse problem incorporating new ice-core data

2. **Solve an inverse problem to infer:**

   - Accumulation-rate history
   - Ice-flow history (external-flux forcing) → ice-divide position

Objectives

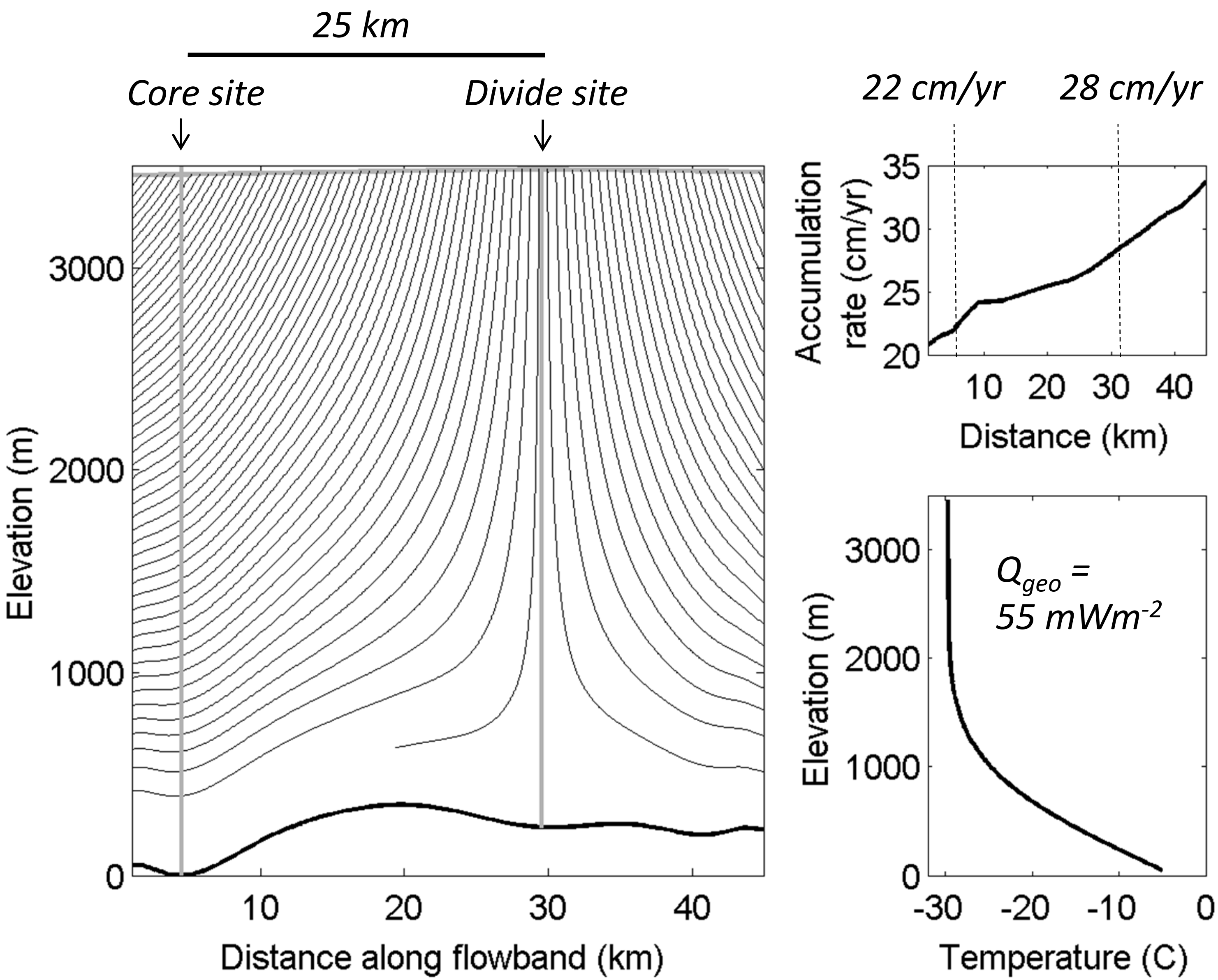
1. **Compare 2-D ice-sheet model realizations to ice-sheet data:**

   - Ice-core depth-age scale
   - Ice-temperature profile
   - Surface-velocity measurements
   - Modern ice-surface profile
   - Internal-layer shapes

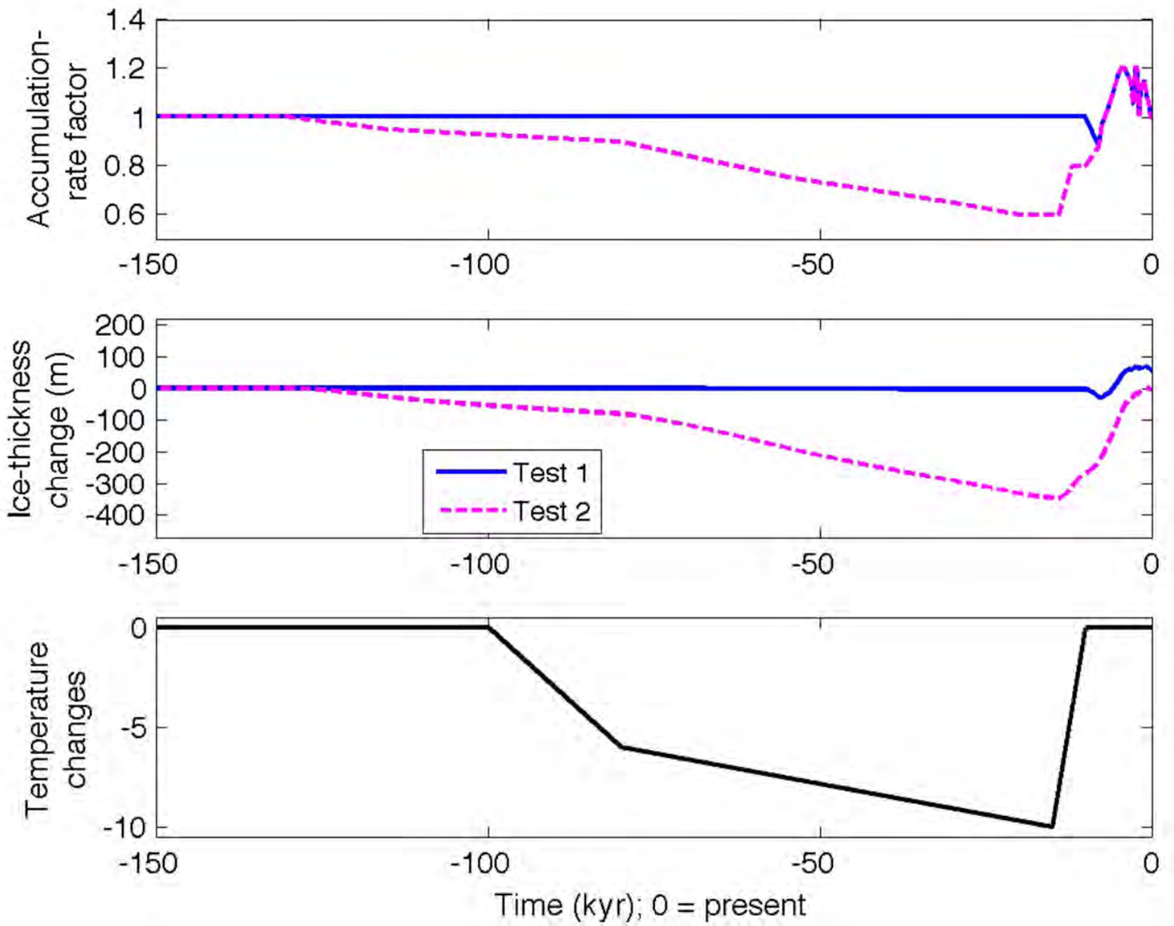
How do variations in accumulation rate, temperature, and ice flow affect realizations of the available data?

2. **Solve an inverse problem to infer:**

   - Accumulation-rate history
   - Ice-flow history (external-flux forcing) → ice-divide position

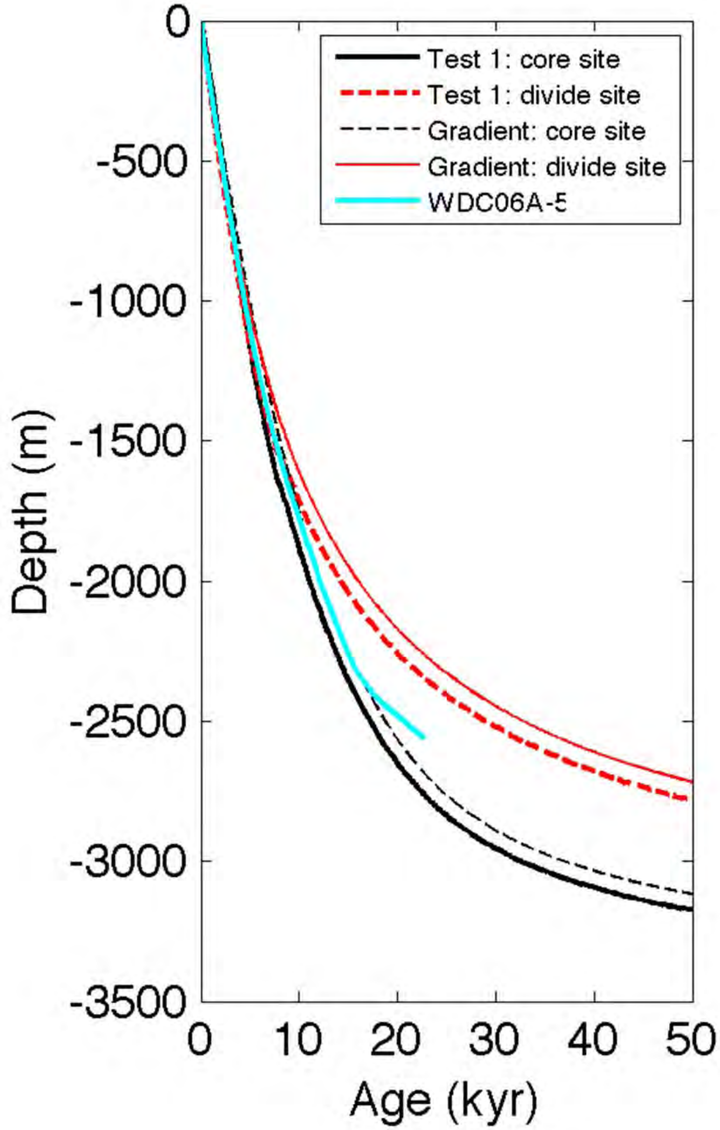

25 km
Core site
Divide site
Elevation (m)
3000
2000
1000
0
10
20
30
40
Distance along flowband (km)
22 cm/yr
28 cm/yr
Accumulation rate (cm/yr)
35
30
25
20
10
20
30
40
Distance (km)
Elevation (m)
3000
2000
1000
0
-30
-20
-10
0
Temperature (C)
Q_geo =
55 mWm-2

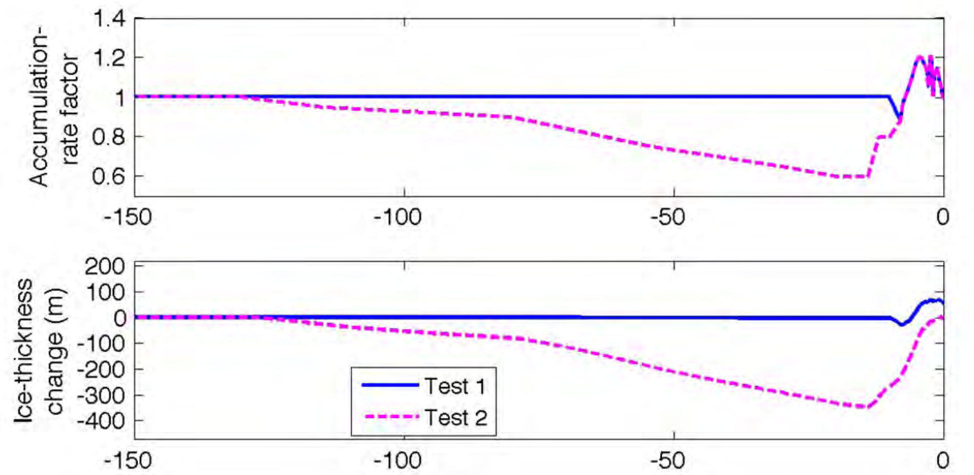
Changes in **accumulation rate**



Test 1:
Modern accumulation in the glacial
Calculated thickness changes
Surface temperature changes

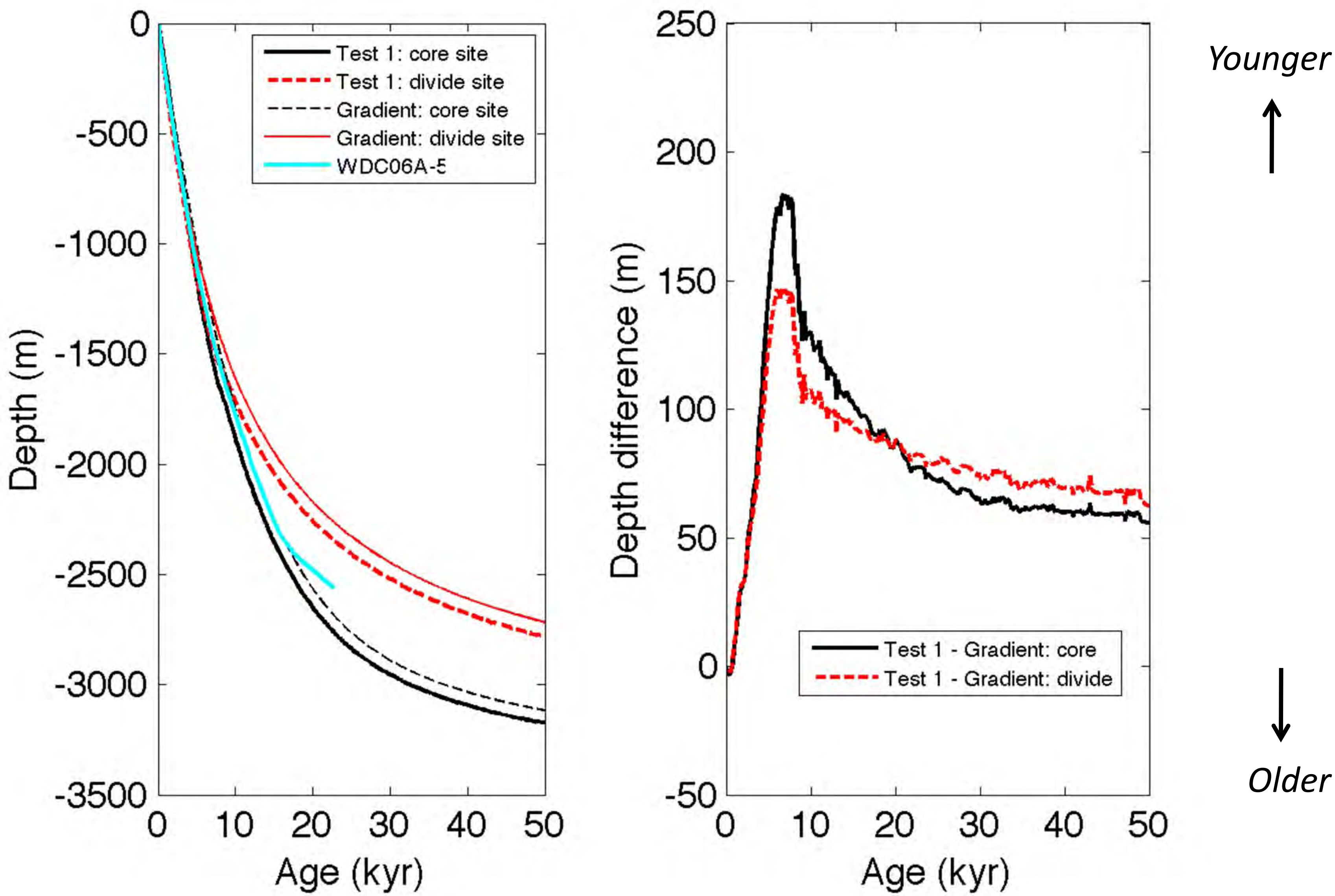
Test 2:
Decreased accumulation in glacial
Calculated thickness changes
Surface temperature changes



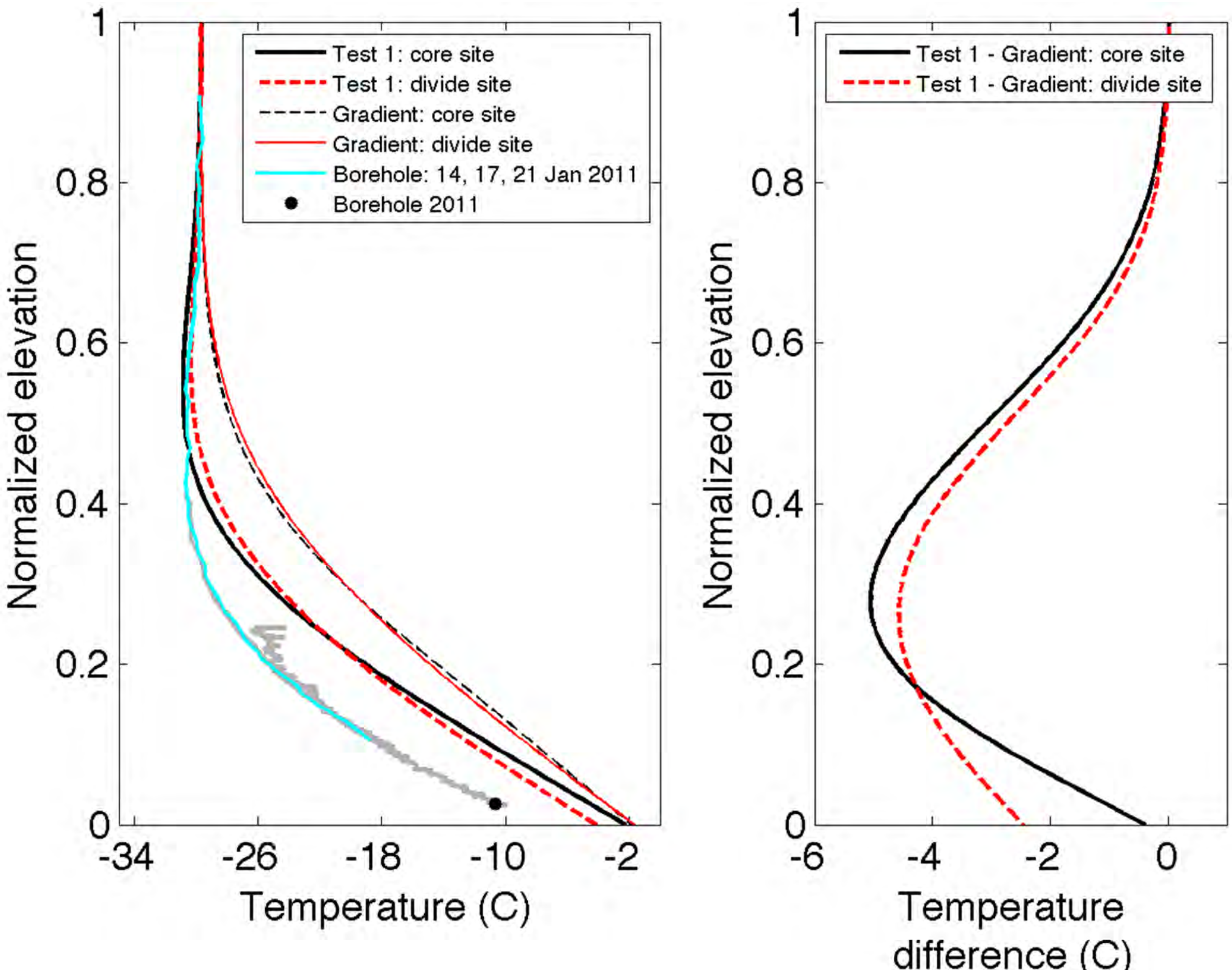


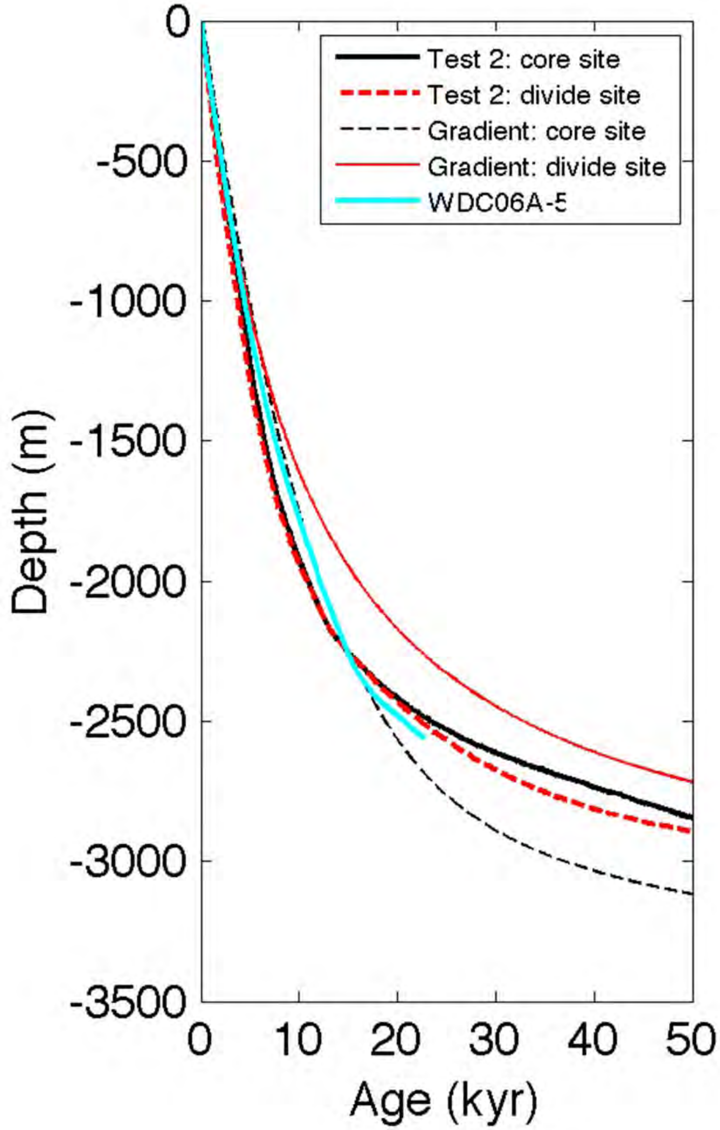
Gradient in accumulation rate
*and **<u>Test 1</u>***
at the core site vs. divide site

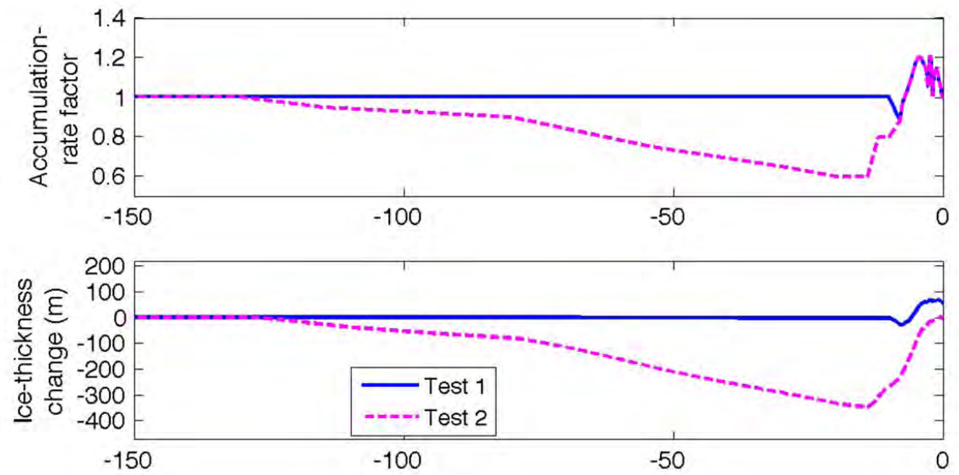
With accumulation rate constant in the glacial and increased in the Holocene, ice at the core site is deeper compared to constant accumulation



With ice-surface temperature variations, the ***temperature profile*** *reflects glacial changes*

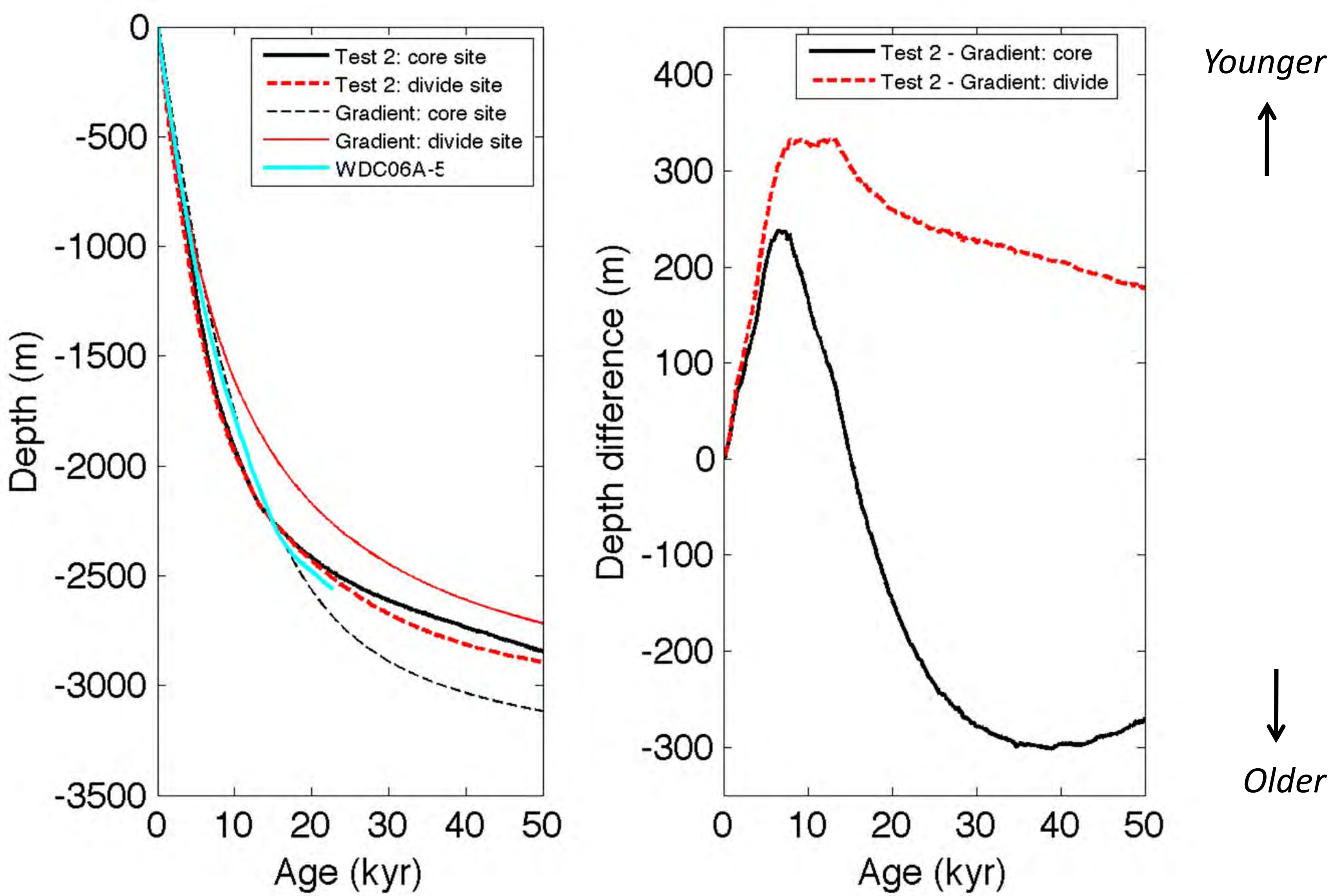




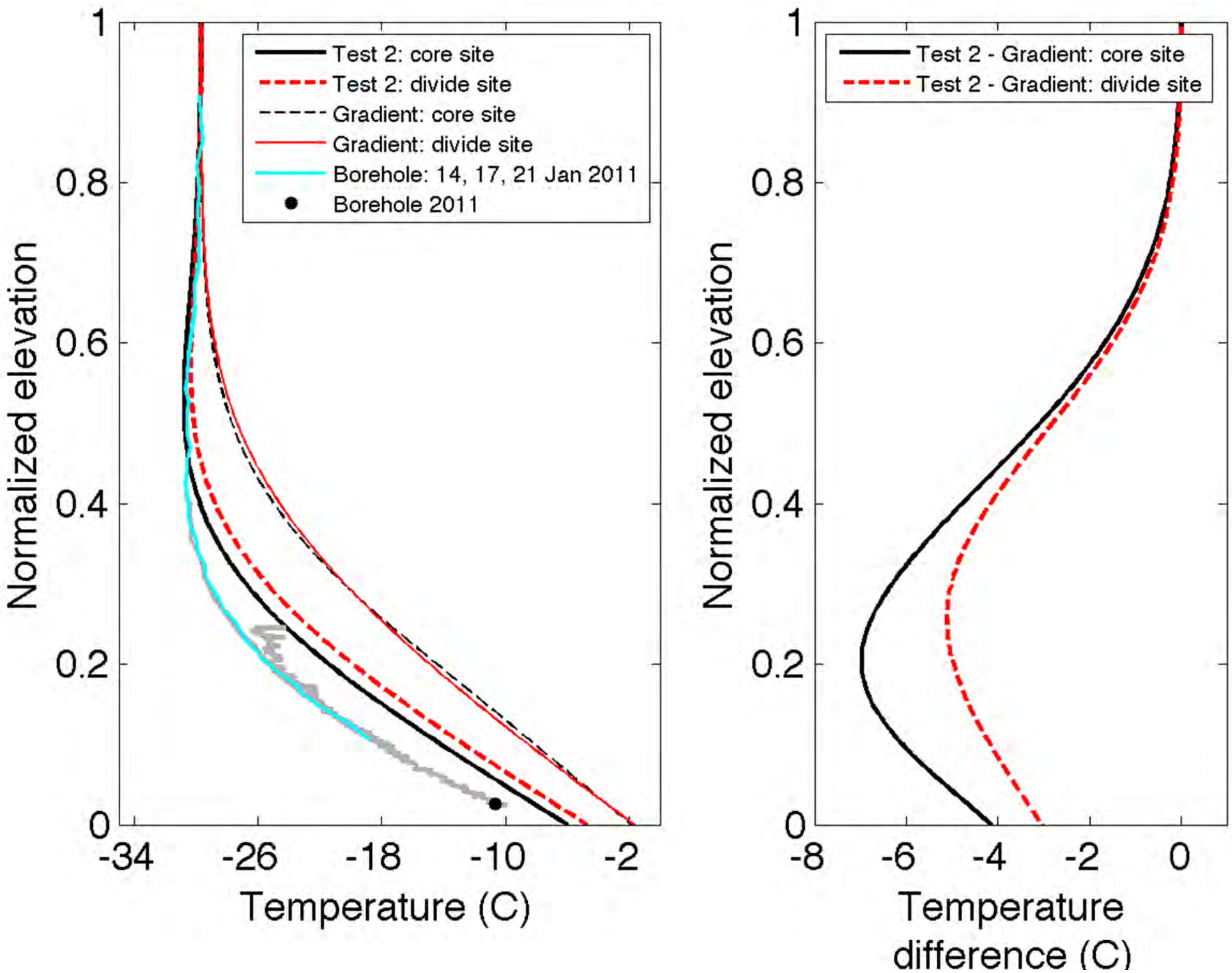


Gradient in accumulation rate
and ***<u>Test 2</u>***
at the core site vs. divide site

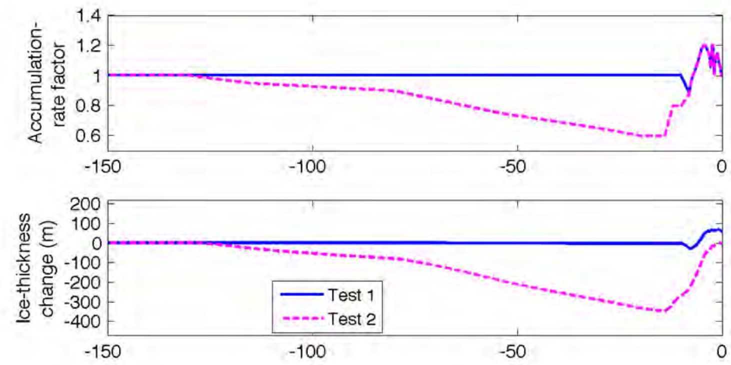
With accumulation rate decreased in the glacial and increased in the Holocene, the depth-age scales at the core site and at the divide site become similar

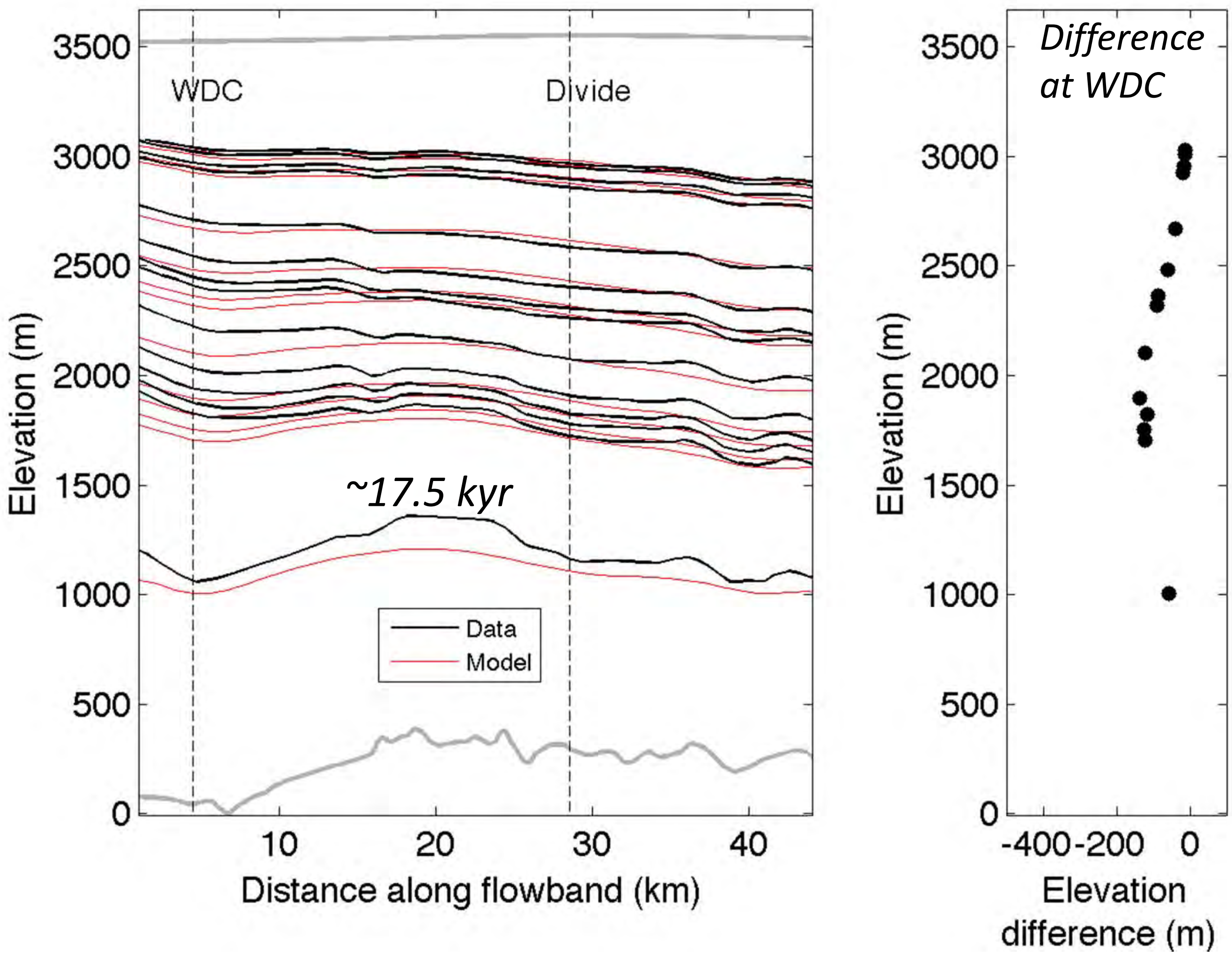


*The **temperature profile** does not change significantly compared to test 1, but the core-site values are colder at depth*

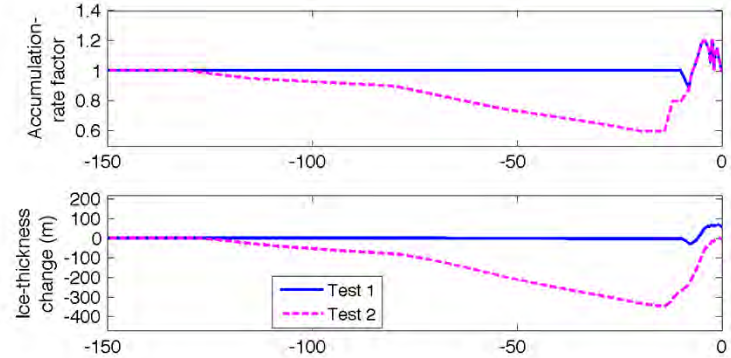


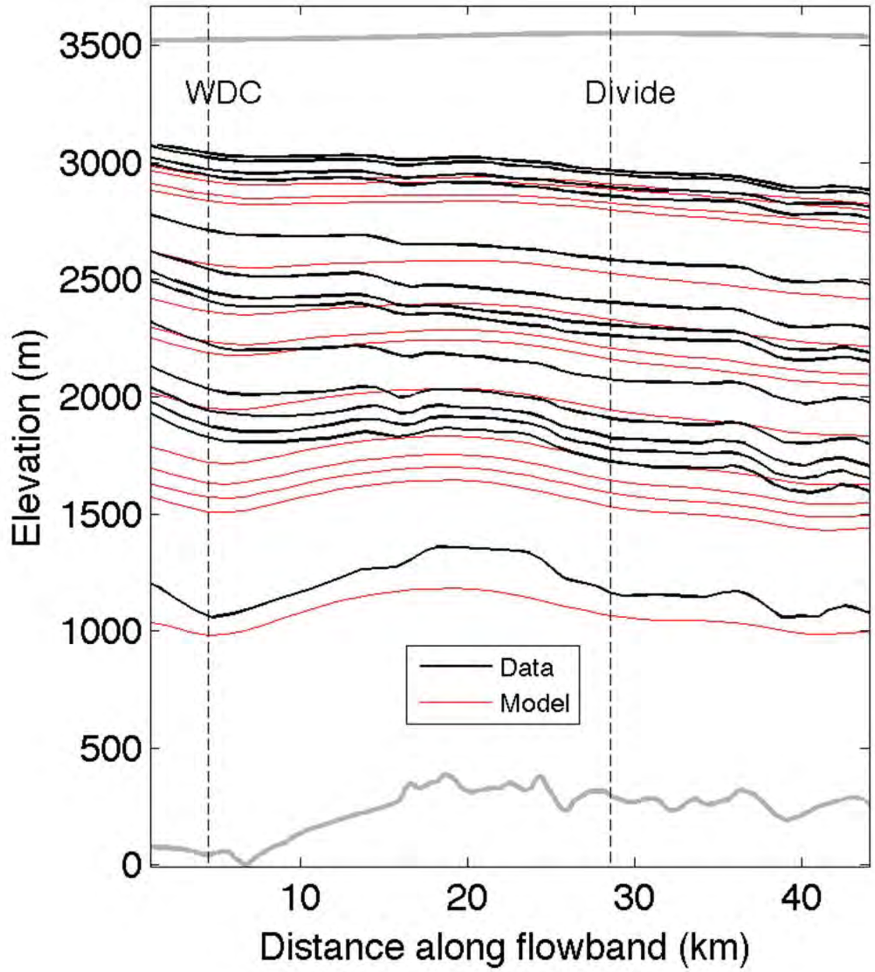
Test 1: Internal layers

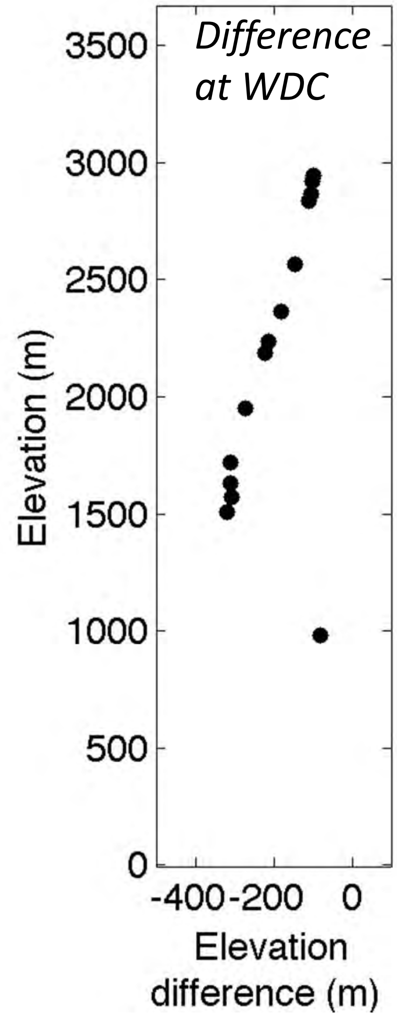




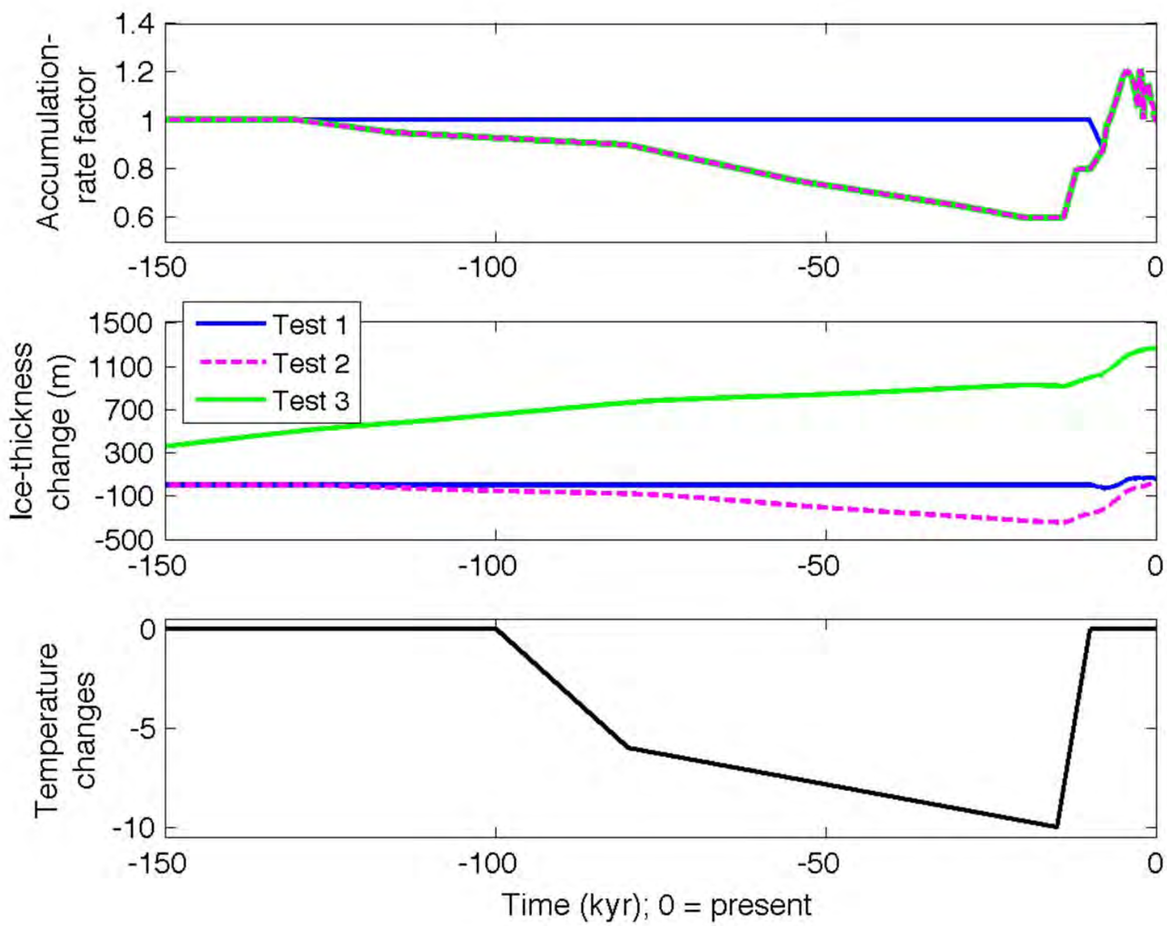
Test 2: Internal layers





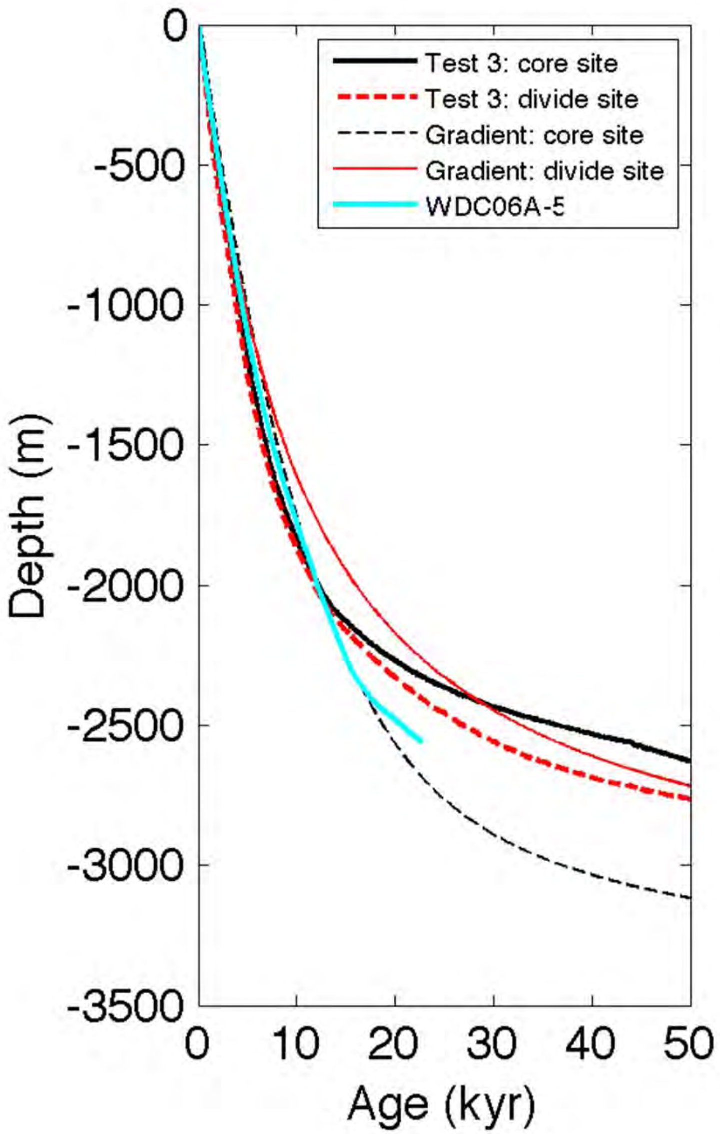


Changes in **ice flow**



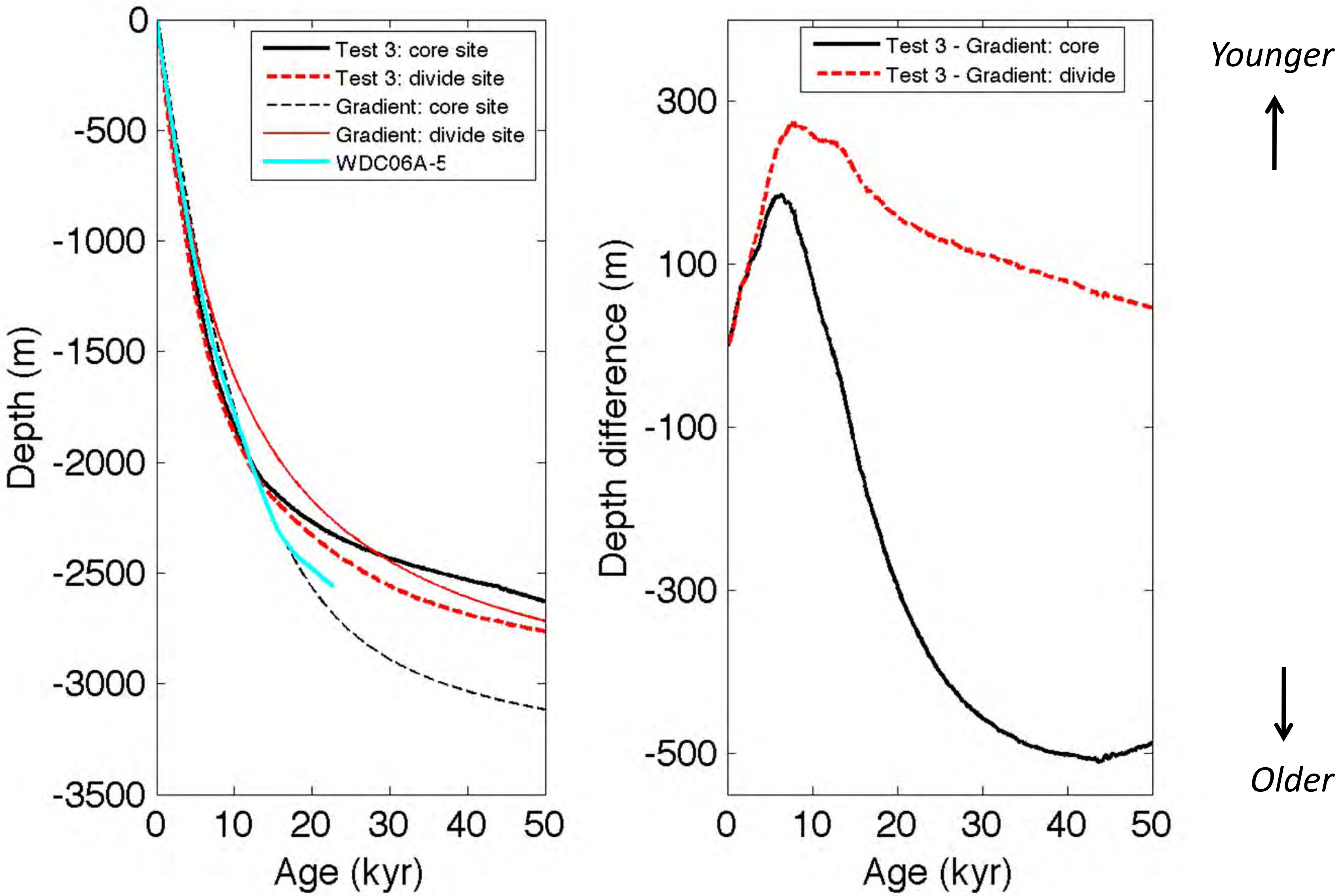
Test 3:
Decreased accumulation in glacial
Prescribed thickening (flow changes)
Surface temperature changes

Thickening gives similar modern ice thickness as test 2

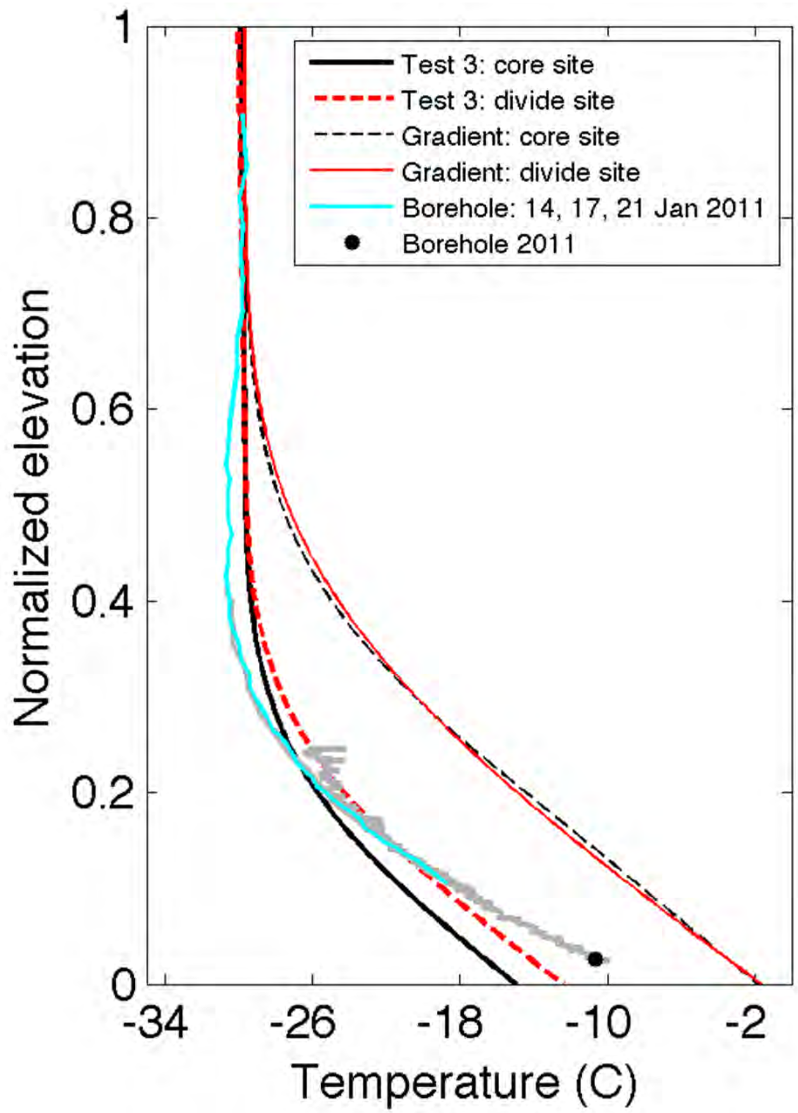


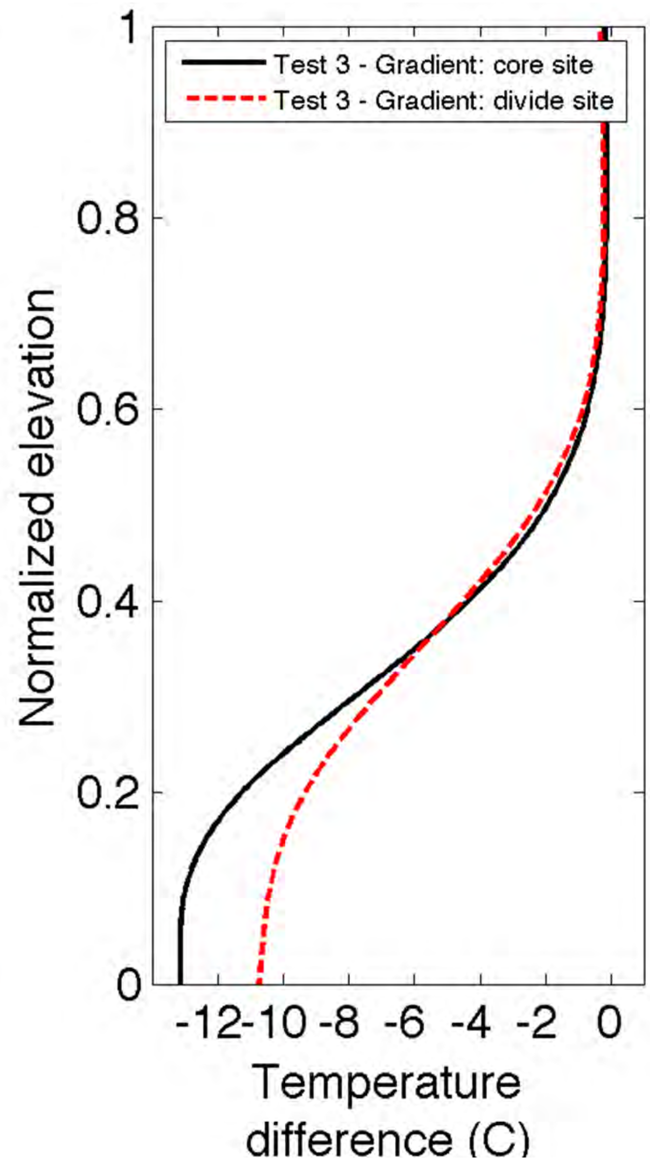
Gradient in accumulation rate
and ***<u>Test 3</u>***
at the core site vs. divide site

With significant ice thickening the difference in the depth-age scales is similar to the case with the same accumulation-rate changes but with thinning in the glacial

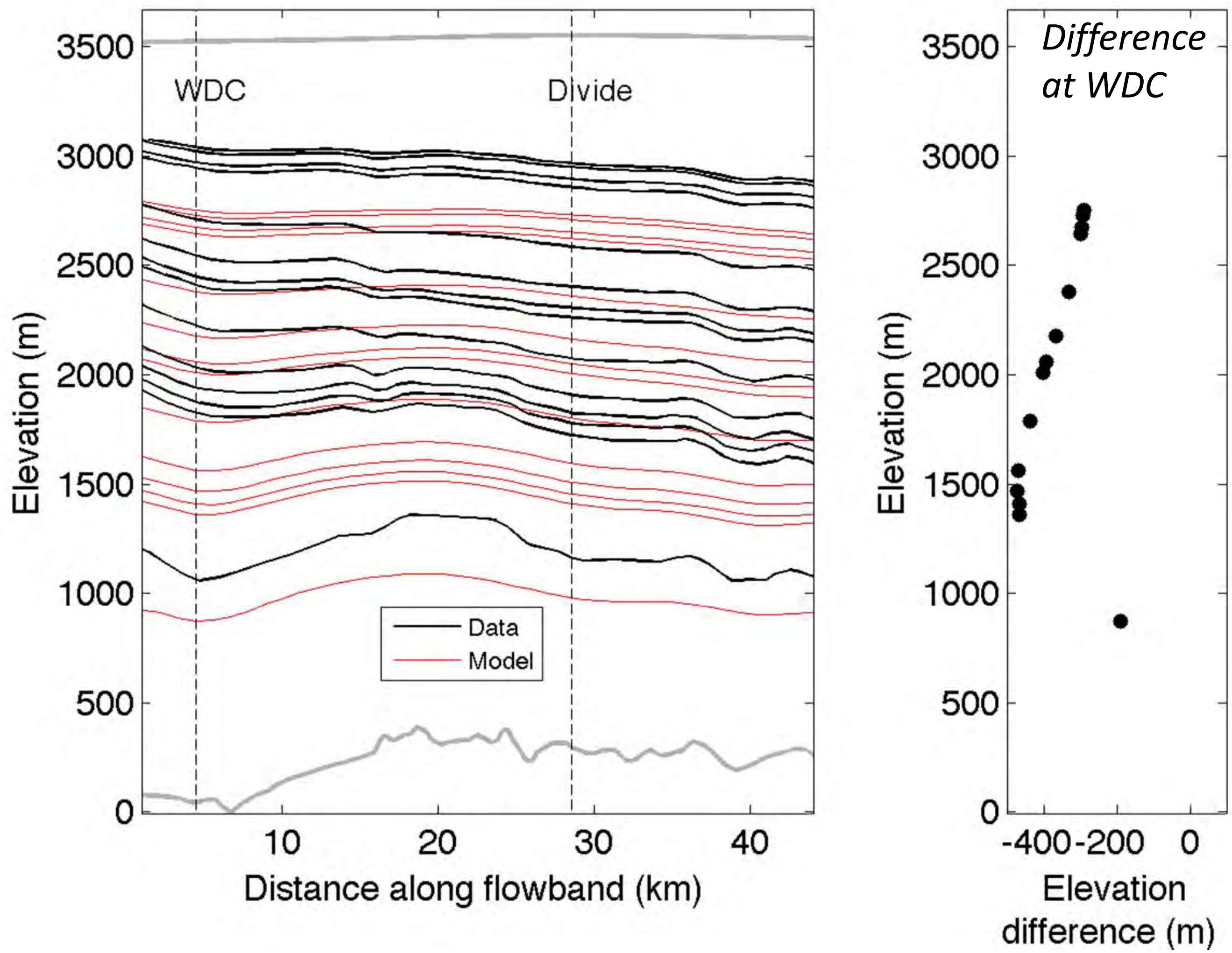


*However, the **temperature profile** does change significantly compared to test 2, the ice-thickness changes are reflected in the ice temperature at depth*





Test 3: Internal layers



Summary

Accumulation-rate changes can have a larger influence on the depth-age scale compared to ice-thickness changes

Ice-thickness changes can have a larger influence on the ice-temperature profile compared to accumulation-rate changes

The internal layers may provide context to separate the influence of changes in accumulation rate, ice thickness, and ice flow at the core site

Objectives

1. **Compare 2-D ice-sheet model realizations to ice-sheet data:**

   - Ice-core depth-age scale
   - Ice-temperature profile
   - Surface-velocity measurements
   - Modern ice-surface profile
   - Internal-layer shapes

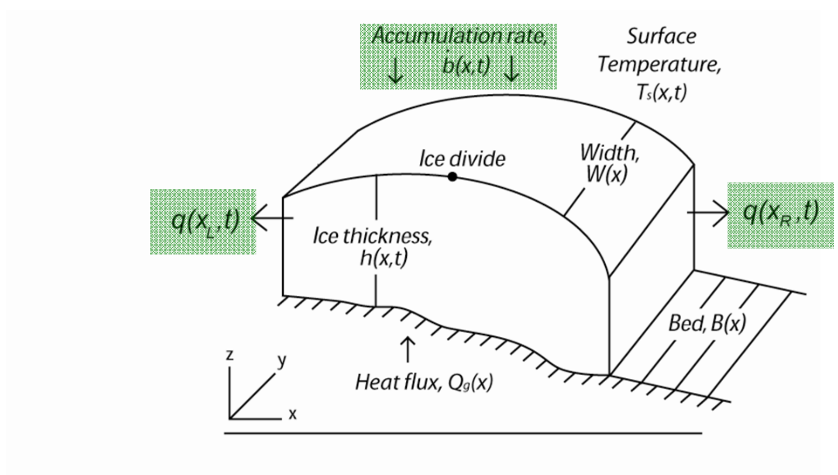
2. **Solve an inverse problem to infer:**

   - Accumulation-rate history
   - Ice-flow history (external-flux forcing) → ice-divide position

How long has the WAIS divide been migrating?

Solve a ***suite*** of inverse problems for:

- only **accumulation-rate history**
- only **external-flux history**
- both **accumulation-rate and external-flux history**



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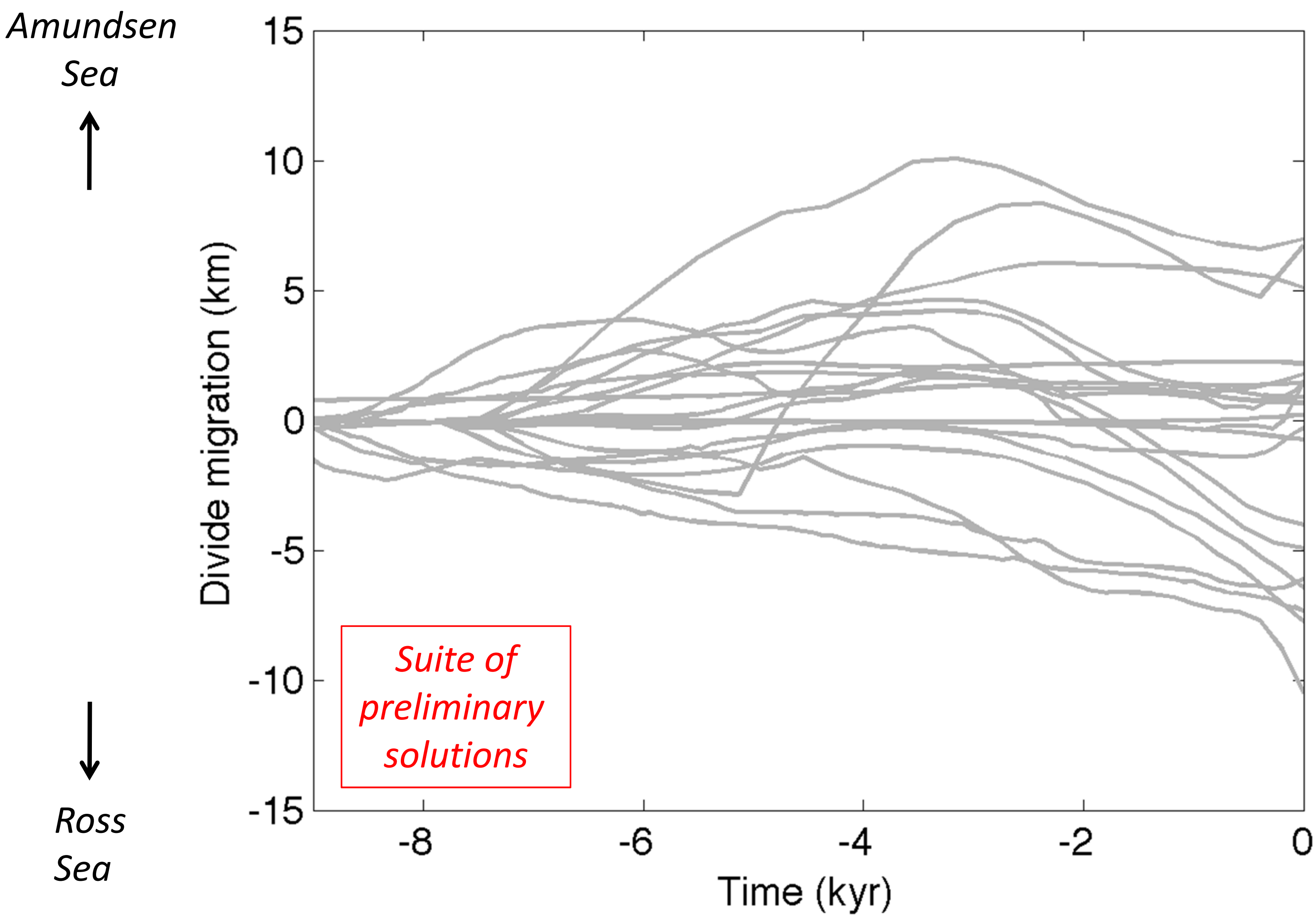

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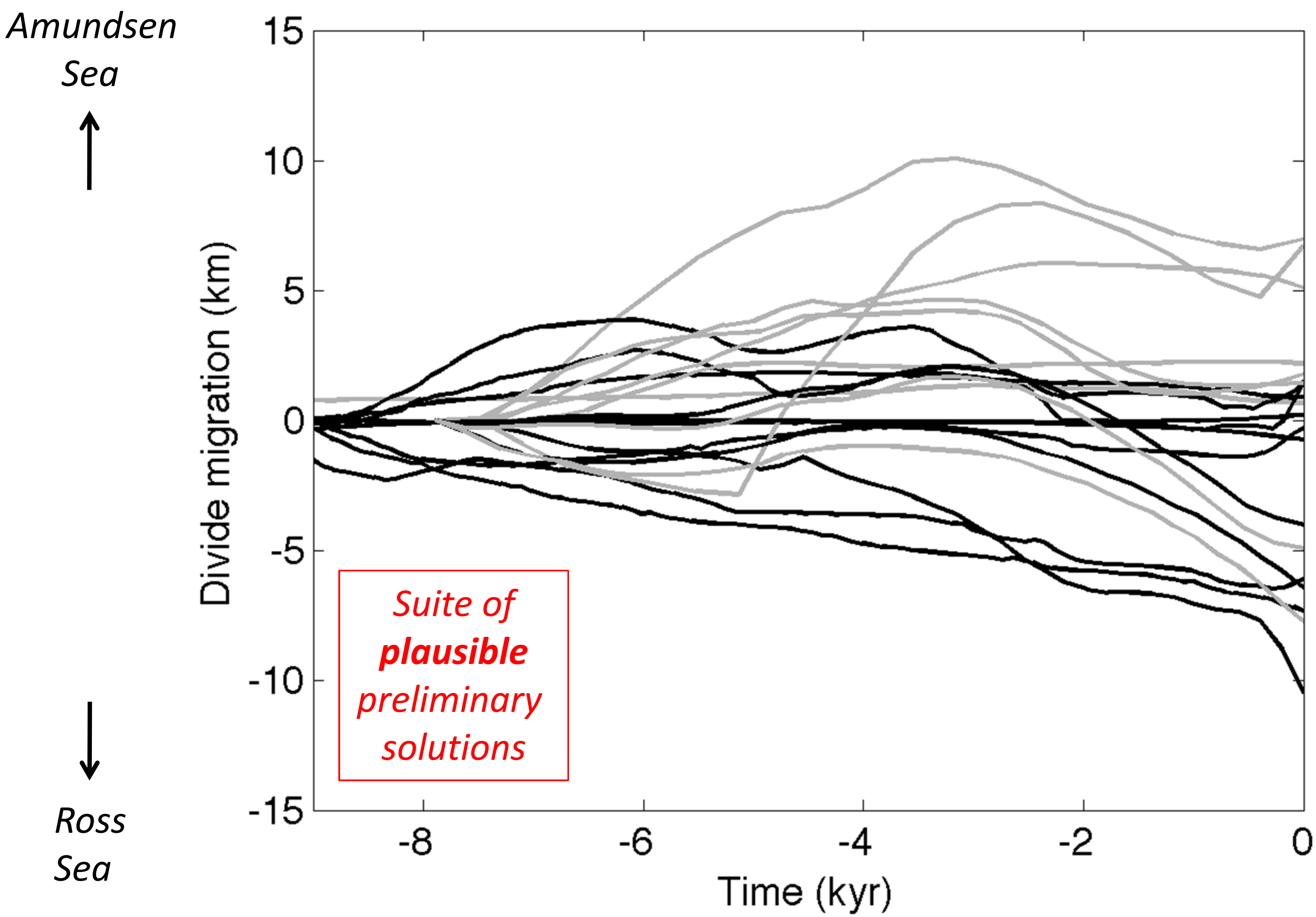

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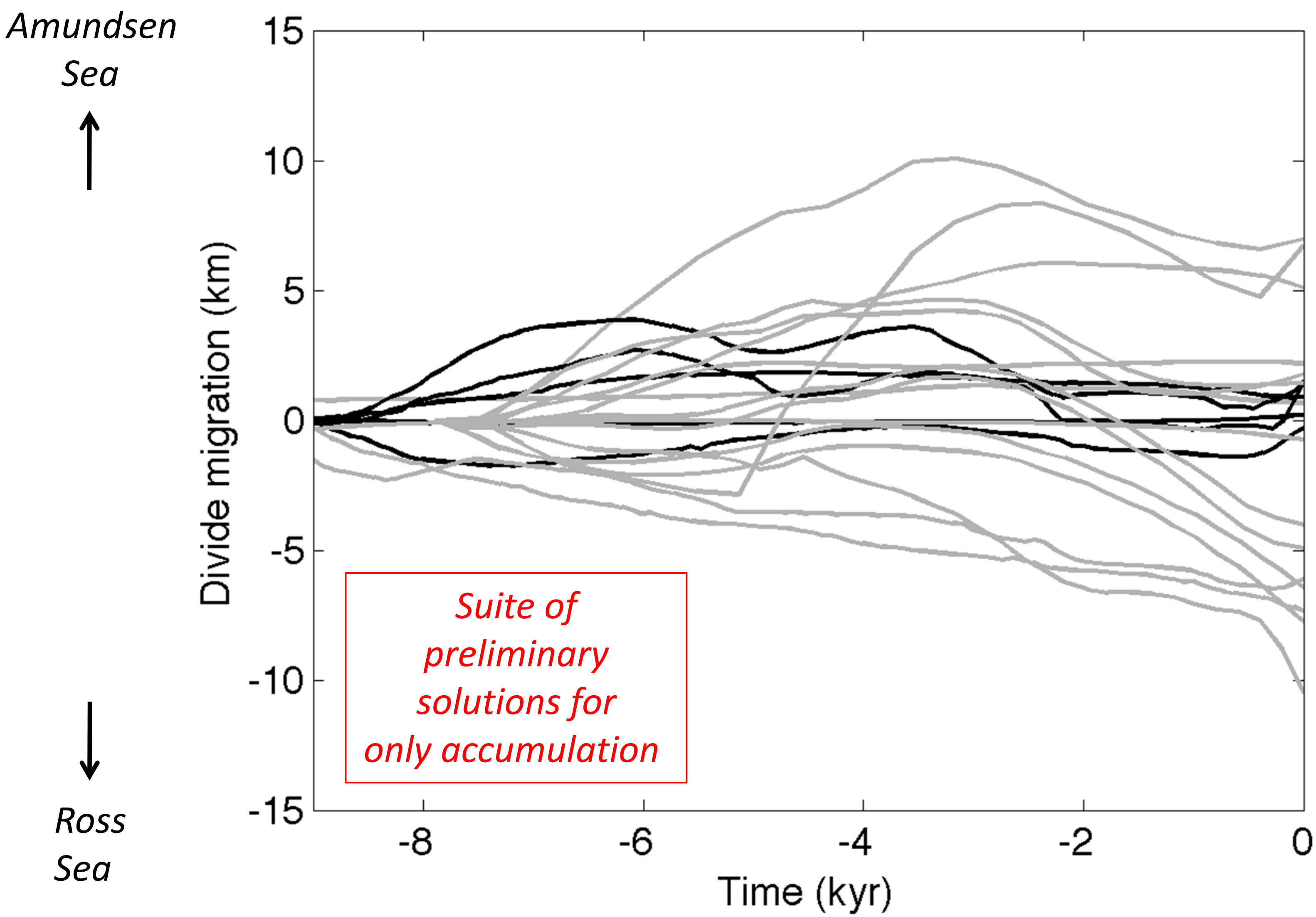
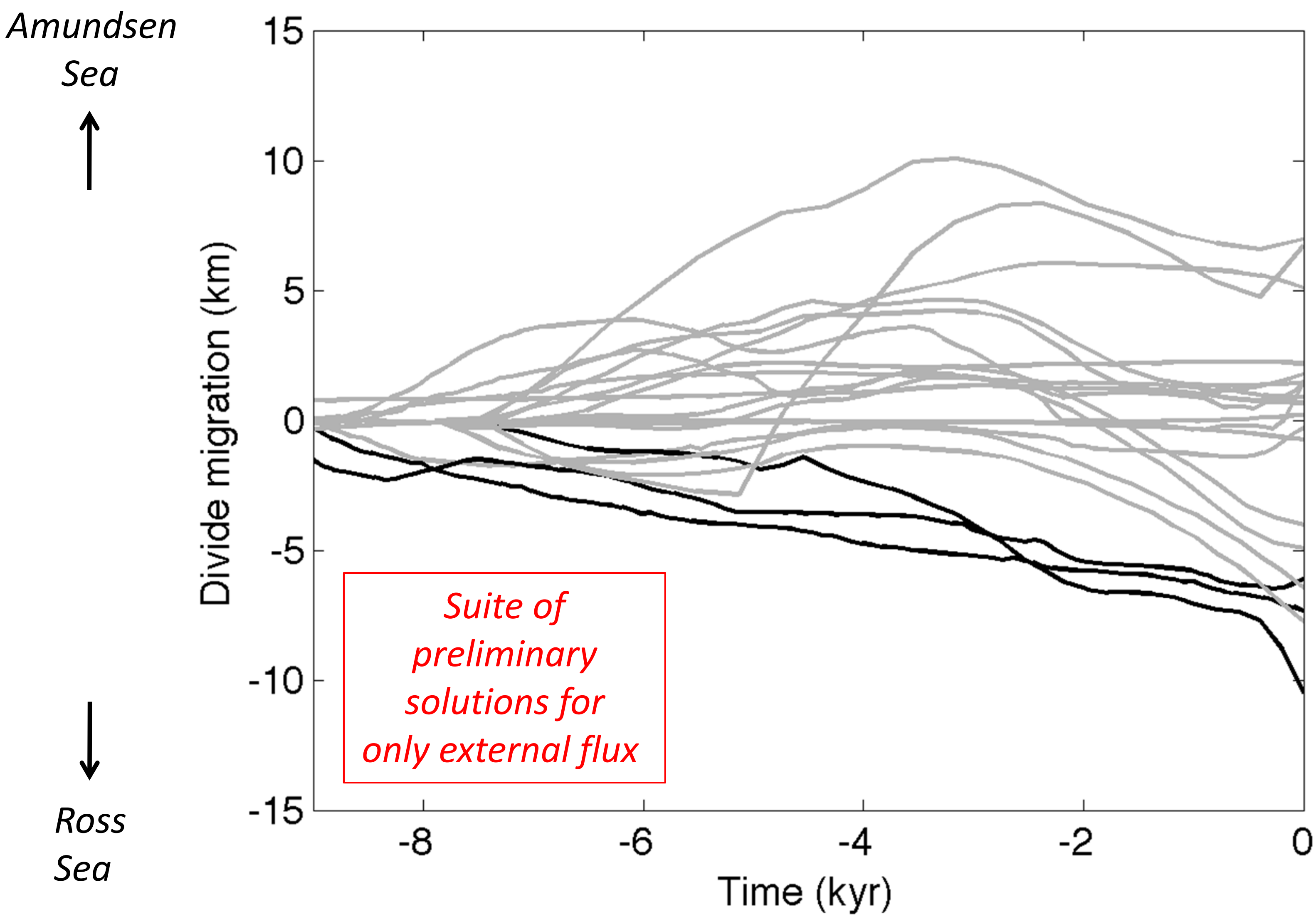


How long has the WAIS divide been migrating?



~~How long has the WAIS divide been migrating?~~

How can we obtain the best set of possible solutions?

1. Incorporate additional *data*:

- Ice-core depth-age scale
- Ice-temperature profile
- Internal layers

This is in progress

2. Incorporate additional *constraints*:

- Behavior characteristics of external-flux forcing
- Better guess at initial conditions

This needs input

~~How long has the WAIS divide been migrating?~~

What can we say so far?

Without changes in external flux over the past 9 kyr, unrealistic histories of accumulation are inferred to fit the data

Without changes in external flux over the past 9 kyr, the model cannot generate a good fit to the layers ***and*** to the modern ice-sheet data

Solving for a history over 9 kyr is likely sensitive to the initial conditions and this should be explored (e.g. solving problem further back in time)

Summary / Conclusions

Accumulation-rate changes have a larger influence on the depth-age scale compared to ice-thickness changes

Ice-thickness changes have a larger influence on the ice-temperature profile compared to accumulation-rate changes

The internal layers, when used with depth-age and ice-temperature data, provide context to infer changes in accumulation rate, ice thickness, and ice flow at the core site – should consider 2-D effects

All available data and constraints are necessary to use in the inverse problem to infer the history of WAIS Divide migration – layers provide the spatial information

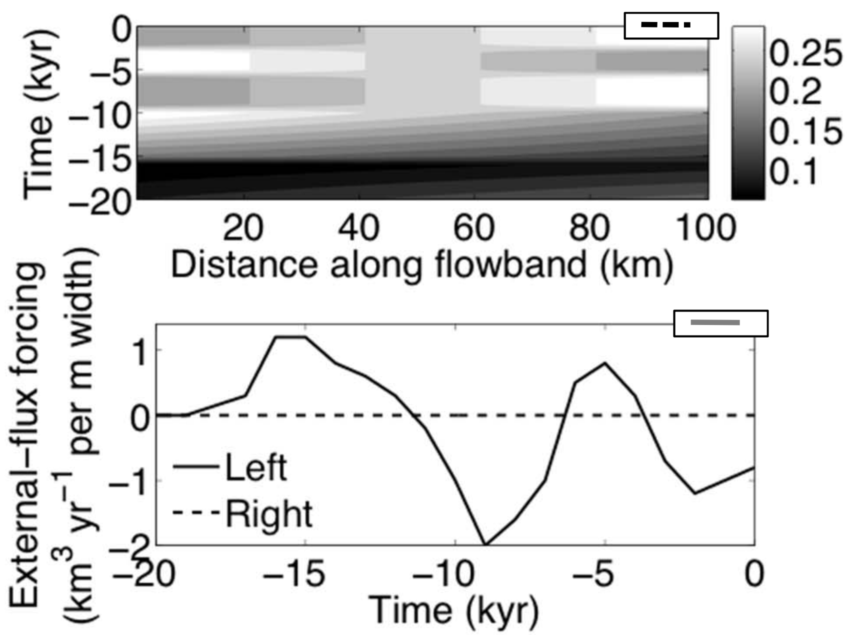
Data value	Size	Symbol
Internal-layer shapes	$N_{layers} \times N_h$	$h_d(x,z)$
Modern ice-surface topography	N_S	$S(x,t_0)$
Modern accumulation rate	$N_{\dot{b}}$	$\dot{b}(x,t_0)$
Modern surface velocity	N_u	$u(x,t_0)$

Model parameter	Size	Symbol
Accumulation-rate history	$N_t \times N_x$	$\dot{b}(x,t)$
External-flux history	$N_t \times [\ N_{x^1}\ N_{x^{end}}\ ]$	$Q_{ext}(x,t)$
Ice flux entering the domain at initial timestep	1	Q_0^{in}
Ice thickness at first spatial node at initial timestep	1	S_0^{in}
Temperature-independent ice-softness parameter	1	A_0
Average geothermal flux	1	Q_{geo}

Accumulation gradient and transients **vs.** flow transients

Example case

Inputs: *accumulation rate or external flux*

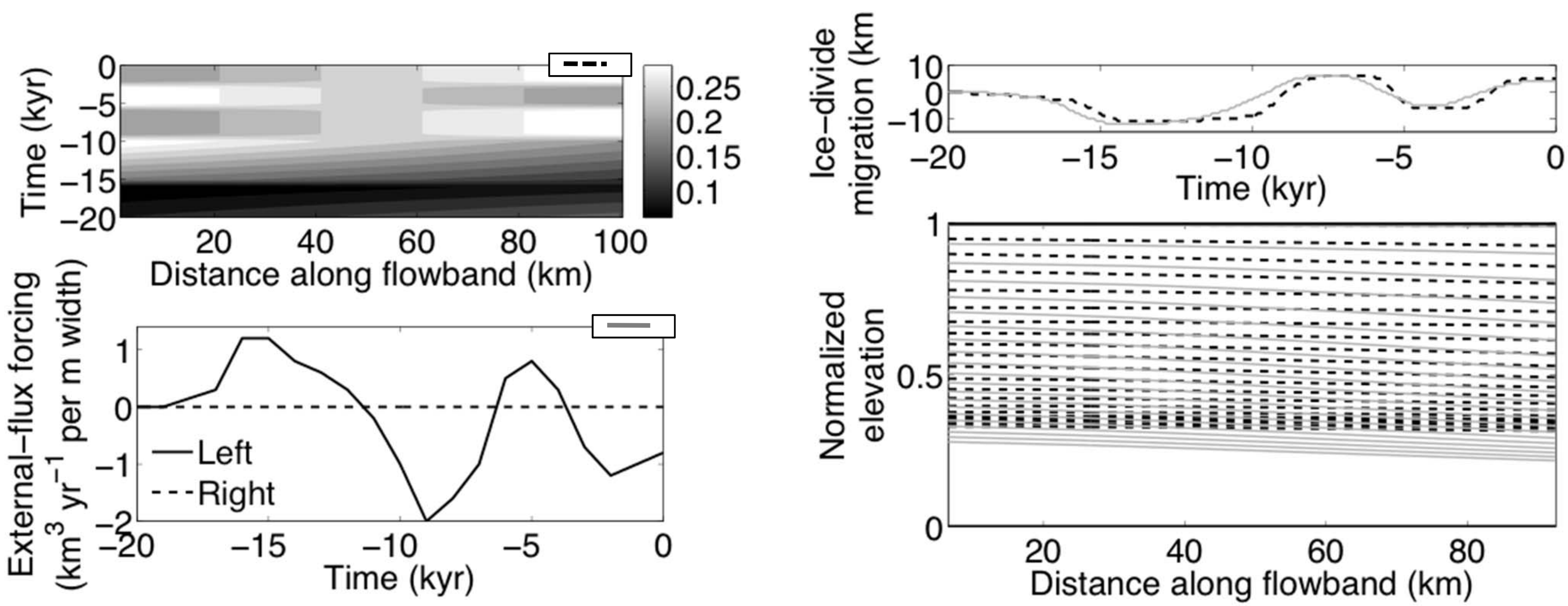


Accumulation gradient and transients **vs.** flow transients

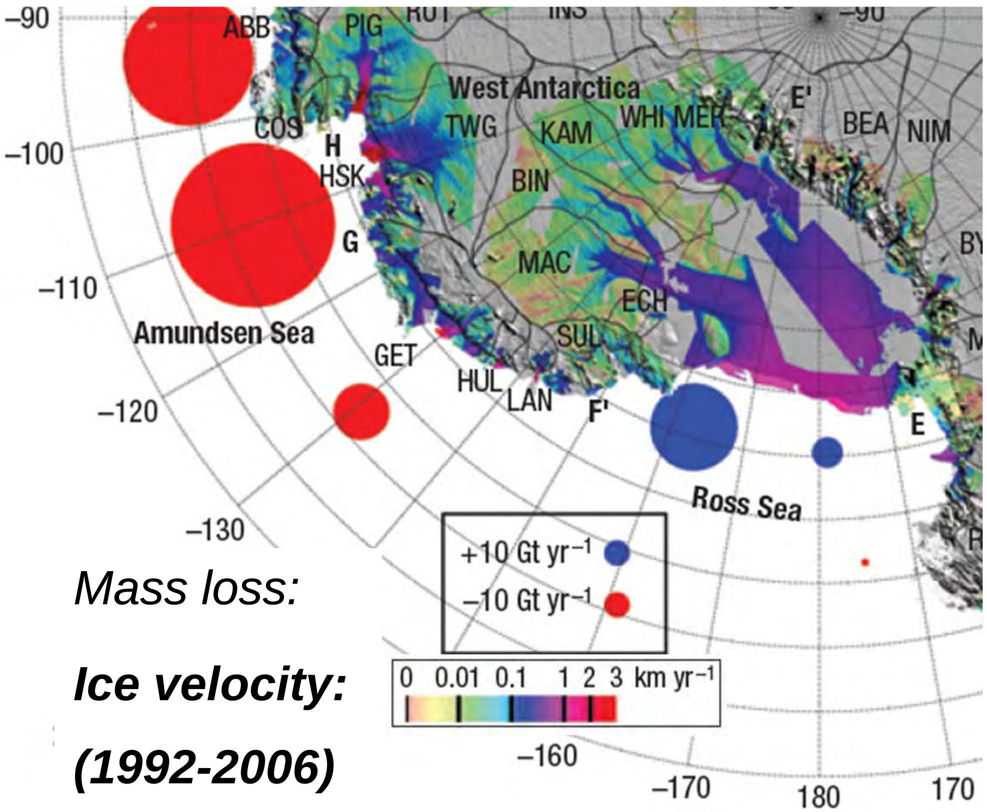
Example case

Inputs: *accumulation rate or external flux*

Outputs: *ice-divide migration and internal-layer shapes*



Ice-divide position and interior ice thickness likely controlled by ice dynamics

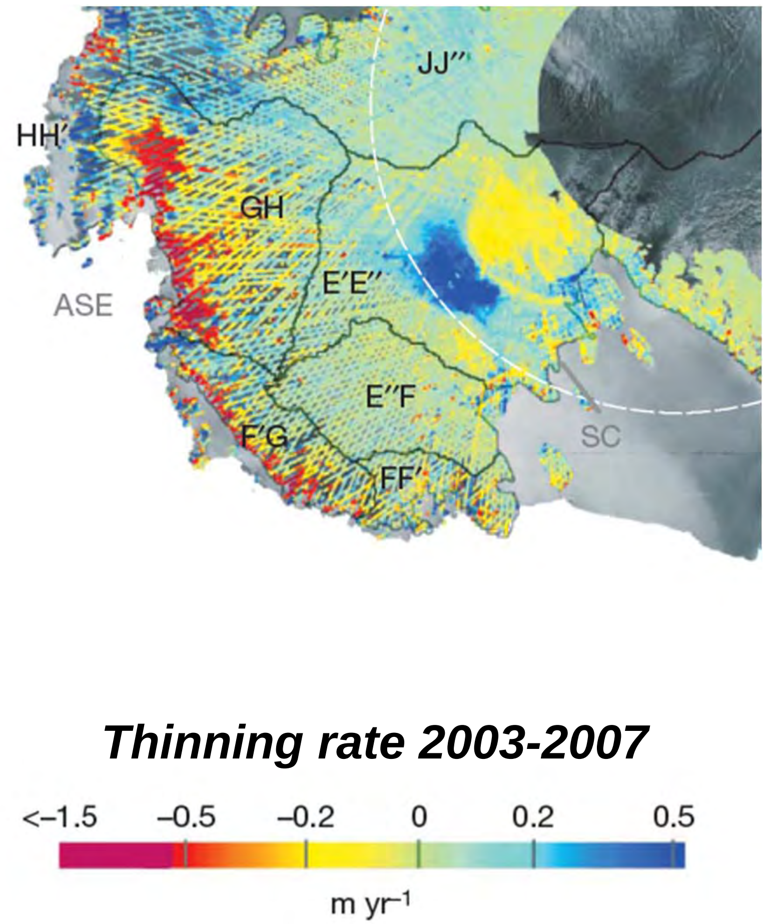


Mass loss:

Ice velocity:

(1992-2006)

Rignot et al. (2008)
(Rignot et al. 2011)



Thinning rate 2003-2007

Pritchard et al. (2009)

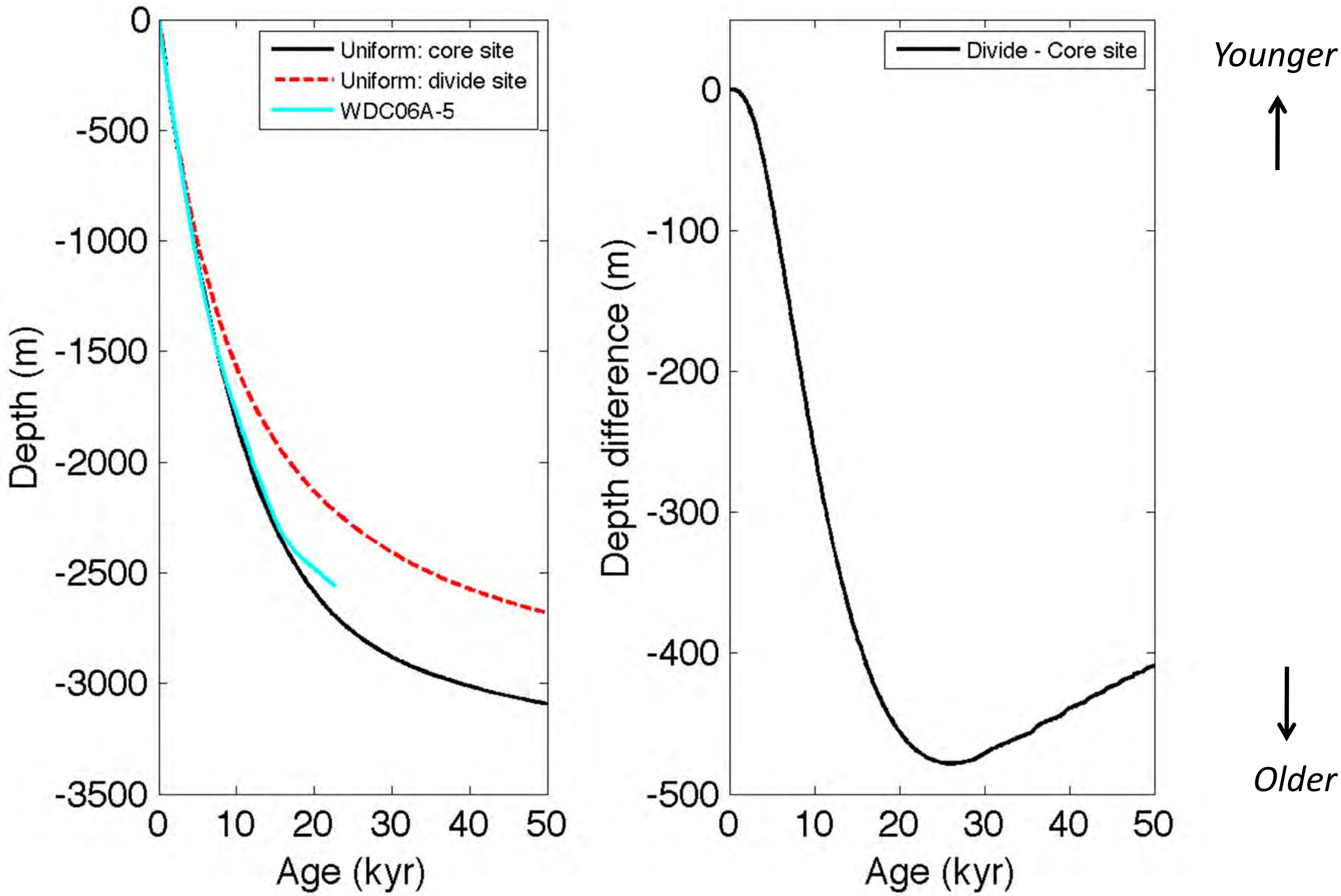
Also e.g. Anadakrishnan et al. (1994), Marshall and Cuffey (2000), Gillet-Chaulet and Hindmarsh (2011)

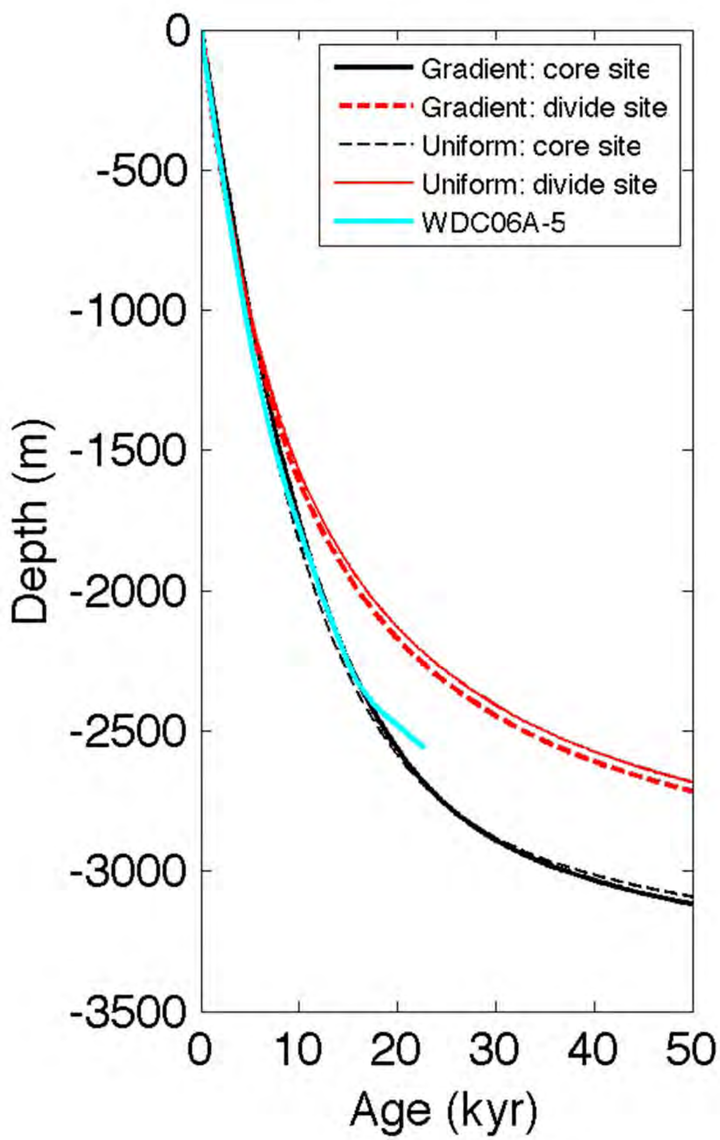
The ice divide may migrate due to:

- Variations in the accumulation *pattern*
- Transients in accumulation *rate*
- Transients in ice flow (external-flux forcing)

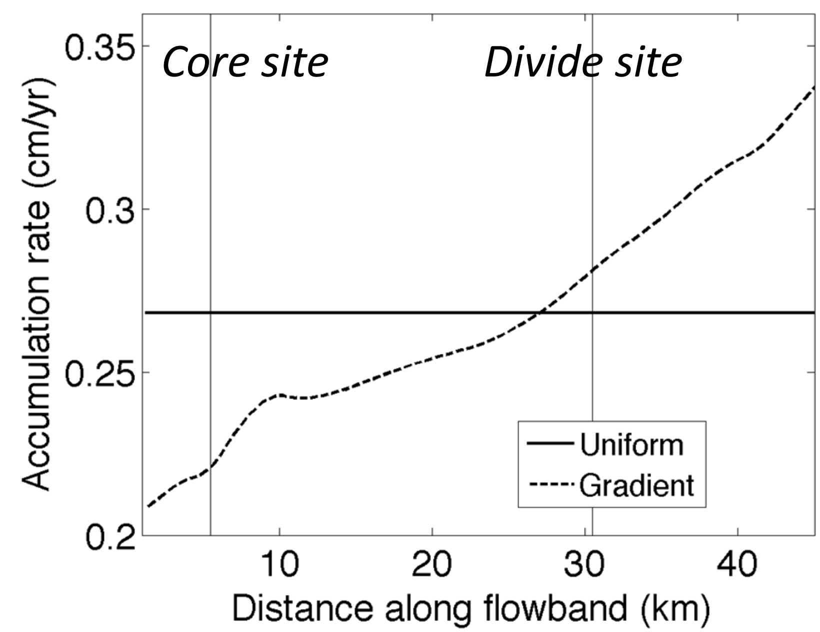
* prescribed surface-temperature history
* prescribed heat flux
* prescribed ice softness
* no basal melting

With a uniform accumulation rate, ice at the core site is deeper compared to the divide





Gradient: core site
Gradient: divide site
Uniform: core site
Uniform: divide site
WDC06A-5
Depth (m)
Age (kyr)



Core site
Divide site
Uniform
Gradient
Accumulation rate (cm/yr)
Distance along flowband (km)

Ice at the divide is consistently deeper because the accumulation rate is higher

Ice at the core site is shallower until ice is older than ~30 kyr because accumulation is lower