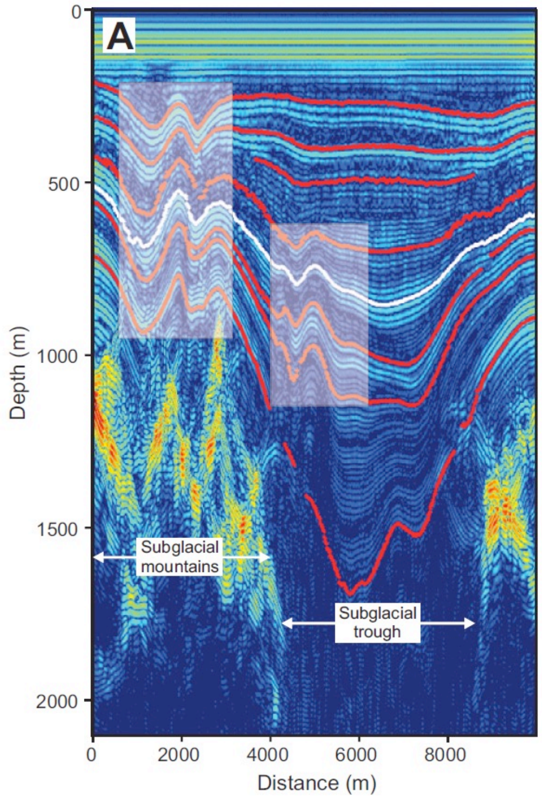
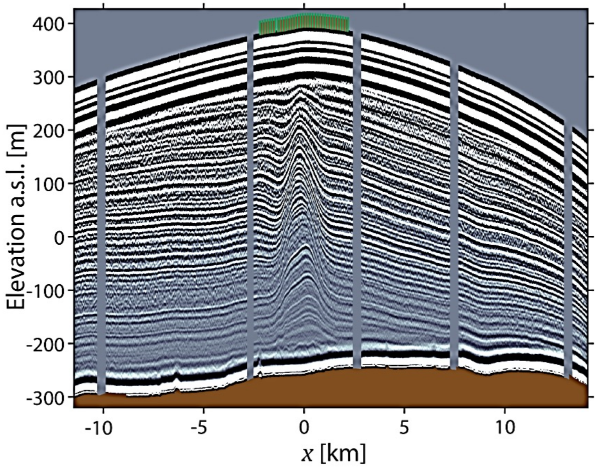
Glaciology
EESCGU4220

Lecture 12: Isochrones and age structure

Radar layers
Isochrones
The age equation
Theoretical isochrones
Applications





Ice-penetrating radar

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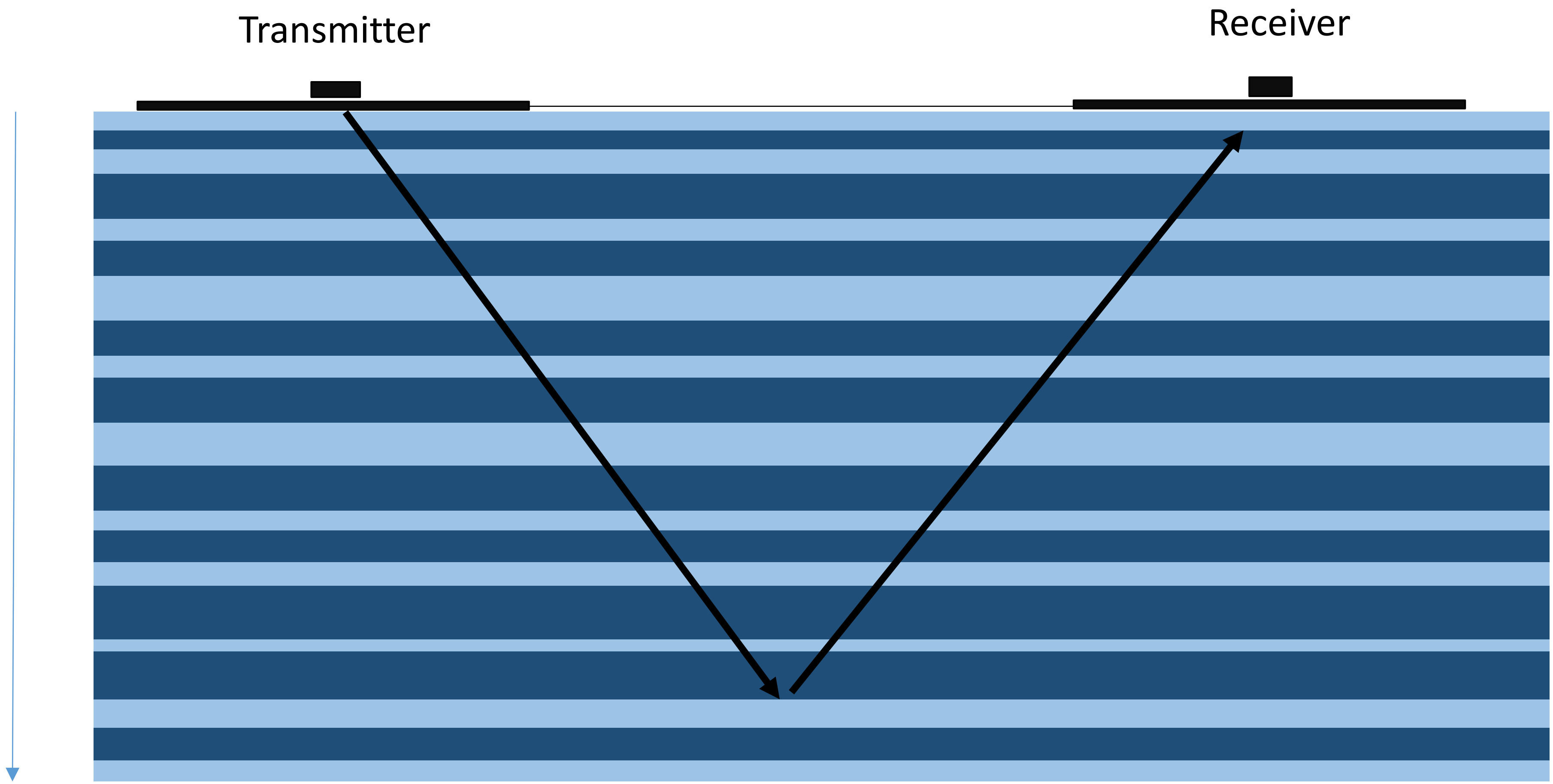

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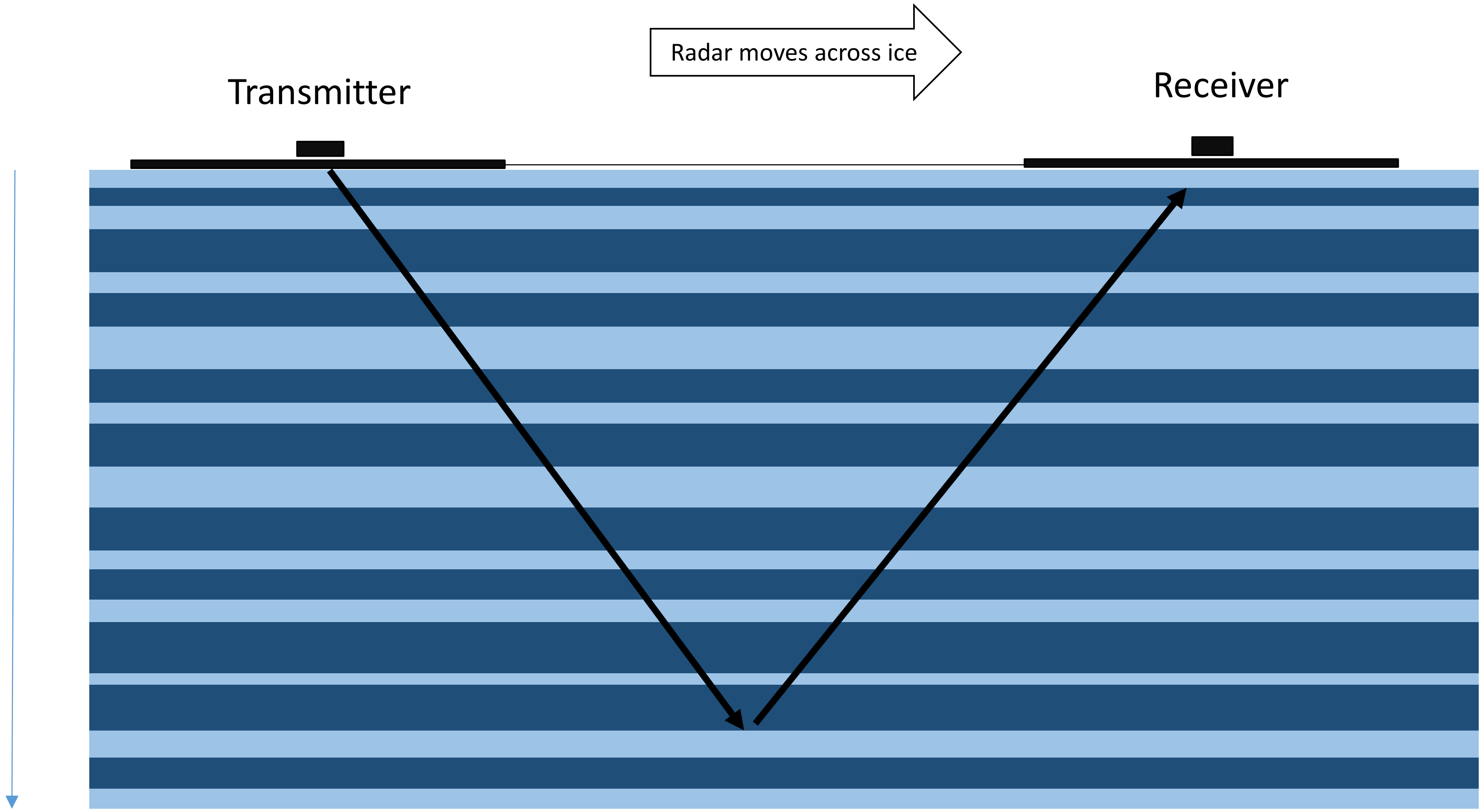
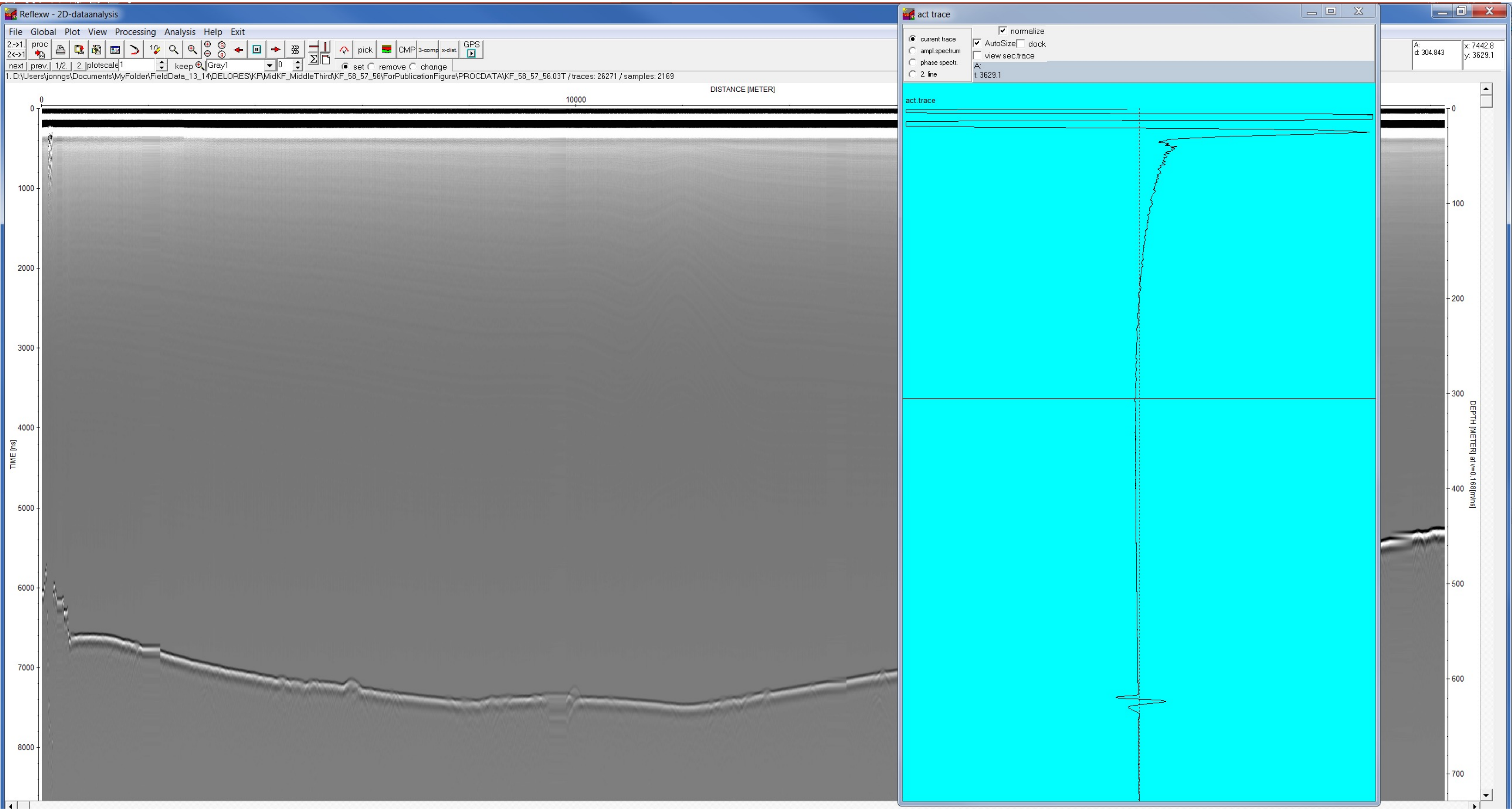


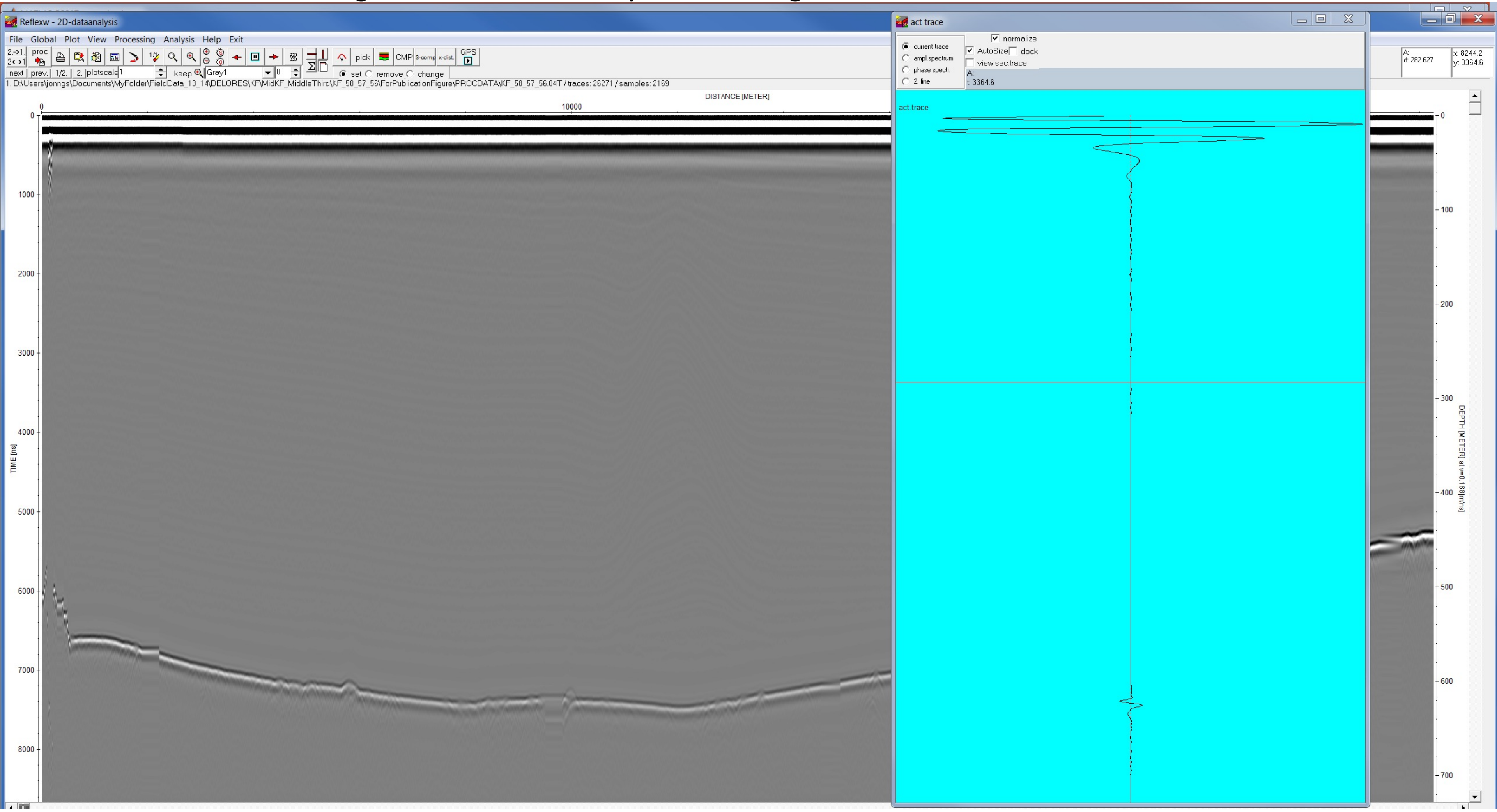
Ice-penetrating radar

Raw data from ground-based ice-penetrating radar



Ice-penetrating radar

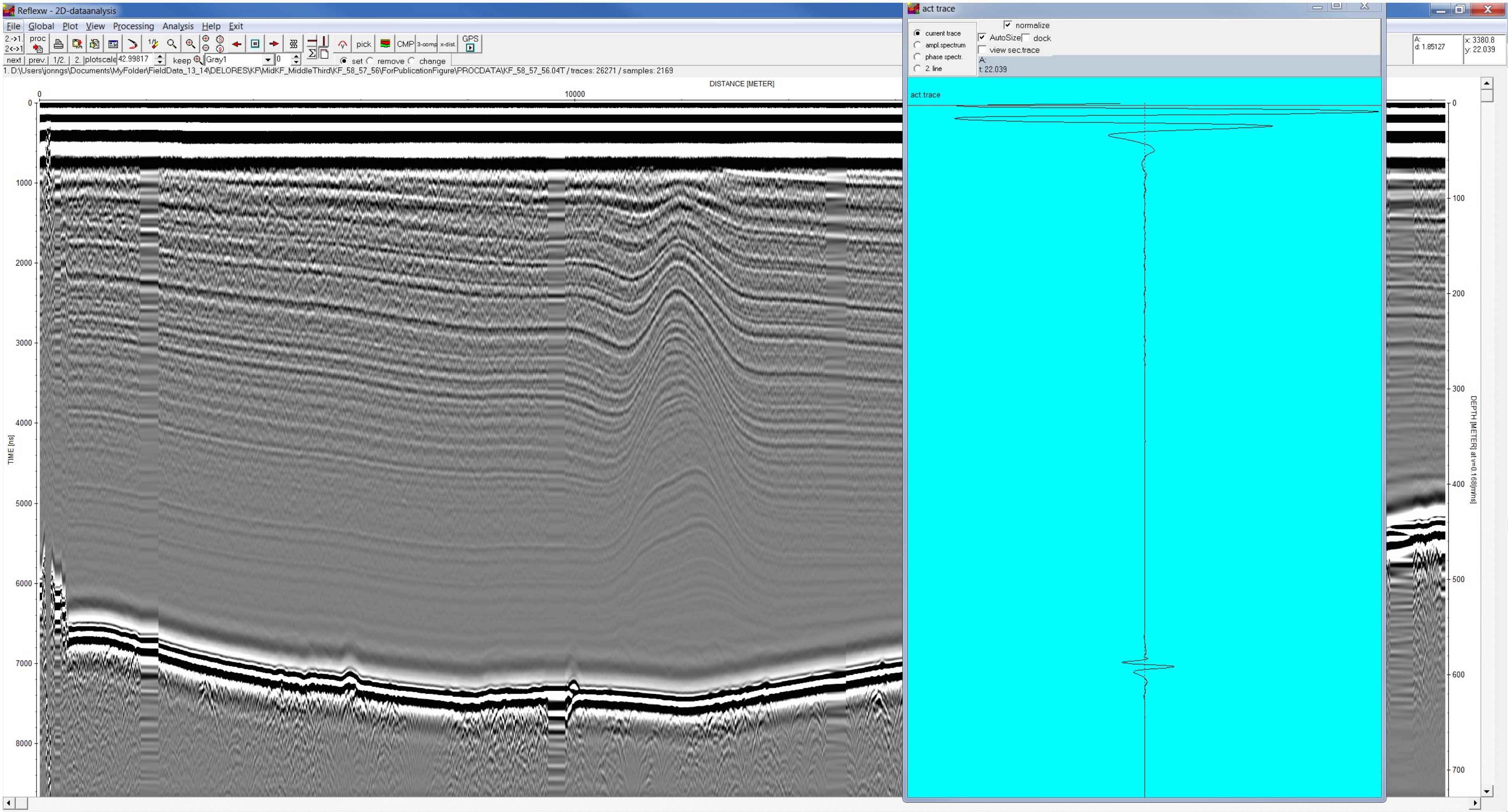
Filtered data from ground-based ice-penetrating radar



https://www.youtube.com/watch?v=spUNpyF58BY

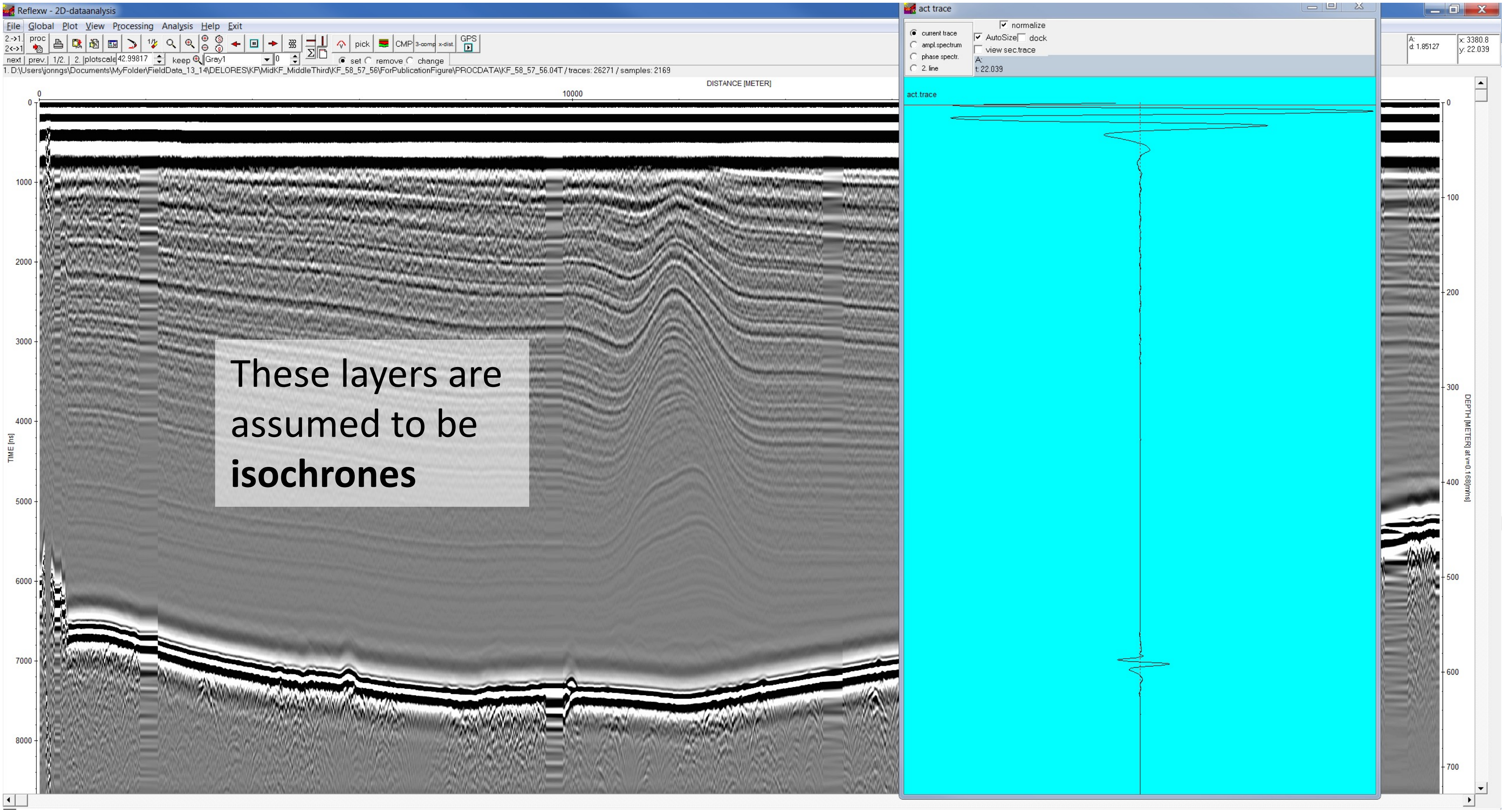
Ice-penetrating radar

Filtered data from ground-based ice-penetrating radar, contrast stretched.



Ice-penetrating radar

Filtered data from ground-based ice-penetrating radar



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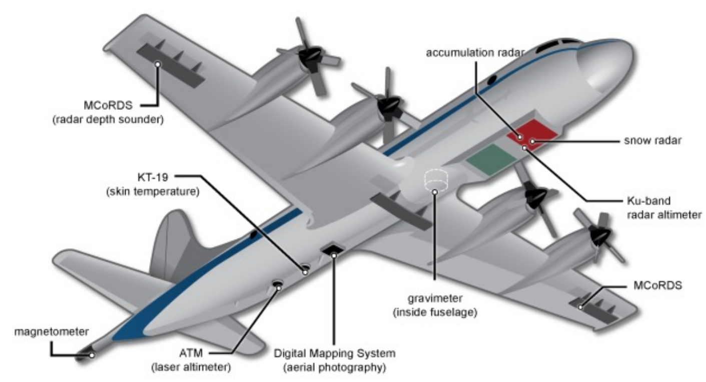
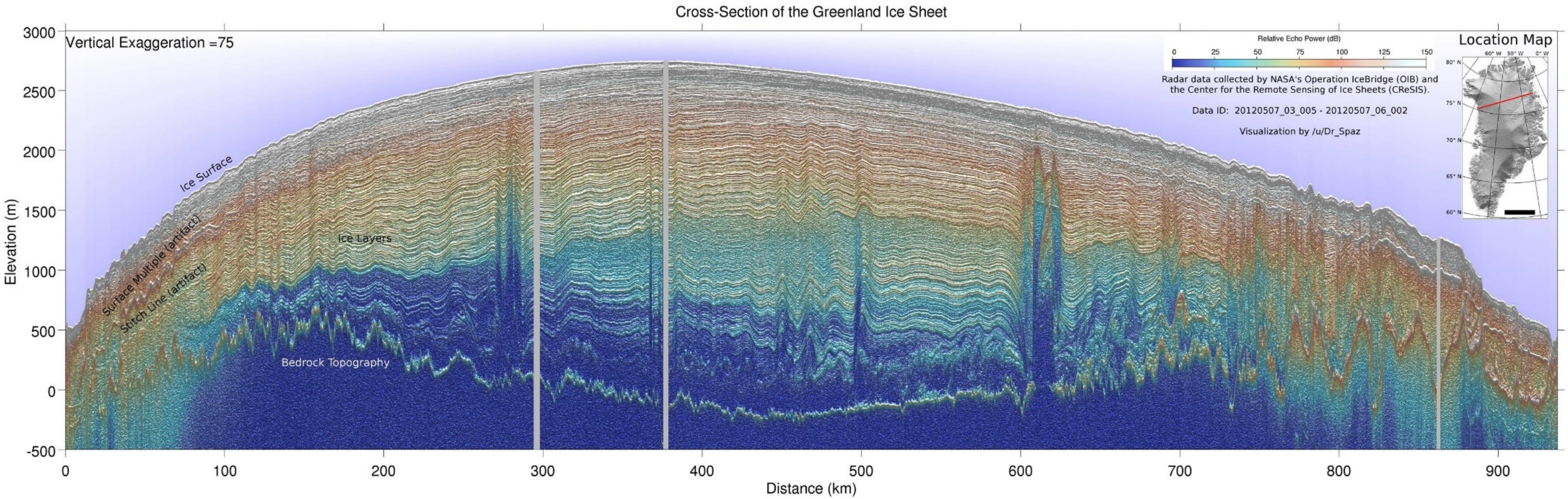
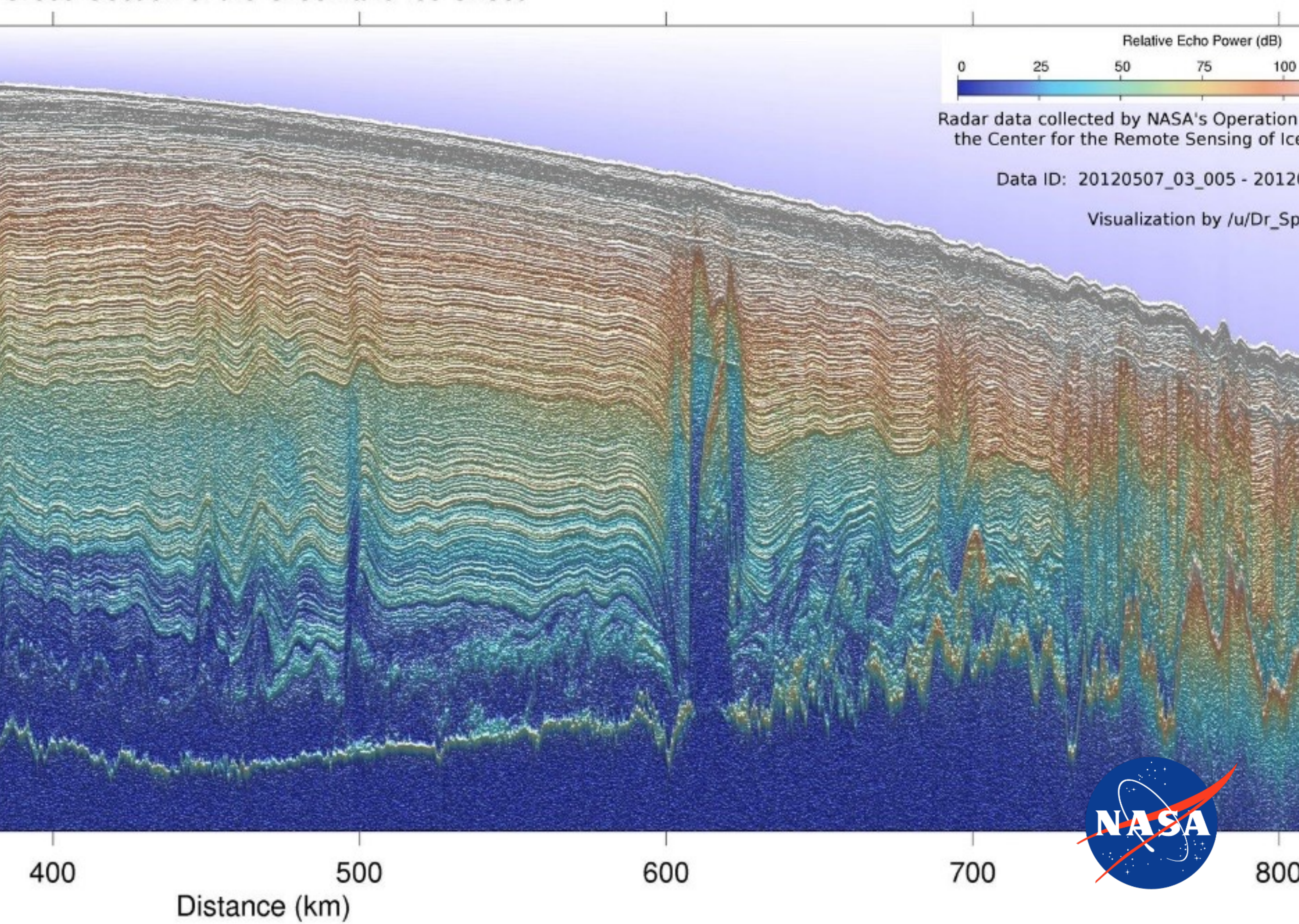
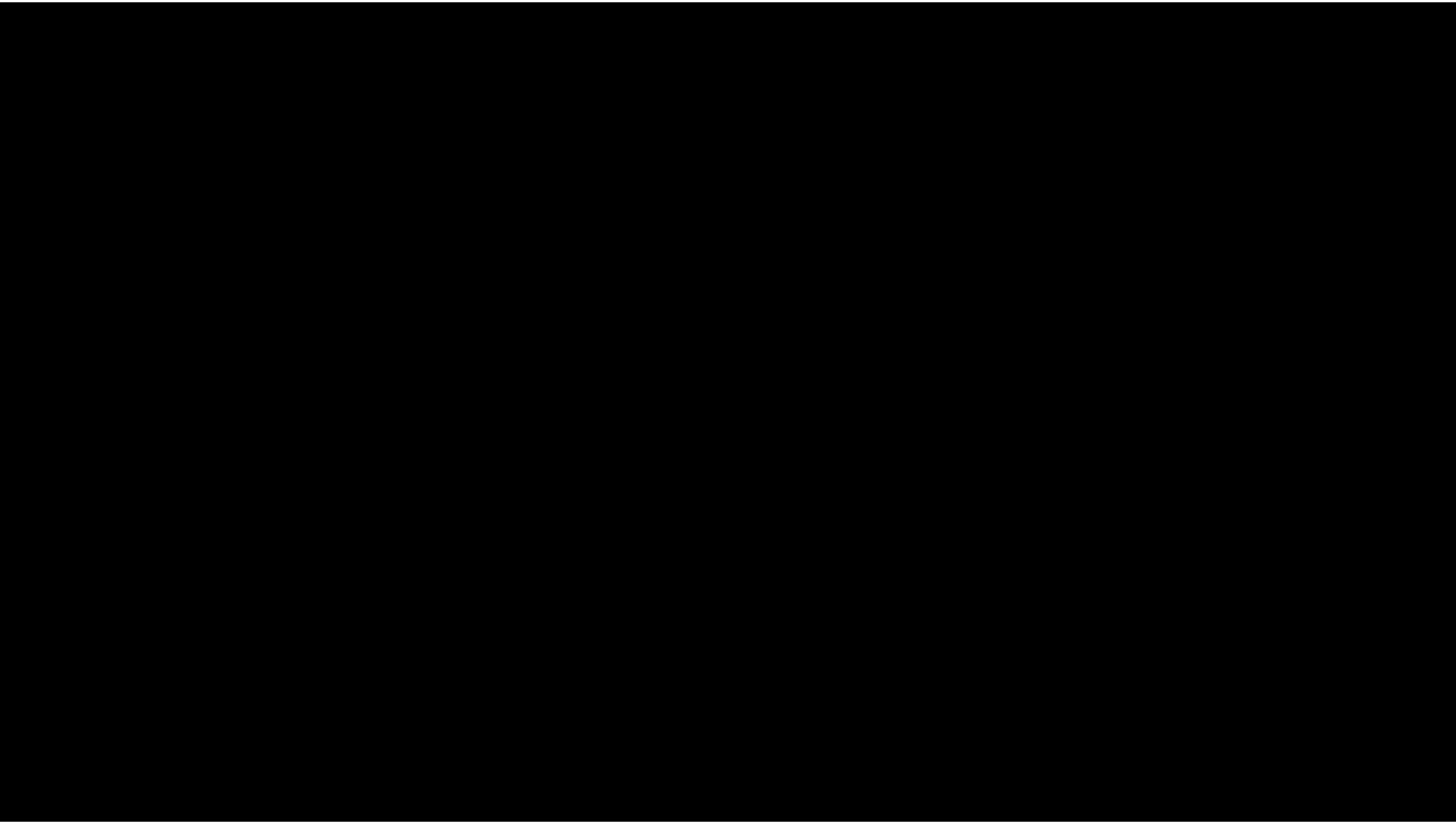




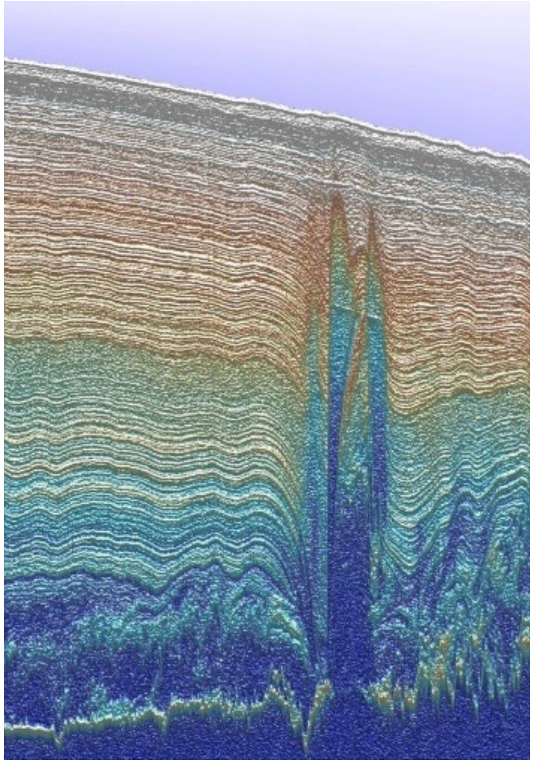

Relative Echo Power (dB)
0
25
50
75
100
Radar data collected by NASA's Operation
the Center for the Remote Sensing of Ice
Data ID: 20120507_03_005 - 2012
Visualization by /u/Dr_Sp
400
500
600
700
800
Distance (km)
NASA

Greenland's age structure from isochrones



The Age Equation

How does age evolve?



The Age Equation

How does age evolve?

We treat age as a scalar field

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Lagrangian coordinate system
(moves with the ice as it flows)

Eulerian coordinate system
(stays stationary in space)

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$$\frac{DA}{Dt} = 1$$

Eulerian coordinate system
(stays stationary in space)

The Age Equation

How does age evolve?

We treat age as a scalar field

Lagrangian coordinate system
(moves with the ice as it flows)

$$\frac{DA}{Dt} = 1$$

Eulerian coordinate system
(stays stationary in space)

$$\frac{\partial A}{\partial t} + \boldsymbol{u} \cdot \boldsymbol{\nabla} A = 1$$

The Age Equation

How does age evolve?

We treat age as a scalar field

In 1D

$$\frac{\partial A}{\partial t} + w\frac{\partial A}{\partial z} = 1$$

The Age Equation

How does age evolve?

We treat age as a scalar field

In 1D

$$\frac{\partial A}{\partial t} + w\frac{\partial A}{\partial z} = 1$$

In 1D, in steady state

$$\frac{\partial A}{\partial z} = \frac{1}{w}$$

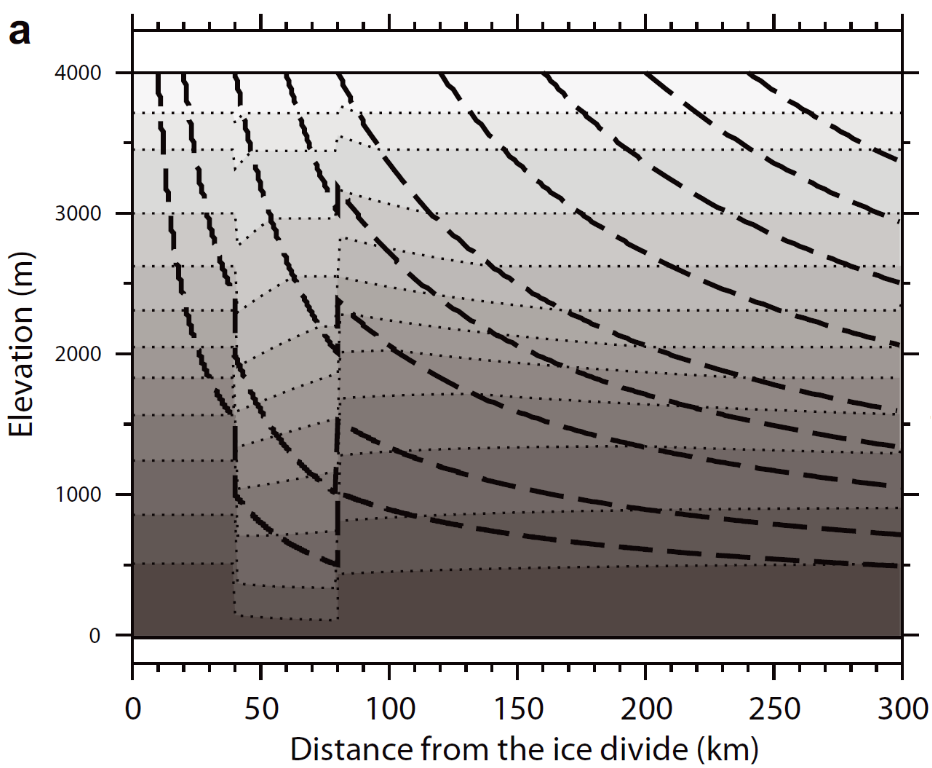
$$A(z = H) = 0$$

Solve this in the same way as we solved the heat equation

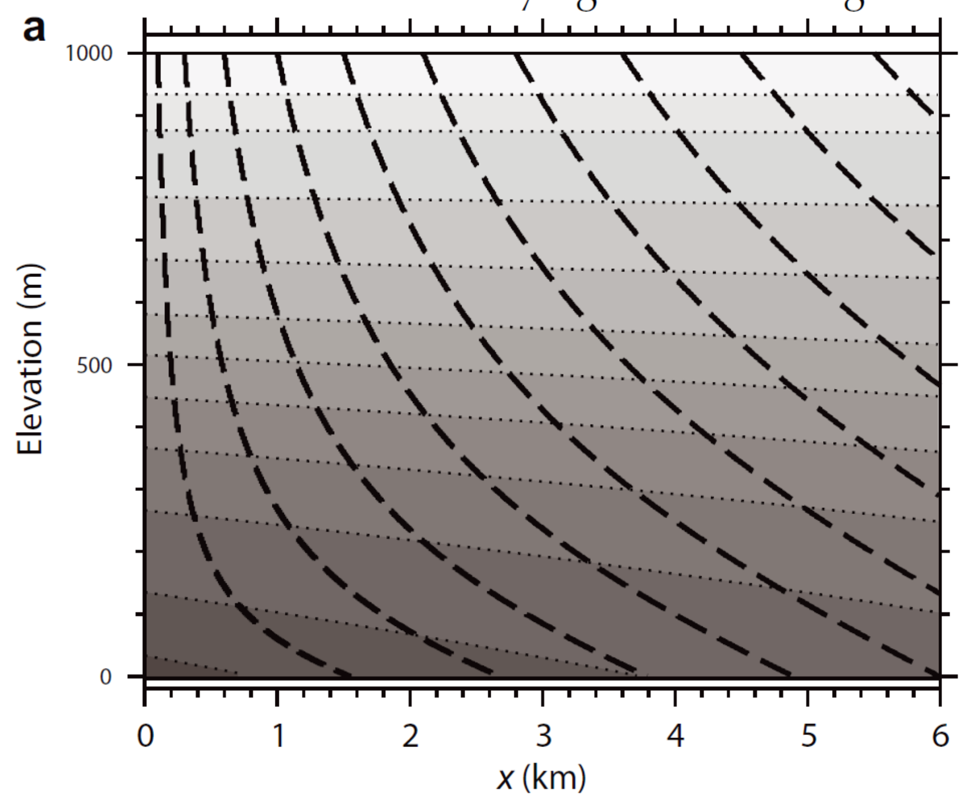
```
def age(p = 3, a_meperyear = 0.1):
    # time domain
    dt_years = 5                           # time step in years
    seconds_per_year = 365*24*60*60        # approximate number of seconds in year
    dt = dt_years*seconds_per_year         # time step in seconds
    time_total_years = 6e4                    # total length of the simulation in years
    T = time_total_years*seconds_per_year; # total length of the simulation in seconds
    time = np.linspace(0,T,round(T/dt))  # the time grid, units [years]

    # space domain
    grid_spacing = 10                            # grid spacing, units [m]
    ice_thickness = 753;                           # The max depth of hte Roosevelt Age depth profile
    depth = np.linspace(0,ice_thickness,round(ice_thickness/grid_spacing))  # spatial grid, units [m]

    # vertical velocity
    accumulation_rate = a_mperyear/seconds_per_year
    vertical_velocity = -accumulation_rate*(1-(p+2)/(p+1)*(depth/ice_thickness) + 1/(1+p) *(depth/ice_thickness)**(p+2))

    # initial conditionon age
    Age = np.zeros((time.size,depth.size))

    # main loop
    for timestep in np.arange(1,time.size):
        Age[timestep,1:] = Age[timestep-1,1:]  + dt * \
            ((vertical_velocity[1:] + vertical_velocity[:-1])/2   * \
            (Age[timestep-1,1:]-Age[timestep-1,:-1])/grid_spacing + 1 )

    # return values
    Age_years = Age/seconds_per_year
    return Age_years, time, depth

# run the model
Age, time, depth = age(a_mperyear=0.2, p = 2)
```

Theoretical isochrones in 2D

Effect of increased sliding (Weertman effect).



Effect of varying basal melting.

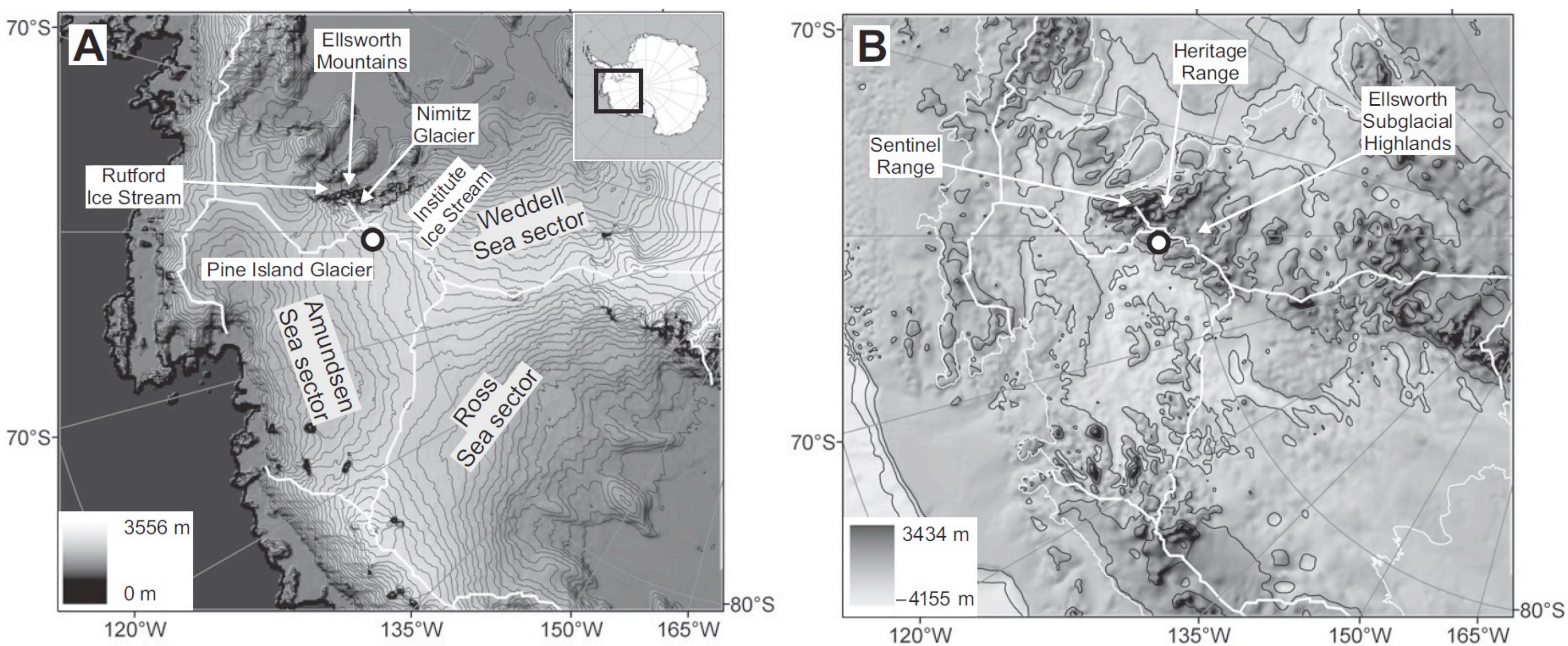


Parrenin and Hindmarsh (2007)

Qualitative interpretations of radar-observed isochrones

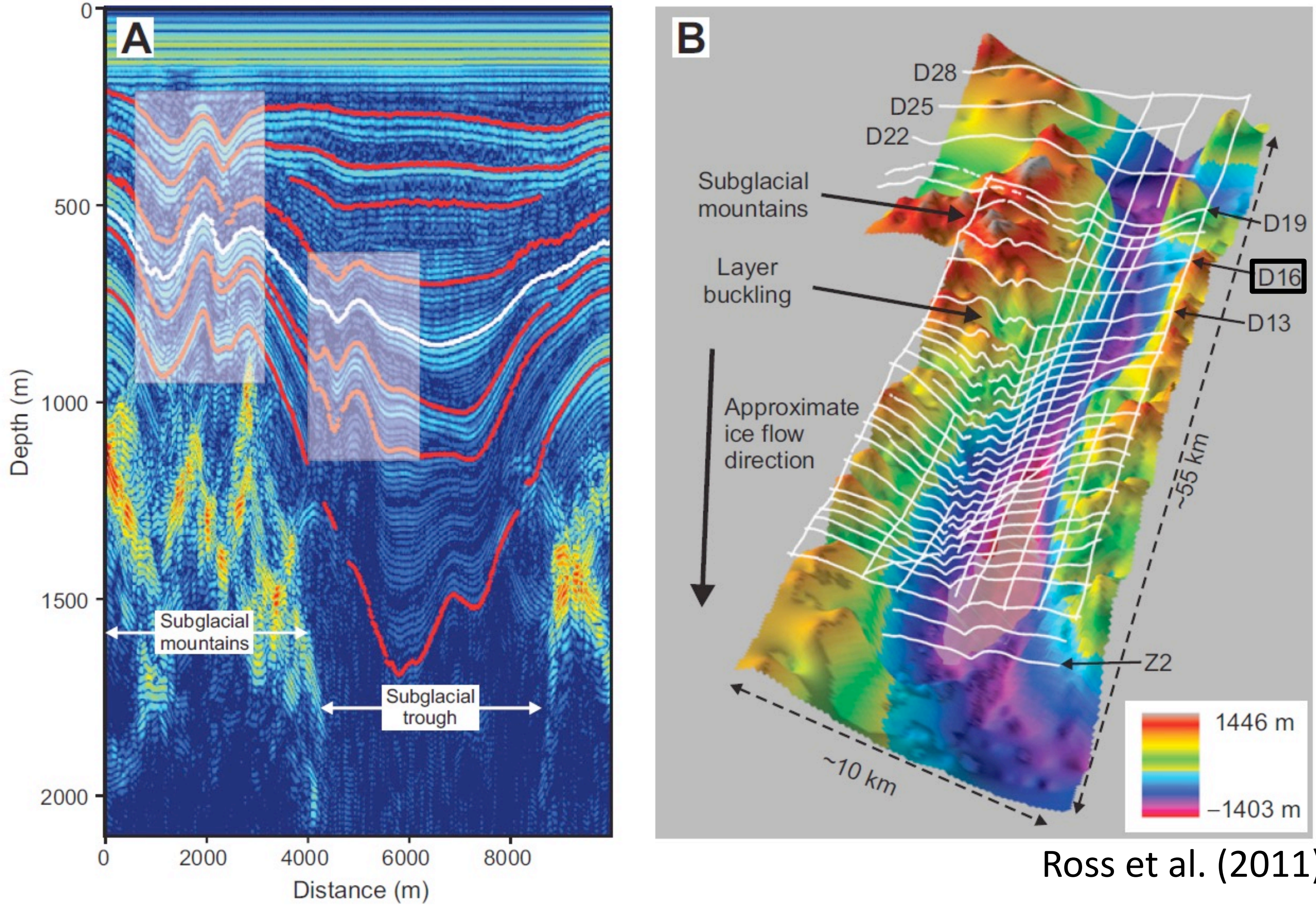
Holocene stability of the Amundsen-Weddell ice divide, West Antarctica

N. Ross[1], M.J. Siegert[1], J. Woodward[2], A.M. Smith[3], H.F.J. Corr[3], M.J. Bentley[4], R.C.A. Hindmarsh[3], E.C. King[3], and A. Rivera[5]



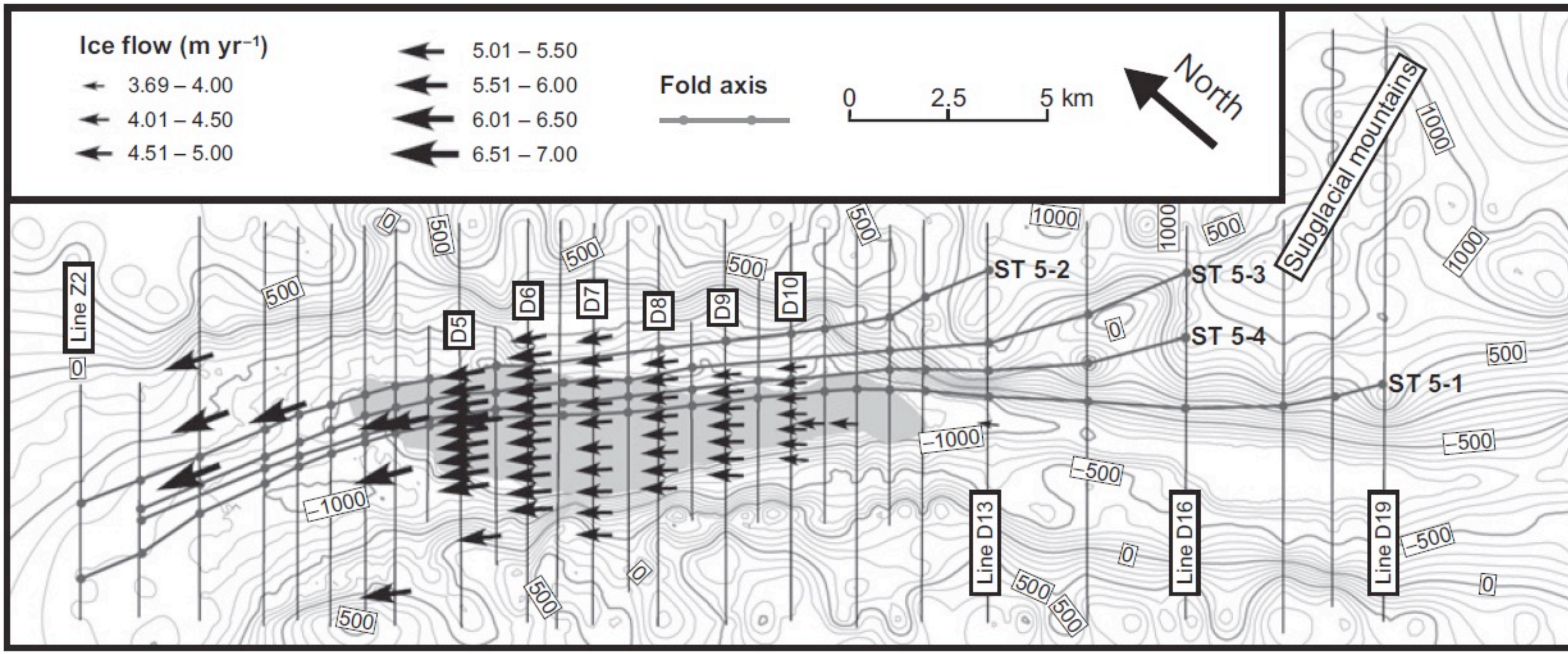
Ross et al. (2011)

Qualitative interpretations of radar-observed isochrones



Ross et al. (2011)

Qualitative interpretations of radar-observed isochrones



“ The internal layering around Ellsworth Subglacial Lake indicates that the configuration of ice flow in this sector of the interior WAIS has been stable for ~7000 yr. ”

Ross et al. (2010)

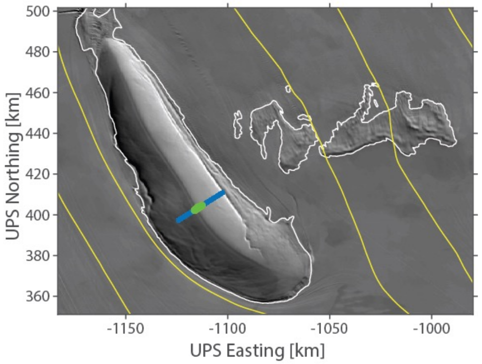
Quantitative analysis of radar-observed isochrones

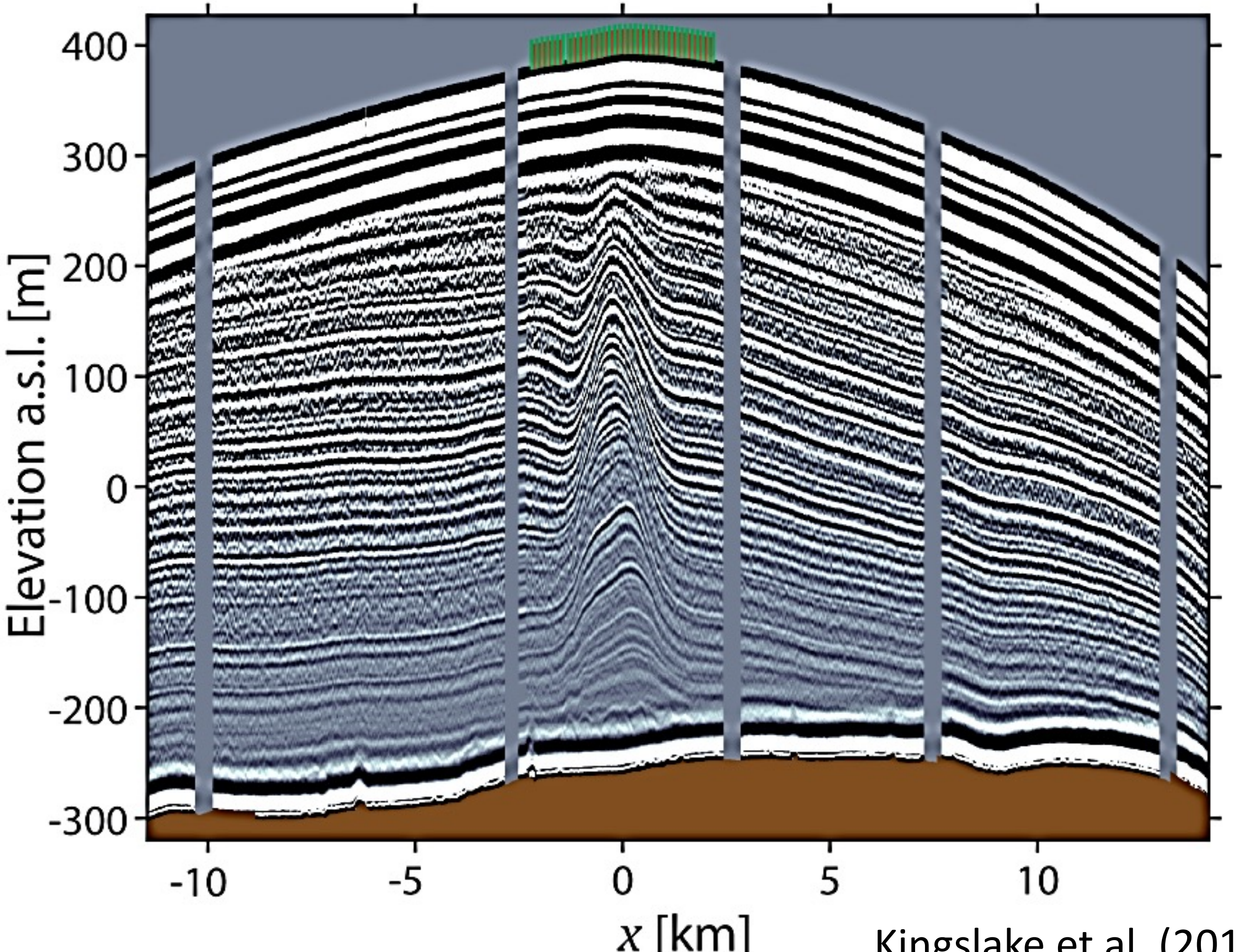
Ice-flow reorganization in West Antarctica 2.5 kyr ago dated using radar-derived englacial flow velocities

Jonathan Kingslake[1,2], Carlos Martín[1], Robert J. Arthern[1], Hugh F. J. Corr[1], and Edward C. King[1]

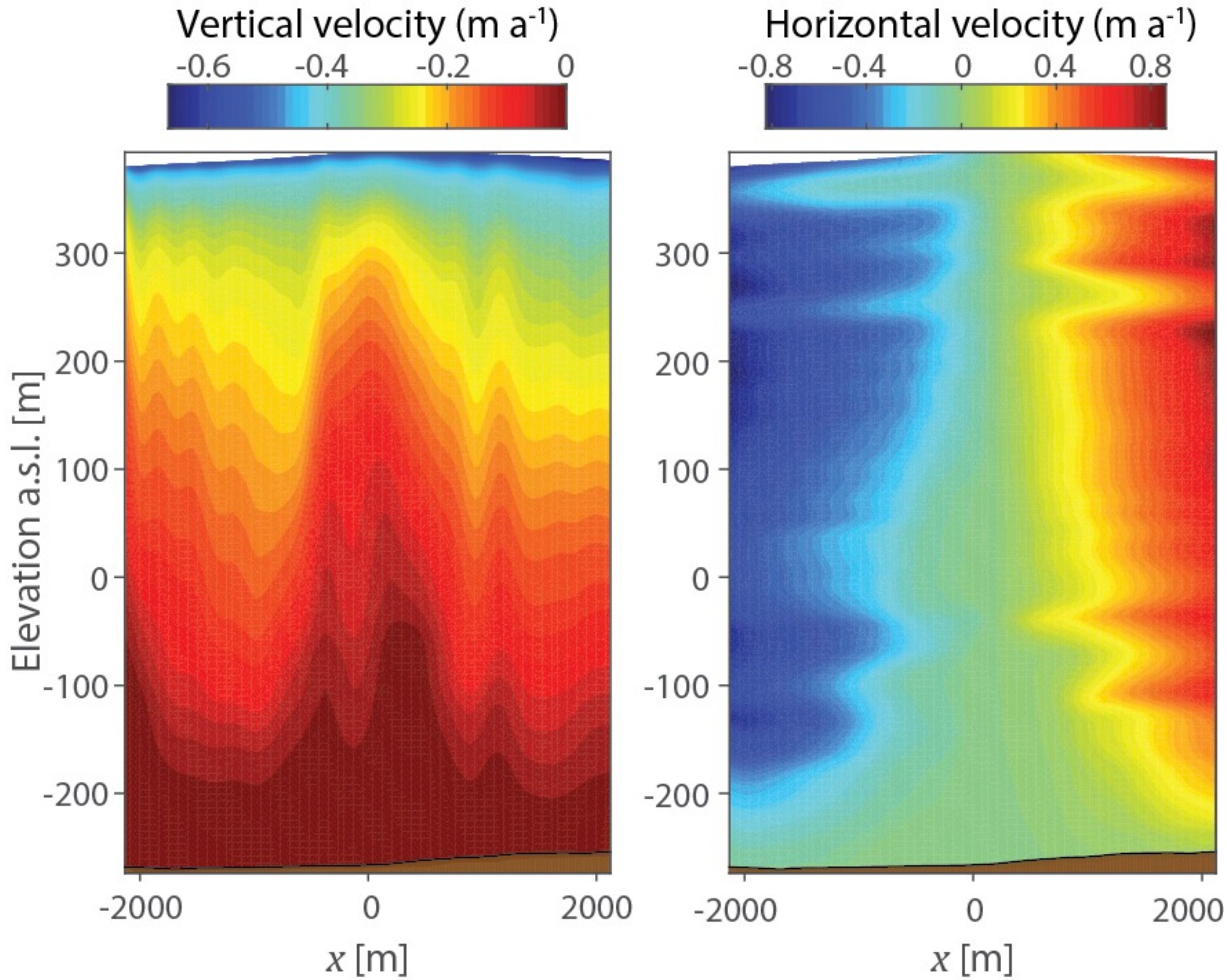
Kingslake et al. (2016)

Quantitative analysis of radar-observed isochrones

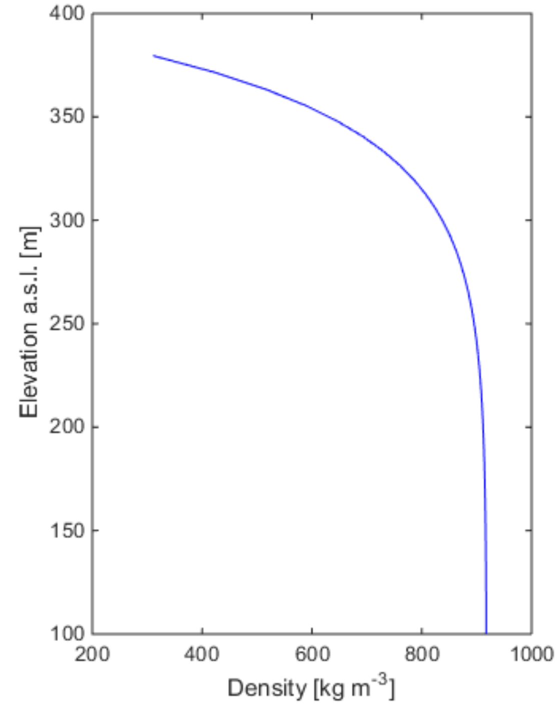




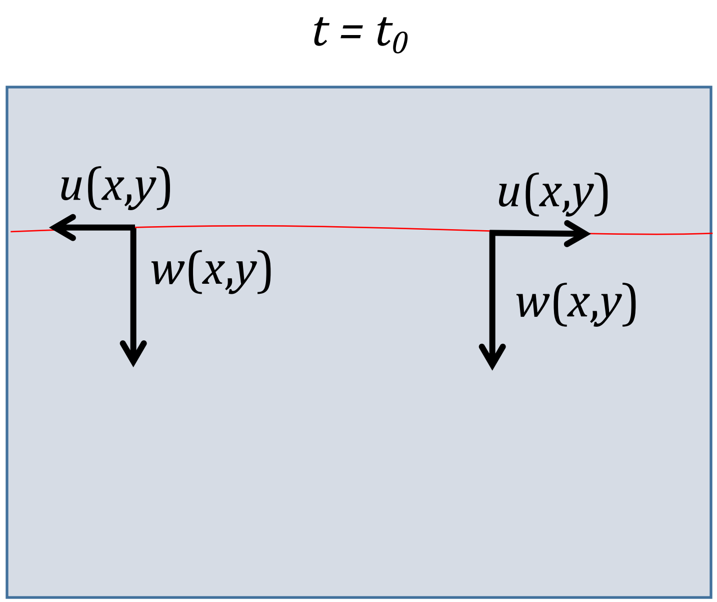
Kingslake et al. (2016)

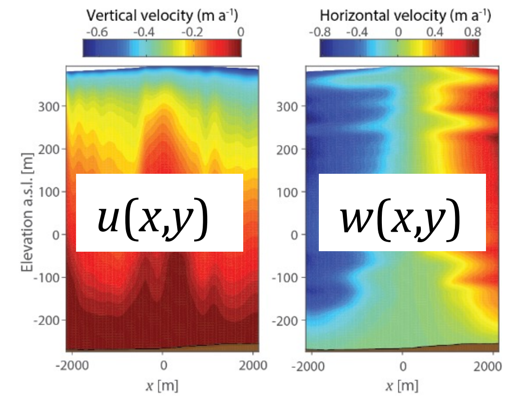


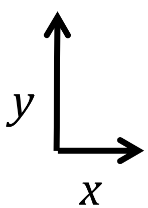
Density profile



Quantitative analysis of radar-observed isochrones







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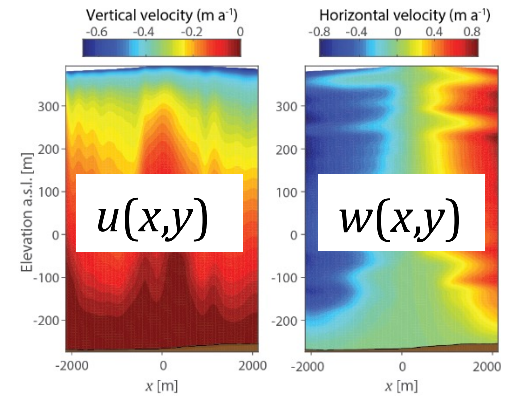

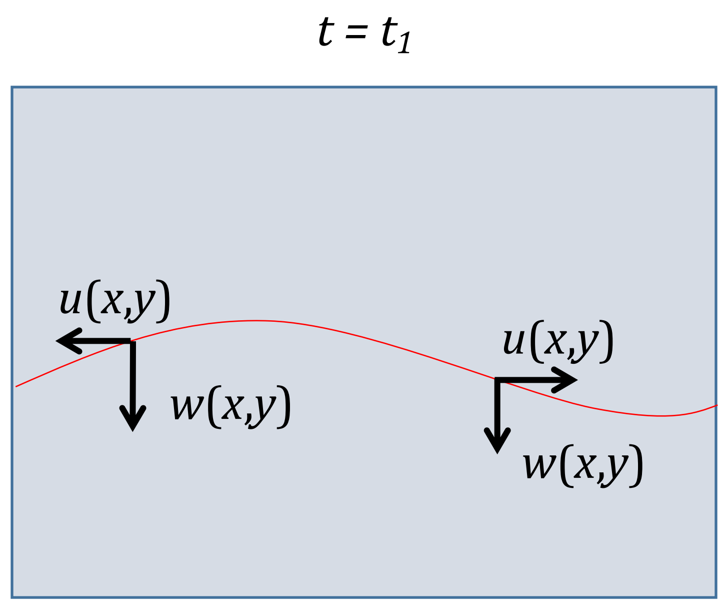

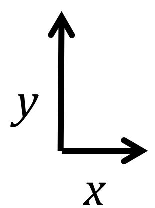

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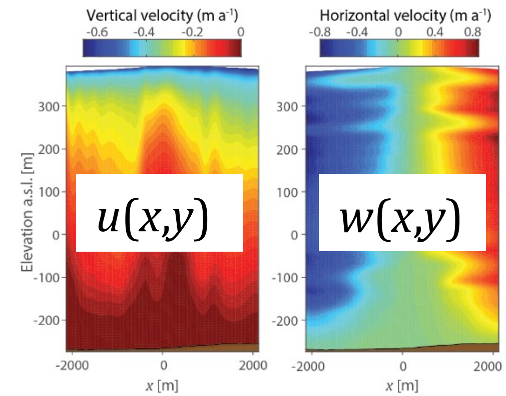
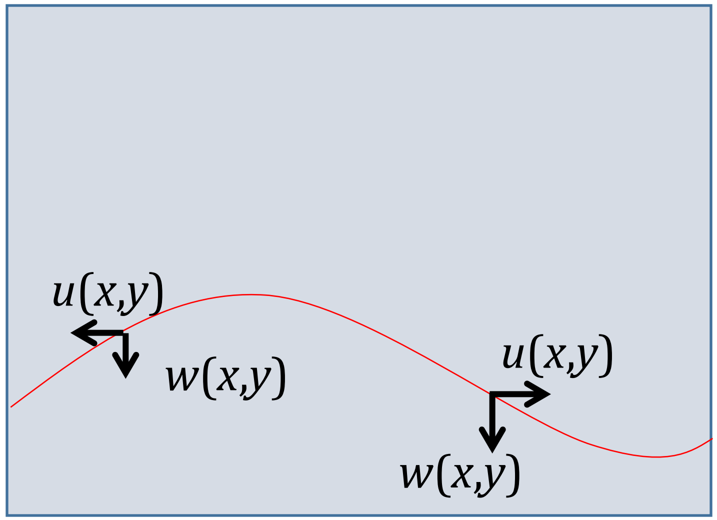
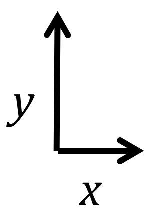
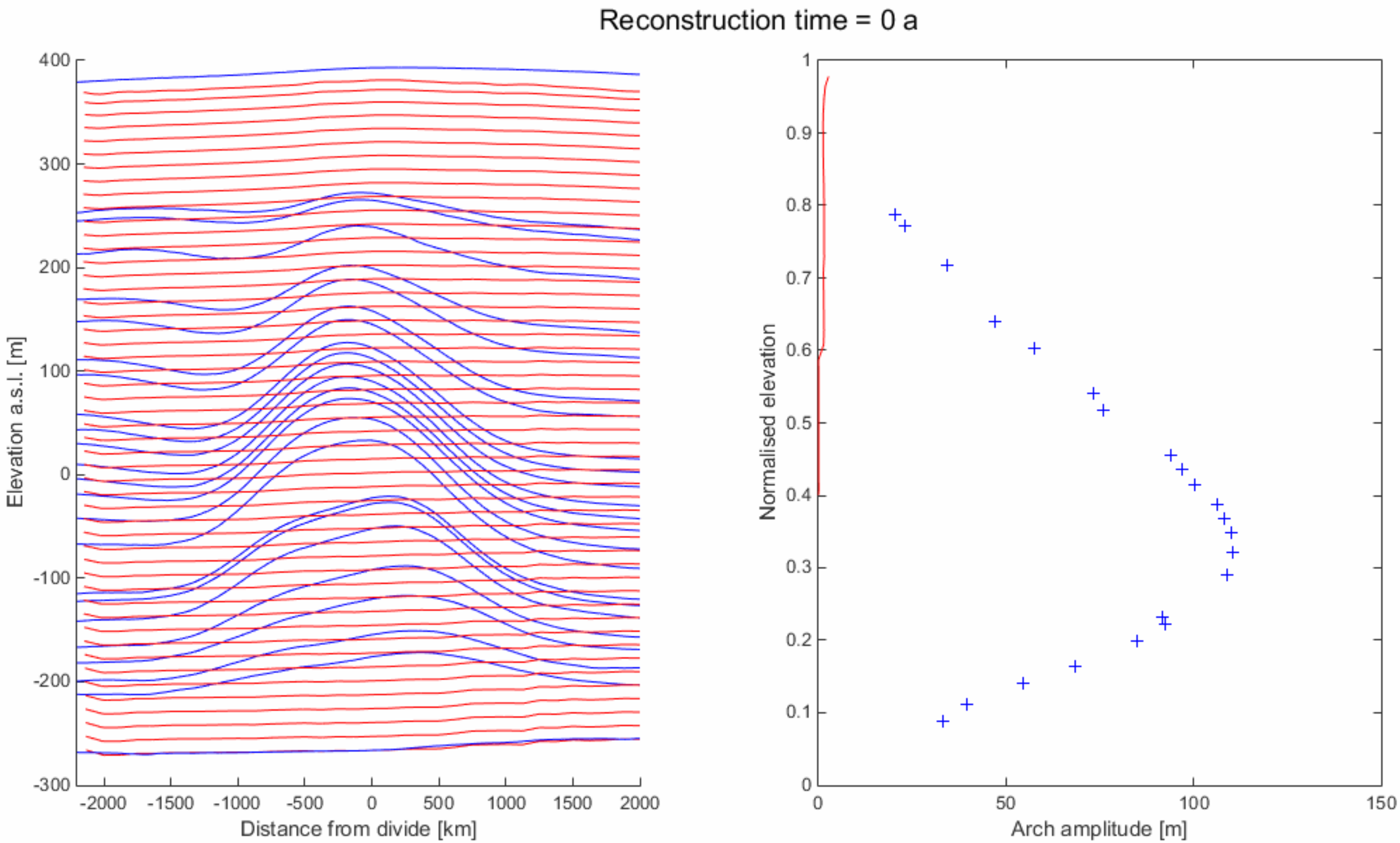


$t = t_2$

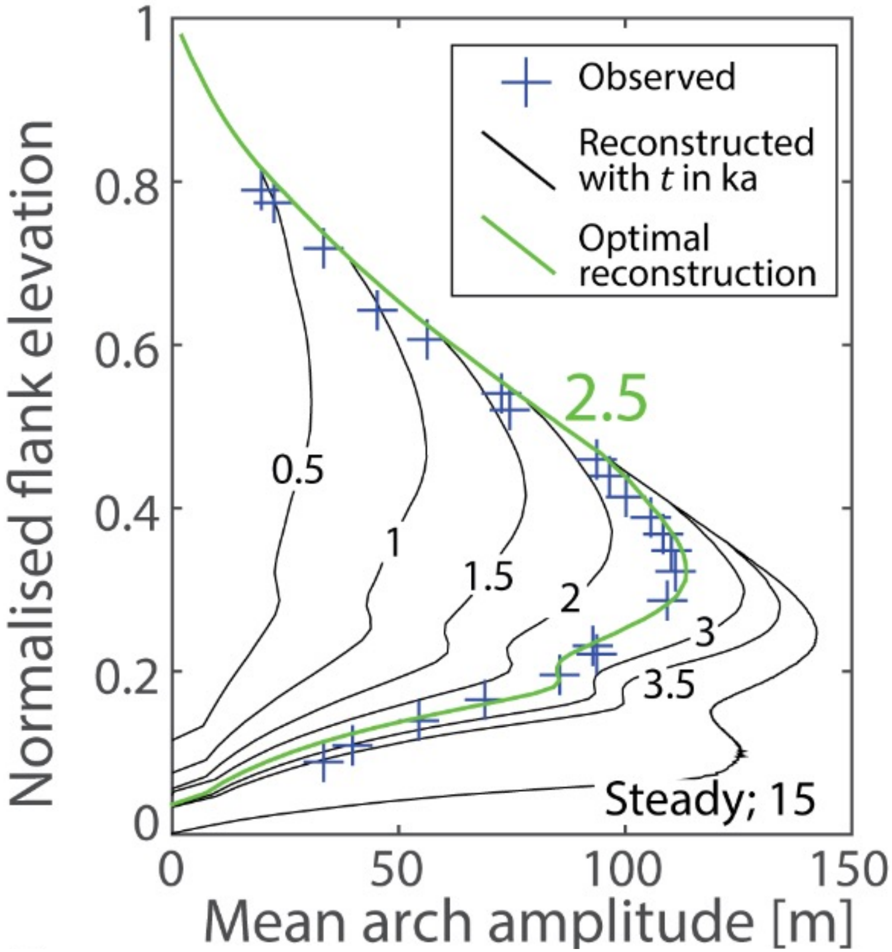


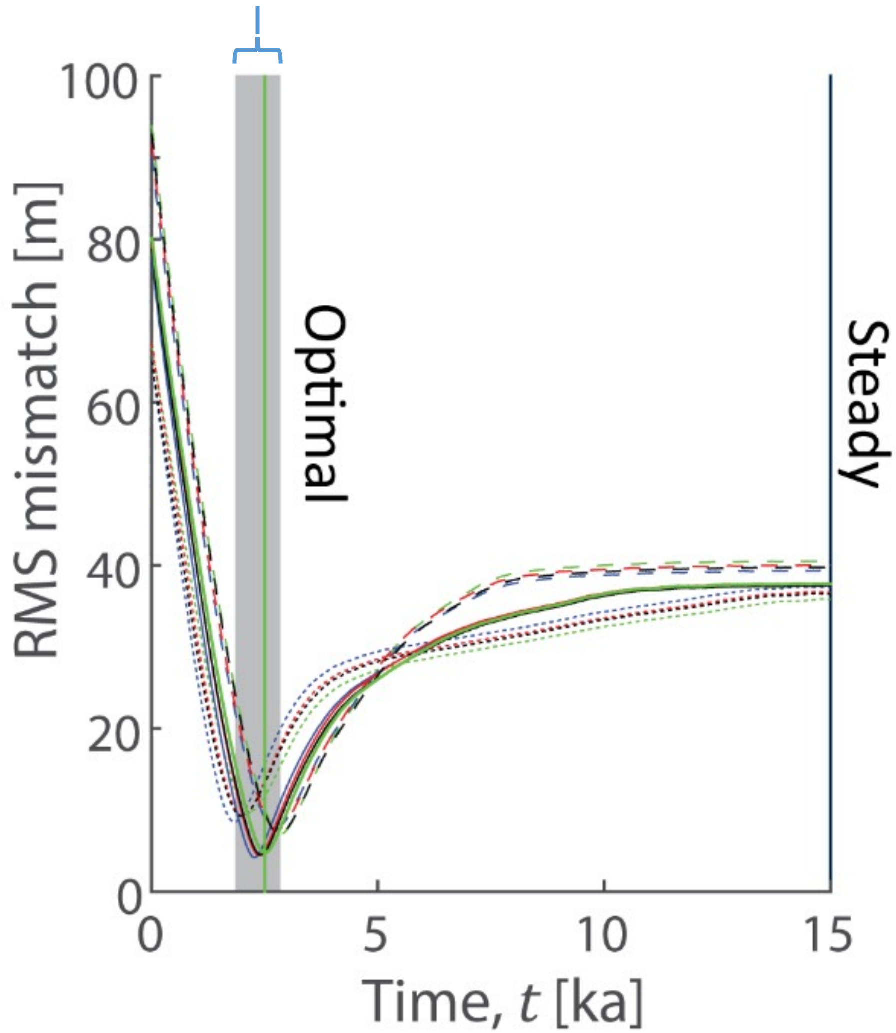




Reconstruction time = 0 a
Elevation a.s.l. [m]
400
300
200
100
0
-100
-200
-300
-2000
-1500
-1000
-500
0
500
1000
1500
2000
Distance from divide [km]
Normalised elevation
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
50
100
150
Arch amplitude [m]

1.8-2.9 ka BP


Observed
Reconstructed with t in ka
Optimal reconstruction
2.5
0.5
1
1.5
2
3
3.5
Steady; 15
Normalised flank elevation
Mean arch amplitude [m]
0
50
100
150
0
0.2
0.4
0.6
0.8
1


Optimal
Steady
RMS mismatch [m]
Time, t [ka]
0
5
10
15
0
20
40
60
80
100

Ice core dating

Climate of the Past

The EDC3 chronology for the EPICA Dome C ice core

F. Parrenin[1], J.-M. Barnola[1], J. Beer[2], T. Blunier[3], E. Castellano[4], J. Chappellaz[1], G. Dreyfus[5], H. Fischer[6], S. Fujita[7], J. Jouzel[5], K. Kawamura[8], B. Lemieux-Dudon[1], L. Loulergue[1], V. Masson-Delmotte[5], B. Narcisi[9], J.-R. Petit[1], G. Raisbeck[10], D. Raynaud[1], U. Ruth[6], J. Schwander[3], M. Severi[4], R. Spahni[3], J. P. Steffensen[11], A. Svensson[11], R. Udisti[4], C. Waelbroeck[1], and E. Wolff[12]

age marker	depth (m)	age (kyr BP)	error bar (kyr BP)
Krakatua	8.35	0.066	0.001
Tambora	12.34	0.134	0.001
Huaynaputina	23.20	0.349	0.001
Kuwae	29.27	0.492	0.005
El Chichon?	38.12	0.691	0.005
Unidentified	39.22	0.722	0.006
Unknown	41.52	0.779	0.006
^{10}Be/^{14}C	107.83	2.716	0.05
^{10}Be/^{14}C	181.12	5.28	0.05
YD/Holocene	361.5	11.65	0.18
PB/BO	427.2	15.0	0.24
^{10}Be peak	740.08	41.2	1
Mt Berlin erupt.	1265.10	92.5	2
term. II	1698.91	130.1	2
air content	1082.34	70.6	4
air content	1484.59	109.4	4
air content	1838.09	147.6	4
air content	2019.73	185.3	4
air content	2230.71	227.3	4
air content	2387.95	270.4	4
air content	2503.74	313.4	4
air content	2620.23	352.4	4
air content	2692.69	390.5	4
air content	2789.58	431.4	4
^{18}O$_{atm}$	2714.32	398.4	6

$$\mathrm{age}(z) = \int_0^z \frac{1}{T(z')\,a(z')}\,dz'.$$

This contains all the ice-flow physics

This contains the climate history

Parrenin et al. (2007)

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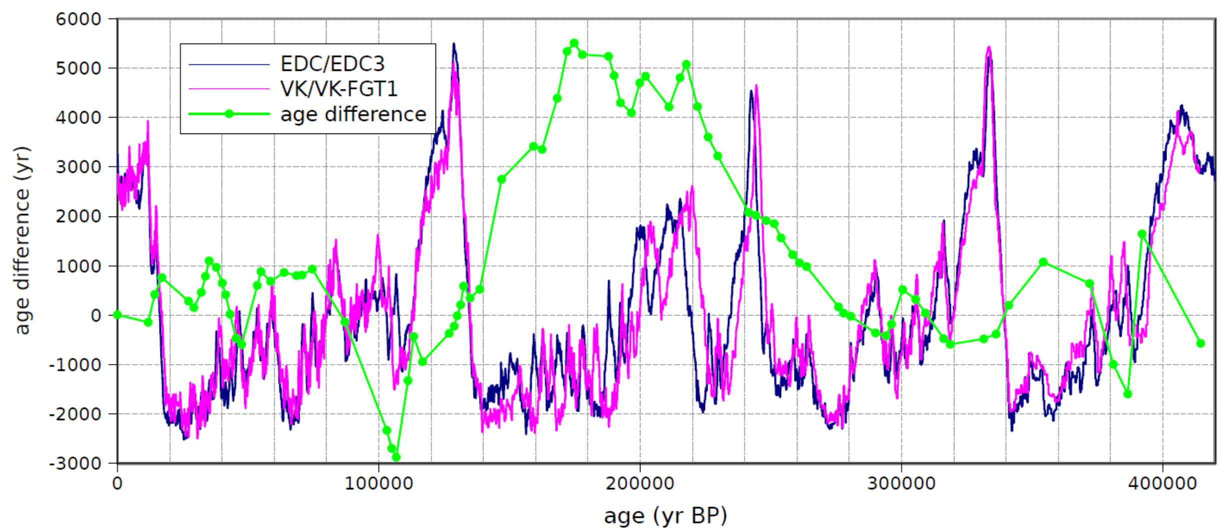

Parrenin et al. (2007)

Summary

- Isochrones can be observed with radar
- Isochrones are age contours.
- Age can be treated as a scalar field, like temperature.
- Age structure is determined by present-day and past accumulation and ice flow.
- Many studies try to understand past accumulation and flow by observing present-day age structure.

References

- Kingslake, Jonathan, Carlos Martín, Robert J. Arthern, Hugh FJ Corr, and Edward C. King. "Ice-flow reorganization in West Antarctica 2.5 kyr ago dated using radar-derived englacial flow velocities." *Geophysical Research Letters* 43, no. 17 (2016): 9103-9112.
- Ross, N., Siegert, M.J., Woodward, J., Smith, A.M., Corr, H.F., Bentley, M.J., Hindmarsh, R.C., King, E.C. and Rivera, A., 2011. Holocene stability of the Amundsen-Weddell ice divide, West Antarctica. *Geology*, *39*(10), pp.935-938.
- Parrenin, Frédéric, J-M. Barnola, J. Beer, Thomas Blunier, E. Castellano, J. Chappellaz, G. Dreyfus et al. "The EDC3 chronology for the EPICA Dome C ice core." *Climate of the Past* 3 (2007): 485-497.
- Parrenin, F. and Hindmarsh, R., 2007. Influence of a non-uniform velocity field on isochrone geometry along a steady flowline of an ice sheet. *Journal of Glaciology*, *53*(183), pp.612-622.