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Brief communication: widespread potential for seawater infiltration on Antarctic ice shelves

Sue Cook et al.

Correspondence to: Sue Cook (sue.cook@utas.edu.au)

Ice Shelf	Bedmap2	CryoSat-2	GLAS	RAMP	REMA	Mean	STD
Abbot	45.0	47.1	50.0	52.1	47.6	48.4	2.7
Amery	0.4	1.7	7.5	8.0	2.0	3.9	3.6
Bach	15.5	22.5	27.6	25.4	19.5	22.1	4.8
Cook	4.2	1.5	0.0	38.0	10.9	10.9	15.7
Crosson	60.0	69.4	74.3	66.9	79.6	70.0	7.4
Dibble	1.7	9.5	25.7	20.7	9.4	13.4	9.7
Dotson	14.0	24.0	24.6	15.3	24.4	20.5	5.3
Drygalski	20.1	17.4	0.0	37.2	23.4	19.6	13.3
Edward VIII Bay	17.3	10.6	21.8	29.5	24.3	20.7	7.1
Filchner-Ronne	0.8	0.4	1.9	1.1	0.3	0.9	0.7
George VI	29.3	33.0	34.7	41.1	36.0	34.8	4.3
Getz	8.2	11.2	16.3	15.8	14.5	13.2	3.4
Jelbartisen & Fimbul	7.3	6.9	17.3	12.6	8.3	10.5	4.4
Larsen C-D	21.9	20.9	22.8	29.0	25.5	24.0	3.3
Mertz	3.8	5.2	0.2	13.3	7.1	5.9	4.8
Moscow University	0.1	1.0	2.0	1.9	0.6	1.1	0.8
Nickerson	45.2	45.7	0.8	54.3	49.7	39.1	21.7
Pine Island	7.5	10.4	20.3	18.6	17.3	14.8	5.5
Prince Harald	55.4	50.8	65.0	68.5	55.6	59.0	7.4
Princess Ragnhild	16.2	15.9	26.8	24.2	15.9	19.8	5.3
Rennick	9.7	9.2	0.0	30.0	17.3	13.3	11.2
Riiser-Larsen & Brunt	31.4	29.6	38.8	38.9	34.1	34.6	4.2
Ross	2.5	2.4	0.1	2.6	2.8	2.1	1.1
Shackleton	29.1	34.9	43.1	42.4	36.7	37.2	5.8
Sulzberger	26.5	26.2	0.1	32.2	30.4	23.1	13.1
Thwaites	3.5	25.1	53.7	30.0	50.4	32.5	20.5
Totten	1.4	5.6	21.5	10.3	6.9	9.1	7.6
Venable	15.0	60.7	72.6	53.0	68.2	53.9	23.0
West	18.4	18.8	41.9	33.0	20.4	26.5	10.5
Wilkins	69.6	82.0	73.2	88.0	73.8	77.3	7.5
All shelves	**8.7**	**9.0**	**11.0**	**12.3**	**10.1**	**10.2**	**1.5**

Table S1: Percentage ice shelf areas covered by 750 kg m^{-3} brine zone, using different surface DEMs as input.

Ice Shelf	Bedmap2	CryoSat-2	GLAS	RAMP	REMA	Mean	STD
Abbot	81.5	81.8	74.1	83.8	84.7	81.2	4.2
Amery	10.1	10.3	13.8	15.0	11.6	12.2	2.2
Bach	41.7	52.6	44.2	48.1	50.3	47.4	4.4
Cook	17.7	10.5	7.0	42.7	28.2	21.2	14.5
Crosson	85.0	83.9	83.0	85.5	88.7	85.2	2.2
Dibble	19.1	22.7	53.5	38.8	27.6	32.3	14.0
Dotson	42.7	54.1	55.2	40.8	54.5	49.5	7.1
Drygalski	40.4	33.9	0.0	55.1	44.5	34.8	20.9
Edward VIII Bay	41.1	28.2	32.8	44.4	43.0	37.9	7.1
Filchner-Ronne	2.4	2.2	3.4	2.8	1.9	2.5	0.6
George VI	50.4	54.8	53.0	63.6	56.9	55.7	5.0
Getz	33.3	43.8	42.8	42.7	45.9	41.7	4.9
Jelbartisen & Fimbul	37.3	37.2	43.9	42.3	37.3	39.6	3.2
Larsen C-D	35.7	34.9	36.0	43.9	40.3	38.2	3.9
Mertz	23.1	18.9	25.9	29.1	28.0	25.0	4.1
Moscow University	0.5	1.8	6.3	3.0	1.9	2.7	2.2
Nickerson	72.1	70.4	31.2	77.4	74.7	65.2	19.2
Pine Island	39.2	58.9	60.7	54.1	67.0	56.0	10.4
Prince Harald	85.3	81.3	89.2	89.4	84.8	86.0	3.4
Princess Ragnhild	40.5	41.3	49.0	46.3	40.1	43.5	4.0
Rennick	28.0	26.5	0.0	43.1	36.1	26.8	16.4
Riiser-Larsen & Brunt	65.6	64.7	67.1	70.0	63.0	66.1	2.6
Ross	12.1	12.1	6.1	12.1	11.8	10.8	2.6
Shackleton	69.9	69.4	74.1	75.7	71.2	72.1	2.7
Sulzberger	52.7	54.7	37.8	62.2	58.5	53.2	9.3
Thwaites	45.9	53.6	81.1	63.3	84.8	65.7	16.9
Totten	8.1	11.2	32.9	19.3	17.6	17.8	9.6
Venable	93.9	93.5	94.5	86.2	99.0	93.4	4.6
West	39.6	36.2	58.4	48.5	40.9	44.7	8.9
Wilkins	94.1	94.6	85.9	98.8	96.6	94.0	4.9
Total	**21.7**	**22.0**	**21.3**	**24.4**	**22.6**	**22.4**	**1.2**

Table S2: Percentage ice shelf areas covered by 800 kg m^{-3} brine zone, using different surface DEMs as input.

Ice Shelf	Bedmap2	CryoSat-2	GLAS	RAMP	REMA	Mean	STD
Abbot	95.5	92.1	93.2	93.2	96.7	94.2	1.9
Amery	20.2	20.7	24.0	24.0	21.5	22.1	1.8
Bach	57.2	65.1	58.4	58.4	69.1	61.6	5.2
Cook	35.5	23.2	46.5	46.5	45.9	39.5	10.3
Crosson	89.6	90.8	89.2	89.2	93.2	90.4	1.7
Dibble	28.6	31.0	49.0	48.1	40.1	39.4	9.4
Dotson	72.1	79.5	60.8	60.8	81.3	70.9	9.9
Drygalski	50.2	47.1	65.7	65.7	56.5	57.0	8.6
Edward VIII Bay	62.1	42.2	58.6	58.6	63.7	57.0	8.6
Filchner-Ronne	8.3	8.0	8.3	8.3	6.7	7.9	0.7
George VI	73.9	78.2	82.3	82.3	81.2	79.6	3.6
Getz	59.8	67.7	65.0	65.0	70.1	65.5	3.8
Jelbartisen & Fimbul	63.6	62.9	66.0	65.6	64.2	64.5	1.3
Larsen C-D	49.5	48.8	58.8	58.8	53.0	53.8	4.9
Mertz	42.1	34.1	49.7	49.7	43.1	43.7	6.4
Moscow University	1.5	2.4	4.8	4.8	3.9	3.5	1.4
Nickerson	82.8	80.6	94.7	94.7	86.1	87.8	6.6
Pine Island	67.2	77.5	77.8	77.8	83.5	76.8	5.9
Prince Harald	95.7	93.1	97.6	97.6	95.2	95.8	1.9
Princess Ragnhild	60.9	62.5	68.1	68.1	60.8	64.1	3.7
Rennick	39.3	35.7	49.5	49.5	44.8	43.8	6.1
Riiser-Larsen & Brunt	87.1	86.0	89.5	89.5	85.6	87.5	1.9
Ross	40.3	43.5	40.1	40.1	40.7	41.0	1.4
Shackleton	82.2	81.3	85.8	85.8	84.2	83.9	2.1
Sulzberger	68.3	69.3	77.8	77.8	74.2	73.5	4.5
Thwaites	80.7	82.8	88.0	88.0	95.4	87.0	5.7
Totten	17.5	19.2	28.8	28.8	27.1	24.3	5.5
Venable	96.8	95.7	89.3	89.3	99.6	94.2	4.6
West	56.8	54.3	64.5	64.5	60.0	60.0	4.6
Wilkins	96.0	96.4	99.2	99.2	98.1	97.8	1.5
Total	**39.3**	**40.4**	**41.2**	**41.2**	**40.1**	**40.5**	**1.0**

Table S3: Percentage ice shelf areas covered by 830 kg m^{-3} brine zone, using different surface DEMs as input.

Identifier	Shelf	Lat (°)	Lon (°)	Brine	Reference
J-9	Ross	-82.375	-168.626	N	(Zotikov et al., 1980)
J9	Ross	-78.367	179.85	N	(Herron and Langway, 1979)
T340	Ronne	-79.4	-64.5	N	(Graf et al., 1988)
B04	Ekströmisen	-70.62	-8.367	N	(Schlosser and Oerter, 2002)
B03	Ekströmisen	-70.62	-8.367	N	(Schlosser et al., 1999)
FB0198	Ekströmisen	-70.73	-8.19	N	(Schlosser and Oerter, 2002)
B15	Filchner-Ronne	-77.935	-55.9361	N	(Graf et al., 1994)
B13	Filchner-Ronne	-76.9811	-52.2678	N	(Graf et al., 1994)
Little America V	Ross	-78.167	-162.22	N	(Gow, 1968)
Lazarev	Lazarev	-69.967	12.92	Y	(Dubrovin, 1960)
Base Roi Baudouin	Roi-Baudouin	-70.4314	24.3106	N	(Tongiorgi et al., 1962)
G1	Amery	-69.451	71.497	N	(Budd et al., 1982)
C-16	Ross	-81.1935	170.4978	N	(Chiang and Langway, 1978)
Q-13	Ross	-78.9568	179.9229	N	(Chiang and Langway, 1978)
R7	Brunt	-75.4	-25.5	Y	(Thomas, 1975)

Table S4: Sources for firn core data mapped in Figure 2.

Shelf	Lat	Lon	Location notes	Reference
Ross	-82.43	169.7		(Neal, 1979)
Ross	-	-	"Transition from valley glacier to ice shelf"	(Robin et al., 1970)
Larsen C	-68	-60	Near rifts in ice shelf	(Smith, 1972; Smith and Evans, 1972)
Wordie	-	-	Towards edges of shelf	(Swithinbank, 1968)
Wilkins	-	-	Map in Figure 2b	(Vaughan et al., 1993)
McMurdo	-	-	Around boreholes in Figure 2e	(Grima et al., 2016)
Brunt	-75.31	-26.7	Attributed to basal marine ice by Walford (1964) but to brine infiltration by Swithinbank (1968)	(Swithinbank, 1968; Walford, 1964)

Table S5: Sources for radar observation of brine on Antarctic ice shelves, mapped in Figure 2.

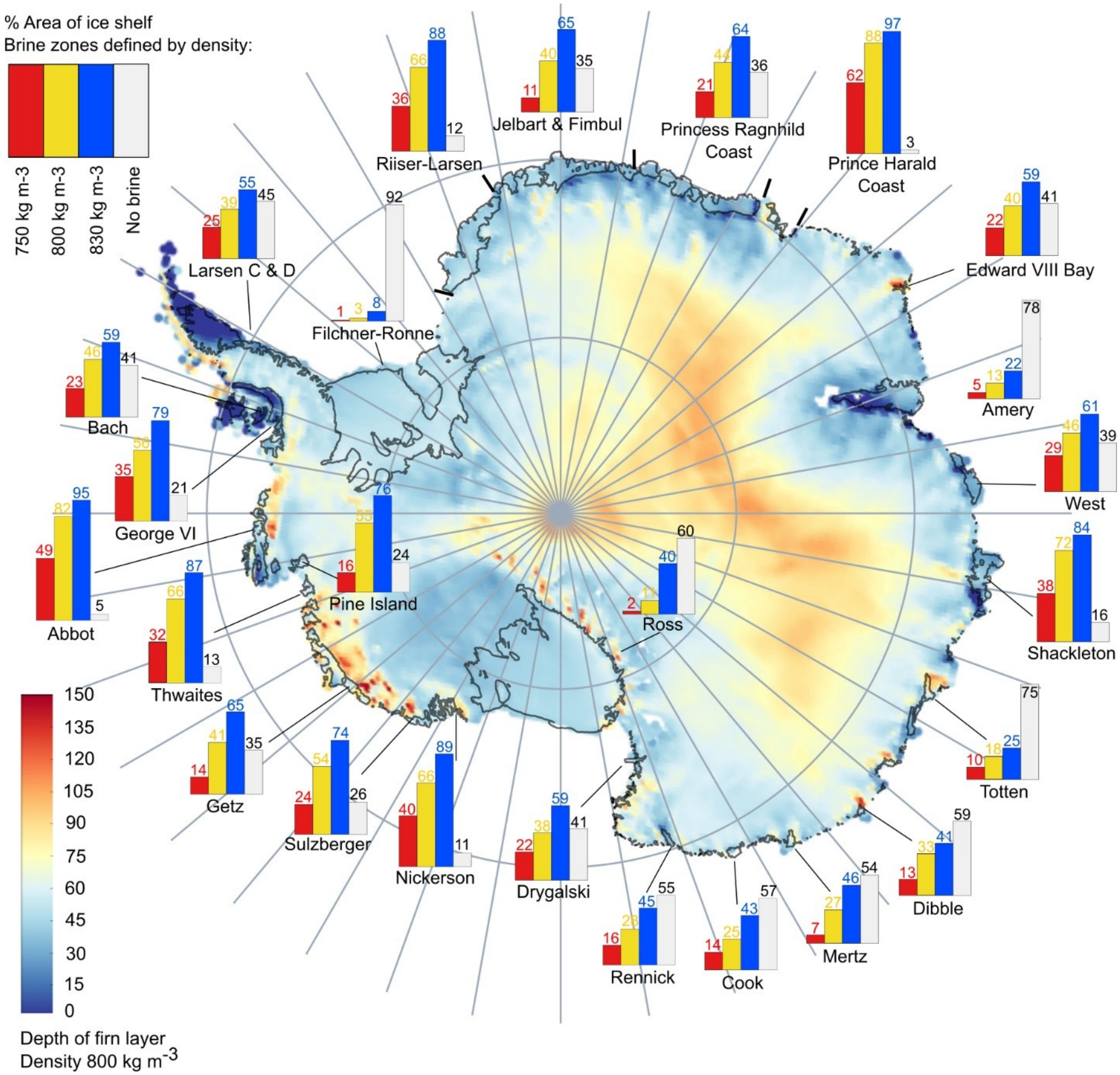

Figure S1: Depth of 800 kg m^{-3} firn layer. Data taken from firn densification model IMAU-FDM (Ligtenberg et al., 2011). Bar charts show the percentage area of selected ice shelves covered by the brine zone, defined with a threshold for firn permeability of 750 kg m^{-3} (red), 800 kg m^{-3} (yellow) and 830 kg m^{-3} (blue). Regions with particularly thick firn layers include Edward VIII Bay and Totten IS.

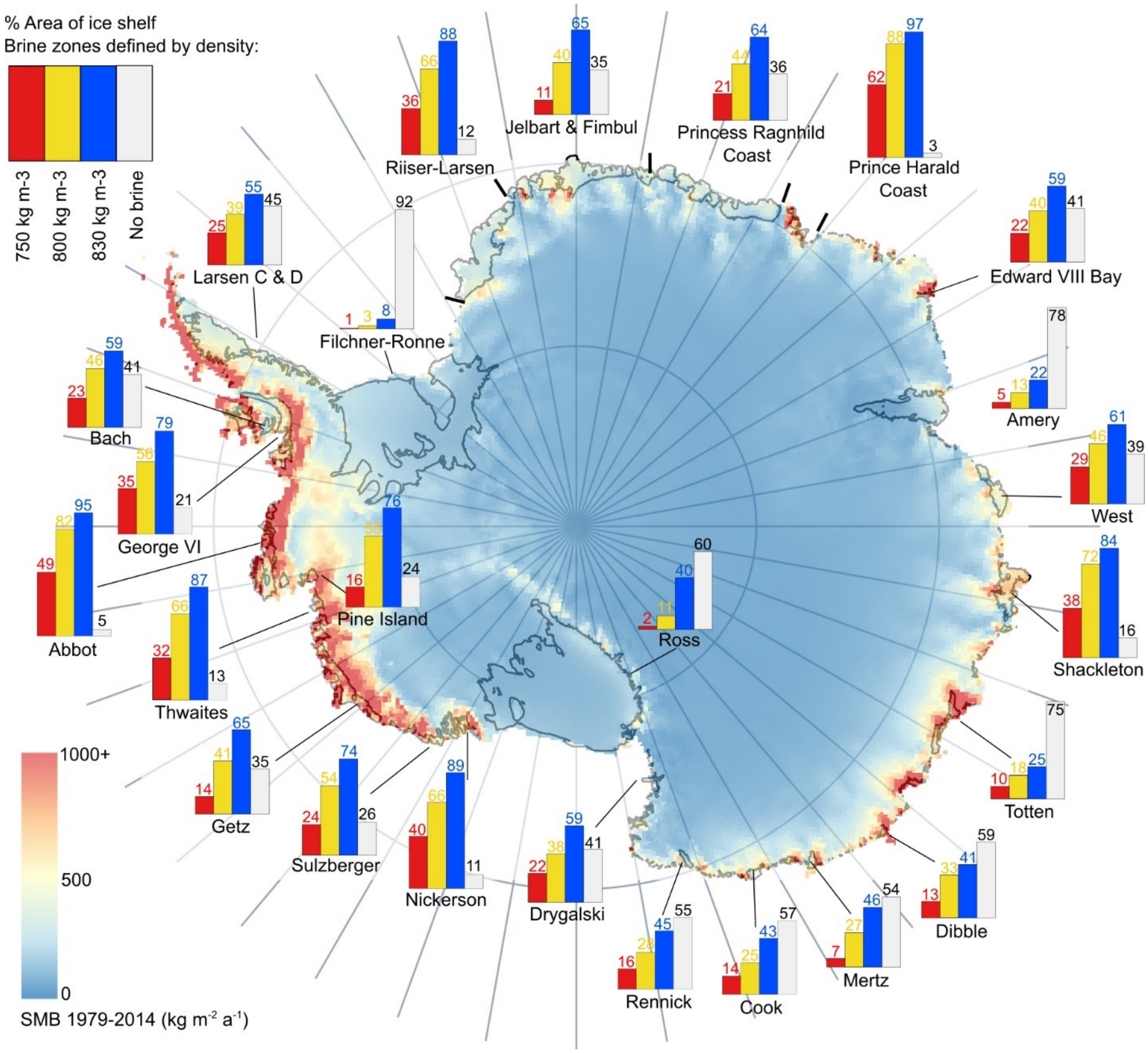

Figure S2: Surface mass balance in kg per square metre per annum (Van Wessem et al., 2014). Bar charts show the percentage area of selected ice shelves covered by the brine zone, defined with a threshold for firn permeability of 750 kg m^{-3} (red), 800 kg m^{-3} (yellow) and 830 kg m^{-3} (blue). High accumulation rates coincide with shelves with large brine zones in the West Antarctic e.g. Abbot, Bach, Sulzberger & Nickerson Ice Shelves as well as in other areas e.g. Edward VIII Bay.

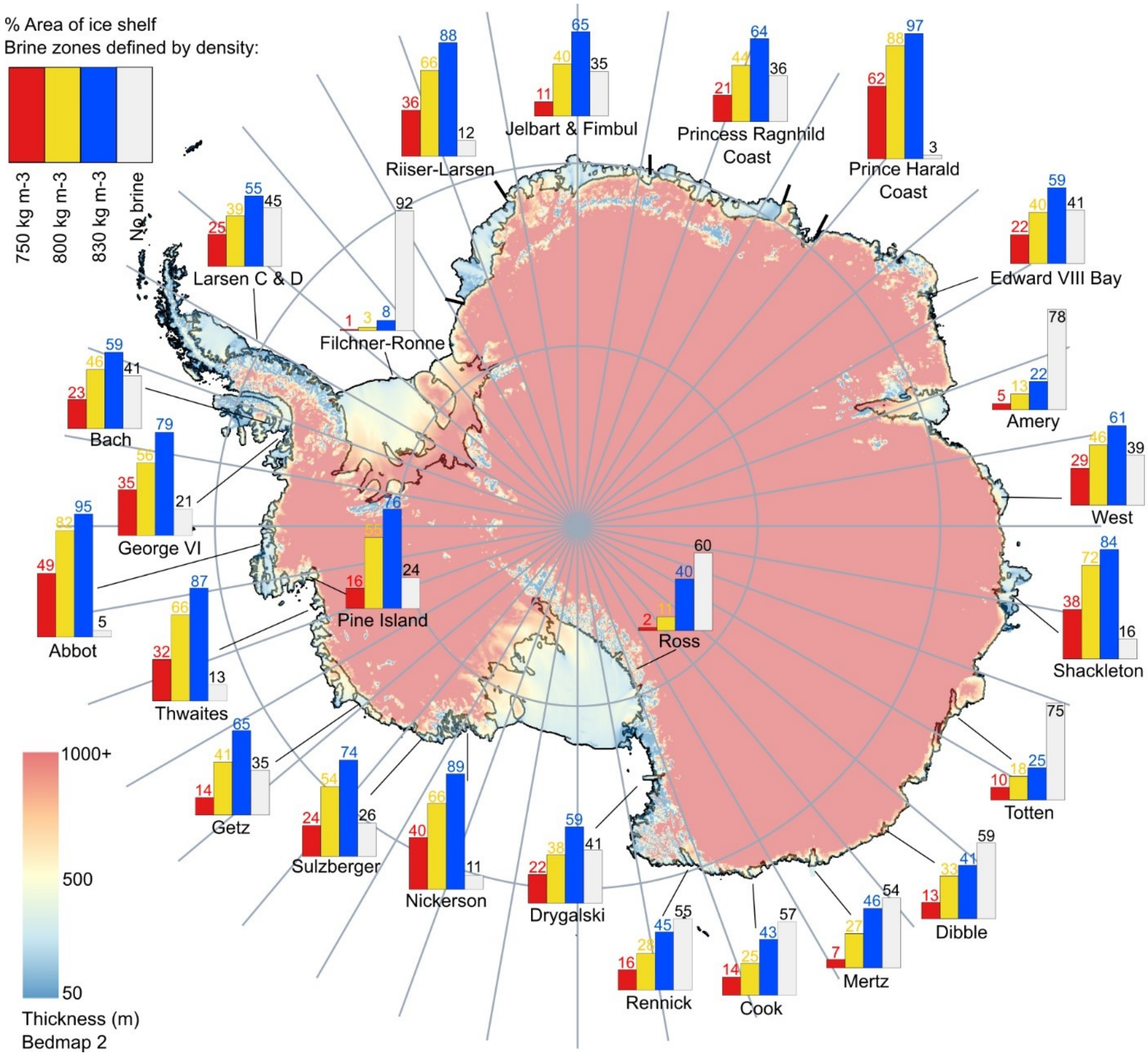

Figure S3: Ice thickness from Bedmap2 (Fretwell et al., 2013). Bar charts show the percentage area of selected ice shelves covered by the brine zone, defined with a threshold for firn permeability of 750 kg m^{-3} (red), 800 kg m^{-3} (yellow) and 830 kg m^{-3} (blue). Some ice shelves with a large brine zone coincide with areas of low ice thickness e.g. Riiser-Larsen and Princess Ragnhild regions and the Shackleton Ice Shelf.

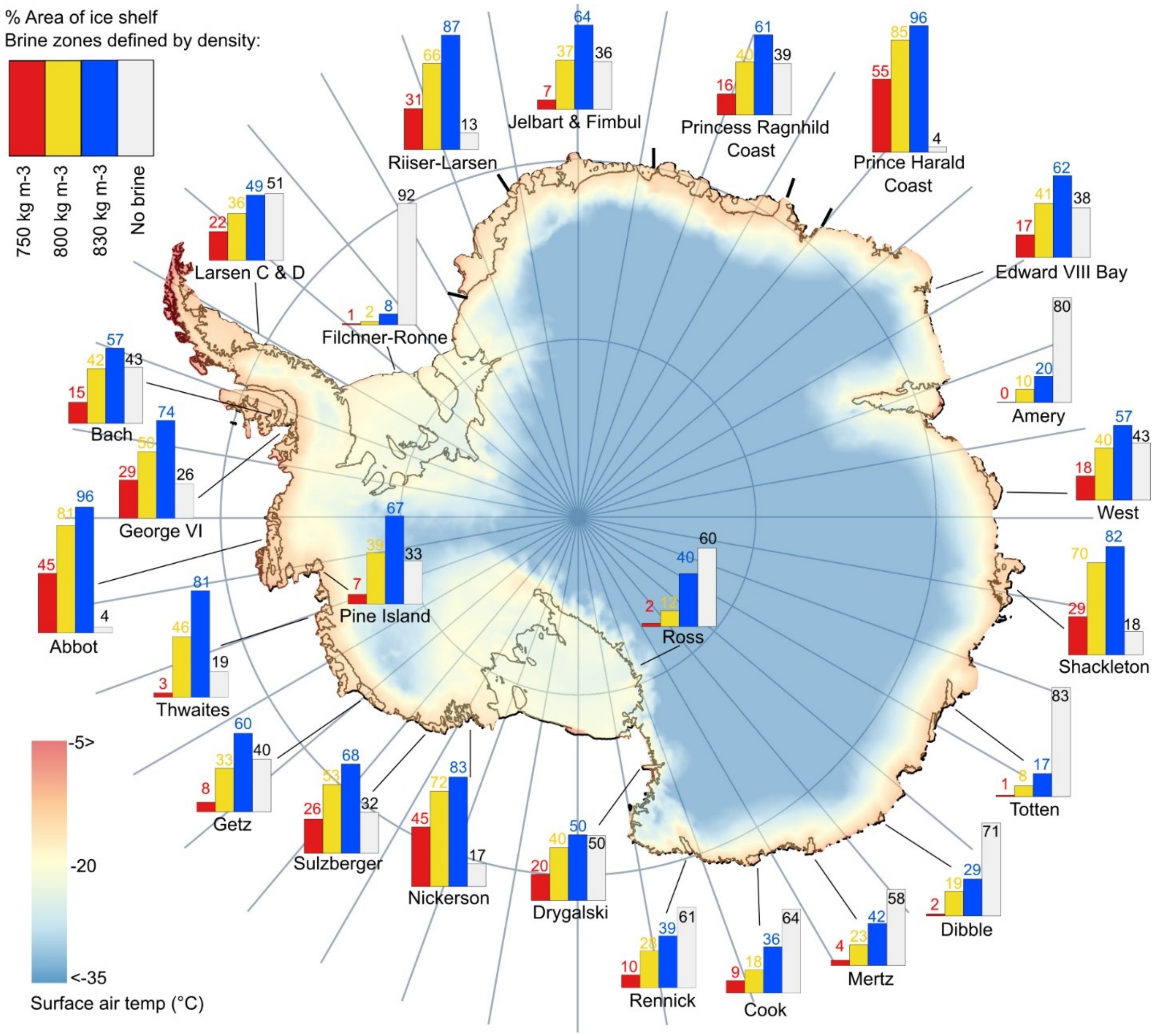

Figure S4: Surface air temperature from ALBMAPv1 Antarctic dataset (Le Brocq et al., 2010; Comiso, 2000). Annual mean temperatures averaged from 1982–2004. Bar charts show the percentage area of selected ice shelves covered by the brine zone, defined with a threshold for firn permeability of 750 kg m^{-3} (red), 800 kg m^{-3} (yellow) and 830 kg m^{-3} (blue). Very low annual mean temperatures will be reflected in the firn layer, and may cause freezing of seawater which will prevent its further infiltration.

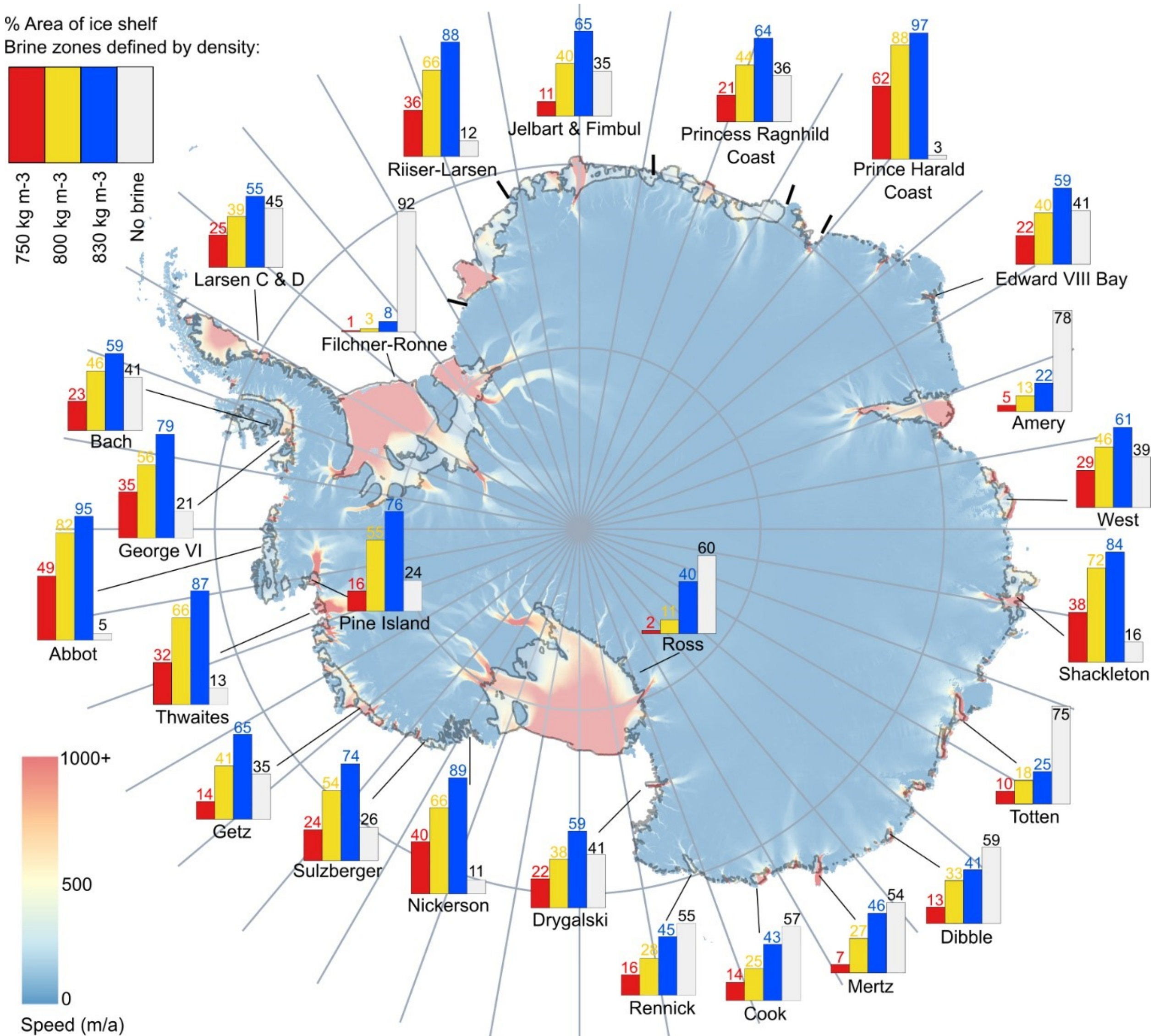

Figure S5: Ice speed from MEaSUREs InSAR-based Antarctica ice velocity map (Mouginot et al., 2017). Bar charts show the percentage area of selected ice shelves covered by the brine zone, defined with a threshold for firn permeability of 750 kg m^{-3} (red), 800 kg m^{-3} (yellow) and 830 kg m^{-3} (blue). Ice shelves with high flow speeds are less likely to be able to maintain a steady state area of liquid brine, if infiltration occurs from the calving front.

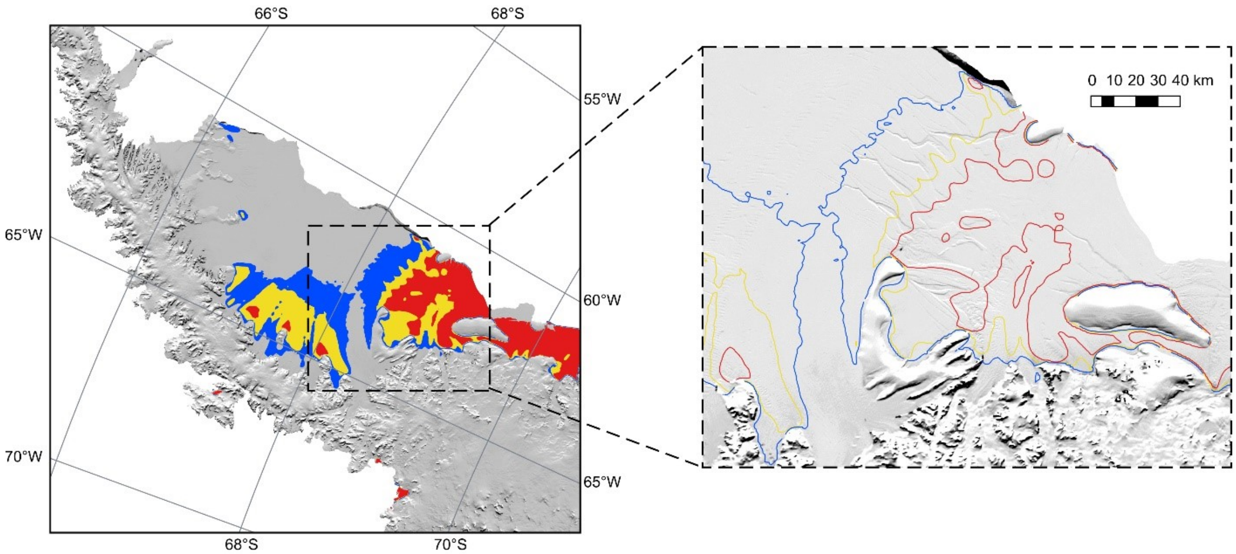

Figure S6: Brine zones on Larsen C ice shelf align with the source of rifts. Coloured areas show potential brine zones as described in Fig. 1. Background imagery is from MODIS Mosaic of Antarctica. The potential brine zone coincides with a region of rifting on the south side of the ice shelf.

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