Age of the Younger Dryas ice-marginal substages in Mid-Norway – Tautra and Hoklingen, based on a compilation of ^{14}C-dates

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The ice-marginal Tautra and Hoklingen Substages in the Trøndelag counties, Mid-Norway, have for a long time been referred to as of early and late Younger Dryas (YD) age, respectively. The basis for this is the regional distribution and morphological correlations of the associated moraines and a number of ^{14}C- datings, mainly of marine shells, previously presented in different papers and map-sheets. In this overview article we present a collection of all ^{14}C-dates associated (more or less accurately) with the Tautra and Hoklingen Substages, a number of 49 and 27 respectively. Using all these dates for a first approximation constrain the Tautra Substage to the age interval 13000 – 12500 cal yr BP and the Hoklingen Substage to 12180 –11600 cal yr BP. Improved accuracy of the age intervals can be obtained by further weighing of geology and stratigraphical positions of the dates. Omitting of dates considered to be slightly too old or too young to be strictly representative, have reduced the number of representative dates for Tautra to 24 and for Hoklingen to 22. The corresponding age intervals are now 12900 – 12620 cal yr BP and 12180 – 11760 cal yr BP, for Tautra and Hoklingen respectively. The Vedde Ash Bed, with established age 12066 ± 42 cal yr BP in western Norway, and dated near Trondheim to 12055 ± 35 cal yr BP, is recorded distally to the Tautra Substage and between the Tautra and Hoklingen Substage deposits, but not closer distally than 5 km and not proximally to the latter. This suggests that the age of the Hoklingen Substage is slightly younger than 12060 cal yr. Shore displacement data in the Trondheim region show a slow regression during Late Allerød and the entire YD, and support the weighed, more accurate age intervals for the Tautra Substage and the interval between the Tautra and Hoklingen Substages.

Olsen, L., Høgaas, F. & Sveian, H. (2015) Age of the Younger Dryas ice-marginal substages in Mid-Norway – Tautra and Hoklingen, based on a compilation of ^{14}C-dates. *Norges geologiske undersøkelse Bulletin*, **454**, 1-13.

Background

The first ^{14}C-dates referring to the Younger Dryas ice-marginal substages – Tautra and Hoklingen – in Mid-Norway (Fig. 1), were carried out during the 1970s and 1980s, respectively. We have included references from the early 1980s (e.g., Andersen et al. 1981, Sveian 1981a, Sveian 1981b, Reite et al. 1982, and Sollid and Reite 1983) as our oldest sources. Most of the dates originate from the 1980-1990s, whereas the most recent dates included here are from various publications from the last decade.

The major part of the dates presented here has been published earlier, albeit on map sheets in reports and publications which may be difficult to obtain. In this paper we compile and present relevant ^{14}C dates and shoreline data in relation to the major Younger Dryas substages from Mid-Norway (Tables 1 and 2; Figs. 1–6). The data is a collection of dates with various accuracy (relevance to the actual substages), obtained from a long period of Quaternary geological mapping.

The regional distribution and location of the mapped lateglacial ice margins in the Trondheimsfjord area is indicated in Fig. 2a (Sveian 1997, Olsen et al. 2013, Olsen et al. 2014), with aerial photographs of the Tautra moraine (substage) at Fosen peninsula, and the Hoklingen moraine (substage) at Straumen, included in Figs. 2b and 2c, respectively. A variety of ice-marginal features occur along the Tautra and Hoklingen zones, such as glaciofluvial deltas and moraine ridges, deposited both subaerially and subaquatically.

Figure 1. Overview map with location of the Tautra and Hoklingen ice-marginal substages in Mid-Norway, as part of the major Younger Dryas (YD) ice-marginal zones in Fennoscandia (grey continuous and stippled lines)*. The area dealt with in this paper is shaded (most of N- and S-Trøndelag counties). Area covered by figures 2 and 3 is framed* (stippled)*. Notice that the YD maximum ice extension, which is indicated as the most continuous ice marginal line around Fennoscandia, is a diachronous event, with and early YD age in the north (Tromsø-Lyngen), the middle zone (Tautra) and the south (Ra), and a late YD age in the west (Herdla).*

Lateglacial marine reservoir age

^{14}C-dates of marine shells from Norway have since the 1970s been corrected for a marine reservoir age expected to be c. 400 (±) yrs along the coast of Norway (Mangerud and Gulliksen 1975), and a standard marine reservoir age of 440 yrs has generally been used both for lateglacial and younger shells. However, more recent studies have shown that the marine surface water reservoir age in the North Sea – Norwegian Sea area has changed over time, from less than 400 yrs in late Allerød to 700 yrs in mid-Younger Dryas, and back to around 400 yrs at the Younger Dryas – Preboreal boundary (Bondevik et al. 1999, Bondevik et al. 2006). Today the marine ^{14}C reservoir age in the North Atlantic area seems to be slightly less than 400 yrs (Mangerud et al. 2006).

The marine ^{14}C reservoir age is ideally defined by the difference between the age of marine organisms and the age of terrestrial plants from the same stratigraphic level. Bondevik et al. (2006) compared ^{14}C-dates of terrestrial plants and marine organisms from the same stratigraphic levels in samples from lake sediments in western Norway, where also the Vedde Ash Bed was present. They concluded that the marine surface reservoir age must have changed considerably during the late Allerød – Younger Dryas – early Preboreal interval, and this should be considered carefully in attempts to make precise correlation between climate records or other events identified in lateglacial to Holocene marine, terrestrial, and ice-core successions.

Therefore, just to indicate how the basis for further regional correlations in Mid-Norway may be improved we have utilized the results from Bondevik et al. (2006) (Table 3) to make corrections of the ^{14}C-ages obtained for the Tautra and Hoklingen ice-marginal formations. These data are however only included in this paper for comparison of ^{14}C-ages in Tables 1 and 2, but not calibrated to calendar years. Further use of these data is postponed to future more precise age estimate studies based on more accurate (representative) regional data.

Results

The locations of the dated samples are spread out from north to south in the Trøndelag region, with a clear dominance (c. ¾) of the Tautra substage dates located in the Trondheim region in the south. Similarly, most (c. ¾) of the Hoklingen substage dates are located in the Steinkjer–Namsos region in the north (Figs. 1–3). The distribution of mollusk shell dates is, naturally, closely related to ice-marginal features which were deposited in contact with a marine environment, i.e. where one could collect shells for radiocarbon dating.

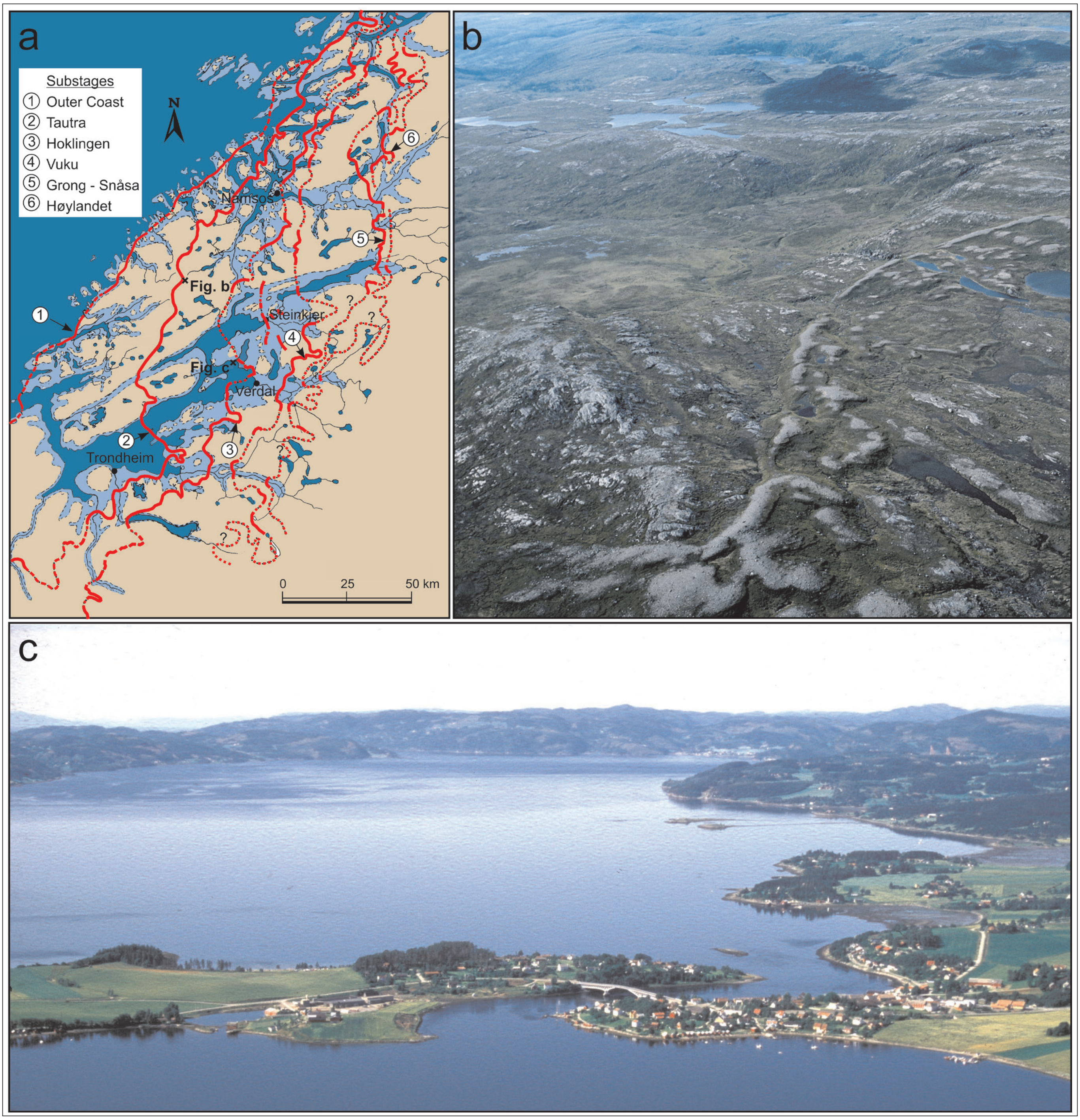

*Figure 2. (a) Lateglacial ice margins (*red lines*) in the Trøndelag region (modified from Sveian 1997). Substages 2 and 3 represent Younger Dryas. Areas below late-/postglacial marine limit indicated (*light blue*), according to Sveian and Solli (1997). (b) The Tautra Moraine (Tautra Substage) at Fosen peninsula (see figure 3). View towards the west. (c) The Hoklingen Moraine (Hoklingen Substage) at Straumen. View towards the southwest.*

Marine mollusk shells of the sediment feeder *Macoma calcarea* is represented in seven of the dated samples referring to the Tautra Substage, and in six of the Hoklingen Substage dating samples. This may have given a slightly too old age (old carbon contamination) for these dates (e.g., Mangerud et al. 2006). In the other shell dating samples, suspension feeders like *Mya truncata*, *Hiatella arctica*, and *Balanus balanus*, are known or inferred to dominate. These are generally expected to give more reliable ^{14}C-ages. The "Macoma" dates have been found seemingly reliable (100-300 yrs too old) and the average Tautra or Hoklingen ages will hence be little affected. However, the uncertainty of the degree of old carbon contamination, have occasionally been found to be quite large, e.g., with ages as much as 1000-2000 yr too old for lateglacial Macoma-sam-

Table 1 . *^{14}C dates constraining the early to mid Younger Dryas Tautra Substage, Trøndelag counties, mid Norway. The original data for marine shells is given without subtraction of reservoir age (column J and O). Dates omitted after screening (see main text) are indicated with pink shading.*

No.	A	B	C	D	E	F	G	H	I	J[d]
	Locality	**Lab. Ref.**	**Geographical position**		**Elevation**	**Site type**	**Dated material**	**Stratigraphical**	**Dating method**	**C^{14}-age yr BP**
			latitude	**longitude**	**m a.s.l.**			**context**	**^{14}C Ams, conv.**	**(older)**
1	Bogen	T-3519	65.07°	11.96°	35	Degl post Tautra	Portlandia arctica	Degl glacimarine	Conv	
2	Gravvikvågen[b]	TUa-821	64.98°	11.80°	30	Hoklingen ice margin	Macoma, hiatella	Marginal moraine	Ams	
3	Rød, Kolvereid	T-9808	64.93°	11.65°	65	Tautra ice margin	Mya truncata	Marginal moraine	Conv	11570
4	Kolvereid	UtC 1242	64.85°	11.63°	70	Tautra ice margin	shell	Proglacial sed.	Ams	
5	Sørbekkmoen	Ua-1585	64.72°	11.50°	12	pre Tautra substage	Hiatella arctica	Subtill glacim.sed.	Ams	11725
6	Sørbekkmoen	UtC 1236	64.72°	11.50°	12	Tautra ice margin	Hiatella arctica	Subtill glacim.sed.	Ams	11410
7	Moelva	UtC 1240	64.70°	11.42°	15	Tautra ice margin	shell	Till	Ams	11240
8	Salsnes	Ua-1005	64.70°	11.42°	12	Tautra ice margin	shell	Glacimarine sed.	Ams	
9	Otterøya[b]	Ua-1003	64.52°	11.23°	90	Tautra ice margin	Macoma calcarea	Glacimarine sed.	Ams	
10	Otterøya[b]	Ua-1004	64.52°	11.23°	90	Tautra ice margin	Macoma calcarea	Glacimarine sed.	Ams	
11	Teigmoen	UtC 1808	64.58°	10.98°	31	pre Tautra substage	Mya truncata	Subtill glacim.sed.	Ams	11500
12	Futdalen	UtC 2102	64.57°	10.97°	40	pre Tautra substage	shell	Subtill glacim.sed.	Ams	11340
13	Teigmoen	T-9267	64.58°	10.98°	32	pre Tautra substage	Mya truncata	Subtill glacim.sed.	Conv	11265
14	Saltnes	UtC 1383	64.45°	11.18°	15	Tautra ice margin	Mya truncata	Till	Ams	
15	Engesdalen	UtC 1386	64.43°	11.09°	110	Tautra ice margin	shell	Delta sed.	Ams	11510
16	Jøssund	UtC 1385	64.35°	10.85°	60	Tautra ice margin	shell	Marine sed.	Ams	
17	Skaudalen	T-6549	63.73°	10.40°	130	pre Tautra substage	shell	Subdelta sed.	Conv	11670
18	N. Lomtjern	T-3858A	63.66°	10.53°	209	Tautra ice margin	gyttja clay, SOL	Postgl first org.	Conv	11190 (P)
19	Rørtjern	T-3860A	63.66°	10.53°	212	Tautra ice dammed	gyttja clay, SOL	Postgl first org.	Conv	10850 (P)
20	Rørtjern	T-4101A	63.66°	10.53°	212	post Tautra deglaci.	gyttja clay, SOL	Postgl first org.	Conv	
21	Selnes[b]	T-5207	63.55°	09.80°	80	pre Tautra substage	Macoma calcarea	Glacimarine sed.	Conv	11330
22	Småtjernet	T-2484A	63.68°	11.00°	170	post Tautra substage	gyttja clay, SOL	Postgl first org.	Conv	
23	Skalitjernet	T-2624A	63.67°	10.97°	170	post Tautra substage	gyttja clay, SOL	Postgl first org.	Conv	
24	Storsvetjernet	T-2571A	63.65°	10.93°	155	post Tautra substage	gyttja clay, SOL	Postgl first org.	Conv	
25	Sveberg	TUa-5486	63.42°	10.75°	165	Tautra ice margin	Mya truncata	Till	Ams	11630
26	Sveberg[b]	TUa-823	63.42°	10.75°	175	Tautra ice margin	Macoma, Yoldia	Till	Ams	
27	Tranggeilen	T-13127	63.58°	10.36°	135	pre Tautra substage	Mya truncata	Till	Conv	11580
28	Trondheimsfj	AAR-5736	63.54°	10.34°	b.s.l.	pre Tautra substage	shell	Glacimarine sed.	Ams	11590
29	Engan[b]	TUa-822	63.42°	10.68°	120	Tautra ice margin	Macoma calcarea	Glacimarine sed.	Ams	11640
30	Vikåsen	T-11100	63.42°	10.53°	150	Tautra ice margin	Whalebone	Subtill glacim.sed.	Conv	11510
31	Voll	TUa-1750	63.41°	10.45°	125	pre Tautra substage	Portlandia arctica	Till	Ams	11620
32	Dragvoll	TUa-895	63.40°	10.47°	160	pre Tautra substage	shell	Till	Conv	11615
33	Steinan	T-3296	63.40°	10.45°	162	pre Tautra substage	Hiatell, Balanus	Deformed glacim.	Conv	11460
34	Okstad	UtC 14601	63.38°	10.40°	110	pro Tautra ice margin	Yoldia sp.	Glacimarine sed.	Ams	
35	Tiller Church	T-787	63.36°	10.42°	155	Tautra ice margin	Whalebone	Delta foreset	Conv	
36	Tiller Plateau	T-	63.36°	10.38°	155	Tautra ice margin	shell	Deformed glacim.	Conv	11540
37	Ånøya (lake)	UtC 15249	63.25°	10.17°	125	pre Tautra substage	Hiatella arctica	Deformed glacim.	Ams	11600
38	Ånøya (lake)	UtC 15248	63.25°	10.17°	125	pre Tautra substage	Mya truncata	Deformed glacim.	Ams	11520
39	Buvika	TUa-4572	63.31°	10.16°	37	pre Tautra substage	Spirorbis sp.	Deformed glacim.	Ams	11460
40	Buvika	TUa-4571	63.31°	10.16°	37	pre Tautra substage	Portlandia arctica	Deformed glacim.	Ams	11540
41	Buvika	TUa-4576	63.31°	10.16°	35	pro Tautra ice margin	Portlandia arctica	Glacimarine sed.	Ams	
42	Buvika	TUa-4575	63.31°	10.16°	42	pro Tautra ice margin	Portlandia arctica	Glacimarine sed.	Ams	
43	Buvika	TUa-4573	63.31°	10.19°	7	pro Tautra ice margin	Portlandia arctica	Glacimarine sed.	Ams	
44	Lundåsen[b]	TUa-2527	63.36°	10.33°	160	pre Tautra substage	Macoma calcarea	Deformed glacim.	Ams	11740
45	Heimdal	UtC 14734	63.35°	10.35°	145	pre Tautra substage	Nuculana pernule	Subtill glacim.sed.	Ams	11450
46	Byneset, Berg	T-14608	63.38°	10.18°	140	pre Tautra substage	Balanus sp.	Till	Ams	11570
47	Børsa	T-14993	63.29°	10.07°	80	pro Tautra ice margin	Hiatella arctica	Degl glacimarine	Conv	
48	Viggja	T-14603	63.33°	10.01°	130	pre Tautra substage	Mya truncata	Subtill glacim.sed.	Conv	11405
49	Viggja	T-14609	63.32°	09.98°	137	pre Tautra substage	Mya truncata	Subdelta sed.	Conv	11710
50	Kvåle	UtC 10104	63.24°	09.77°	45	pre Tautra substage	Portlandia arctica	Ice marginal sed.	Ams	11720
51	Kvåle	TUa-7541	63.24°	09.77°	50	pre Tautra substage	Portlandia arctica	Degl sed.	Ams	11390
52	Løftmoen	TUa-7540	63.19°	09.80°	145	pre Tautra substage	Mya truncata	Delta slope sed.	Ams	11480
53	Kregnes	UTC 14735	63.24°	10.23°	165	Tautra min. ice marg.	Nuculana pernule	Delta slope top	Ams	
54	Søberg	T-11072	63.25°	10.29°	165	Tautra min. ice marg.	Balanus sp.	Palaeobeach sed.	Conv	
55	Klæbu	UtC 14597	63.28°	10.45°	175	post Tautra substage	Hiatella arctica	Delta sed.	Ams	
56	Jonsvatnet, (VA)	(Vedde Ash)	63.37°	10.53°	180	post Tautra substage	Freshwater algae	Lacustrine sed.	Ams[c]	
	Average age:									11457 (N= 30)

[a] Correction: Reservoir age is generally set at 440 yr according to Mangerud and Gulliksen (1975). However, it changed from 440 yr to 500 yr between 10700 and 10600 ^{14}C-yr BP, to 600 yr at 10500, 500 yr at 10450, 700 yr at 10400, 600 yr at 10300-10200, 500 yr at 10100, and back to 440 at 10000 ^{14}C-yr BP (simplified after Bondevik et al. 2006).

[b] Shell type: Macoma calcarea included in sample, also indicated with grey shading.

[c] AMS ^{14}C-dated sample from Vedde ash layer in sediments at a locality south of Sverresborg (Table 2, H34, Nordmyra locality, Olsen 2003).

[d] Dating of samples from older units, meaning from units that are either reworked in sediments in the moraine zone or from sediments older than the Tautra substage. Dating of samples from units younger or equal to the Tautra substage, meaning from proglacial sediments, or deglaciation sediments from the moraine zone or younger sediments proximal to the substage.

[e] The uncertainties in column M and R are simply copied from the calibration tables of Reimer et al. (2013), and are therefore not "real" uncertainties.

(P) indicates dating of plant remains in sediments.

K Uncertainty +/- 1 std dev	L Calibrated age IntCal13	M[e] Uncertainty +/- yr	N[a] Age J adjusted for reservoir age	O[d] C^{14}-age yr BP (younger or equal)	P Uncertainty +/- 1 std dev	Q Calibrated age IntCal13	R[e] Uncertainty +/- yr	S[a] Age O adjusted for dev. reservoir age	T References
				10770	250	12200	35	10170	Andersen etal. 1981
				11125	85	12635	59	10625	Sveian, unpubl.
80	13080	38	11130						Bargel et al. 1994
				11440	80	12900	55	11000	Bargel et al. 1994
145	13215	48	11285						Bargel et al. 1994
140	12865	55	10970						Bargel et al. 1994
60	12705	69	10800						Bargel et al. 1994
				10975	215	12555	55	10475	Sveian 1992
				11080	190	12610	63	10480	Sveian 1991, 1992
				10935	275	12525	45	10435	Sveian 1991, 1992
90	12965	42	11060						Bargel et al. 1994
120	12785	60	10900						Bargel et al. 1994
110	12720	70	10825						Bargel et al. 1994
				11050	90	12595	65	11450	Bargel et al. 1994
110	12980	40	11070						Bargel et al. 1994
				10700	80	12055	38	10150	Sveian, unpubl.
120	13160	44	11230						Reite & Olsen 2002
200	13070	47	11190 (P)						Reite et al. 1982
110	12725	70	10850 (P)						Reite et al. 1982
				10410 (P)	110	12385	15	10410 (P)	Reite et al. 1982
80	12765	61	10910						Reite & Olsen 2002
				10330 (P)	270	12110	45	10330 (P)	Kjemperud 1982,1986
				10480 (P)	200	12420	18	10480 (P)	Kjemperud 1982,1986
				10200 (P)	200	11960	41	10200 (P)	Kjemperud 1982,1986
55	13125	43	11190						Sveian, unpubl.
				11085	100	12610	63	10535	Sveian, unpubl.
140	13085	38	11140						Feragen 1997
70	13095	40	11150						Rise et al. 2006
85	13135	43	11200						Sveian, unpubl.
145	12980	40	11070						Reite 1994
85	13120	43	11180						Rokoengen et al. 1997
75	13110	43	11175						Rokoengen et al. 1997
90	12920	51	11020						Reite et al. 1982
				11420	90	12880	55	10980	Olsen et al. 2007, 2014
				11430	190	12890	55	10990	Reite et al. 1982
	13040	34	11100						Rokoengen, unpubl., 2007
60	13100	42	11060						Olen et al. 2014
50	12990	39	11080						Olsen et al. 2014
60	12920	51	11020						Solberg et al. 2008
60	13040	34	11100						Solberg et al. 2008
				11315	55	12760	61	10875	Solberg et al. 2008
				11040	55	12590	65	10460	Solberg et al. 2008
				11000	65	12570	62	10460	Solberg et al. 2008
85	13230	49	11300						Olsen et al. 2007, 2014
80	12910	53	11010						Olsen et al. 2007, 2014
90	13080	38	11130						Olsen et al. 2007, 2014
				11065	185	12600	64	10465	Olsen et al. 2007, 2014
165	12860	56	10965						Olsen et al. 2007, 2014
115	13200	47	11270						Olsen et al. 2007, 2014
60	13210	47	11280						Olsen et al. 2007, 2014
50	12840	57	10950						Olsen, unpubl.
50	12940	46	11040						Olsen et al. 2014
				11330	70	12770	60	10890	Olsen, unpubl.
				10960	140	12545	51	10460	T.Moseid (Nemec et al. 1999)
				11030	80	12585	64	10430	Olsen et al. 2007, 2014
				10285[c]	90	12055	35	10285	Sætre 2005, Olsen 2003
	12995 (N= 30)		11075 (N= 30)	10906 (N= 19)		**12496** (N= 19)		10576 (N= 19)	

Table 2. *^{14}C dates constraining the late Younger Dryas Hoklingen Substage, Trøndelag counties, mid Norway. The original data for marine shells is given without subtraction of reservoir age (column J and O). Dates omitted after screening (see main text) are indicated with pink shading.*

No.	A Locality	B Lab. Ref.	C Geographical position latitude	D longitude	E Elevation m a.s.l.	F Site type	G Dated material	H Stratigraphical context	I Dating method ^{14}C Ams, conv.	J[d] C^{14}-age yr BP (older)
1	Bogen	T-3519	65.07°	11.96°	35	Degl pre Hoklingen	Portlandia arctica	Degl. glacimarine	Conv	10770
2	Moelva	Ua-1006	64.70°	11.41°	15	Pre Hoklingen subst.	shell	Subtill glacim.sed.	Ams	10580
3	Svartdalen	UtC 1241	64.63°	11.53°	60	Degl pre Hoklingen	shell	Till	Ams	10450
4	Otterøya[b]	Ua-1003	64.52°	11.23°	90	Pre Hoklingen subst.	Macoma calcarea	Subtill glacim.sed.	Ams	11080
5	Otterøya[b]	Ua-1004	64.52°	11.23°	90	Pre Hoklingen subst.	Macoma calcarea	Subtill glacim.sed.	Ams	10935
6	Vemundvik	Ua-1007	64.53°	11.55°	15	Post Hoklingen subst.	Hiatella arctica	Degl. sed. overlying moraine	Ams	
7	Sandåhatten	T-7286	64.67°	11.67°	120	Post Hoklingen subst.	shell	Degl. glacimarine	Conv	
8	Vesterdalen	T-6301	64.05°	11.59°	120	Post Hoklingen subst.	shell	Degl. glacimarine	Conv	
9	Sprova[b]	T-6605	64.13°	11.35°	135	Post Hoklingen subst.	Macoma calcarea	Degl. glacimarine	Conv	
10	Sundan	T-5259	64.08°	11.60°	150	Post Hoklingen subst.	Mya truncata	Sub palaeobeach sed.	Conv	
11	Sæterdalen	T-6300	64.07°	11.43°	160	Post Hoklingen subst.	shell	Degl. glacimarine	Conv	
12	Verstad	T-4919	63.93°	11.25°	152	Post Hoklingen subst.	Balanus sp.	Degl. glacimarine	Conv	
13	Verstad	T-4918	63.93°	11.25°	152	Post Hoklingen subst.	Mytilus edulis	Degl. glacimarine	Conv	
14	Herstad, øvre	T-4259A	63.90°	11.27°	165	Postglacial peat	Peat, SOL	Postgl., first org. sed.	Conv	
15	Herstad, øvre	T-4259B	63.90°	11.27°	165	Postglacial peat	Peat, SOL	Postgl., first org. sed.	Conv	
16	Granavatn	T-4257	63.90°	11.27°	147	Post Hoklingen subst.	Mya truncata	Degl. glacimarine	Conv	
17	Leinkammen	T-5260	63.93°	11.45°	168	Pre Hoklingen subst.	Hiatella arctica	Glacimarine, deform.	Conv	10920
18	Leinkammen	T-5261	63.93°	11.45°	168	Pre Hoklingen subst.	Hiatella, Balanus	Glacimarine, deform.	Conv	10880
19	Leirådalen	T-3999	63.78°	11.68°	142	Post Hoklingen subst.	Mytilus, Hiatella	Degl. glacimarine	Conv	
20	Tromsdalen	T-3998	63.75°	11.70°	200	Post Hoklingen subst.	Hiatella, Balanus	Vuku substage moraine	Conv	
21	Småtjernet	T-2484A	63.68°	11.00°	170	Pre Hoklingen subst.	Gyttja, SOL	Degl., first org. sed.	Conv	10330 (P)
22	Skalitjernet	T-2624A	63.67°	10.97°	170	Pre Hoklingen subst.	Gyttja, SOL	Degl., first org. sed.	Conv	10480 (P)
23	Storsvetjernet	T-2571A	63.65°	10.93°	155	Pre Hoklingen subst.	Gyttja, SOL	Degl., first org. sed.	Conv	10200 (P)
24	Frigård[b]	TUa-1091	63.40°	10.92°	175	Hoklingen substage	Macoma calcarea	Delta slope marine sed.	Ams	
25	Sveberg[b]	TUa-823	63.42°	10.75°	175	Pre Hoklingen subst.	Macoma, Yoldia	Till	Ams	11085
26	Fosslidalen[b]	UtC 1803	63.38°	10.78°	170	Post Hoklingen subst.	Macoma calcarea	Degl. glacimarine	Ams	
27	Fossmoen	TUa-5485	63.37°	10.77°	170	Post Hoklingen subst.	Balanus sp.	Degl. glacimarine	Ams	
28	Klæbu	UtC 14597	63.28°	10.45°	175	Pre Hoklingen subst.	Hiatella	Degl delta sed.	Ams	11030
29	Jonsvatnet, (VA)		63.37°	10.53°	180	Pre Hoklingen subst.	Freshwater algae	Lacustr. sed., ash layer	Ams	10285[c]
30	Søberg	T-11072	63.25°	10.29°	165	Pre Hoklingen subst.	Balanus sp.	Palaeobeach sed.	Conv	10960
31	Søberg	TUa-966	63.25°	10.29°	165	Pre Hoklingen subst.	shell	Palaeobeach sed.	Ams	10810
32	Søberg	T-11071	63.25°	10.29°	165	Pre Hoklingen subst.	Mya, Hiatella	Palaeobeach sed.	Conv	10595
33	Sverresborg	UtC 15252	63.42°	10.36°	137	Hokl sea lev 155 masl	Hiatella arctica	Glacimarine diamicton	Ams	10714
34	Nordmyra	TUa-3621	63.36°	10.33°	163	Pre Hoklingen subst.	Freshwater algae	Lacustr. sed., ash layer	Ams	10285
	Average age:									10643 (N= 14)

[a] Correction: Reservoir age is generally set at 440 yr according to Mangerud and Gulliksen (1975). However, it changed from 440 yr to 500 yr between 10700 and 10600 ^{14}C-yr BP, to 600 yr at 10500, 500 yr at 10450, 700 yr at 10400, 600 yr at 10300-10200, 500 yr at 10100, and back to 440 at 10000 ^{14}C-yr BP (simplified after Bondevik et al. 2006).
[b] Shell type: Macoma calcarea included in sample, also indicated with grey shading.
[c] Dated material (freshwater algae) is from Vedde ash layer in sediment at a locality south of Sverresborg (H34, Nordmyra locality).
[d] Dating of samples from older units, meaning from units that are either reworked in sediments in the moraine zone or from sediments older than the Hoklingen substage. Dating of samples from units younger or equal to the Hoklingen substage, meaning from proglacial sediments, or deglaciation sediments from the moraine zone or younger sediments proximal to the substage.
[e] The uncertainties in column M and R are simply copied from the calibration tables of Reimer et al. (2013), and are therefore not "real" uncertainties.
(P) indicates dating of plant remains in sediment.

ples in other parts of Norway (NGU, unpublished dates from Troms county). This suggests that the 13 "Macoma" dates should be excluded from the age range and average estimates, which is done accordingly (Tables 1 and 2).

Age intervals and average ages

The age interval obtained from the 49 Tautra Substage ^{14}C-dates is 11017 – 10466 ^{14}C-yr BP (with a standard reservoir age of 440 years subtracted) – or 11075 – 10576 ^{14}C-yr BP with marine reservoir age correction according to data presented by Bondevik et al. (2006). Ages corrected for deviating YD marine reservoir age are presented in brackets in the following text. The statistical average age of the 49 ^{14}C-dates is 10742 ± 275 ^{14}C-yr BP (10826 ± 250 ^{14}C-yr BP) (Tables 1, 2 and 3).

The age interval for the 27 Hoklingen Substage ^{14}C-dates is 10203 – 9970 ^{14}C-yr BP (10242 – 10010 ^{14}C-yr BP). The average age is 10087 ± 117 ^{14}C-yr BP (10126 ± 116 ^{14}C-yr BP).

K Uncertainty +/- 1 std dev	L Calibrated age IntCal13	M[e] Uncertainty +/- yr	N[a] Age J adjusted for reservoir age	O[d] C^{14}-age yr BP (younger or equal)	P Uncertainty +/- 1 std dev	Q Calibrated age IntCal13	R[e] Uncertainty +/- yr	S[a] Age O adjusted for dev. reservoir age	T References
250	12200	35	10170						Andersen et al. 1981
260	11890	38	10080						Bargel et al. 1994
170	11615	37	10010						Sveian 1992
190	12610	63	10380						Sveian 1991, 1992
275	12525	43	10335						Sveian 1991, 1992
				10240	165	11215	46	9800	Sveian 1991
				10290	90	11250	42	9850	Sveian 1991
				10550	90	11830	37	10040	Sveian 1991
				10750	120	12150	38	10150	Sveian 1991
				10430	130	11530	38	9990	Sveian 1991
				10680	160	12035	37	10130	Sveian 1991
				10760	190	12180	35	10160	Sveian 1989
				10420	150	11435	40	9980	Sveian 1989
				10000 (P)	130	11400	16	10000 (P)	Reite et al. 1982
				10280 (P)	150	12050	36	10280 (P)	Reite et al. 1982
				10390	130	11370	38	9950	Reite et al. 1982
120	12510	41	10320						Sveian 1989
190	12470	39	10280						Sveian 1989
				10430	130	11470	40	9990	Reite et al. 1982
				10370	130	11340	39	9930	Reite et al. 1982
270	12110	45	10330 (P)						Kjemperud 1982. 1986
200	12420	18	10480 (P)						Kjemperud 1982. 1986
200	11845	24	10200 (P)						Kjemperud 1982. 1986
				10725	95	12090	39	10325	Sveian, unpubl.
100	12610	63	10385						Sveian, unpubl.
				10650	80	12000	36	10150	Sveian, unpubl.
				10525	55	11790	38	10025	Sveian, unpubl.
80	12585	64	10330						Olsen et al. 2007, 2014
90	12055[c]	35	10285[c]						Sætre 2005, Olsen 2003
140	12545	51	10460						T.Moseid (Nemec et al. 1999)
75	12320	40	10210						T.Moseid (Nemec et al. 1999)
130	11920	38	10095						T.Moseid (Nemec et al. 1999)
46	12070	39	10140						Olsen, unpubl. 2007
90	12055	35	10285						Olsen 2003
	12183 (N= 14)		10242 (N= 14)	10410 (N= 13)		**11607** (N= 13)		10010 (N= 13)	

Using IntCal13 and Marine13 data (Reimer et al. 2009) for calibrating the ^{14}C ages (without subtraction of reservoir age, which is already accounted for in the calibration tables), the resulting age interval for the Tautra Substage (n=49) is 12995 – 12496 cal yr BP (mean: 12746 ± 250 cal yr BP) (Fig. 4), and 12183 – 11607 cal yr BP (mean: 11895 ± 288 cal yr BP) for the Hoklingen Substage (n=27).

Improvement by weighing of data

We know from the mapped geology and the stratigraphical location of the dating samples that some dates used to constrain the Tautra and Hoklingen Substages are from sediments and events assumed to be 100-200 yrs younger or older than the substages' actual ages. More accurate substage age-intervals can therefore be obtained if the dates to some degree are weighed. For example, omitting all the dates representing events that are considered to be too old or too young in Table 1, including

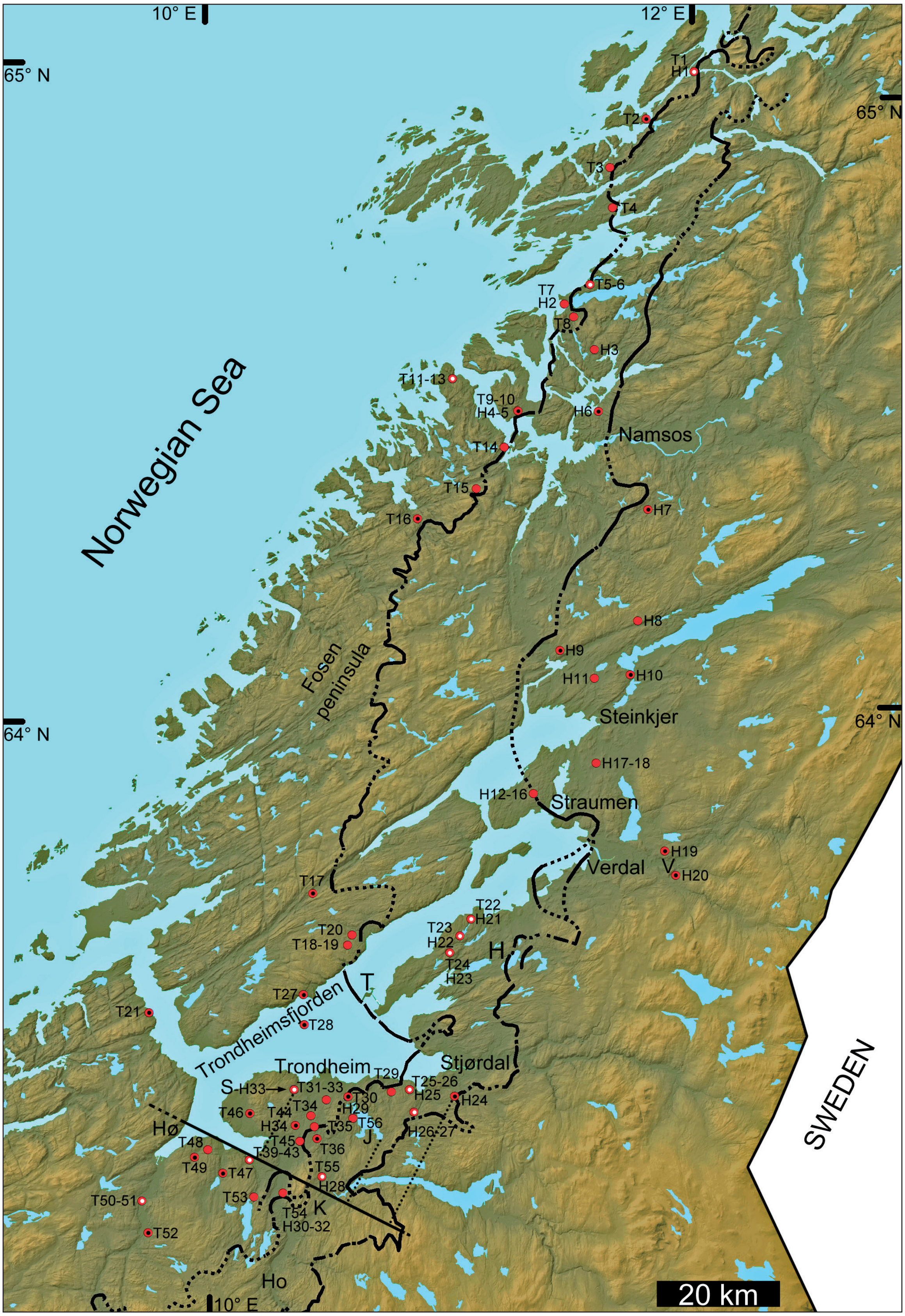

Figure 3. Coloured relief image of most of the Trøndelag region (frame and grey shading in figure 1), with locations of ^{14}C-dated samples used to constrain the ages of the Tautra (T-samples) and Hoklingen (H-samples) ice marginal substages. Moraines and inferred ice front positions are indicated with black continuous and stippled lines. Locations of dated samples with Macoma calcarea are also included here, but omitted in the age estimates of the substages. Single localities with a black inner dot have been subject to screening (all dates omitted), whereas the white inner dots symbolize that one or more, but not all of the dates have been subject to screening (see text). Profile line for the projected shorelines in figure 6 is indicated, approximately normal to the Younger Dryas isobase direction (N32°E). For more details, see Tables 1 and 2. Locations: Hø – Høgåsen. Ho – Hovin. K – Kaldvelldalen. J – Jonsvatnet and Jervan. Type localities: T – Tautra. H – Hoklingen.

those located at longest distance from the ice-marginal deposits (Fig. 3), reduces the number of relevant dates to less than half (24 of 56) and narrows the age range for the Tautra Substage by 273 yrs. The dates omitted, in addition to "Macoma" shell dates, are nos. 5, 11, 17, 27, 28, 30, 31, 32, 33, 36, 37, 38, 39, 40, 46, 49, 50, and 52 (too old), and nos. 1, 16, 22, 23, 24, 47 and 55 (too young). Similarly, omitting nos. 6 Vemundvik, 7 Sandåhatten, 10 Sundan, 19 Leirådalen and 20 Tromsdalen, which are all put in relation to a younger substage raises the minimum age and narrows the age range by 160 yrs (raises mean age by 80 yrs) for the Hoklingen Substage. The associated weighed age intervals would then be 12889 – 12624 cal yr BP (mean: 12756 ± 132 cal yr BP) and 12183 – 11761 cal yr BP (mean: 11972 ± 211 cal yr BP), for the Tautra (n=24) and Hoklingen (n=22) substages respectively.

However, a screening of dates like this may imply a loss in regional data representation. Thus, before using 'improved' age assignments like this the gain in age accuracy should be considered against possible reduced regional validity. In this paper we choose to show both the regional data representation for the entire Trøndelag region (Fig. 4, blue curve) and a curve showing the age ranges based on the dates we consider most accurate for the Tautra and Hoklingen Substages in Mid-Norway (Fig. 4, black curve).

The Vedde Ash Bed stratigraphical marker horizon has an age of 12066 ± 42 cal yr BP in western Norway, according to Lohne et al. (2013). Within our study area the bed is recorded distally to the Tautra Substage and between the Tautra and Hoklingen Substage deposits at Jonsvatnet (locality T56 and H29, Tables 1-2) and dated to 12055 ± 35 cal yr BP (Olsen 2003, Sætre 2005). The Vedde Ash Bed is not recorded the closest 5 km distally (Fig. 5) and not proximally to the Hoklingen ice marginal deposits. This suggests that the lower age limit for the Hoklingen Substage should be adjusted to c. 12060 cal yr BP (or c. 12020 cal yr BP if the age is set to younger than the 'entire' Vedde Ash age interval 12066 ± 42 cal yr BP). The apparent age deviation between the Vedde Ash Bed and the slightly younger Hoklingen Substage may be explained by the increased reservoir age around 10,200–10,300 ^{14}C yr BP (Table 3), which reduces the 12183 cal BP age limit by at least 150 years.

Shorelines

Shorelines representing the sea level during the Tautra and Hoklingen Substages are reconstructed as proxy shorelines for the Trondheim area (Fig. 6)(Reite et al. 1999, Olsen et al. 2014). Observations used here for the Trondheim area are from the sites Kvammen, Tiller, Torgård and Sverresborg, and from the area west of Trondheim data from the Høgåsen site is used (Figs. 3 and 6). Data from east of Trondheim is from Leistadåsen (shore platform in bedrock), and Frigård and Jervan (ice marginal deltas). Sverresborg (Fig. 3), which the shorelines refer to, includes four different shorelines, (1) the Allerød shoreline (lateglacial marine limit), discontinuous

Table 3. *Comparison between ^{14}C ages of terrestrial plant remains and marine organics from western Norway, and resulting marine surface water reservoir age, simplified after Bondevik et al. 2006: Science 12, 1514-1517.*

Terrestrial ^{14}C-age	Marine ^{14}C-age	Reservoir age
10000 yr	c. 10440 yr	c. 440 yr
10100 yr	c. 10600 yr	c. 500 yr
10200 yr	c. 10800 yr	c. 600 yr
10300 yr	c. 10900 yr	c. 600 yr
10400 yr	c. 11100 yr	c. 700 yr
10450 yr	c. 10950 yr	c. 500 yr
10500 yr	c. 11100 yr	c. 600 yr
10600 yr	c. 11100 yr	c. 500 yr
10700 yr	c. 11140 yr	c. 440 yr
10800 yr	c. 11240 yr	c. 440 yr
10900 yr	c. 11340 yr	c. 440 yr
11000 yr	c. 11440 yr	c. 440 yr

shore platform in bedrock, 175 m a.s.l., (2) the Tautra maximum shoreline, irregular shelf in loose deposits, 165 m a.s.l. (and notch in bedrock at adjacent bedrock hill), (3) the Tautra minimum shoreline, distinct shelf in bedrock, 160 m a.s.l., and (4) the Hoklingen shoreline, slightly arched shore platform/shelf in loose deposits, 153–155 m a.s.l. Shorelines 2 and 3 are both ascribed to the Tautra period due to morphological correlations and especially that shoreline 3 is described as a particularly distinct lateglacial shoreline, easy to record as it is the most prominent early YD shoreline eroded in bedrock in the Trøndelag region as (e.g., Reite et al. 1999, Olsen et al. 2014). The height difference between the two

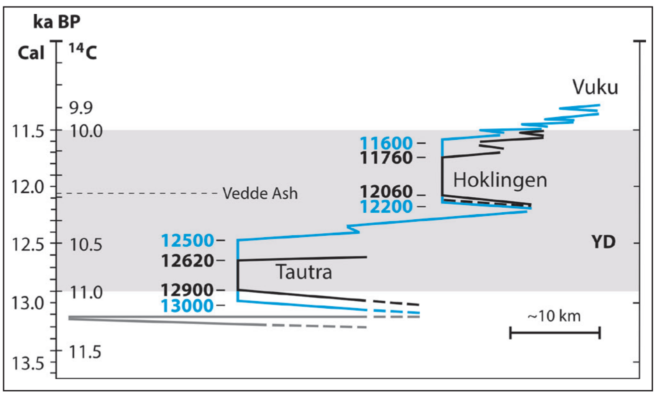

*Figure 4. Time–distance (glaciation) curves for the Tautra and Hoklingen ice-marginal substages in Mid-Norway, between significant lateglacial ice-marginal oscillations from late Allerød and early Preboreal time. Position of the stratigraphic marker horizon, the Vedde Ash Bed (T56 and H29, Tables 1-2, and figure 5) is indicated. YD= Younger Dryas. Blue curve indicates unweighed data, and **black** curve indicates weighed data (see text). Blue and **black** numbers indicate unweighed and weighed age constraints, respectively, for the substages in cal yr BP. Weighed, lower age limit for the Hoklingen Substage is set to 12060 cal yr BP (see text).*

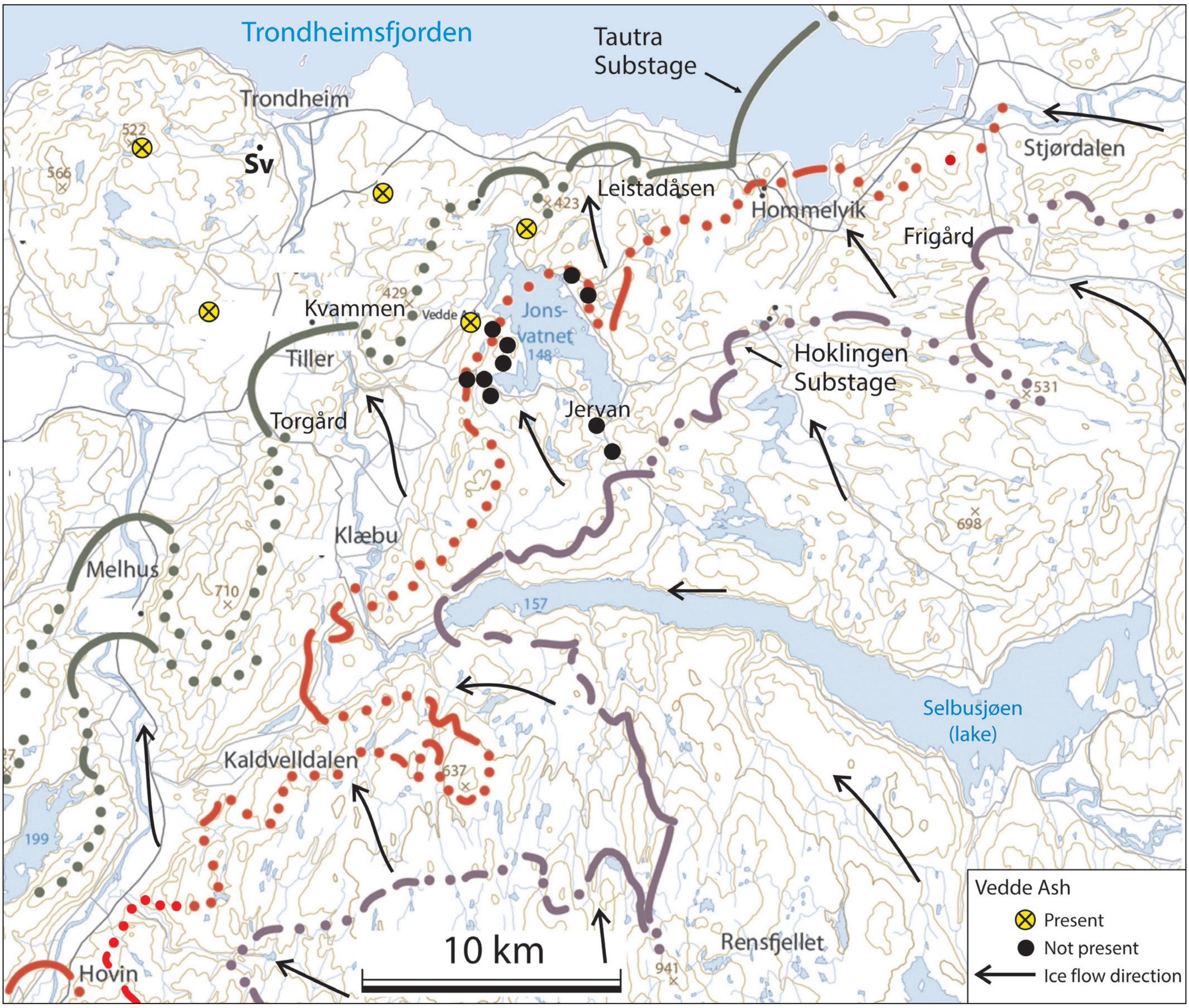

Figure 5. The Vedde Ash bed occurrences in the Trondheim area distally to the Tautra and Hoklingen Substages, and negative records of this stratigraphical marker horizon between the more discontinuous ice marginal substage Hommelvik–Jonsvatnet–Kaldvelldalen–Hovin and the Hoklingen Substage (after Olsen 2003, Sætre 2005, Olsen et al. 2014). The approximate locations of the main sites used for shoreline reconstruction in figure 6 are also indicated. Sv – Sverresborg (close to Trondheim).

Tautra shorelines is 5 m at Kvammen and Torgård. Shoreline 2 is typically represented by the Tautra ice-marginal delta terrace surfaces at Kvammen and Torgård (Tautra maximum), whereas shoreline 3 (Tautra minimum) is typically cut into these terraces 4-5 meter below the top surfaces in the Trondheim area. Shorelines 2 and 3 are supposed to represent maximum and minimum sea levels during the Tautra Substage interval, and may in some areas probably correspond to maximum and minimum ice margin positions during the Tautra Substage, as indicated for the area south of Trondheim in figure 3.

The gradient for shoreline 2 is here just tentatively estimated to 1.5 m km^{-1}, which is similar to the gradient (c. 1.5 m km^{-1}) for the early YD shoreline in Kjemperud's (1982, 1986) reconstruction from the area to the W and NW of Trondheim. On the basis of observations at Sverresborg, Tiller, Torgård, Kvammen and Leistadåsen the gradient of shoreline 3 is found to be 1.4 m km^{-1} (Figs. 5 and 6). Shoreline 4 is attributed to the Hoklingen Substage as it is observed on the ice marginal deltas at Frigård and Jervan and can also be found as shore features at a lower elevation than the Tautra minimum shoreline. A Hoklingen substage shoreline c. 154-155 m a.s.l. at Sverresborg is also in agreement with the reconstruction from Sveian and Olsen (1984) for the Verdal area, which has a shoreline from 10000 ^{14}C-yr BP with a gradient of 1.1 m km^{-1}. The Hoklingen shoreline we have reconstructed (Fig. 6) has a gradient of c. 1.2 m km^{-1}, which is close to the gradient of c. 1.3 m km^{-1} found by Kjemperud (1982) for the late YD shoreline reconstructed from the adjacent area to the west of Verdal. The difference is however noticeable, but two dates at 10330 ± 270 and 10480 ± 200 ^{14}C-yr BP of the soluble fraction of gyttja sediments representing the late YD shoreline after Kjemperud (1982) may indicate that it is older than the Hoklingen Substage and associated shoreline. If that is correct, then a slightly different gradient as indicated should be expected.

At Sverresborg the height difference between the two Tautra shorelines turns out to be 5 m. Between the Tautra shorelines and the Hoklingen shoreline it is from 10–12 m (maximum) to 5–7 m (minimum), and is thought to increase slightly in size towards the east (right in Fig. 6). It appears to be a relatively slow shoreline displacement rate during the entire Younger Dryas (mean vertical displacement at Sverresborg c. 1 m/100 yr). The black curve (Fig. 4) show that the weighed (assumed more accurate) age intervals is in fair agreement with the height differences between the Tautra maximum, Tautra minimum and Hoklingen shorelines (Figs. 4 and 6).

Implications for deglaciation history and climatic variations during Younger Dryas

Considerable ice-retreat by calving in the Trondheimsfjord region during Allerød was succeded by a YD readvance from the E and NE to the Tautra position in N-Trøndelag (Reite 1995, Rise et al. 2006). The presence of Allerød clay overlain by YD till suggests a readvance of at least 15-20 km (Fig. 4, Reite 1994). South of Trondheim the Tautra Substage in S-Trøndelag is seemingly represented by a halt/stillstand in the ice-margin, an interruption in the ice retreat, rather than a major ice readvance, as inferred by less frequent push-moraines and an abundance of frontal melt-out features. This may indicate a glacial environment more influenced by cold-based ice south of Trondheim than in the north, where features indicating warm-based ice are more abundant (push moraines, drumlins, etc.).

The ice margin retreat before the Hoklingen Substage readvance is inferred to have reached at least to locality Leinkammen south of Steinkjer (H17-H18, Table 2), 10 km proximally to the large ice-marginal deposit at Straumen (Fig. 2c and 3). At Leinkammen glaciomarine clays are deformed and overrun by ice assumed of Hoklingen age. Hoklingen Substage moraines have been mapped and morphologically correlated more or less continuously from north of Namsos to more than 50 km south of Trondheim (Fig. 2a), which indicates a considerable readvance in the whole region. The early YD Tautra Substage is still considered to represent the maximum YD position in Mid-Norway (Fig. 1). However, the corresponding late YD ages make it likely to correlate the Hoklingen Substage with the maximum YD position in western Norway (the Halsnøy-Herdla Substage), which also represent a considerable readvance (e.g., Mangerud 2000).

The distance parallel to ice flow direction between the positions of Tautra and Hoklingen ice-marginal deposits varies between 10 and 50 km (Figs. 2–3), with an average regional distance of 20–25 km. This is quite similar to the distance between the likely correlative YD Ra and Ås-Ski moraines (maximum and minimum positions) in the Oslofjord area (Fig. 1; and, e.g., Andersen et al. 1995). The difference in ice

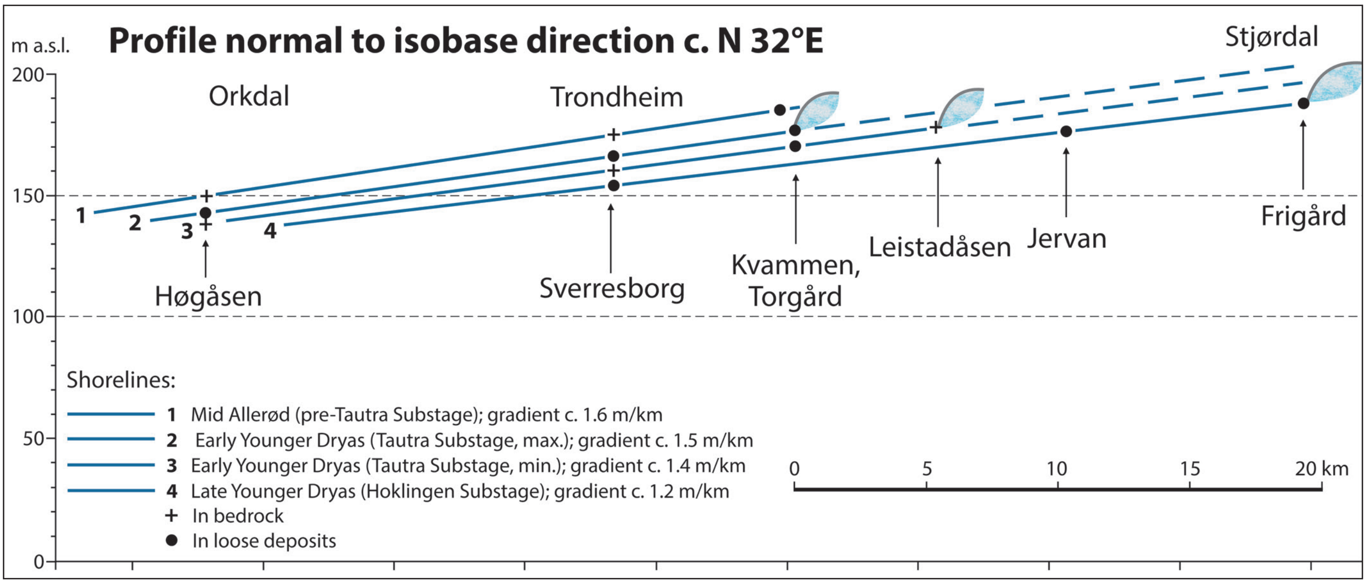

Figure 6. Generalised shorelines representing mid to late Allerød time, and the YD Tautra maximum, Tautra minimum and Hoklingen substages sea levels in the Trondheim area. Sverresborg, the central locality where all four shorelines are represented is indicated (S in figure 3, Sv in figure 5). The positions of the main sites for the Tautra substage shorelines (Kvammen, Torgård and Leistadåsen, see figure 5) are indicated. Høgåsen, a site west of Trondheim where Tautra shorelines are inferred to be represented both in bedrock and loose deposits, is indicated in figure 3 (Hø). The site Tiller is not indicated, but is located just adjacent to Kvammen and Torgård to the W (left). The proper Hoklingen substage shoreline recorded at Stjørdal (185 m a.s.l. at Frigård) and at Jervan (175 m a.s.l., figure 5 and J in figure 3) is also indicated (black dots). The gradient of the Hoklingen substage shoreline is slightly steeper than the gradient (c. 1.1 m km^{-1}) found for the shoreline directly following the Hoklingen Substage, as reconstructed by Sveian and Olsen (1984) west of Verdal. Profile line for the projected shorelines is indicated in figure 3. Positions of Tautra maximum, minimum and Hoklingen ice margins are indicated.

surface elevation varied according, with an assumed vertical difference of several hundred meters in areas near the ice margins and 150–200 m height difference in the mountains south in the study area (Olsen et al. 2013, Olsen et al. 2014). The ice volume that have melted during deglaciation between the Tautra and the Hoklingen Substages, along a 300 km transect from north to south in Trøndelag, must therefore have been larger than 20×0.2×300 km (c. 1200 km^3). This represents a vast body of melted ice, which indicates more than small adjustments of ice retreat and distribution due to topographical variations. Consequently, a relatively strong climatic amelioration during mid-Younger Dryas is suggested to explain the difference in area extension and volume of ice associated with the Tautra and Hoklingen Substages (Reite 1995). Two of the largest ice-marginal glaciofluvial deposits in the area, Kaldvelldalen and Hovin, are located between the Tautra and Hoklingen moraines, indicating high meltwater drainage in this period. However, the relatively clear indications of climatic amelioration during mid-YD in central Norway, as seen from the glacier retreat history, are not clearly recognized in the palaeovegetation history. Though, an increase in pollen from thermophilous trees and reduced content of none-tree pollen during mid-YD are recorded in the Trondheim area (Hafsten and Mack 1990). Pollen and plant macro fossils of YD age in central Norway indicates small variations during YD, but no significant climatic amelioration during mid-YD, as indicated by the ice retreat history.

A climatic amelioration during mid-YD is not recognized from the palaeovegetation record in other parts of Norway either, although with a few exceptions. One of these exceptions is at Andøya in northern Norway where such data have been recorded (Vorren and Alm 2009, Vorren et al. 2009), which may indicate some regional climatic variations during Younger Dryas in other parts of Norway too. This is also supported with data from the marine record where variations in sea ice conditions changed during YD, for example with significantly less sea ice during mid-YD than during early YD in Northern Norway (e.g. Cabedo-Sanz et al. 2013).

The elevation of the Hoklingen ice-marginal moraines reaching at least 1100 m a.s.l. NE of Oppdal (Fig. 1, and Olsen et al. 2007, Olsen et al. 2013, Olsen et al. 2014) show that the mountain areas in the inland to the E and SE of Oppdal were not fully deglaciated in YD, as proposed by Dahl et al. (2005) and Paus et al. (2006). However, some mountain areas above 1250 m a.s.l. in this region may well have been at least partially deglaciated in the transition between YD and Holocene, as shown by Paus et al. (2015).

Acknowledgements
The ^{14}C-dates referred to in this paper have been carried out as a part of the general Quaternary geological mapping made by the Geological Survey of Norway during the last decades. Stein Bondevik and John Inge Svendsen have reviewed the original manuscript and given comments and suggested changes that have improved the revised version of the manuscript significantly. Irene Lundqvist has drawn the figures. We are grateful to all these persons.

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