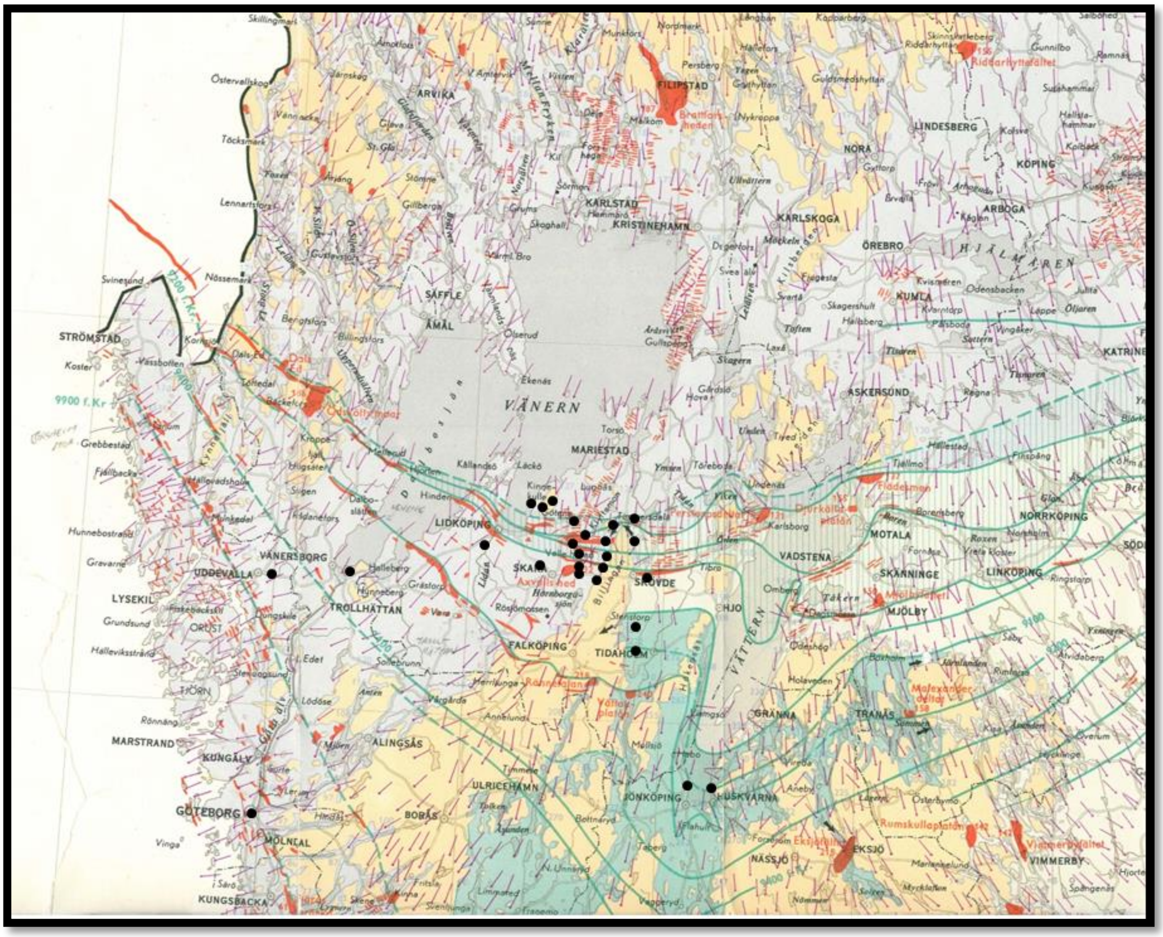
The 2nd annual NORDQUA field trip

Deglacial history and geomorphic development of the area between Vänern and Vättern: Younger Dryas moraines, the Baltic Ice Lake drainage and the dynamic Vättern Lobe



Field trip leaders: **Helena Alexandersson, Martin Bernhardson, Svante Björck, Tom Dowling, Sarah Greenwood, Mark Johnson, Per Möller, Tore Påsse, Colby Smith, Henrik Swärd, Per Wedel, Christian Öhrling**

Guidebook by Mark D. Johnson with contributions from those listed above

Contents

Information

Dates and Times: We leave from Geovetarcentrum at Wavrinsky's Plats by one bus at 8:30 on 21/9. We will make a stop at Landvetter airport at 16:00 on the 24th.

Course requirements:

This field trip will be a course for 3 ECTS credits. Upon completion of the course requirements, I will sign a Gothenburg University certificate that you have fulfilled the requirements for this 3-credit course. Here are the requirements:

- • You must maintain a field note book to document the stops (I will look at these on the bus home!)
- • Have a familiarity with the pdf's of articles for this trip. I am preparing and selecting about 10 'essential' papers for our trip. These I will be sending out two weeks before you arrive for your perusal.
- • Every person will present a short, 5-minute (power point or not) presentation of their current or planned research project. This will be on the three evenings we will be at *Flämslätt*.
- • After the trip, you will submit within two weeks a short paper (5 pages) answering key questions that have arisen during the trip. These questions will be developed during the trip and assigned to you afterwards.

When all this is satisfactorily completed, I will issue the certificate.

Payment: The cost of the trip is 3000 SEK. This must be paid before you can get on the bus!

Meals and Lodging: All meals and lodging are covered by the expenses. Therefore, I need to know of any menu restrictions ASAP. We will be staying at Flämslätt (http://flamslatt.se/) in beautiful Valle Härad for all three nights on the road. We will have dinner and breakfast each day, and they will provide us with a lunch-sack. Please bring sheets and towels! But you can also buy these there for 60 SEK a day. We will be staying hostel-style in rooms with 2-4 beds per room—we will sort this out when we arrive!

Clothing: Prepare for anything! Rain, sun. We will do some moderate hiking and investigate some steep exposures, so appropriate shoes… To save our reputation with the bus company, it might also be good to have 'on the bus' shoes' and 'in the field' shoes. If you are careful with the mud, this is not necessary.

Articles for the course

These articles were sent out to all participants as pdf's.

Björck, S., & Digerfeldt, G. (1984). Climatic changes at Pleistocene/Holocene boundary in the Middle Swedish endmoraine zone, mainly inferred from stratigraphic indications. In *Climatic changes on a yearly to millennial basis* (pp. 37-56). Springer Netherlands.

Björck, S., & Digerfeldt, G. (1986). Late Weichselian–Early Holocene shore displacement west of Mt. Billingen, within the Middle Swedish end-moraine zone. *Boreas, 15*(1), 1-18.

Björck, S. (1995). A review of the history of the Baltic Sea, 13.0-8.0 ka BP. *Quaternary International, 27*, 19-40.

Cleland, C. E. (2013). Common cause explanation and the search for a smoking gun. *Geological Society of America Special Papers, 502*, 1-9.

Greenwood, S. L., O'Regan, M., Swärd, H., Flodén, T., Ananyev, R., Chernykh, D., & Jakobsson, M. (2015). Multiple re-advances of a Lake Vättern outlet glacier during Fennoscandian Ice Sheet retreat, south-central Sweden. *Boreas*.

Jakobsson, M., Björck, S., Alm, G., Andrén, T., Lindeberg, G., & Svensson, N. O. (2007). Reconstructing the Younger Dryas ice dammed lake in the Baltic Basin: Bathymetry, area and volume. *Global and Planetary Change*, *57*(3), 355-370.

Johnson, M. D., & Ståhl, Y. (2010). Stratigraphy, sedimentology, age and palaeoenvironment of marine varved clay in the Middle Swedish end-moraine zone. *Boreas*, *39*(2), 199-214.

Johnson, M. D., Benediktsson, Í. Ö., & Björklund, L. (2013). The Ledsjö end moraine—a subaquatic push moraine composed of glaciomarine clay in central Sweden. *Proceedings of the Geologists' Association*, *124*(5), 738-752.

Johnson, M. D., Kylander, M. E., Casserstedt, L., Wiborgh, H., & Björck, S. (2013). Varved glaciomarine clay in central Sweden before and after the Baltic Ice Lake drainage: a further clue to the drainage events at Mt Billingen. *GFF*, *135*(3-4), 293-307.

Lidmar-Bergström, K., Bonow, J. M., & Japsen, P. (2013). Stratigraphic Landscape Analysis and geomorphological paradigms: Scandinavia as an example of Phanerozoic uplift and subsidence. *Global and Planetary Change*, *100*, 153-171.

Lundqvist, J., & Wohlfarth, B. (2000). Timing and east–west correlation of south Swedish ice marginal lines during the Late Weichselian. *Quaternary Science Reviews*, *20*(10), 1127-1148.

O'Regan, M., Greenwood, S.L., Preto, P., Swärd, H., & Jakobsson, M, (in press). Geotechnical and sedimentary evidence for thick-grounded ice in southern Lake Vättern during deglaciation. *GFF.*

Smith, C. A., Engdahl, M., & Persson, T. (2014). Geomorphic and stratigraphic criteria used to date the Råda Landslide, Västra Götaland, Sweden. *GFF*, *136*(3), 507-511.

Strömberg, B. (1992). The final stage of the Baltic Ice Lake. *SGU series Ca. Research paper*, (81), 347-353.

Strömberg, B. (1994). Younger Dryas deglaciation at Mt. Billingen, and clay varve dating of the Younger Dryas/Preboreal transition. *Boreas*, *23*(2), 177-193.

Swärd, H., O'Regan, M., Ampel, L., Ananyev, R., Chernykh, D., Floden, T., Greenwood, S. L., Kylander, M. E., Mörth, C. M., Preto P., & Jakobsson, M. (in press). Regional deglaciation and postglacial lake development as reflected in a 74m sedimentary record from Lake Vättern, southern Sweden, *GFF.*

Introduction

The 2nd Annual NORDQUA field trip is designed as a PhD course to visit important sites that show the geomorphic and Quaternary geologic character of the area between Lakes Vänern and Vättern in southwest Sweden. These include classic sites, but there has also been a flurry of recent activity that have added to the overall story.

Take-home messages

Among the BIG TAKE-HOME MESSAGES for this trip are the following

- The Quaternary story is played on an ancient bedrock landscape that consists of a subcambrian peneplain, which is intact in places, but also altered elsewhere to a fissure-valley landscape (Sw. *sprickdalslandskap*) as a result of Mesozoic weathering and subsequent removal of weathered products. Inselbergs with a Paleozoic sequence (Kinnekulle, Halleberg, Hunneberg, Billingen) remain on parts of the peneplain and we will visit these. Very little glacial erosion has occurred in the Quaternary. *Day 1.*
- The stratigraphy of the area contains glacial, fluvial, lake and marine sediments deposited during deglaciation across the Pleistocene Holocene boundary. *All days.*
- Readvance and slowed-retreat of the Scandinavian ice sheet during the Younger Dryas produced a series of moraine ridges (push moraines mostly) referred to has the Middle Swedish end-moraine zone. These ridges were made by ice-marginal oscillations during overall retreat during the YD. *Day 2.*
- Areas below 100-200 meters in the area were submerged under the ocean (west of Billingen) of beneath a series of ice-dammed lakes (east of Billingen) so that fine-grained glaciomarine and glaciolacustrine sediments dominate the lowland areas. Much of these sediments (marine and lake) are varved. *All days.*
- Emergence of the land to today's level has occurred through a complicated interplay of isostatic uplift, sea level change and changing outlets of dammed lakes. *All days.*
- Following and during emergence, eolian activity created distinct dune fields, and OSL dates reveal when these activities occurred. *Day 2.*
- Some of the glaciomarine sediments are sensitive and prone to failure. Some of these failures occurred soon after deglaciation and are associated with faulting that occurred during times of rapid uplift. *Day 1.*
- Glacial Lake Tidan formed between Billingen and Vättern during deglaciation and had a complicated history of level changes, as well as several times of connection with the Baltic Ice Lake. *Day 3.*
- The Baltic Ice Lake drained catastrophically near the end of the YD, and there is sedimentologic, stratigraphic and geomorphic evidence that supports the drainage occurred
    - initially subglacially
    - under, through or over stagnant ice lying in the Lången basin
    - over the southern trough of Klyftamon and
    - into the North Sea at the western edge Klyftamon. *Days 2 and 4.*
- West of Klyftamon, Baltic ice lake drainage deposits are found in a stratigraphic sequence sandwiched between two distinct varved sequence whose character can be explained by the opening of the Närke strait and the start of the Yoldia Sea episode.
- De Geer moraines, which were called 'annual moraines' (Sw. *årsmoräner*) by Gerard De Geer may likely be annual! *Day 3.*
- A remarkable landscape of dead-ice landforms (Valle Härad) turns out to be quite complex with a surface geomorphology that is best explained by gradual development during the YD, parallel with end-moraine formation. *Day 2.*
- A lobe of the ice sheet extended into the Vättern basin, and recent evidence shows that the 'Vättern Lobe' acted somewhat independently of the surrounding ice sheet. This is shown by geotechnical evidence recently found in a Vättern core.
- Cl^- content in pore water of the varved sequence found in the Vättern core, which appears to have peaks in the Alleröd and at the end of the YD, lends considerably strength to the idea that the Baltic Ice Lake has an earlier drainage during the Alleröd. This drainage was first suggested in shoreline-displacement curves in southern Sweden that indicated a lake-level drop during the Alleröd. *Days 3 and 4.*
- Complex geological questions are solved following multiple paths opf inquiry and searching for a 'smoking gun.'

Bedrock geology of the field-trip

The bedrock geology of the area is well summarized elsewhere, but the most important elements are the gneiss and granite crystalline bedrock of Precambrian age as well as the isolated remnants of a formerly extensive Paleozoic cover occurring in Billingen, Kinnekulle, Halleberg and Hunneberg. Figure 1 shows the bedrock geology of southern Sweden.

Baltic Ice Lake drainage and the Middle Swedish end-moraine zone between Skara and Götene

Baltic basin water bodies during deglaciation

Perhaps the most dramatic and the most researched event during the late Quaternary of Sweden is the development of water bodies in the Baltic basin, including the drainage of the Baltic Ice Lake.. Following the Late Glacial Maximum (LGM) (Fig. 2), and as the ice margin of the Scandinavian Ice Sheet (SIS) melted northwards , water began to be ponded in front of the ice in the Baltic basin (Fig. 3). The resulting development of the well-known Baltic stages (Baltic Ice Lake, Yoldia Sea, Ancylus Ice Lake, and Littorina Sea; Figure 4) is a result of the interplay of four factors:

- Retreat of the ice margin,
- Eustatic sea-level rise,
- Isostatic rise of the crust, and
- The topography revealed by the retreating ice.

The interaction of these four factors produced the unique sequences of stages that have been studied for over a hundred years by geologists, physical geographers, archeologists, and paleobiologists (Figure 4). A summary of these stages is provided by Björck (1995, 2008) and Andrén (2003a, 2003b, 2003c, 2004), and Table 1 outlines the age and character of these stages.

Deglaciation along the Swedish west coast

The deglaciation along the Swedish west coast took place over at least 5000 years and produced a series of ice-margin positions marked by ice-marginal-delta moraines and push moraines (Figure 5). Remarkably, except for these moraines and the thick clays that fill the valleys (see next section), little glacial sediment occurs in the excursion area, and in most places, the bedrock is devoid of a till cover, even above the marine limit (‘HK’). These moraines/ice-margin positions were formed at the same times as the Baltic Ice Lake expanded on Sweden’s east coast, and many of them were formed with the ice margin standing in the ocean. The ages of these west-coast moraines, including the Halland coastal moraines (see Fernlund, 1988, 1993), the Gothenburg moraines (see Wedel, 1971), the Berghem moraine (see Ronnert and Wedel, 1989), and the Levene, Trollhättan (Johansson, 1982) and Younger Dryas moraines, have been recently summarized by Lundqvist and Wohlfarth (2001) (Table 2, Figure 6).

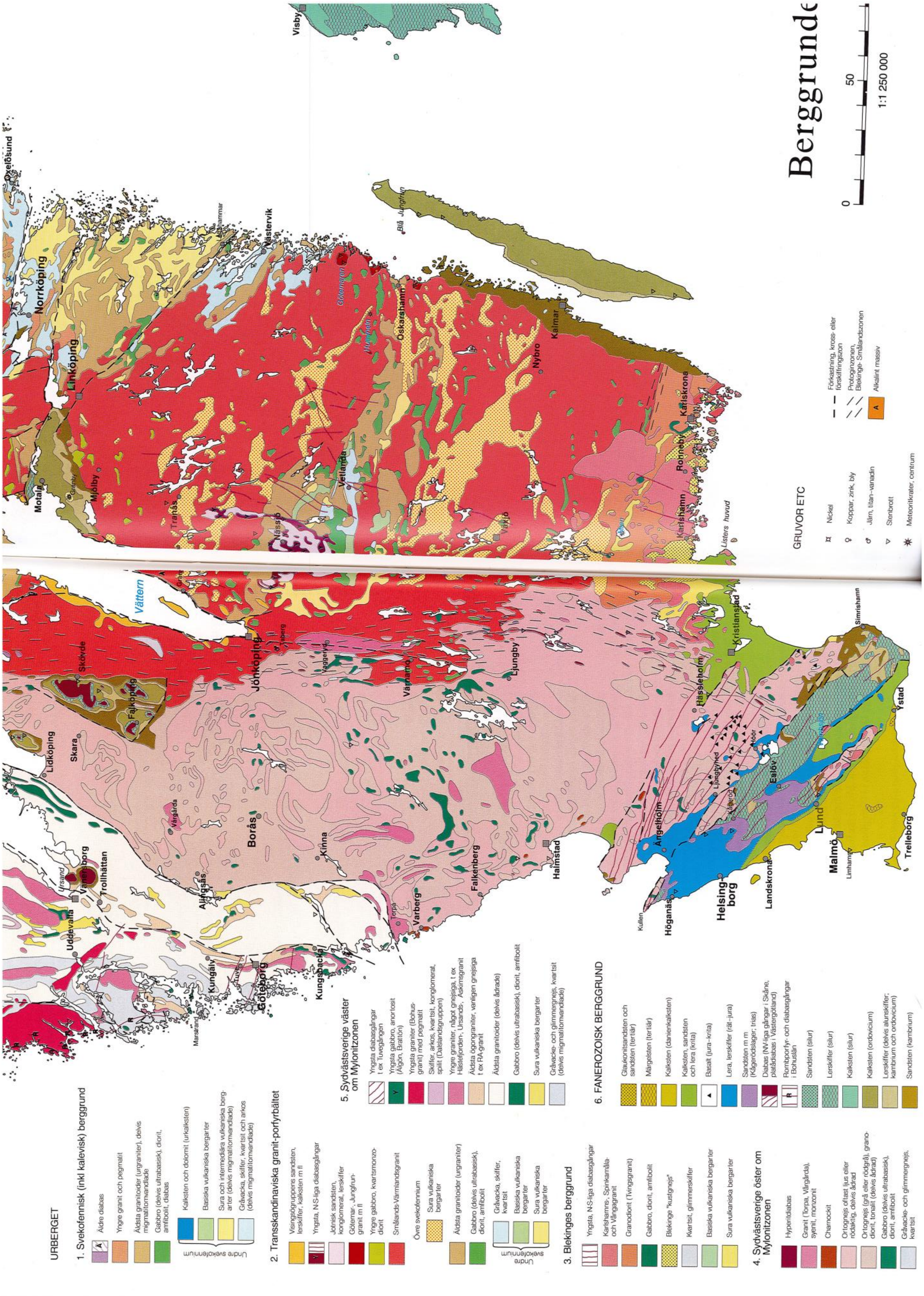


Figure 1.—From Sverige's National Atlas, Berg och Jord.

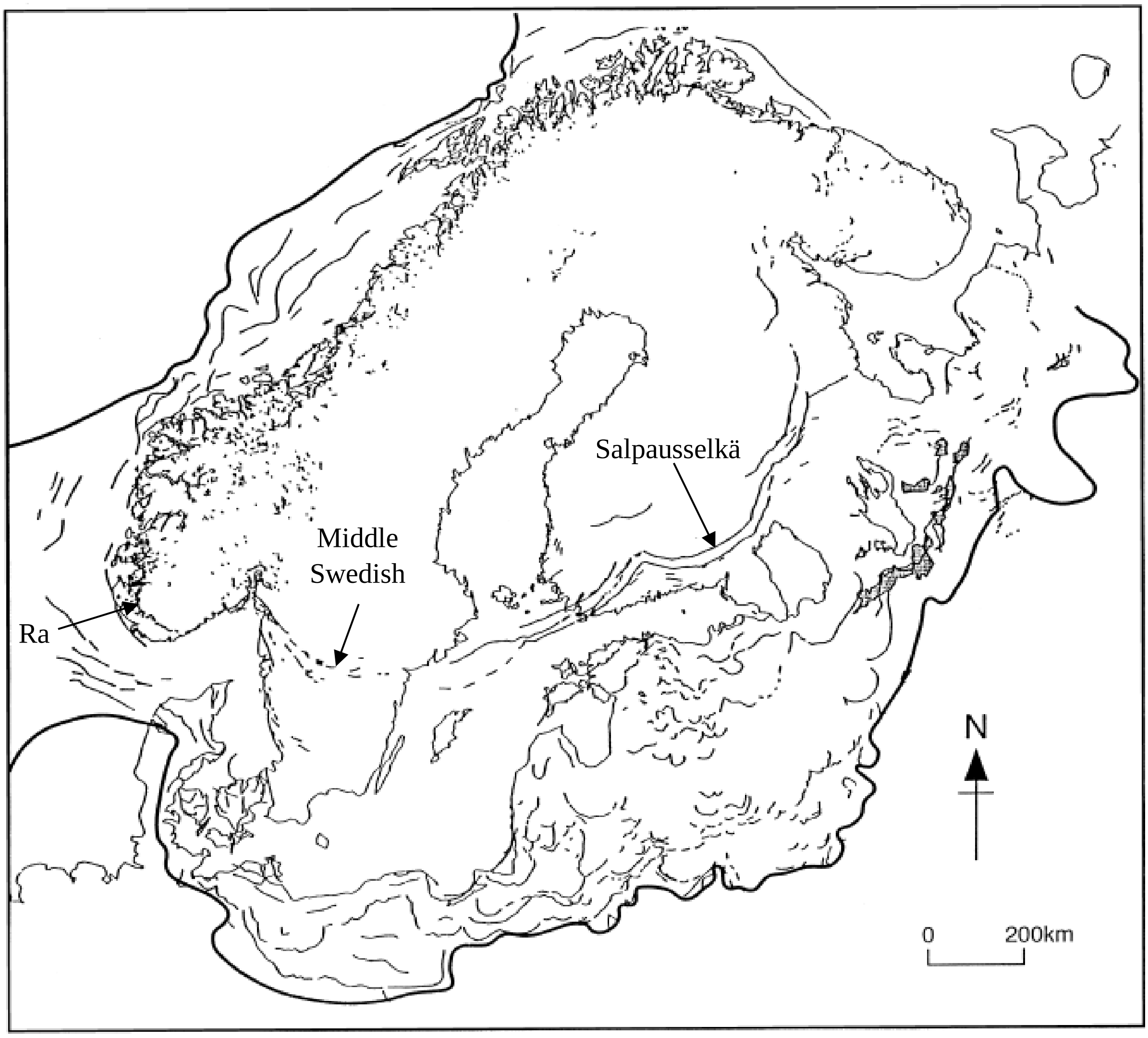


Figure 2. Map of northern Europe showing the maxiumum coverage of the Scandinavian Ice Sheet (heavy black line) and mapped end moraines (thin black lines) from Boulton and others (2001). The Salpausselkä (2-3 ridges), Middle Swedish (2-10 ridges), and Ra end moraines were formed during the Younger Dryas.

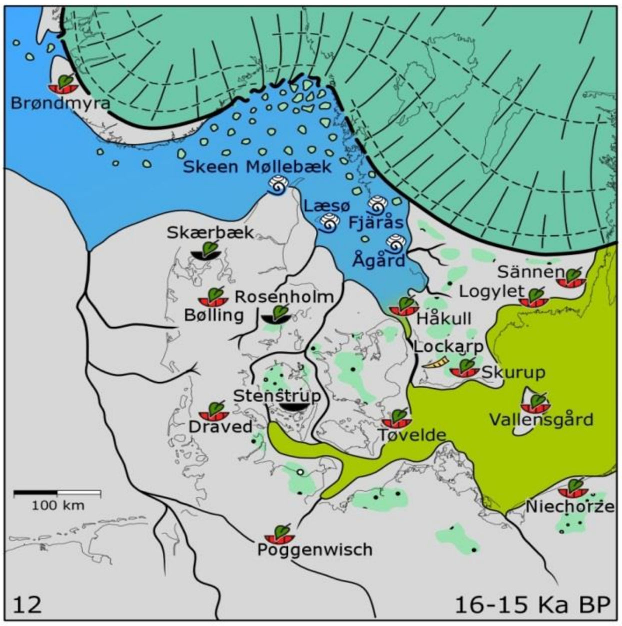


Figure 3. Paleogeographic map of southwestern Scandianvia at 16-15 Ka (calendar years) BP (Houmark-Nielsen & Kjaer, 2003). Forest green—SIS; olive green—fresh water, early Baltic Ice Lake; blue—ocean; lime green—dead ice. Leaves, shells, and names refer to dated paleoecological sites upon which the map is made.

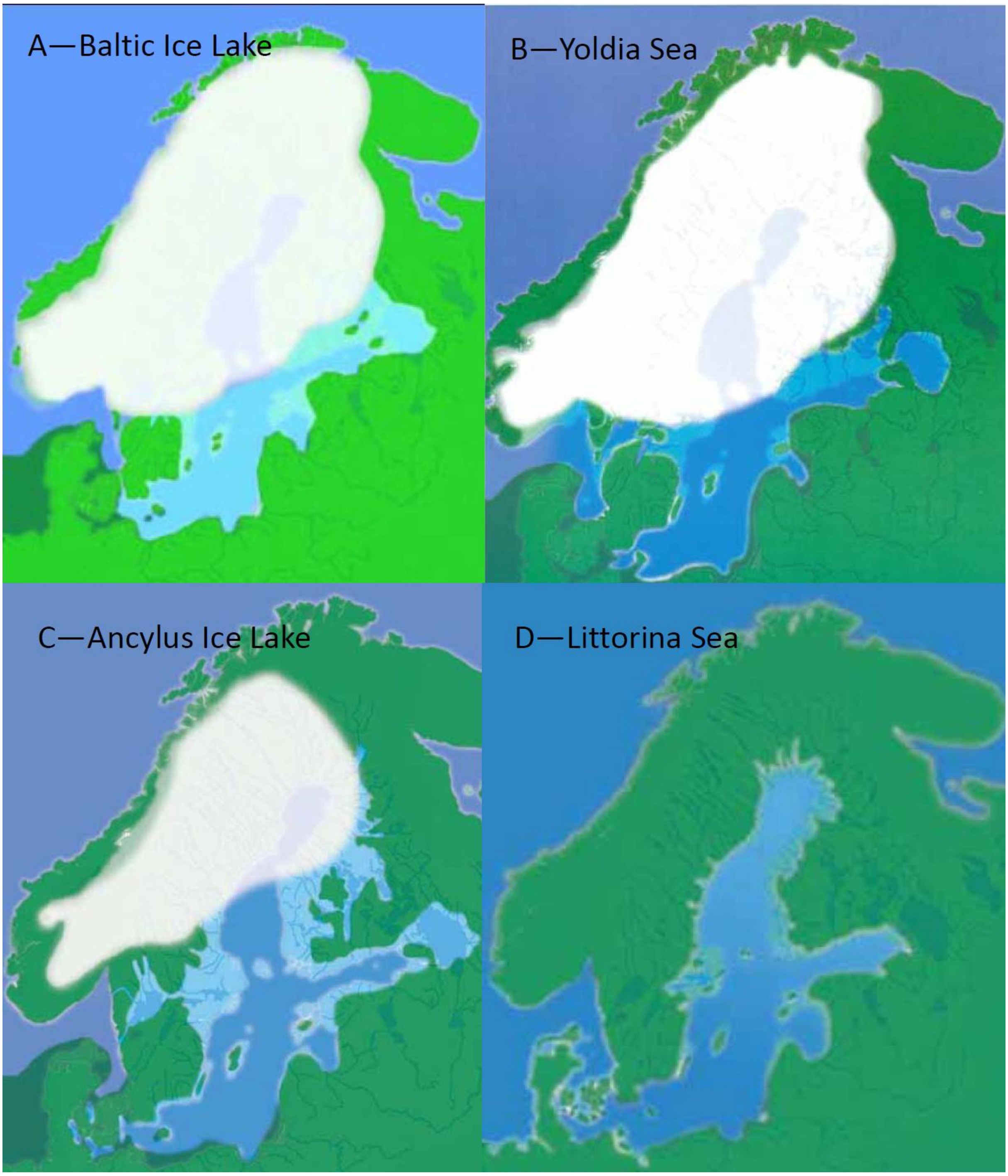


Figure 4—The stages of the ice lakes and seas in the Baltic basin during deglaciation. A shows the Baltic Ice Lake at around 11,600 yBP just before drainage. B shows the Yoldia Sea after the drainage at around 11,200 yBP. C shows the Ancylus Ice Lake at 10,500 y BP prior to outflow through Öresund. D shows the Lirrorina Sea at 6500 yBP. Images take n from Andrén (2003a, 2003b, 2003 c and 2004)

Table 1. Stages of the water bodies in the Baltic basin (from Björck, 2008)

Stage	Outlet(s)	Starting age (CAL ybp)	Duration	level	Comment
Littorina Sea	Öresund	10,000	Till present	Sea level	1000-2000 years before salt ingresses
Ancylus Ice Lake	Oteid, Steinsleva, Göta Älv, and finally Öresund	10,700	700	Up to 10-15 m above sea level	10-m fall at 10,200
Yoldia Sea	Närke Strait	11,600	900	Sea level	2nd drainage of BIL at 11,600
Baltic Ice Lake	Öresund	~15,000	~3400	A few to 25 m above sea level	1st drainage of BIL at 13,000

The Middle Swedish end-moraine zone

A major focus of this excursion during the first two days is to view and discuss the geomorphology, structure, and origin of the Middle Swedish end-moraine zone (MSEMZ), especially west of Billingen. The MSEMZ consists of a series of moraine ridges found throughout southern Sweden (Figure 6). These have also been referred to as the 'Younger Dryas moraines' because they were formed during the YD cold event, and they were formed at the same time as the Salpausselkä moraines in Finland and the Ra (and Ås?) moraine/s in Norway. The moraines in Finland were formed during overall ice-margin retreat whereas as the moraines in Norway represent a significant readvance at this time (up to 40 km) (Donner, 1995; Mangerud and others, 1979). In the western portion of the MSEMZ in Sweden, a readvance of approximately 4 km is shown at Dals Ed (Johansson, 1982). The MSEMZ consists not only of moraine ridges (one to ten in number) but also deltas and zones of thickere till (Lundqvist, 1988). Two ridges comprise the MSEMZ at Dals Ed and east of Vättern around Linköping). West of Dals Ed, the two lines converge to one and become the Ra moraine in Norway. On the east and west sides of Billingen, the multiple moraine ridges were formed during oscillating ice-margin retreat (Strömberg, 1994; Johnson and Ståhl, 2010). However, it is not known how far the ice-margin retreated during the Allerød Chronozone, prior to the formation of the oldest ridge in the MSEMZ. Based on shoreline-displacement curves in southern Sweden, Björck and Digerfeldt (1984) discovered evidence for a sudden, 10-m drop in the level of the BIL during the Allerød—the only logical location for this Allerød drainage is at Billingen, implying that the ice margin retreated at least 15 km during the Allerød (Figure 7). On this field trip, we will discover new evidence for this earlier drainage.

The current names of these moraines are a bit confusing. As we will see, the middle Swedish end-moraine zone consists of several ridges in the field area. However, the names 'Skövde moraine' and 'Billingen moraine' have been used for these as well (Figure 6). From the map in Figure 6, an implication is that the southern-most ridge in the MSEMZ could be the Skövde moraine. However, Berglund's explanation of the 'Skövde moraine' is that it consists of several moraines. So it is unclear if the 'moraine' is one or several ridges. Moreover, the southern-most ridge at Skövde is not necessarily of the same age as the southern-most ridge throughout the zone, therefore it is misleading to extend this name elsewhere. I have chosen to name the individual ridges west of Billingen for clarity, and to refer to the MSEMZ as a whole.

Figure 5. Glaciotectonic structures visible in the Levene moraine in an gravel pit in Levene. Photo by Jan Lundqvist , 1968 (Lundqvist and Wohlfarth, 2001).

Table 2. Estimated radiocarbon and calendar-year ages for southwest coast Sweden end moraines (Lundqvist and Wohlfarth, 2001; Björck, 2008; Johnson and Ståhl, 2010)

Ice-margin position	Radiocarbon age, ka	Calendar-year age, ka	Mangerud et al (1974) chronozone terminology	Greenland isotope event*
(during drainage)**	10	11.6	Younger Dryas-Preboreal boundary	GS-1-Holocene boundary
Middle Swedish end moraines***	10.4-11.8	12.1	Younger Dryas Chronozone	GS-1
Levene moraine	11.3	13.4	Allerød Chronozone	GI-1c?
Trollhättan moraine	11.8-11.9	14.2	Older Dryas Chronozone	GI-1d?
Berghem moraine	12.25-12.35	14.2-14.4	Bølling Chronozone	GI-1e?
Gothenburg moraine	12.6-12.7	14.5-15.4	Bølling Chronozone	GS-2a?
Halland coastal moraines	14.0-14.1	16-18	'Oldest Dryas'	GS-2

**Correlated using calendar ages of moraines and the ice core. Not correlated on the basis of interpreting events.*

***No geomorphic ridge, that we know of, marks the ice-margin position when drainage of the BIL occurred, with the exception of the ridge at Timmersdala. Nonetheless, this ice-margin position was referred to as the "Billingen Moraine" by Berglund (1979) and Lundqvist and Wohlfarth (2001).*

****The southernmost ridge in the MSEMZ has been referred to as the Skövde Moraine" (Berglund, 1979; Lundqvist and Wohlfarth 2001).*

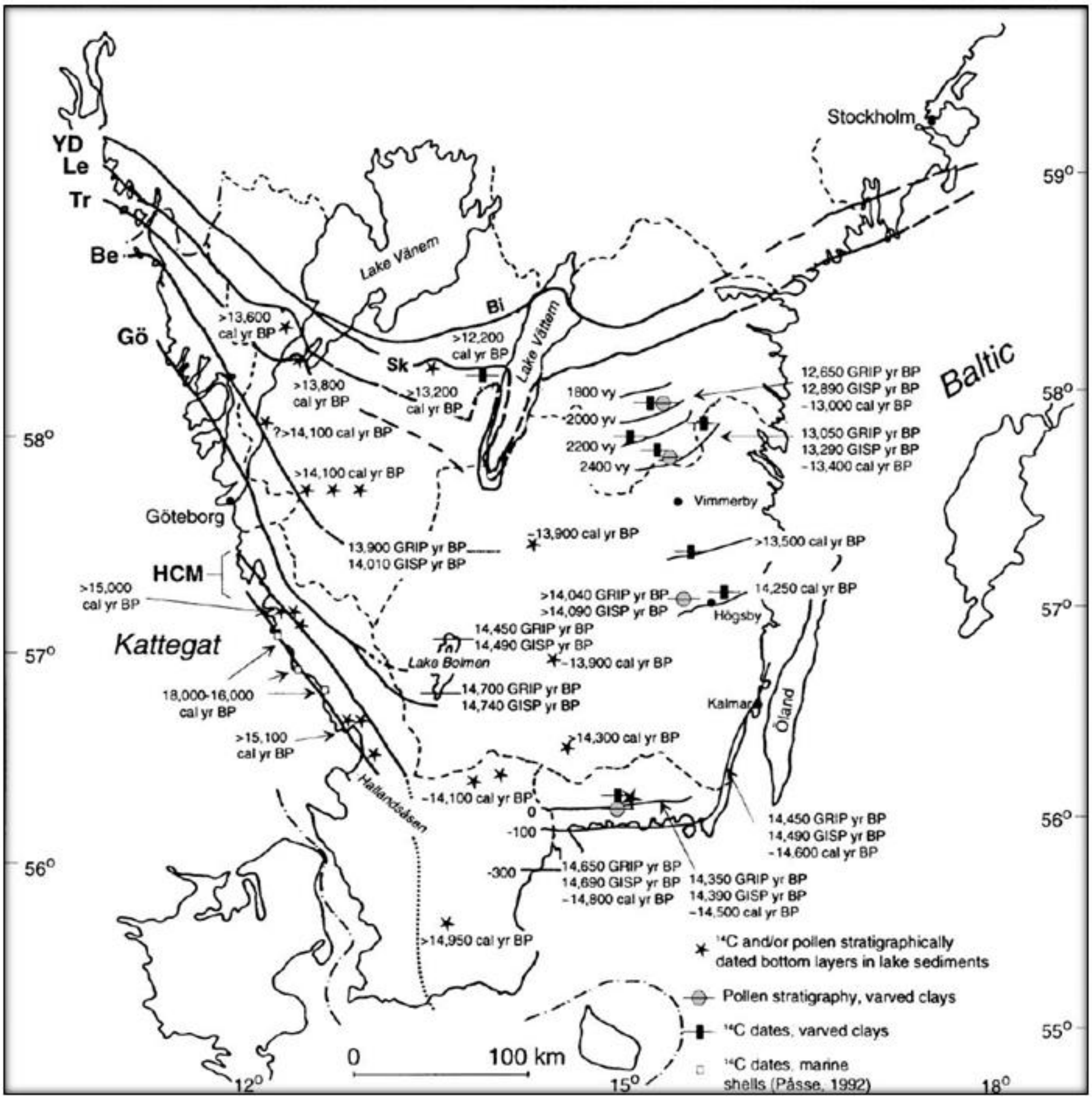
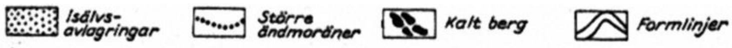


Figure 6. Map of southern Sweden showing ages of ice-margin positions. From Lundqvist and Wohlfarth (2001).

The 'Billingen moraine' is a great problem because there is no Billingen moraine (!). That is, the term 'Billingen moraine' has used is the ice-margin position at the time of the last drainage. However, there is almost no geomorphic evidence for this line, and its location is not uncontroversial. But nowhere is it represented by a moraine ridge. I recommend that we no longer use these terms.

lingen med omgivningar. Från G. Lundqvist (1961, fig. 13).



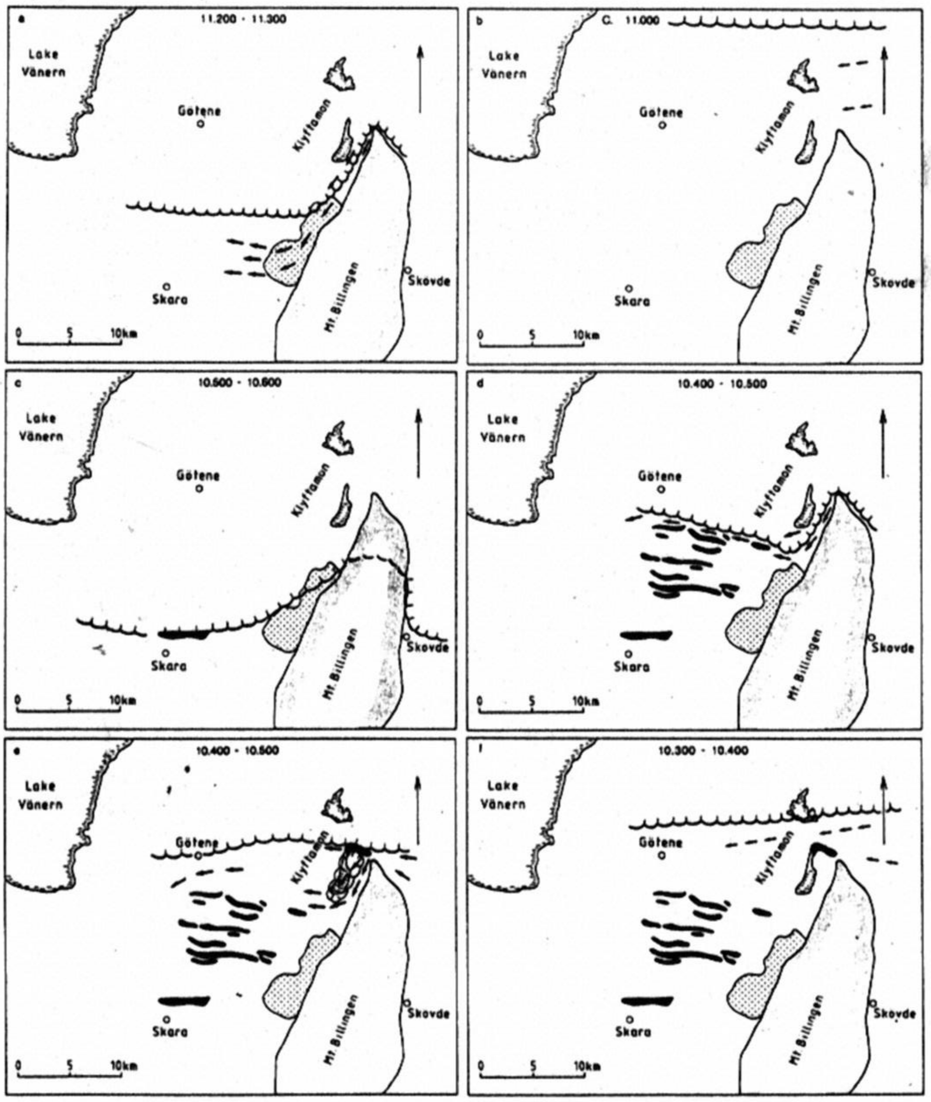


Fig. S11:7. Skiss över Baltiska Issjöns två tappningar. Öster om Billingen är issjön dämd till en nivå av 151 m ö nuvarande havsyta. Väster om Billingen står världshavets yta på 125 m ö h. Från Björck & Digerfeldt (1984, fig. 7).

Figure 7.—Sequence of ice-marginal retreat at Billingen according to Björck and Digerfeldt (1984)

SW Swedish end moraines compared to the GRIP ice core

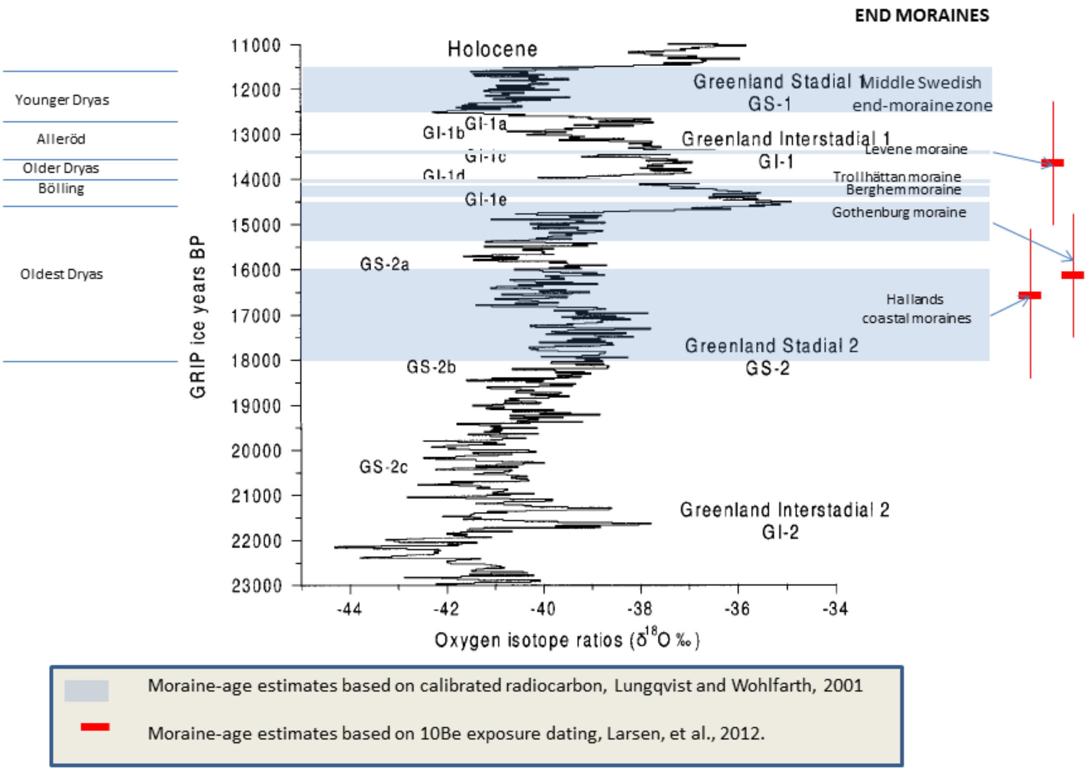


Figure 8.—Comparison of the calibrated radiocarbon dates and exposure dates on the moraines in SW Sweden (Figure 6) compared to the GRIP ice core.

Drilling and road excavation during 2006-2009 west of Billingen in the excursion area have revealed that (1) most of the 20-30 m of clay occurring between the MSEMZ ridges is undisturbed, marine, and varved; (2) this clay was deposited during the Younger Drays Chronozone; and (3) the moraine ridges are composed of YD clay pushed glaciotectonically into push moraines during small oscillations of the overall retreating ice (Johnson and Ståhl, 2010).

Evidence for BIL drainage west of Billingen

There is abundant evidence for the catastrophic drainage of the Baltic Ice Lake (for example, Strömberg, 1992; Björck, 1995)! At this time, 7000 km^3 of water drained westwards, and the water level in the Baltic basin reached sea level, beginning the Yoldia Sea phase. It is essentially certain that the ice margin stood at the northern tip of Billingen when this drainage occurred. However, the geomorphic and sedimentologic evidence of this event west of Billingen pales in comparison to the size of the event. In fact, during the IGCP excursion in 1990 (see Lundqvist and Saarnisto, 1990), many international participants visiting Billingen were profoundly unimpressed with the evidence for drainage. This led Strömberg to revisit key field areas previously described by Lundqvist and others (1931) and to 'rediscover' the boulder, drainage deposits of Klyftamon (Strömberg, 1992).

In addition to the *rullstensfält* on Klyftamon (Figure 9), other lines of evidence have been pointed out as indicating BIL drainage, including (1) areas of bedrock on Billingen and Klyftamon washed clean of sediment (Lundqvist and others, 1931; Påsse 2006a, 2006b)(Figure 9), (2) chaotic sand and gravel beds around Götene sandwiched between beds of varved clay (Johansson, 1937; Johnson and others, 2010), and (3) the deposits at Timmersdala. We will visit all of these sites on this trip. In addition to these, isotopic and sedimentologic records from cores in SW Sweden and in the Skagerrak and

Kattegat have been tentatively, but not conclusively, tied to not only the final the BIL drainage event, but also the proposed Allerød drainage. See Johnson and others (2010) for a discussion of this evidence.

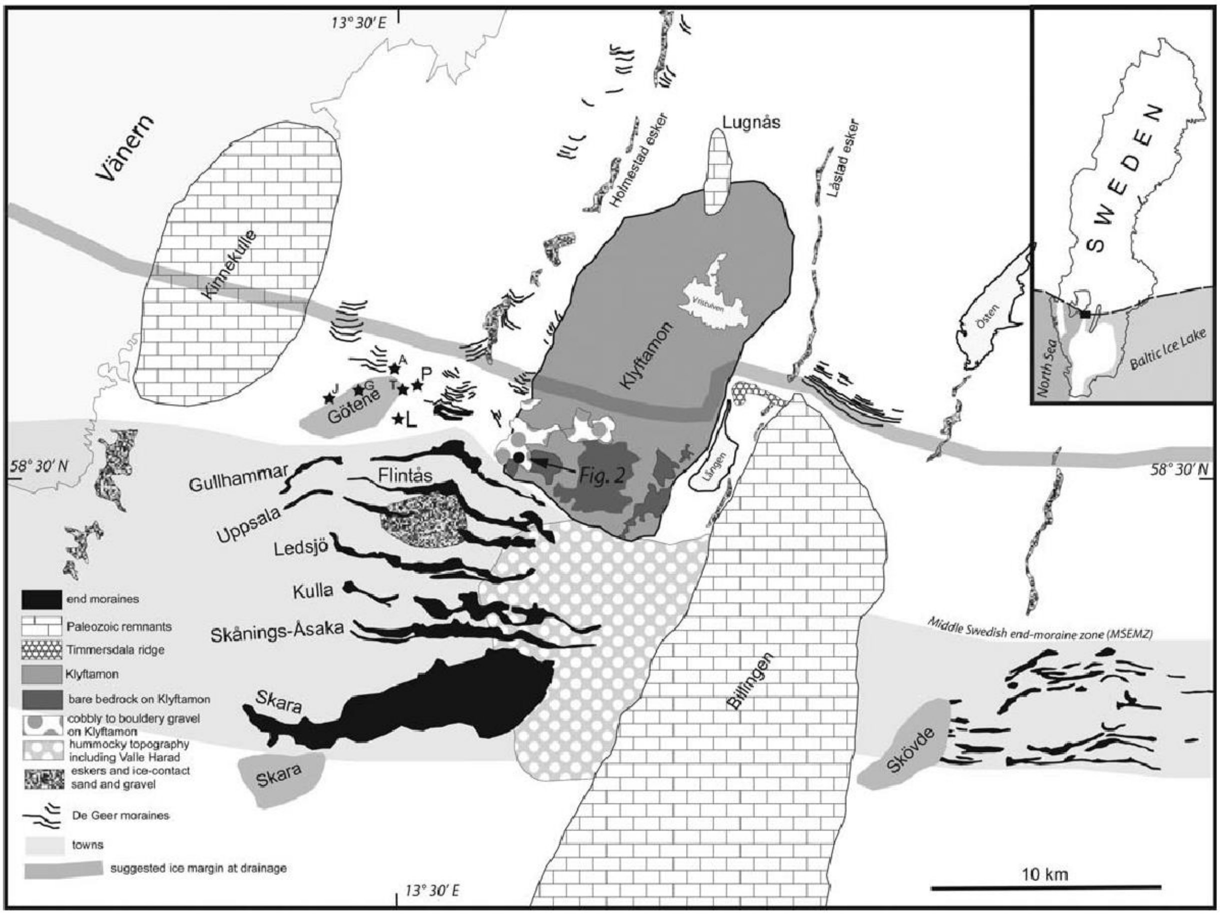


Figure.9.—Map from Johnson and others (2013) showing geomorphic features and towns between Skövde and Kinnekulle. Inset shows location of study area in Sweden. Sites described in text include A=middle ages theme park (Arns By), G=ICA grocery store in Götene, J=Simon Johansson (1937) site west of Götene, L=E20 exposure near Länsmansgården, M=gravel pit near Mellommossen, P=E20 exposure at Pellagården, T=thermal-water pipes in Götene, and Ti=gravel pit near Tisslaberget. Information taken from our field notes, Frödin (1916), and Påsse (2006a, 2006b). The suggested ice margin is drawn based on Strömberg (1992). The ice-margin position over mt. Kinnekulle and through Vänern is less certain.

Marine clay, Uddevalla shellbanks, Swedish fjords, the highest shoreline, and the Holocene marine regression

During deglaciation of the southwestern Sweden, the isotstatic depression of the crust meant that much of this region was below sea level. Figures 10 and 11 show the marine limit (*högsta kustlinjen, 'HK')* throughout Sweden. The value of the marine limit is dependent on primarily three interacting factors: (1) the amount of isostatic crustal depression at each point (which is in turn a function of ice thickness and time), (2) the eustatic sea level when each point was deglaciated, and (3) the time of deglaciation at each point. Nearly everywhere in Sweden, the marine limit was formed immediately upon ice-margin retreat. That is, the shoreline regressed immediately following deglaciation. The question of marine transgression following deglaciation has been raised in a few places, but generally, is not thought to have occurred, and if it did, only in a minor local way.

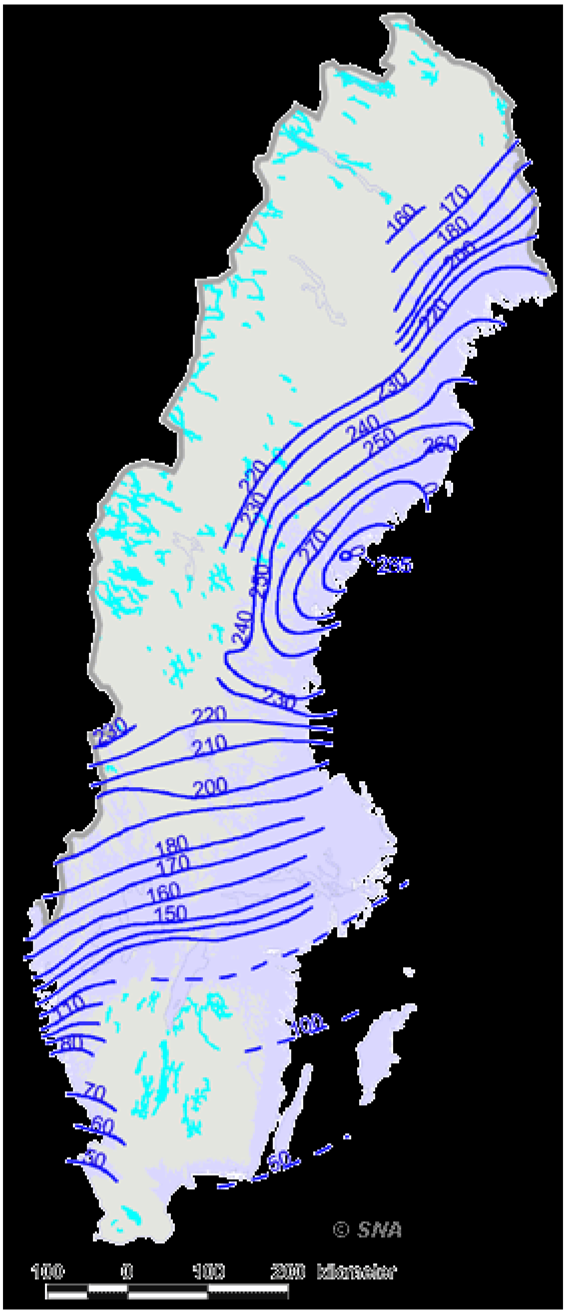


Figure10.—'HK' map of Sweden from Sveriges National Atlas.

Marine clay—'glacial clay,' 'post glacial,' and the Pleistocene/Holocene boundary

The bedrock valleys of the west coast are filled with up to 100 m of marine clay that has been referred to as 'glacial clay,' for those clays deposited proximal to the ice margin during ice retreat (therefore, a 'time' term), and 'post-glacial' clays for those deposited after roughly 9000-10,000 radiocarbon years ago. Because the transition between the glacial and post-glacial clays is considered to be continuous, a large effort in the 70's and 80's was made to find a stratotype boundary for the Pleistocene-Holocene boundary. Though considerable amount of detiled information was collected for this stratotype, it was concluded not to establish the stratotype here. See Cato and others (1982) and Olausson (1982) for details. The paleoenrionemtn of the west cost clays as investigated by Fredén (1988)

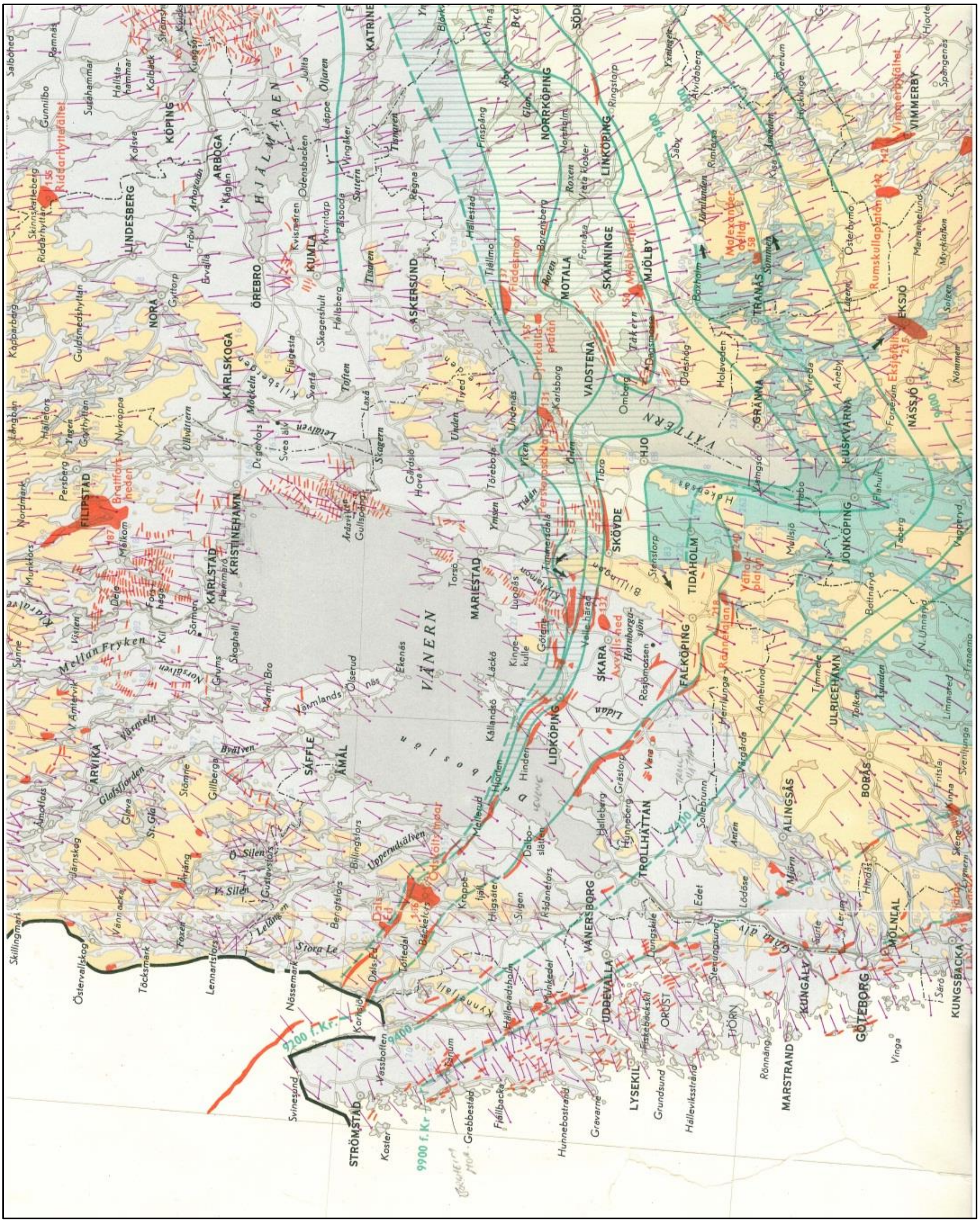


Figure 11.—Portion of Karta over landisens avsmältning *I Sverige by G. Lundqvist (1961). Light blue=land covered by the sea after deglaciation, marine limit given in places in metres; Green=land covered by the Baltic Ice Lake (light green) or local ice-dammed lakes (dark green); Tan=land above the marine-BIL limit; Red=ice-marginal deltas, end moraines, and DeGeer moraines, in places with paleoshoreline elevation in metres; Purple= striations; Green lines=recession lines; Black arrows=glacial-lake outlet.*

West-coast shells banks

The outflow of water from the Baltic basin during the Yoldia Sea phase was forced to pass through rather narrow passages along the relatively higher topography along the Swedish west coast (Fig. 12). At various points, the outflow of fresh water, and the inflow of marine water created local conditions that allowed for 'blooms' of shelly fauna and the creation of dense, thick shell banks. These were mapped and studied by Fredén (1988) who classified the fossils and interpreted paleoenvironment. Many of these shellbanks existed fror a realtively short periods of time indicating that optimal conditions for their formation (the circulation pattern and the delivery of nutrients) were quite dynamic.

Swedish fjords

Fjords along he Swedish west coast lack the dramatic relief of the Norwegian fjords, but nevertheless bear many similarities, particularly that many have a rather shallow opening to sea and a deeper in land portion in which circulation is constrained.

The fjord topography was created not by glaciers, but by extensive, deep weathering during the Mesozoic along existing fractures and faults in the Precambrian bedrock. The formation of this *sprickdalslandskap* is the subject of our final day of this excursion.

Poor circulation has led to low-oxygen conditions in several fjords. Current global warming has been suggested to be a factor in creating higher oxygen demand, and 'dead' fjord bottoms. However, recent research has shown that oxygen poor conditions have developed in Gulmars fjord during the past, notably during the Medieval Warm Period (Filipsson and Nordberg, 2010).

'HK' and the Holocene marine regression

The marine limit ('HK') in the excursion area ranges from about 100 m in the Gothenburg area to over 150 m north of Uddevalla (Figure 10).This fictitious(!) coastline, is a time-transgressive level marking the highest point marine waters reached following deglacation. At each locality where HK can be measured, it can be assumed that this level was established the moment ice retreated from that locality; that is, at the ice margin. The actual shoreline level at HK marks where ocean-meets-land *at that moment*, because both isostatic rise of the crust and eustatic sea-level rise are ongoing. In the Gothenburg area, relative sea level fall (combined effects of isostacy and eustacy) following deglaciation was on the order of 30-35 cm per year—HK was not HK for long at each point!

The successive displacement of the shoreline, not only in Sweden, but in all of Scandinavia, has been a central research question in Quaternary research. Although dated localities exist where shoreline sediment has been found, the primary method that has been used to track shoreline displacement has been the lake-isolation method.

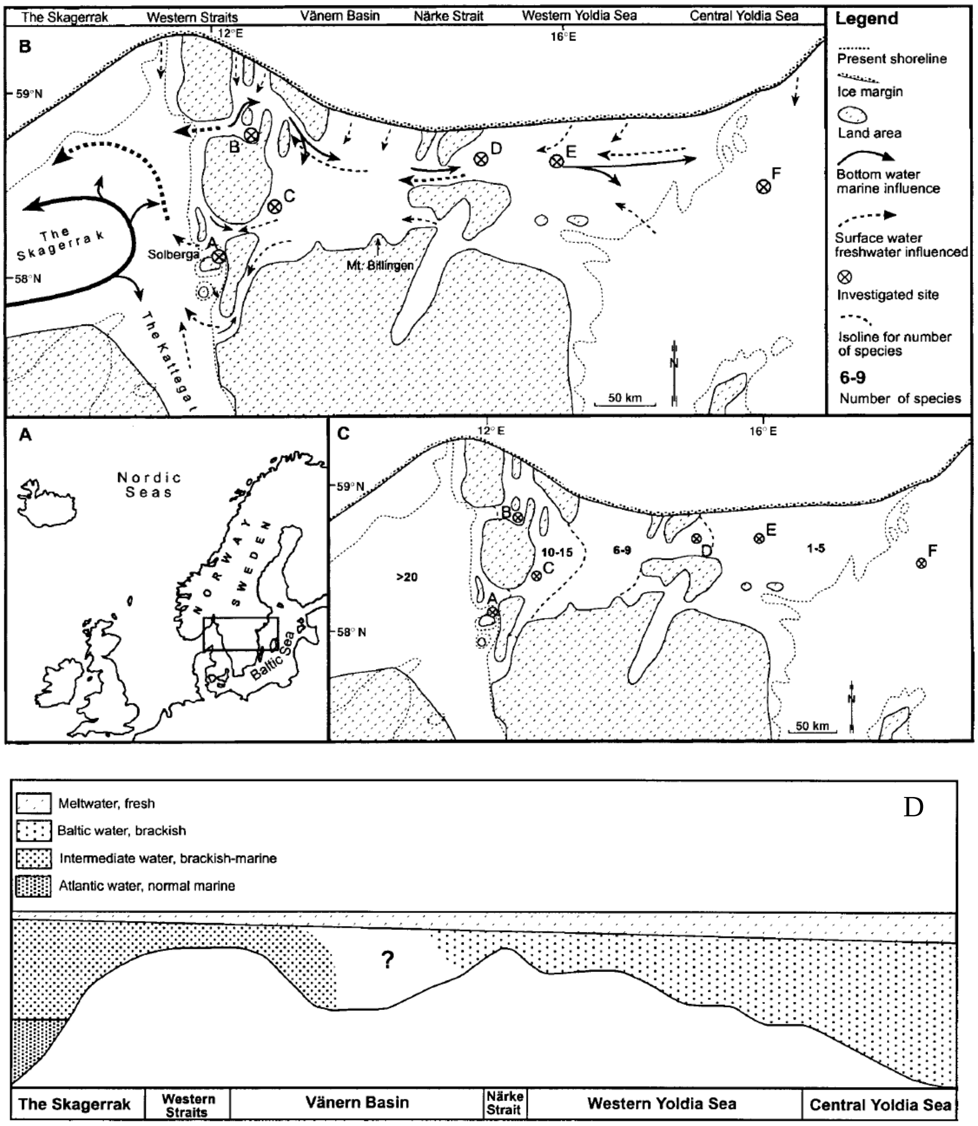


Figure 12. Figure from Schoning and others (2001) that shows the paleogeography and circulations of the sea during the Yoldia Sea stage. Numbers in C refer to number of species of forams and ostrcods found at these sites. Together with 13δC measurements, they were able to suggest the distribution of water masses shown in D.

Bedrock geomorphology—ancient deep weathering along fractures and Pleistocene glacial modification

The relation between different topographies in basement rocks with associated saprolites and cover rocks of different age has been used to interpret the morphotectonic evolution in southernmost Sweden (e.g. Lidmar-Bergström, 1995, 1996). In areas where the Precambrian basement emerges from below Palaeozoic cover rocks, for instance at Kinnekulle and Halle-and Hunneberg, it is extremely flat with a relative relief below 20 m and labelled the sub-Cambrian peneplain. The peneplain is regarded as the primary surface from which all younger basement relief has evolved (e.g. Lidmar-Bergström, 1996).

In SW Sweden the basement emerges from below Mesozoic sedimentary rocks and the relief is undulating hilly or strongly joint-aligned with a higher amplitude (c. 135 m; Johansson, 2000) and associated with deep kaolinitic saprolites (Lidmar-Bergström, 1995). The etched joint-aligned relief continues further north along the west coast in Bohuslän, but there Mesozoic cover rocks occur only offshore in the Skagerrak. Pleistocene glaciations have left clear and ubiquitous imprints of glacial erosion in the etched "joint valley landscape" in Bohuslän. Low rock bosses are scraped by ice and almost totally stripped with wide extensions of bare rocks. The intervening depressions are flat-floored due to depositions of glacio-marine clays and silts. Residues of preglacial saprolites are reported only from dm-wide fissures at road cuttings and quarries (Mattsson, 1962, Lidmar-Bergström et al, 1997, Johansson et al, 2001), unlike other areas in southern and south-eastern Sweden where deep zones of saprolites containing corestones are common (Lidmar-Bergström et al, 1997). Thus the main relief in Bohuslän has been interpreted as pre-glacially deep-weathered with a subsequently erosion of saprolites (=etching), while landforms in the minor scales have been described as completely glacially scoured. Similar landscapes of areal glacial scouring exist in shield terrain in Canada and other parts of Fennoscandia, Scotland, west Greenland, at the edges of the Antarctic Ice Sheets, in Patagonia and the South Islands of New Zeeland (Sugden and John, 1976). "Landscapes of arela glacial scouring" has been described as low relief terrain (<100 m) that everywhere bears signs of glacial erosion, comprising irregular depressions with intervening rock bosses scraped by ice. Linton (1963) used the term "knock and lochan" topography for areas in north-west Scotland. For the same area, Thomas (1995) has argued that glacial modification is associated with stripping of preglacial relief, exposing the basal weathering surface to different degrees of further reshaping. In Bohuslän it is obvious that the "knock and lochan" characters mainly are due to joint-guided preglacial etching and subsequent stripping. Since the relief farther east at the sub-Cambrian peneplain has not been glacially reshaped into this type of landscape, it can be suggested that etched relief of low amplitude is a prerequisite for "knock and lochan" topography to develop (Johansson, 2000).

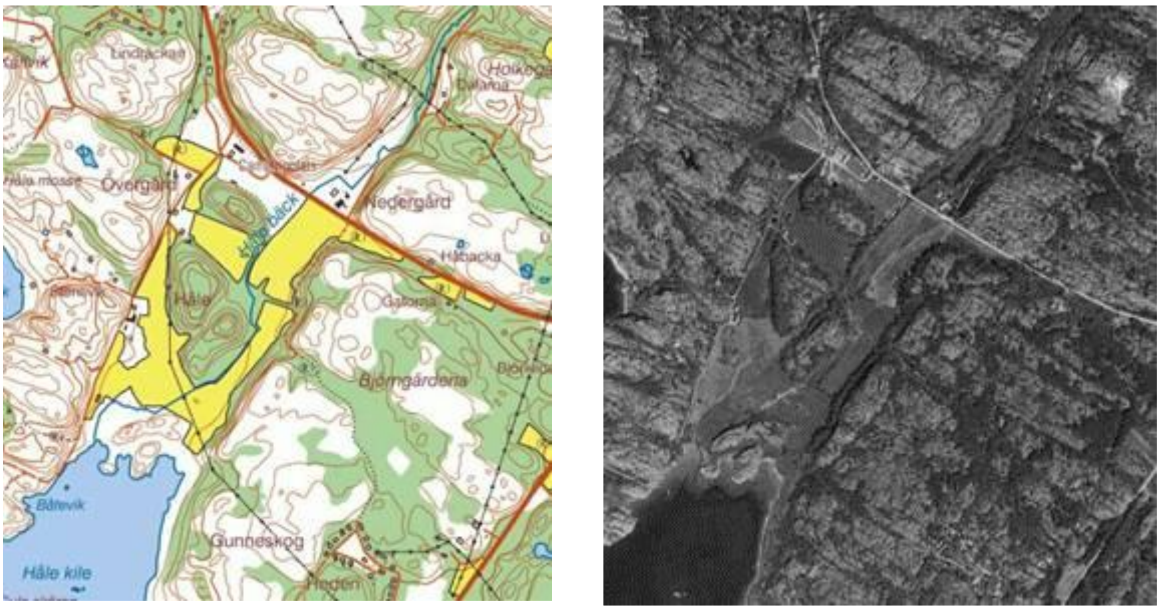


Fig 13. Depressions, or basins, have developed through deep weathering along master joints. While growing in size, basins coalesce and form maze-like pattern of depressions separated by more compact upland rock blocks.

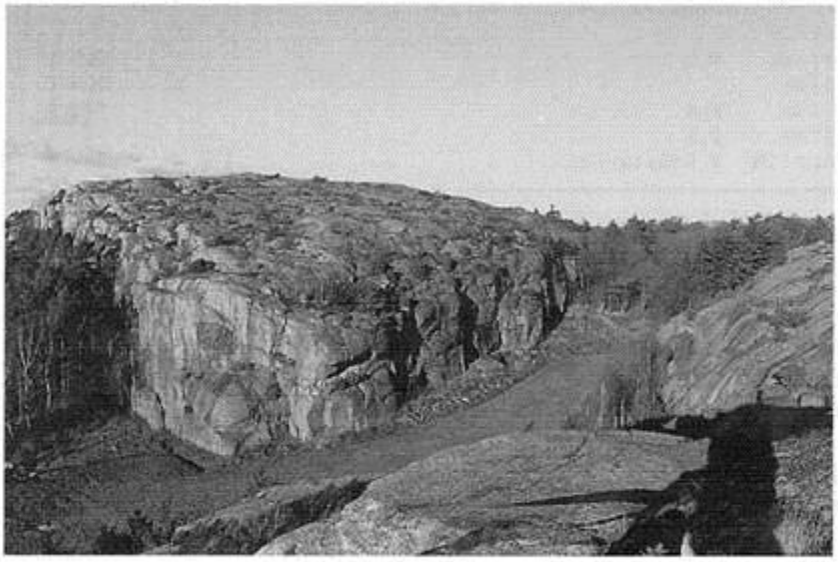


Fig. 11. A granite hill 1.5 km south of Hunnebostrand (see Fig. 9 for location). The cliff to the right strikes N–S and its wall is striated with numerous p-forms. No striae or p-forms have been found on the cliff to the left, which strikes WNW–ESE. Roches moutonnées with striae from ENE and p-forms are ubiquitous on the summit surface above the cliffs. Plucking has caused a stepped pattern above the vertical WNW–ESE striking cliff.

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Fig. 14. Granite sheet controlled roches moutonnées (left) and glaciofluvial forms (right) at Ramsvik.

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Glacial Lake Tidan

Glacial Lake Tidan (GLT) is a special glacial lake that is not often discussed, but important for this field trip. GLT existed in the low area just east of Billingen and the highland that borders the west side of Vättern, called Hökensås.(Fig. 15, 16). Numerous outlets occurred for this lake, and the lake lowered every time the retreating ice margin opened a lower outlet (Fig. 17)(Påsse & Pile, in press). At one point in its development, it was connected and at the same level as the Baltic Ice Lake, but later uplift closed this connection (where the black arrow is in the figure). It is also not clear the sequence events that occurred with GLT as the ice margin approached the position when the BIL drainage occurred. It is likely that GLT drained to the BIL prior to the drainage, but this is not completely clear.

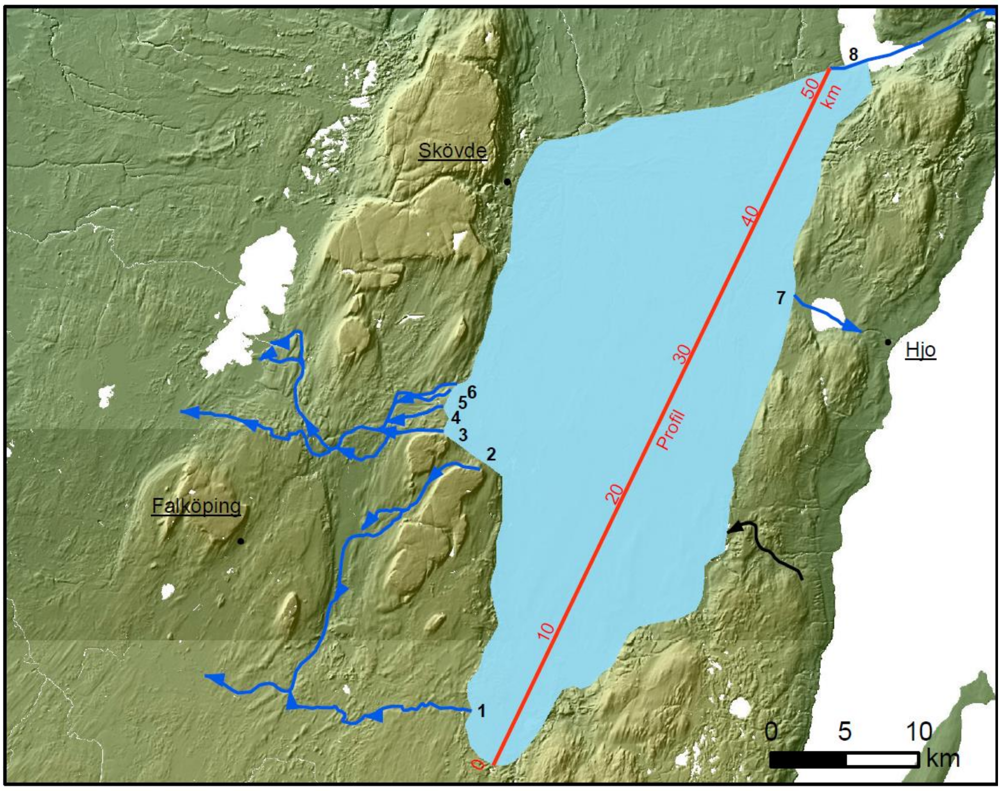


Figure 15.—The location of glacial Lake Tidan (lighter blur color). It is important to note that at no time did a lake of the size shown exist. The lake lake expanded as the ice sheet retyreated to the north, and as new outlets were formed, the lake level dropped (see Figure 16). The sequence of the outlets are shown and numbered in chronological order (from Påsse & Pile, in press). The black arrow represents a stage where GLT and the Baltic Ice Lake were connected and at the same level.

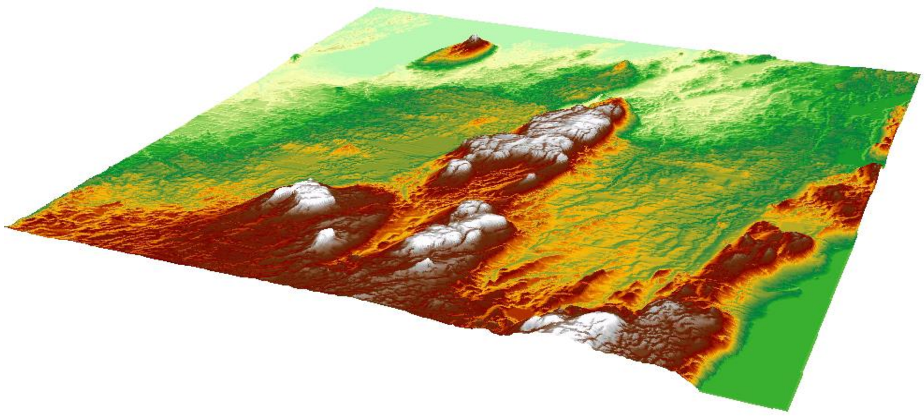


Figure 16.—A DEM of the region where the basin between Billingen and Hökensås is clearly visible. (from Påsse & Pile, in press).

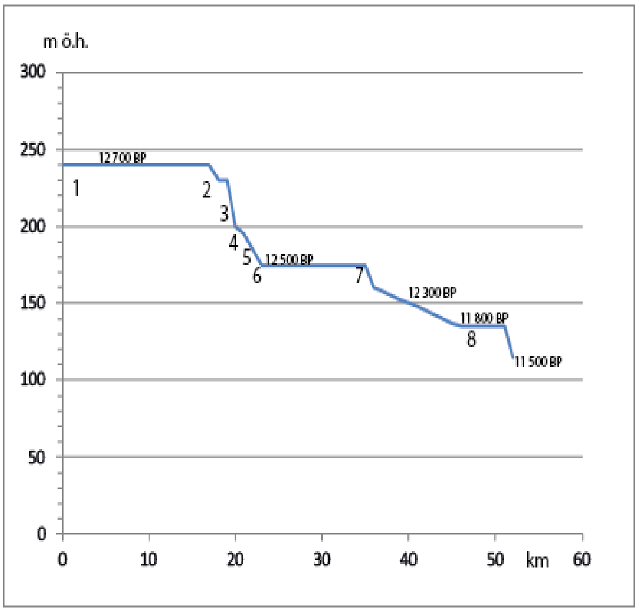


Figure 17.—Lake levels of glacial Lake Tidan. Numbers refer to outlets shoiwn in Fig. 15. The ages are in calender years (from Påsse & Pile, in press).

The dynamic Vättern Lobe

It has long been known that an extention of the Scandinavian Ice Sheet extends the length of Vättern during the deglaciation. This can be seen on the cover of this guide; G. Lundqvist's ice-retreat map. A detailed study by Waldmarsson (1986) illuminated the dynamics of the lobe, and we will visit sites described from that study. However, a slurry of papers from a Stockholm group have shown the Vättern Lobe to have been somewhat more dynamic than the surrounding ice, and it is this story that is featured on this trip (Jakobsson et al., 2014; Greenwood, et al., 2015; Swärd, et al., in press; O'Regan, et al., in press) .

Figure 18 shows how the Vättern Lobe changed through time. Compare with Figure 6.

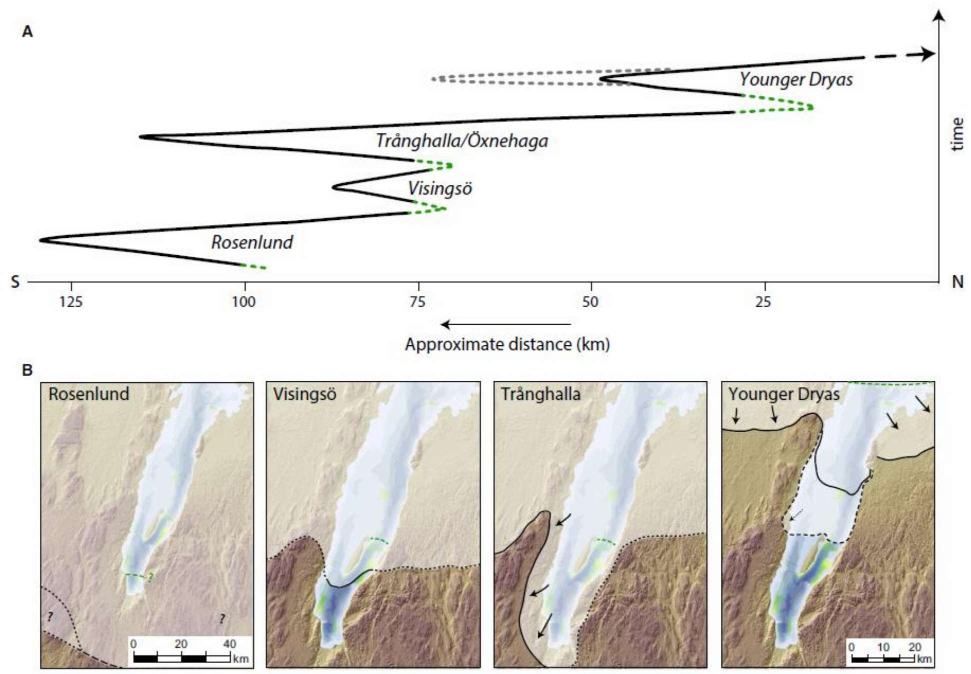
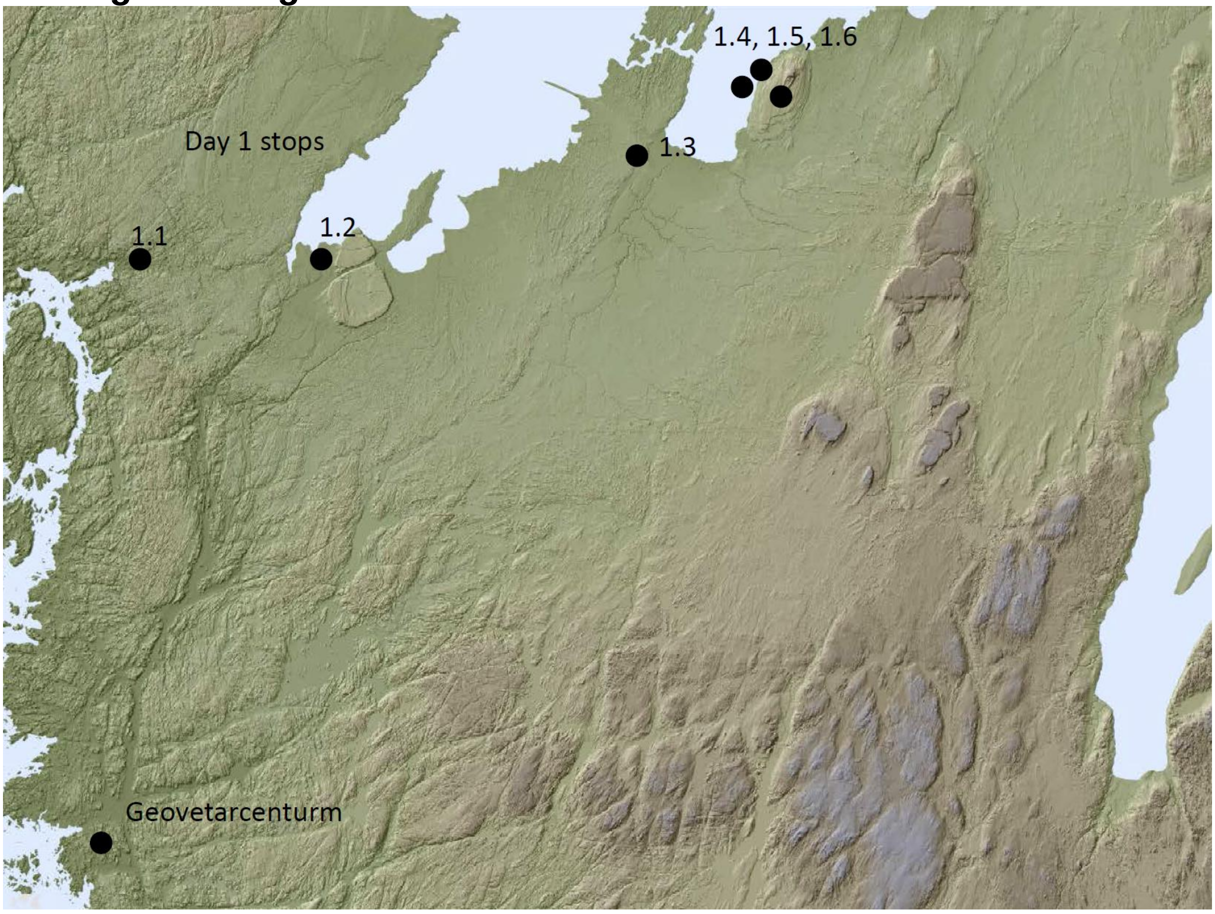


Fig. 10. Re-advances in Lake Vättern during deglaciation and the Younger Dryas, interpreted from offshore data presented herein and onshore terrestrial stratigraphy presented by Waldemarson (1986). A. Time-distance diagram, with an approximately representative distance scale, and even distribution through time. Retreat positions (in green, corresponding to those in the map panels, B) mark the minimum northerly retreat of ice prior to each re-advance event (i.e. ice must lie here or further north in each case). B. Map view of each re-advance, with corresponding prior retreat position (green dashed lines). Ice-advance limits are shown in black, based on seismic unit or geomorphological limits. The Rosenlund advance is based on Waldemarson's (1986) assertion that the Rosenlund diamict is found 30 km south of Vättern, but we have no constraint on its form or position. Dotted black lines represent uncertain/speculative ice margins. Arrows indicate marginal flow direction.

Figure 18.—From Greenwood etal., (2105)

Stops

Day one—September 21, 2015—The Bedrock Landscape and the Geologic Setting



Geovetarcentrum—Göteborg to Uddevalla

Location: SW Sweden, Göteborg to Uddevalla

Questions: What is causing the landscape relief? What has been the effect of glaciations?

Relevant excursion papers: Lidmar-Bergström et al (2013)

Background: See the section on bedrock geomorphology in the introduction. From Göteborg to Uddevalla (and beyond) we travel through a sub-Mesozoic etch surface 'etched' into the subcambrian peneplain. All of this area as we travel to the Shell Banks was under the highest shoreline during deglaciation. Glacial erosion is minor. See Figures 19-22.

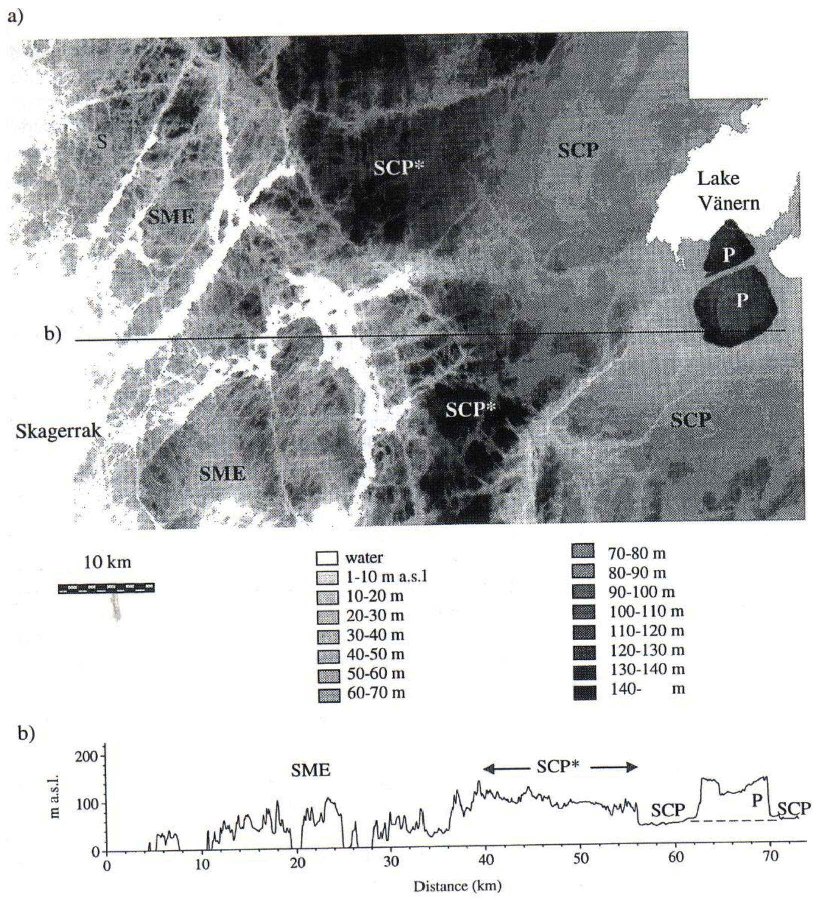


Fig. 2. a) Digital elevation data grouped in 10 m classes of the study area in SW Sweden. SCP: sub-Cambrian peneplain. SCP: uplifted and dissected sub-Cambrian peneplain. SME: sub-Mesozoic etchsurface. S: the Sotenäset peninsula. b) E-W topographic profile across the three palaeosurfaces.*

Figure 19.-- *From Johansson (2000) showing Halleberg and Hunneberg, the subcambrian peneplain exposed, and the etch surface that characterizes the coastal topography.*

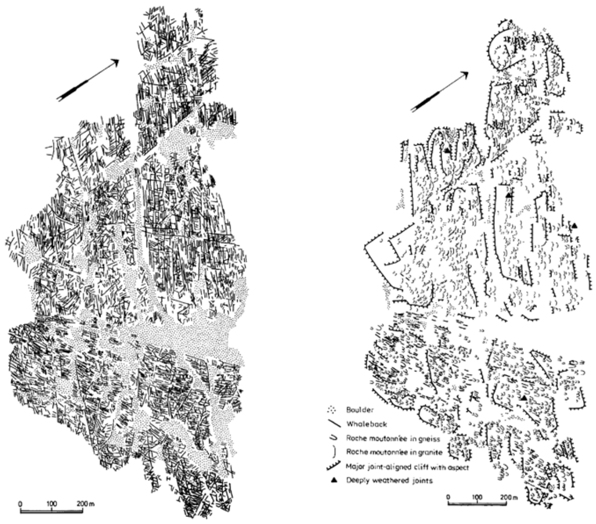


Figure 20.—From Olvmo and Johansson, (2002). Detailed structural and geomorphic map of a Bohus area hill showing the control of structure on valley formation.

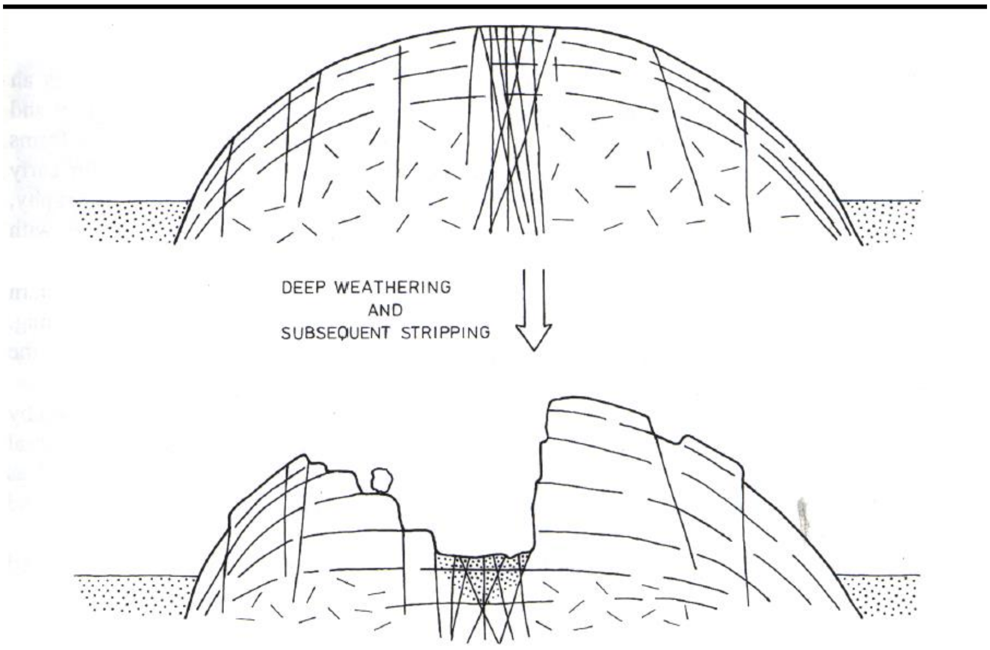


Fig. 5. Model of basin development through etching along densely spaced secondary joints located in the central parts of a domed rock block. Saprolite residues are marked with dots. On the right side of the basin lateral growth is supressed by a boundary joint and a marginal scarp has developed through partial stripping of saprolite. On the left side there is no single boundary joint and instead a stepped pattern has evolved by guidance from both jointing and sheeting. The model is based on measurements presented in Fig. 7 in paper IV.

Figure 21.—model showing deeper weathering where fissure are more closely spaced, with a resulting valley following removal of the weathered products.

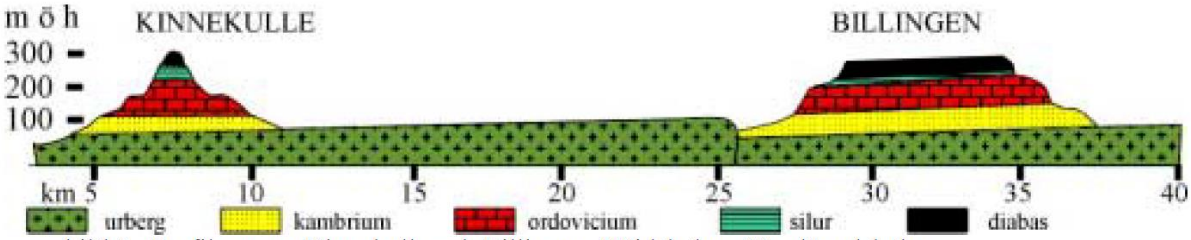


bild 3. Profil genom Kinnekulle och Billingen. Höjdskalan=11 x längdskalan.

Figure 22.-- Cross section from Kinnekulle to Billingen. The fault west of Billingen underlies Valle Härad.

Stop 1.1 The Shell Banks at Uddevalla (Tore Påsse)

Location: Kuröd shell bank, Uddevalla

Questions: Why this concentration of shells? Why was this mined? What does this site reveal about isostatic and eustatic changes?

Background: See the notes in the introduction. As Sweden rose above the world ocean, the Vänern basin became more and more isolated from the rest of the sea, and numerous straits became outlined (see Fig. 23). This created unique locations for enriched biologic activity generated by the reaction currents coming through these straits. A rich fauna occurs here, but the ages of these fossils actually occur over a rather short range.

MARINE LIFE AND DEGLACIATION CHRONOLOGY OF THE VÄNERN BASIN

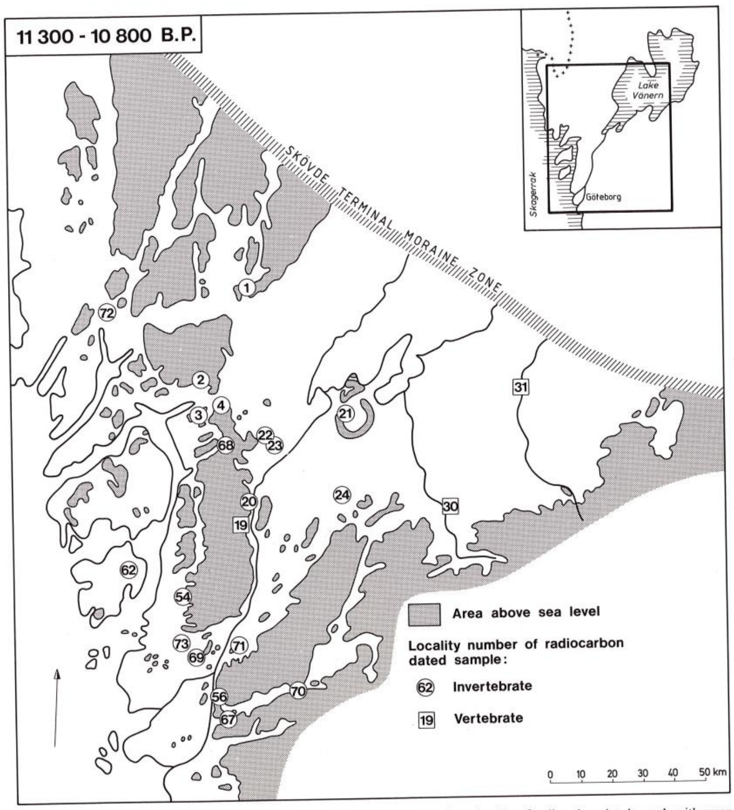


Fig. 51. Generalized palaeogeographical map of c. 10 800 years B.P. Numbers refer to locality of radiocarbon dated sample with mean value between 11 300 and 10 800 years B.P., see Table 2.

CURT FREDÉN

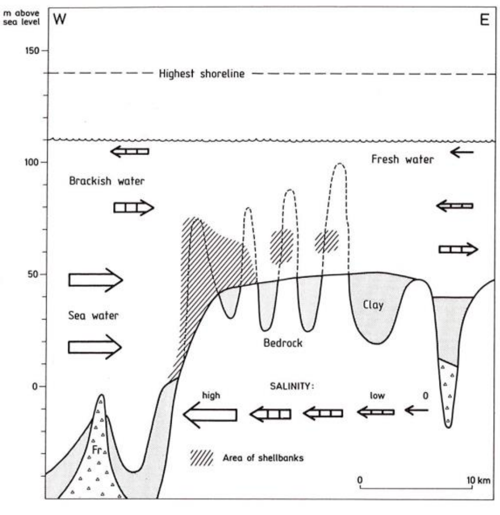


Fig. 19. A longitudinal section of the valley profile between Uddevalla and Vänersborg, Figs 13–14. The ridge (Fr) to the left is part of the Berghem terminal moraine and forms the threshold of Byfjorden. The shallow, southernmost part of lake Vänern is seen to the right. Hilly areas in the valley are shown by broken lines. Tentative estimation of hydrographical conditions correspond to about 11 000 years B.P., cf Fig. 22. All the shell-banks in the vicinity of Uddevalla are found on the western slopes, i.e., the habitats have been exposed to sea water leeward of the outgoing melt water currents.

Figure 23.—From Fredén (1988). (above) A paleogeographic map showing the ice margin and the areas covered by the western sea at the start of the Younger Dryas. Kuröd is point 4 on this map.(below) A sketch showing circulations conditions associated with shell-bank formation.

Stop 1.2 Nordkråken, Halleberg and Hunnberg (Mats Olvmo and Svante Björck) LUNCH

Location: Nordkroken

Questions: What creates peneplains? What is the age of the peneplain? How have eustatic sea level rise and isostatic crustal rebound varied through deglaciation?

Relevant excursion papers: Lidmar-Bergström et al., 2013; Björck & Digerferldt (1984, 1986)

Background: This site was nominated to be 'geologic site of the year' last year for the impressive display of the subcambrian peneplain (Fig. 22), here slightly modified by glacial erosion. The formation of peneplains remains a mystery, it seems, but it is clear here that they exist! To the east, Halleberg rests on this surface and you can easily imagine the plain continuing underneath the butte; underneath the Cambrian sandstone. Björck and Digerfeldt (as well as others) carried out many lake-isolation studies here to characterize shoreline displacement (see Figure 24).

16 *Svante Björck and Gunnar Digerfeldt* BOREAS 15 (1986)

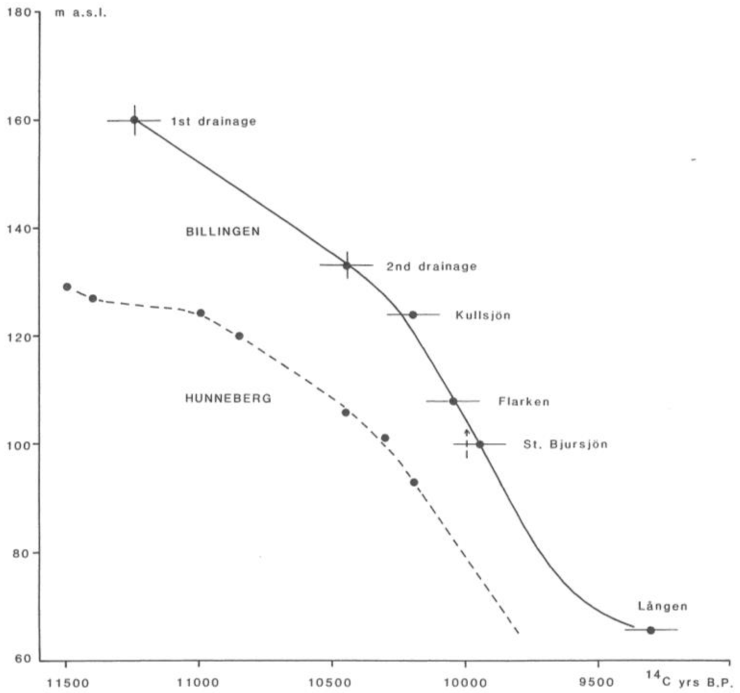


Fig. 18. A Late Weichselian–Early Holocene shore displacement curve for the north-western tip of Mt. Billingen (Lake Lången's threshold) based on Fig. 17. Björck & Digerfeldt's (1982) curve from Hunneberg is shown as a comparison. The arrow marks the possible transgression discussed in the text.

Figure 24.—shoreline displacement curves for the Halleberg-Hunneberg area as well as closer to Billingen. From Björck & Digerfelt (1986).

Stop 1.3 Råda landslide (Colby Smith)

Location: Råda, near Lidköping, Sweden

Questions: What caused this landslide? How can the age be determined?

Relevant excursion papers: Smith et al., (2014)

Background: (Figure 25) Landslides in sensitive clays in Sweden are an important concern and risk. It is thought also that increased precipitation (due to climate change) may increase slide frequency in these thixotropic clays. However, it is increasingly clear, that a number of ancient landslides in

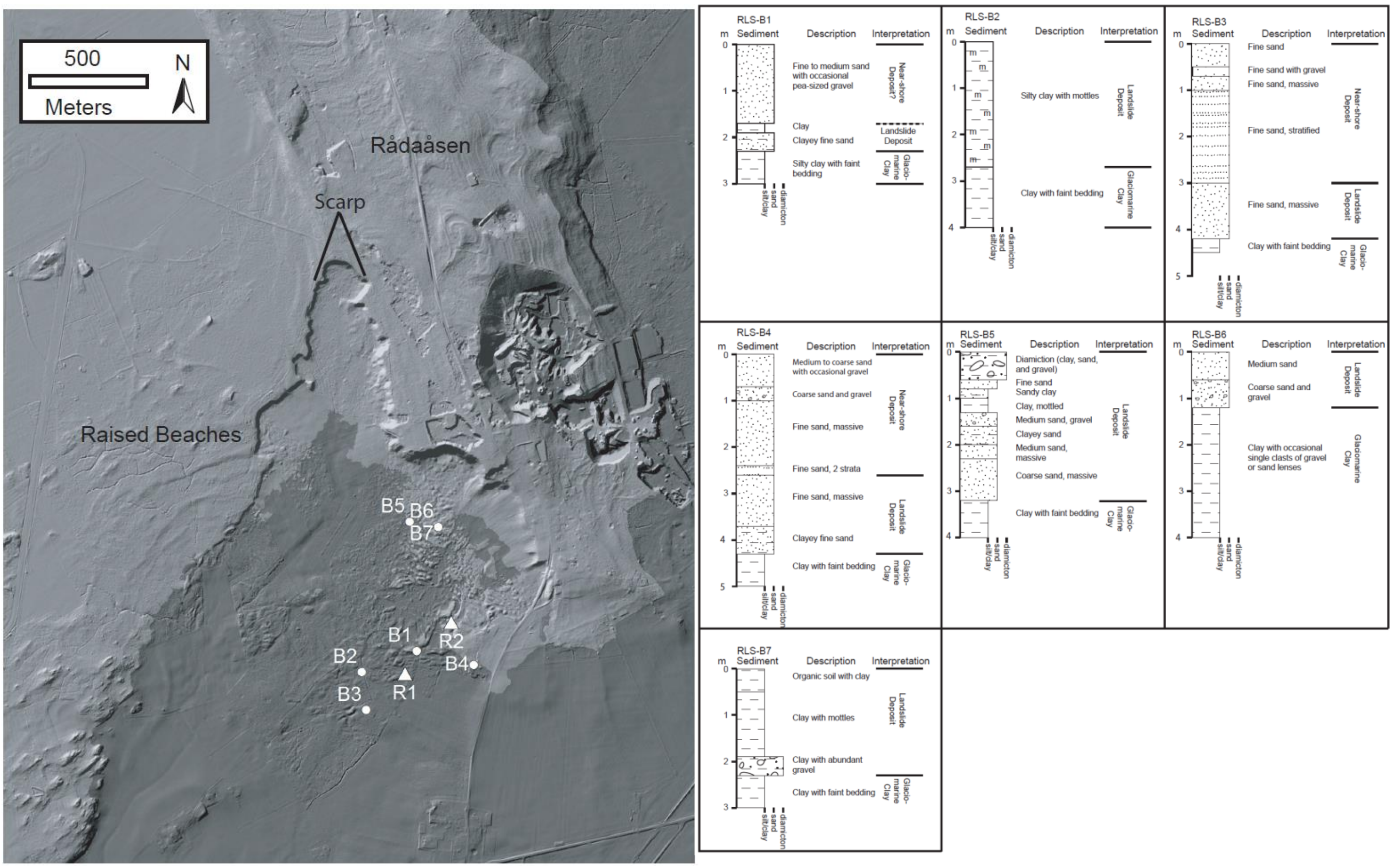


Figure 25.—From Smith et al, 2014 showing LiDAR hillshade of the Råda slide and stratigraphic columns.

Scandinavia have perhaps been triggered by greater seismic activity due to rapid isostatic uplift associate with rapid deglaciation. Is the Råda slide one of these?

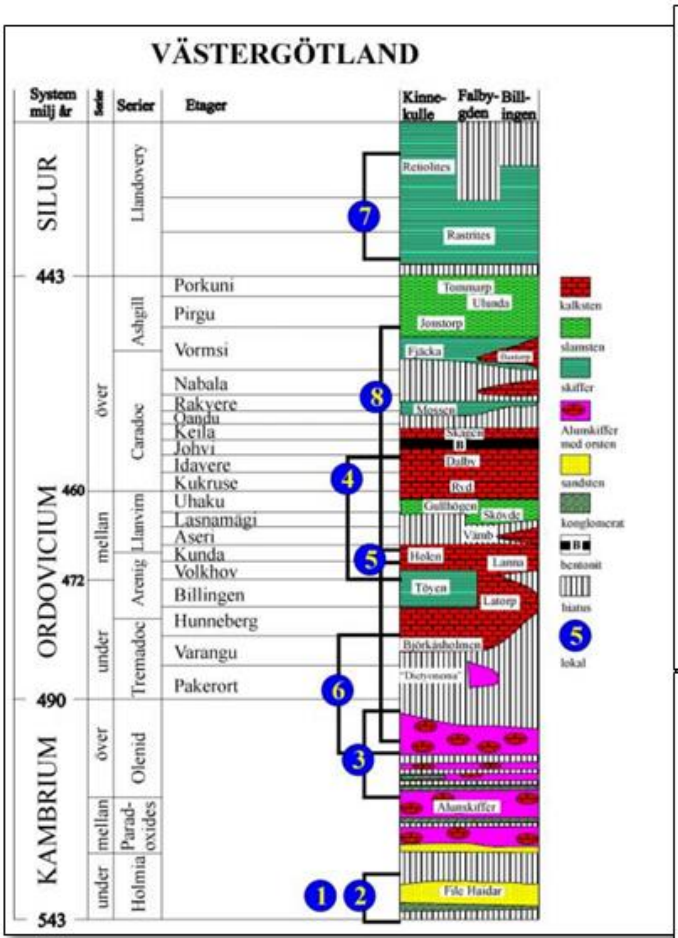
Stop 1.4 Råbäck harbor (Mats Olvmo)

Location: Råbäck, Kinnekulle, Sweden

Questions: Again, peneplain questions!

Relevant excursion papers: ---

Background: A locality that shows the contact between the subcambrian peneplain and the overlying Cambrian sandstone. The gneiss below is weathered. There are dreikanter in the conglomerate. We may also look for trilobites in the overlying shale if there is time. Figures 26 show the Paleozoic stratigraphy on Kinnekulle.



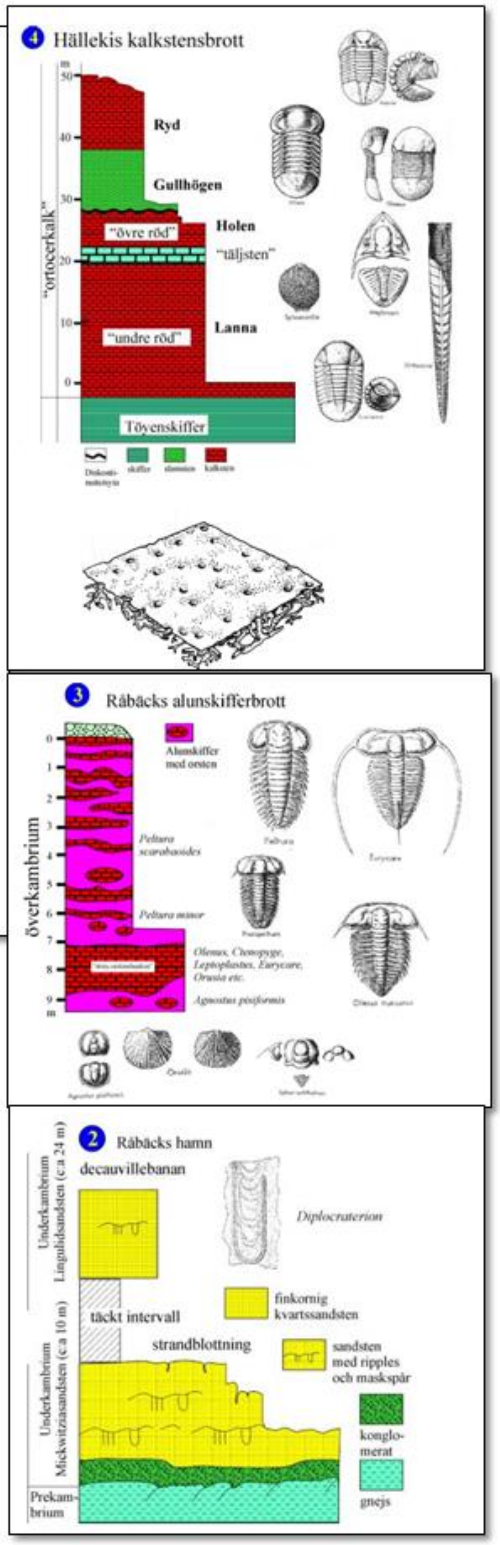
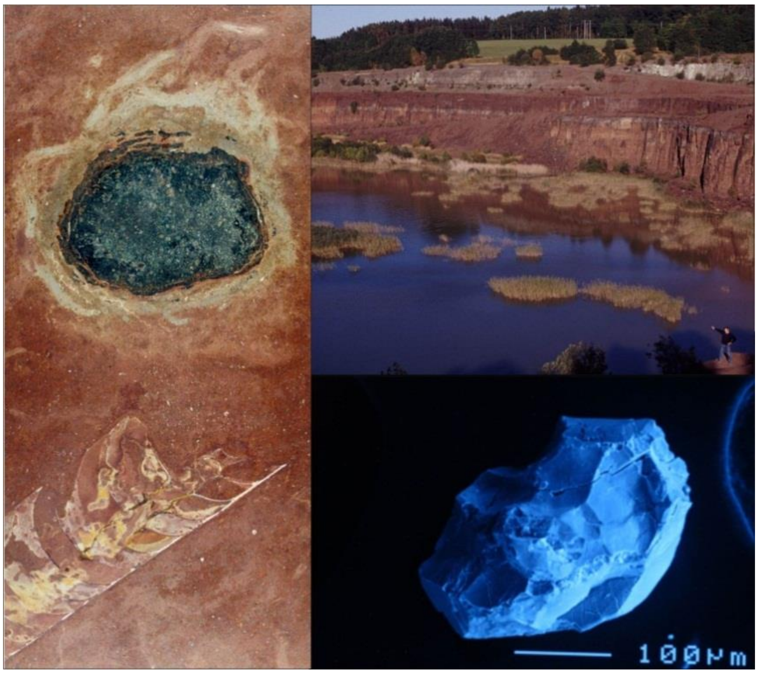


Figure 26.—Paleozoic stratigraphy on Kinnekulle

Stop 1.5 Hällekis limestone quarry (Mark Johnson)

Location: Hällekis, Kinnekulle

Background: The discovery of fossil meteorites by Tassarini at Kinnekulle and the subsequent search for them by Birger Schmitz and quarry workers at Thorsberg has turned up one of the most sensational stories in all of geology.



At this stop, we will review the story of the discovery and the implications of abundant fossil meteorites in this Ordovician sequence.

From Schmitz and Häggström (2006): “A systematic search for fossil meteorites has been conducted since 1992 in mid-Ordovician marine limestone in the Thorsberg quarry at Kinnekulle, southern Sweden. Within the project, more than fifty fossil meteorites, 1–20 cm in diameter, have been found during quarrying of the ancient, lithified sea floor. The number of fossil

Figure 27.—Fossil meteorite together with Orthocerus (L), quarry at Hällekis (UR); and chromite grain (LR). (Courtesy, Burger Schmitz)

meteorites found compared to the area quarried is far too high to be explained by a meteorite flux to Earth similar to that of thpresent. There is no indication that the meteorites have been concentrated into a small area of the sea floor after impacting on Earth. Schmitz et al. (1996, 2001) therefore suggested that accretion rates of meteorites were one to two orders of magnitude higher during a part of the Middle *Figure*

Ordovician than at the present. This idea is consistent with argon isotope gas retention ages of recent meteorites showing that a major collision/disruption event affected the L chondrite parent body 450–500 Myr ago (McConville et al. 1988; Keil et al. 1994; Bogard 1995). The major and trace element composition of relict chromite grains from the fossil meteorites in the Thorsberg quarry indicate that all or almost all meteorites found are L chondrites (or possibly LL chondrites) (Schmitz et al. 2001). The amount of cosmic ray produced noble gases in the chromite grains increases the higher up in the strata a meteorite is found (Heck et al. 2004). This is consistent with an origin of all the meteorites from one major asteroid breakup event.”

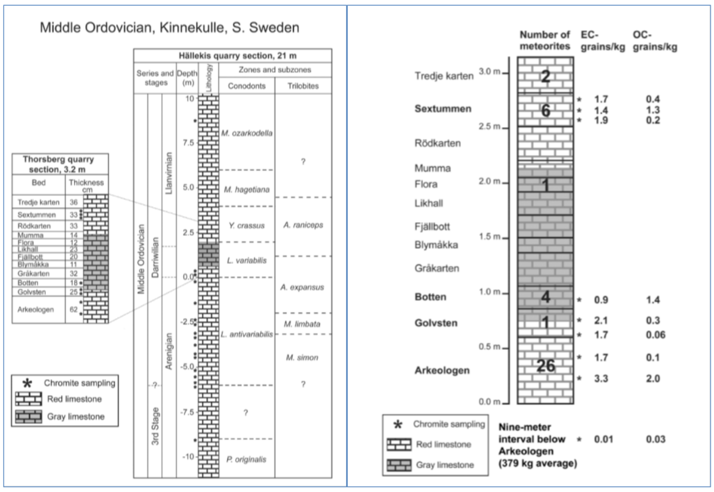


Figure 28.—Chromite anomalies n the sequence at Hällekis

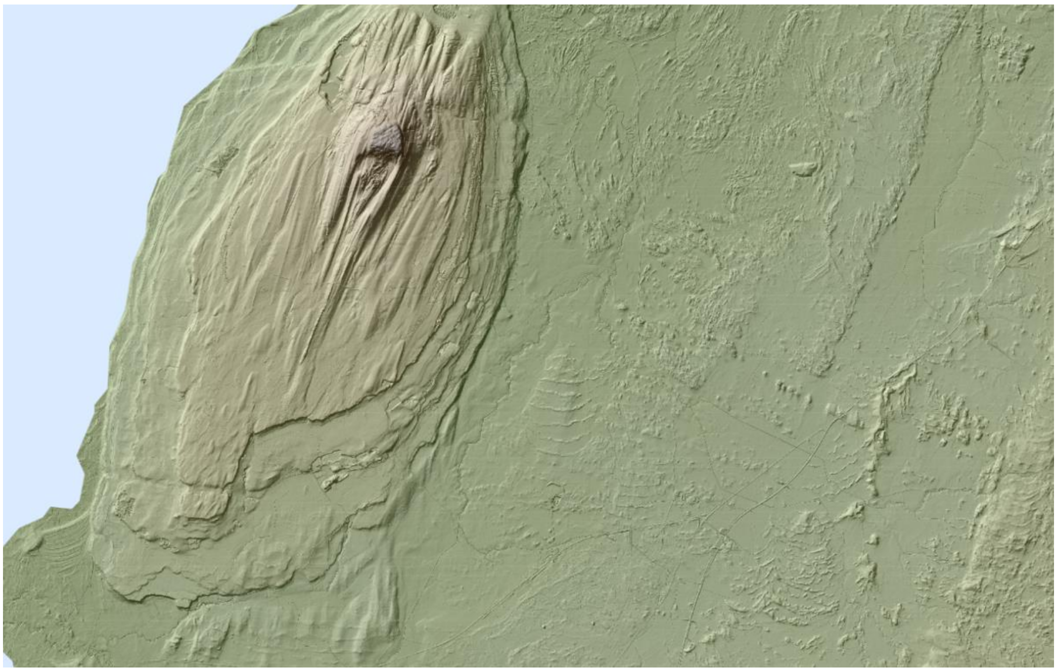
Stop 1.6 Top o’Kinnekulle: drumlins, a first view of the drainage area and a good till stop (Per Möller, Tom Dowling and Mark Johnson)

Location: Kinnekulle

Questions: How are drumlins formed? What is the genesis of the till exposed at the top?

Relevant excursion papers: --

Background: Kinnekulle is another inselberg, or erosional remnant, of the once extensive Paleozoic cover. Here, the top shows spectacular drumlins, which has been studied by Dowling and others (2013). Here, the drumlins are clearly influenced by the presence of the diabase cap of Kinnekulle, and the drumlins are covered with blocks of this rock type. Till outcrops are not common on this excursion, and till is not common in SW Sweden. However, there is an outcrop of till at the top of Kinnekulle that we will get a chance to dig in.



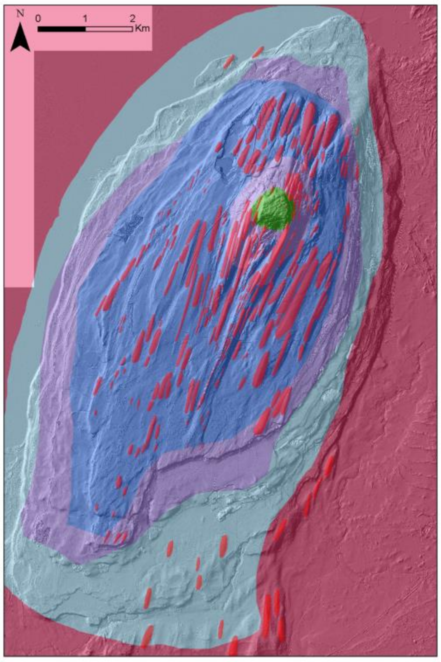
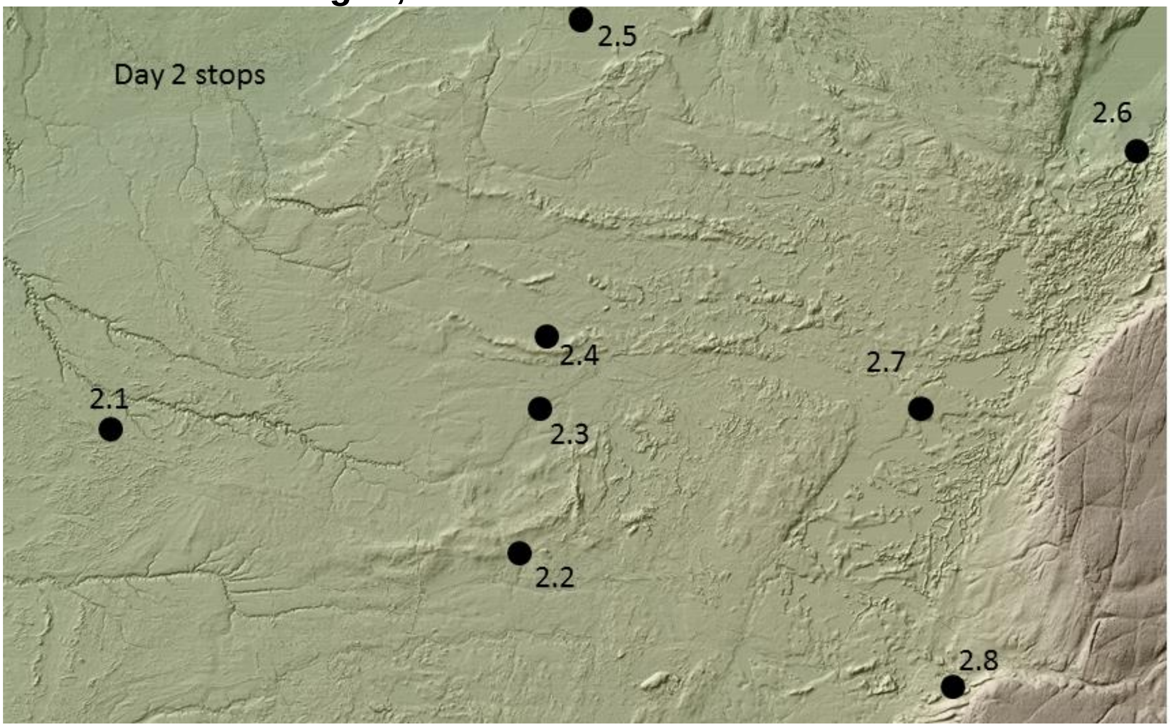


Figure 29.—LiDAR hillshade of Kinnekulle (above); drumlins (in red) and geology (left; nice figure from Tom!). Magenta=crystallibe basement/gneiss; gray=sandstone; purple&blue=Cambrian shale and Ordovician limestone; lavender=Silurian shale; green=Permian diabase.

Day two—September 22, 2015—The Middle Swedish End moraine zone west of Billingen, sand dunes and Valle Härad



Stop 2.1 Händene dune field (Helena Alexandersson & Martin Bernhardson)

Location: Händene NW of Skara

Questions: What is the age of the dune fields? What climatic events do they imply? What are the strengths and weaknesses of OSL dating? Where did the sand come from?

Background: Aeolian deposits in Sweden are mainly of three types: coastal dunes, inland dunes and cover sand. The inland dunes, which are the focus here, are formed by winds not coming (locally) from the sea or a lake and are today found in scattered localities from Skåne in the south to Norrbotten in the north. The largest and most continuous dune fields are located in south-central Sweden (Värmland-Dalarna) while south thereof dunes mainly occur singly or in small groups. Most of the sand in the dunes was deposited just after deglaciation or uplift above sea level, but while some dunes (e.g. Bonäsheden in Dalarna [1] and nearby Starmoen in Norway [2]) show very rapid deposition with limited reactivation, others show lengthier duration of sand drift (e.g. Brattforsheden in Värmland [3]) and yet others reveal reactivated dune formation during the mid- or late Holocene (e.g. Vittskövle in Skåne [4]).

The dunes of Västergötland are the target of an ongoing research project that looks into their chronology, geomorphology and sedimentology to decipher depositional processes, palaeoenvironments and the history of sand drift. Most dunes in this area are heaps or crescentic ridges, but some are parabolic or linear ridges. Preliminary dating results, so called rangefinder OSL, indicate at least two generations of sand drift and dune formation in the area. The older event may possibly be of longer duration or consist of more than one event in the Skara area, compared to the Skövde and Tidaholm areas where data are less scattered. In Tidaholm a younger event is also recognised.

The dunes here at Skogalund are examples of linear to parabolic dunes. A parabolic shape suggests that the dune formed when vegetation was present and could keep the ends of the dune in place, while the central part continued its migration.

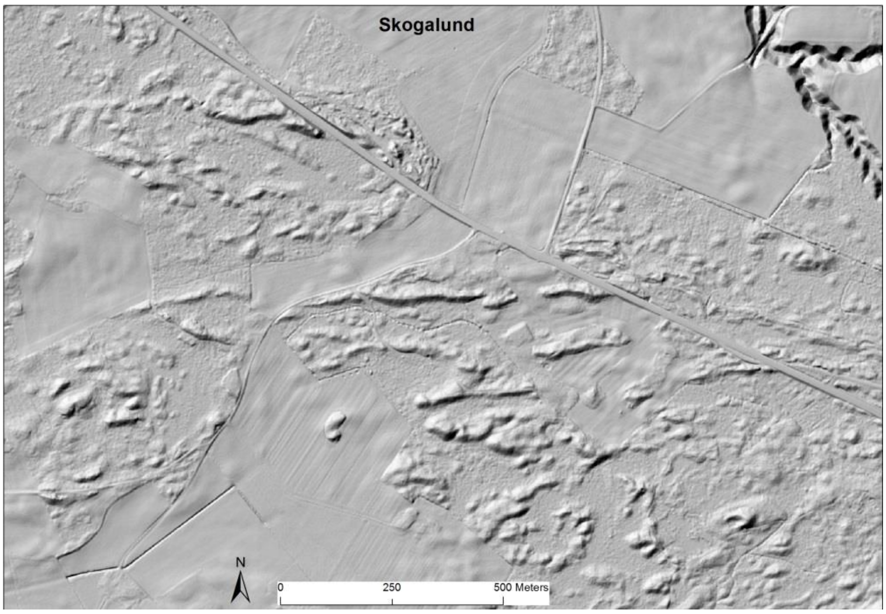


Fig. 30. LiDAR image of the dunes at Skogalund (upper); LiDAR image of a prominent set of crescentic dunes at Bäckåsen, 5 km SSW of Skogalund (lower).

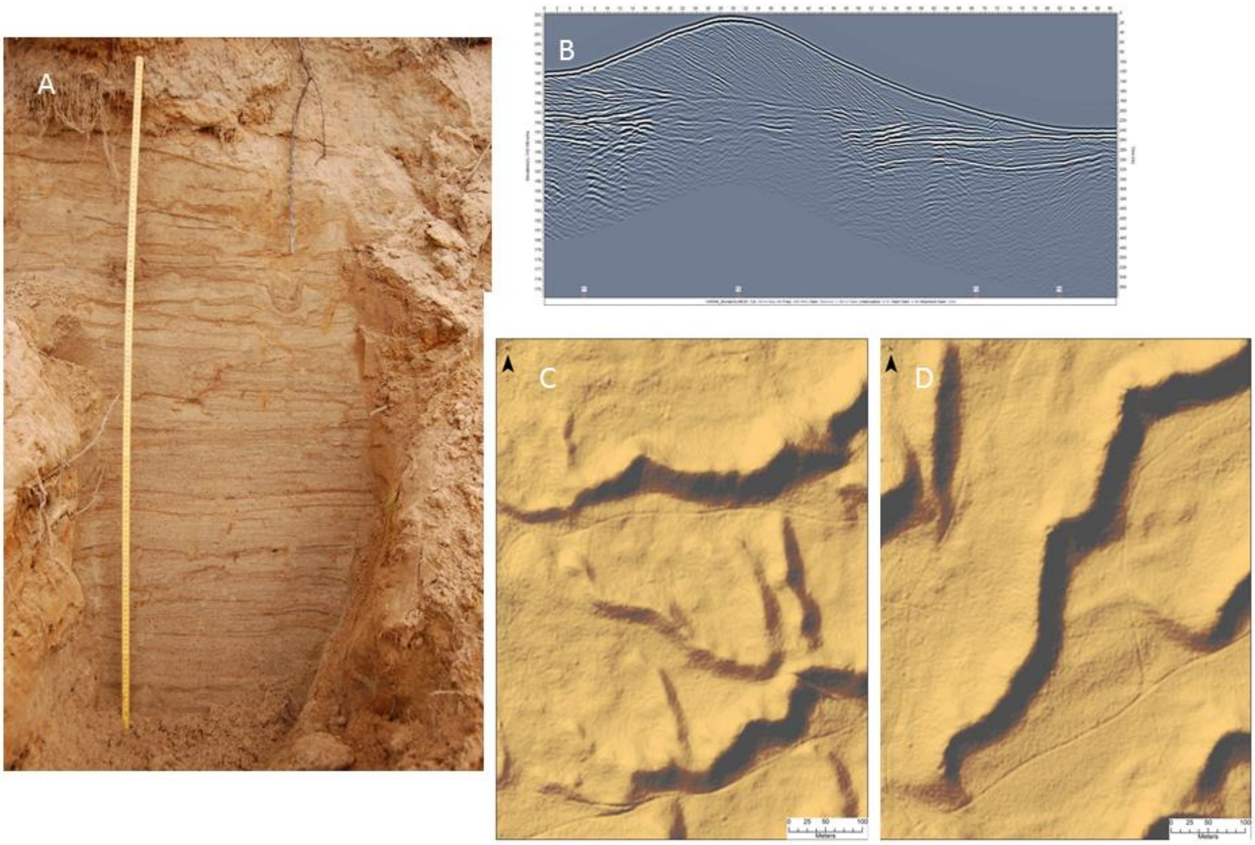


Fig. 31. A: The aeolian sand in the studied dunes in this area is commonly massive, particularly in the upper part due to bioturbation, or has lamination reflecting grain fall, grain flow and wind-ripple migration on the dune leeside. Here is an example from Karstorp, 9.5 km SW of Skogalund. The deformation structure just beneath the hanging root may be a foot impression. B: Example of ground-penetrating radar (GPR) profile across a dune at Bonäsheden, Dalarna. The profile reveals clear cross-bedding, typically with dips less than the angle of repose, and only minor evidence of re-activation or erosional events. The profile is oriented NNW-SSE. C: Example of parabolic dune from Bonäsheden, Dalarna. D: Example of transverse, crescentic dune from Bonäsheden, Dalarna.

References

1. Bernhardson, M., *Aeolian dunes in Dalarna, central Sweden: a case study from Bonäsheden.* in prep.
2. Alexanderson, H. and M. Henriksen, *A short-lived aeolian event during the Early Holocene in southeastern Norway.* Quaternary Geochronology, in press.
3. Alexanderson, H. and D. Fabel, *Holocene chronology of the Brattforsheden delta and inland dune field, SW Sweden.* Geochronometria, 2015. **42**: p. 1-16.
4. Kalińska-Nartiša, E., M. Nartišs, and H. Alexanderson, *Chronology of the aeolian-coastal events in the Kristianstad plain, SE Sweden.* In prep.

Stop 2.2 Skara end moraine(s) (Mark Johnson and Per Wedel)

Location: Brunnsboäng nature preserve east of Skara

Questions: What is the age and structure of the oldest YD moraine here?

Relevant excursion papers: Johnson and Ståhl, 2010

Background: West of Billingen, the MSEMZ consist of about 7 distinct ridges. The Skara ridge is the southernmost, the widest and the oldest. It is composed of thrust clay and till and several eskers are present.

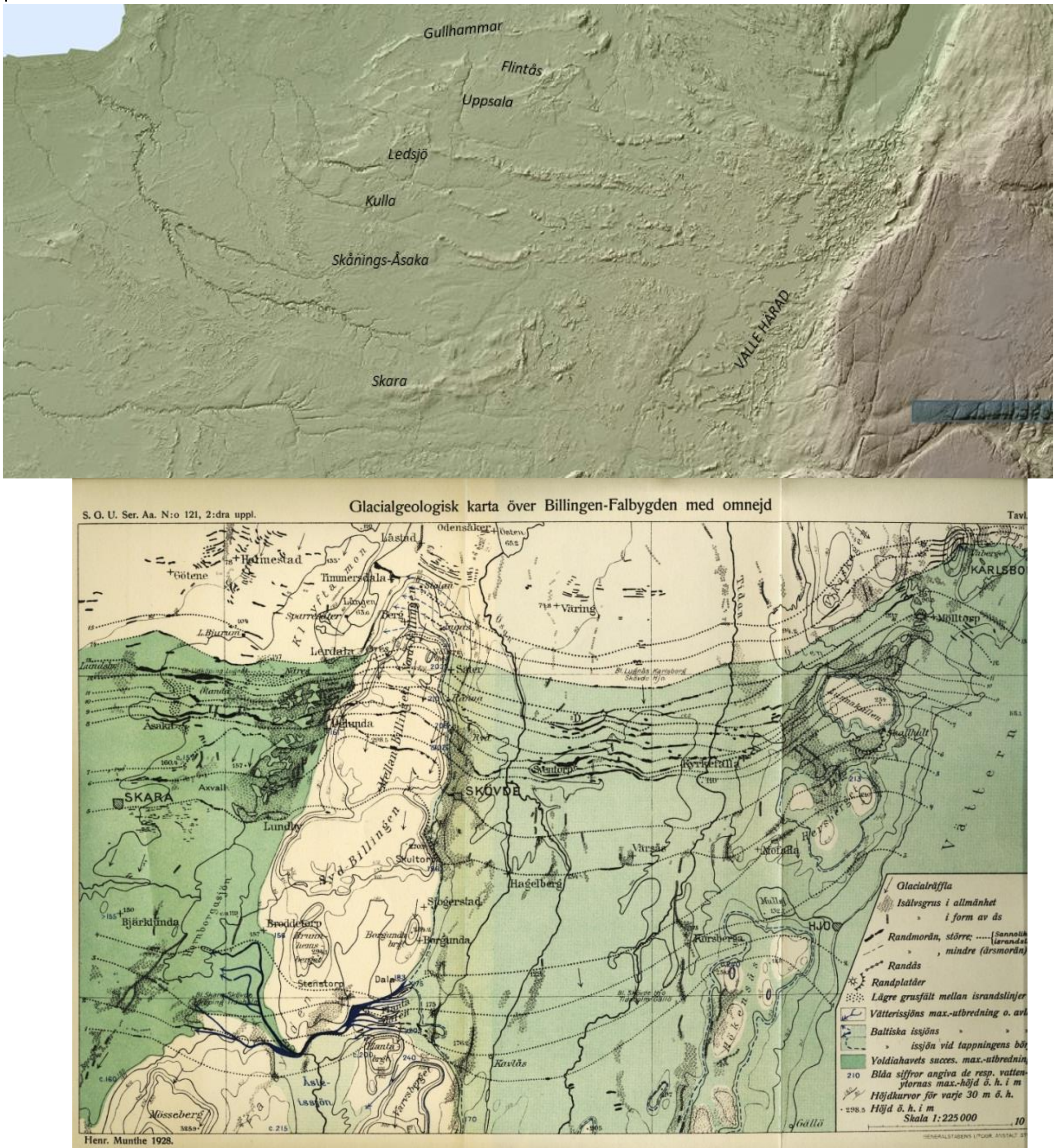


Figure 32.—LiDAR image with moraine ridges named. Below, plate from Munthe and others (1927) showing the middle Swedish end moraines, Billingen, and numerous other geomorphologic features.

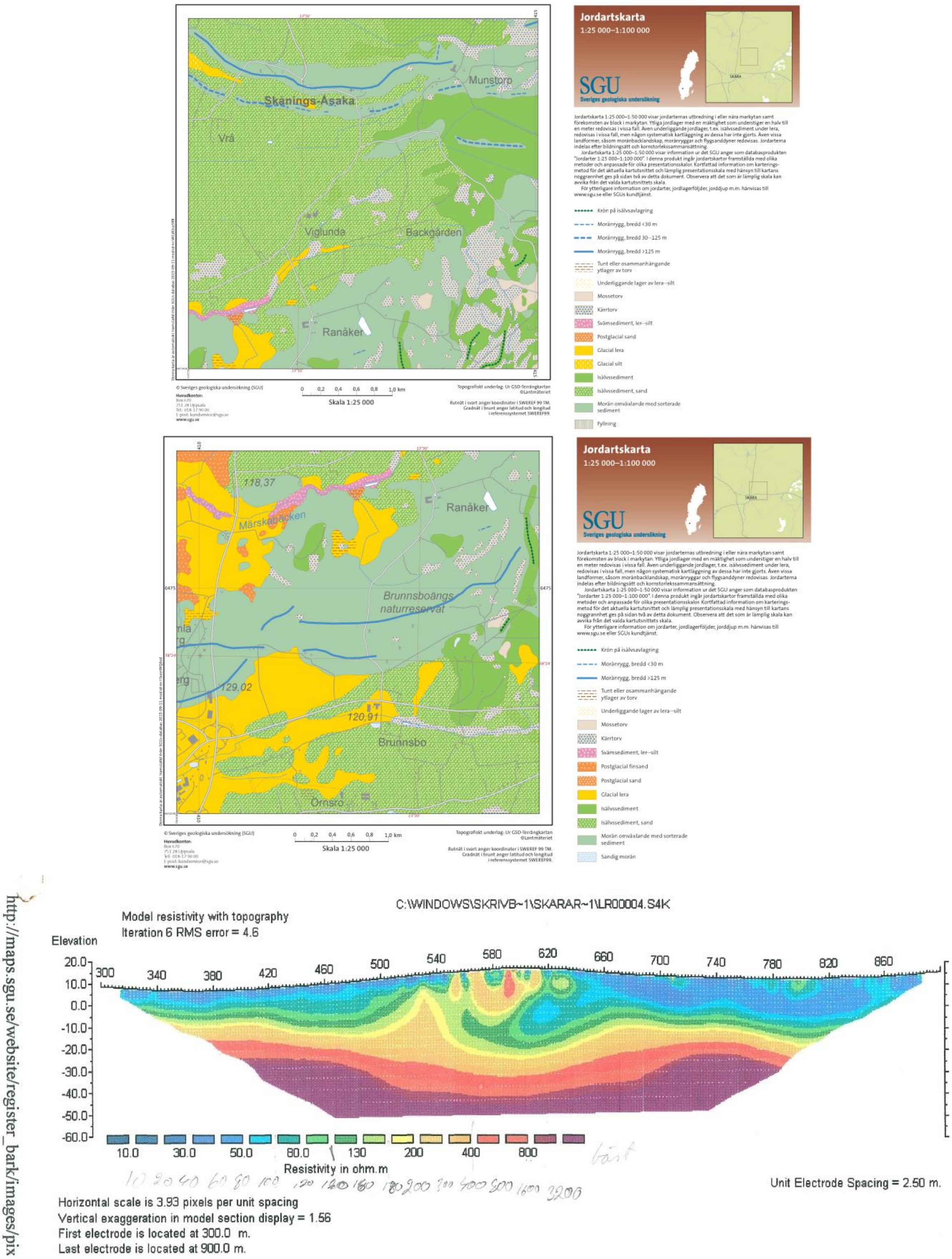


Figure 33. Top—SGU surface-geology map of Stop 2.3, Viglunda. Middle—SGU surface geology map of Skara ridge and Brunnsboängs nature preserve, Stop 2.2. Bottom—Resistivity profile across the Skara ridge at Stop 2.2, from Wedel, unpublishged.

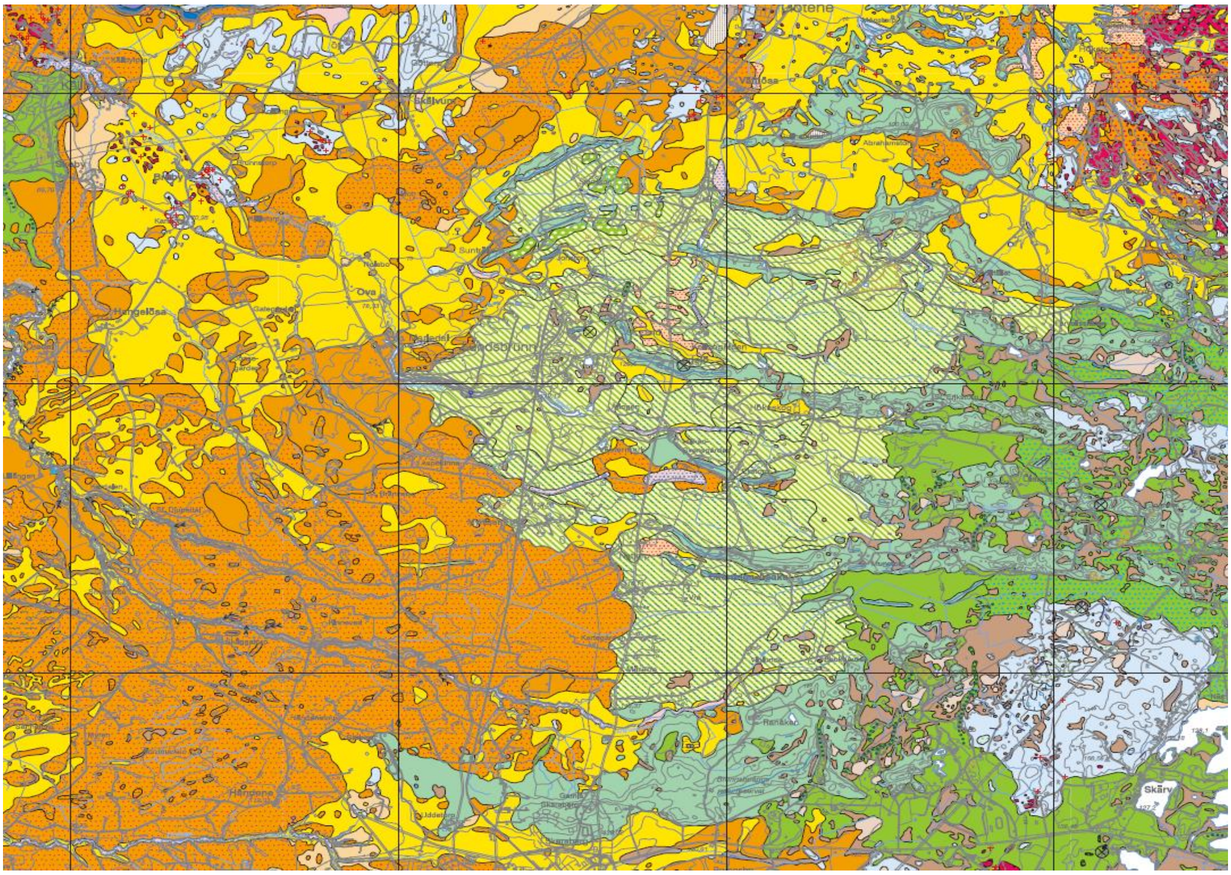


Figure 34.—Portion of the Skara NW surficial deposits map of Påsse (2006b). Compare with Figure 9 and 32. Orange=sand; yellow=clay; red=bare crystalline bedrock; light blue=till; light green and green=sand and sand&gravel; sage green=moraine ridges.

Stop 2.3 Viglunda outwash plain (Mark Johnson)

Location: Viglunda, directly south of Skånings-Åsaka church. Small gravel.

Questions: What is the stratigraphy here? What is the origin of this sand and gravel? Ice-wedge casts have been seen here—what do they indicate? What is the relationship of ice retreat, shoreline displacement, clay sedimentation and sand&gravel sedimentation? What is the provenance of this sediment? Surface elevation is 121-122 m.

Relevant excursion papers: Johnson and Ståhl 2010

Background: This site is an intermoraine flat. The stratigraphy is shown in Figure 35. There is 20 m of varved marine clay below this sand, which in turn overlies bedrock (with perhaps some thin coarse sediment at the contact). The varves are relatively undisturbed (they have not been overridden). There is a coarsening upward sequence of sands at the top, and we interpret the uppermost sediment to be fluvial. The surface gradient here slopes upward to the east towards Valle Härad (Fig. 32). It grades up to the pitted outwash plain at Eggby (Stop 2.7). Eastwards from this site, the maximum class size increase from pebble to cobble. Therefore, we have the following sequence of events during the YD (1) ice advance to the Skara ridge removes nearly all sediment above bedrock, (2) ice retreats and varved clays are deposited, (3) water depth shallows while outwash progrades from the east, (4) Viglunda emerges and fluvial sediment is deposited, and (5) ice-wedge casts are formed.

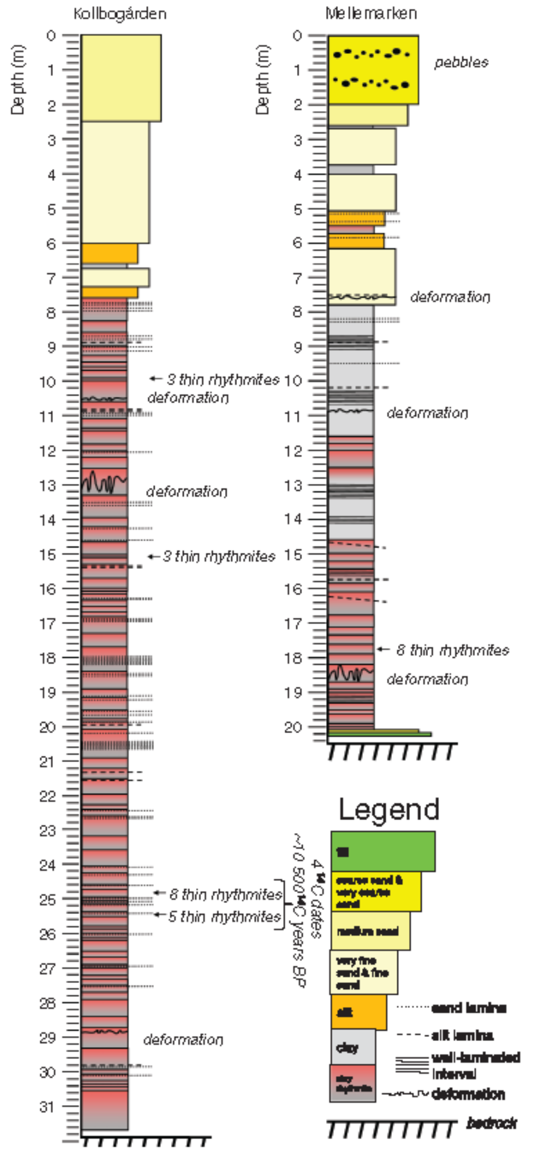


Fig. 4. Sediment logs from cores at Kollbogården (115 m a.s.l.) and Mellemarken (117 m a.s.l.). Locations are shown in Fig. 1.

Figure 35.—Sediment columns from Johnbson and Ståhl (2010). Both are taken from between moraines in the intermoraine flats. The Mellmarken core is within site of the Viglunda stop; the Kollbogården is north of the Ledsjö moraine.

Stop 2.4 Skånings-Åsaka moraine and church (but also Ledsjö ridge) (Mark Johnson)

Location: At Skånings-Åsaka church

Questions: How are these moraines made? What is the timing of moraine formation and marine-clay sedimentation? Why all the boulders on the older ridge?

Relevant excursion papers: Johnson and Ståhl (2010), Johnson, Benediktsson & Björklund (2013).

Background: S-Å is a classic location in the MSEMZ with its double ridge and picturesque church. Drill holes here show the ridge is mostly made of clay, but there is some sand and diamicton, too. The serendipitous exposure at Ledsjö (second ridge to the north), which we will drive by, shows the ridge there to be made of glaciotectonized clay along with some penecontemporaneous ice-marginal sand sedimentation. The structural features make clear that the ice advance twice to make the Ledsjö ridge (Figure 36, 37).

It is our interpretation that the ridges are composed of clay that was deposited immediately before an ice-front oscillation. That is, when the S-Å moraine was made, no varved clay existed to the north. This means that moraine formation AND clay sedimentation occurred concurrently during oscillations—each ridge is made of clay that had *just* been deposited in front of it during retreat. This is supported by the YD dates (Figure 35) and the undisturbed nature of the clay. It is also possible to identify in two columns sedimentation contemporaneous with the formation of next ridge to the north.

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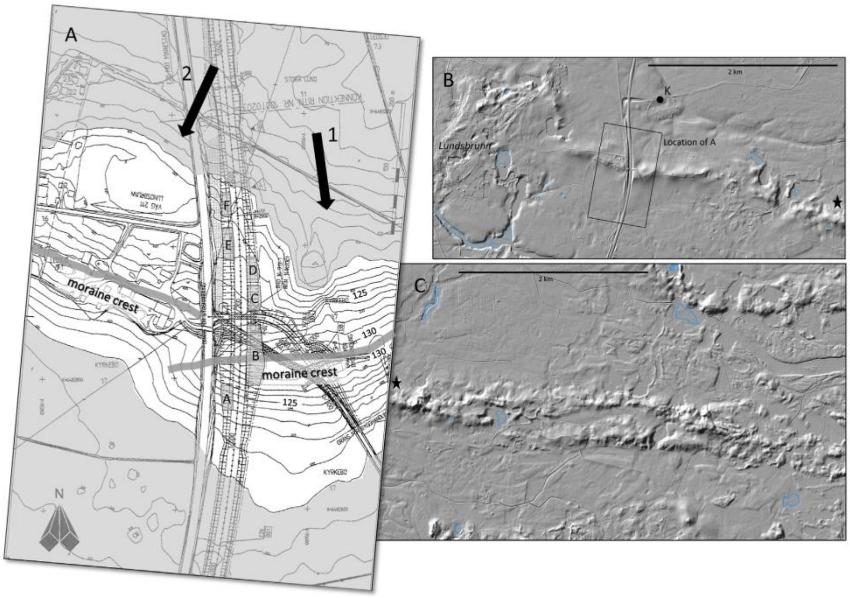


Fig. 2. (A) Topographic map of the Ledsjö end moraine at the location of the highway excavation. Contour interval 1 m, shaded area is below 120 m a.s.l. Note that at the excavation site, the moraine has two crests, with the eastern crest older by cross-cutting relations. Arrows show ice-flow during the first and second phase of the ridge formation. Boxes with numbers show locations of the individual sites described in the text. Map courtesy of WSP, Sweden. (B and C) LIDAR images of the lateral extent of the Ledsjö moraine. Location shown in Fig. 1. Stars in B and C show overlap in the two images. 'K' is the location of the Kollbogården drill core. Note in C the double-crested nature of the moraine and its greater hummocky appearance. (For interpretation of the references to color in the text, the reader is referred to the web version of the article.)

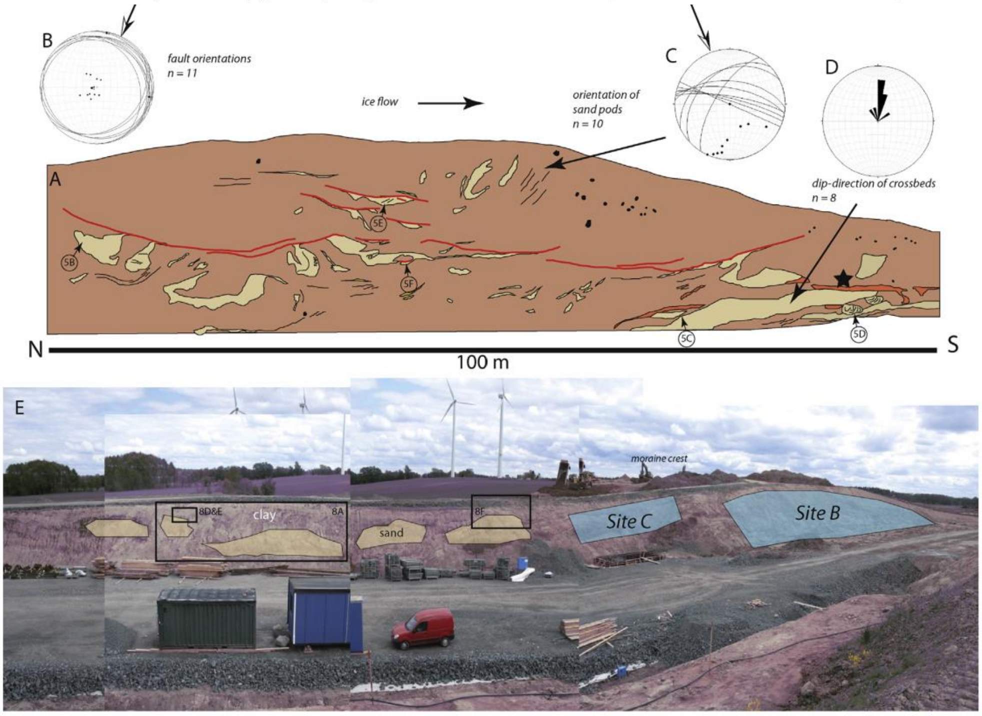


Fig. 4. Sketch and structural data from Site B, the crest region. Legend shown in Fig. 3. (A) Sketch showing predominantly clay with numerous sand pods, mostly deformed. Sand and gravel lens in the distal part of the outcrop show no deformation. Numbered circles show locations of photos shown in Fig. 5. The star indicates an *in situ* bed of undeformed gravelly sand. (B) Orientation of fault surfaces. (C) Orientation of the axes of the sand pods in the upper, central part of the exposure indicating deformation from the NNW. (D) Dip directions of cross beds in cross bedded pebbly sand indicating current flow toward the ice margin. (E) Overview of the moraine exposure showing the locations of sites B and C. Sand pods pictured in the left part of the photo are from site C and are shown in Fig. 8.

Figure 36.—Two figures from Johnson, Benediktsson&Björklund, 2013. We will drive by this ridge after stop 2.3.

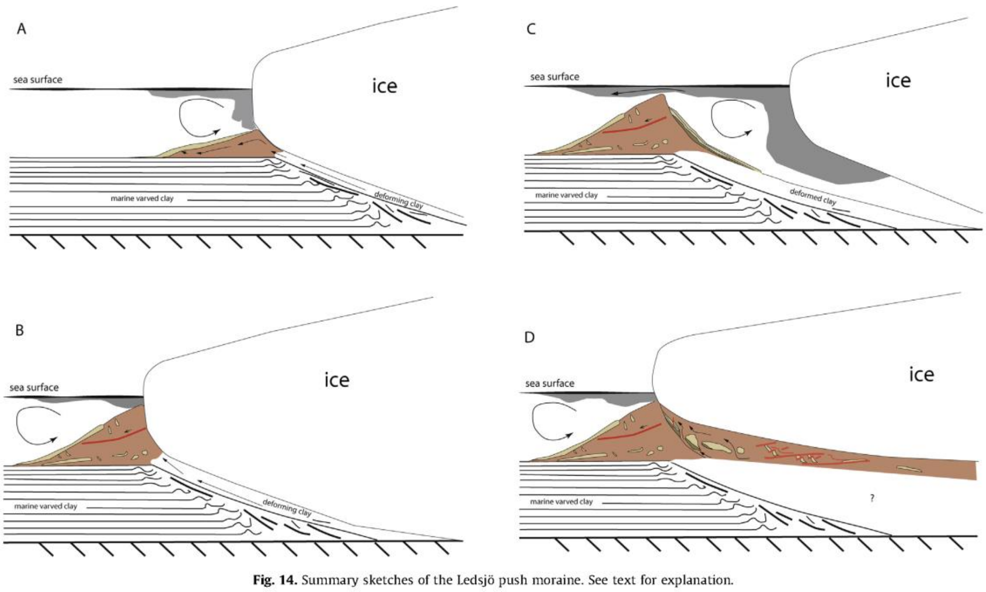


Figure 37. Sequence of events for the Ledsjö ridge (Johnson, Benediktsson&Björklund, 2013).

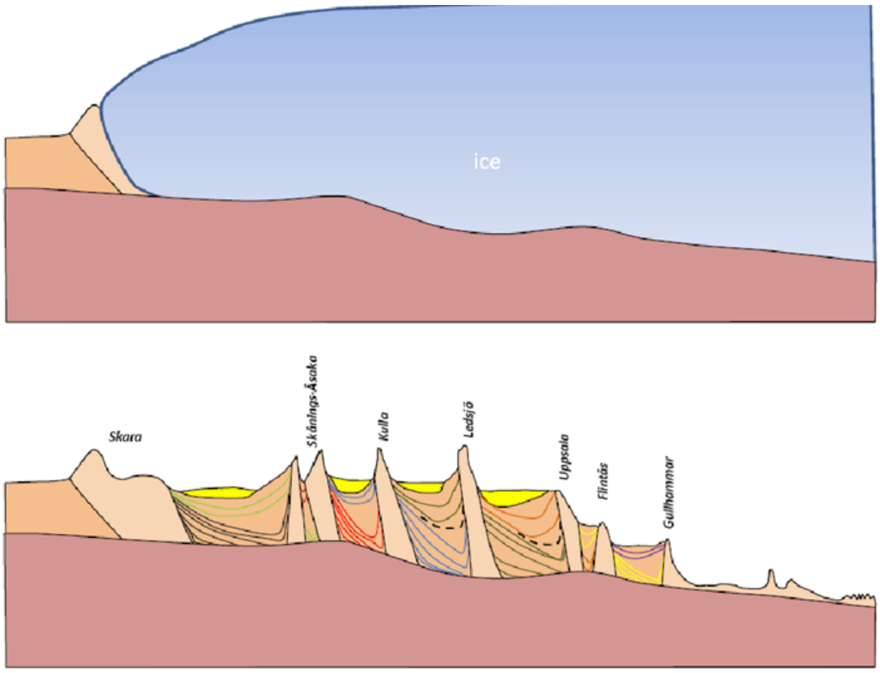


Figure 38. Conceptual model of the stratigraphic and age relationship between clay in the ridges and beneath the inter-moraine flats. In the upper diagram, we show the ice at the Skara ice-margin position and little or no sediment preserved above bedrock to the north. As the ice retreats, marine clay, much of it varved, is deposited. In the lower diagram, we show a conceptual picture of the relationship between the clay under the flats and in the ridges. The ridges are composed of clay and minor amounts of other sediment thrust into push moraines. Colored lines represent bedding in the clay beneath the intermoraine flats. Lowermost beds are deformed during ice readvance. Lines of similar color represent beds of similar age. Heavy dashed line represent coarser sediment (sand or silt) deposited contemporaneously when at ice was respectively at the adjacent Ledsjö and Uppsala ice-margin positions.

Stop 2.5 Holmestad (Mark Johnson)

Location: Holmestad church, east of Götene, elevations 74-79 m.

Questions: What is the mechanism for distal deposition of drainage sediment? Why is there a change in varve character before and after the drainage? Where was the ice margin at the time of drainage? Why are there two drainage layers?

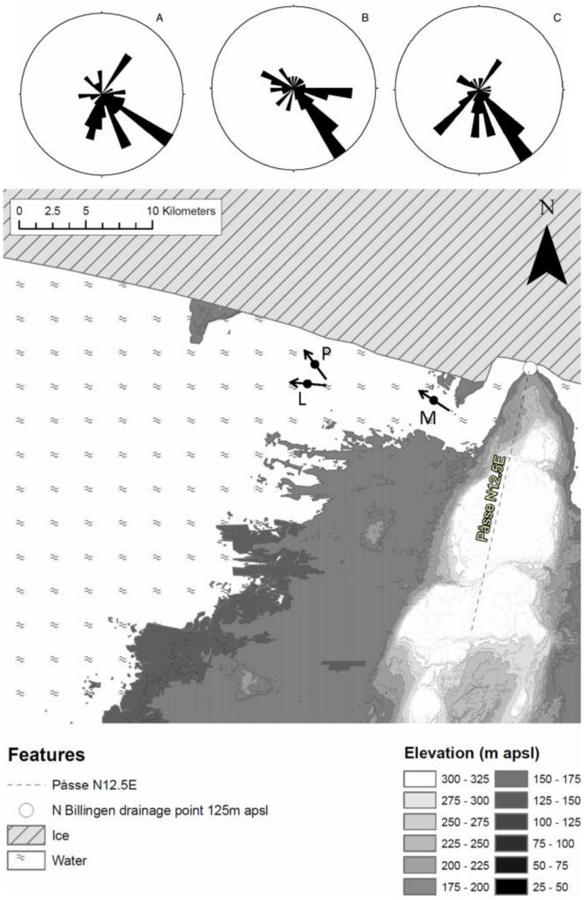
Relevant excursion papers: Johnson et al, 2013, GFF

Background: During construction of E20, new exposures of coarse sediment interpreted to be BIL drainage sediment were discovered. This sediment has been found in several locations (see Figure 9) overlain and underlain by two different sequences of varved clay (Figure 38). Fabric measurements on pebbles show that they were deposited by a northwesterly current (Figure 39). Water depth here was perhaps 50 m during the drainage. We estimated perhaps up to 40 varves below this sequence here—what would that mean?

6 *Johnson et al.: New exposures of Baltic Ice Lake drainage sediments* GFF 132 (2010)

Fig. 3. Photographs of sediment exposed at Pellagården. **A.** Exposure on west-facing side of roadcut showing DeGeer-moraine till ridge draped by the lower varved clay, the gravelly sand, and the upper varved clay. **B.** Portion of core taken from the lower varved clay. Arrows mark the sharp contact between the winter (red) and summer (gray) layers. **C.** The gravelly sand bed showing graded and sharp lower contact and generally disorganized structure. The woman's shoes are approximately upon the upper contact with the upper varved clay. **D.** Close-up, with pencil for scale, showing bedding in the gravelly sand unit and the presence of interstitial mud. **E.** Portions of four varves from the upper clay unit.

Figure 38.—Drainage sediment exposed at Pellegården. From Johnson and others (2010).



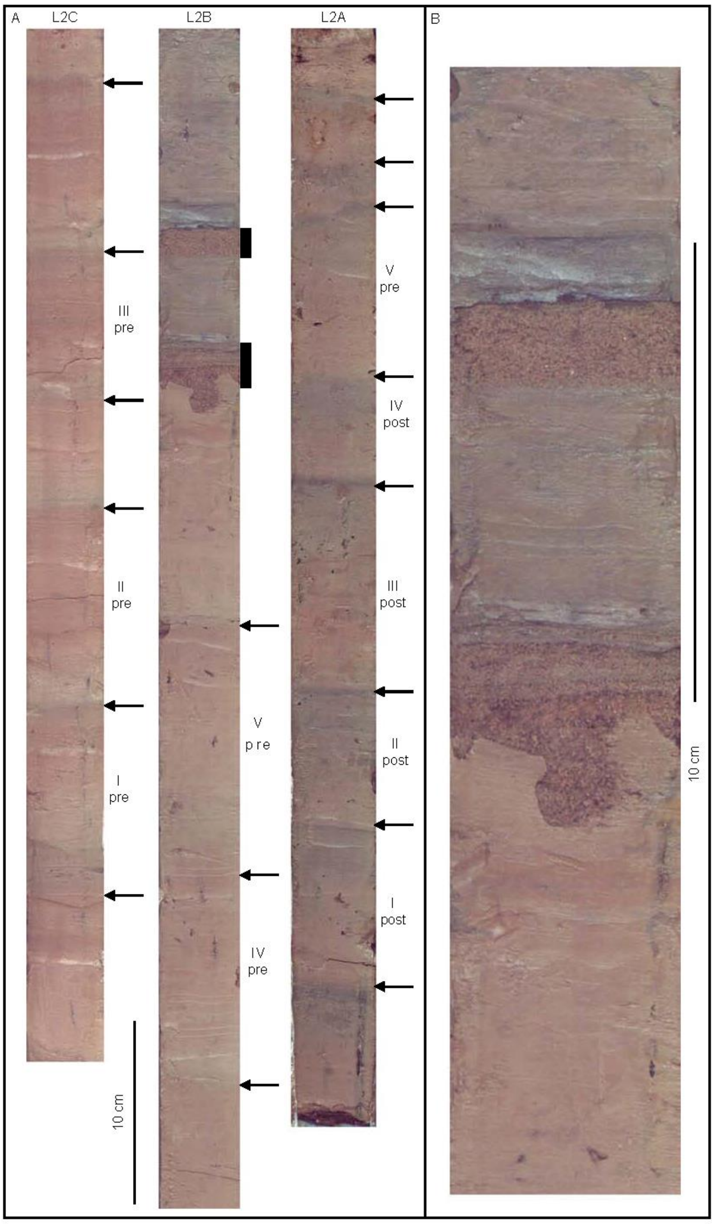


Figure 39.—(left above) Three rose diagrams from fabric measurements in the coarse sediment at Pellegården (top) and (left) relationship to a similar measurement at Länsmansgården and (M) on Klyftamon. (Below) core from Länsmansgården (from Johnson et al, 2013) showing pre-drainage varves (left column and middle up to black bar), drainage sediments (two!)(black bars), and post drainage sediment.

Stop 2.6 Lerdala (Tore Påsse) LUNCH

Location: North edge of Valle Härad, the town of Lerdala.

Questions: How was Valle Härad made? What is its stratigraphy?

Relevant excursion papers: Björck&Digerfeldt 1984,

Background: Valle Härad is a ‘classic’ site in Swedish glacial geology and geomorphology. It is the poster-child of ‘kame landscapes’ or ‘dead-ice landscapes’(Figure 9). It is also home to many (8?9?) nature reserves. Here we will see eskers and kames of various names, kettles and such, but also areas that have not been collapsed. It is composed largely of ‘outwash’, but the stratigraphy is likely complicated—there are few drill holes to confirm this—but it is likely that the thickness of sediments (40-60 m, Björck&Digerfeldt, 1984) contain some diamicton (deposited during ice-margin oscillations) and clay (deposited during the same). Björck&Digerfeldt (1984) suggest (see Figure 7A in this guide) that much sediment was deposited during the Alleröd. However, the new LiDAR images show progressive development of at least the surface geomorphology from south to north (Figure 40).

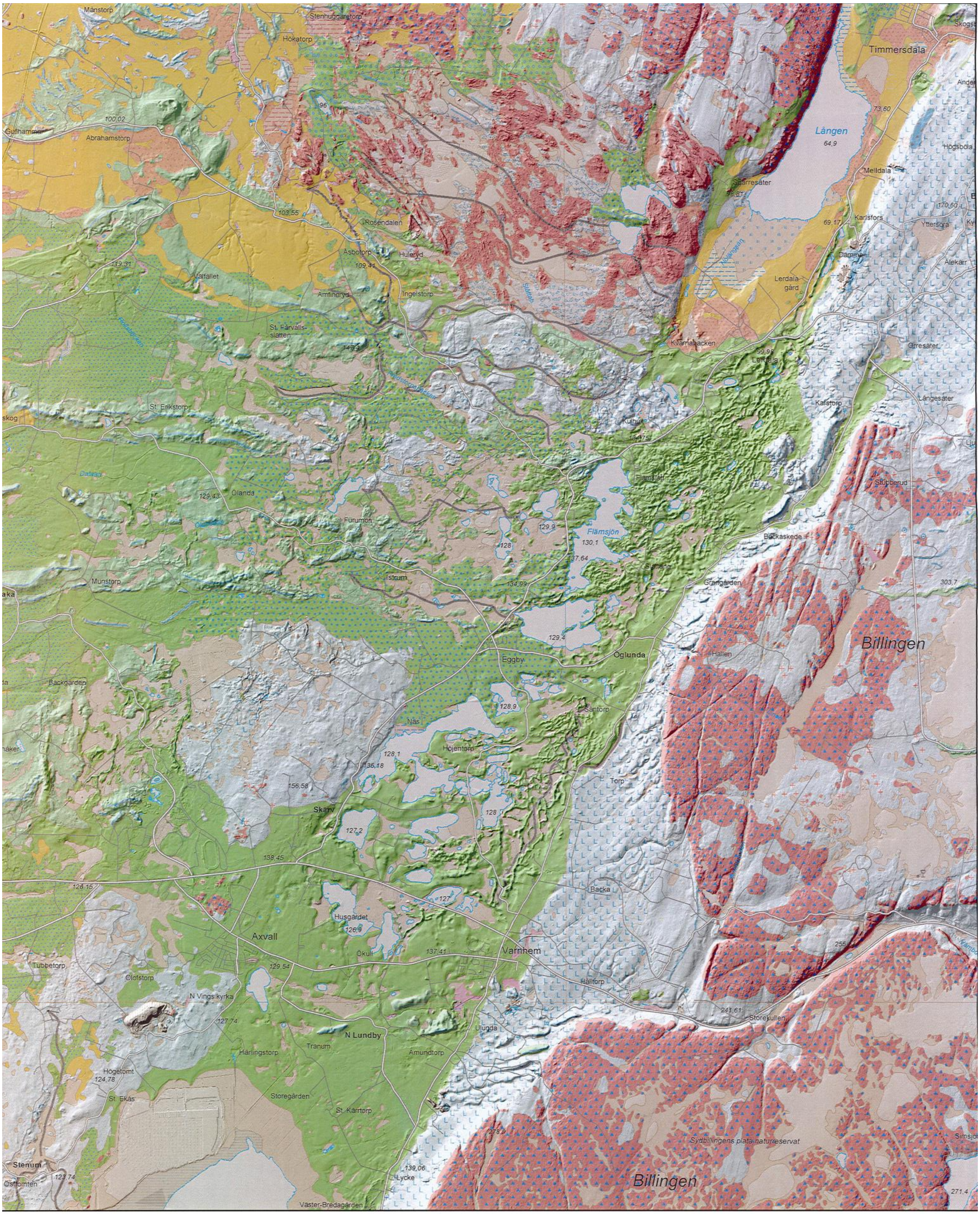


Figure 40.—LiDAR hillshade plus surficial geology made by Tore. Lerdala (stop 2.6) is in the esker-net at the north end of Valle Härad. Eggby (Stop 2.7) is in the middle of VH. Axvall and Varnhem (Stop 2.8) is at the south end of VH.

Stop 2.7 Eggby (Tore Påsse)

Location: The town of Eggby in Valle Härad,

Questions: What is the timing of sedimentation and landform formation here in VH? Same questions as before! What causesd those esker nets to form, and do they indicate something about where the ice margin lay?

Relevant excursion papers: --

Background: This outwash surface is relatively uncollapsed , and is at 135-140 m. This surface is a fluvial surface that grades to Stop 2.3 (Viglunda)—they were formed concurrently. Significantly, prior to the formation of the Skara ridge, drainage was to the south. Here, ice had retreated further north and drainage went to the west, a pattern that continued through the deglaciation of VH. Much of the collapse pits in VH are 'below' this fluvial surface (pitted outwash). However, there are also landforms that 'stick above' this surface implying that VH is not simply a large collapsed outwash plain. Furthermore, there are ice-marginal channels visible coming down from Billingen, and at least one of the ridges (S-Å) can be traced into VH. These features indicate that at least the surface sediments and landforms are of YD age.

Stop 2.8 Axvall Hed and Varnhem (Mark Johnson)

Location: Axvall and Varnhem

Questions: Is Axvall Hed a delta? How to interpret the stratigraphy seen in Figure 41? What would the ages be of the sediment?

Relevant excursion papers: ---

Background: Axvall Hed is a nearly flat, gravel landform occurring at 131-135 m (which is about the sea level here during the Alleröd. It has been called a delta, but it seems to lack the surface gradient and internal stratigraphy to be considered a delta. It is clear that Axvall Hed is south of the collapsed topography that characterizes VH. SWECO made a seris of boreholes across Axvall Hed,and I show four of these in Figure 41 (the other boreholes were not helpful or significant or available). It is clear that there is a stratigraphy of

- Gravel over
- Fine material (including clay) over
- Gravel over
- Bedrock.

We can discuss what this stratigraphy represents.

Varnhem is a locality situated in Skara Municipality, Västra Götaland County, Sweden with 707 inhabitants in 2010.[1] Varnhem is the location of the oldest known stone church in Sweden outside of Scania, erected in the 1040s at the latest. It is also the location of a Christian cemetery which was in use during the end of the ninth century. The Cistercian Order established Varnhem Abbey around 1150, not far from the old church. A new abbey church was erected to replace the older church; the abbey church is still in use. Varnhem and in particular its abbey has received additional attention in recent years due to it being the main location of The Knight Templar trilogy written by Jan Guillou, and subsequently filmed. Arn Magnusson, the hero character of the series is portrayed as living there. Birger jarl and his family lie buried in Varnhem.

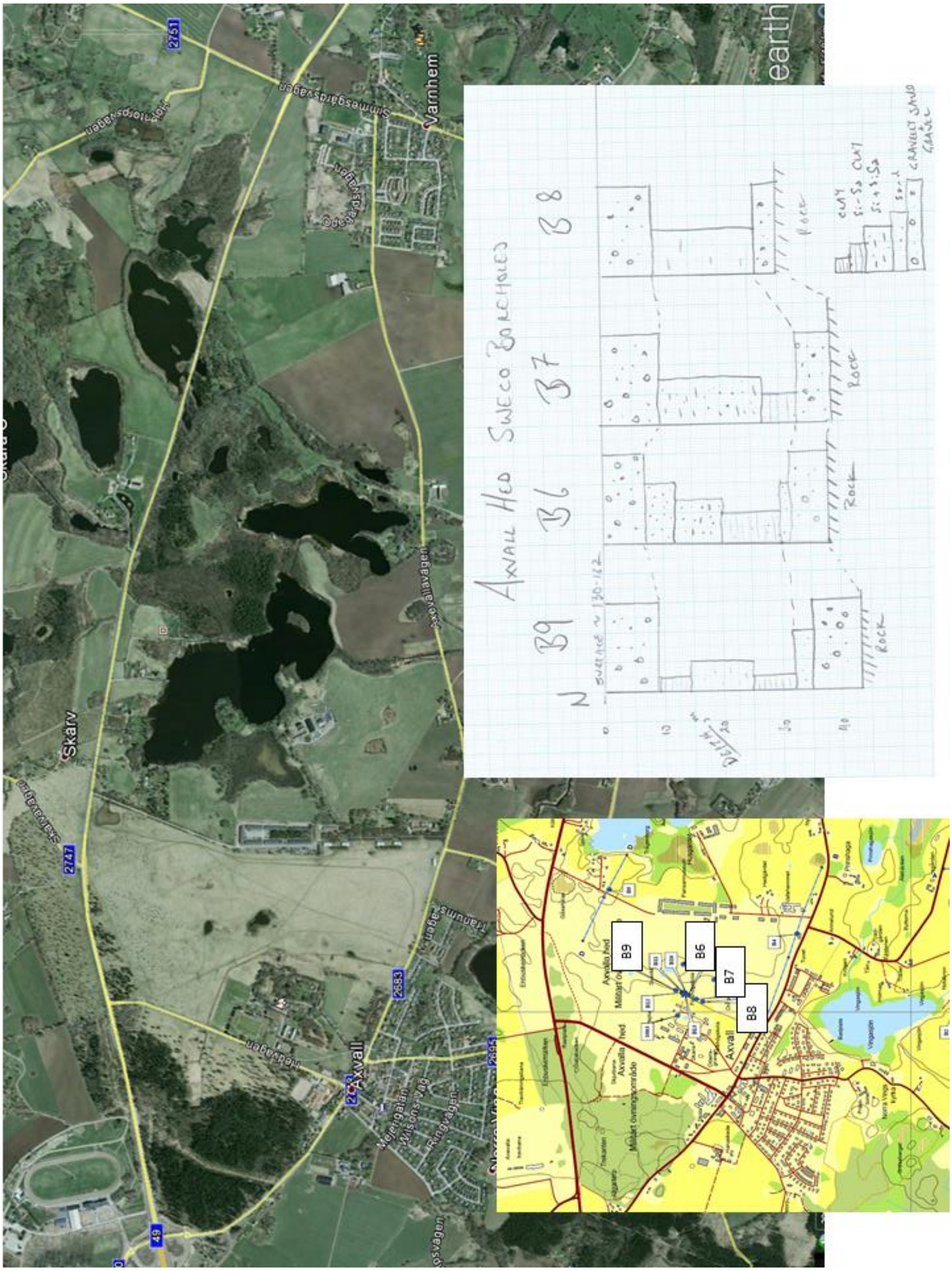
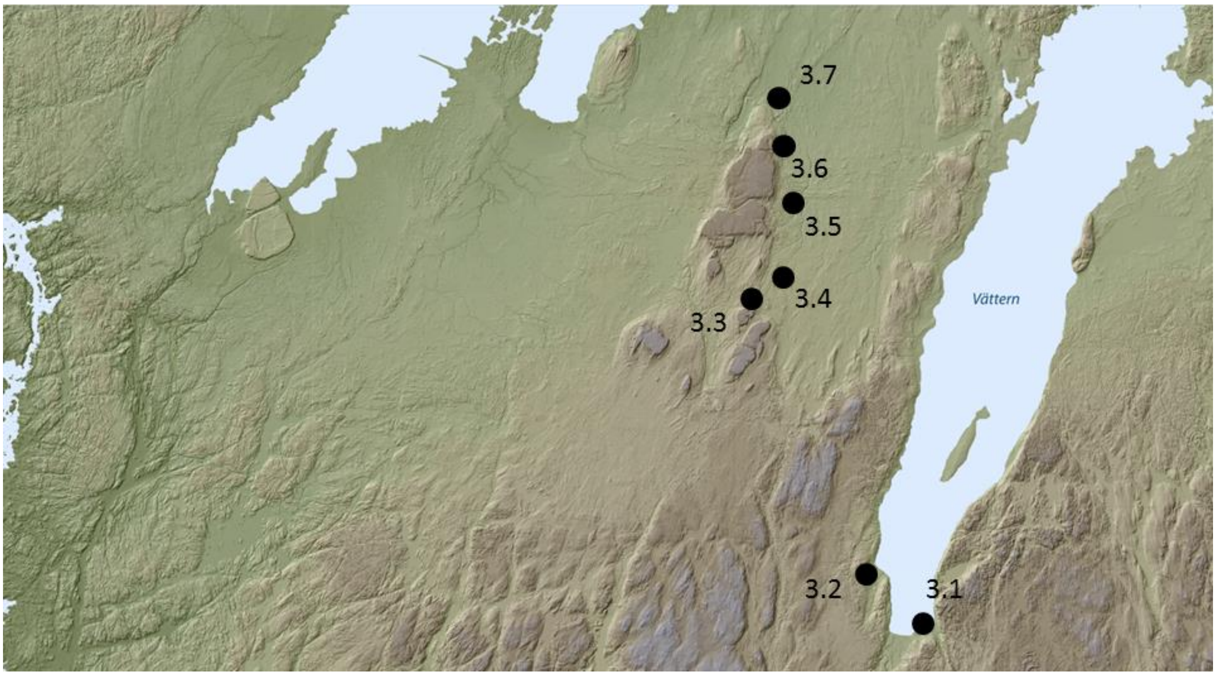


Figure 41. North is to the left! Google Earth dump of Axvall Hed and Varnhem (church at top of figure). Inset shows SWECO drillhole locations. I have sketched out four of these with B9 being the northernmost. The surface is 130-132 m and not clearly sloping south. There is a clear tripartite stratigraphy over bedrock in each of the boreholes.

Day three—September 23, 2015—Vättern, glacial Lake Tidan, MSEMZ east and DGMs



Stop 3.1 Rosenlundsbankar (Sarah Greenwood and Henrik Swärd)

Location: Rosenlund in Jönköping, at the southern edge of Vättern

Questions: How independent was the Vättern Lobe from the rest of the ice sheet? Was this an ice stream? What is the evidence for multiple readavnces in the Vättern basin? Is the chlorine peak found in the Vättern core a *smoking gun* for the early drainage?

Relevant excursion papers: Greenwood et al, 2015; Swärd, in press: O'Regan, in press; papers by Björck; Cleland, 2014

Background: The three papers listed above (plus a paper by Jakobsson et al (2014)) represent a flurry of activity around the Vättern lobe. Based on stratigraphic, sedimentologic and geotechnical evidence, this group has been able to show several advances of the Vättern Lobe (see Figure 18)into the lake during deglaciation. . Comparing Figure 28 to figure 6, one can see at least one extra ice-advance that is recorded in Vättern as opposed to the prominent ice-margins on the west coast. These papers also show an exciting variety of geomorphic forms on the bottom of Vättern as a result of these ice advances. The geotechnical evidence can be seen in Figure 42.
Perhaps the most exciting about this research is the presence of a chlorine peak (Fig. 42). As ice retreated (and readavanced) through the Vättern basin, there was a series of glacial lakes (including the Baltic ice lake) that occupied the basin. Thus, the clays deposited there are lacustrine (and varved!). The post glacial clay (units 2a and 2b) in Figure 42 are interpreted as being deposited after the drainage of the BIL. However, the Cl- peak 10 m below this level can be interpreted as an incursion of salt water associated with an earlier BIL drainage. This earlier drainage was proposed by Svante based on shoreline displacement curves in Blekinge (southern Sweden) (Figure 43). Much to Svante's credit, he has tried to argue away this early drainage (figure 44). But now there is evidence that the early drainage occurred! Is the chlorine peak a smoking gun?
Figures 45 and 46 shows the seismic stratigraphy that the Stockholm group has produced as well as the location of Rosenlundsbankar. The sections in Figure 46 have been redrawn from Waldemarson's (1986) thesis.

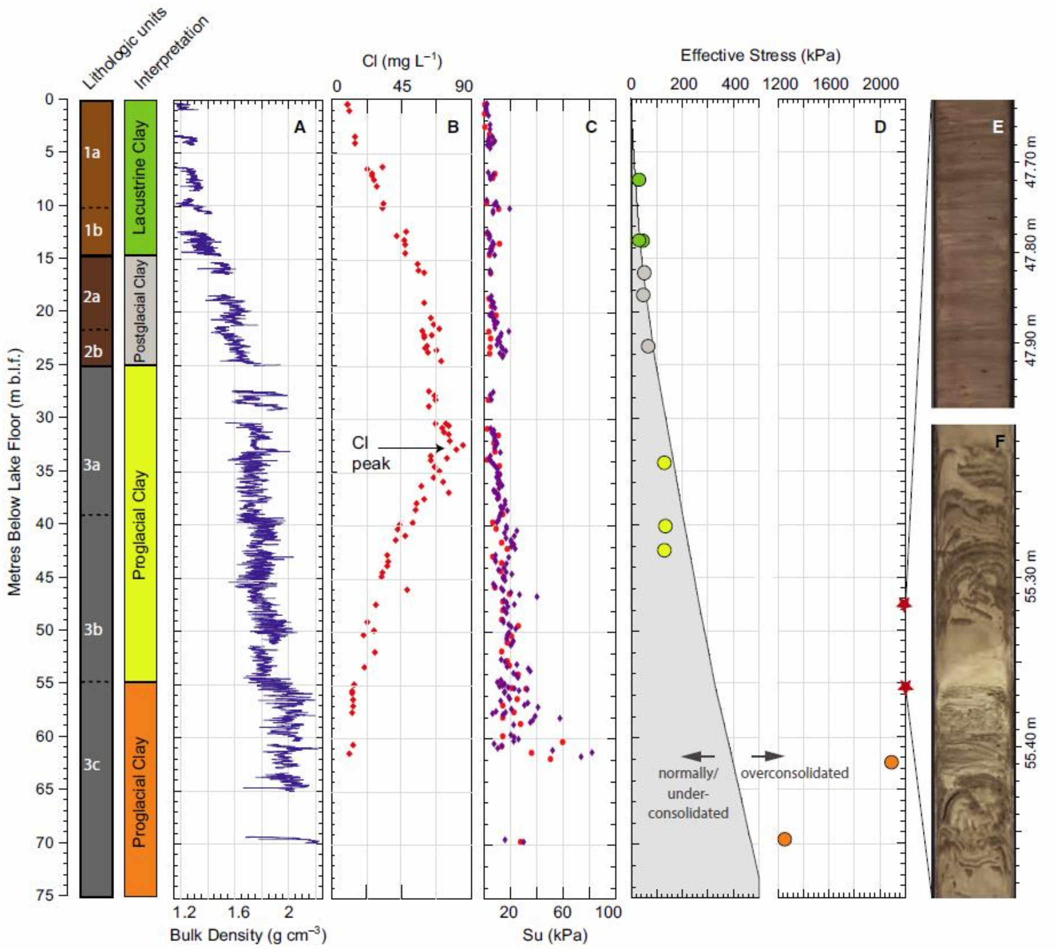


Fig. 2. Physical and geochemical properties of the recovered composite drill core, with lithological interpretation (from Swärd *et al.* in press; O'Regan *et al.* in press). A. Multisensor core logger derived bulk density. B. Pore-water chloride concentration. C. Undrained shear strength from fall cone (purple) and penetrometer (red) measurements. D. Preconsolidation pressures (coloured circles, according to lithological Unit) from oedometer samples with threshold stress envelope for normally consolidated – over-consolidated sediment. Photographs show examples of laminated clays above the Unit 3b–c transition (E); and glaciotectonized sediment in the lower (Unit 3c) part of the sequence (F). The combination of over-consolidated sediments, coarser grained intervals of sediment, and the intense deformation witnessed in this interval, together argue against coring-related deformation, and suggest deformation of Unit 3c under a substantial grounded ice mass.

Figure 42 from Greenwood and others, 2015.

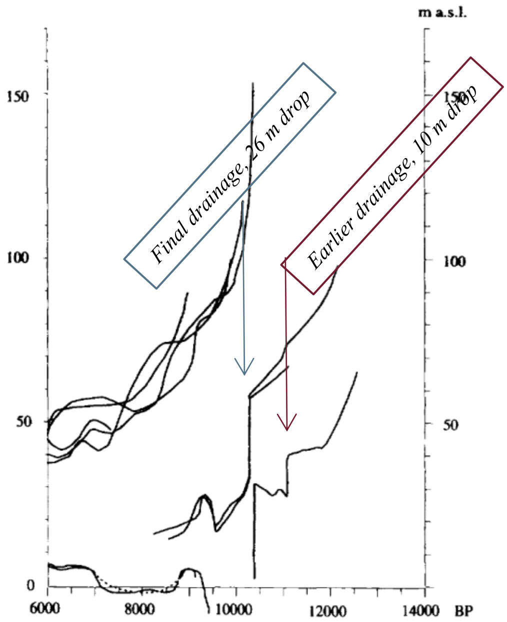


FIG. 2. A set of shore displacement curves from the Swedish Baltic Sea coast between 6.0 and 14.0 ka ^{14}C BP, based on Berglund (1964), Liljegren (1982), Björck (1979), Björck and Möller (1987), Svensson (1989), Persson (1979), Fromm (1976), Sandgren and Risberg (1990), Åse and Bergström (1982), and Miller and Robertsson (1981). The graph is modified from Björck and Svensson (1992) compiled from Svensson's shoreline database.

Figure 43.—From Björck 1995 showing the initial evidence for the earlier drainage.

TABLE 1. Arguments against and in support of a drainage of the Baltic Ice Lake at ca. 11.2 ka BP

Against a Drainage

1. No deposits can for *certain* be related to such a drainage.
2. No distinct regional change in the character or colour of the varved clays from that period has yet been found.
3. No distinct drainage signal can be found in the marine sediments off the Swedish west coast.
4. No clay-varve evidence for a significant oscillation (ice-withdrawal/ice-readvance) during the Allerød/Younger Dryas (AL/YD) transition has been found east of Mt. Billigen.
5. No marine influence in the Baltic in AL/YD.

Supporting a Drainage

1. The huge (1 km³) 'kame complex' of Valle Härad (interpreted as *the* drainage deposits by Björck and Digerfeldt, 1984) was free from ice before 10.2 ka BP and is restricted upwards by the late AL shore level.
2. The shore displacement in Blekinge shows a very rapidly falling Baltic Ice Lake level (5–10 m) in the late AL followed by a transgression in the early YD.
3. The shore displacement in E Småland indicates a rapid Baltic Ice Lake regression in the late AL.
4. Several studies in the Baltic countries suggest a rapid lowering of the Baltic Ice Lake in the late AL, followed by a YD transgression.
5. The 11.5 ka BP shoreline in the Baltic is approximately situated at the Öresund threshold level, while the 11.0 ka BP shoreline is 5–10 m below that level.
6. The small height difference between the 11.0 ka BP shoreline and the last, 25 m up-dammed Baltic Ice Lake shore line 700 years later, suggests that the 11.0 ka BP shoreline was formed in the sea.
7. The stratigraphy of Lake Vänern's AL/YD sediments (Dennegård, 1984) indicates high discharges of fresh-water in the late AL.
8. Independent studies in and around the Lake Vänern basin (glacial stratigraphy/morphology, shore displacement, clay stratigraphy) suggest a significant glacial oscillation west of Mt. Billingen during the AL/YD, allowing drainage of the Baltic Ice Lake.

Figure 44.—Table from Björck 1995 in which pros and cons of this early drainage are weighed.

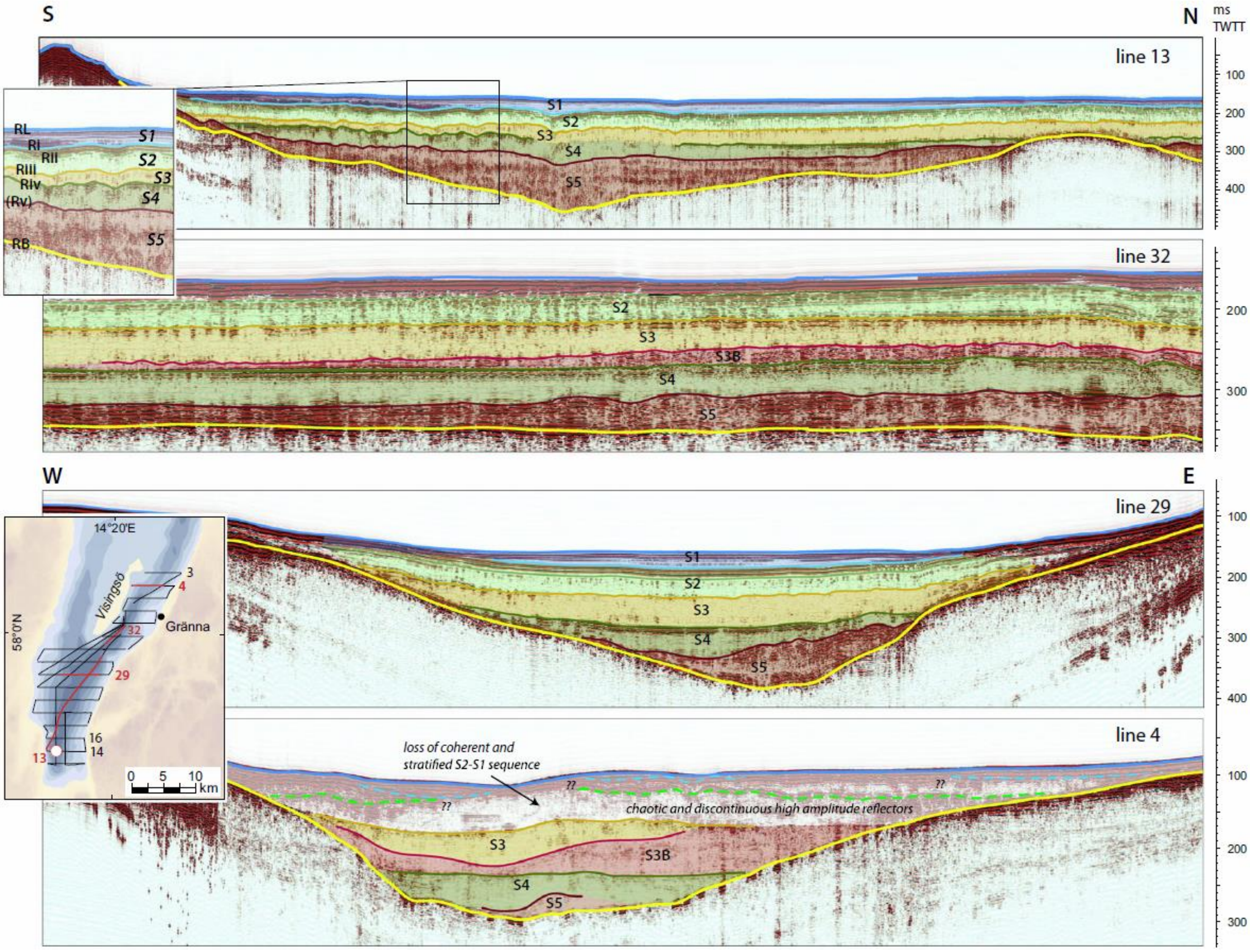


Figure 45 from Greenwood and others, 2015. Seismic records from Vättern.

Figure 46. Location of Rosenlundsbankar and a redrawing of Waldemarsson's (1986) stratigraphy showing two diamictions separated by lacustrine sediment.

Stop 3.2 Bankeryd (Sarah Greenwood) LUNCH

Location: Somewhere NW of Jönköping!

Questions: Which evidence seen in the cores can be traced to glacial deposits on land on land? Was there a proglacial lake around Vättern? When was it connected to the BIL?

Relevant excursion papers: Greenwood et al, 2015

BOREAS Re-advances of Lake Vättern outlet glacier, south-central Sweden 9

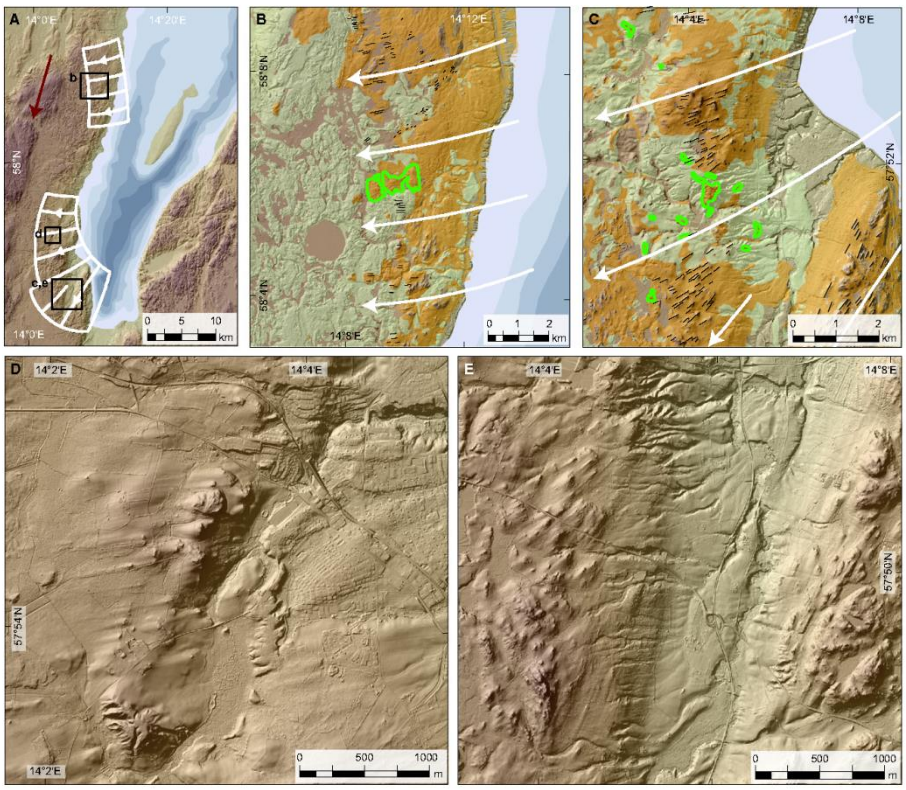


Fig. 7. In two areas along the western shore of Vättern (A), crag-and-tails record westward, onshore ice movement (white flowsets), which contrast with the regionally extensive, broadly southwards palaeo-flow (red arrow). Mapped glacial lineations are in black (B, C), shown with greater zoom in (D) and (E), and which are summarized by palaeo-ice flowsets in white. Till that corresponds to the distribution of E–W lineations overlies thick glacifluvial deposits that record an earlier northwards retreat of ice (B, C): till in orange, glacifluvial deposits in green, bright green outlines indicate where till overlies glacifluvial. We correlate this westward, onshore re-advance with the over-consolidated proglacial lake clay (U3c) in the drill-core, and link both lines of evidence with our interpreted Trånghalla re-advance.

Figure 47.—From Greenwood and others—geomorphic features along the SW edge of the Vättern Lobe.

Stop 3.3 Glacial Lake Tidan, Dala (Tore Påsse)

Location: Dala, SE of Stenstorp, Sweden

Questions: What is the age of glacial Lake Tidan when it passed through this outlet?

Relevant excursion papers: --

Background: This is one of the outlets of glacial Lake Tidan. The elevation is around 185-190 here, that is, well above the level of the BIL. Please read the introduction and look at Figures 15-17 and 48.

Stop 3.4 Glacial Lake Tidan, Ljusslingbackarna (Tore Påsse)

Location: Ljusslingbackarna, Sweden

Questions: What is the genesis of these sediments? What was the lake level, age of glacial Lake Tidan?

Relevant excursion papers: --

Background: Numerous eskers and deltas can be found on the bottom of the glacial lake: eskers showing ice cover, and marginal deltas formed into the lake ('kame deltas') (Figure 48).

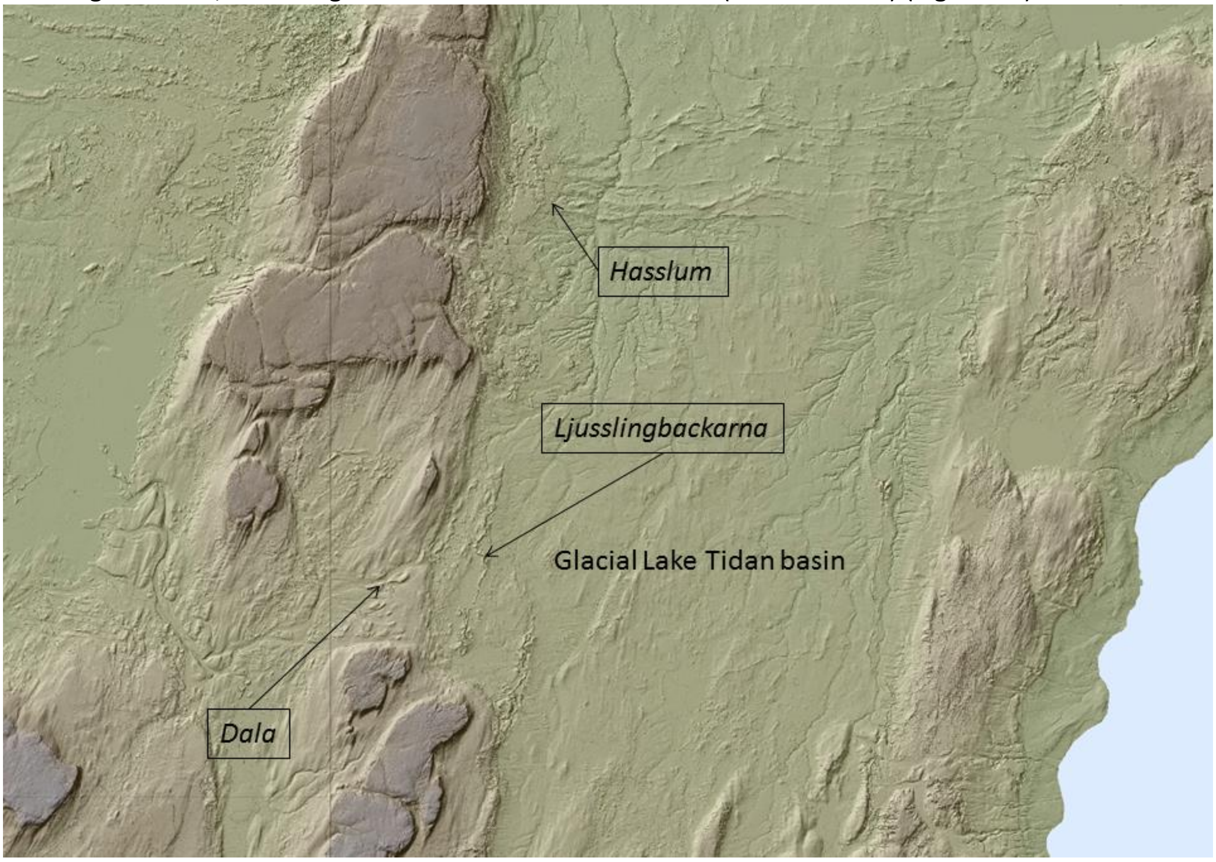


Figure 48.—LiDAR image showing the location of stops 3, 4, and 5 on day three.

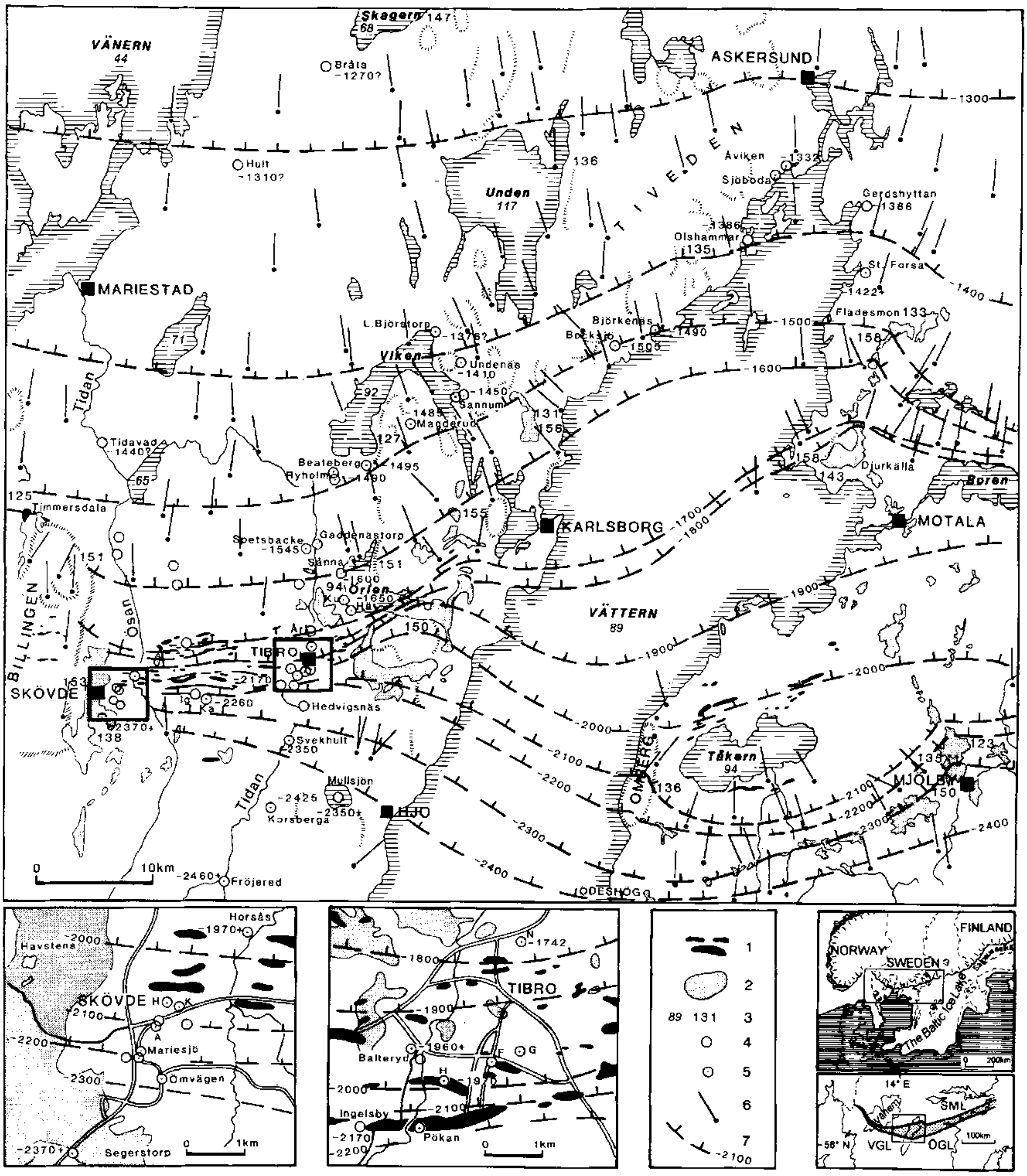
Stop 3.5 Hasslum (Mark Johnson and Tore Påsse)

Location: Hasslum area of Skövde

Questions: How were these moraines formed? What is the genesis of the sediment here? Did these moraines form in glacial Lake Tidan of the BIL?

Relevant excursion papers: Strömberg, 1994

Background: Here is a rather poor exposure in the southernmost of the MSEMs on the east side of Billingen. The pit contains mostly sorted sediment with some deformation. We should be able to get a reasonable idea of the internal structure of the moraine. Near the entrance to the pit is a section of clearly varved sediment. Strömberg (1994) has worked out the varve chronology for this area (Figure 49-50).



ig. 1. Deglaciation in the Mt. Billingen–northern Lake Vättern area. Lower maps: The Skövde and Tibro areas. Moraines in the Tibro rea according to Andersson & Wastegård (1988). Key map: location of the investigation area. The approximate extent of the Weichselian e and dry land just before the final drainage of the Baltic Ice Lake. The Middle-Swedish end moraine belt dotted, SML = Södermanland, GL = Västergötland, ÖGL = Östergötland. Legend: (1) Moraines, mainly glaciofluvial ridges. (2) Large accumulations of glaciofluvial aterial, mainly deltas. (3) Lake levels (in italics) and late-glacial shore levels according to shorelines, delta surfaces, etc. (4) Varve easurement sites from Ahlmann (1916), Caldenius (1944), Nilsson (1968) and Björck & Digerfeldt (1989). (5) Varve measurement sites om Strömberg (1977a, 1985b and later). (6) Youngest glacial striae according to the geological maps, K. E. Bergsten (1943), and easurements by the author. (7) Ice recession lines. Dates in varve years before zero (±0 = 7288 BC; Cato 1987). Skövde A, H, K and = Aspelund, Hasslum, Kylarvägen and Segerstorp. Tibro F, G, H and N = Fågelviken, Gymnasium, Hönebolet and North. ä = Hästhagen, Ig = Igelstorp, Ka = Kaggelstorp, Ku = Kulabäcken.

Figure 49.—Varve sites and ice-retreat isochrones from Strömberg, 1994.

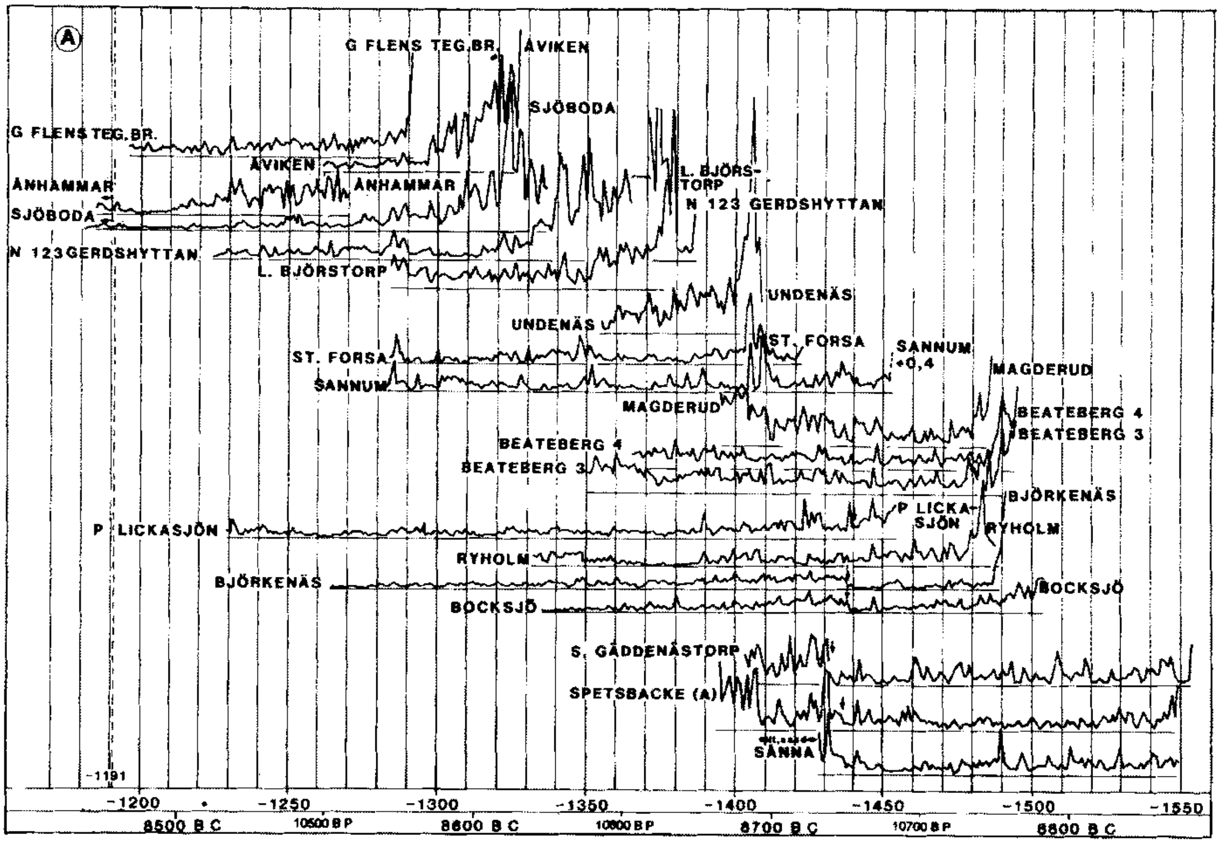


Figure 50.—An example of a varve correlation diagram from Strömberg, 1994.

Stop 3.6 Kvarntorp and Billingen (Tore Påsse)

Location: Kvarntorp, 13 km North of Skövde along Billingen's NE slope

Questions: What is the evidence for the BIL and YS shorelines on the NW side of Billingen? Can the drainage be subglacial?

Relevant excursion papers: --

Background: The magnitude of the drainage of the BIL at Billingen is based on evidence that the BIL's shoreline at Billingen was 150 m a.s.l., whereas the shorelines from the sea on the west reside now at 125 m. Unfortunately, abundant evidence for these shorelines is lacking. At Esbjörntorp, we find shoreline (?) sediment that Bo Strömberg states is the only/best evidence for the 150-m level on the NE side of Billingen. In Figure 51, these deposits are mapped as green with white dots. It has been suggested they are shoreline deposits built after the drainage, because they occur around 125 m. However, we suggest they may represent a subglacial initiation of drainage. Figure 52 represents three lines of evidence for the location of the ice margin in the field area at the time of the drainage.

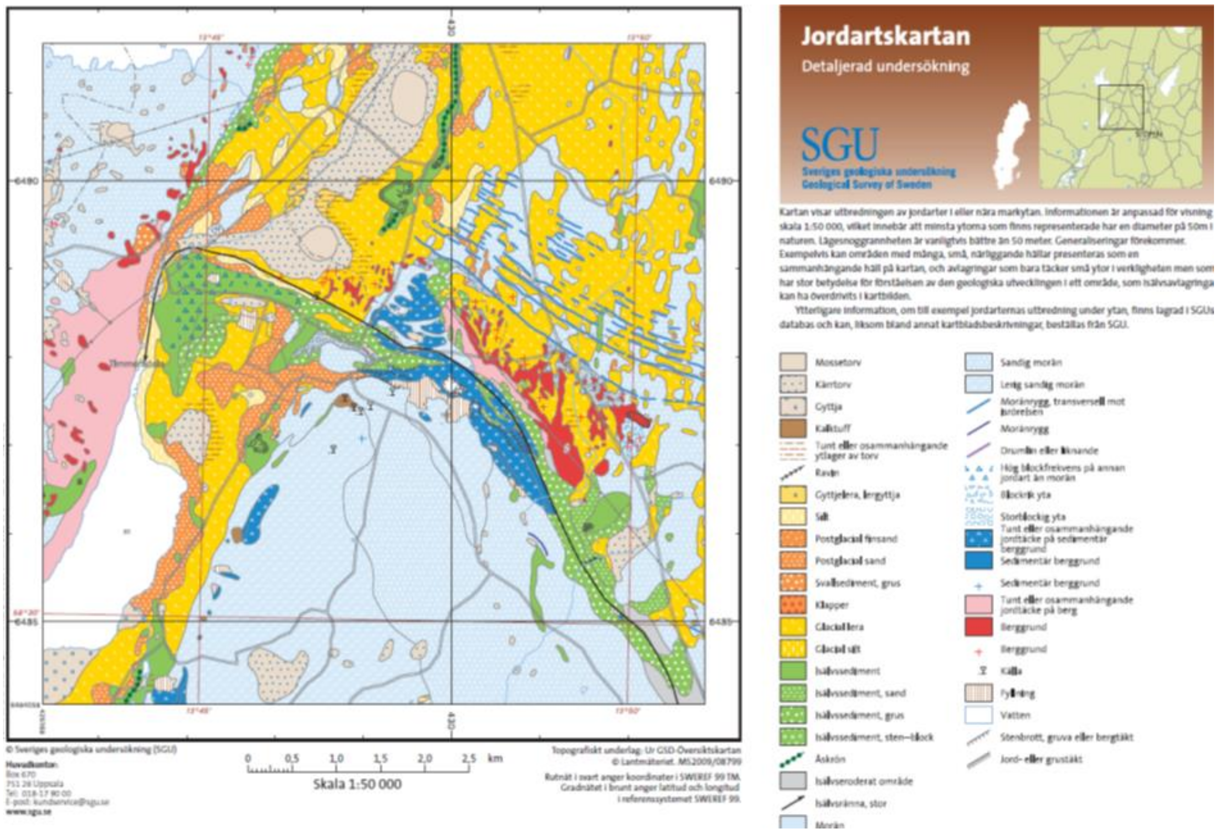


Figure 51.—SGU surficial-deposits map of the northern tip of Billingen.

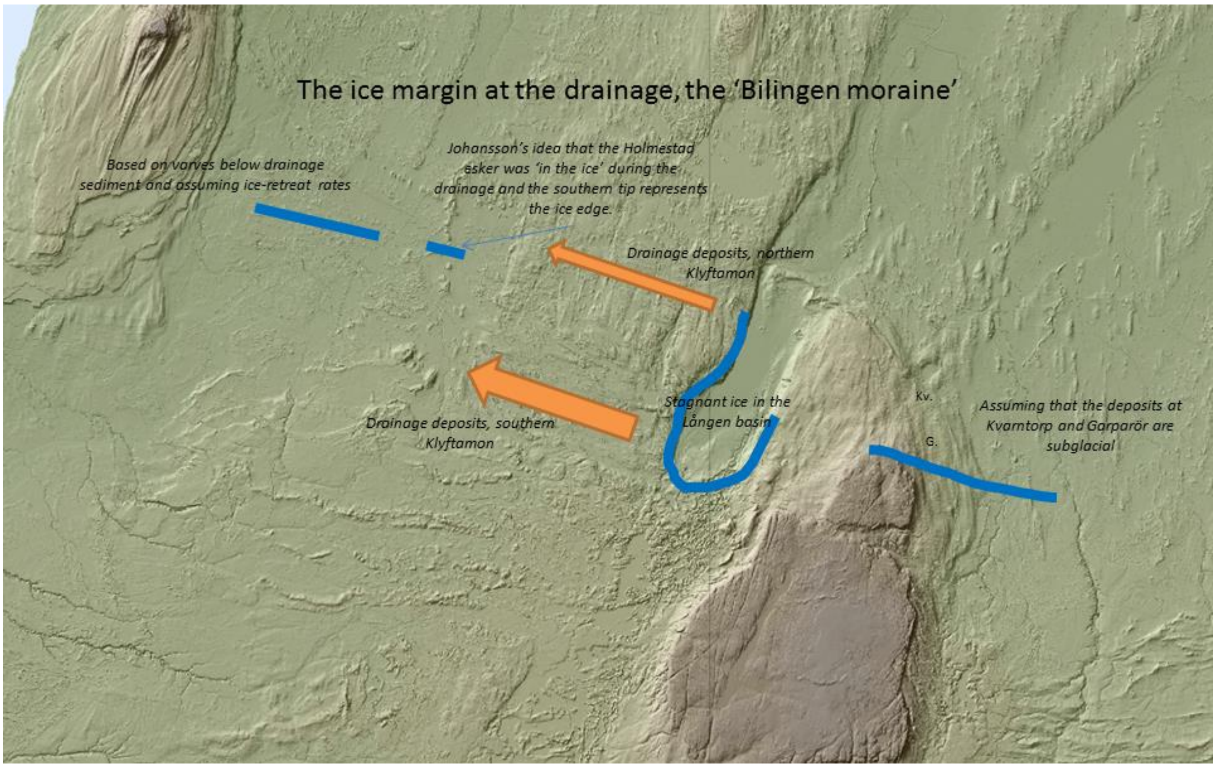
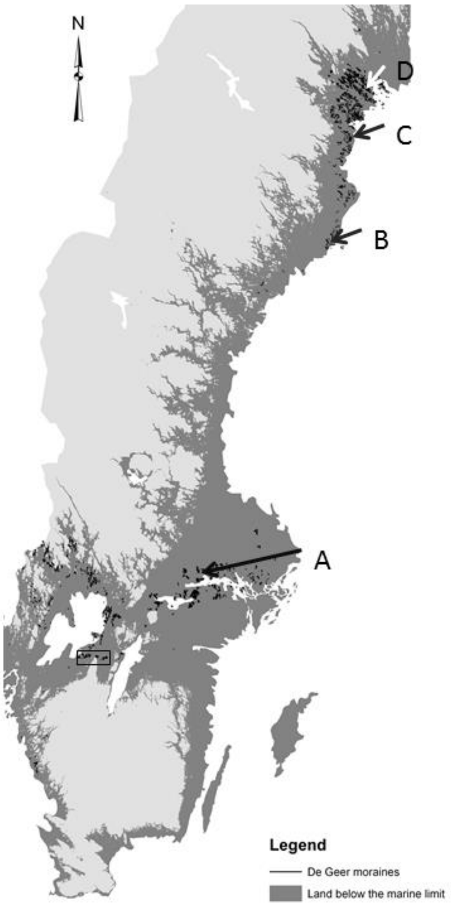


Figure 52.—Blue lines represent the position of the ice margin at the time of the drainage.



Stop 3.7 Låstad De Geer moraines (Mark Johnson)

Location: Highway 26, just north of Timmersdala

Questions: How are De Geer moraines made? Are they annual?

Relevant excursion papers: --

Background: Gerard De Geer first recognized ridges like these and called them *årsmoräner.* He was able to correlate certain fields of these small ridges to the local varve chronology and could convince himself that they were formed annually, likely by a winter advance/push. This idea was criticized by several in the 50's and 60's, and this lead to a belief that they could not be annual. It is clear today that there are many areas where the number of DGMs exceeds the annual ice-retreat rate. They were also renamed 'De Geer moraines' to 'honor' their discoverer.

Fig.—53 from Bouvier et al, in press. Left, distribution of DGMs in Sweden. Below, DGMs north of the MSEMZ, including those at this stop.

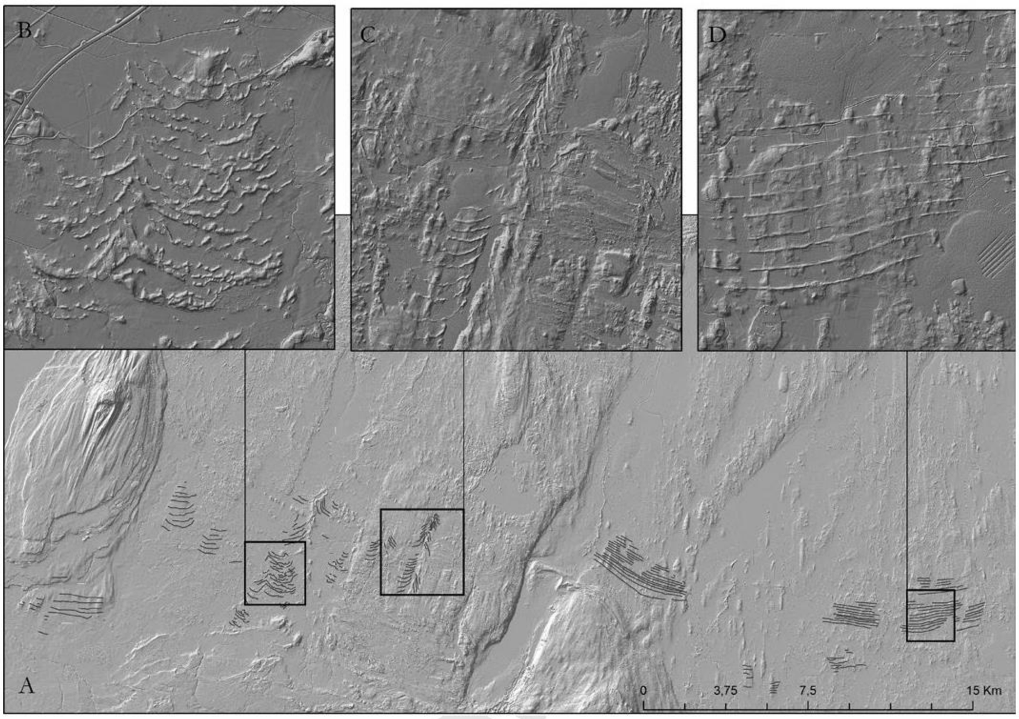


Fig. 4. DGMs in south-central Sweden; location shown in Fig. 2. **A.** Location map for **B**, **C**, and **D**; the drumlinized hill on the left is Mt. Kinnekulle. The numerous DGMs in "**A**" occur immediately north of the Middle Swedish end-moraine zone; several of the moraine ridges are visible in the lower left. **B.** DGMs with cuspate forms, which we interpret to represent location of longitudinal crevasses in the glacier. **C.** Embayed DGMs on the higher area known as Klyftamon. The apex of the angled DGMs implies the location of the mouth of a subglacial tunnel. **D.** Evenly spaced DGMs.

In a recent study at Göteborg (Bouvier et al, GFF, in press), a claim is made that although DGMs can be made by several processes, most are made as winter push ridges, and in those areas where DGMs are regular and evenly spaced (like at this site), they strongly suggest that their spacing is a good indication of the local ice-retreat rate. They suggest that there can be annual and interannual DGMs. It is clear that the ice-retreat from the varve chronology is imprecise for many parts of Sweden where DGMs occur (especially in the north), and it is also difficult to identify clearly the difference between 'regular spaced ridges' and those that are not—it is somewhat a qualitative judgement. Nonetheless, Bouvier et al argue that it is likely that evenly spaced moraines represent the local ice-retreat rate.

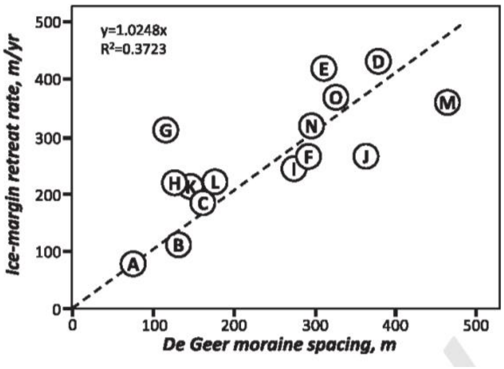
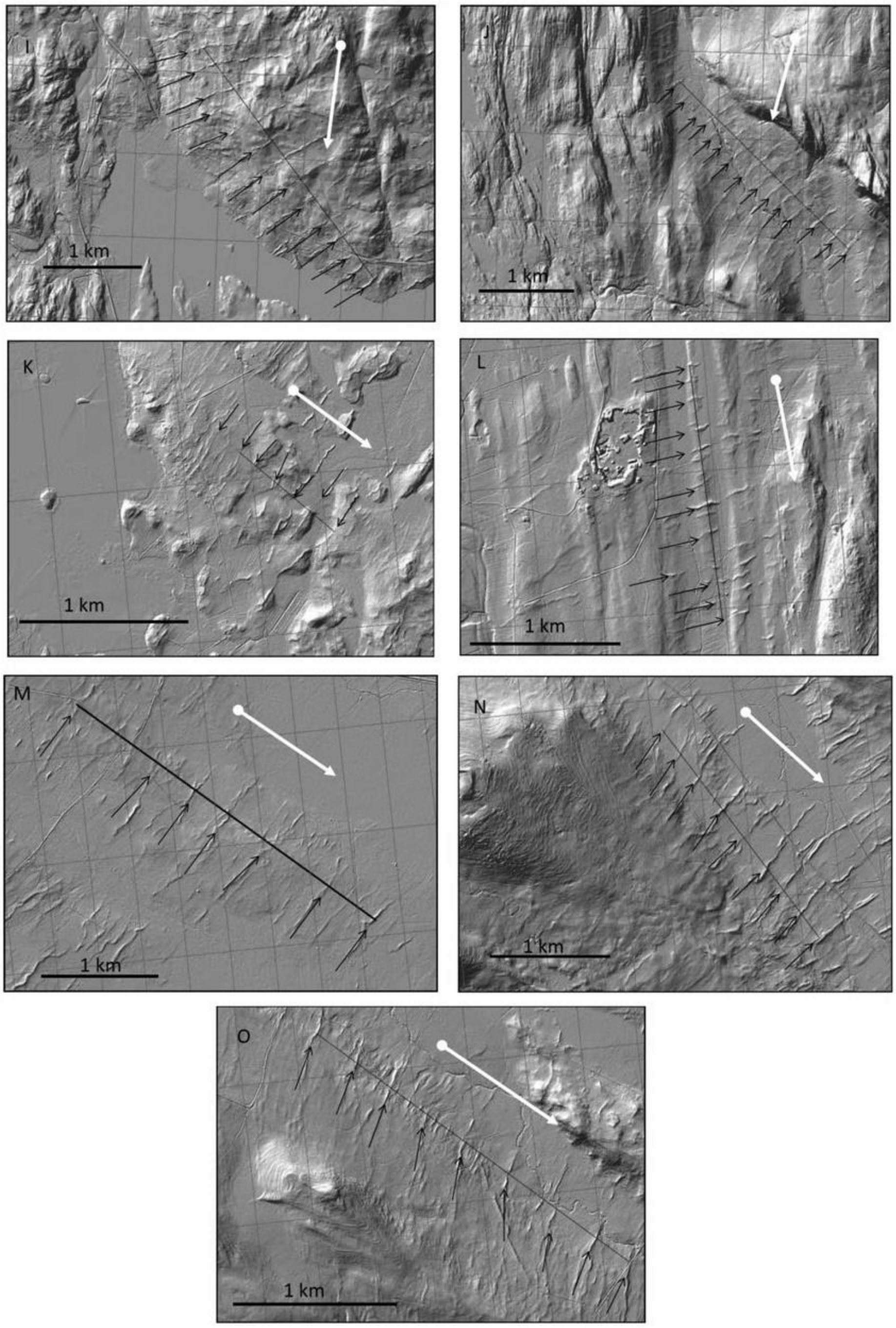
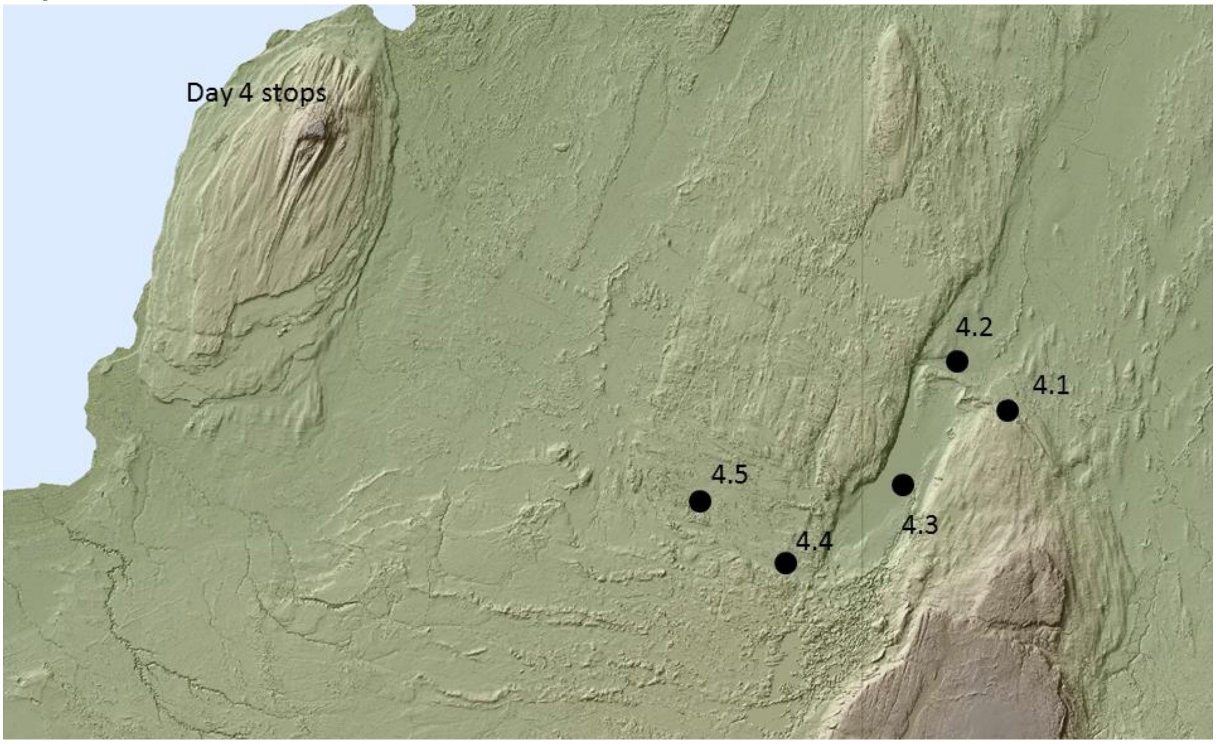


Figure 54.—(right) from Bouvier et al (in press). Comparison of DGM spacing and ice-retreat rate (determined from De Geer's varve chronology) for 15 randomly chosen DGM swarms in Sweden. The results show a correlation between spacing and retreat rate, which argues that the DGMs likely are annually formed.

Figure 55.—(below) from Bouvier et al, in press. Seven of the 15 randomly chosen fields showing annual DGMs and interannual DGMs.



Day 4—September 24, 2015—Billingen, Timmarsdal, Lången and Klyftamon—THE DRAINAGE!



Stop 4.1 St. Stolan at Billingens northern point (Mark Johnson)

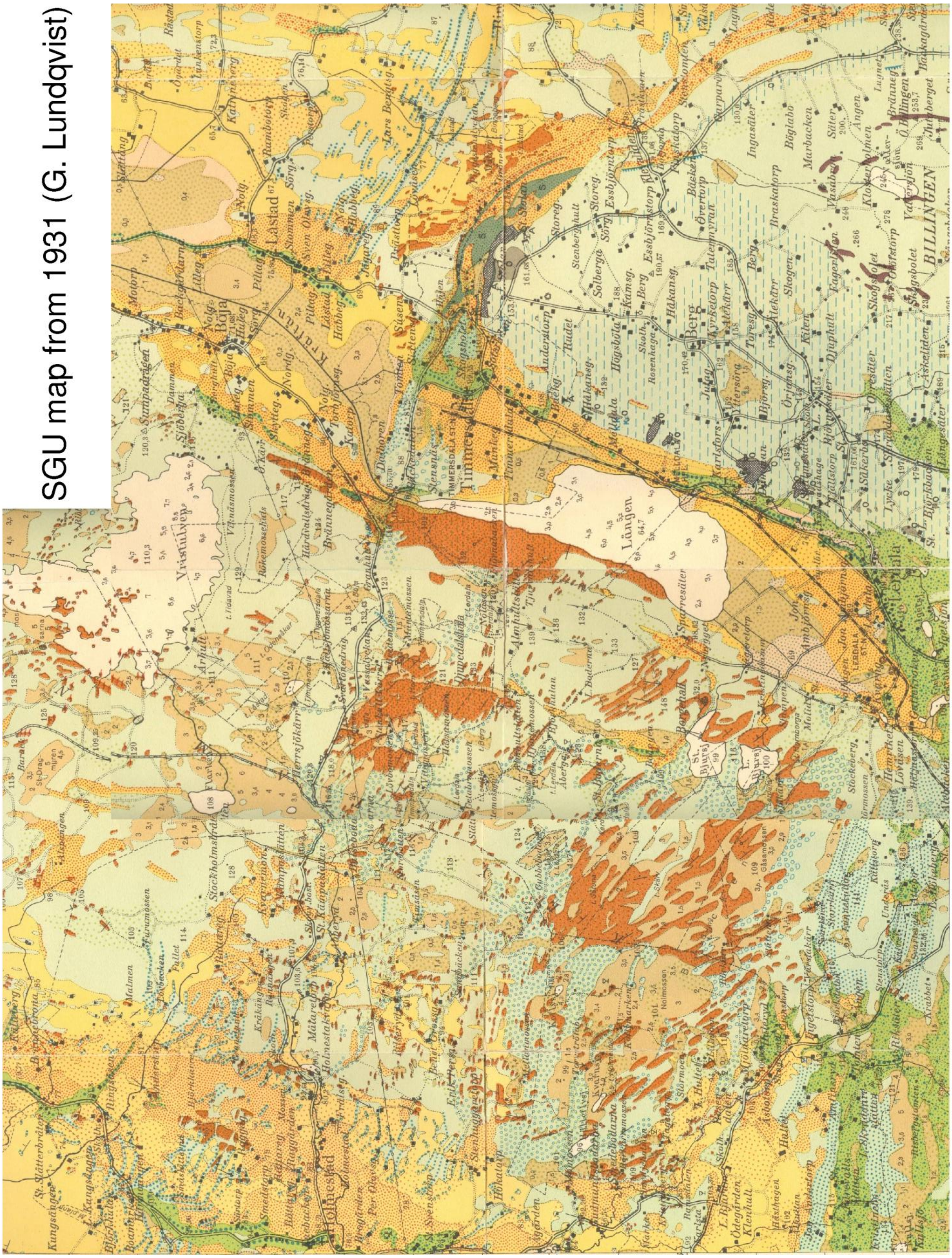
Location: Northern tip of Billingen, an abandoned quarry in Cambrian sandstone

Questions: What is the evidence for the drainage here?

Relevant excursion papers: Strömberg, 1992

Background: Today's stops deal with the drainage (the final drainage if there was an earlier one), its character, duration, location, geomorphology and sedimentology. St. Stolan has been a classic site to visit as it shows the removal of all glacial sediment down to the sandstone bedrock (and crystalline bedrock just to the north). These exposed rocks can be seen in olive green and orange on G. Lundqvist's map from 1931 (Fig. 56.) and in blue and red of Tore Påsse's maps from 2006 (Fig. 57.)

Fig. 56 (next page).—Surficial deposits map of G. Lundqvist from 1931.



SGU map from 1931 (G. Lundqvist)

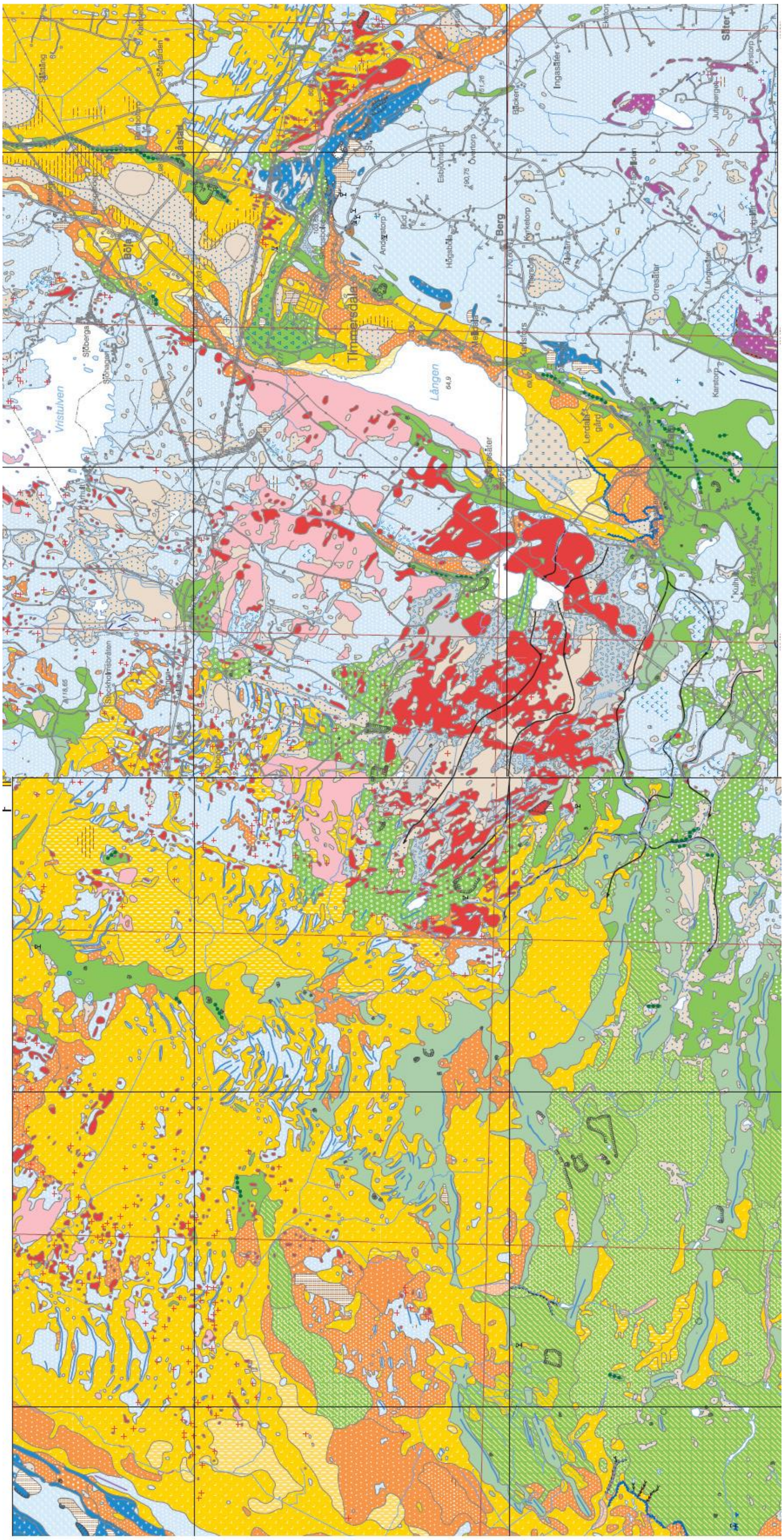


Fig. 57.—Surficial geologic maps from Tore (Påsse, 2006a, 2006b).

Stop 4.2 Timmersdala (Tore Påsse)

Location: ridge immediately north of the town of Timmersdala

Questions: How was this ridge made? What is the sediment provenance? What is the the sediment genesis? Where was the ice when this ridge was made? What is the explanation for the sandstone blocks on the surface?

Relevant excursion papers: --

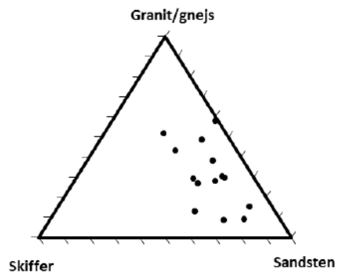
Background: Timmersdala is a classic drainage site in part because it was became a central part of the discussion about the drainage between G. Lundqvist and Simon Johansson, each offering different views on the origin of the ridge. Lundqvist thought it was primarily a moraine with some drainage deposits on top, whereas Johansson thought of it entirely as being composed of drainage sediment. The feature is clearly mapped on both the maps in Figs 56 and 57. Jan Lundqvist said to me once that it is either (1) an end moraine, (2 a subglacial drainage deposits or a (3) supraglacial drainage deposit deposited in a crevasse. Its origin is still a mystery, but recent highway construction has shown us what it is made of. Several important observations from the recent exposures:

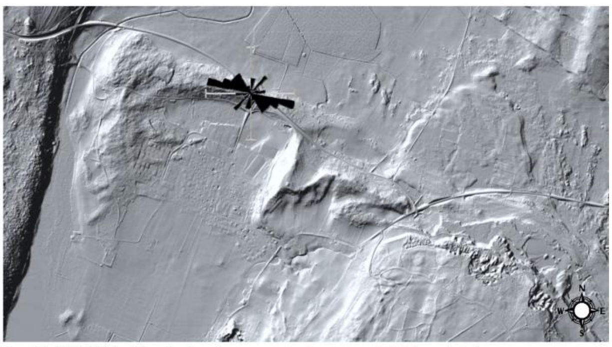
1. The bulk of the sediment at this stop is composed of poorly sorted, clast-rich diamicton that is not till (Figure 58). This is interpreted to be drainage sediment.
2. This sediment is dominated by clasts derived from the tip of Billingen (sandstone, shale) but also granite, which can come from till eroded on Billingen (Figure 59).
3. Further west, finer sediments such as sand dominate.
4. The sediments are arranged in a package that clearly shows prograding structures—the ridge contains sediment that accumulated east to west—the ridge grew west.
5. Sandstone blocks are common on top of the ridge, but not many within the ridge.

Figur 14 - (A) Exponering vid Timmersdala som visar ett något rundat sandstensblock, materialet är dåligt sorterad med lerig-siltig grus. Bilden visar en svag överlappning (IMBRIKATION) av materialet. (B) Bilden är lik den i (A), materialet består av synlig skiffer och sandstens stenar som är dåligt sorterade. (C) Bilden är tagen strax efter att de påbörjat vägbyggnationen. (D) Exponering av Timmersdalavallen under vägbyggnationen. (E) En närbild av föregående bild (D). (F) En närbild av föregående bild (E). Alla bilder är tagna av Mark Johnson.

Fig 58. Photos of the coarse, poorly sorted diamicton at Timmersdala during road construction.

Fig. 59.—Lithologies from several grain-size fractions for three samples of 2-32 mm plus three transects counting 64-256 mm clasts. 256 mm clasts (Pizzaro, 2012).





Figur 17 – LiDAR-bild kombinerad med rosdiagrammet som visar ryggens och blockens orientering.

Fig. 60.—Orientation of blocks (>1 m) on top of Timmersdala ridge—most are sandstone—some are crystalline.

Stop 4.3 Lången (Svante Björck)

Location: Lake Lången, north of Lerdala, south of Timmersdala.

Questions: Why does this lake exist? Why are there no drainage deposits here? What is the evidence for stagnant ice?

Relevant excursion papers: papers by Björck (1995) and Björck and Digerfeldt (1984, 1986)

Background: Lake Lången is a somewhat shallow lake that lies in the lowland between Klyftamon and Billingen. (Fig. 57). It is surrounded by post-glacial clay. Cores of the lake show a variety of sediments but glacial sediments at the base (clayey till) overlain by lacustrine sediment, some of which is varved. There is no evidence for the drainage here. The idea that stagnant ice lay in the Lången basin can be dated back to Ramsay (1924) and most researchers have concluded that stagnant is required to explanation the drainage features. Here, we give an argument from geochemistry and an argument from clast analysis.

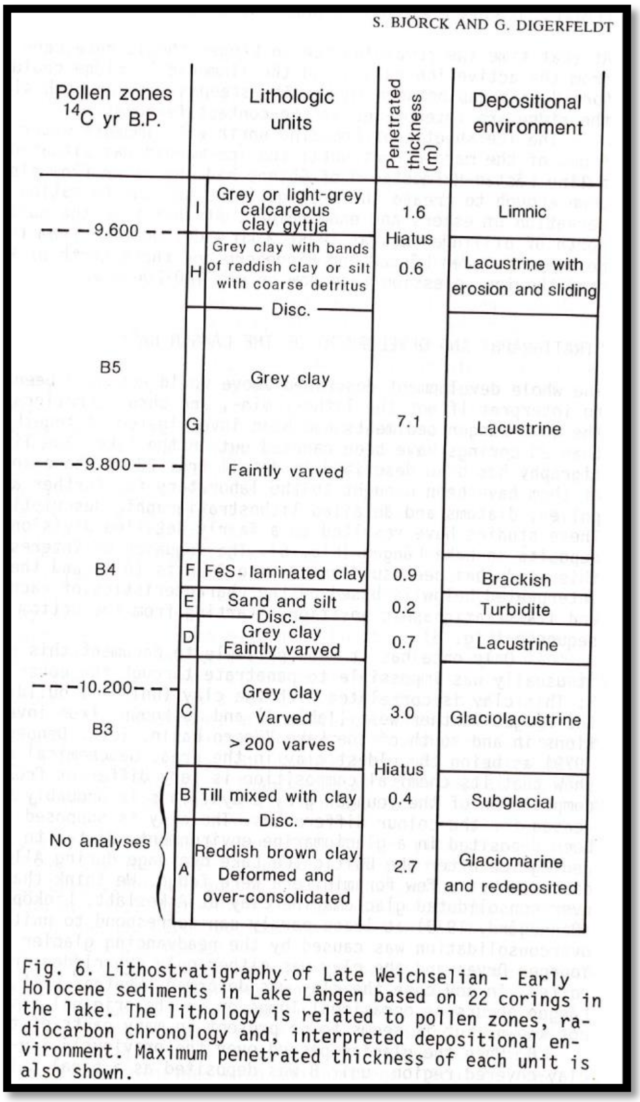


Fig. 6. Lithostratigraphy of Late Weichselian - Early Holocene sediments in Lake Lången based on 22 corings in the lake. The lithology is related to pollen zones, radiocarbon chronology and, interpreted depositional environment. Maximum penetrated thickness of each unit is also shown.

Figure 61.—From Björck and Digerfeldt (1984), composite stratigraphy from several cores (22?) in Lången.

Detailed geochemistry was carried out on this core by Siv Olsson (Olsson, 1991). Geochemistry was also carried out on the Länsmansgården core (Stop 2.5) and the geochemical signatures of the pre- and post-drainage sediments allowed for correlation.

This correlation, shown in Figure 62, shows that there is a hiatus in the Lången core during which the drainage occurred. The simplest explanation (since the sediment below the hiatus is till) is that there was stagnant ice in the basin.

The other argument is based on clast analysis performed initially by Lundqvist (1931). As shown is Figure 63. The drainage deposits have higher Ss concentrations. Despite, a sandstone source from Lugnås, the surrounding concentration in the till (between the red arrows) is insufficient to explain the increased Ss in the drainage deposits. The Ss must come from Billingen. And the only way it can get to Klyftamon is if there is stagnant ice.

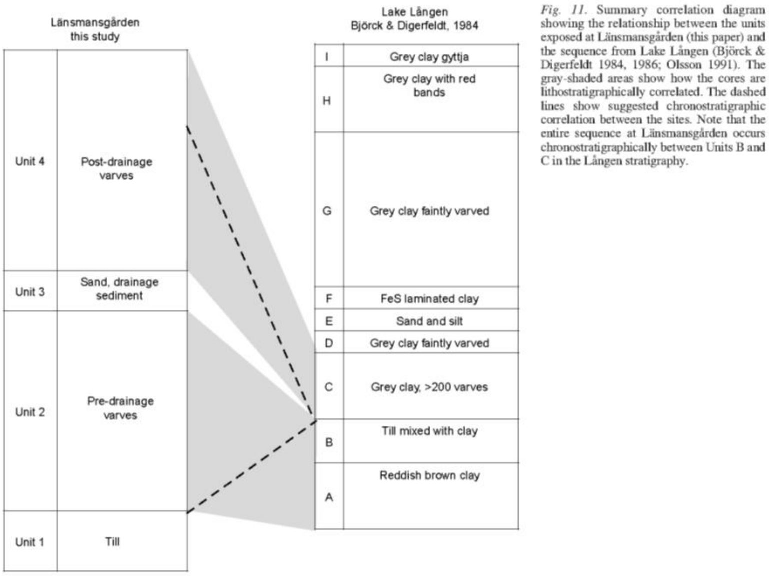


Figure 62.—correlation from Johnson and others, 2013, between Länsmansgården (continuous sedimentation during the drainage) and Lången. Gray bands represent lithostratigraphic correlation; black dashed lines show chronostratigraphic correlation. This shows that the deposition of Länsmansgården units 2, 3 and part of 4 occurred during the Lången hiatus, presumably because it was ice filled.

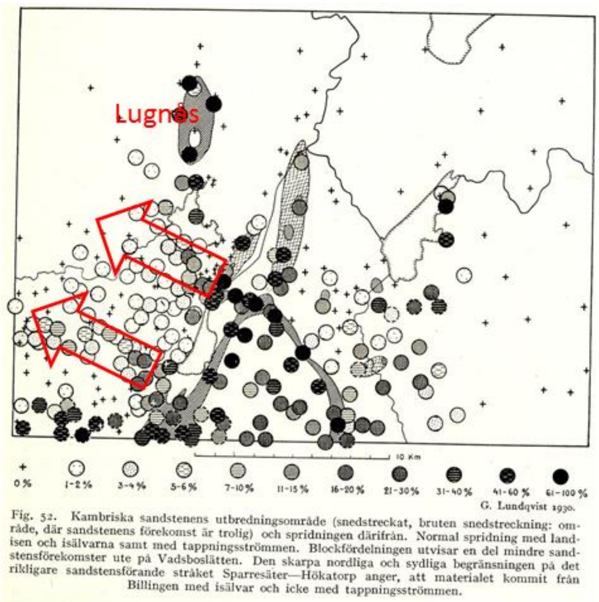


Figure 63.—Concentration of Cambrian sandstone in sediment (till, outwash, drainage sediment). The two red arrows mark the southern and northern path for the drainage. Between the arrows, sandstone concentration are from till. The higher concentrations in the 'arrows' must come from Billingen.And can't get there without stagnant ice.

Stop 4.4 Rännas erosional valley (Tore Påsse)

Location: Rännas, on Klyftamon

Questions: What have been the relative roles of erosion and deposition during the drainage event? Was the drainage event short (less than two years) or long (decades)?

Relevant excursion papers: sfn

Background: Look back at Figure 9 and you can see that the southern part of Klyftamon has extensive bare bedrock in the east and boulder deposits in the west: the sketch in Figure 9 is derived from mapping by Påsse, 2006 (Fig.57). The bare bedrock has long been thought to be due to erosion by the drainage event. Because the date of the drainage event is well known (11,625-11,690 cal YBP, Björck personal communication; new defined Holocene boundary is at 11,650 cal YBP), these bedrock surfaces have been used to calibrate the ^{10}Be cosmic-dating technique (Stroeven, ert al., 2015). Figure 64 (from Isaksson Dreyer and Johansson, 2013) shows the bedrock surfaces as well as boulder deposits. In addition to the boulder deposits, there are several channels (arrows in Figure 57) that testify that channel erosion occurred during this event.

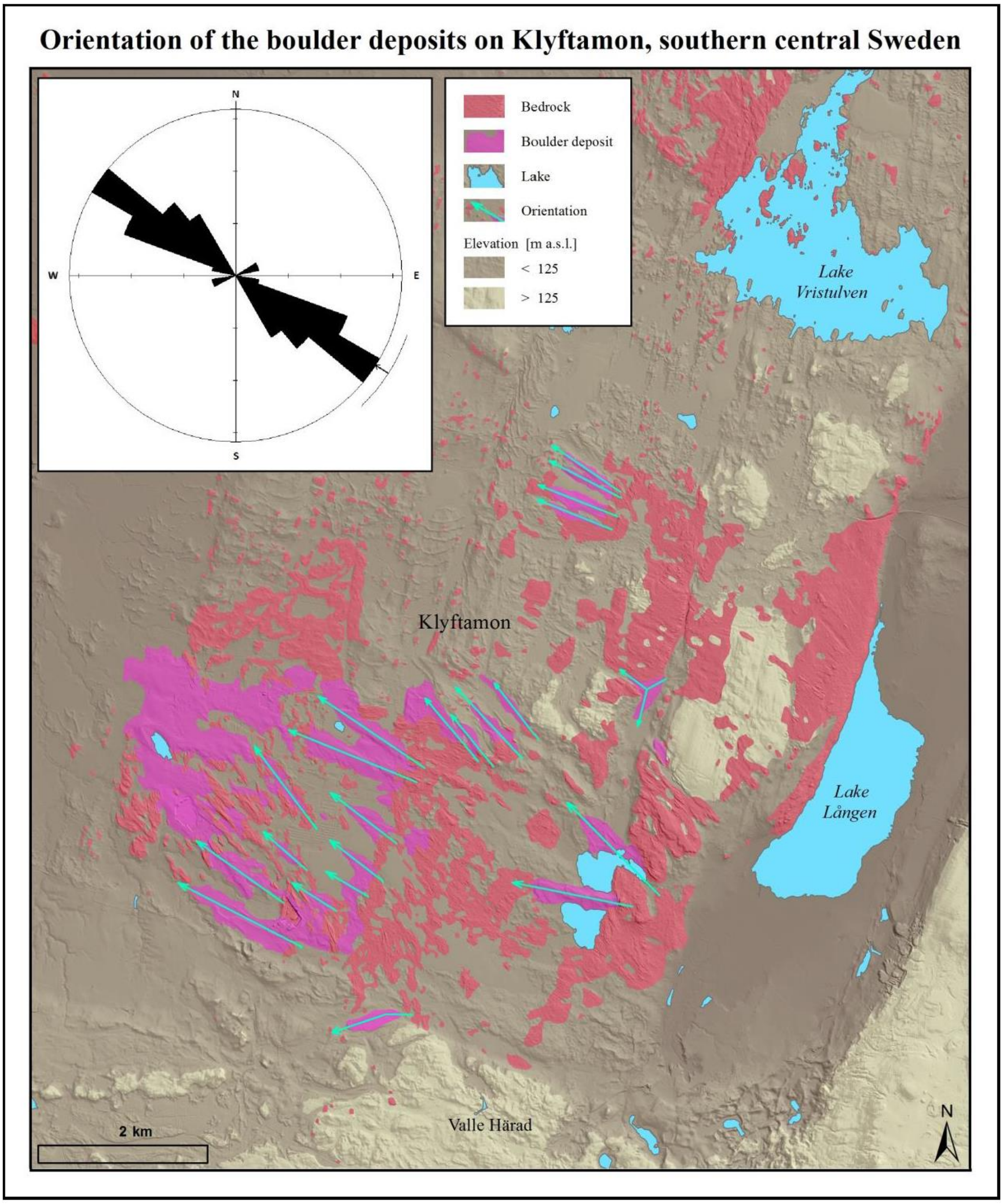


Figure 16. Orientation of the elongated boulder deposits on Klyftamon. The mean orientation is NW – W-NW, as visualized by the rose diagram. Note the arrow pointing in the mean resultant direction of the landforms, 123-303°. The arc shows the 95 % confidence interval for the mean direction. The boulder deposits appear to be located in the northern and southern drainage zones, as identified by Lundqvist (1931) and Björck and Digerfeldt (1984). Note the presence of bedrock to the E, SE or E-SE of every deposit. The highest marine limit has been found at 125 m a.s.l. only at the tip of Mt. Billingen. In this map it has not been adjusted for isostatic tilt and is thus not to be considered the exact position of the sea-level at the time of drainage. The highest coastline varies with distance from the tip of Mt. Billingen.

Figure 64.—Boulder deposoits, barebedrock and boulder-deposit oreitnbations on Klyftamong (iskasson Dreye & Johansson, 2013).

Stop 4.5 Stora Mon boulder pit (Mark Johnson and Christian Öhrling)

Location: Stora Mon gravel pit

Questions: What is the mechanism for deposition here? Why is there a coarse-grain cut off and a fine-grain cut off? What is the provenance of the sediment? How does this sediment get rounded?

Relevant excursion papers: Strömberg, 1992

Background: Most of the figures shown here are the products of some bachelor's theses at Göteborg, including Bergström, 2012, Isaksson Dreyer & Johansson, C., 2013, and Johansson, C. and Isaksson Dreyer, O. 2013. (Johansson is now named 'Öhrling').

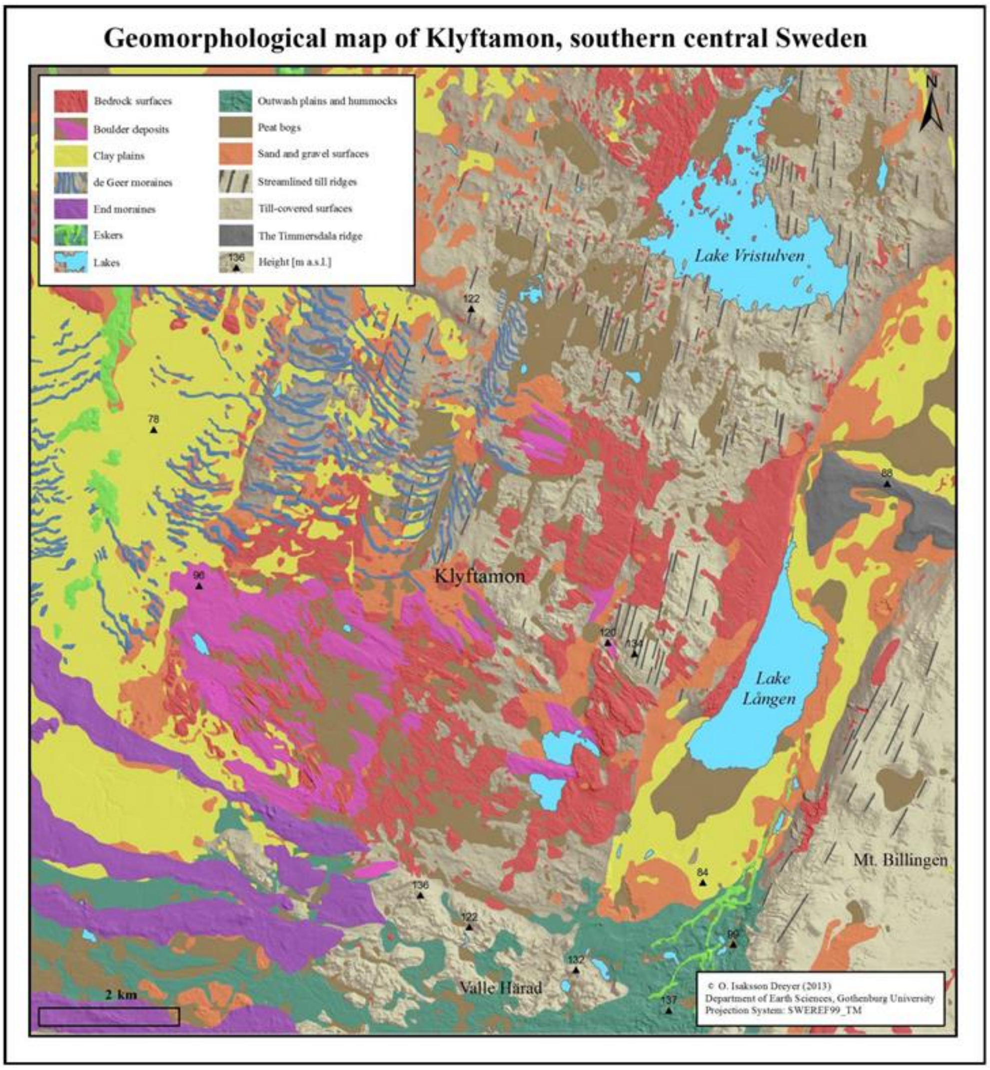


Figure 9. Geomorphological map of Klyftamon with surroundings. Large areas of southern Klyftamon feature barren bedrock with peat bogs and boulder deposits in between the exposures. Note that the boulder deposits appear to stretch out in a NW – SE direction and that the westernmost deposits take the form of a vast field. Clay accumulates in depressions and is therefore found in more low-lying terrain, as opposed to the till which generally covers somewhat elevated areas. The end moraines are the large, northernmost ridges of the middle Swedish end-moraine zone, while the smaller de Geer moraines are closely spaced and reveal the annual positions of the retreating ice-margin. Eskers commonly trend roughly perpendicular to the ice-margin and often terminate in outwash plains. The hummocks are a part of the Valle Härad complex and the sand and gravel surfaces occur in patches. Streamlined till ridges are small-scale, linear elements thought to portray the direction of the ice movement. They do not occur in either of the drainage zones, unlike the Timmersdala ridge, a local landmark that stretches out in the direction of the northern spillway.

Figure 65.— Geomorphological map of Klyftamon from Isaksson Dreyer and Öhrling (2013).

There is a clear orientation to the boulder depsoits, and there is a change in their morphology as the trough deepens to the west /Figure 66) —shallow bars have slip faces in a couple places; in the middle reaches, the bars are lee-side accumulations (around bedrock knobs), and the large mass in the west (where this put us) is interpreted as more rapid

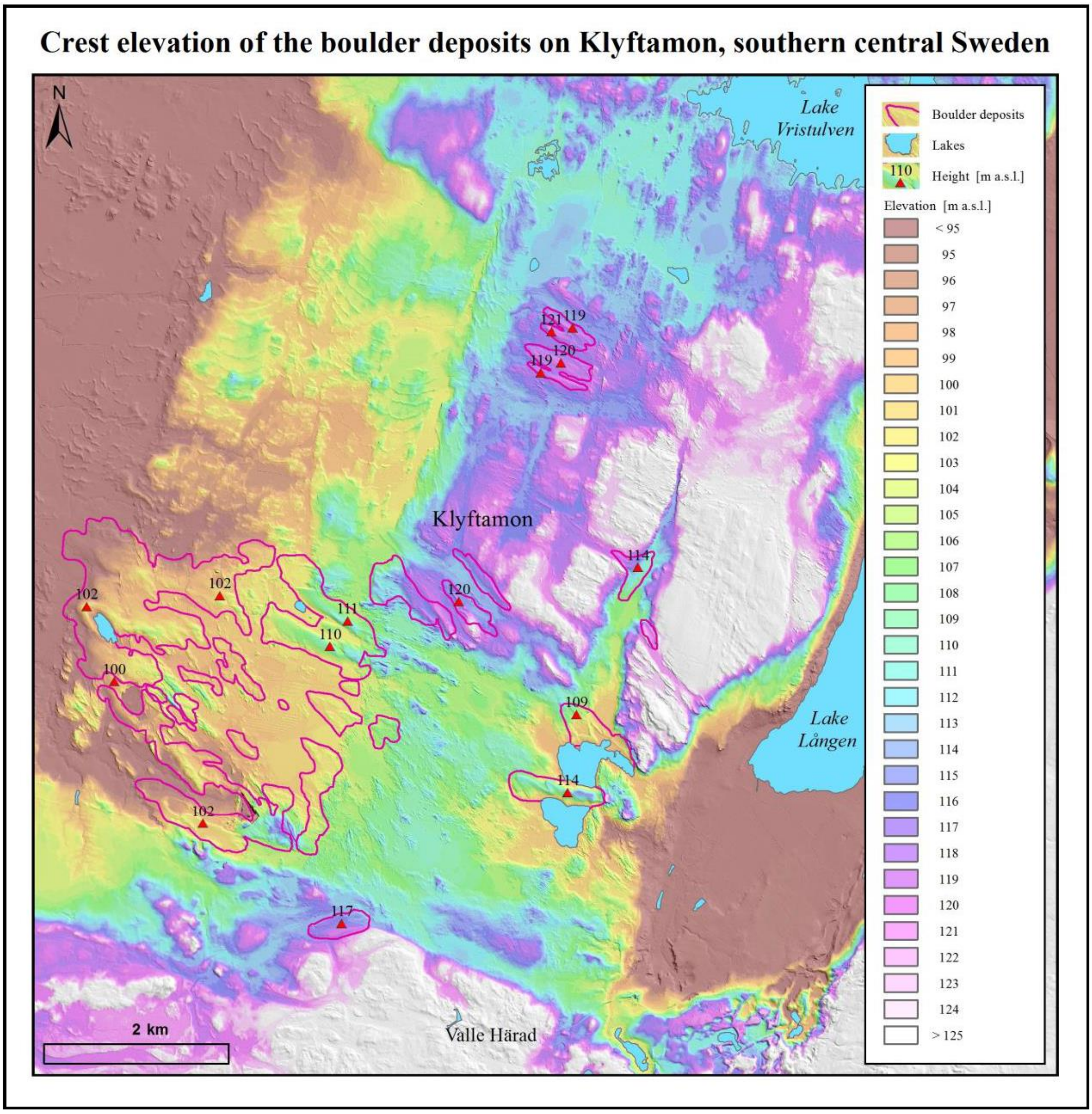


Figure 14. Crest elevation of the boulder deposits in Klyftamon. The highest marine limit has been found at 125 m a.s.l. only at the tip of Mt. Billingen. In this map it has not been adjusted for isostatic tilt and is thus not to be considered the exact position of the sea-level at the time of drainage. The highest coastline varies with distance from the tip of Mt. Billingen. The water depth to the crests of the landforms at each site varied between 2 – 20 m (values are adjusted for isostatic tilt according to the model presented by Påsse, 1983). Since the area slopes gently to the west the landforms in the western part of Klyftamon were deposited in deeper water. The landforms with a specified crest height are the ones that were visited during the fieldwork. Note that the topography becomes abruptly lower to the west of the westernmost boulder field and that many of the boulder deposits are located in a band of low topography that stretches W-NW from the southernmost part of the Lången basin. The northernmost deposits are sites 10.1 – 10.4 and appear to be situated on a local plateau, surrounded by more low-

Figure 66.—DEM of the area with boulder deposits outlined

deposition as water deepens into the open ocean. The grainb size of the sediment here at Stora Mon was measured using a photographic+GIS technique combined with traditional sieve and pipet analysis (Fig. 67). The material has a coarse-size limit as well as a fine-size limit. The sediment is also crudely imbricated, but shows flow to the NW. There is also a clear decrease in grain size from east to west through this south Klyftamon trough (Figure 68). One can calculate (a ranbge!) of velocaities from the max size or the D90 size of boulders, and we show results in Figure 69. These velocities match the velocities found by Elam (2012).

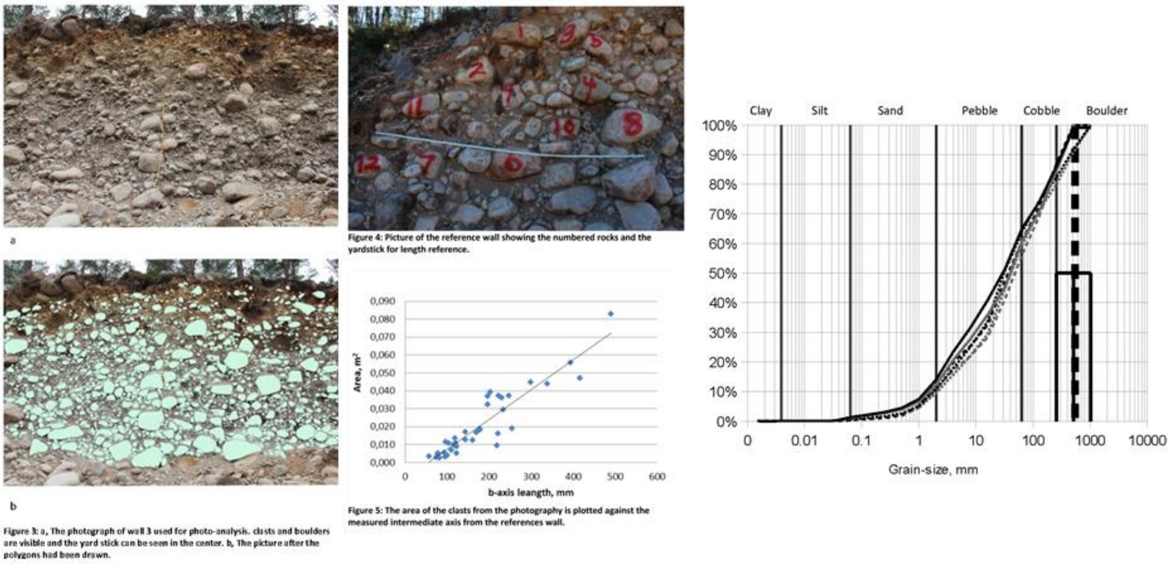


Figure 67. Grain size analysis of the Stora Mon sediment

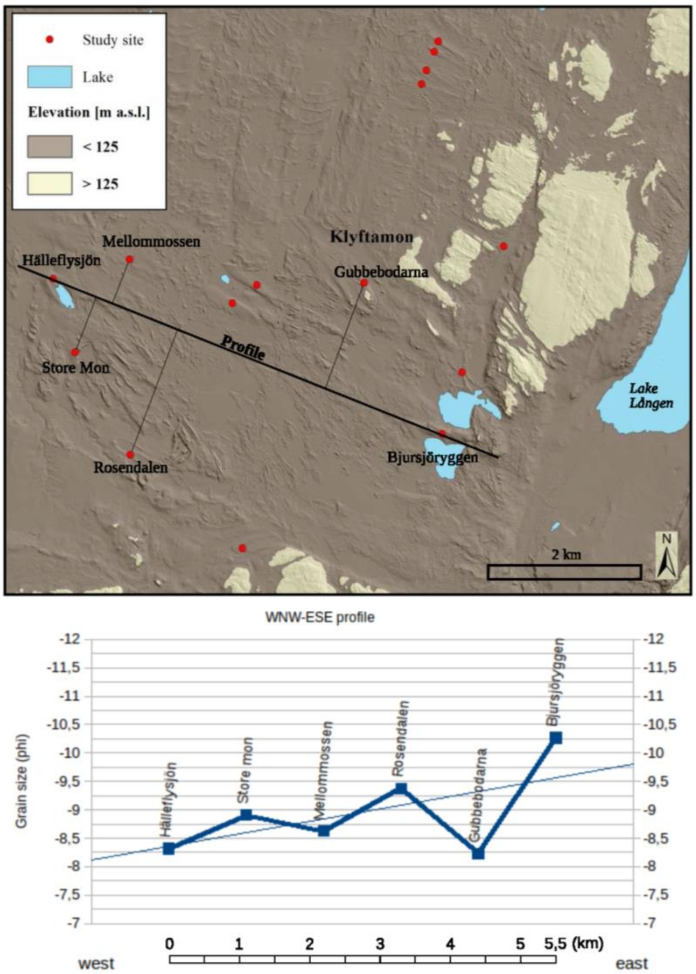


Figure 14. Profile over Klyftamon with the D_{90} value from six of eight boulder transects. The trend line shows that the grain size is decreasing to the west (the Φ value increases with decreasing grain size). The smaller grain size at Gubbebodarna (site 9) is diverging from the trend.

Figure 68.—Grain size decreases to the west in these boulder deposits (Johansson and Isaksson Dreyer, 2013).

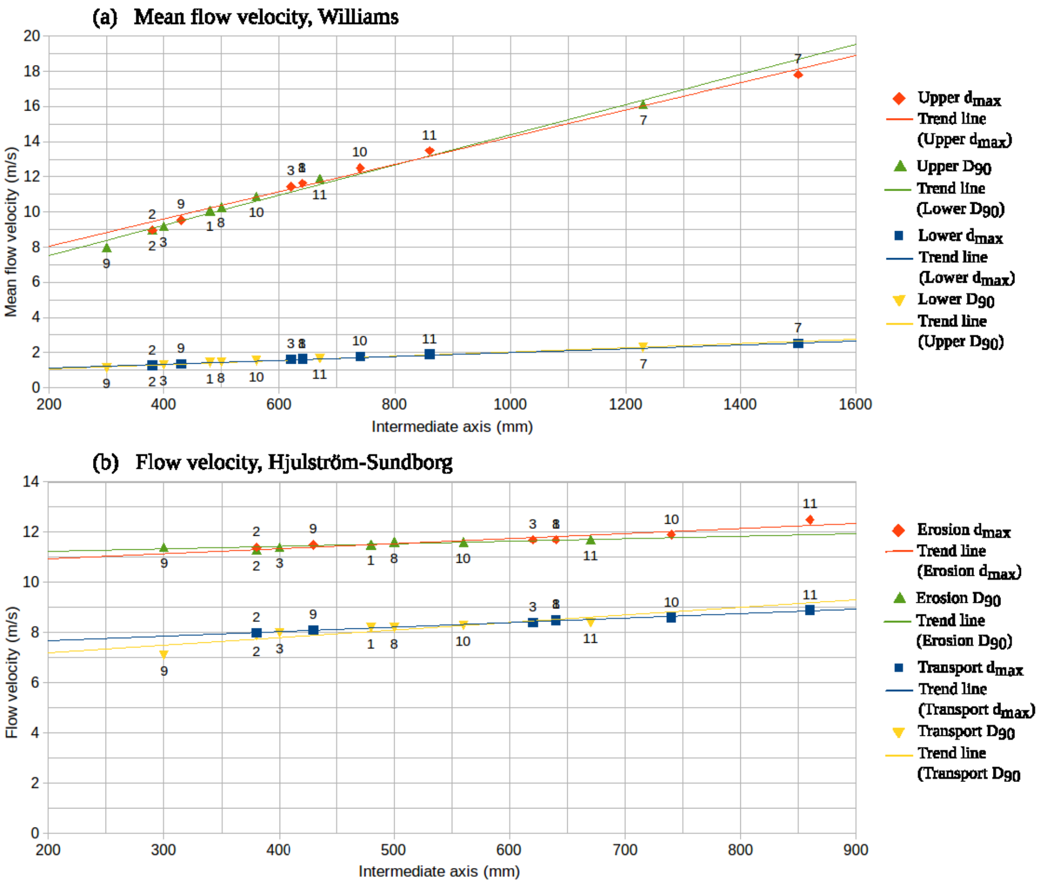


Figure 18. Mean flow velocities at the sites where boulder-transects were done. (a) Calculations based on the empirical equations by Williams (1983). Site no. are displayed as labels and names can be translated using e. g. *Table 1* (b) Estimations from Hjulström - Sundborg diagram (*Figure 11b*). Bjursjöryggen is left out because the diagram does not cover such large grain size. Note that the scales are different in (a) and (b).

Figure 69.—Calculated velocity of the boulder deposits according to different sources. Johansson and Isaksson Dreyer, 2013.

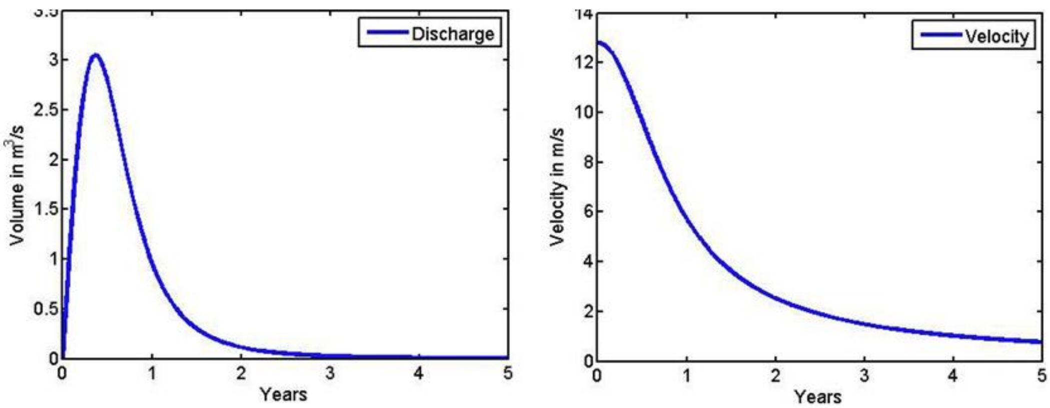


Figure 70. From Elam (2012).—estimated discharge and velocity at the outlet modeled.

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