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Stable oxygen isotope evidence for mobility in medieval and post-medieval Trondheim, Norway

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ABSTRACT

Immigration and mobility in the medieval and post-medieval periods in Norway have, up until now, mainly been discussed on the basis of historical sources. This paper presents the results of stable oxygen isotope ($\delta^{18}O$) analyses of the 1st and 3rd molars from 95 individuals from medieval and post-medieval Trondheim, as well as new information about the $\delta^{18}O$ composition in the precipitation and drinking water in Trondheim. Through these analyses, the authors have attempted to shed light on the age of migrating individuals and directions of migration, to investigate temporal changes with regard to migration, and to make suggestions regarding the proportion of immigrants to locals in the population.

The results show that the majority of the immigrants came from areas to the north or east of Trondheim, and some travelled at least 800–1000 km to come to Trondheim. It has also been shown that a large proportion of the medieval individuals moved during childhood. Both with regard to child mobility and migration in general, the evidence suggests that the migratory activity decreased from the medieval to the post-medieval period.

1. Introduction

Questions regarding immigration and mobility in medieval and early post-medieval Norway have received little academic attention. Research into pre-modern immigration in Norway has been carried out mainly by historians and has been based largely on historical sources (Opsahl, 2007; Opsahl and Sogner, 2003), while other sources of information that could contribute to the development of a more detailed picture of the pre-modern population have been largely ignored. The historical sources present a picture of a country with immigration as an integral part of its development, but studies of the actual people of the time have the potential to develop a much more detailed picture of the population. Against this background, this study set out to improve the understanding of immigration and mobility in medieval and post-medieval Norway. To do so, the study focused on one of the largest and most important towns in Norwegian history, Trondheim, where a large population study was undertaken. Stable oxygen isotope analyses of enamel apatite carbonates were used to determine possible geographic origins and mobility of 95 skeletonised individuals. This study primarily attempts to investigate to what extent people were born and grew up in the town where they ended their lives, and to identify people who were born elsewhere and moved there. Having determined who was not born in Trondheim, it was also investigated where the people who moved to Trondheim came from and whether they moved as adults or during childhood.

Trondheim was amongst the largest and most important towns in Norway from medieval times to the present and it was the main royal residence from the beginning of the 10th to the beginning of the 13th century. From 1030, Trondheim was the most important pilgrimage destination in Scandinavia and maintained its popularity throughout the Middle Ages, until the Reformation in 1537. The reason for this popularity was that king Olav II Haraldsson was buried there after he was killed during the battle at Stiklestad in 1030. He was canonised already in 1031 and a wooden chapel was built above his burial site. In 1070, King Olav Kyrre removed the wooden chapel and started building the stone church that was the beginning of what would later be known as the Nidaros Cathedral. The Cathedral was finished around 1300. The Archdiocese of Nidaros was founded in 1152/53 with Trondheim as the archbishop's seat and the town became the ecclesiastical “capital” of the Norse world until the Reformation (Moseng et al., 2007).

Trondheim was chosen for this study for several reasons. Firstly, there are no other Norwegian towns with better preserved and/or better documented skeletal material. Secondly, due to Trondheim's position as both an archbishop's residence and a pilgrimage destination,

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one could expect people to have travelled from far afield to visit the town during the Middle Ages - travellers who likely would have made an impact on the composition of the town's population. Thirdly, Trondheim was an important port along the trade route for dried fish from northern Norway down to Bergen, and further on into more southern areas of Europe. Trade continued to be important in Trondheim even after Bergen obtained a near monopoly as a port for exporting dried fish in the Middle Ages. As both an ecclesiastical and royal administrative centre, both local trade and regional trade were important (Helle, 2006). Lastly, Trondheim has been one of the most important Norwegian towns during the last thousand years, which makes it interesting in itself.

To investigate the above questions, stable oxygen isotope analysis was applied. Mammalian bones and teeth contain hydroxyapatite $(Ca_{4.5}[(PO_4)_{2.7}(HPO_4)_{0.2}(CO_3)_{0.3}](OH)_{0.5})$ (Kohn et al., 1999). Because humans, like all large mammals (>1 kg), have an almost constant body temperature, the oxygen isotope compositions of the carbonate ($\delta^{18}O_C$) and phosphate ($\delta^{18}O_P$) components of their hydroxyapatite only vary with that of oxygen fluxes (Longinelli, 1984; Bryant and Froelich, 1995; Kohn, 1996). The main input of oxygen is liquid water (~75%; Bryant and Froelich, 1995; Daux et al., 2008), which generally comes from local reservoirs (wells, springs, creeks, rivers), in turn derived from meteoric waters (e.g. Rozanski, 1985; Fritz et al., 1987; Ingraham and Taylor, 1991; Kortelainen and Karhu, 2004).

The isotopic fractionations in hydroxyapatite formation, which take place during the metabolic reactions resulting from water ingestion, are well understood, and the oxygen isotopic composition of local water can be estimated by applying water-to-phosphate (Longinelli, 1984; Luz et al., 1984; Levinson et al., 1987; Daux et al., 2008) or water-to-carbonate conversion equations (Chenery et al., 2012) to measured $\delta^{18}O_P$ and $\delta^{18}O_C$. Therefore, measurements of $\delta^{18}O_C$ or $\delta^{18}O_P$ in teeth and bones have been widely used for assessing the origin and movements of humans (e.g. White and Spence, 1998; Dupras and Schwarcz, 2001; Budd et al., 2004; Müller et al., 2003; Evans et al., 2006a; Evans et al., 2006b; Prowse et al., 2007).

2. Material and methods

The material for this study consists of first and third molars (M1 and M3) from human skeletal remains exhumed from five different archaeological excavations in the town centre of Trondheim, Norway (Søndregate, Folkebibliotekstomten, Vår frue kirke, Vestfrontplassen and Servicebygget) (Fig. 1) and of four modern contemporaneous M3 teeth collected by a dentist in Trondheim. A total of 95 individuals have been sampled from the archaeological sites, of which 41 date back to the medieval period, while the remaining 54 were buried between approximately 1600 and the 1890s. The material was selected with the idea of having an equal number of individuals from the medieval and post-medieval periods, as well as an equal number of males and females within each group. As always, however, preservation sets its own limits for good intentions, and the final sample used in this study consists of 41 medieval skeletons of which 16 were male, 24 were female and 1 of undetermined sex, while the post-medieval sample consists of 54 individuals: 37 males, 13 females and 4 of undetermined sex.

2.1. Oxygen isotopic composition of environmental water ($\delta^{18}O_W$) in Trondheim and in the surrounding regions

Since the isotopic composition of tooth enamel carbonate derives from environmental water, this study focuses on identifying both spatial (Central Norway and surrounding areas) and temporal (from medieval times to present) variation.

The oxygen isotopic composition in precipitation in Norway is not very well established, and except for the GNIP (Global Networks of Isotopes in Precipitation) station at Lista on the south coast, there is no available data for mainland Norway. The only available information for Trondheim comes from different modulations (GNIP, isomap.org and OIPC). Modulations will, however, never be as accurate as local water analyses. Moreover, local measured waters should be preferred to estimations for calibrating the present day value of enamel $\delta^{18}O$ (Daux et al., 2008).

Thus, a precipitation collector was set up outside the premises of the NGU (Norges Geologiske Undersøkelser), at about three kilometres from the medieval graveyards located in the centre of Trondheim, and about four kilometres from the post-medieval graveyards. The distance from the archaeological sites to the ocean is about the same as the distance from the NGU to the ocean, and all of them are at the same approximate elevation, so there is every reason to believe that the precipitation samples collected at the NGU are representative of the

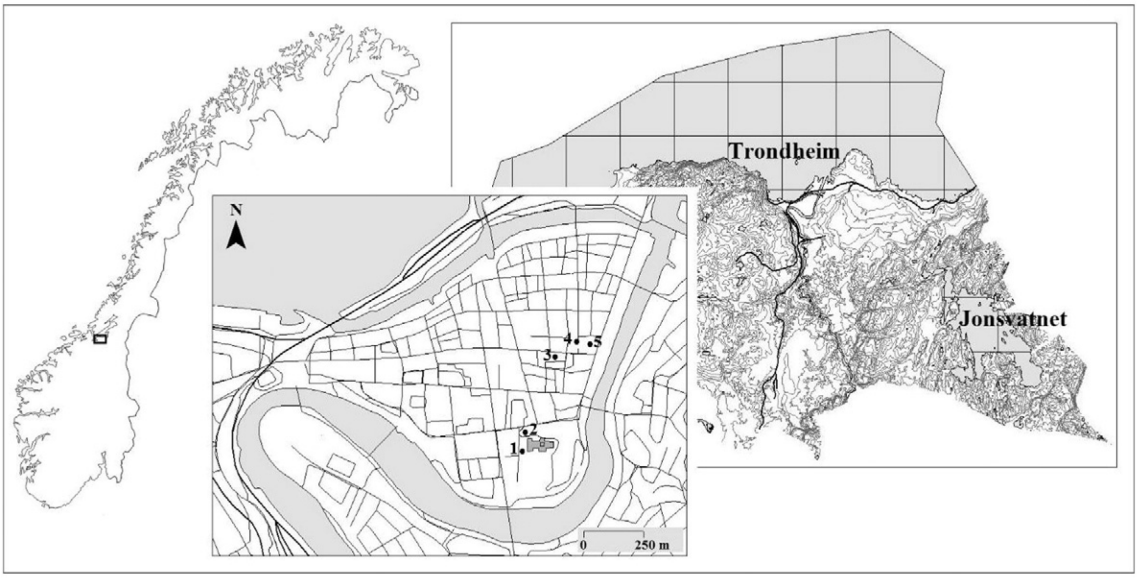

Fig. 1. Maps showing Norway with the location of Trondheim (left), the municipality of Trondheim with Lake Jonsvatnet (right), and the town centre of Trondheim with the five archaeological sites providing the skeletal material for this study (front): 1. Vestfrontplassen (1585–1897); 2. Servicebygget (1585–1897); 3. Vår Frue Kirke (16th–mid-19th century); 4. Søndregate (mid-12th century–1531); 5. Folkebibliotekstomten (1175–1275).

town centre where the individuals in this study were buried and may have lived. To minimise evaporation, a funnel shaped collector was used, and to maximise consistency, the samples were collected on the last day of each month, from January to December 2013. The water samples were then stored in a fridge, in light-proof and air-tight 100 ml bottles until they were shipped to the GNS Science laboratory (Wellington, New Zealand). To avoid prolonged storage, the samples were sent in two batches, the first after six months and the second at the end of the twelve months. The $\delta^{18}O$ ratios were determined on a GVI AquaPrep attached to a GVI IsoPrime mass spectrometer by the equilibration method. 400 μl of water were equilibrated with 3 ml of headspace flushed with CO_2 for 24 h at 25.5 °C. The CO_2 was extracted and analysed by dual inlet on the IsoPrime. All oxygen results are reported with respect to SMOW (Standard Mean Ocean Water), normalised to internal standards (Table 1). The external reproducibility of oxygen isotope measurements is close to 0.1‰.

Until the late 1960s, different parts of Trondheim received drinking water from different local sources (Brohan et al., 2006). Today the people in the city and suburban areas all get their drinking water from one single source, Lake Jonsvatnet. This lake is at an elevation of 150 m. It drains water from the surrounding mountains, which culminate at about 500 m. The residence time of water in the lake is about 10 years (Bjørgum and Broch, 1996). Two tap water samples were collected from Trondheim, in October 2014 and September 2015, and analysed at the Laboratoire des Sciences du Climat et de l'Environnement (Gif-sur-Yvette, France) with a Picarro MODELE with a precision of ±0.2‰ (1σ).

2.2. Air temperature-$\delta^{18}O_W$ and $\delta^{18}O_C$-$\delta^{18}O_W$ relations

The oxygen isotopic compositions of environmental waters (which derive from precipitation) depend on temperature, amount of precipitation and air mass trajectory. For mid-latitudes, rough linear correlations are observed between the $\delta^{18}O_W$ of meteoric waters and air temperature. Several relationships have been established (e.g. Dansgaard, 1964; Yurtsever and Gat, 1981; Rozanski et al., 1992; Rozanski et al., 1993; Fricke and O'Neil, 1999). Dansgaard's (1964) equation, which was obtained from North Atlantic stations, has been used hereafter for traducing temperature in $\delta^{18}O_W$ ($\delta^{18}O_W = 0.695 \times T - 13.6$, where T is the air temperature in °C).

The Eq. (6) from Daux et al. (2008) modified by Chenery et al. (2012) was used to convert $\delta^{18}O_C$ in $\delta^{18}O_W$ ($\delta^{18}O_W = 1.59 \times \delta^{18}O_C - 48.63$). Application of this conversion leads to a model uncertainty of ±1.0‰ (2σ) according to Chenery et al. (2012).

Table 1
$\delta^{18}O_W$ in monthly precipitation in Trondheim, precipitation amount and mean temperature at Voll meteorological station, 3 km south-east of Trondheim (Norwegian Meteorological Institute data) in 2013. The $\delta^{18}O_W$ value for January is an estimate (average of December and February values).

Month	$\delta^{18}O_W$/VSMOV2 (‰)	Precipitation (mm)	Mean temperature (°C)
January	−10.72	42.3	−3.8
February	−10.79	44.4	−2.6
March	−9.73	91.8	−2.7
April	−8.10	37.1	3.6
May	−7.68	40.8	11.9
June	−7.27	100.1	12.5
July	−6.85	78.1	14.2
August	−8.62	85.8	13.8
September	−8.89	58.3	11.0
October	−9.14	88.2	5.9
November	−8.08	116.5	2.5
December	−10.64	84.1	2.5
Yearly mean	−8.77[a]		

[a] Yearly weighted mean.

2.3. Determination of $\delta^{18}O$ in human remains

2.3.1. Three point life history

To discover possible migration of the individuals during their life time, the sampling was carried out so as to document different times of their life. As long as both teeth were preserved, samples were taken from tooth enamel on a first and a third molar for each individual. These teeth represent two points in life and the burial place is known for every individual, which is the third point in the life history of these people. The crown development of the first molar begins at around birth and is completed by the time an individual reaches 2.5–3 years. The third molar is the last tooth to be developed; the crown starts developing between 7 and 10 years and is normally completed between 12 and 16 years old (Hillson, 1996:123, Schour and Massler, 1940a; Schour and Massler, 1940b). Thus, the first molar will represent the period between the 1st and 3rd year of life while the third molar samples will represent an age between ~8 and 14 years of age. As they were buried in Trondheim it is reasonable to assume that this is where they died and spent the last period of their lives.

2.3.2. Breastfeeding effect

Since the age at the end of weaning in modern or ancient non-industrialized human societies was typically around 2–2.5 years (e.g. Shahar, 1990; Richards et al., 2002; White et al., 2004; Sellen, 2001), the M1 and M3 teeth collected at Trondheim were likely formed respectively during and after the breastfeeding period. Human milk contains about 87% water (Jenness, 1999), and is isotopically heavier than environmental water (Roberts et al., 1988). Weaning is a gradual process. Breast-fed children generally do not have other sources of water than their mother's milk at the beginning of their life. Fresh water and solid food are progressively incorporated in the diet until the end of weaning. The $\delta^{18}O$ values of teeth enamel are set by equilibrium fractionation with the body fluids, which themselves derive from the water ingested. Therefore, the M1 teeth can record the effect of milk consumption (as the milk water is heavier than the environmental water), whereas the M3 teeth compositions may reflect the ingestion of environmental water solely. In agreement with this statement, in archaeological remains, M1 teeth are generally isotopically heavier than M3 (by <1‰; Evans et al., 2006b; White et al., 2005; Wright and Schwarcz, 1999; Wright and Schwarcz, 1998). In the interpretation of the enamel $\delta^{18}O$ of the M1 and M3 teeth collected in Trondheim, possible breastfeeding effects are to be taken into account.

2.3.3. Analyses

As there is a consistent offset between the oxygen isotopic composition of the carbonate and phosphate components of enamel hydroxyapatite, both components are suitable for oxygen analysis. Most studies of human oxygen isotope compositions have focused on phosphates, which are less susceptible to isotopic exchange. However, the oxygen signal was also shown to be well preserved in the carbonate component of archaeological human tooth enamel (Chenery et al., 2011) Here we chose to analyse $\delta^{18}O_C$ rather than $\delta^{18}O_P$.

One hundred milligrams of enamel was obtained from each M1 and M3 using a Dremel 8100 multi tool with a circular blade which was changed between each sample. A piece of the enamel was cut off the crown and care was taken to keep the enamel sample in one piece, which was wrapped in tin foil and sealed in separate containers sent to the laboratory for preparation and analysis. Each sample was taken as a slice from the side of the tooth; no samples were taken from the occlusal surface.

The enamel was sonicated and ground to a fine powder. An aliquot was weighted out and kept in a 120 °C oven for 24 h. The oxygen isotopic analyses were performed at the GNS Science's stable Isotope Laboratory. No pre-treatment of the enamel was carried out. CO_2 was obtained by acid hydrolysis using phosphoric acid at 50 °C and collected by cryogenic distillation. Isotopic ratios were measured on a dual inlet ratio GVI

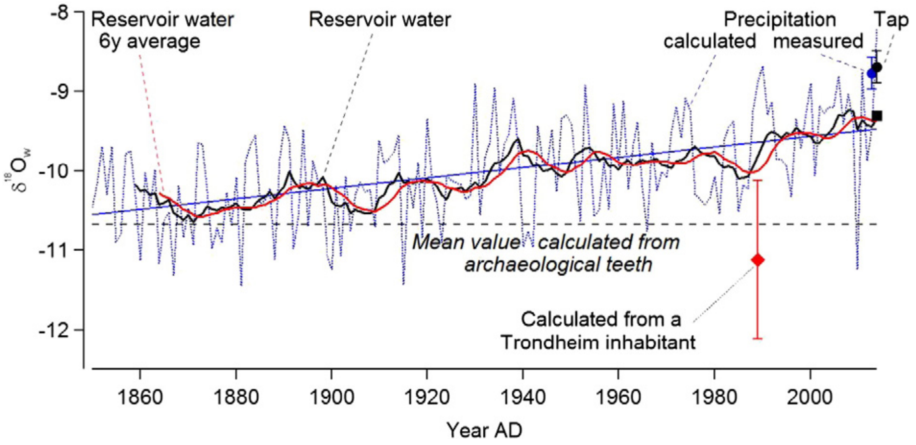

Fig. 2. Oxygen isotopic composition of water. Blue dotted and straight lines: precipitation composition calculated from yearly temperature using Dansgaard's (1964) equation and trend. Black line: reservoir composition calculated by averaging the precipitation over 10 years, time of residence of the water in the reservoir. Red line: reservoir water average over 6 years, the time of mineralisation of the M3 teeth. Black square: present-day calculated value of the reservoir water. Blue circle: mean value of yearly weighted precipitation sampled along 2013. Black circle: Tap water collected in 2014 and 2015 in Trondheim. Black dotted line: Mean value of the $\delta^{18}O_C$ of the archaeological teeth converted to $\delta^{18}O_W$ using Chenery et al.'s (2012) equation. Red diamond: $\delta^{18}O_C$ of the M3 tooth of an inhabitant of Trondheim converted in $\delta^{18}O_W$ representing the mean tap water composition over ~1975–1989. The error bar corresponds to a ± 1‰ error arising from model uncertainty (2σ; Chenery et al., 2012).

Isoprime mass spectrometer. One must note that our data may not be fully comparable to values measured on enamel samples which have been subjected to pre-treatments intended to remove any secondary carbonates (Koch et al., 1997; Grimes and Pellegrini, 2013).

All results are reported as per mil (‰) normalised to the PDB scale using an in-house carbonate reference material (GNS Marble; reported value of -6.4‰ for $\delta^{18}O$) calibrated against NBS19 certified reference material. The external precision for these measurements are better than 0.2‰.

The values were then converted into the SMOW scale using Coplen's (1988) equation ($\delta^{18}O_{C/SMOW} = 1.03091 \times \delta^{18}O_{C/PDB} + 30.91$).

2.4. Sampling sites

2.4.1. Folkebibliotekstomten

Twenty seven individuals come from this graveyard. It has traditionally been believed that the church at this site was the church of St. Olav, but this has been challenged (Christophersen, 1994; Nordeide, 1997) and at present there is no agreement as to the name of this church. What is known, however, is that this church dates back to the early 12th century and that it became part of the Franciscan monastery in the late 13th century (Christophersen, 1994). From this it can be assumed that this was not a monastic church before this point and that during the period dealt with in this project it is likely to have been a parish church. A parish church graveyard, as opposed to graveyards belonging to cathedrals and monasteries, would have accepted burials from all layers and fractions of the population within the parish and, thus it can be argued that people buried here would have been representative of the general public. It may not, however, be representative of the town population as a whole due to differences that may exist between populations belonging to different churches. The inclusion of individuals from different graveyards, whenever possible, would increase the likelihood of putting together a representative sample and should be recommended.

Anderson and Göthberg (1986) also concluded that this was a parish church based on the age composition in the sample. Thus, there is no reason to assume that the people buried in this cemetery are not representative of the general population in the parish, and possibly also Trondheim at the time. However, considering the distribution of these 27 skeletons in the graveyard, one could suggest that this sample may be largely void of the most affluent members of society. It has been shown that an individual's placement in the graveyard was determined by the person's social status; the upper classes being buried close to the church while members of the lower classes were buried closer to the graveyard fence (Hamre, 2011). Only 4 of the 27 individuals in this sample were buried in relatively close proximity to the church, while those

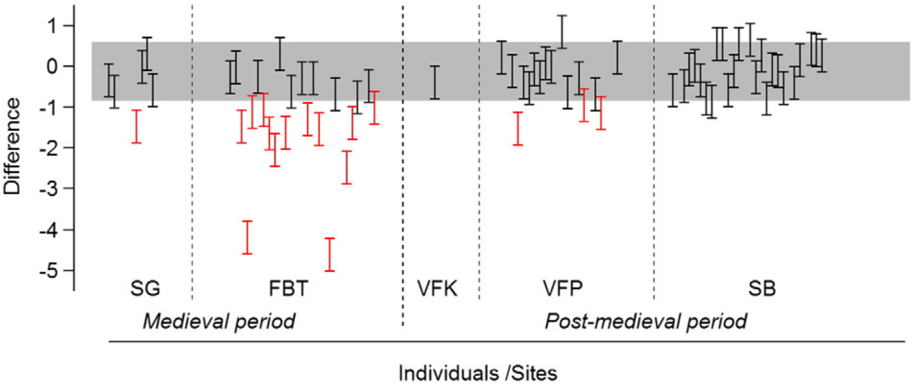

Fig. 3. Difference between the $\delta^{18}O_C$ of the M1 adjusted for weaning (with offsets ranging from 0.2‰ to 1‰) and the $\delta^{18}O_C$ of the M3 of the individuals excavated at Trondheim. The shaded area corresponds to ± 0.6‰ accepted range of variation, that is, to individuals who have likely not migrated during childhood. The red bars correspond to the individuals who may have migrated during childhood. SG: Søndregate; FBT: Folkebibliotekstomten; VFK: Vår frue kirke; VFP: Vestfrontplassen; SB: Servicebygget.

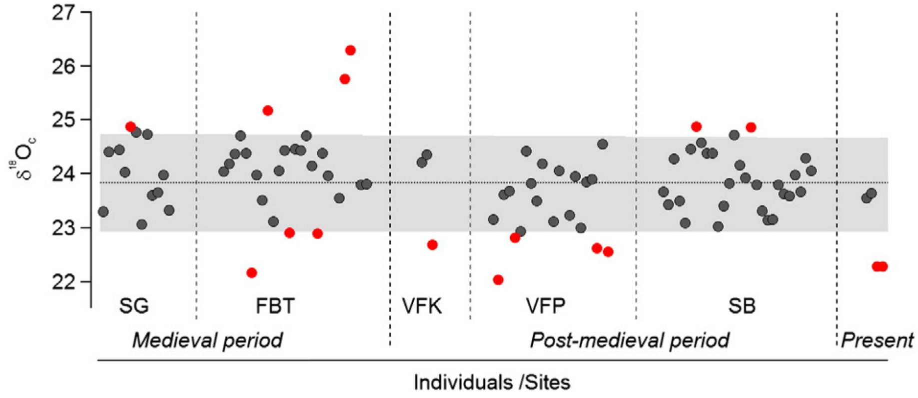

Fig. 4. Oxygen isotopic composition of the M3 teeth of the individuals excavated at Trondheim (column 6, Table 2). The shaded area corresponds to an intra-populational variability of 0.9‰. The red dots correspond to the individuals who may have migrated to Trondheim after the age of 14 years old. SG: Søndregate; FBT: Folkebiblioteksomten; VFK: Vår frue kirke; VFP: Vestfrontplassen; SB: Servicebygget.

remaining were buried in the middle and outer parts of the graveyard. Therefore, it is unlikely that high status individuals are a significant part of this sample.

All the individuals included from this excavation used in the study have been determined to have been buried between 1175 and 1275 (Christophersen and Nordeide, 1994).

2.4.2. Søndregate

The church ruins and parts of the cemetery excavated at Søndregate are believed to be the remnants of the church of St. Olav, which was in use from the middle of the 12th century (Ramstad, 2002:100) until it burned down during the 16th century, most likely in a fire in 1531 (Ramstad, 2002:202). The exact use of the church during the first part of its existence is somewhat uncertain, but it became a parish church around the middle of the 13th century, which makes it reasonable to assume that this church was accessible to the general public, at least during most of the time it was in use. Thirteen individuals from this excavation were included in this study.

2.4.3. Vår frue kirke

The material from this site only consists of four individuals, all of which can be dated to the post-medieval period (Ian Reed, pers. com.). No accurate dating exists for these skeletons, but a time of burial between the 16th century and the mid-19th century is likely, based on these burials' stratigraphic relation to known expansions of the church. During this period, Vår Frue Kirke was the main church in Trondheim and on the basis of this, one could suggest that the individuals buried here came from the more affluent layers of society. Most of the inhumations excavated from this site were coffin burials and many had wrought iron handles which also suggests wealth (Ian Reed, pers. com.).

2.4.4. Vestfrontplassen

Twenty-two individuals come from the excavations at Vestfrontplassen which is part of the graveyard connected to the Nidaros Cathedral. This part of the graveyard was in use from 1585, when the cathedral became a parish church, until the closure of the graveyard in 1897 (Reed et al., 1998). This part of the graveyard seems to have had a very particular use. In 1663, an attempt was made to create social order within the graveyard by dividing it into different price zones and it is stated that cavalry and soldiers who died within the parish could be buried free of charge in an area matching the Vestfrontplassen excavation (Reed et al., 1998). Thus, the individuals exhumed from this area may not be representative of the general population but rather of a military population. This is also one of the least prestigious areas of the graveyard. Therefore, people buried here without a connection to the military are likely to have come from the lower layers of society.

2.4.5. Servicebygget

Twenty-eight skeletons come from this excavation. It uncovered another part of the graveyard of Nidaros Cathedral and the individuals exhumed during this excavation would have been buried during the same approximate period as skeletons excavated at Vestfrontplassen. This area of the graveyard was, however, not used particularly for members of the military. Similarly to Vestfrontplassen, the area uncovered during the Servicebygget excavation was also among the cheapest zones of the graveyard and one has to expect that the people buried here would have come from the lower strata of society (Yilmaz and Sellevold, 2006).

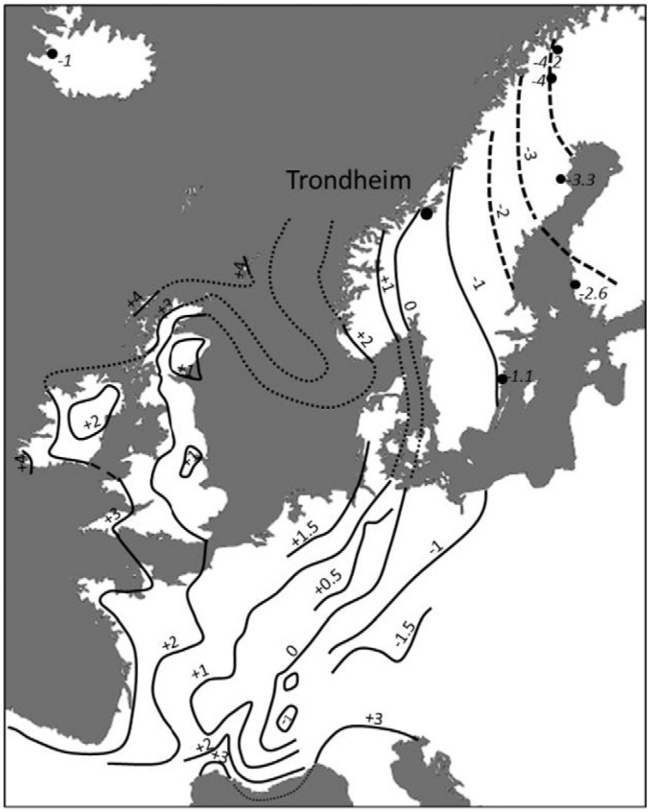

Fig. 5. Deviation of the $\delta^{18}O_W$ from −9‰ (the yearly weighted precipitation in Trondheim in 2013 = ~−8.8‰; the mean temperature in 2004–2014 converted to $\delta^{18}O_W$ = ~−9.3‰) based on a compilation by C. Chenery. British Geological Survey (based on Darling et al. (2003) and Lecolle (1985)).

Table 2

Oxygen isotopic composition of the carbonate of first and third molars (M1 and M3 resp.) tooth enamel of human beings buried in Trondheim, Norway ($\delta^{18}O_C$, in ‰ versus VSMOW; columns 5 and 6) at Søndregate (SG), Folkebibliotekstomten (FBT), Vår Frue Kirke (VFK), Vestfrontplassen (VFP), Servicebygget (SB).

Environmental water derived from the M3 teeth isotopic composition ($\delta^{18}O_W$; calculated using Chenery et al.'s (2012) equation and expressed in ‰ versus VSMOW; column 7).

Migrations: Symbols in Migr. child and Migr. adult columns (8 and 9) designate individuals whose M1 and/or M3 isotopic compositions are consistent with migration during childhood and adulthood respectively; Δ/∇: immigration induces an increase/decrease of the $\delta^{18}O_W$ of the imbibed water.

$\Delta\ \delta^{18}O_W$ child: gradient of isotopic composition of environment water crossed between childhood and teenage (between ~3 and ~14) by migrants. The two values correspond to the inclusion of uncertainties regarding the effect of breastfeeding on the isotopic composition of the M1 teeth in the calculation.

$\Delta\ \delta^{18}O_W$ adult: gradient of isotopic composition of environment water crossed during adulthood by migrants.

1 Site	2 Age of burial	3 Sex	4 Age at death	5 M1 $\delta^{18}O_C$	6 M3 $\delta^{18}O_C$	7 M3 $\delta^{18}O_W$	8 Migr. child	9 $\Delta\ \delta^{18}O_W$ child	10 Migr. adult	11 $\Delta\ \delta^{18}O_W$ adult
SG	~1150–1531	M	18–30	23.57	23.31	−11.57				
SG	~1150–1531	F	30–50	24.38	24.41	−9.82				
SG	~1150–1531	?	12–18	24.29						
SG	~1150–1531	M	30–50		24.46	−9.74				
SG	~1150–1531	M	50+		24.04	−10.41				
SG	~1150–1531	F	30–50	24.01	24.88	−9.07	Δ	1.7–3.0	∇	−1.7
SG	~1150–1531	M	18–30	25.36	24.78	−9.23				
SG	~1150–1531	M	12–18	23.96	23.07	−11.95				
SG	~1150–1531	F	30–50	24.76	24.74	−9.30				
SG	~1150–1531	F	30–50		23.61	−11.09				
SG	~1150–1531	M	30–50		23.66	−11.01				
SG	~1150–1531	M	50+		23.99	−10.49				
SG	~1150–1531	M	50+		23.33	−11.54				
FBT	1175–1275	M	18–30	24.38	24.05	−10.39				
FBT	1175–1275	F	18–30	24.76	24.19	−10.17				
FBT	1175–1275	F	30–50	23.51	24.38	−9.87	Δ	1.7–3.0		
FBT	1175–1275	F	18–30	21.13	24.72	−9.33	Δ	6.0–7.3		
FBT	1175–1275	F	18–30	23.87	24.39	−9.85	Δ	1.2–2.4		
FBT	1175–1275	F	30–50	22.51	22.17	−13.38			Δ	2.7
FBT	1175–1275	F	18–30	23.51	23.98	−10.51	Δ	1.1–2.3		
FBT	1175–1275	F	18–30	22.46	23.52	−11.24	Δ	2.0–3.3		
FBT	1175–1275	F	18–30	23.71	25.18	−8.60	Δ	2.7–4.0	∇	−2.2
FBT	1175–1275	M	18–30	24.02	23.13	−11.86				
FBT	1175–1275	F	18–30	23.05	24.07	−10.36	Δ	2.0–3.2		
FBT	1175–1275	F	18–30	24.42	24.44	−9.77				
FBT	1175–1275	F	30–50		22.92	−12.19				
FBT	1175–1275	M	30–50	24.78	24.47	−9.73				
FBT	1175–1275	M	18–30	23.73	24.44	−9.77	Δ	1.4–2.7		
FBT	1175–1275	F	18–30	25.02	24.72	−9.33				
FBT	1175–1275	F	30–50	23.21	24.15	−10.24	Δ	1.8–3.1		
FBT	1175–1275	F	30–50		22.91	−12.21				
FBT	1175–1275	M	30–50	20.38	24.39	−9.85	Δ	6.7–8.0		
FBT	1175–1275	M	30–50	23.88	23.97	−10.52				
FBT	1175–1275	F	18–30	23.81						
FBT	1175–1275	F	30–50	21.66	23.55	−11.19	Δ	3.3–4.6		
FBT	1175–1275	F	18–30	24.97	25.77	−7.66	Δ	1.6–2.9	∇	−3.1
FBT	1175–1275	F	18–30	26.14	26.30	−6.82			∇	−4.0
FBT	1175–1275	M	30–50	23.24						
FBT	1175–1275	F	30–50	23.92	23.81	−10.78				
FBT	1175–1275	M	30–50	23.39	23.82	−10.76	Δ	1.0–2.3		
VFK	~1500–~1850	F	30–50		24.22	−10.12				
VFK	~1500–~1850	M	50+	24.57	24.36	−9.90				
VFK	~1500–~1850	F	30–50		22.69	−12.55			Δ	1.8
VFK	~1500–~1850	F	12–18	24.93						
VFP	1585–1897	M	30–50	23.99	23.17	−11.79				
VFP	1585–1897	M	50+		22.04	−13.59			Δ	2.9
VFP	1585–1897	M	18–30	24.11	23.62	−11.08				
VFP	1585–1897	M	30–50	22.77	23.69	−10.97	Δ	1.8–3.1		
VFP	1585–1897	?	30–50	23.02	22.83	−12.33			Δ	1.6
VFP	1585–1897	M	30–50	23.01	22.95	−12.14				
VFP	1585–1897	M	30–50	24.94	24.43	−9.79				
VFP	1585–1897	F	30–50	24.15	23.83	−10.74				
VFP	1585–1897	M	50+	24.17	23.50	−11.27				
VFP	1585–1897	M	30–50	24.79	24.20	−10.16				
VFP	1585–1897	M	30–50	24.12						
VFP	1585–1897	M	18–30	24.56	23.13	−11.86				
VFP	1585–1897	M	30–50	24.02	24.06	−10.38				
VFP	1585–1897	F	30–50	23.00						
VFP	1585–1897	F	18–30	23.55	23.24	−11.68				
VFP	1585–1897	M	30–50	23.61	23.96	−10.54				
VFP	1585–1897	M	30–50		23.01	−12.05				
VFP	1585–1897	M	12–18	23.77	23.86	−10.70				
VFP	1585–1897	F	18–30	23.36	23.91	−10.62	Δ	1.2–2.5		
VFP	1585–1897	M	30–50		22.63	−12.65			Δ	1.9

(continued on next page)

Table 2 (*continued*)

1	2	3	4	5	6	7	8	9	10	11
Site	Age of burial	Sex	Age at death	M1 $\delta^{18}O_C$	M3 $\delta^{18}O_C$	M3 $\delta^{18}O_W$	Migr. child	$\Delta\ \delta^{18}O_W$ child	Migr. adult	$\Delta\ \delta^{18}O_W$ adult
VFP	1585–1897	F	30–50		24.56	−9.58				
VFP	1585–1897	M	18–30	23.38	22.57	−12.75			Δ	2.0
SB	1585–1897	M	18–30	23.68	23.67	−11.00				
SB	1585–1897	M	30–50		23.44	−11.36				
SB	1585–1897	M	30–50	24.41	24.29	−10.01				
SB	1585–1897	M	30–50	24.00	23.50	−11.27				
SB	1585–1897	M	30–50	23.70	23.10	−11.91				
SB	1585–1897	M	18–30	24.72	24.47	−9.73				
SB	1585–1897	M	18–30	24.70	24.89	−9.06			∇	−1.7
SB	1585–1897	M	30–50	24.33	24.59	−9.54				
SB	1585–1897	M	12–18	25.55	24.39	−9.85				
SB	1585–1897	?	30–50	25.55	24.39	−9.85				
SB	1585–1897	M	30–50	23.05	23.04	−12.00				
SB	1585–1897	M	30–50	23.90	23.41	−11.41				
SB	1585–1897	F	30–50	24.98	23.83	−10.74				
SB	1585–1897	?	30–50		24.73	−9.31				
SB	1585–1897	M	18–30	25.40	24.17	−10.20				
SB	1585–1897	M	30–50	24.26	23.93	−10.59				
SB	1585–1897	M	30–50	25.73	24.87	−9.09			∇	−1.7
SB	1585–1897	M	30–50	23.61	23.80	−10.79				
SB	1585–1897	M	18–30	23.84	23.32	−11.56				
SB	1585–1897	M	30–50	23.63	23.15	−11.83				
SB	1585–1897	F	30–50	23.22	23.16	−11.81				
SB	1585–1897	F	30–50		23.81	−10.78				
SB	1585–1897	M	30–50	23.82	23.63	−11.06				
SB	1585–1897	F	18–30	24.33	23.59	−11.13				
SB	1585–1897	F	30–50		23.98	−10.51				
SB	1585–1897	M	18–30	24.69	23.67	−11.00				
SB	1585–1897	?	18–30	25.28	24.30	−10.00				
SB	1585–1897	M	18–30	24.93	24.06	−10.38				
	Present	M	40		23.60					

3. Results

Our aim was to determine if the individuals buried in Trondheim originated from the town and grew up there. By comparing the oxygen isotopic composition of M1 and M3 teeth and by performing a statistical analysis of the M3 data we can document possible moves during and after childhood. By comparing these values to the one of the enamel in equilibrium with the environmental water at the time of death, we can also gain insights into migrations which may have occurred during the individuals' teenage years or adulthood. However, the variability of the isotopic compositions of teeth in a population is not only due to the integration of migrants. Indeed, the change of beverage (milk/water) during early childhood and variability of dietary habits in a population can induce respective inter-tooth (M1 vs M3) and inter-individual differences of isotopic compositions. Spatial and temporal climate variations can also induce changes of $\delta^{18}O_C$ through the modification of the $\delta^{18}O_W$. Taking into account the possible impacts of nutritional and climatic changes on the isotopic composition of their tooth enamel, we have identified the likely migrants in the Trondheim burial sites.

3.1. Present day composition of environmental water

The monthly values of the $\delta^{18}O_W$ of precipitation sampled in Trondheim in 2013 are presented in Table 1. The data for January was estimated because the measured value, equal to −19.86‰, was not plausible. Indeed, such a value, corresponds to Arctic environments (for instance, values as low as this one are measured, although seldom, further north in NY-Alesund in Svalbard, Norway; GNIP data). The extreme depletion of this sample may be attributable to the small amount of precipitation this month (44 mm), which was composed mainly of two days of snowfall (Bjørn Frengstad, pers. com.), and is not likely to represent a complete sample. The yearly weighted $\delta^{18}O_W$ of the precipitation in Trondheim in 2013 is −8.77‰. The oxygen isotopic composition of the Trondheim tap waters sampled in October 2014 and September 2015 are −8.77 ± 0.2‰ and −8.61 ± 0.2‰ respectively (mean ~ −8.7‰).

A series of yearly mean $\delta^{18}O_W$ extending from 1850 to the present was calculated from the temperature CRUTEM4 (Osborn and Jones, 2014; Jones et al., 2012) using Dansgaard's (1964) equation. It shows a ~1‰ increase from the second half of the 19th century, at the inception of the warming trend, to now. We calculated the 10-year running mean to take into account the buffering effect of water residing in natural reservoirs (10 years in Lake Jonsvatnet).

The mean temperature in Trondheim in 2014 and the average values of 2004–2014 (taking into account the buffering effect of water residing about 10 years in the reservoir), are both equal to ~6 °C which corresponds to $\delta^{18}O_W$ = ~−9.3‰. This value is close to that of the tap water. Though it should be confirmed, in particular with additional $\delta^{18}O_W$ measurements, the consistency of the measured and calculated values supports using Dansgaard's (1964) equation for deriving $\delta^{18}O_W$ from temperature in the study area.

The $\delta^{18}O_C$ of an M3 tooth from an adult male, presently living in Trondheim, was analysed. He has always lived in Trondheim and is now 40 years-old (which means that his M3 was completed ca. 1989). The $\delta^{18}O_W$ calculated from the M3 is ~−11‰ in 1989, while at the same time the composition of the reservoir water averaged over 1983–1989, the approximate time of mineralisation of the M3, is about −10‰. This 1‰ discrepancy may be due to the combination of analytical and model errors, and could perhaps also be due to the consumption of non-local drinks between ~8 and 14 years (Fig. 2).

3.2. Migration during childhood

As stated in Section 2.3., the oxygen isotopic compositions of the M1 and M3 teeth of an individual can be different because of the change of beverage from milk to water during early childhood. This effect can induce a bias in the interpretation of isotopic differences between M1 and M3 in terms of migration. We therefore sought to quantify and eliminate the breastfeeding effect from the Trondheim teeth database prior to interpreting the differences between the M1 and M3 teeth compositions. We then evaluated if the isotopic composition of the drinking water, ingested by nursing mothers or by the individuals themselves, could vary in response to differences in mean temperatures during the times of formation of the two teeth.

As already mentioned, the mean enrichment of M1 teeth with respect to M3 is generally <1‰. Moreover, within a population the inter-individual variability of the enrichment is frequently several tenths of a per mil (Evans et al., 2006b; White et al., 2005; Wright and Schwarcz, 1999; Wright and Schwarcz, 1998). To take this possible variability into account, we have calculated adjustments of the isotopic composition of the M1 of the present database to compensate for offsets ranging from 0.2‰ to 1‰.

The M1 and M3 are formed at two different periods of life (0–3 and ~8–14 years), during which the mean temperature may be different. We tested this assumption using the Trondheim temperature series provided by CRUTEM4 for the period 1970–2014. Using Dansgaard's (1964) equation, we transformed it into a $\delta^{18}O_W$ series with which we calculated the 10-year running mean ($\delta^{18}O_{W\text{-}10}$) to take into account a 10-year residence time in the reservoir. Then, we calculated the differences between $\delta^{18}O_{W\text{-}10}$ averaged over packs of 3 years (time for M1 mineralisation) and packs of 6 years (time for M3 mineralisation). These differences are contained in a ± 0.30‰ interval ($\pm 1\sigma$). Such dispersion translates into a ±0.13‰ possible difference between the $\delta^{18}O_C$ of the M1 and of M3. In the past, water may have resided for shorter times in smaller reservoirs. Our calculation yields an isotopic difference of 0.2‰ if the residence time is only 3 years.

We considered that if the isotopic composition of the M1 (adjusted for weaning) and M3 differed by >0.6‰ (2 analytical uncertainties +0.2‰ possible effect of temperature change), then migration during childhood was likely. This value is rather conservative as there is no compensation for errors in the calculation.

The compositions of M3 teeth are not statistically different from those of adjusted M1 (at $\alpha = 0.05\%$). However, they differ by >0.6‰ in 16 out of the 70 individuals (whatever the value of the adjustment; Fig. 3). This indicates that in these cases, the difference between the M1 and M3 $\delta^{18}O_C$ is neither attributable to breast-feeding nor to climate, but may be ascribed to a migration of the individuals between 3 years old and early teenage years. Most of the possible migrants were buried at the Folkebibliotekstomten site (13 out of 17), three at Vestfrontplassen and one at Søndregate. Three quarters of these (11/17) were females. At the Folkebibliotekstomten site, more than half of the individuals are potentially migrants. For all the 17 likely migrants, $\delta^{18}O_C$ increased from M1 (adjusted value) to M3.

3.3. Migration after early teens

The periods during which the various cemeteries were in use are known, but not the precise dates of each burial. Therefore, at each site the excavated individuals may not be contemporaries. The time of mineralisation of all the teeth analysed at a site may thus correspond to different temperature conditions. To estimate the incidence of these conditions on the distribution of the isotopic values, we calculated a theoretical standard deviation (SD) of the M3 $\delta^{18}O_C$ over the 1900–2014 period using the CRUTEM4 temperature and assumed that the individuals drank water derived from the reservoir. The obtained range of M3 is ±0.2‰. The published values of intra-populational variability are generally larger. Indeed, White and Spence (1998) report SD ranging from ±0.3‰ to ±0.8‰ in Mexico, Fricke et al. (1995) between ±0.1‰ and ±0.9‰ in Greenland, while ±0.8 to 0.9‰ have been reported in other populations (e.g. Daux et al., 2005). In addition to temperature changes, other effects, such as different diets (e.g. Daux et al., 2008), may cause variations of the $\delta^{18}O_C$. In order to identify migrants, we defined extreme values of $\delta^{18}O_C$ of the M3 as those above/below the average of all the data (23.88‰) plus/minus a conservative possible intra-populational variability of 0.9‰ (Fig. 4). Among the M3 teeth of the 88 buried individuals, 12 may be ascribable to individuals having migrated during adulthood (after ~14 years). Three of them had moved during childhood (between M1 and M3 completions). The isotopic compositions of their M1 are close to the average $\delta^{18}O_C$ of the M1 teeth of the whole population (23.99‰), while those of their M3 are significantly above the average oxygen ration of the M3. These characteristics are compatible with an early life in Trondheim, a move after the age of 14 and a return to Trondheim a few years later.

4. Discussion: possible origin of migrants

The origin of the buried individuals cannot be determined precisely. Indeed, the uncertainty (model error) on $\delta^{18}O_W$ calculated from $\delta^{18}O_C$ is about 1‰ (Chenery et al., 2012). Moreover, since medieval times, the study area has very likely undergone changes in mean temperature with consequential variations of the isotopic composition of the environmental water. Such changes would make the comparison between past and present $\delta^{18}O_W$ irrelevant for the recognition of migrants. However, according to reconstructions of the variations of the spring-summer temperature in coastal northern (from 1548 to 1989; Kirchhefer, 2001) and western (1734–2003; Nordli et al., 2003) Norway, the largest temperature variation at the pluri-decadal scale occurred over the last century. Therefore, we assume that the effect of temperature on $\delta^{18}O_W$ has been relatively constant across the medieval and post-medieval periods and that the spatial gradient (relative variations) of $\delta^{18}O_W$ has not changed through time. Under such hypotheses, we can compare the present gradient of $\delta^{18}O_W$ (Fig. 5) to the calculated variations of $\delta^{18}O_W$ (Table 2) that have accompanied the migrations 1) during childhood from the difference between M1 (adjusted) and M3 compositions, and 2) after 14 years from the deviation of individual $\delta^{18}O_C$ from the mean of the whole archaeological M3 set.

The 17 migrants who migrated during childhood all moved along a gradient of increasing $\delta^{18}O_W$. According to the present isotopic distribution, the change of 1 to 4‰ (Table 2) corresponds to migrations from more or less distant locations in Northern Norway and Sweden. They are also compatible with more eastern locations. One individual (in FBT) corresponds to a migration along a 6–7‰ gradient, consistent with a long distance migration from an Arctic location (in Siberia, Greenland or at the northern tip of Scandinavia).

Among the 12 migrants who moved after 14 years of age, six moved along a gradient of increasing values (+1.6‰ to +2.9‰), that is from 300 to 400 km North or East, the others along a gradient of decreasing values (−4‰ to −1.7‰) from the South-West (Scotland, for instance) or South (southern France or northern Italy or Spain).

Three migrants moved during childhood along a gradient of increasing $\delta^{18}O_W$, and after 14 years of age along a gradient of decreasing composition, the amplitude of the back and forth moves being close (+1.7‰ to 3‰ versus −1.7‰ for instance). A likely scenario is that the individuals lived in Trondheim during their early childhood, moved southwards during childhood, and moved back to Trondheim between 14 years and death.

5. Conclusions

The investigations discussed in this article have provided new information about the pre-modern population in Trondheim. Age of migrating individuals and directions of the migrations have been discussed, temporal changes have been shown, and suggestions have been made regarding the proportion of immigrants versus locals in the population. An unexpected high level of child mobility has been shown in the medieval material with 36% of all medieval individuals having moved during childhood, and as much as 57% if looking at the Folkebibliotekstomten site alone. As noteworthy as the child mobility in the medieval material is the lack of the same amongst the post-medieval individuals, as only 7% of these seem to have migrated during childhood. There are, at least, two questions here that require further investigation: firstly, how can such a high level of medieval child mobility be explained and, secondly, why is there hardly any evidence of child mobility in the early modern material? With regard to migration during adulthood, quite few migrants have been identified: 12.5% of the medieval individuals and 13% of the individuals in the post-medieval material. Thus, overall, 40% of the medieval individuals were born elsewhere from where they were buried while the same scenario only applies to 17% of the post-medieval individuals. This does, however, not necessarily mean that most people were born and grew up in Trondheim, but it rather means that the majority of the population seems to have been born in the larger region surrounding Trondheim. Due to inaccuracies in the methodology and analyses, the individuals born in areas surrounding the town will not have been distinguished from people having been born in the town. What seems to be a clear pattern, however, is the decreased migratory activity in the post-medieval period in comparison to medieval times. Can these temporal changes be explained by changes in society as a result of the Reformation?

Although this investigation has provided new information about the migratory patterns of pre-modern population in Trondheim, it also poses several new questions, in particular questions surrounding how these results can be explained in the light of societal changes, which would have come about as a result of the Reformation. These are complex questions which require a closer discussion within the framework of historical and archaeological sources.

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