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An alternative interpretation of the Viking sundial artefact: an instrument to determine latitude and local noon

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An eleventh century artefact, a fragment of a compass dial found at Uunartoq in Greenland, is widely accepted as proof of the ability of Vikings to navigate with sun-compasses. The artefact is half of a wooden compass dial bearing deliberately incised lines that were interpreted as gnomonic lines valid on the day of equinox and near the summer solstice at the 61st latitude. Supposed loose markings of cardinal directions and several unexplained scratches are visible on this find. We offer here a new possible interpretation that some of these scratches might be fundamental lines of a geometrical construction process used for forming the gnomonic lines. Our hypothesis renders the cardinal directions to be precisely marked in the dial and assigns exact dates to both gnomonic lines. We reinterpret the artefact as a combination of sun-compass and sun shadow board designed for appointing local solar noon and the length of the noon shadow at open sea, playing a role analogous to that of a late-mediaeval backstaff. Greenland occurrence of geometrical construction of gnomonic lines, a known cultural asset of ancient European people, may denote that mediaeval Norse people not only shared in European culture, but used its achievements, even in the utmost frontiers.

1. Introduction

From the eighth to the eleventh century, Vikings ruled Scandinavia and North Atlantic islands using their

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outstanding maritime skills. Coastal navigation and taking of cues from characteristic landmarks were preferred; sighting stars, sea currents and sea animals provided information about current positions. Even without knowledge of the magnetic compass, Vikings routinely crossed the high seas by sailing directly west or east along given latitudes marked by prominent settlements or coastal landmarks [1,2]. Norse merchant ships regularly sailed more than 2500 km along the 61st latitude to reach Greenland and returned to Norway loaded with hides, skin ropes and walrus ivory [2,3]. It is accepted by the scientific community that Viking navigators used primitive sun-compasses [1] to guide their ships during the season of bright Nordic nights.

Sun-compasses are close relatives to sundials. A still sundial provided with gnomonic lines may be used to read local solar time and to register passing seasons by following the daily movement of the shadow. Also, a sun-compass has a levelled dial marked with hyperbolic gnomonic lines, but it is rotated to fit the shadow tip to the lines. In this position, the major axis of the hyperbola is parallel to the north–south direction, and can be used as an independent reference bearing [1]. As the shadow follows significantly different paths at different latitudes and during different times of the year, a series of gnomonic lines should be marked on the compass to improve accuracy. Gnomonic lines may be formed experimentally, but sophisticated methods of their geometrical construction are millennia-old cultural assets [4–6].

The prominent artefact evidence for Norse solar navigation is a fragment of an eleventh century compass dial, now part of the collection of the Danish Maritime Museum ([1]; figure 1*A*). It was found under the ruins of a Benedictine convent by archaeologist Veabek in Uunartoq in Greenland in 1948 [7], and was later identified as a fragment of an early sun-compass used on board Viking ships along the 61st latitude [1]. The artefact is half of a round wooden disc, with a diameter of 70 mm, bearing deep scratches and a side scallop resembling compass divisions. A whole but unmarked wooden disc with identical diameter was found in the same locality, denoting that possibly several similar instruments were created there [7].

Two scratches in the face of the dial fragment were proved to be incised more than once, which shows that they were formed deliberately ([1]; figure 1). These lines were interpreted as incomplete gnomonic lines valid at the equinoxes and near the summer solstice (figure 1*B*,*C*), while a series of 16 notches and a depression located at about 90° from them were considered to be approximate markings of north and east (figure 1*A*). The artefact was accepted to be a sun-compass after comparison with handheld sun-compasses with similar dimensions, but provided with complete gnomonic lines calibrated for a series of times and latitudes, were tested on board small sailing ships and were and found to be efficient marine navigational instruments [1].

Without questioning the general usability of handheld sun-compasses, we attempt to explain the puzzling premature ending of incised gnomonic lines and a possible function of other prominent, but yet unexplained, scratches visible on the face of the artefact dial. We reveal some conformities between the scratches on the find and added lines of geometrical construction algorithms used for creating sundials. These analogies allow us to explain more details than earlier studies of the artefact, and urge us to create an alternative reconstruction of the instrument. We propose that the find may primarily not have been a sun-compass, but rather a sophisticated sun shadow board used for determining the current latitude, which is a vital piece of information for latitude sailors. Other primitive instruments like the kamal, the cross-staff and the backstaff are known to be used for this function in other geographical areas during the mediaeval era [8].

2. Material and methods

Measurements were performed on a digital model of the artefact dial fragment found in Uunartoq. Dimensions of the artefact and positions of the incised markings were taken from high-resolution photographs published by Thirslund [1], and digital photographs kindly provided by the Danish Maritime Museum (figure 1). Digital photographs were traced after scaling to the reported 70 mm diameter of the original artefact (figures 1 and 2). The centre of the circle fitted to the curved outline of the fragment was considered as the centre of the dial fragment. Slopes of

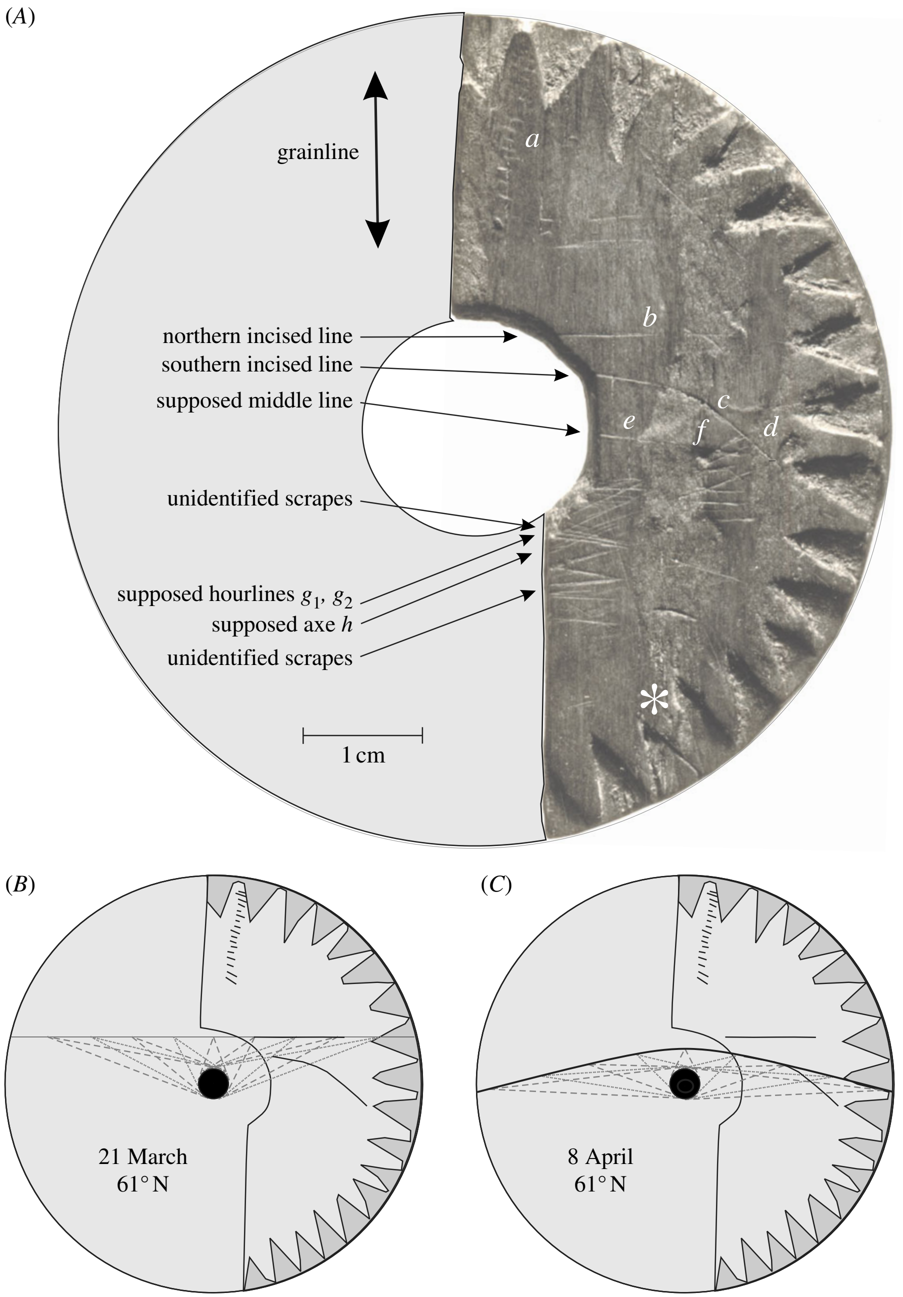

Figure 1. (*A*) Photograph of the eleventh century sundial artefact fragment found by Veabek in Uunartoq in Greenland in 1948. The photograph was kindly provided by the Danish Maritime Museum. The supposed outline of the missing part is symbolized by grey shading; a double-headed arrow shows the grainline of the timber. Earlier studies identified two deliberately incised lines that were interpreted as gnomonic lines (*b* and *c*). A series of 16 notches in the upper segment (*a*) was considered to be a loose marking of north, a depression about 81° from it (*d*) was taken as the marking of east. One cog of the alleged irregular compass division was corrected by the woodcarver (asterisk). Markings in the middle and lower segments were taken as random scratches and were disregarded. Some of these lines are precisely straight (*e*, g_1, g_2 and *h*), and run from the middle section of the dial to the supposed southern gnomonic line. The intersection of *e* and g_1 is even marked by a depression (*f*). (*B*) The northern straight incised line was taken as the straight path of the shadow on the day of equinox marking the east–west direction. (*C*) The southern incised line *c* was taken as a gnomonic line valid on a summer day, although no valid gnomonic line fits to it. (Online version in colour.)

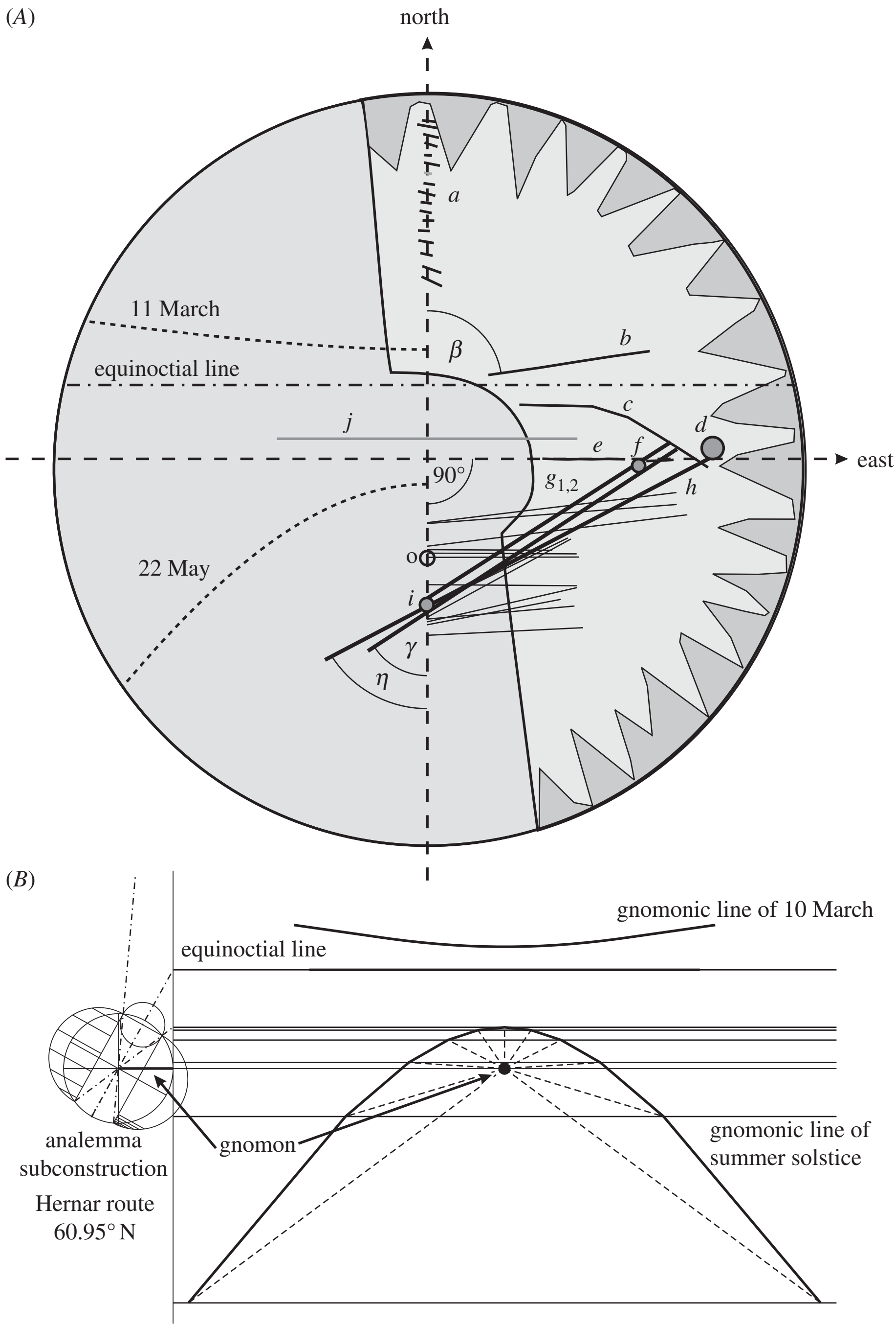

Figure 2. (*Caption opposite.*)

straight scratches were calculated by substituting them with straight lines connecting their ending points. Distances between individual notches in the northern part of the dial were defined by the distances of their midpoints.

A repeated incision is clear evidence of forming a line deliberately, but it is expected only in the case of stressed lines that have dedicated practical functions. The artefact dial bears several scratches that may originate from impairments, but also may have been purposefully added by

Figure 2. (*Opposite.*) (*A*) Scratches and depressions in the face of the compass dial artefact. Lines considered to be purposefully added are shown as thick lines; uninterpreted but potentially functional scratches are shown as thin lines. Line *e* is considered to be parallel to the east–west line. The series of 16 notches (*a*) marks true north. An additional notch shown in grey was added between the anomalously distant sixth and seventh notches. The equinoctial line (dash-dot line) is not incised, its position is defined by the intersection of lines *b* and *a*. The northern and southern incised lines (*b* and *c*) are gnomonic lines valid on 11 March and 22 May at latitude 63.43° N, but they are to be used with a low rectangular gnomon (*j*) with a height of 4.0 mm and width of 28 mm. The east–west direction is marked by line *e*. Two parallel straight lines (g_1 and g_2) run to it from the southern part of the fragment enclosing 56.4° and 57.7° with the north–south line. Their intersections with *e* are marked by *f*. A further straight line (*h*) runs to *c* and intersects it near *d*. It encloses $\eta = 62.4°$ with the north–south line. The intersections of *g* and *h* and the north–south line are close to each other, marking a common origin *i*. Position *o* of an 8.2 mm high central gnomon predicted by the hypothesized construction lines is shown as a hollow circle. The path of the shadow tip of this gnomon on 11 March and 22 May (dot lines) are shown in the left side of the figure. (*B*) Construction of approximate gnomonic lines at the Hernar transatlantic route (60.95° N) for a 8.7 mm high gnomon, using the method of Vitruvius. Major sections of the gnomonic lines are provided, but lengths for projection lines (dashed lines) are determined by a small and complicated sub-construction.

the woodcarver. To avoid mistaking random scratches with deliberately incised lines, only those that are on the face of the dial, are not parallel to the grainline of the material, are marked with a prominent sign, enclose angles close to special angles or form a clearly regular pattern (figures 1 and 2; table 1) are considered to be purposefully formed.

The arrangement of supposed purposefully formed lines was compared with that of lines produced during typical geometrical constructions of pelekinon-type horizontal sundials (figure 3). The analemma-based construction method described by Vitruvius and a trigon-based method were examined [4,5]. Variants of both methods were used in mediaeval times for constructing horizontal sundials, and they provide approximations of identical hyperboles (figures 2*B* and 3). Principles underlying the construction processes are based on spherical trigonometry and astronomy, and may be found in specialized handbooks [5,6].

Analemma-based methods require creating an auxiliary geometrical model of the apparent seasonal and daily movement of the sun in the sky scaled by the size of the gnomon (figure 2*B*). Gnomonic lines are formed by projecting the sun through the gnomon tip into the sundial plane. Trigon-based construction methods are simplified versions of analemma-based ones, based solely on the seasonal shift of gnomonic lines on a sundial, and are more appropriate for constructing small instruments (figure 3). Predetermined hour lines of the dial are projected onto the so-called trigon, which is the three straight lines enclosing 24° and representing the noon shadow of the gnomon on the days of equinoxes, and summer and winter solstices. To mimic contemporary astronomical conventions, the Earth's axial tilt of 24° and a circular Earth orbit were considered.

Trigon-based methods provide only the intersections of gnomonic lines and hour lines and a pattern of construction lines, which is similar to that seen on the artefact dial (figures 2*A* and 3). The hour lines and the axe line that is perpendicular to the middle line of the trigon and encloses the latitude angle λ with the north–south line originate from a single common base point located south of the base of the gnomon. Further fundamental lines are the north–south line and the east–west line intersecting at the base of the gnomon. Angles enclosed by hour lines and the north–south line are to be calculated using the sundial formula (table 2),

$$\tan_{\alpha_n} = \sin\lambda \cdot \tan(15° \cdot n), \tag{2.1}$$

where λ is the latitude of the sundial, n is the number of hours to or past noon and α_n is the angle enclosed by the corresponding hour line and the north–south line. The classical astronomical hour angle of 15° is taken as the hourly shift of the sun in the sky. Theoretically, any hour angles could be used, but there is no reason to presume use of a custom division of the day in an era characterized by obeying traditions. Only hour lines intersecting with the equinoctial line may

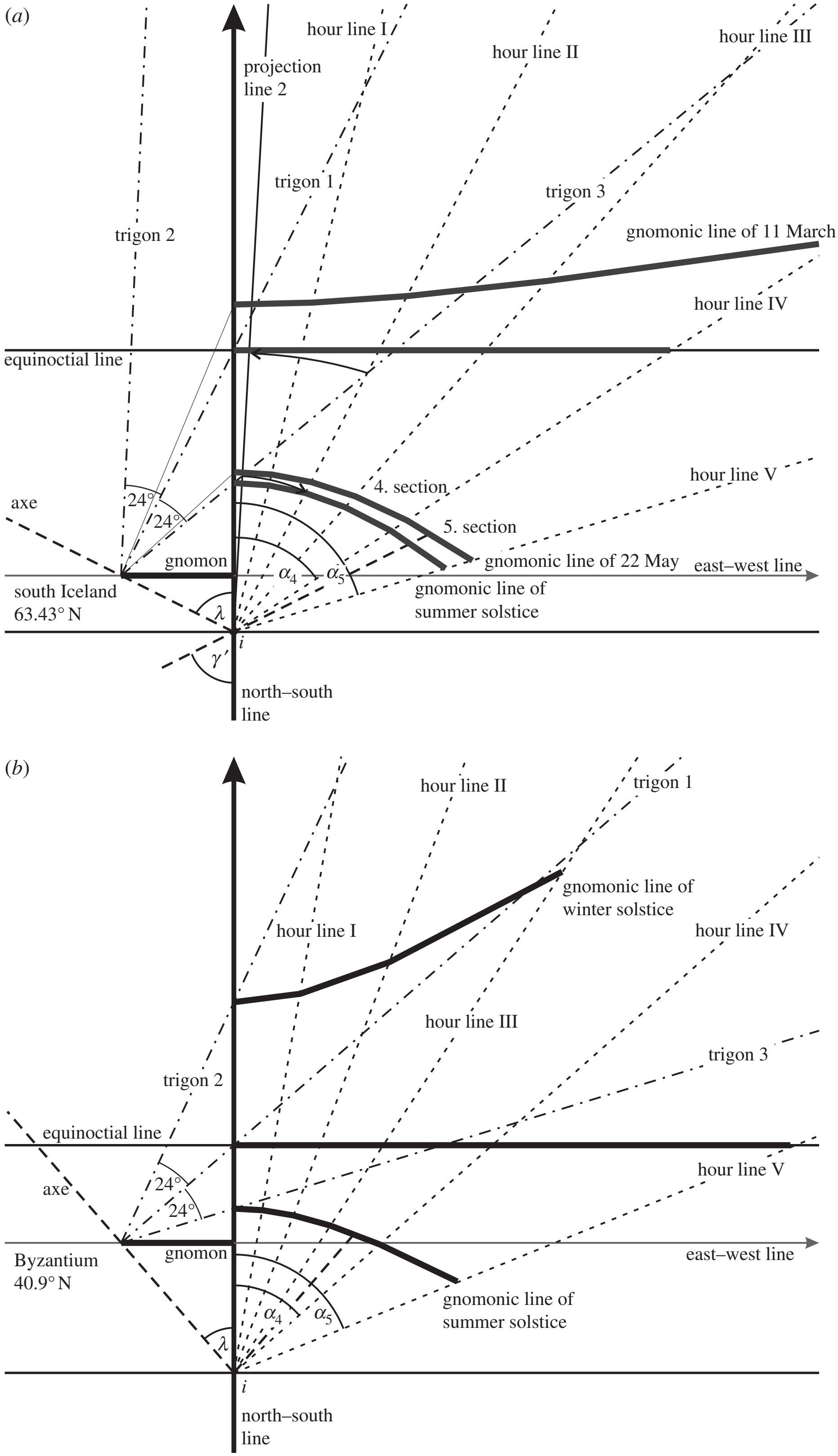

Figure 3. (*Caption opposite.*)

Figure 3. (*Opposite.*) Fundamental lines of the trigon-based constructions of horizontal sundials with 20 mm high gnomons. The first step of construction is drawing the north–south line followed by the line symbolizing the axe of the Earth enclosing the angle of latitude λ and defining the centre of the construction *i*. Then, hour lines are drawn tilted by angles α_1, α_2, α_3, α_4 and α_5 from the north–south line. The gnomon height is determined by the length of the section of the east–west line between the axe (gnomon top) and the north–south line (gnomon base). The middle trigon line starting at the gnomon top and perpendicular to the axe cuts the north–south line at the tip of the noon shadow at the equinoxes, marking the position of the equinoctial line. Two lateral lines of the trigon enclosing $\pm 24^\circ$ with the middle one mark tips of the noon shadows at summer and winter solstices. Ancient scholars prescribed the value 24° instead of 23.44°, the real value of the Earth's axial tilt. Points of gnomonic lines are constructed by projecting the intersections of the equinoctial line and individual hour lines onto the middle trigon line, then these points are connected with the base point to gain corresponding projection lines. Intersections of the lateral trigon lines and projection lines are projected back onto the corresponding hour line to find the points of the gnomonic lines of summer and winter solstices. Eastern and western branches of the gnomonic line are drawn by mirroring the figure to the north–south line. Drawn portions of the gnomonic lines are determined by λ. (*a*) The gnomonic line of the summer solstice constructed for Nordic latitudes will terminate at the east–west line, providing a pattern similar to the one seen on the Uunartoq artefact. (*b*) At southern latitudes, this gnomonic line extends well south of the east–west line.

Table 1. Angles enclosed by lines marked on the artefact sundial and the supposed north–south line (see figures 1*A* and 2*A*).

line	angle (°)
a	0
b	81.2
inner section of *c*	91.3
middle section of *c*	105.0
outer section of *c*	121.8
e	90
g_1	57.7
g_2	56.4
h	62.4

be projected, which later is the path of the shadow tip at the equinoxes. Use of the traditional 15° hour angle provides only five suitable hour lines before and after noon; thus trigon-based methods provide only the inner section of gnomonic lines (figure 3).

Latitudes were defined by the ratio of the height of the gnomon and its noon shadow length on the day of equinox, measured in whole units following the description of ancient authors [4]. The latitude of the mediaeval Hernar route (61.03° N) can be approximated by the ratio 5 : 9, defining the latitude of 60.95° N, whereas the most convenient 1 : 2 ratio happens to define 63.43° N, the latitude of the odd-shaped mount Hjørleifshøfdi in the southernmost tip of Iceland (tables 2–4).

Positions and slopes of added lines and segments of the constructed approximate gnomonic lines were calculated using our custom-made computer program. Slopes of hour lines used in the trigon-based construction and latitudes coded by supposed hour lines visible on the artefact dial were calculated using the classical sundial formula (equation (2.1)). Slopes of considered scrapes were compared with those of hour lines calculated for latitudes of notable Atlantic Viking era localities between 40° and 66° N (tables 2–4).

Parameters of gnomonic lines valid at given latitudes on particular days of the year were calculated by our custom-made computer program. Atmospheric refraction was not considered. Dates were assigned to the incised gnomonic lines by considering their outermost sections to be

Table 2. Angles enclosed by hour lines and the north–south line at notable latitudes of the Viking era calculated using the classical sundial formula. Values marked with asterisks are possible intended slopes of lines g_1 and/or g_2 (see figures 1*A*, 2*A* and 3).

	latitude				
hour line	40.9° N Byzantium	51.7° N Vinland	60.9° N Hernar	63.4° N Iceland South	65.6° N Iceland North
I	10.0°	11.9°	13.2°	13.5°	13.7°
II	20.7°	24.4°	26.8°	27.3°	27.7°
III	33.2°	38.1°	41.2°	41.8°	42.3°
IV	48.6°	53.7°	56.6°*	57.2°*	57.6°*
V	67.7°	71.2°	73.0°	73.3°	73.6°

Table 3. Angles enclosed by the north–south line and segments of gnomonic lines constructed using a trigon-based method at notable latitudes of the Viking era. Values marked with asterisks are possible intended slopes of sections of line *c* (see figures 1*A*, 2*A* and 3).

	latitude				
gnomonic line segment	40.9° N Byzantium	51.7° N Vinland	60.9° N Hernar	63.4° N Iceland South	65.6° N Iceland North
summer solstice I	93.2°	93.5°	93.8°*	94.0°*	94.1°
summer solstice II	99.5°	100.3°	101.5°	101.9°	102.3°
summer solstice III	105.4°	106.9°	108.9°	109.6°	110.3°
summer solstice IV	105.6°	113.1°	116.2°	117.2°	118.3°
summer solstice V	115.5°	118.8°	123.1°*	124.6°*	126.0°

Table 4. Angles enclosed by the north–south line and segments of gnomonic lines constructed using a trigon-based method and at latitudes of 60.95° and 63.43° N on the dates supposedly marked on the artefact dial. Values marked with asterisks are possible intended slopes of sections of lines *b* and *c* (see figures 1*A*, 2*A* and 3).

	latitude			
	60.95° N Hernar		63.43° N Iceland South	
gnomonic line segment	10 March	1 June	11 March	22 May
1.	88.6°	93.7°	88.6°	93.7°
2.	86.0°	101.0°	86.0°	100.9°
3.	83.8°	108.2°	83.8°	108.0°
4.	82.1°	115.2°	82.2°	114.9°
5.	81.2°*	121.8°*	81.3°*	121.5°*

the fifth linear section of constructed approximate gnomonic lines connecting the fourth and fifth hour lines at latitudes 60.95° and 63.43° N (tables 3 and 4; figure 3*a*). The Gregorian date on which the corresponding section of the constructed gnomonic line has equal slope with that of the outer section of the incised line was taken as the date of the gnomonic line.

3. Results

(a) Considered lines on the artefact dial

The series of 16 notches (*a*), gnomonic lines (*b* and *c*) and depression (*d*) interpreted by earlier studies as deliberate markings were considered to be added purposefully (figures 1*A* and 2*A*). A clearly visible deep depression (*f*) with a diameter of 1 mm is located in the middle section of the dial. Such a depression could be created by the tip of a sharp knife, and we considered it to be a purposeful marking. It is positioned at the intersection of two well-visible straight lines (*e* and g_1). There is a further line (g_2) that is nearly parallel to g_1 and tangential to *f*. A less apparent line (*h*) runs to the depression *d* and intersects with *c* near to its outer ending point. Line *e* reaches *c* only 0.3 mm north from the intersection of *c* and *h*, forming a common intersection of the three lines. All three lines terminate within 1 mm from the intersection point. Moreover, the extension of line *e* is tangential to *d*.

Line *e* runs 0.9 mm north from the centre of the dial. Out of the 16 notches (*a*), 13 clearly intersect with the line perpendicular to *e* and pass through the centre of the dial, later referred to as line *a*. Distances between the sixth and seventh notches are about twice the average distance between other notches, thus an additional notch was added at half the distance between them. The distance between the midpoints of the now 17 notches was found to be 0.93 ± 0.1 mm, forming a precise scale (linear fitting: $r = 0.99902$, s.d. $= 0.21557$, $p < 0.0001$). Considering the irregular slopes and lengths of the individual notches, they can be accepted as lying at 90° to line *e*. On positioning the dial fragment with line *e* running parallel to the east–west direction, line *a* serves as the north–south line. Note that the extensions of lines g_1, g_2 and *h* would intersect very close to line *a*, marking out a possible base point (*i*; figure 2*A*). Thus, we considered line *e* to be the representation of the east–west line and used it as a reference to measure the bearing of other lines (table 1). Subsequently, line *b* was not considered to represent the equinoctial line, but to be a section of an ordinary hyperbolic gnomonic line.

Also the side scallop was not considered to code cardinal directions, despite its similarity to modern compass roses. Obviously, it was formed erroneously; one of its cogs in the southern half was even corrected by the woodcarver (figure 1*A*). The northeastern quarter is divided into eight segments, as in modern compasses, although divisions add up only to about 86°. But the existing part of the southeastern quarter wears nine sections, leaving space for at least two more cogs in the lost portion. The scallop could only have represented some notable bearings, or could have been a decoration.

(b) Characteristic lines of geometrical constructions

Analemma-based methods provide complete approximate gnomonic lines for the daylight period (figure 2*B*). If copied to the artefact dial, such gnomonic lines would extend well over the edge of the compass dial. However, incised gnomonic lines of the artefact dial terminate well before the edge of the dial and no southeast-running lines are visible. Projection lines used in such constructions run not only northeast, but also southeast. No lines running southeast are seen on the artefact. Moreover, the complicated auxiliary construction of an appropriate analemma-based construction would be far too small to be performed in the case of the artefact dial using primitive tools (figure 2*B*). This pattern of construction lines does not conform to any detail of the artefact dial, and thus this construction method was neglected.

Similarities between the pattern of the trigon-based construction and considered lines of the artefact dial are conspicuous, although a complete construction algorithm cannot be reconstructed. Lines g_1 and g_2 enclose the north–south lines 57.7° and 56.4°, respectively (table 1). When interpreting them as the fourth hour line, their slopes refer to 60.3° and 65.95° N, the latitudes of the southern tip of Greenland, and that of the northwestern tip of Iceland, respectively. It is more logical to consider them as approximations of a single intermediate value (table 1).

Their mean slope 57.05° refers to 62.97° N, a latitude angle that nearly equals the slope of line *h* (table 1). It is only slightly less than 63.43°, the latitude coded by the 1 : 2 ratio of gnomon height and noon shadow length at the equinoxes, and happens to be the latitude of the southernmost tip of Iceland. Considering the supposed common origin of *h*, g_1 and g_2, *h* could be interpreted as the axe line, the slope of which codes the intended latitude of operation (figure 2*A*). Line *c* continues after intersecting with lines g_1 and g_2, but terminates after intersecting with line *e* and *h*, just like the fifth segments of the constructed gnomonic lines (figures 2*A* and 3 and tables 1 and 2). The arrangement of lines *c* and *e* is also similar to that of the east–west line and the termination of the constructed gnomonic line at high latitudes; the gnomonic line terminates north of the gnomon (figure 3). Although the purpose of line *e* cannot be deduced, it is worth noting that line *c* terminates shortly beyond their intersections.

(c) Dates and gnomon positions coded by gnomonic lines

Dates can be assigned to gnomonic lines only at given latitudes. The latitude of 63.43° N, which can be easily constructed, and that of the transatlantic Hernam route (60.95° N) were examined (table 4). The northern incised line is assigned to 10 and 11 March, dates before spring equinox. The southern incised line would refer to 22 May and 1 June, respectively. Note that the later dates would slightly change, if the elliptical Earth orbit were to be considered. Deviation between slopes of the fifth line segment of gnomonic lines calculated for summer solstice at the Hernam route and that of the outer section of line *c* is small (tables 1 and 4), thus line *c* might also be accepted as a gnomonic line near summer solstice at its latitude.

(d) Assessing the position of the gnomon

The equinoctial line is not incised on the dial fragment; its position can only be presumed. Its intersection with the north–south line nearly coincides with that of the asymptotes of gnomonic lines in the equinox period. If the common intersections of *a*, g_1, g_2 and *h* are accepted as the base point of a hypothesized trigon-based construction with a slope of *h* coding the latitude, a central gnomon is given with a height of 8.2 mm and a position north of the base point (figure 2*A*). Extensions of three short close-lying parallel scratches being parallel also to line *e* on the artefact intersect line *a* close to this point, however, may easily be a meaningless coincidence (figures 1 and 2*A*). Obviously, lines *b* and *c* are positioned too close and far too lateral to belong to a single central gnomon. They could represent only the shadow of a significantly lower gnomon positioned east, northeast from the centre. The vertices of a wide rectangular gnomon would be adequate for this role while not breaking the presumed symmetry of the artefact (figures 2*A* and 4).

Unfortunately, the exact dimensions of the rectangular gnomon to be used with the incised lines cannot be calculated because lines *b* and *c* are combinations of straight sections, not hyperboles. We can assume that the slope of *h* codes the latitude 63.43° N and the lines *b* and *c* are valid gnomonic lines on 11 March and 22 May, respectively. One must have a preconception of gnomon height to calculate the position of the equinoctial line and vice versa. Line *b* can be considered to be a straight approximation of a nearly perfect V-shaped gnomonic line valid in the equinox period. Thus, *b* can be taken as the asymptote of a hyperbolic line, which intersects the equinoctial line and the north–south line in a single point. On the other hand, the gnomon must be positioned laterally enough to cast a shadow reaching line *c* on 22 May. These conditions are satisfied by a 28 mm wide and 4 mm high rectangular gnomon placed 0.8 mm north from line *e* (figures 2 and 4). However, the above parameters of the gnomon are not derived from consistent positions and slopes of considered lines on the artefact, and an unknown secondary scaling procedure must be assumed to link them to classical trigon-based construction methods.

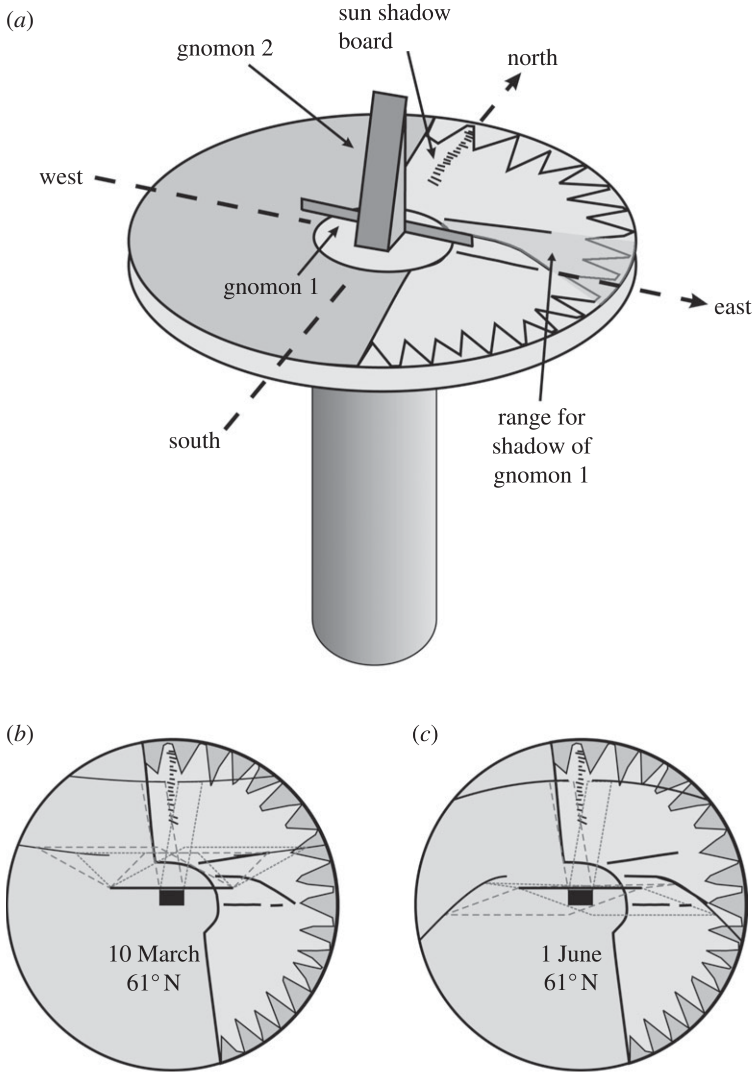

Figure 4. (*a*) Reconstruction of the compass dial artefact as a combination of a sun-compass and a sun shadow board providing an interpretation for several incised lines. The gnomonic lines belong to a low rectangular gnomon and serve to identify the noon period. The series of 17 notches in the north form a fine scale for reading the noon shadow length of a second high central gnomon with a height chosen for the given latitude and time of year. Deviation from the desired latitude can be read with a resolution of about 0.1°, but only crude bearings can be taken from the compass at intermediate solar elevation angles. Both gnomons may have different figures while keeping their function. (*b*) In springtime, an 11 mm high central gnomon should be used for crossing the North Atlantic Ocean along the 61st latitude. (*c*) During summer, a 28 mm high central gnomon should be used on the same route.

4. Discussion

(a) Arguments for an alternative interpretation

The use of sun-compasses is restrained chiefly by unfavourable weather conditions and extreme high or low solar elevation angles. The shadow of the gnomon quickly lengthens as the sun approaches the horizon, whereas it shortens when it rises and nears the zenith. Even at high latitudes, sun-compasses need thin and high gnomons and large dials to provide a well-visible shadow during the day. Nonetheless, handheld sun-compasses with dimensions similar to that of the Uunartoq find, but bearing complete gnomonic lines, were thoroughly tested on open sea and were found to be functional navigational instruments [1]. We do not wish to challenge the concept of sun-compass in general, but suggest a reinterpretation of the Uunartoq find.

The artefact could have been used as a sun-compass, but its dimensions are far from optimum in this role; a larger dial and complete gnomonic lines would be more practical. It has a diameter of a mere 70 mm and a large central hole with a diameter of 17 mm (figure 1*A*), probably a socket for a grip. Dimensions and the exact position of its gnomon can only be conjectured. An interpretation of the straight incised line *b* as the equinoctial line showing the straight path of the shadow on the day of equinox at the 61st latitude implies a central gnomon with a height of 4.3 mm that would cast shadow on the dial at solar elevation angles higher than 7° (figures 1*B* and 2*A*). As the incised lines terminate well before the edge of the dial, the shadow tip would lie beyond them when the sun is seen lower than about 9° above the horizon (figure 1*B*). The incised lines end beside the large central hole; thus the compass could operate only at solar elevation angles lower than about 27°, limiting its usage to fairly short periods of the day. It is not surprising that some scholars hypothesized a lost central section with a pin-like gnomon and a complement of the gnomonic lines ([1]; figure 1*B*,*C*).

Imperfections of the supposed gnomonic lines and loose markings of cardinal directions also challenge the sun-compass interpretation. The supposed marking of north lies 8.7° east from its appropriate bearing; earlier studies attributed its loose marking to the erroneous division of the compass rose. The southern incised line resembles a hyperbola, but does not fit to the real path of the shadow tip of a central gnomon on any date. This line is a composition of three linear sections positioned far too peripheral to be the path of the shadow tip near summer solstice, whereas the bearing of its outer section is too southern to be the path of the shadow tip sometime in the equinox period. Fair, but not good fit could be achieved about three weeks after the equinoxes (figure 1*C*).

Loose marking of directions and erroneous incision of fundamental functional lines are hardly tolerable on a navigational instrument upon which the fate of the ship and its precious cargo, life of mates and prestige of the navigator depend. The above puzzling details might be flaws originating from the primitive production environment, and the fragment dial may even be a discarded shoddy piece. However, they justify alternative interpretations assuming more precise workmanship and assigning functions to unexplained markings.

The premature termination of the incised gnomonic lines renders it improbable that they were formed experimentally (figure 1). It would imply that marking the path of the shadow was ceased a few hours before sunset, which is a most illogical move during creation of a solar navigational instrument meant for getting accurate bearings in most possible situations. Using such truncated gnomonic lines is rational only if their outer sections are excrescent or the applied forming method could produce only their inner sections. Trigon-based geometrical construction of sundials is such a limited method and produces a pattern of added lines similar to that of the markings on the artefact. This raises the possibility that this instrument was a product of developed engineering based on ancient cultural assets and might be produced in several copies.

Associating lines seen on the face of the sundial artefact with specific functions is a hard task; we do not have enough information to draw any unequivocal conclusion. We have to rely on measured slopes of single lines. We have no information on how precisely the dial was carved, but lines could hardly be incised into the wood with an error of less than 1°. The artefact is a fragment, so its original orientation can only be presumed, and we cannot correct slope readings based on presumed symmetry. Thus, read slopes should be considered as estimations with a bias of at least 1°. It is the nature of the corresponding formulae that a bias of about 1° in reading results in a 10° bias of calculated corresponding latitude and a bias of several days in dates assigned to gnomonic lines. Conclusions should be based on consistency rather than the precise parity of values.

(b) Reconstruction of the sundial artefact as a sophisticated sun shadow board

Our results inspire an alternative reconstruction of the dial fragment: it might have been a sun shadow board combined with a crude sun-compass for identifying local noon and reading latitude. As sea currents and winds unavoidably divert ships, long-range latitude sailing can hardly be performed without regular checking of the current latitude. Checking the noon elevation of the sun is the simplest way of reading latitude at high latitudes in the season of perpetual light, especially in open sea.

Direct observation of the sun disc is very hazardous. Measuring the length of the noon shadow is more convenient, and it probably was an important daily task of Viking navigators [2]. However, it is not trivial to appoint the noon period offshore without knowing the local time or having an independent reference for the bearing of the sun. Fixed sundials are useless on a ship that rotates and tilts freely on the water. Also marking the noon shadow length on parts of the hull would be misleading because ever-changing headings would spoil the reading. One may follow the shortening shadow using a sun shadow board, which is a levelled board wearing a gnomon surrounded by concentric circles. The navigator should observe the shadow tip during the midday period and note the innermost ring it touches [2]. The instrument would also provide true directions by land, but not on board a floating ship. It is a serious inconvenience that the solar elevation angle changes slowly in the noon period. Missing the start of the lengthening of the shadow would spoil the reading; thus, the observer must keep tracking the shadow through several hours. Levelling the board on a tumbling ship for such a long time is also problematic.

A sun-compass can be used for noting local noon without knowing true directions, even if it is crudely implemented. The path of the shadow greatly varies through the year, but the central sections lie relatively close to each other, even at high latitudes. Accurate orientation of a sun-compass requires distinct gnomonic lines for distinct times of the year, but for noting the noon period, the two lines valid on days of the lowest and highest noon solar elevations in the sailing season would be sufficient. Should such a compass be fixed and precisely aimed, then the shadow tip would always fall between the two lines (figure 4). In case the true directions and the local time at sea are not known, the compass can be rotated until the shadow tip falls between the gnomonic lines. But only during the local noon period is it possible to rotate the levelled dial to fit the shadow tip between their approaching central sections. The outer sections of the lines are not used for this function. True directions cannot be precisely obtained, and also the length of an identified noon period will vary through the sailing season. However, at high latitudes, the sun seems to move parallel with the horizon, and the solar elevation hardly changes for more than an hour. Even a crude sun-compass can be used to identify this period and define a window for performing quick and precise observations of the length of the noon shadow.

A small crude sun-compass like the one carved on the artefact dial would greatly facilitate the work of the navigator, allowing him to precisely time his most vital observation on long Nordic summer days. The two incised gnomonic lines refer to the middle of March and the end of May, dates characteristic of extreme solar elevations during the nautical season in the North Atlantic region. Note that precise forming of the gnomonic lines is not required! The instrument would be functional if the noon shadow length and bearing of the outer sections of the gnomonic lines are correctly marked. Incised lines on the artefact meet these requirements, although they are crude approximations of hyperbolic gnomonic lines.

We found that the incised gnomonic lines imply a wide rectangular gnomon, which is not practical on a sun-compass, especially not on such a small one. The area covered by the gnomon is lost for gnomonic lines reducing both operation period and accuracy. Such a design could be justified only by the need of reserving the central space for a more important component. In this case, it might have been a secondary gnomon with a height of 10–30 mm. It could be used for reading the length of the noon shadow on the scale formed by the notches on the northern part of the dial (figure 4). Distances between these notches on the northern half of the fragment are remarkably homogeneous. Simpler marking of north, such as carving a cross or incising the north–south line, would not only be sufficient, but even more precise; thus, the careful incision of the notches in this cardinal position denotes another fundamental function. If the local noon period can be identified in any other way, concentric circles of the sun shadow board may be reduced to such a simple scale along the north–south line (figure 4*a*,*b*).

Combination of a crude sun-compass and a reduced sun shadow board could provide the Viking navigator with a small handheld instrument, allowing him to quickly and directly read deviation from a reference latitude (figure 4), while being as practical as the late-mediaeval backstaff. Simple trigonometric calculations reveal that the Uunartoq artefact with its scale of 0.9 mm divisions and a central gnomon is suitable for the reliable detection of a 0.1° change in the noon solar elevation, which translates to a 0.1° deviation from the desired latitude. As the nautical mile (1852 m) is a unit of length that is about 1 arc min (0.017°) of latitude measured along any meridian, theoretically the artefact is suitable for detecting deviation of even six nautical miles (about 11 km) from an intended route. Setting the height of the central gnomon before departure to obtain a cast shadow reaching the middle notch of the scale would allow the navigator to use the instrument on any Nordic route any time during the nautical season. Levelling such a small dial is not trivial on board a tumbling ship, but various sound methods were suggested by earlier studies; for example, the dial may be floated in a small vessel filled with water, or a longish weight may be attached to the grip while gently holding it with two fingers. The latter method was successfully tested with small sun-compasses on board small yachts and replicas of Viking ships [1].

Such a combination of a sun-compass and a sun shadow board is practical only as a nautical instrument. Travelling over rough terrain along given latitudes is hardly possible; an accurate compass would be more practical to find the way between landmarks. If used always at a single given latitude, the artefact might have functioned as a portable calendar, but a larger fixed instrument would have been much more practical for such a purpose. The incised sections of the gnomonic lines are insufficient for measuring time through the day; so the instrument is probably not a portable sundial. But the puzzling short daily operation period of the sun-compass part can be justified by the primary function of a sun shadow board. As the sun-compass function is meant only for identifying the noon period, operation at low solar elevation angles is irrelevant.

We conclude that cardinal directions are precisely marked in the instrument with line *e* and the series of notches *a*, although it was used for locating position, not for orientation. It is logical to assume that notches *a* and line *e* were first engraved through the centre, and then superficial lines of the construction lines were added. The functional gnomonic lines were emphasized by incising them two or three times. The irregular side scallop that was interpreted earlier as a compass rose might have been added as a last step, maybe as a decoration (figure 1*A*). Although the instrument had a constrained compass function, the navigator rather could maintain course by wind, waves and tracking cast shadows of ship parts [2].

(c) Geometrical construction of the sun-compass

Although the Uunartoq artefact seems to be a complicated navigational instrument using advanced astronomical knowledge, its empirical construction is not beyond the limits of people building ocean-going vessels. Yet, the most exciting remark of our study is the striking similarity of the scrapes on the dial fragment to the patterns of trigon-based construction of horizontal sundials. A complete construction procedure that would provide the lines seen on the artefact cannot be reconstructed, but conformity should not be ignored. Dialling was highly developed in ancient European cultures, and Vikings could possibly access such practical knowledge by trade connections, military service in southern countries or socializing with Christian proselytizers [9–11]. Sundials are not common among contemporary artefacts of the Viking era, and gnomonics is thought to be poorly understood in mediaeval North Europe. Few examples are to be found like the one in the wall of Saint Gregory's church in Kirkdale, North Yorkshire, UK, which was created by Christian priests in the mid-eleventh century on the order of a wealthy landowner of Viking origin [10]. It proves that sundials were constructed using more than purely empirical methods in the years of making the Uunartoq artefact, although the spread and level of this knowledge is questionable.

Theoretically, the latitude of use and marked dates of a sundial can be unambiguously extracted from the arrangement of lines on a sundial constructed geometrically. Unfortunately, the sundial artefact does not provide enough details; even the position of the gnomon must be deduced. Even presuming keen precision of the maker would give about 10° of bias in calculating the latitude of hour lines. However, it is highly conceivable that latitude 63.43° N was intended based on the slope of the supposed axe line. This latitude could easily be coded by the ratio of gnomon height and equinoctial noon shadow length of 1 : 2, a perfect start for a geometrical construction, which is easy to reproduce at a small size, even with crude tools. The resulting gnomonic lines would serve well on a sun-compass to be used at latitudes between the southern tip of Greenland and the northern tip of Iceland, the region roamed by Icelandic and Greenlandic sailors.

The strongest argument against empirical and that for geometrical construction of gnomonic lines is their premature termination well before the edge of the dial. It is an inevitable aftermath of geometrical construction, a serious flaw in the case of a dedicated sun-compass, but venial for a sundial. Several fundamental lines required in the construction procedure were not found on the artefact, but the complete construction pattern was not necessarily incised on the instrument. Lines could have been copied from a masterpiece incising only some cardinal points and indispensable reference lines. In fact, it is the most efficient method, if the figure is to be scaled down and/or several copies of the instrument are to be produced.

Conformity of the pattern of a trigon-based geometrical sundial construction and scratches of the eleventh century sundial artefact found in Greenland raise stirring questions. The first known Icelandic nautical table originates only from the twelfth century, while success of earlier Viking navigators is hardly conceivable without some limited scientific background. Did Vikings use special nautical sundials that were produced using sophisticated dial-construction methods? Were there trained people producing such instruments in the remote Greenland colony? Did Norse sailors use navigational instruments crafted by professionals, probably in several copies? Should it be verified by future archaeological evidence, it would be a stirring sign of active use of ancient astronomical knowledge in a remote eleventh century Viking colony, a clear sign of profound cultural connections between mediaeval Norse colonists of America and ancient European cultures.

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