Archaeoastronomy, no. 7 (*JHA*, xv (1984))

THE TWO MAJOR MEGALITHIC OBSERVATORIES IN SCOTLAND

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The methods given in this paper are as complete as we know how to make them. Many of the points are explained more fully in the references cited, and so these references must be used by the reader who wishes to follow closely as he goes through the present paper. A list of the symbols used is given at the end of this article.

We propose to justify by a slightly different approach some of our megalithic astronomical results, and will consider two of the larger sites, Brogar and Temple Wood. The initial data for each line are taken from our previous publications. These data we know are correct as we returned many times to the sites and fully checked the field work.

As shown in our publications before 1983 in which we describe our search for relevant declinations within each lunar band,[1] we determined the values of the nominal declinations mainly by trial and error, especially where Δ was involved, so that all the measured values finally gave roughly the same value of the obliquity ε. In this paper we have refined the method of determining the value of Δ so that the final approach is less empirical.

In the calculations the three angles involved are latitude, azimuth and observed altitude, these last corrected for mean lunar parallax and refraction adjusted for temperature difference from tabulated values. With these data the 'observed' declination of the notch δ_o and the hour angle measured from the meridian are evaluated. We are now able to apply to the hour angle the appropriate longitude of the Moon and of the Sun (see Figure 1) to obtain the hour of day H (measured from midnight) when the Moon was at the notch. Knowing H we can then choose the time of year (March, June, September or December) for best visibility of the Moon at the notch. The appropriate numerical value and the sign of the mean perturbation Δ can then be determined by referring again to Figure 1. Thereafter for each sight-line the combination of the numerical values of the terms

$$\pm (\varepsilon \pm i \pm s \pm \Delta)$$

yields the numerical value of the nominal declination closest to δ_o, the observed declination. The value for ε used at this stage is the average obtained in our 1980 analysis,[2] namely 23°53′.1. As we have the option of taking $\Delta = 0$ (see below, "Lines with no Δ"), nominal declination obtained by this approach will differ from δ_o by less than $\Delta/2$.

The different approach in determining Δ and s described above over-rides part of the empirical approach used on, for example, three lines in Table 10.1 of our *Megalithic remains in Britain and Brittany*,[3] where difficulty arose because $(s - \Delta)$ is near in numerical value to $+\Delta$, and $(-s + \Delta)$ is near to $-\Delta$. (The three lines involved were Hellia from *L*, Mid Hill from Comet Stone, and Ravie Hill from *HF* over *T*.) Dr Heggie discusses this point in his recent book.[4] We believe that the present method gives a better solution when such cases arise.

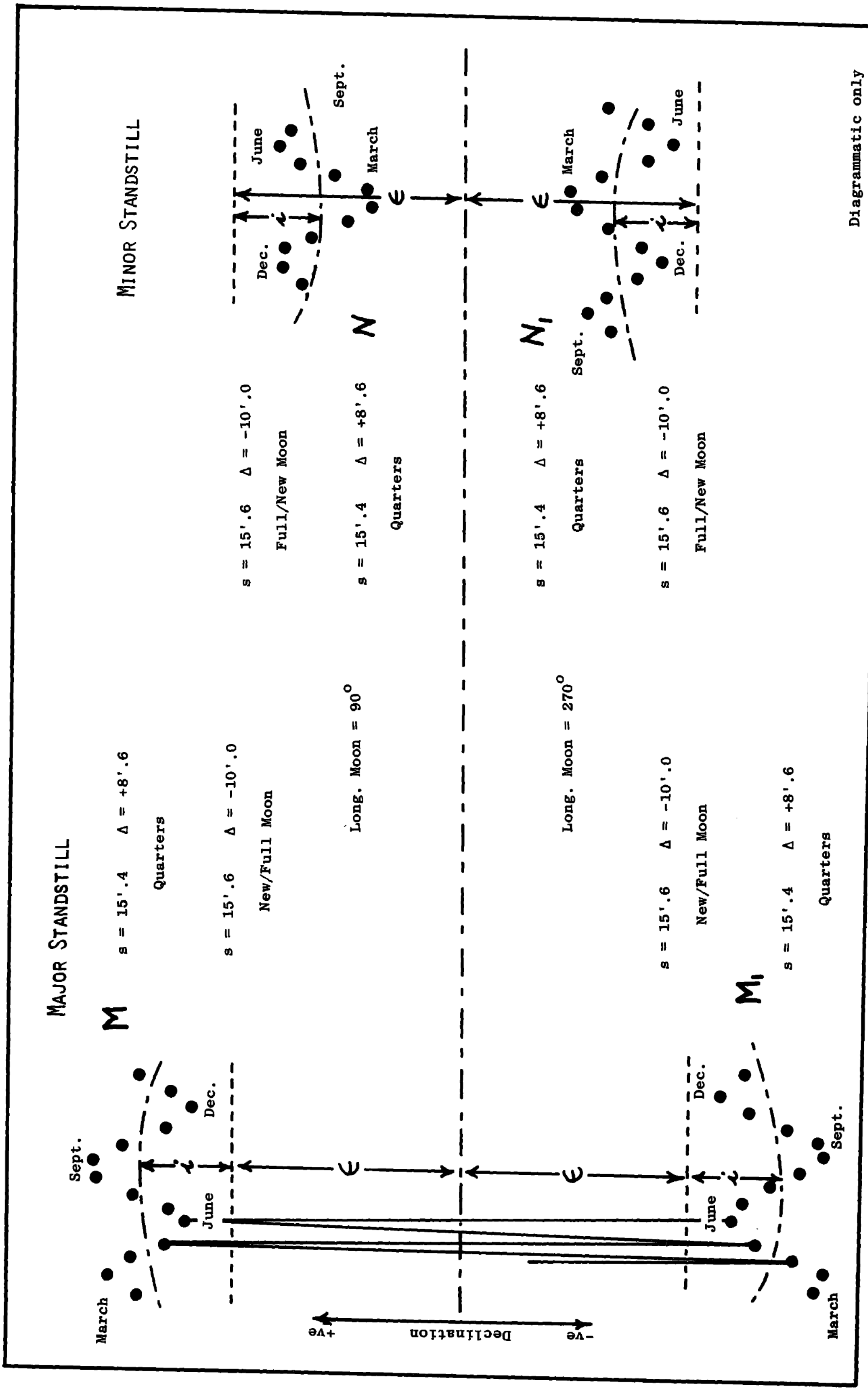

FIG. 1. Conditions at the standstills. Note that the Major and Minor Standstills are 9.3 years apart, and that Δ applies to *i*.

Brogar

To consider first the site in Orkney at Brogar (Figure 2), we believe that originally this ring was established as a general backsight for two main foresights, namely the cliffs at Hellia for the lower limb of the setting Moon and the notch on Mid Hill for the upper limb of the rising Moon.

The steady fall in the obliquity of the ecliptic meant that after several centuries' use the observers found that in order to retain the same two foresights, they had to move outside the ring; and so a number of new backsights were set up. Dating will be discussed later.

Perhaps the most important line is that from the Comet Stone to Mid Hill. A peculiar low ridge on the ground is found running away from the Comet Stone towards the north-west and south-east.

On Thomas's plan, made last century,[5] this ridge seems to form part of a cart track but an examination of the ground at the Comet Stone shows that it cannot have formed part of this track originally because the ridge runs through the low mound around the Comet Stone. We made a careful survey of the ground near the Comet Stone and found a definite ridge. Spot levels were taken on top of the ridge

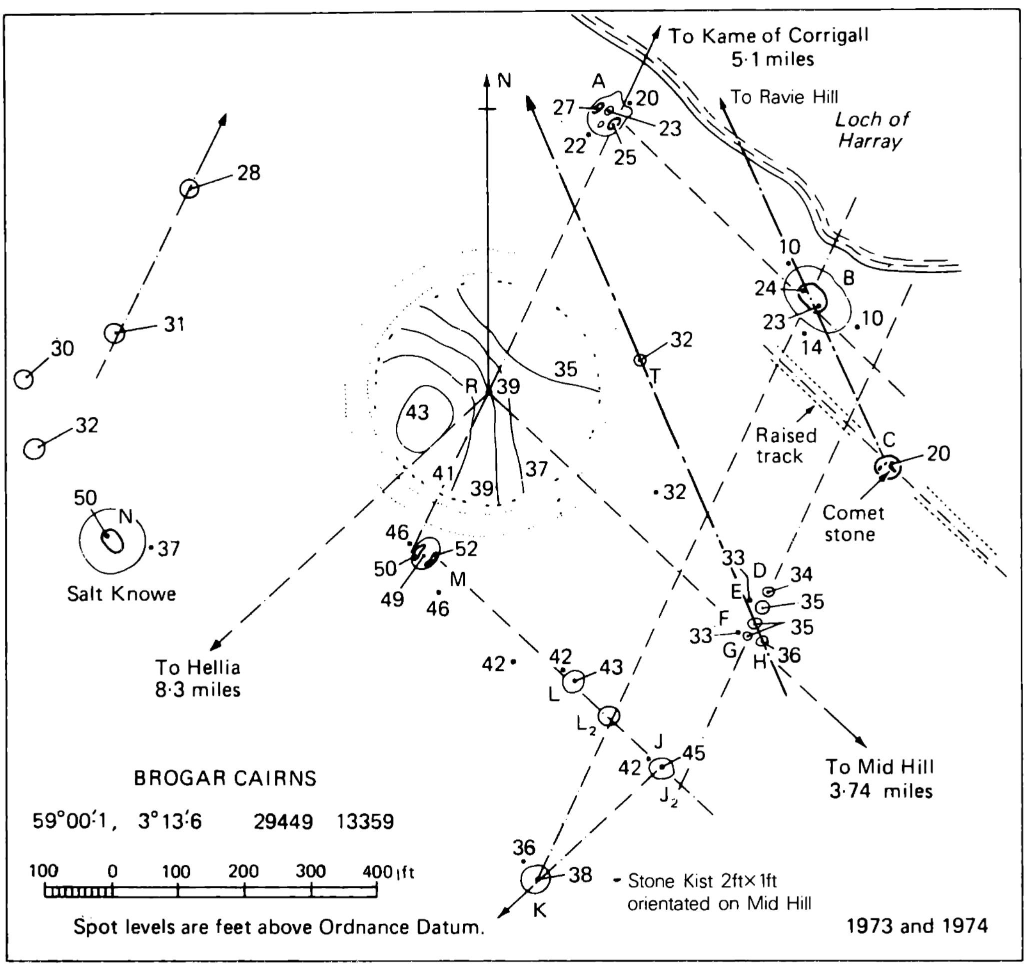

FIG. 2. Survey of the cairns and ring at Brogar. Ravie Hill is 8 miles away. (From A. Thom and A. S. Thom, *Megalithic remains in Britain and Brittany*, courtesy of Oxford University Press.)

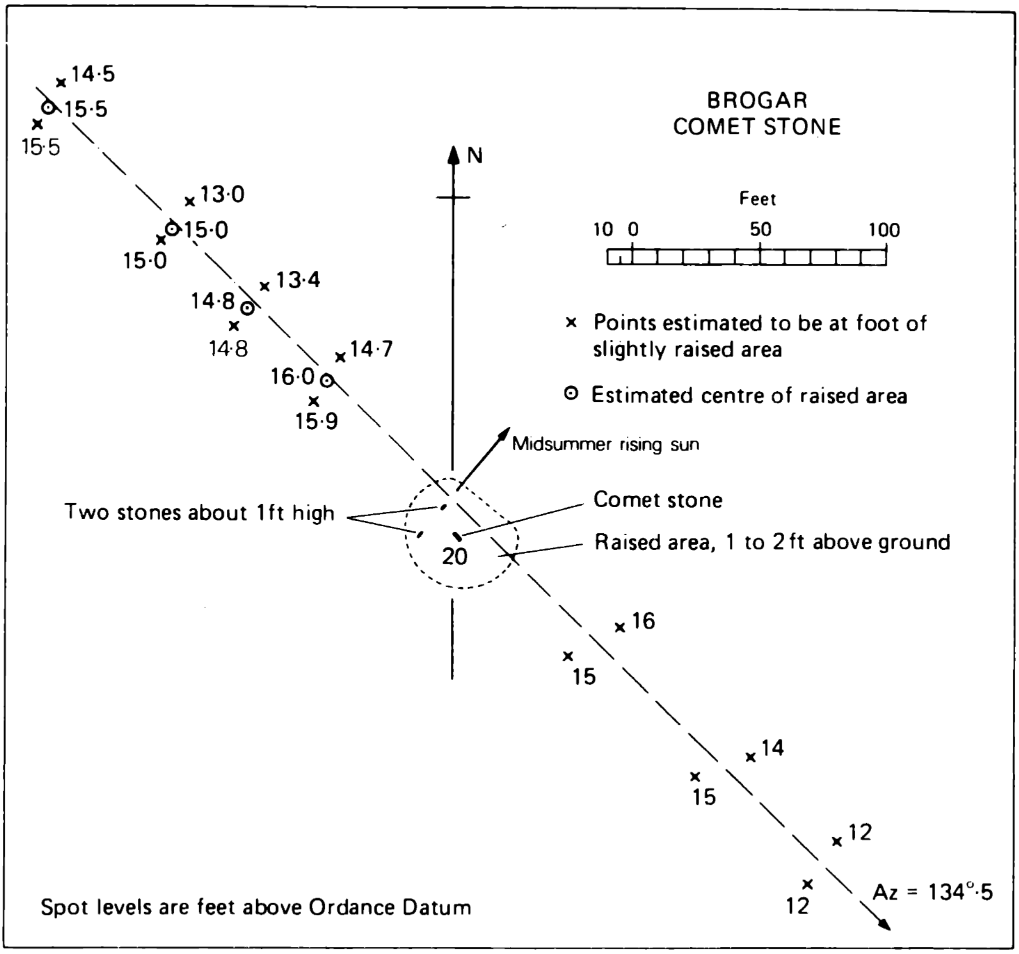

FIG. 3. The Comet Stone and raised ridge. (From A. Thom and A. S. Thom, *Megalithic remains in Britain and Brittany*, courtesy of Oxford University Press.)

and at the bottom of each side-slope. The survey is shown here in Figure 3. We found that the ridge centre-line passes close by the Comet Stone and points directly at the Mid Hill foresight;[6] in fact, in the same direction as the two sides of the Comet Stone slab. Thus this complex is undoubtedly a backsight for the excellent and unequivocal foresight on Mid Hill. Bear in mind that there is another very good natural foresight provided by the cliffs at Hellia for the Moon setting with about the same declination,[7] and it will be seen that the whole site was undoubtedly a large lunar observatory.

Accordingly, at Brogar and Temple Wood we decided to recalculate all the lines for which we have knowledge, using our latest information on methods (see below). We have already seen above that one of the backsights consists of a ridge running along the surface of the ground and passing close to the Comet Stone. The other backsights consist of mounds. We have been asked why megalithic man used this method instead of adhering to his usual practice of erecting stones. Who are we that we should decide what type of backsight he should use? Perhaps he intended to erect stones later as he did at the Comet Stone.

The backsights consist mainly of a row of four mounds or heaps, M, L, L_2 and J. This row itself points to Mid Hill but if we look across it either way from the top of the ridge on which it stands, we find that excellent viewing points exist for other foresights such as Hellia or Kame of Corrigal. A separate mound *K* lies to the south-west. We believe that the observer of Mid Hill from the row is meant to stand as far back in the row as possible, that is, on the ground at *M*. Thomas says that M was a "Large Tumulus–dilapidated"; presumably an assistant stood on the top of this to give a few seconds' warning to the man on the ground below, that the Moon's upper limb was about to appear.[8]

Temple Wood

To understand our continued interest in Temple Wood as a lunar observatory, the student is referred to our description of the site in *Megalithic lunar observatories.*[9] We point out here that the claimed lunar foresights are indicated by lines of stones or by an orientated stone.

Tables 1 and 2

We now proceed to explain Tables 1 and 2, column by column. The necessary mean numerical values of Δ (without sign), *s* (without sign), *p* and *i* required for the calculation will be found with Table 2; the sign of Δ and *s* has to be determined for each case. These mean values were obtained by L. V. Morrison.[10]

Column 1 gives the foresight;
column 2 gives the backsight;
column 3 gives the azimuth of the foresight from the backsight, determined carefully from the Sun with a good theodolite and a good watch;
column 4 is the observed altitude of the foresight;
column 5 is the temperature estimated for the month and the hour from the modern Kirkwall (Orkney) values;
column 6 is the astronomical refraction from Reid's *Nautical almanac* where it is tabulated for 50° F; here it is corrected for the estimated temperature;[11]
column 7 is the mean parallax of the Moon;
column 8 is the geocentric altitude obtained from columns 4, 6 and 7;
column 9 is the month or season;
column 10 is the hour of the day *H* (local mean time, see below).
column 11 gives times of sunrise or sunset.

Where there are alternative times we use the times which would give the best seeing conditions; for instance at Temple Wood, *A* from *Q*, we did not use September at $14^h\ 42^m$, as it would have been bright daylight.

Column 12 is declination δ_o of the foresight, calculated by using the spherical triangle formula

$$\sin \delta_o = \sin \varphi \sin h + \cos \varphi \cos h \cos A.$$

Column 13 gives the nearest nominal value, i.e. the combination of ε, *i*, *s* and Δ which gives the closest value to the declination δ_o. For the initial value of ε here we took 23°53′.1.[12] At the major and minor standstills in March and September, mean Δ was taken as 8′.6; in June and December, 10′.0.

Column 14 gives the obliquity of the ecliptic deduced from columns 12 and 13; for this we must know the difference between the declination δ_o and the obliquity of the ecliptic, and this difference we can now obtain, knowing the nominal value of the declination in terms of *i*, Δ and *s*. We calculate for equinoxes and solstices, March, June, September, and December, the time

TABLE 1. Brogar (latitude 59°0′.1).

1	2	3	4	5	6	7	8	9	10	11	12	13	14
Foresight	Backsight	Azimuth	Observed altitude	Temperature	Refraction	Mean parallax	Geocentric altitude	Month/ phase	Hour H	Sunrise or sunset	Declination δ_o	Nominal declination	Deduced obliquity ε_o
									h m	h m			
Hellia	*JK*	227°50′	65′.2	50°F	−23′.8	57′.4	1°38′.8	June/full	03 24	02 46	−18°43′.2	$-(\varepsilon - i)$	23°51′.9
Hellia	*JK*	227°50′	65′.2	50°F	−23′.8	56′.4	1°37′.8	Sept./1st qr	21 24	18 08	−18°44′.1	$-(\varepsilon - i)$	23°52′.8
Hellia	*L*	227°36′	64′.6	50°F	−23′.8	56′.4	1°37′.2	Sept./1st qr	21 24	18 08	−18°50′.3	$-(\varepsilon - i + s - \Delta)$	23°52′.2
Hellia	*M*(gr.level)	227°13′	65′	50°F	−23′.7	57′.4	1°38′.7	June/full	03 24	02 46	−18°58′.2	$-(\varepsilon - i + s)$	23°51′.3
Hellia	*M*(gr. level)	227°13′	65′	50°F	−23′.8	56′.4	1°37′.6	Sept./1st qr	21 24	18 08	−18°59′.2	$-(\varepsilon - i + s)$	23°52′.5
Mid Hill	Comet Stone	135°07′.8	128′.8	40°F	−18′.1	56′.4	2°47′.1	Mar./3rd qr	02 48	06 04	−18°50′.3	$-(\varepsilon - i + s - \Delta)$	23°52′.2
Mid Hill	*M*	133° 27′.8	120′.1	40°F	−18′.8	56′.4	2°37′.7	Mar./3rd qr	02 42	06 04	−18°20′.2	$-(\varepsilon - i - s - \Delta)$	23°52′.9
Ravie Hill	*HF* over *T*	336°47′	14′	50°F	−31′.6	57′.4	0°39′.8	June/full	22 18	21 16	28°53′.7	$\varepsilon + i - \Delta$	23°55′.0
Kame	*K*	24°10′	58′.2	50°F	−24′.5	56′.4	1°30′.0	Sept./3rd qr	21 54	18 08	29°29′.0	$\varepsilon + i + s + \Delta$	23°56′.3
Ravie Hill	Comet Stone over *B*	336°23′	15′	40°F	−32′.3	56′.4	0°39′.1	Mar./1st qr	04 12	06 04	28°47′.4	$\varepsilon + i - s$	23°54′.1
Ravie Hill	Comet Stone over *B*	336°23′	15′	50°F	−31′.4	57′.4	0°41′.0	June/full	22 12	21 16	28°49′.2	$\varepsilon + i - s$	23°56′.1

i = 5°08′.7

Equinox: Δ = 8′.6; mean parallax p = 56′.4; s = 15′.4

Solstice: Δ = 10′.0; mean parallax p = 57′.4; s = 15′.6

TABLE 1A. Brogar. (See Table 1 for columns 3 and 4.)

1	2	5	6	7	8	9	10	11	12	13	14
Foresight	Backsight	Temperature	Refraction	Mean parallax	Geocentric altitude	Month/phase	Hour H	Sunrise or sunset	Declination δ_o	Nominal declination	Deduced obliquity ε_o
							h m	h m			
Hellia	*JK*	40°F	-24′.4	61′.3	1°42′.1	Dec./full	12 24	15 02	-18°40′.2	$-(\varepsilon - i - s + \Delta)$	23°55′.2
Hellia	*L*	50°F	-23′.8	59′.1	1°39′.9	Sept./1st qr	21 24	18 08	-18°47′.8	$-(\varepsilon - i)$	23°56′.5
Hellia	*L*	50°F	-23′.8	61′.3	1°42′.1	June/full	03 24	02 46	-18°45′.8	$-(\varepsilon - i)$	23°54′.5
Hellia	*M* (ground level)	50°F	-23′.8	59′.1	1°40′.3	Sept./1st qr	21 24	18 08	-18°56′.7	$-(\varepsilon - i + s - \Delta)$	23°57′.9
Mid Hill	Comet Stone	40°F	-18′.1	59′.1	2°49′.8	Mar./3rd qr	02 48	06 04	-18°47′.9	$-(\varepsilon - i)$	23°56′.6
Mid Hill	Comet Stone	40°F	-18′.1	61′.3	2°52′.0	Dec./full	08 48	08 51	-18°45′.8	$-(\varepsilon - i)$	23°54′.5
Mid Hill	*M*	40°F	-18′.8	59′.1	2°40′.4	Mar./3rd qr	02 42	06 04	-18°17′.7	$-(\varepsilon - i - s - \Delta)$	23°53′.6
Ravie Hill	*HF* over *T*	40°F	-32′.6	59′.1	0°40′.5	Mar./1st qr	04 18	06 04	28°54′.4	$\varepsilon + i - s + \Delta$	23°53′.2
Kame	*K*	50°F	-24′.5	59′.1	1°32′.8	Sept./3rd qr	19 54	18 08	29°31′.7	$\varepsilon + i + s + \Delta$	23°58′.3
Ravie Hill	Comet Stone over *B*	50°F	-32′.3	59′.1	0°41′.8	Mar./1st qr	04 12	06 04	28°50′.0	$\varepsilon + i - s$	23°57′.4
Ravie Hill	Comet Stone over *B*	50°F	-31′.4	61′.3	0°44′.9	June/full	22 12	21 16	28°53′.0	$\varepsilon + i - s$	24°01′.0

i = 5°08′.7
Equinox: Δ = 8′.6; mean parallax $p = 59'.1$; $s = 16'.1$
Solstice: Δ = 10′.0; mean parallax $p = 61'.3$; $s = 16'.7$

TABLE 2. Temple Wood (latitude = 56°07′.3).

1	2	3	4	5	6	7	8	9	10	11	12	13	14
Foresight	Backsight	Azimuth	Observed altitude	Temperature	Refraction	Mean parallax	Geocentric altitude	Month/phase	Hour H	Sunrise or sunset	Declination δ_o	Nominal declination	Deduced obliquity ε_o
									h m	h m			
A	S_5S_4	317°52′.5	4°37′.2	40°F	−10′.8	56′.4	5°22′.8	Mar./1st qr	02 42	06 02	29°18′.3	$\varepsilon+i+s$	23°54′.2
	S_5S_4	317°52′.5	4°37′.2	40°F	−10′.8	57′.4	5°23′.8	Dec./full	20 42	15 27	29°19′.2	$\varepsilon+i+s$	23°54′.9
	S_1	316°59′	4°37′.7	40°F	−10′.8	56′.4	5°23′.3	Mar./1st qr	02 42	06 02	28°55′.8	$\varepsilon+i-s+\Delta$	23°53′.9
	Q	317°12′.6	4°37′.7	40°F	−10′.8	56′.4	5°23′.3	Mar./1st qr	02 42	06 02	29°01′.6	$\varepsilon+i$	23°52′.9
	Q	317°12′.6	4°37′.7	40°F	−10′.8	57′.4	5°24′.3	Dec./full	08 42	08 28	29°02′.5	$\varepsilon+i$	23°53′.8

i = 5°08′.7
Equinox: Δ = 8′.6; mean parallax p = 56′.4; s = 15′.4.
Solstice: Δ = 10′.0; mean parallax p = 57′.4; s = 15′.6.

TABLE 2A. Temple Wood. (See Table 2 for columns 3 and 4.)

1	2	5	6	7	8	9	10	11	12	13	14
Foresight	Backsight	Temperature	Refraction	Mean parallax	Geocentric altitude	Month/phase	Hour H	Sunrise or sunset	Declination δ_o	Nominal declination	Deduced obliquity ε_o
							h m	h m			
Temple Wood A	S_5S_4	40°F	−10′.8	59′.1	5°25′.5	Mar./1st qr	02 42	06 04	29°20′.7	$\varepsilon+i+s$	23°55′.9
Temple Wood A	S_5S_4	40°F	−10′.8	61′.3	5°27′.7	Dec./full	08 42	08 28	29°22′.7	$\varepsilon+i+s$	23°57′.3
Temple Wood A	S_1	40°F	−10′.8	59′.1	5°26′.0	Mar./1st qr	02 42	06 04	28°58′.2	$\varepsilon+i-s+\Delta$	23°57′.0
Temple Wood A	Q	40°F	−10′.8	59′.1	5°26′.0	Mar./1st qr	02 42	06 04	29°04′.1	$\varepsilon+i$	23°55′.4
Temple Wood A	Q	40°F	−10′.8	61′.3	5°28′.2	Dec./full	08 42	08 28	29°06′.0	$\varepsilon+i$	23°57′.3

i = 5°08′.7
Equinox: Δ = 8′.6; mean parallax p = 59′.1; s = 16′.1
Solstice: Δ = 10′.0; mean parallax p = 61′.3; s = 16′.7

of day (the hour H) when the Moon was on the foresight. Preferably this should happen in darkness but for the lower limb of the June full Moon setting over Hellia cliffs and for the December full Moon setting at Temple Wood we made exceptions because of the large horizon altitude (see below). Having found suitable months we can determine the relevant mean lunar perturbation Δ by studying Figure 1.

Collected values of the obliquity ε_o are given in Tables 3 and 4.

Typical Examples

Typical examples of part of the calculation are given in Tables 7 and 8. Here the calculation of the geocentric altitude is straightforward. It is obtained by adding together the observed altitude, the total refraction (negative) and the relevant mean parallax. The hour angle (H.A.) is then calculated by spherical trigonometry using the azimuth A, the latitude φ and the geocentric altitude h;

$$\cot \text{H.A.} = (\cos\varphi \tan h - \sin\varphi \cos A)/\sin A.$$

We then add the longitude of the Moon and subtract the longitude of the Sun, Figure 1. We convert the angle thus obtained to time in order to obtain the hour of the day (H) from midnight (local mean time). Knowing the time of sunrise and sunset (*Nautical almanac*) we can decide if the Moon was on the horizon in darkness or in daylight. In general we use only the cases when we consider the Moon would be visible and for them we then calculate the declination from known azimuth and geocentric altitude. The declination is then increased or decreased by i (5°08′.7). The value obtained must then be decreased or increased by Δ (see Figure 1). Finally we apply the appropriate semi-diameter, s, and so obtain the value of the obliquity ε_o, Tables 7 and 8.

Several cases have no Δ in the nominal value for declination and for these it is correct to take the mean of a solstitial and an equinoctial value (see Figure 1). An adjustment of 0′.7 is necessary for these evaluations of obliquity, see below.

We are assuming throughout this paper that the erectors extrapolated by some means or another in order to obtain backsight positions between successive moonrises or moonsets on the foresights, to indicate occurrence of maximum or minimum lunar azimuth.

The Correction c

At the top left-hand side of Figure 1 it is seen how the chain-dotted curve of declination falls below its highest point at ($\varepsilon + i$). Any one recorded observation of maximum lunar declination will in general thus be too low. We allow for this by applying a *mean* correction c of 0′.3. We must allow for the fact that the curve joining the large black dots (the monthly lunar declination maxima) demands a similar correction. It so happens that this correction is also 0′.3, as we have described elsewhere.[13] (The values for the various cases will be found in Table 5.) We can give only a mean value of c to apply each time. In the evaluation of ε_{os} and ε_{on}, these mean values of c, given in Table 5, are re-used in Tables 3 and 4, column 6 and applied in column 7.

TABLE 3. Brogar and Temple Wood: collected values of the obliquity of the ecliptic using the south declination.

1	2	3	4	5	6	7	8	9	10
Foresight	Backsight	Month	Nominal declination	Deduced obliquity ε_o	c	$\varepsilon_o + c$	$-0'.7$ correction when $\Delta = 0$	ε_{os} (mean of 5)	Residual R
				23°	′	23°	23°	23°	
Hellia	*JK*	June	$-(\varepsilon - i)$	51′.9	0	51′.9			
						52′.35	51′.65		0.74
Hellia	*JK*	Sept.	$-(\varepsilon - i)$	52′.8	0	52′.8			
Hellia	*L*	Sept.	$-(\varepsilon - i + s - \Delta)$	52′.2	+ 0.3 + 0.3 = 0.6	52′.8	52′.8		0.41
								52′.39	
Hellia	*M*	June	$-(\varepsilon - i + s)$	51′.3	0	51′.3			
						51′.9	51′.2		1.19
Hellia	*M*	Sept.	$-(\varepsilon - i + s)$	52′.5	0	52′.5			
Mid Hill	Comet Stone	March	$-(\varepsilon - i + s - \Delta)$	52′.2	+ 0.3 + 0.3 = 0.6	52′.8	52′.8		0.41
Mid Hill	*M*	March	$-(\varepsilon - i - s - \Delta)$	52′.9	+ 0.3 + 0.3 = 0.6	53′.5	53′.5		1.11
									r.m.s. 0.84

TABLE 3A. Brogar and Temple Wood: collected values of the obliquity of the ecliptic using the south declination.

1	2	3	4	5	6	7	8	9	10
Foresight	Backsight	Month	Nominal declination	Deduced obliquity ε_o	c	$\varepsilon_o + c$	$-0'.7$ correction when $\Delta = 0$	ε_{os} (mean of 5)	Residual R
				23°		23°	23°	23°	
Hellia	*JK*	Dec.	$-(\varepsilon - i - s + \Delta)$	55′.2	0	55′.2	55′.2		0.3
Hellia	*L*	Sept.	$-(\varepsilon - i)$	56′.5	$+0.3 - 0.3 = 0.0$	56′.5			
						55′.5	54′.8		0.7
Hellia	*L*	June	$-(\varepsilon - i)$	54′.5	0	54′.5			
Hellia	*M*	Sept.	$-(\varepsilon - i + s - \Delta)$	57′.9	$+0.3 + 0.3 = 0.6$	58′.5	58′.5		3.0
								55′.5	
Mid Hill	Comet Stone	Mar.	$-(\varepsilon - i)$	56′.6	$+0.3 - 0.3 = 0.0$	56′.6			
						55′.55	54′.85		0.65
Mid Hill	Comet Stone	Dec.	$-(\varepsilon - i)$	54′.5	0	54′.5			
Mid Hill	*M*	Mar.	$-(\varepsilon - i - s - \Delta)$	53′.6	$+0.3 + 0.3 = 0.6$	54′.2	54′.2		1.3
									r.m.s. 1.53

TABLE 4. Brogar and Temple Wood: collected values of the obliquity of the ecliptic using the north declination.

1	2	3	4	5	6	7	8	9	10
Foresight	Backsight	Month	Nominal declination	Deduced obliquity ε_o	c	$\varepsilon_o + c$	+ 0′.7 correction when $\Delta = o$	ε on (mean of 6)	Residual R
				23°	′	23°	23°	23°	
Ravie Hill	Comet Stone over B	June	$\varepsilon + i - s$	56′.1	0	56′.1			
						55′.1	55′.8		0.55
Ravie Hill	Comet Stone over B	March	$\varepsilon + i - s$	54′.1	0	54′.1			
Ravie Hill	HF over T	June	$\varepsilon + i - \Delta$	55′.0	+ 0.3 - 0.3 = 0.0	55′.0	55′.0		0.25
Kame	K	Sept.	$\varepsilon + i + s + \Delta$	56′.3	+ 0.3 + 0.3 = 0.6	56′.9	56′.9		1.65
								55′.25	
Temple Wood A	S_5S_4	March	$\varepsilon + i + s$	54′.2	0	54′.2			
						54′.55	55′.25		0.00
Temple Wood A	S_5S_4	Dec.	$\varepsilon + i + s$	54′.9	0	54′.9			
Temple Wood A	S_1	March	$\varepsilon + i - s + \Delta$	53′.9	+ 0.3 + 0.3 = 0.6	54′.5	54′.5		0.75
Temple Wood A	Q	March	$\varepsilon + i$	52′.9	0	52′.9			
						53′.35	54′.05		1.20
Temple Wood A	Q	Dec.	$\varepsilon + i$	53′.8	0	53′.8			
									r.m.s. 0.92

TABLE 4A. Brogar and Temple Wood: collected values of the obliquity of the ecliptic using the north declination.

1	2	3	4	5	6	7	8	9	10
Foresight	Backsight	Month	Nominal declination	Deduced obliquity ε_o	c	$\varepsilon_o + c$	+0′.7 correction when $\Delta = 0$	ε_{on} (mean of 6)	Residual R
				23°		23°	23°	23°	
Ravie Hill	Comet Stone over *B*	June	$\varepsilon + i - s$	61′.0	0	61′.0			
						59′.2	59′.9		2.5
Ravie Hill	Comet Stone over *B*	Mar.	$\varepsilon + i - s$	57′.4	0	57′.4			
Ravie Hill	*HF* over *T*	Mar.	$\varepsilon + i - s + \Delta$	53′.2	0.6	53′.8	53′.8		3.6
Kame	*K*	Sept.	$\varepsilon + i + s + \Delta$	58′.3	0.6	58′.9	58′.9		1.5
								57′.4	
Temple Wood *A*	S_5S_4	Mar.	$\varepsilon + i + s$	55′.9	0	55′.9			
						56′.6	57′.3		0.1
Temple Wood *A*	S_5S_4	Dec.	$\varepsilon + i + s$	57′.3	0	57′.3			
Temple Wood *A*	S_1	Mar.	$\varepsilon + i - s + \Delta$	57′.0	0.6	57′.6	57′.6		0.2
Temple Wood *A*	*Q*	Mar.	$\varepsilon + i$	55′.4	0	55′.4			
						56′.35	57′.1		0.3
Temple Wood *A*	*Q*	Mar.	$\varepsilon + i$	57′.3	0	57′.3			
									r.m.s. 1.9

TABLE 5. Correction c to apply to observed declination δ_o.

	Minutes		
$+(\varepsilon+i+\Delta)$	$+0.3+0.3$	=	$+0.6$
$+(\varepsilon+i-\Delta)$	$+0.3-0.3$	=	0.0
$-(\varepsilon+i+\Delta)$	$-0.3-0.3$	=	-0.6
$-(\varepsilon+i-\Delta)$	$-0.3+0.3$	=	0.0
$-(\varepsilon-i-\Delta)$	$+0.3+0.3$	=	$+0.6$
$-(\varepsilon-i+\Delta)$	$+0.3-0.3$	=	0.0
$+(\varepsilon-i+\Delta)$	$-0.3+0.3$	=	0.0
$+(\varepsilon-i-\Delta)$	$-0.3-0.3$	=	-0.6

When there is no Δ the sum total of the c corrections is zero.

Lines with No Semi-diameter s

In three lines, Hellia from *JK*, Ravie Hill from *HF* over *T* and Temple Wood *A* from *Q*, semi-diameter *s* is not involved. We imply that at each observation the azimuth of the centre of the Moon's orb was recorded. For this, two observers were needed, one recording the upper limb, the other the lower limb. Space exists on the ground for such observations at the listed nominal declinations; at each site the mean position on a line joining the two points records the Moon's centre. Obviously no seasonal semi-diameter adjustment ($s = 15'.4$ or $15'.6$) is required in such cases.

Adjustment for Lines with No Perturbation Δ

For analysing lines with no Δ, since this implies averaging observed maxima or minima at March and June, or June and September, or December and March (see Figure 1), we apply an allowance of 0′.7 for difference in mean Δ (8′.6 and 10′.0), see column 8, Tables 3 and 4. For Temple Wood *A* from *Q*, the sample calculation of ε_o for insertion in Table 2 is shown in Table 8.

Tables 3 and 4

In Table 3 we show the calculated discrepancies, or residuals, *R* (column 10), from the mean value ε_{os} (namely 23° 52′.4) together with their root mean square, 0′.8, and in Table 4 we show the discrepancies from the mean value ε_{on} of 23° 55′.25 together with their root mean square (r.m.s.) 0′.9. The average of the two means is 23° 53′.8. ε had this value about 1700 B.C.

It will be seen that all the discrepancies *R* are small and that the overall r.m.s. (see Table 6) is 0′.9. This is very much lower than any of the individual values of Δ and *s* and is the best possible indication that we are on the right lines. The largest discrepancy is that for Kame of Corrigal from *K*. We have shown in a recent paper[14] that the r.m.s. of the discrepancies *R* for 42 lines in Great Britain is either 1′.34 or 1′.53. When now, however, we select the 11 lines which belong to Brogar and Temple Wood observatories, then the r.m.s. *R* reduces to 0′.89.

We examined the foresight at Kame of Corrigal and found that much alteration has taken place on the ground here. Was this an attempt by megalithic man to alter the foresight?

TABLE 6. Collected results from Tables 3 and 4.

	Number of lines	r.m.s. R
South declination	5	0′.84
North declination	6	0′.92
South and north declination together	11	0′.89
North declination without Kame	5	0′.69
South and north declination without Kame	10	0′.77

Graze = $\frac{1}{2}(\varepsilon_{os} - \varepsilon_{on})$ for south and north declination together = −1′.43

Graze = $\frac{1}{2}(\varepsilon_{os} - \varepsilon_{on})$ for south and north declination together, without Kame = −1′.26

Mean obliquity = $\frac{1}{2}(\varepsilon_{on} + \varepsilon_{os})$, for south and north declination together = 23°53′.8

Mean obliquity = $\frac{1}{2}(\varepsilon_{on} + \varepsilon_{os})$, for south and north declination together, without Kame = 23°53′.7

If we remove the Kame line, the overall r.m.s. R for the remaining 10 lines (see Table 6) becomes 0′.77, the mean ε becomes 23°53′.7 and this indicates a date about 1690 B.C.

Probably a considerable part of the r.m.s. R is unavoidable, since we do not know how far away in time any one observation was from the standstill ($\varepsilon \pm i$) and so we can never know the real correction for curvature, c. We have used a time mean value of $c = 0'.3$ but the actual value may in some cases be as large as 1′.0.[15] It should be borne in mind that when we apply the correction for curvature, c, we can only use a mean value and the actual value might be very much larger than 0′.3, and so it is quite surprising to find the overall r.m.s. value of R as low as 0′.89 (or 0′.77 without Kame). There can be no doubt that the erectors took particular care with the two lunar observatories, but since these were probably not erected at the same time the actual value of ε varied, introducing a possibility of error in our conclusions.

As explained above, the success of the whole operation is indicated by the small size of the final residuals. Serious critics of this paper will need to show where we have gone wrong in calculating these residuals. The value we obtained above for the overall r.m.s. R, namely 0′.89, is much lower than any mean value we have obtained previously.

It seems to us that the only method of explaining the low values of the residuals is to assume that all these backsights were erected during a stretch of time. The present results indicate that the date was near the middle of the second millenium.

Graze

This is the amount by which the observed altitude is altered due to the beginning of an incoming ray of light over any intermediate ridge or over the foresight itself. It increases numerically the known effect of refraction. The bending is produced by the variation with height in the density of the air close to the ridge (difference between ground temperature and air temperature assumed to take effect between one hour before sunset and one hour after sunrise). No allowance needs to be made for graze in these calculations. As we explain below, the mean graze can be evaluated when the obliquity ε_o is obtained from observations of north and south declinations.

For the latitude φ of Brogar, and for the relevant declination δ, and for altitude *h* nearly zero, $d\delta/dh \cong \sin\varphi/\cos\delta = 0.9$.[16] Similarly for Temple Wood, $d\delta/dh = 0.95$. We can therefore afford to omit $d\delta/dh$ or its reciprocal while investigating the graze amounting to between 1′ and 2′ change in refraction. For the present purposes we can think of graze and declination change as numerically the same.

Empirically,[17] graze is given by $\frac{1}{2}(\varepsilon_{os}-\varepsilon_{on})$, where negative and positive declinations are involved. An increase in altitude numerically raises north declinations but lowers south declinations. Since the value of ε_o depends on the numerical value of the declination it is evident that the mean ε_o will not be affected by errors in altitude provided the errors are always of the same sign. The difference between the two values of ε_o is twice the error in altitude. Since graze leads to an error in altitude, this allows the mean graze to be determined.

The overall graze has a value of $\frac{1}{2}(23°52'.4 - 23°55'.25) = -1'.4$. When Kame is omitted (see Table 6), graze is $-1'.3$. These values agree with the values we have obtained in other investigations. Worked out in this way, the small angle obtained will also eliminate any error in mean obliquity introduced by not allowing for the segment of the Moon's limb which had to show above the horizon before it could be recorded by the observers.

The justification for our present hypothesis is that the residuals are small compared with the values of s and Δ that were used to build up the final value of the obliquity (Tables 1 and 2, column 13).

The obliquity had the value of 23°53′.8 about 1700 B.C., a date similar to those obtained by us in other investigations, namely 1750 B.C. ± 100 years by solar dating,[18] and 1657 B.C. ± 54 by lunar dating.[19]

Attempt to Date the Ring

We have attempted to find the date of construction of the main circle. The contours showing the surface inside of the ring indicate that the ground is not level. Why was a more level site not chosen? Was it perhaps because from the site it is possible to see two usable foresights? We suggest that the other two were found later to be suitable, as the knowledge and experience of the erectors developed.

The site allows an observer ample area upon which to move about and establish backsights.

In general, given two natural foresights, a position can be found for a backsight from which the foresight can be used to show the setting or rising points of two celestial bodies.[20] Consider observing the Sun setting behind the top of a hill. The locus of all points from which one can see the phenomenon is a line across country. Suppose there is another hill and another body; then there will be another cross-country line. A backsight can be placed where the lines cross and this will serve both foresights, but it will be only by chance that this backsight can serve for a third foresight. Apparently the Ring of Brogar is in such a position that the required backsights for four foresights could be placed in its immediate neighbourhood.

Our hypothesis is that the site was chosen initially because of the suitability of Mid Hill for observing the minor lunar standstill using the upper limb of the rising waning quarter Moon. Hellia cliffs were also suitable for the minor standstill using the lower limb of the setting full or nearly full Moon.

Several small stones exist inside of the ring.[21] No surface evidence exists at the centre R but we performed the necessary calculations and give them here, using the centre R with its known position and level. Calculations indicate the declinations of Mid Hill and Hellia to be (for mean $p = 56'.9$) respectively $-18°33'$ and $-19°06'$. By trial and error, for mean $s = 15'.5$ and zero Δ, these two declinations yield respectively $\varepsilon_o = 23°57'.2$ and $\varepsilon_o = 23°59'.2$; the mean ε_o shows a date of about 2400 B.C., which might be acceptable. We record this calculation but do not weight it at all, since we have no evidence of a backsight position other than assumption of ring centre.

Lines with No Δ

In five cases we take observations of $(\varepsilon \pm i \pm s)$ at different months along the same sightline as being independent for evaluation of ε_o, see column 14 in Tables 1 and 2; and in the statistical treatment, Tables 3 and 4, we take the means of each pair, column 7 in Tables 3 and 4. The assumption is that when the erectors wished to mark $\varepsilon \pm i$, they observed at solstice and equinox (when Δ has opposite sign) and marked the mean position. Different hours of day and seasons result in different temperature and so different refraction. Parallax is also different, but the adjustment of 0'.7 for variation of Δ is made in Tables 3 and 4 before the final statistical treatment.

Moonrise and Moonset on the Same Lunar Day at Brogar

For the June full Moon setting over Hellia from *JK* (see Table 1), because of the high altitude of this foresight, we used the Moon setting after sunrise, believing it would be clearly visible. It is worthy of note that at a March minor standstill, the

TABLE 7. Typical calculation. Brogar: Hellia from *L*. Latitude $\varphi = 59°00'06''$.

	March	June	September	December
Azimuth	227°36'	227°36'	227°36'	227°36'
Altitude	64'.6	64'.6	64'.6	64'.6
Temperature	40°	50°	50°	40°
Refraction	-24'.5	-23'.8	-23'.8	-24'.5
Mean parallax	56'.4	57'.4	56'.4	57'.4
Geocentric altitude	1°36'.5	1°38'.2	1°37'.2	1°37'.5
Hour angle H.A.	231°	231°	231°	231°
Longitude of Moon	-90°	-90°	-90°	-90°
Add	141°	141°	141°	141°
Longitude of Sun	0°	90°	180°	270°
Subtract	141°	51°	321°	231°
Hour *H*	9.4	3.4	21.4	15.4
	daylight	daylight	dark	dark
Declination δ_o	-18°51'.2		-18°50'.3	-18°50'.0
i	5°08'.7		5°08'.7	5°08'.7
	23°59'.9		23°59'.0	23°58'.7
Δ	8'.6		8'.6	10'.0
	24°08'.5		24°07'.6	23°48'.7
s	15'.4		15'.4	15'.6
Obliquity ε_o	23°53'.1		23°52'.2	24°04'.3
Nominal declination	$-(\varepsilon - i + s - \Delta)$		$-(\varepsilon - i + s - \Delta)$	$-(\varepsilon - i - s + \Delta)$

observer, by using the appropriate backsight and the third quarter Moon's lower limb, sees the declination of the rising Moon on Mid Hill to be almost the same as that of the same March Moon setting over Hellia. We suggest that the observations could have been made over Mid Hill from the Comet Stone in March in the dark at 02^h48^m and in daylight next morning over Hellia from *L* at 09^h24^m (see typical calculation Table 7). This latter observation we believe to be possible in daylight when using the lower limb of the quarter Moon and not the upper limb. Because this moonset occurred in broad daylight, it was not used in the main analysis, Table 1; the September moonset was used there. The calculations for this daylight setting of the Moon are shown in Table 7, yielding $\varepsilon_o = 23°53'.1$ for comparison with $\varepsilon_o = 23°52'.2$. The notched Hellia horizon sloping in the direction of the Moon's path and silhouetted by the lower limb of the Moon at its altitude of 1°06′ should be sufficiently visible in daylight for use of the full and quarter Moon. Could ritualistic practices have taken place during the 6^h36^m 'lunar day' while the observers watched the Moon rise, pass over the southern sky, and set? Our calculations indicate that the minor standstill occurred during this particular lunar day.

Discussion

(a) What is the effect of our not using maximum lunar parallax? Some people may be of the opinion that, since we assume extrapolation to have been done for each observation, we have been wrong not to use maximum lunar parallax at equinoxes (59′.1) and at solstices (61′.3) for major and minor standstills, along with the relevant correct semidiameters $s = 16'.1$ and $16'.7$. With these figures in mind we calculated each obliquity again, beginning from latitude, observed azimuth and altitude. In six cases new nominal declinations had to be chosen, to give the values nearest to the observed declinations altered because of the different values adopted for parallax. Different months of observation had to be considered, involving changed temperature and refraction adjustment. The results are tabulated in Tables 1A, 2A, 3A and 4A, where it will be seen that the average ε_{os} is 23°55′.5 and the average ε_{on} is 23°57′.4. Graze angle amounts to −1′.0 and the mean of ε_{os} and ε_{on} is 23°56′.4, which gives a date of about 2125 B.C. As seen in columns 10, Tables 3A and 4A, the residuals and the relevant r.m.s. values are well above the amounts which we are prepared to accept. It would appear to us to be unacceptable to adopt this solution and much better to accept the first one expounded in this paper, namely to use mean parallax of 56′.4 at equinoxes and 57′.4 at solstices.

We have come to the conclusion that the sight lines at each site were almost certainly erected to show mean values over a long period of years, unlikely to be less than 93 years. The Moon's parallax variation is discussed in *Megalithic lunar observatories*.[22]

(b) We are aware that Dr D. C. Heggie and Dr C. L. N. Ruggles do not agree with our method of employing the observed declination (δ_o) within the lunar bands, as described in *Megalithic lunar observatories*[23] and in this paper. Here we simply agree to disagree. We claim that Brogar and Temple Wood (and the other 30 or so lunar sites) are lunar observatories. We have applied all the corrections about which we know, and report the findings here. Not many more lunar sites are being reported — at least one writer we know is being put off by adverse criticism, and so

TABLE 8. Typical calculation. Temple Wood: *A* from *Q*.

	March	June	September	December
Azimuth	317°12′.6	317°12′.6	317°12′.6	317°12′.6
Altitude	4°37′.7	4°37′.7	4°37′.7	4°37′.7
Temperature	40°	50°	50°	40°
Refraction tabulated	-10′.5			10′.5
Refraction correction	-0.3			-0.3
Refraction	-10′.8			10′.8
Mean parallax	56′.4			57′.4
Geocentric altitude	5°23′.3			5°24′.3
Hour angle H.A.	310°	310°	310°	310°
Longitude of Moon	90°	90°	90°	90°
Add	40°	40°	40°	40°
Longitude of Sun	0	90°	180°	270°
Subtract	40°	310°	220°	130°
Hour *H*	2.7	20.7	14.7	8.7
	dark	daylight	daylight	14 mins after sunrise
Declination δ_o	29°01′.6			29°02′.5
i	5°08′.7			5°08′.7
Obliquity ε	23°52′.9			23°53′.8

statistical analysis can go no further at present. The sites exist, however, and each one poses the question: Why were they built? We put forward our hypothesis for all to consider, namely that the builders were observing and recording the Moon's movement and attempting to predict eclipses.[24]

Taking an extremely negative approach, we say: let a similar but fictitious site be chosen anywhere in the country in a position with foresights all round. Thereafter let an analysis be made using our approach. If histograms of δ_o can be produced which repeat our findings within the lunar bands, with small residuals and consistent dates that fit the solar dating already done, then and only then will we be convinced that our hypothesis should be changed.

Conclusion

By separating out the 8 Brogar and 3 Temple Wood lines from the other observing sites we show how carefully these two observatories were constructed. Recalculations have been made for the obliquity of the ecliptic obtained from each of the lines of these two major lunar observatories in Scotland. We found that the overall r.m.s. of the residual errors was smaller than we had ever obtained before and that the mean date, about 1700 B.C., was still similar to dates we had previously obtained from solar and lunar alignments.

Acknowledgements

We wish to thank Mr L. V. Morrison for carefully going over an early draft of the paper and pointing out one or two discrepancies, as well as making some helpful suggestions, and Dr D. C. Heggie, who read over an early version of the paper and gave helpful advice. We are also indebted to Mrs H. M. Gustin who assisted with the calculations.

List of Symbols

A	azimuth
c	curvature correction
δ	declination
δ_o	declination, calculated from observations
Δ	perturbation of lunar orbit
ε	obliquity of ecliptic
ε_o	obliquity of ecliptic, calculated from observations
ε_{on}	mean ε_o from all north declinations (δ_o)
ε_{os}	mean ε_o from all south declinations (δ_o)
φ	latitude
h	geocentric altitude
H	hour of day, measured from midnight, when Moon is at the notch
H.A.	hour angle
i	inclination of lunar orbit
R	residual, namely $\varepsilon_o + c - \varepsilon_{os}$ (or ε_{on})
s	lunar semidiameter

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