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RESEARCH ARTICLE

An Analysis of the Alignment of Archaeological Sites

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Abstract—There are hundreds, perhaps thousands, of sites of archaeological importance throughout the world. In this study, the alignments of more than two hundred ancient sites were measured and analyzed. Sites are organized into eight geographic regions: South America, Mesoamerica, North America, Europe, the Middle East, Africa, Asia, and the Pacific Ocean. Google Earth imagery and measurement tools were used to estimate the alignment of linear and rectilinear structures at these sites with respect to true (geographic) north. In considering standard celestial and geographic reasons for the alignments, many were found to be oriented to the cardinal directions, in the directions of solstices and other solar events, to lunar standstills, and to certain stars. A number of sites in China and Thailand were likely aligned to magnetic north at the time of construction using a compass. Some sites appear to have been aligned to "sacred directions" that include Islamic qibla and Quechua *ceques*. Site-alignment statistics reveal similarities and differences between geographical regions in terms of how sites within regions are aligned. Perhaps the most unexpected finding is that the alignment of about half of the sites could not be explained in terms of any of the explanations considered.

Keywords: archaeoastronomy; solstices; archaelogical alignment; sacred places; sacred directions; lunar standstills

INTRODUCTION

Evidence throughout the world suggests that human civilizations have a tendency to build their cities, and sacred and other places of importance, in specific directions. Many of the oldest pyramids and temples are aligned to the cardinal directions—north, south, east, and

west, sometimes with uncanny precision, such as the pyramids on the Giza plateau in Egypt (Lehner, 1997). The Angkor temples in Thailand (Magli, 2016) and certain earthen mounds in China also are aligned to the cardinal directions, as were early Chinese cities (Sparavigna, 2013). Although the cardinal directions can be determined readily from the motion of the sun and stars, there is evidence that the Chinese used the magnetic compass in some cases to align places of importance based on principles of geomancy and Feng Shui (Charvátová et al. 2011).

There are many places that are aligned to the cycles of the sun and moon, specifically to the northernmost and southernmost rising and setting of the sun and moon, called solstices and lunar standstills, respectively. Stonehenge is aligned both to solstices and to lunar standstills (Hawkins, 1965). Some Egyptian temples, most notably the Temple of Amun-Re at Karnak, are aligned to the winter solstice sunrise/summer solstice sunset (Shaltout & Belmonte, 2005). The head of the Great Serpent Mound in Ohio points toward the summer solstice sunset (Hardman & Hardman, 1987). Some of the most sacred places on earth are aligned to the moon, including the Kaaba in Mecca (Hawkins & King, 1982) and the Golden Temple in Amritsar.

There is evidence that some sites may have been aligned to the point on the horizon where certain stars and planets of importance once rose. Examples include the ancient city of Teotihuacan, north of Mexico City, thought to be aligned to the Pleiades (Aveni, 2001) and the Temple of Hathor at Dendera in Egypt, aligned to Alkaid, a star in Ursa Major (Shaltout & Belmonte, 2005). The Caracol at Chichen Itza is believed to have been oriented to observe the planet Venus.

The misalignment of certain places with respect to the cardinal directions has been explained in terms of local factors including topography and landscape. A part of Mexico City surrounding the ancient Aztec capital of Tenochtitlan is aligned in a direction slightly south of east. One theory is that the site was rotated in order to compensate for the shift in the position of the sun when it rose over Templo Mayor on the equinox rather than directly east at the horizon (Aveni et al., 1988). Ridderstad (2009) proposes a number of reasons why Knossos on the island of Crete is misaligned by about 10° south of east.

Finally, there are sites aligned toward places of spiritual importance. Today many mosques face toward Mecca. However, there are

other sacred directions called qibla that are also used to align mosques (King, 2018). In Peru, imaginary lines known as ceques (Krupp, 1994) emanate out from the center of the city of Cuzco in all directions, one of which passes through the Inca fortress of Sacsayhuamán.

This paper analyzes the alignments of more than two hundred archaeological sites from across the world. The next section, Alignment Hypotheses, defines eight hypotheses against which alignments are assessed. The following section, Alignments of Archaeological Sites, presents our findings organized by geographic region. And the last section, Analysis of Alignments, summarizes the results of our analysis. Based on the distribution of site alignments, we show that there are interesting similarities and differences among geographic regions. Surprisingly, the alignment of about half of the sites considered in this study cannot be explained by any of the hypotheses considered.

ALIGNMENT HYPOTHESES

From a review of the archaeological and archaeoastronomical literature, eight basic explanations were identified to account for the orientation of an archaeological site: 1) to cardinal directions (i.e. facing north, south, east, and west), 2) to solstice sunrise or sunset directions, 3) to sunrise or sunset directions on days when the sun passes directly overhead, 4) to directions of major and minor lunar standstills, 5) to a planet, 6) to a star or constellation, 7) to magnetic north, and 8) in the direction of an earth site of religious or spiritual importance. We also discuss other explanations such as landscape and topography.

Cardinal Directions

The cardinal directions can be established either by observing the motion of stars at night or the path of the sun during the day or over the course of the year. A site aligned to the cardinal directions faces sunrise and sunset twice a year on the spring and autumn equinoxes.

Solstices

Many ancient sites reference the directions of the sun on the first day of summer and winter (solstices). To determine if a site is aligned to the solstices, define the following angles:

α – azimuth angle of the sun (measured clockwise with respect to true north),
θ – elevation angle of the sun above the horizon,
ϕ – latitude of the site,
δ – solar declination. The tilt of the earth on its axis, the obliquity, ε, is what causes the seasons.

The solar declination is the tilt of the earth toward the sun, which varies with the season, $-\varepsilon \le \delta \le \varepsilon$, reaching its largest and smallest values on the summer and winter solstices, respectively. On the spring and fall equinoxes, $\delta = 0°$.

The following solar path equation (Figure 1) relates the solar azimuth, the solar elevation, the latitude of the site, and the solar declination:

$$\cos\alpha = (\sin\delta - \sin\theta \sin\phi) / \cos\theta \cos\phi \quad (1)$$

and can be used to calculate the azimuth angle of the sun at sunrise and sunset on the summer solstice

$$\alpha_{s\uparrow} = \cos^{-1}(\sin\delta / \cos\phi) \quad (2a)$$

$$\alpha_{s\downarrow} = -\cos^{-1}(\sin\delta / \cos\phi) \quad (2b)$$

and on the winter solstice:

$$\alpha_{w\uparrow} = \cos^{-1}(-\sin\delta / \cos\phi) \quad (3a)$$

$$\alpha_{w\downarrow} = -\cos^{-1}(-\sin\delta / \cos\phi) \quad (3b)$$

The obliquity changes slowly over time, less than 2° over a period of 41,000 years. The present value is 23.43°. Due to changes in obliquity, solar alignments established in the distant past no longer line up exactly. By inverting Equation 1 we can determine when an alignment at a given angle would have lined up with a solstice or some other event by solving for the obliquity as a function of azimuth angle at sunrise or sunset:

$$\delta = \sin^{-1}(\cos\alpha \cos\phi) \quad (4)$$

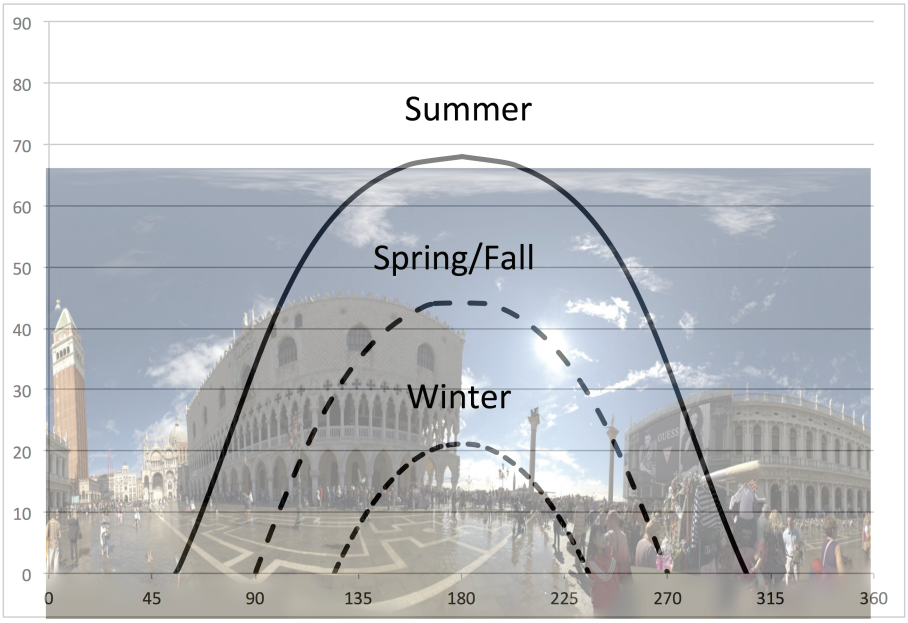


Figure 1. Seasonal path of the sun (Equation 1) plotted over panoramic photo facing south taken at Piazza San Marco, Venice. Photo credit: https://www.openfootage.net/Openfootage/Vorschau/ContactSheet_Piazza-San-Mar.jpg

It is noted that these equations do not take into account the local horizon, which may be affected by mountains and hills that cause the sun and moon to rise later and set earlier than over a flat horizon, and do not model atmospheric refraction that affects the appearance of celestial objects close to the horizon, both of which can be important factors in the alignment of certain sites.

Zenith Passage

At the equator, the sun passes directly overhead at noon on the equinox. Within the zone of the tropics, the sun can still pass overhead on certain other days. This occurs on days when the solar inclination is equal to the site's latitude. An alignment occurs either at sunrise or sunset when

$$|\phi| = 90° - |\alpha| \tag{5}$$

Lunar Standstills

The plane of the moon's orbit is tilted by 5.1° relative to the ecliptic. Because of its orbit, the moon can rise and set more northerly and more southerly than the sun. Due to the effects of the sun's gravity, the moon's orbital plane does not stay fixed in space but precesses, causing the monthly angles of moonrise and moonset to change over an 18.6-year cycle. Every 18.6 years the moon rises at its maximum northerly direction, which is known as a major lunar standstill. A minor lunar standstill occurs 9.3 years later when the moon rises at its minimum northerly direction. The moonrise and moonset azimuth angles at a standstill are

$$\alpha_{m\uparrow} = \cos^{-1}(\sin\mu / \cos\phi) \tag{6a}$$

$$\alpha_{m\downarrow} = -\cos^{-1}(\sin\mu / \cos\phi) \tag{6b}$$

where μ is the lunar declination which is $\mu = \pm(\varepsilon + 5.1°)$ for a major standstill and $\mu = \pm(\varepsilon - 5.1°)$ for a minor standstill.

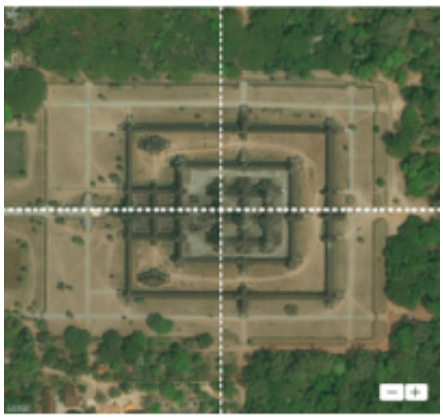
Figure 2 shows several examples of sites aligned to the sun and moon.

Planetary Alignments

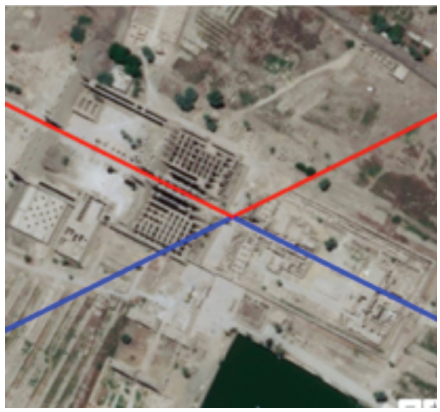
The motion of the planets is along the imaginary line defined by the plane of earth's orbit around the sun known as the ecliptic. As a result, a planet can appear to rise anywhere between the summer and winter solstice sunrise directions and set anywhere between the summer and winter solstice sunset directions. For example, the maximum northern and southern setting directions of Venus observed at the Caracol in Chichen Itza are the same as the solstice sunset directions.

Stellar Alignments

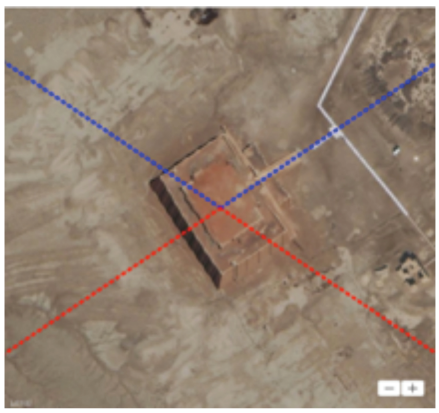
It is convenient to think of the stars existing on the inside of a celestial sphere. As earth revolves on its axis, stars appear to rotate around the celestial poles. In addition to obliquity, the earth's axis precesses in a 26,000-year cycle about the ecliptic pole. The direction in which a star rises and sets on the horizon depends on its location on the celestial sphere, the latitude of the site where it is observed, and the time of observation with respect to the precessional cycle.



A) Angkor Wat—Cardinal Directions



B) Karnak—Solstices



C) Ziggurat of Ur—Major Lunar Standstills

D) Koh Ker—Zenith Passage

Figure 2. Examples of sites aligned to the sun and moon. There are two sets of lines in B) through D), since solstices, lunar standstills, and zenith passages occur twice a year. Photo credit: Apple Maps.

Alignments to Magnetic North

There is evidence that ancient sites in certain parts of the world were aligned using a magnetic compass. Unlike the geographic poles, the magnetic pole is constantly in motion (Figure 3). In order to determine the alignment of a site to a pole (or any reference location on the surface of the earth), let A, B, and C be the locations of a site, the geographic North Pole, and the magnetic pole at a given time, respectively (Figure 4).

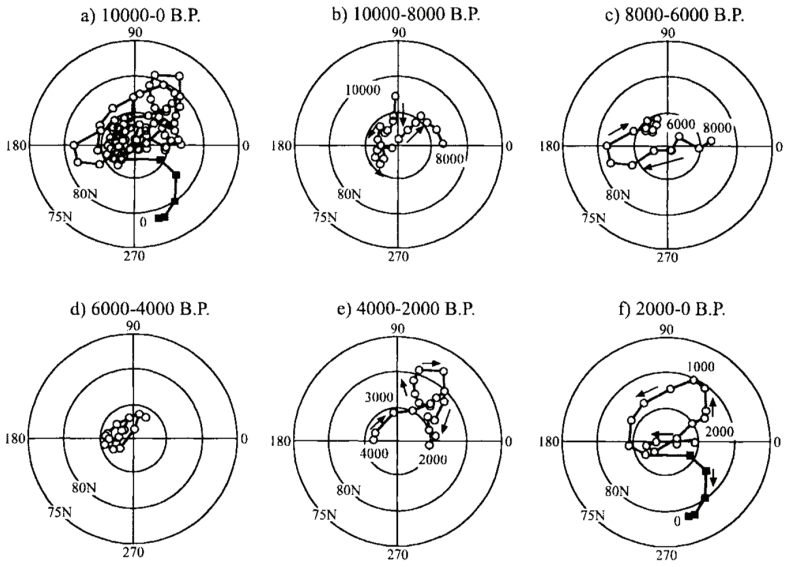


Figure 3. Estimated locations of the north geomagnetic pole over the past 10,000 years (from McElhinny & McFadden, 2000).

If (λ_A, φ_A) and (λ_C, φ_C) are the latitudes and longitudes of the site and reference locations, define the angles

$$\begin{aligned} a &= \frac{\pi}{2} - \lambda_C, \\ c &= \frac{\pi}{2} - \lambda_A \\ B &= \varphi_C - \varphi_A \end{aligned} \tag{7}$$

We wish to solve for the angle A (the azimuth angle of the reference location from the site) as a function of the locations of A and C on the sphere. Starting with the sine and cosine rules for spherical triangles:

$$\frac{\sin A}{\sin a} = \frac{\sin B}{\sin b} = \frac{\sin C}{\sin c} \tag{8}$$

and

$$\cos b = \cos a \cos c + \sin a \sin c \cos B \tag{9}$$

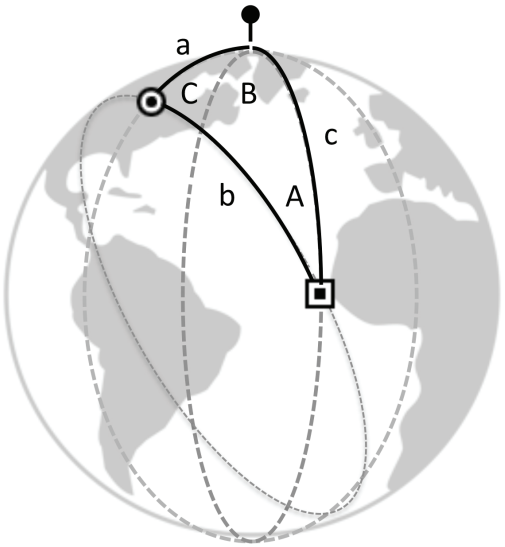


Figure 4. The locations of a site A, North Pole B, and reference C are the vertices of a spherical triangle. Edges of spherical triangles are great circles. The angle A is the azimuth of the reference location measured at the site.

since $\sin b = \sqrt{1 - \cos^2 b}$

$$\sin A = \frac{\sin a \sin B}{\sin b} = \frac{\sin a \sin B}{\sqrt{1 - \cos^2 b}} \tag{10}$$

$$A = \sin^{-1}\left[\frac{\sin \mathrm{a} \sin \mathrm{B}}{\sqrt{1 - (\cos a \cos c + \sin a \sin c \cos B)^2}}\right] \tag{11}$$

Using the estimated location of the north geomagnetic pole at a given time, it is possible to approximate the compass direction of magnetic north at a site at that time (Figure 5A).

Alignments to "Sacred Directions"

As noted above, Equation 11 can compute the azimuth angle at any location to any other location on the surface of the earth and can be used to evaluate alignments to "sacred directions" that include Islamic

A) **Chongling Mausoleum of Emperor Dezong of Tang aligned to geomagnetic pole at 83°N 45°E.**

B) **Dome of the Rock in Jerusalem faces Petra.**

Figure 5. Sites aligned in other directions.

qibla and Quechua ceques (Lon, 2005). For example, using Equation 11 it can be determined that the Rock of the Dome in Jerusalem is aligned in the direction of Petra in Jordan (Figure 5B).

ALIGNMENTS OF ARCHAEOLOGICAL SITES

The selection of archaeological sites from across the world is a challenging exercise in itself. More than two hundred sites were identified from a variety of sources including UNESCO's World Heritage Center, Wikipedia, Google Earth, and scientific and popular literature. The selected sites contain linear and rectilinear structures that are well-resolved and visible in overhead imagery. Google Earth imagery and measurement tools were used to measure heading (azimuth) angles. Alignments are indicated in Tables 1–8 according to the following key:

Cardinal directions, i.e. geographic poles, and equinoxes (E)
Magnetic pole at the time of construction (X)
Zenith passage (Z)
Solstices (S)
Major and minor lunar standstills (M,m)
Stellar alignments (st)
Alignments to "sacred directions" (D)

Measured angles of rectangular structures and rectilinear features are listed two ways: by a NW to NE facing angle between –45° and +45°, and a NE to SE facing angle between 45° and 135°.

In a previous aerial archaeological study using Google Earth (Lepionka & Carlotto, 2015), heading measurement errors were found to be as small as 0.1° between widely spaced, well-defined, point-like features. Measurement errors at some of the sites considered here could be somewhat higher, particularly for ruined structures that lack a well-defined edge and for smaller structures with short edges. In this study, a structure is classified as being in alignment with a cardinal or other direction if the sides of the structure are within approximately 1° of that direction. For solar and lunar alignments, a site is considered aligned to a solstice or lunar standstill if a structure at the site, or an alignment between structures at the site, is within the range of solstice or lunar standstill directions at that latitude over the earth's 41,000-year obliquity cycle.

In general the alignment hypotheses represent eight mutually exclusive directions or ranges of direction at a particular site (although at certain latitudes minor lunar standstill moonrise/moonset directions and zenith passage sunrise/sunset directions can overlap). In addition to these eight alignment hypotheses (plus "unknown"), there are sometimes other explanations for the alignment of the site as noted in the tables and discussed in the accompanying text.

Africa

Table 1 lists the sites examined in Africa, most of which are in Egypt. About half of the sites are aligned to the cardinal directions. Most of these are pyramids in Lower Egypt. Shaltout and Belmonte (2005) analyzed the orientation of more than one hundred temples in Upper Egypt and Lower Nubia to discover that they face many different directions with a somewhat greater concentration of alignments in the east–southeast direction. This is in agreement with our finding of sites aligned to solstices and major and minor lunar standstills. Their principal conclusion is that local topography (the course of the Nile River) was more important than astronomy in aligning the foundations of the temples. Our finding that half of the sites examined in Egypt do not appear to be aligned to obvious astronomical events is consistent

TABLE 1
Alignments of Sites in Africa

Name	Latitude	Longitude	North	East	Alignment
Algeria, Jabal Lakhdar	35.063404	1.183731	-5	85	
Egypt, Abu Rawash, Pyramid of Djedefre	30.032262	31.074714	0	90	E
Egypt, Abusir, Pyramid of Neferefre	29.893770	31.201454	0	90	E
Egypt, Abusir, Pyramid of Neferirkare	29.895093	31.202249	0	90	E
Egypt, Abusir, Pyramid of Sahure	29.897622	31.203367	0	90	E
Egypt, Abydon, Temple Ramses II	26.186426	31.916280	44.2	134.2	
Egypt, Abydos, Osirion	26.184099	31.918465	36.3	126.3	
Egypt, Abydos, Pyramid of Ahmose I	26.175056	31.937822	36	126	
Egypt, Abydos, Temple Seti I	26.184968	31.919183	36.3	126.3	
Egypt, Cairo, Mosque of Ibn Tulun	30.028691	31.249394	-39	51	
Egypt, Dahshur Pyramid of Senusret III	29.818888	31.225550	0	90	E
Egypt, Dahshur, Bent Pyramid	29.790449	31.209324	0	90	E
Egypt, Dahshur, Pyramid of Amenemhat II	29.805807	31.223038	0	90	E
Egypt, Dahshur, Red Pyramid	29.808882	31.206113	0	90	E
Egypt, Deir Bahari, Mortuary Temple of Mentuhotep II	25.737375	32.606178	23.2	113.2	S
Egypt, Deir el Medinah, Temple of Hathor	25.728846	32.602128	-40	50	
Egypt, Dendara, Sacred Lake	26.141807	32.669532	16.1	106.1	
Egypt, Dendera, Temple of Hathor	26.141914	32.670205	18.9	108.9	st ,m
Egypt, Edfu Temple of Horus	24.976747	32.873087	12.8	102.8	
Egypt, Elephantine, Temple of Khnum	24.084492	32.886206	-42	48	
Egypt, Giza, Khafre	29.975726	31.130800	0	90	E
Egypt, Giza, Khufu	29.979067	31.134040	0	90	E
Egypt, Giza, Menkaure	29.975811	31.131242	0	90	E
Egypt, Kom Ombo	24.452085	32.928353	43.3	133.3	
Egypt, Lisht, Pyramid of Amenemhat I	29.574802	31.225304	0	90	E
Egypt, Lisht, Pyramid of Senusret I	29.560160	31.221130	0	90	E
Egypt, Luxor West, Temple Ramses III	25.719683	32.600711	-42	48	
Egypt, Luxor, Karnak, Temple of Amun Re	25.718484	32.659044	26.6	116.6	S
Egypt, Meidum Pyramid	29.388368	31.157503	0	90	E
Egypt, Pyramid of Teti	29.875142	31.221847	-12.5	77.5	
Egypt, Saqqara, Mastaba of Shepseskaf	29.838852	31.215273	0	90	E
Egypt, Saqqara, Pyramid of Djedkare-Isesi	29.850983	31.220924	0	90	E
Egypt, Saqqara, Pyramid of Djoser	29.871397	31.216532	5	95	
Egypt, Saqqara, Pyramid of Khendjer	29.832363	31.224043	0	90	E
Egypt, Saqqara, Pyramid of Pepi II	29.840246	31.213496	0	90	E
Egypt, Saqqara, Pyramid of Qakare Ibi	29.841590	31.217712	-10	80	
Egypt, Saqqara, Pyramid of Unas	29.868182	31.215012	0	90	E
Egypt, Saqqara, Pyramid Userkaf	29.873332	31.219334	0	90	E
Egypt, Shunet El Zebib	26.189510	31.908055	-41.7	48.3	
Egypt, Siwa Oasis, Amun Temple	29.201375	25.516151			
Egypt, Temple of Edfu	24.978092	32.873475	3	93	
Egypt, Temple of Esna	25.293444	32.556125	-23	67	M
Egypt, Temple of Hathor, El Kab	25.138586	32.828651	-44	46	
Egypt, Temple of Isis at Shenhur	25.861040	32.776808	10	100	
Egypt, Temple of Ramses II	25.727588	32.610283	41	131	
Egypt, Zawyet El Aryan, Layer Pyramid	29.932820	31.161262	-12	78	
Ethiopia, Bete Giyorgis	12.031714	39.041190	5.8	95.8	m
Ethiopia, Yeha Temple	14.285703	39.019114	11.4	101.4	
Sudan, Dangeil, Amun Temple	18.131307	33.959800	16.5	106.5	

E = cardinal directions, i.e. geographic poles, and equinoxes. M,m = major and minor lunar standstills. S = solstices. st = stellar alignments (aligned to Alkaid in Ursa Major).

with this conclusion. The Temple of Hathor at Dendera was very likely aligned to the star Alkaid in the constellation Ursa Major, which is associated with the Egyptian goddess Hathor.

If no alignment is given, the explanation is unknown. In some cases, there may be more than one explanation for an alignment.

Asia

Table 2 lists sites examined in Asia. Many of the sites in China considered here are ancient earthen mounds that are aligned either to the cardinal directions or thought to have been aligned in the direction of the magnetic pole at the time of construction (Charvátová et al., 2011). Some of the sites considered in Thailand are temples that could also have been aligned to the north geomagnetic pole (Iyemori et al., 2011). Magli (2016) determined that a very clear pattern of cardinal orientation and alignment occurs in numerous temples in and around Angkor. Although some sites appear to reference the solstices in their construction and many are aligned to one another in solstitial directions, none of the sites themselves are aligned to the solstices. Unlike in Egypt, we were unable to find any sites in Asia oriented to solstices. Several were oriented, however, in directions that correspond to lunar standstills. Three sites located in the Tropic of Cancer might have been aligned to the sun on so-called "zenith passage days" when the sun passes directly overhead. McKim Malville (2015) analyzed 31 sites in India and found that two-thirds were aligned to the cardinal directions, solstices, and zenith passages. About half of the sites examined in other parts of India did not have an obvious explanation for their alignment.

Europe

Table 3 shows the alignments of ancient sites in Europe. Unlike Africa with many of its sites aligned in the cardinal directions and Asia with many of its sites aligned either to true (geographic) north or geomagnetic north, about half of the sites examined in Europe are aligned to solstices and lunar standstills. Palantine Hill, which was the earliest settlement in ancient Rome, is aligned to major lunar standstills. The Parthenon, which sits atop the Acropolis, is not aligned to solstices or to lunar standstills. Dinsmoor proposed that it was aligned to the

TABLE 2
Alignments of Sites in Asia

Cambodia, Koh Ker	13.783220	104.537453	-12.5	77.5	Z	
Cambodia,Preah Khan of Kompong Svay	13.403820	104.754210	-28.2	61.8	M	
China, Chongling Mausoleum of Emperor Dezong of Tang	34.707380	108.828530	-4.2	85.8	x	Aligns to geo-magnetic pole around 400 CE
China, Jinling Mausoleum of Emperor Xianzong of Tang	34.570992	108.265923	-9	81	x	Aligns to geo-magnetic pole around 600 CE
China, The Lianhu Altar	36.632869	101.746123	15.8	105.8	S	NE-SW diagonal aligned to solstice
China, Tomb of Consort Ban	34.379801	108.704492	-11	79		
China, Tomb of Emperor Ai of Han	34.400855	108.764606	0	90	E	
China, Tomb of Emperor Cheng of Han	34.374896	108.698001	-10	80	x	Aligns to geo-magnetic pole around 900 CE
China, Tomb of Emperor Gaozu of Han	34.434691	108.876647	-14	76		
China, Tomb of Emperor Hui of Han	34.422895	108.841317	-17	73		
China, Tomb of Emperor Jing of Han	34.443823	108.940784	0	90	E	
China, Tomb of Emperor Ping of Han	34.397774	108.712421	0	90	E	
China, Tomb of Emperor Wen of Sui	34.287850	108.022890	-3	87	x	Aligns to geo-magnetic pole around 400 CE
China, Tomb of Emperor Wu of Han	34.338085	108.569684	-8	82	x	Aligns to geo-magnetic pole around 700 CE
China, Tomb of Emperor Xuan of Han	34.181063	109.022312	0	90	E	
China, Tomb of Emperor Yuan of Han	34.390303	108.739114	0	90	E	
China, Tomb of Emperor Zhao of Han	34.361753	108.640108	-11	79	x	Aligns to geo-magnetic pole around 800 CE
China, Tomb of Empress Dou	34.235825	109.118614	22.6	112.6	m	
China, Tomb of Empress Dowager Bo	34.220993	109.096341	21.6	111.6	m	
China, Tomb of Empress Fu	34.402608	108.772545	-4	86	x	Aligns to geo-magnetic pole around 1000 CE
China, Tomb of Empress Li	34.340327	108.562002	-9.5	80.5	x	Aligns to geo-magnetic pole around 800 CE
China, Tomb of Empress Lü	34.433824	108.881292	-10.2	79.8	S	NW-SE diagonal aligned to solstice
China, Tomb of Empress Shangguan	34.363135	108.630538	-8	82	x	Aligns to geo-magnetic pole around 900 CE
China, Tomb of Empress Wang (a)	34.393242	108.733835	0	90	E	
China, Tomb of Empress Wang (b)	34.446291	108.947500	0	90	E	
China, Tomb of Empress Wang (c)	34.178951	109.028396	0	90	E	
China, Tomb of Empress Xu (a)	34.374648	108.684740	-9.5	80.5	x	Aligns to geo-magnetic pole around 800 CE
China, Tomb of Empress Xu (b)	34.127340	109.055786	0	90	E	
China, Tomb of Empress Zhang Yan	34.423195	108.836961	-15	75		
China, Tomb of Marquis Zhang Ao	34.427745	108.851209	-15	75		
China, Tomb of Princess Chengyang of Emperor Taizong	34.615600	108.493140	-6	84	x	Aligns to geo-magnetic pole around 500
China, Tomb of Princess Xincheng of Emperor Taizong	34.623650	108.498880	-21	69		
China, Yarnaz Valley,Yarkhoto	42.952022	89.061138	-40	50	M	
India, Amritsar, Golden Temple	31.619938	74.876511	33.2	123.2	M	
India, Chidambaram, Chidambaram Nataraja	11.399234	79.693715	-1	89	E	
India, Chitoor, Srikalahasti Temple	13.749686	79.698308	0	90	E	
India, Kanchipura, Ekambareswarar Temple	12.847302	79.699525	18.3	108.3	m	
India, Khadirbet, Dholavira	23.886907	70.213776	-5	85		
India, Madhya Pradesh, Sas Bahu Temple	16.018856	75.881959	-4	86		
India, Madhya Pradesh, Tigawa Temple	23.690196	80.066918	-10	80		
India, Mahabalipuram, Shore Temple	12.616492	80.199267	13	103	Z	
India, Rameshwar Mandir	16.217680	73.462012	-14	76		
India, Shri Martand Sun Temple	33.745588	75.220286	-13.9	76.1		
India, Sigiriya	7.957173	80.760031	8.3	98.3	Z	
India, Tamil Nadu					E,S,Z	Malville's analysis of 31 temples (see text).
India, Thanjavur, Brihadisvara Temple	10.782614	79.131735	-20.5	69.5	st,m	Aligned toward Pleiades at the time of construction
India, Tiruvannamalai, Annamalaiyar Temple	12.231884	79.066790	11.4	101.4	Z	
India, Udaipur Rajasthan, Sas Bahu Temple	24.735191	73.716283	-16	74		
India, Venkateswara Temple	13.683250	79.347195	-7	83		
Indonesia, Gunung Padang	-6.994518	107.056383	-20	70		
Inner Mongolia, Xanadu	42.356388	116.184304	0	90	E	
Japan, Osaka Castle	34.687298	135.525826	5.7	95.7		
Maldives, Thinadhoo	0.530107	72.997170	43	133	D	Oriented in the direction of Petra
Pakistan, Harappa	30.628104	72.863909	0	90	E	
Russia Por-Bazhyn	50.615271	97.384872	9.5	99.5		
Thailand Angkor Wat	13.412469	103.866986	0	90	E	
Thailand, Ayutthaya, Wat Phra Mahathat	14.356943	100.567509	-5.3	84.7	x	Aligns to geo-magnetic pole around 900 CE
Thailand, Kao Klang Nai, Sri Thep	15.465521	101.144681	9.5	99.5		
Thailand, Prasat Hin Phimai	15.220930	102.493861	-22	68		
Thailand, Prasat Mueang Tam	14.496089	102.982608	-11	79		
Thailand, Prasat Phanom Rung	14.532044	102.940223	-5.5	84.5	x	Aligns to geo-magnetic pole around 600 CE
Thailand, Prasat Si Khoraphum	14.944574	103.798352	0	90	E	
Thailand, Wat Phra Sri Rattana Mahathat	14.798673	100.613862	0	90	E	

D = alignments to “sacred directions”. E = cardinal directions, i.e. geographic poles, and equinoxes. M,m = major and minor lunar standstills. S = solstices. st = stellar alignments. X = magnetic pole at the time of construction. Z = zenith passage.

TABLE 3
Alignments of Sites in Europe

Bosnia, Pyramid of the Sun	43.977259	18.176514	8.4	98.4		Artificiality not established
Greece, Athens, The Parthenon	37.971517	23.726590	-13.5	76.5		Aligned to sunrise on Athena's birthday
Greece, Delphi Amphitheater	38.482477	22.500577	-38.2	51.8	D	Oriented in the direction of Knossos
Greece, Knossos	35.297863	25.163092	11.8	101.8		Adjusted equinox alignment
Greece, Mycenae, Lion Gate	37.730752	22.756500	-40	50		Aligned to topography
Greece, Mycenae, Tomb of Agamemnon	37.726725	22.754367	10.5	100.5		Aligned to topography
Greece, The Temple of Artemis	37.949611	27.363921	21	111		
Italy, Rome, Circus Maximus	41.885944	12.485215	36.7	126.7	M	
Italy, Rome, Palantine Hill	41.889209	12.487459	36.7	126.7	M	
Italy, Sardinia, Monte d'Accoddi	40.790754	8.448908	9.1	99.1		
Malta, Gozo, Ġgantija Temple	36.047260	14.269015	37	127	M	
Spain, Mosque-Cathedral of Cordoba	37.878906	-4.779387	-30.4	59.6	S	
Spain, Naveta d'Es Tudons	40.003075	3.891653	-19.2	70.8	m	
Turkey, Hagia Sophia	41.013140	28.983182	34.3	124.3	S	
Turkey, Hattusa	40.019943	34.615455	38	128	M	
UK, Calanais Standing Stones	58.197566	-6.745127				
UK, Glastonbury Tor	51.144444	-2.698611	-26.5	63.5	m	
UK, Stonehenge	51.178868	-1.826163			S,M,m	

D = alignments to “sacred directions”. M,m = major and minor lunar standstills. S = solstices.

sunrise on the birthday of the Greek goddess Athena (Hannah, 2013). That the Acropolis also appears aligned in the same general direction and predates the Parthenon by hundreds, perhaps thousands, of years would seem to challenge that dating and the reason for its alignment. Maravelia (2002) proposes that the alignment of a number of tholus tubes in Mycenae are based on topographical not astronomical considerations.

North America

Most of the Native American/indigenous sites examined in North America are aligned to the cardinal directions, solstices, or lunar standstills (Table 4).

TABLE 4
Alignments of Sites in North America

Canada, AB, Badlands Guardian	50.010370	-110.113133			E	Geoglyph aligned to north. Artificiality not established
US, California, Blythe Intaglios, B1	33.800585	-114.532055	0	90	E	Geoglyph aligned to north
US, California,Blythe Intaglios, B3	33.800402	-114.538078	29	119		
US, Georgia, Ocmulgee National Monument	32.838868	-83.606114	34	124	M	
US, New Mexico, Chaco Canyon, Pueblo del Arroyo	36.060854	-107.966300	24	114	M	
US, Ohio, Great Serpent Mound	39.026420	-83.431091	27.7	117.7	S	"Head" faces solstice
US. Illinois, Cahokia, Monks Mound	38.660158	-90.062466			S,M	

E = Cardinal directions, i.e. geographic poles, and equinoxes. M = major lunar standstills. S = solstices.

Pacific Ocean

About half of the sites in the Pacific appear to have astronomical alignments (Table 5). The Ahu platforms on which the Easter Island Moai look out to the sea were built in a variety of orientations around the island. Three of the alignments may be astronomical. The Temple of Nan Dawas at Nan Madol in Micronesia is aligned in the direction of the zenith passage sunrise. A megalithic structure called the Ha'amonga'a Maui Trilithon along with most of the structures on the island of Tonga are aligned in a northeast direction that has no known explanation.

TABLE 5
Alignments of Sites in the Pacific Ocean

Chile,Easter Island, Ahu Akivi	-27.115014	-109.395043	-2.7	87.3	E
Chile,Easter Island, Ahu Nau Nau	-27.074425	-109.322455	-19.6	70.4	m
Chile,Easter Island, Ahu Tahai	-27.140076	-109.427314	8.3	98.3	
Chile,Easter Island, Ahu Tongariki	-27.125774	-109.276933	30	120	S
Chile,Easter Island, Ahu Vinapu	-27.174098	-109.405737	8.1	98.1	
Micronesia, Nan Madol	6.844537	158.335795	-33	57	M
Micronesia, Nan Madol, Temple of Nan Dawas	6.844537	158.335795	7	97	Z
Samoa, Pulemelei Mound	-13.735237	-172.324399	-7.3	82.7	
Tonga, Ha'amonga 'a Maui Trilithon	-21.136606	-175.048087	32.7	122.7	*

* Entire island of Tonga aligned in the same direction. E = cardinal directions, i.e. geographic poles, and equinoxes. M,m = major and minor lunar standstills. S = solstices. Z = zenith passage.

The Middle East

Only four of the sites examined in the Middle East have an apparent explanation for their alignment (Table 6). The Kaaba in Mecca analyzed in detail by Hawkins and King (1982) was found to be most accurately aligned to the moon, which is one of several directions or qibla that are sacred in Islam. The Ziggurat of Ur (Sparavigna, 2016) and the Great Mosque of Sana'a in Yemen also are aligned to the moon. The Dome of the Rock in Jerusalem is oriented toward Petra in Jordan.

South America

About a third of the sites examined in South America are aligned to the cardinal directions, solstices, or lunar standstills (Table 7). Another third appear to be aligned to face either the city of Cuzco in Peru's Sacred Valley or the city of Caral in the Supe Valley. A number of lines

TABLE 6
Alignments of Sites in the Middle East

Iran, Chogha Zanbil	32.008997	48.521593	-43.5	46.5	
Iraq, Dur-Kurigalzu	33.353671	44.202164	-39.6	50.4	
Iraq, Tower of Babel	32.536284	44.420803	-11.3	78.7	
Iraq, Ziggurat of Ur	30.962711	46.103126	-33.3	56.7	M
Jerusalem, Dome of the Rock	31.778087	35.235306	-7.3	82.7	D
Jerusalem, Western Wall	31.776657	35.234470	-12.1	77.9	
Jordan, Petra, Temple of the Winged Lions	30.330297	35.442554	17.5	107.5	
Jordan, Qasr ll-Abd, Irak Al-Amir	31.912785	35.751941	-15	75	
Jordan, Umayyad Mosque in Amman	33.511593	36.306657	-6.4	83.6	
Lebanon, Baalbek, Temple of Jupiter	34.006694	36.203826	-12.2	77.8	
Saudi Arabia, Mecca, Kaaba	21.422510	39.826174	-34.9	55.1	M
Turkey, Harran	36.865021	39.031565	9.6	99.6	
Yemen, Great Mosque of Sana'a	15.353123	44.214876	-25	65	M

* Oriented in the direction of Petra. D = alignments to “sacred directions”. M = major lunar standstills.

TABLE 7
Alignments of Sites in South America

Bolivia, Chincana Labyrinth	-15.990127	-69.202952	44	134	D	Oriented in the direction of Cuzco
Bolivia, Puma Punku	-16.561720	-68.680046	2	92		
Bolivia, Quenuani	-16.259407	-69.171270	-20	70	S	
Bolivia, Tiwanaku	-16.554933	-68.673487	2	92		
Peru, Caral-Supe	-10.893458	-77.520540	19.5	109.5	S	Oldest city in the Americas
Peru, Caral-Supe, Huanca Pyramid	-10.893458	-77.520540	19.5	109.5		
Peru, Chan Chan	-8.103554	-79.070760	19.5	109.5	m	Name "Chan Chan" may refer to sun or moon
Peru, Chavin	-9.594527	-77.177002	14.7	104.7	D	Oriented in the direction of Caral-Supe
Peru, Cuzco	-13.518587	-71.975952				Center of Quechua ceques or pathways
Peru, Huanuco Pampa	-9.875388	-76.816395	0	90	E	
Peru, Huayna Picchu, Temple of the Moon	-13.151931	-72.546507			M	Faces north to view full range of lunar motion
Peru, La Centinela	-13.450075	-76.172233	5.6	95.6		
Peru, Machu Picchu, Temple of the Three Windows	-13.163592	-72.545414	-34.7	55.3		
Peru, Machu Picchu, Terraces	-13.164219	-72.544831	-25	65		Oriented in a solar direction
Peru, Marcahuasi, Face	-11.775670	-76.581853	43	133	D	Oriented in the direction of Caral-Supe
Peru, Nazca Lines	-14.712825	-75.174850	19.3	109.3	D	Oriented in the direction of Cuzco
Peru, Ollantaytambo, Temple of the Sun	-13.257536	-72.267129	-35	55		
Peru, Sacsahuaman	-13.509330	-71.980916			D	"Head" of a puma represented by the city of Cuzco
Peru, Sechin Bajo	-9.464809	-78.265259	-25.5	64.5	S	
Peru, Warawtampu	-10.465490	-76.536647	-24.2	65.8	D	Oriented in the direction of Caral-Supe
Peru. Chotuna	-6.720363	-79.952796	0	90	E	

D= alignments to “sacred directions”. E = cardinal directions, i.e. geographic poles, and equinoxes. M,m = major and minor lunar standstills. S = solstices.

and geoglyphs in Nazca appear to point toward, away from, or at right angles to Cuzco. The alignment of sites to Cuzco is consistent with a set of directions that emanate from Cuzco called ceques. The remainder of the sites in South America have no obvious explanation for their alignment, including the large megalithic structures at Machu Picchu, Olantaytambo, Tiwanaku, and Puma Punku, whose origins are poorly understood.

Mesoamerica

In analyzing the alignments of Mayan sites, Aveni found that 16 percent are aligned west of north, while the other 86 percent are aligned east of north (Aveni, 2001). He concludes that an eastern skew was a standard architectural practice over a wide area in Mexico. A peak around 25° south of east suggests that many sites were aligned to solstices. As shown in Table 8, more than 75 percent of identified alignments lie in solar or lunar directions. What is particularly interesting about Mesoamerica is the large fraction of sites whose alignments are unknown. Fuson (1969) suggested the possibility that Mayan temples were aligned to magnetic north using a compass. Carroll (1979) analyzed about four dozen Mesoamerican sites and found that almost all of them were not aligned to magnetic north, based on their assumed date of construction.

TABLE 8
Alignments of Sites in Mesoamerica

Belize, Altun Ha, Sun God Pyramid	17.763950	-88.347061	7.6	97.6		
Belize, Xunantunich	17.088922	-89.141631	-10.3	79.7	D	Oriented in the direction of Uxmal
El Salvador, Tazumal	13.979547	-89.674131	18	108	m	
Guatemala, Mixco Viejo	14.871668	-90.664167	12.5	102.5	D	Oriented in the direction of Uxmal
Guatemala, Tikal	17.222094	-89.623614	8.6	98.6		
Guatemala, Yaxchilan	16.899655	-90.967093	30.4	120.4	D	Oriented in the direction of Chichen Itza
Honduras, Copan, Step Pyramids	14.840000	-89.140000			Z	Multiple orientations between -4 and +4 deg.
Mexico, Acatitlan	19.550000	-99.170000	20.3	110.3	Z	
Mexico, Alta Vista	23.478544	-103.945607				Multiple alignments
Mexico, Bonampak	16.704000	-91.065000	38	128		
Mexico, Calakmul	18.105392	-89.810829	8.8	98.8		
Mexico, Calixtlahuaca	19.335038	-99.697570	-30	60	M	
Mexico, Chalcatzingo	18.676715	-98.770783	6.8	96.8		
Mexico, Chichen Itza	20.680000	-88.570000	21	111	M,Z	Also cenotes, crop cycles, Venus min/max settings
Mexico, Chimalacatlan, C1	18.446236	-99.105878	-34.7	55.3	M	
Mexico, Chimalacatlan, C2	18.444804	-99.104331	28.7	118.7	m	
Mexico, Cholula	19.058305	-98.301906	25	115	S	
Mexico, Coba, Grand Pyramid	20.492974	-87.724195	-39	51		
Mexico, Comalcalco	18.278200	-93.200327	24	114	S	
Mexico, Cuauhtinchan Archeological Site, Cuauhcalli	18.953500	-99.502888	15.4	105.4	m	
Mexico, Cuicuilco	19.301021	-99.183798				Circular structure
Mexico, El Cerrito Archaological Zone	20.551376	-100.444027	7.4	97.4		
Mexico, El Tajin, Pyramid of the Niches	20.448058	-97.378242	14.5	104.5		
Mexico, El Tajin, Southern Ballcourt	20.448058	-97.378242	0	90	E	
Mexico, El Tajin, Tajin Chico	20.448058	-97.378242	40	130		
Mexico, El Tepozteco	19.000786	-99.101558	26	116	m	
Mexico, La Venta	18.103191	-94.040946	-12.2	77.8	D	Oriented in the direction of Comalcalco
Mexico, Mayapan	20.629823	-89.460590				Multiple orientations between -5 and +10 deg.
Mexico, Mitla	16.927049	-96.359348	12	102		
Mexico, Monte Alban	17.042122	-96.768184	6.45	96.45		
Mexico, Monte Alban, Building J	17.042122	-96.768184	-43	47	st	Aligned to Capella, points to Building P with zenith tube.
Mexico, Palenque, North Group	17.483978	-92.046320	10.1	100.1		
Mexico, Palenque, Temple of the Inscriptions	17.480000	-92.050000	20.6	110.6		
Mexico, Tenango	19.108425	-99.597693	14	104		Multiple orientations between 12 to 16 deg.
Mexico, Tenochtitlan	19.435000	-99.131389	7	97		Adjusted equinox alignment
Mexico, Teotihuacan	19.692500	-98.843889	15.6	105.6	st	Pleiades. Also mountains, pecked crosses, 260 day cycle
Mexico, Tiatelolco	19.450994	-99.137510	8.5	98.5		
Mexico, Tula	20.064451	-99.340500	15.47	105.47	m	
Mexico, Tulum	20.210000	-87.430000	22.3	112.3		
Mexico, Uxmal, Palace of the Governors	20.359444	-89.771389	30	120	S	Most southern Venus rise, 750 CE
Mexico, Uxmal, Pyramid of the Magician	20.359444	-89.771389	9.2	99.2		
Mexico, Uxmal, Templo Mayor	20.359444	-89.771389	19.6	109.6	Z	
Mexico, Xochicalco, Grand Pyramid	18.803889	-99.295917	0	90	E	
Mexico, Xochicalco, Temple of Quetzalcoatl	18.803889	-99.295917	15.4	105.4		

D = alignments to “sacred directions”. E = cardinal directions, i.e. geographic poles, and equinoxes. M,m = major and minor lunar standstills. S = solstices. st = stellar alignments. Z = zenith passage.

ANALYSIS OF ALIGNMENTS

The graphs in Figure 6 plot the distribution of site alignments within each of the eight geographic regions. Site distributions are con-

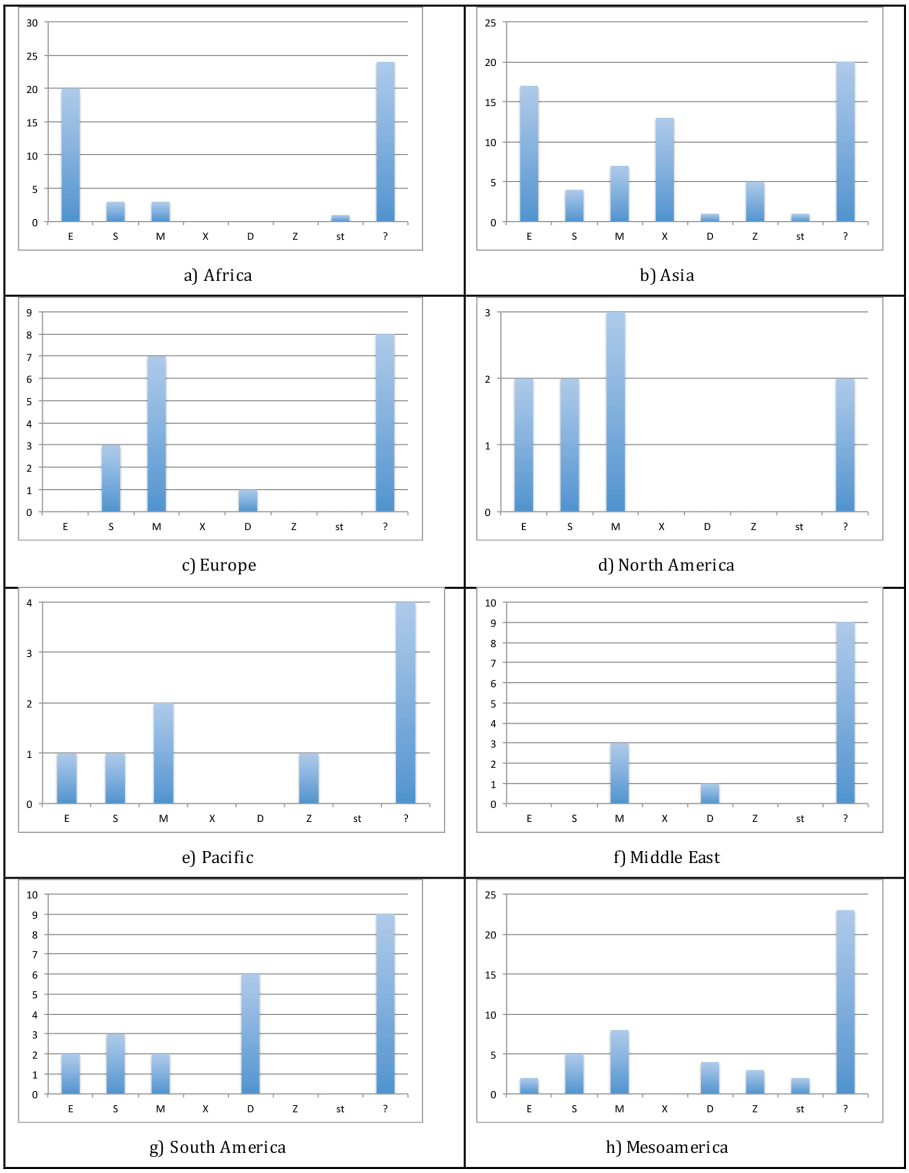


Figure 6. Site-alignment distributions.

TABLE 9
Region-to-Region Similarity (Euclidean Distances) Based on Similarity of Site-Alignment Distributions

	Africa	Asia	Europe	North America	Pacific	Middle East	South America	Mesoamerica
Africa		0.236314729	0.860343049	0.339688139	0.425130316	1.033093278	0.574979099	0.536565501
Asia	0.236314729		0.491470099	0.210654053	0.185381944	0.634548611	0.340786284	0.223090278
Europe	0.860343049	0.491470099		0.13324338	0.149421488	0.112603306	0.395618368	0.131227043
North America	0.339688139	0.210654053	0.13324338		0.055510204	0.329081633	0.308899891	0.106363379
Pacific	0.425130316	0.185381944	0.149421488	0.055510204		0.305	0.316686391	0.058472222
Middle East	1.033093278	0.634548611	0.112603306	0.329081633	0.305		0.477071006	0.253472222
South America	0.574979099	0.340786284	0.395618368	0.308899891	0.316686391	0.477071006		0.147209895
Mesoamerica	0.536565501	0.223090278	0.131227043	0.106363379	0.058472222	0.253472222	0.147209895	

verted to probabilities (relative frequencies) over the set of alignments {E,S,M,X,D,Z,st} where "M" represents both major and minor lunar standstills. If $\vec{r}(i)$ and $\vec{r}(j)$ are the alignment probabilities within two geographic regions, we define the similarity between the two regions by

$$d(i,j) = \|\vec{r}(i) - \vec{r}(j)\|$$

Table 9 lists similarities between regions in terms of their alignment probabilities.

Figure 7 depicts the similarity between geographic regions using a distance-preserving nonlinear mapping algorithm (Carlotto, 1993). Regions on the edge of the map are the most distinct from other regions in terms of their alignment statistics. For example, South America is different from the other regions in terms of the large number of sites that are aligned to other sites. Africa, mainly Egypt, is distinguished by its many pyramids aligned to the cardinal directions. Asia is unique in that most of its sites are aligned either to true north or to geomagnetic north. Most sites in Europe are aligned to solstices or lunar standstills, while sites in the Middle East are aligned only to the moon. Almost all of the sites in North America that were built by indigenous people are aligned to the sun or moon.

DISCUSSION

Across all eight geographic regions, 19% of the sites considered are aligned to the cardinal directions, 9% to solstices, 15% to lunar standstill, 5% to the geomagnetic pole at the time of construction, 5% to other sites, 4% to zenith passages, and 1% to stars. About 42% of the sites (95 out of 224) are anomalous in that they cannot be explained by

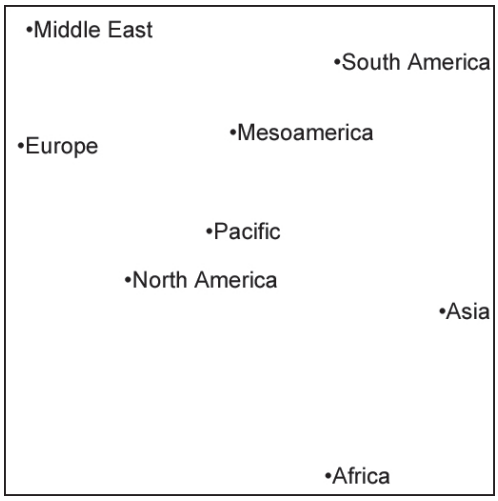


Figure 7. A 2-D map depicting similarities between geographic regions based on their site-distribution statistics.

any of our alignment hypotheses. Some of these sites may have aligned for other reasons, e.g., the alignment of the Parthenon to the sunrise on Athena's birthday or to conform to the landscape and topography as at Teotihuacan. Other structures such as Hindu temples in India (Daware, 2017) may have been aligned at the discretion of the builder without any obvious plan. It is also possible that some sites may not have been purposefully aligned at all.

That the alignment of so many sites cannot be explained is surprising. About half of the sites, on average, within all of the geographic regions (with the exception of North America) cannot be explained in terms of alignment (Figure 8). This would suggest that the reason for the non-alignment could be global and not local in nature. This possibility is considered in a subsequent paper.

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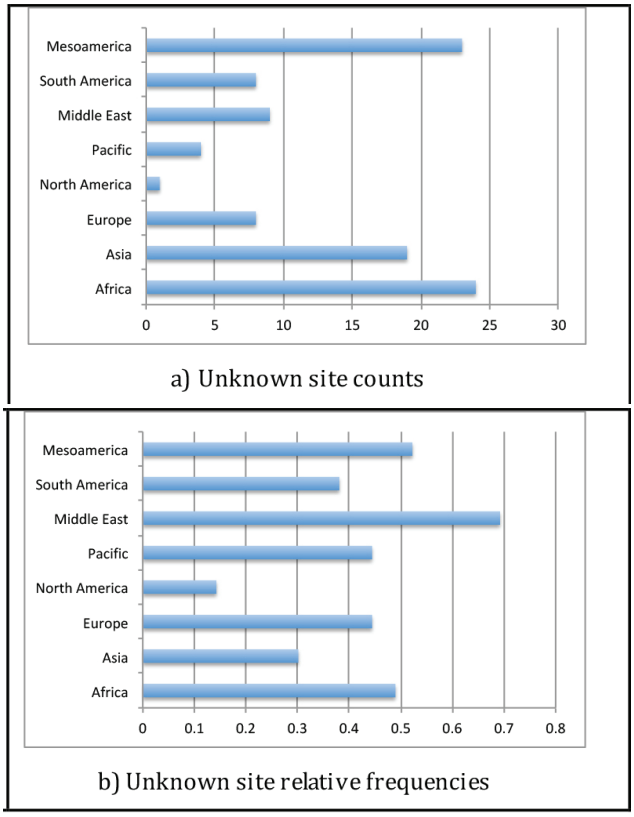

Figure 8. Geographic distributions of unknown-alignment sites.

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