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Diet and Health Changes at the End of the Chinese Neolithic: The Yangshao/Longshan Transition in Shaanxi Province

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ABSTRACT In this paper we discuss diet and health changes of millet agriculturists in Northern China, Shaanxi province, during the period 7,000–4,000 BP. An episode of intensive climatic oscillations that preceded the onset of colder climate circa the fifth millennium BP divides the period (Shi et al. [1993] Global Planet. Change *7:*219–233). The onset of the cooler climate marks the decline of the egalitarian society of Yangshao and the rise of the chiefdom-like society of Longshan.

Skeletal materials from the two sites of Beiliu and Jiangzhai are from the earlier phases of Yangshao culture (7,000–6,000 BP), while remains from the Shijia site were excavated from the terminal phase of Yangshao culture (6,000–5,000 BP), a phase that would be expected to show adjustments to strong climatic fluctuations. Human remains from the Longshan culture (5,000–4,000, BP) were found at the Kangjia site. In order to investigate whether the trajectory of diet and health changes persisted beyond the Longshan, a skeletal sample from the Xicun site of the Western Zhao Dynastic period (3,800–2,200 BP) is included in our analyses.

All Yangshao sites in our study are characterized by low frequencies of anemia and carious lesions. Some subsistence changes probably occurred during the later phase of Yangshao culture that resulted in elevated masticatory stress and occlusal macrowear among the Shijia people. However, deterioration of community health did not begin until the Longshan, when increased occurrence of porotic hyperostosis and caries is accompanied by decreased adult stature. The transition to softer, more extensively processed food during Longshan is evident in decreased rates of occlusal wear. Increased population density and diminished food values were most likely responsible for these changes. Poor health persisted into the subsequent Dynastic period of Western Zhao. Am J Phys Anthropol 117: 15–36, 2002.

Considerable climate change following a prolonged mid-Holocene climatic optimum (8,000–5,000 BP) is documented worldwide around 5,000 BP (Shi et al., 1993, 1994; Cohen, 1998; Thompson et al., 1995; Bond et al., 1997; Lamb, 1995; Sandweiss et al., 1996; Krishnamurthy et al. 1995; Sun and Chen, 1991; Jinqi, 1991). The signature of this change is not always clear and varies with the different methods used to track paleoclimate. Whether the change was rapid or slower and preceded by oscillations is not certain. DeMenocal et al. (2000) suggested that the onset of colder and drier climate worldwide was rapid and took place circa 5,000 BP. However, there is evidence for a prolonged period of climatic oscillations in China with very cold episodes during the fifth millennium BP (Shi et al., 1993).

In this paper we focus on subsistence adaptations of millet farmers from northern China that were established during the period of climatic optimum, as well as the adjustments made to the suggested period of oscillations and instability and subsequent onset of colder and more arid climate. The Yangshao culture (7,000–5,000 BP) developed during the time of the climatic optimum. For the two millennia of its existence, the Yangshao population remained sparse and static. Little evidence of social stratification is found for this time, and the Yangshao society is assumed to be egalitarian (Chang, 1986; Liu, 1996a). The later phase of this culture must have been affected by the weather oscillations that preceded Yangshao demise circa 5,000 BP. The period of colder and drier weather was accompanied by the rise of a new dominant culture in northern China, Longshan (5,000–4,000 BP), the predecessor of early dynasties.

The steady decline of Yangshao and rapid population growth of the chiefdom-like society of Longshan were probably related to environmental changes at

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the end of the fifth millennium BP (Liu, 1996a; Underhill, 1994; Cohen, 1998). Environmental deterioration at that time reduced the availability of wild food sources. Millet, a crop with a high tolerance to cold and aridity, was ideal under the new weather conditions. Further agricultural intensification in response to proposed climate change increased the caloric base, which permitted rapid population growth at the Yangshao-Longshan transition. As people aggregated into larger centers, their access to wild food resources became even more limited and their diet narrowed.

Stable isotope analysis of human bone has suggested that the proportion of millet in the diet increased from 58% to 70% from the Yangshao to Longshan periods (Cai and Qui, 1984). However, our data (Pechenkina and Ambrose, unpublished findings) suggest that millet constituted approximately 75% of the Yangshao diet, based on the analysis of bone specimens from the sites we discuss here.

A poorer diet due to reduced availability of animal protein, vitamins, and minerals, the result of proposed agricultural intensification during Longshan, would have negatively impacted community health. The decline of sanitation due to increased population density in Longshan villages should have further exacerbated this problem. Health deterioration with agricultural intensification has been documented for a vide range of populations worldwide (reviewed in Cohen, 1989, 1997; Larsen, 1995, 1997). Dietary changes are evaluated in this study from dental wear, oral pathology, and indicators of masticatory stress, such as osteoarthritis of the temporomandibular joint and exostosis formations. The consequences of the Yangshao-Longshan transition for community health are evaluated by analysis of anemia indicators (porotic hyperostosis and cribra orbitalia), achieved adult stature, and the frequency of growth disruption lines in dental enamel.

YANGSHAO AND LONGSHAN NEOLITHIC TRADITIONS

The people of the Yangshao culture were not the first farmers in Northern China. The earliest noncontroversial evidence of millet domestication dates to 8,500 BP (Chang, 1986; Yan, 1992). By 7,000 BP, traces of millet agriculture are found in nearly every site in the region. Later, during the Yangshao cultural tradition, ubiquitous storage pits and a broad variety of stone spades and fine harvesting knives suggest intensive agriculture (Yan, 1992). Foxtail millet (*Setaria italica*) was the dominant crop in Northern China during the Yangshao (Chang, 1983; Ho, 1977). Other staples included broomcorn millet (*Panicum miliaceum*), found at the Jiangzhai site in Lington County, and rice from the Quanhucun and Zhangbasi sites in Huaxian County (Yan, 1992). According to stable isotope data, millet constituted more than half of the Yangshao diet (Cai and Qui, 1984), although animal and plant remains from the Yangshao sites suggest that the other part of the diet was a broad-spectrum one with heavy reliance on fishing, deer and small mammal hunting, and domesticated animals such as pigs, chickens, and dogs (Yan, 1992).

Several Yangshao phases are usually distinguished for each geographic area. In Shaanxi province, where our Neolithic materials came from, the two early, roughly overlapping phases of Banpo and Jiangzhai (7,000–6,000 BP) were followed by the Shijia phase starting at ~6,000 BP (Chang, 1992). The latter is marked by a new burial practice, one with numerous secondary burials in a single tomb (Gao and Lee, 1993).

The Yangshao-Longshan transition coincided with intensive climate fluctuations, with cold episodes leading to environmental deterioration (Shi et al., 1994; Bi and Yuan, 1998), conditions less favorable for foraging and agriculture. However, at the transition time, the density of sites in north China increased as the population grew. Resulting social tension was expressed in warfare, which is evidenced archaeologically in the spread of the large fortified centers that characterize the Longshan period (Liu, 1996a; Underhill, 1989, 1994).

Environmental deterioration triggered by the colder climate at the end of Yangshao period required subsistence adjustments such as stronger specialization on one staple. Millet is known to be extremely resistant to cold and drought and dependable under poor climatic conditions (Cohen, 1998; Crawford, 1992). Therefore, increasing reliance on millet would not be surprising during the Longshan time, and was supported by stable isotope analysis of human bones (Cai and Qui,1984). A shift towards increased dependence on domestic herbivores such as water buffalo and sheep or goats was suggested by the zooarchaeological record (Liu, 1996b).

Longshan culture was marked by a number of technological innovations, such as a fast-turning wheel for pottery production and widespread use of copper. Tool assemblage, pottery design, and domestic architecture also experienced remarkable advances. Monochrome lustrous burnished black pottery with very thin, up to eggshell-thin, walls replaced the red painted pottery of Yangshao. New shapes of pots came into fashion that imitated metal vessels in their sharply angled profiles. Tripod vessels that will become common during the later Bronze age made their appearance at this time (Watson, 1974; Li and Gao, 1979).

The Longshan period is often viewed as the foundation for succeeding early dynasties, such as Zhou, Shang, and Xia. Architectural features typical of early dynasties, such as labor-intensive rammed earth walls surrounding large settlements, can be traced to the Longshan period and represent the emergence of regional hierarchies. Early ritual objects or power goods such as engraved jade axes and carved burnished black vessels were found at Longshan sites (Li and Gao, 1979). Differentiation of housing and burial practices, together with the

TABLE 1. Age scores based on first principal components analysis of five age indicators

Site	Culture	N	Male/female ratio	Age scores: Mean	Minimum	Maximum	Mean interpolated PC score (average age)
Beiliu	Yangshao	10	0.67	1.22	−0.34	2.20	65.96
Jiangzhai	Yangshao	37	1.64	−0.25	−1.99	1.24	44.92
Shijia	Yangshao	49	1.88	0.003	−1.96	1.21	48.50
Kangjia	Longshan	16	1.66	−0.19	−1.77	1.85	45.77
Xicun	Western Zhao	23	1.3				

emergence of elite goods and ritual materials, point to the development of social stratification and inequality and a chiefdom level of social organization (Underhill, 1989, 1994).

The striking differences between Yangshao and Longshan artifact assemblages provoked numerous hypotheses about an intrusive influence of northern, northeastern, or southern cultures. The idea of intrusion of rice-growing populations from the south was developed by Huber (1983), based on an abrupt change in ceramic style and settlement pattern. While exogenous influences cannot be completely dismissed, the intermediate Miaodigou II culture overlaying Yangshao levels on some sites provides evidence for an indigenous transition between Yangshao and Longshan (An, 1980; Watson, 1974).

In this paper, we present data from human skeletal remains from the two consecutive phases of Yangshao culture, Jiangzhai (7,000–6,000 BP) and Shijia (6,000–5,000 BP), which we compare with the Longshan site of Kangjia (4,500–4,000 BP). Skeletal materials from the Western Zhao dynastic period (3,800–2,200 BP) were also used to evaluate whether the trajectory of dietary and health changes observed between Yangshao and Longshan traditions were temporary or persisted into the later Dynastic period. Variation in subsistence strategies and health status among these sites is assessed with a number of diet and health indicators.

We propose that changing climatic conditions triggered a number of subsistence adjustments that expanded the caloric base of the population. Consequent population growth and aggregation of people into larger centers led to declining sanitation and the deterioration of community health. Food-processing techniques such as milling and cooking may have reduced the dietary value of millet and further exacerbated health problems.

MATERIALS AND METHODS

Samples

Skeletal materials were made available for study by the Banpo Museum in Xi'an, Shaanxi province, and come from archaeological sites in the Xi'an district and adjacent counties, Shaanxi province. The materials analyzed were from three Yangshao sites (Jiangzhai, Shijia, and Beiliu) and one Longshan site (Kangjia). All sites are located within the Yangshao nuclear area, as outlined by Ho (1975). A collection from the Xicun site of the later Western Zhao dynastic period was also included in the study: these skeletons were excavated by a team led by Jiao Nanfeng, from the Qin and Han Research Office, Shaanxi Archaeology Institute, Xi'an (Table 1).

Jiangzhai (Linton County) is a large village located on the eastern bank of the Linhe River (Xi'an Banpo Museum, 1988). The site is over 30,000 m^2 in extent, of which 17,000 m^2 were excavated. Five radiocarbon determinations are available, and they span the range of 4,890–5,970 BP, using a corrected half-life of 5,730 (Institute of Archaeology, CASS, 1991). The site is stratified, and five phases have been recognized (Xi'an Banpo Museum, 1988). The skeletal materials reported here were pooled across phases, but most were from Phase II.

The Shijia site is a Yangshao culture village located on the west bank of the Qui River, Weinan County (Banpo Museum and Weinan County Museum, 1978). The site covers approximately 20,000 m^2. A single determination of 5,000 ± 100 radiocarbon years, using a corrected half-life of 5,730, is available (Institute of Archaeology, CASS, 1991). This date falls towards the upper end of the range of dates from Jiangzhai, so the skeletal material probably postdates most of the skeletons from Jiangzhai. The Beiliu site, also from Weinan County, has only one radiocarbon determination of 6,390 ± 90 radiocarbon years, which positions this site as the earliest among the Yangshao skeletal samples in our study.

The Kangjia village of Longshan is from Linton County. The site has been excavated several times (Xi'an Banpo Museum 1985; Liu, 1996b). Two calibrated radiocarbon dates are available: 4,550 ± 130 and 4,565 ± 135. They fall into the range of the late Longshan period (ca. 4,500–4,000 BP), more than 400 years after the collapse of Yangshao.

Bone preservation was good, with cortices preserved due to the loess environment in which the interments were made. However, postcranial skeletons were often incomplete and were represented by only a few bones, mainly due to selection during excavation and storage. The pooled Yangshao sample was represented by 74 complete or fragmented adult crania, of which 57 had at least a partial corresponding ossa coxarum suitable for sex and age observations. Fifty individuals also had at least one corresponding complete long bone, totaling 223 complete long bones for the Yangshao sample. Sixteen individuals of the Longshan sample were represented by 9 complete and 4 partial skulls, and 13

TABLE 2. Traits used in analysis of occlusal macrowear[1]

No.	Name of trait	Description
1	M_1 buccal wear	Sum of wear scores on mesiobuccal and distobuccal quadrants
2	M_1 lingual wear	Sum of wear scores on mesiolingual and distolingual quadrants
3	M_1 wear orientation	Calculated according to formula (ml + dl) − (mb + db) for M_1
4	M_2 buccal wear	Sum of wear scores on mesiobuccal and distobuccal quadrants
5	M_2 lingual wear	Sum of wear scores on mesiolingual and distolingual quadrants
6	M_2 wear orientation	Calculated according to formula (ml + dl) − (mb + db) for M_2
7	M_1–M_2 wear	Calculated as a difference between M^1 and M^2 total wear scores, each obtained as a sum of Scott scores for four quadrants
8	C crown height	Maximum distance from cementoenamel junction to tip of crown of lower canine, measured on buccal surface
9	C wear	Wear score for lower canine, estimated as in Buikstra and Ubelaker (1994)

[1] Traits 10–18 were calculated for upper teeth and are analogous to 1–9 above. The crown height of canine was measured to the nearest tenth of a millimeter.

partial postcranial skeletons. The Western Zhao sample consisted of skeletal materials from the Xicun site. The skulls and postcranial skeletons were stored separately, so that skulls were not matched to the postcranial bones for the majority of cases. The total number of adult crania in this sample was 23, of which only 7 could be matched to os coxarum. Therefore, sex and age estimation for the Western Zhao sample is generally uncertain. In addition, 634 loose teeth were available from the same site. The Xicun materials were not used in those analyses where controlling for age was required. Sample sizes for each indicator by site are specified in Figures 3–11.

Sex was assigned from pelvic morphology (Phenice, 1969; Buikstra and Ubelaker, 1994) and cranial seriation by robustisity (Krogman and Isçan, 1986). The Jiangzhai site was represented by 37 adult skeletons, 23 of which we identified as male and 14 as female. Among 49 skeletons from Shijia site, 32 were male and 17 were female. Among 10 adults from the Beiliu site, 6 were identified as female and 4 as male. Sixteen adult Longshan skeletons (10 males and 6 females) were present from the Kangjia site at Linton County. Subadult skeletons were highly underrepresented. The burials of most children were commonly made in urns, and these materials were not available for osteological analysis. A Yangshao subadult sample of 13 was obtained by pooling materials from the Beiliu, Jiangzhai, and Shijia sites. No subadult skeletons were available for the Longshan sample.

Dental wear and masticatory stress

Several indicators of dental macrowear were employed to assess the toughness and consistency of food. Independent wear scores were obtained for each of four quadrants of a molar tooth: mesio-buccal (mb), disto-buccal (db), mesio-lingual (ml), and disto-lingual (dl), according to the system developed by Scott (1979a). This method assigns a score from 1–10 to every quadrant according to the development of wear facets and, in older individuals, the amount of dentine exposed. The advantage of this method over others is that it provides a score for the early stages of dental wear, prior to dentine exposure. Wear scores on canines were obtained according to an analogous system presented by Buikstra and Ubelaker (1994). Eighteen wear indicators were than derived from the measurements and scores, as shown in Table 2. Dentitions with evidence of malocclusion or severe caries, or with a composite molar wear score over 33, were excluded from the analysis, since such extreme wear confounds the wear pattern.

Teeth were visually screened for specific wear patterns that could be the result of task-related tooth use, such as chipping, interproximal wear, and lingual surface attrition of maxillary anterior teeth (LSAMT), as described by Milner and Larsen (1991), Turner and Machado (1983), and Lukacs and Pastor (1988).

The exostosis on mandible and maxilla, also known as mandibular and maxillar tori, or hyperostosis, was taken as evidence of masticatory stress. Here we avoid the term torus maxillaris, since it should refer only to continuous and well-developed bony ridges, while in our samples the majority of exostosis cases were in the shape of isolated nodules or short vertical ridges. This interpretation of exostosis variation is supported by growing clinical and bioarchaeological evidence (Eggen and Natving, 1991; Scott et al., 1991; Halffman et al., 1992; Kerdpon and Siririungrojying, 1999). Exostosis was scored independently at two locations: on the lingual portion of the mandible (torus mandibularis) (Fig. 1), and on the buccal portion of the maxilla (buccal exostoses) (Fig. 2). Based on morphology, the exostosis was classified as mild, moderate, or severe. A mild score corresponded to nodules, or intermittent rather than complete ridges (Fig. 1A). Continuous ridges with a thickness of less than 1 cm were given a moderate score. A severe score was assigned only to a maxilla or a mandible in which ridges were over 1 cm thick (Fig. 1B).

The likelihood of osteoarthritis in the temporomandibular joint (TMJ) is known to increase with heavy masticatory loads or when teeth are used as tools (Richards and Brown, 1981; Webb, 1995). Degenerative alterations at the TMJ were scored for

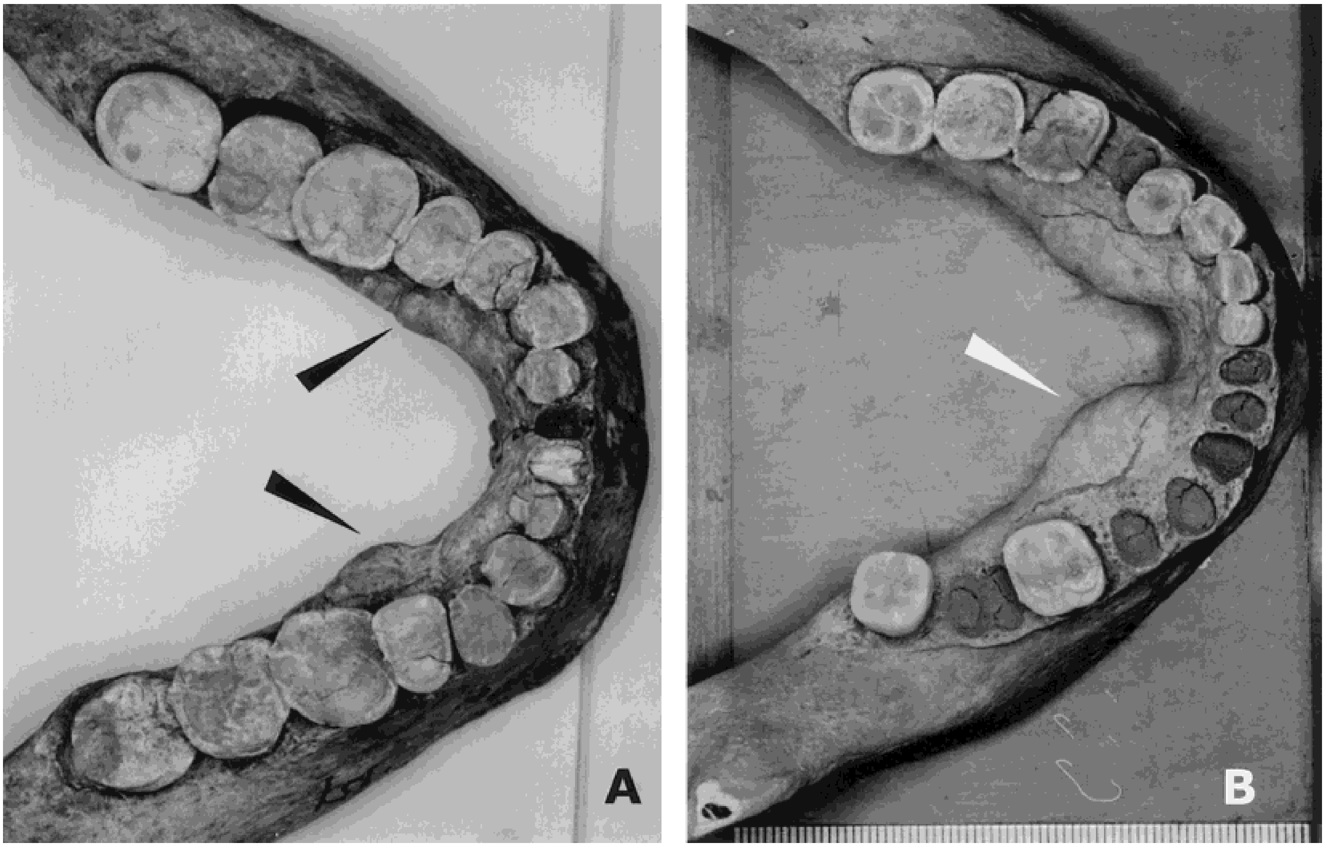

Fig. 1. Different degrees of torus mandibularis development on Yangshao mandibles. **A:** Mild intermittent ridges. **B:** Severe extensive formations. Arrowheads point at exostosis on the lingual side of maxillae.

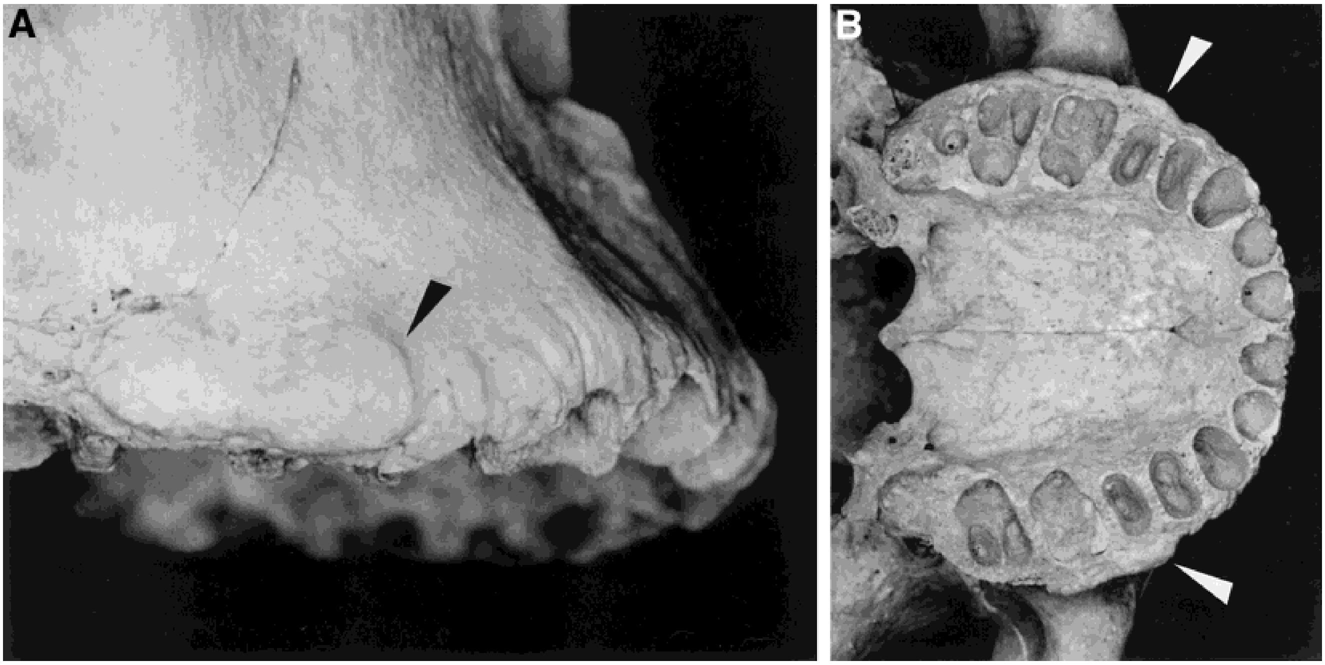

Fig. 2. Examples of buccal exostosis on Shijia maxilla, lateral (**A**) and inferior (**B**) view. Arrowheads indicate nodules of exostosis on the buccal side of maxillae.

both erosions and osteophytes, according to the stages outlined by Richards and Brown (1981): absent; mild or minimal erosion, localized to either the anterior or posterior surface of the mandibular condyle or temporal surface, or mild lipping of mandibular condyles; moderate, presenting extended erosion that affects more than one surface of the TMJ or substantial oseteophytosis of the mandibular condyle covering most of the border; and severe, massive deterioration of the joint extending to the temporal arch and affecting most of the temporal articular surface and mandibular condyle.

Indicators of oral health and stress markers

Carious lesions, antemortem tooth loss, and calculus accretion were scored by visual observation. Carious lesions were noted by location and site, but are discussed here only by occurrence in the posterior or anterior dentition. The lesion had to completely penetrate the enamel, as judged by a probe or bright light, in order to be scored as carious. A missing tooth was scored as an antemortem loss if considerable remodeling was observed in the dental socket. Frequency of antemortem tooth loss was then calculated from the number of tooth sockets present. Calculus was scored following Brothwell (1981) as absent; mild, covering less than one third of the crown; moderate, covering from one third to two thirds of the crown; and severe, covering more than two thirds of the crown. Linear enamel hypoplasia (LEH) was scored following the method described in Goodman et al. (1987) on the labial surfaces of anterior incisors and canines, since these teeth have a prolonged period of formation and are more prone to develop hypoplasia (Goodman and Armelagos, 1985; Goodman and Rose, 1990; Santos and Coimbra, 1999). Only linear defects observable macroscopically or through a magnifying glass were scored.

Porotic hyperostosis (PH) was scored by visual observation at the occipital, parietal, and frontal bones, and at the orbital roof. The later is noted as cribra orbitalia (CO). Both porotic hyperostosis and cribra orbitalia were subdivided into four severity classes, following criteria suggested by Buikstra and Ubelaker (1994) as: absent; mild, simple porosity; moderate, coalescent pores and thickening; and severe, macroporosity with a significant amount of appositional bone and large pore size. No radiographs for skulls were available for confirming the diagnosis.

Long bone lengths were converted into Z-scores by subtracting the mean of the pooled sample and dividing the difference by the standard deviation. Whenever more than a single long bone was present for an individual, the Z-scores were averaged, and the average Z-score was used as an indicator of individual stature. Variation among sites and between sexes was assessed from differences in average Z-scores. This method was preferred to direct stature estimates, since the conventional formulae assume known population bone proportions and can result in unpredictable errors, depending on which particular long bones were present for each individual. Moreover, stature estimates reduce the variance available for analysis in an amount proportional to $(1 - r_{ij})$, where r is the Pearson product moment correlation between stature (i) and limb bone length (j) (Benfer, 1997).

Controlling for age

Age structure of samples. Most of the diet and activity indicators listed above are known to be age-dependent, and their comparison among samples with different age structures presents a challenge to the investigator. In the rather fragmentary Neolithic skeletons, the criteria for age estimation were restricted to a few indicators available for most individuals. Age scores were independently obtained, based on morphological changes in the pubic symphysis (PB) and auricular surface (AS) (Meindl et al., 1985; Lovejoy et al., 1985; Todd, 1920), and the degree of cranial suture obliteration. The latter was scored for 10 ectocranial landmarks of vault (VS) and lateral-anterior (LS) systems, and three endocranial landmarks (ES). Four stages defined by Meindl and Lovejoy (1985) were used.

Multiple regression was used to provide estimates for individuals who were missing one or more aging criteria. A composite age score was obtained as the weighted sum of five age scores (PB, AS, VS, LS, and ES) through a principal components analysis of the Spearman correlation matrix.

The first unrotated factor explained 70.6% of the total variation and significantly correlated with all age scores. Therefore it was interpreted as age. The vector of standardized age scores was premultiplied by loading coefficients of the first unrotated principle component. The standardized age score was obtained from the formula $0.88VS + 0.84LS + 0.85ES + 0.90PB + 0.72AS$. Composite age scores were scaled to a 60-year range from 20–80 years. The lowest factor score was assumed to be equivalent to the youngest adult, 20 years of age, and the oldest individual was arbitrarily assigned an age of 80. Remaining individuals were given age estimates in years by linear interpolation of the factor scores. Age scores for the four samples and the scaled means obtained through this analysis are summarized in Table 1. Average age varied little among the sites. Beiliu and Shijia individuals are somewhat older in adult average age at death; Jiangzhai specimens are the youngest. However, based on Student's *t*-test, the differences are not significant, even between the Shijia and Jiangzhai sites ($t = 1.34$, 84 df, $P = 0.19$).

General linear modeling (GLM). General linear modeling analysis (Gill, 2001), with age as the covariate and site and sex as grouping factors, was employed to evaluate the differences among samples with somewhat different age structures. Covariance analysis relies on a significant linear relation between age and health or dietary indicators to increase the power of the analysis of variance. Variance analysis proceeds with age-adjusted scores in order to detect statistically significant differences among grouping factors. Observationally scored

TABLE 3. Occlusal macrowear indicators: two-way analysis of variance for general linear model, with age as covariate and site and sex as grouping factors[1]

Dependent variables		Site		Sex		Site * sex		Age (covariate)	
		F (2 df)	*P*	F (1 df)	*P*	F (2 df)	*P*	F (1 df)	*P*
1	M_1 buccal wear	4.95	**0.012**	0.11	0.748	2.67	0.082	29.84	**0.000**
2	M_1 lingual wear	3.63	**0.036**	0.25	0.618	0.90	0.415	28.39	**0.000**
3	M_1 wear orientation	4.92	**0.013**	4.41	**0.041**	0.03	0.855	5.37	**0.013**
4	M_2 buccal wear	0.52	0.567	0.96	0.299	0.20	0.798	50.74	**0.000**
5	M_2 lingual wear	1.13	0.286	1.52	0.254	0.11	0.697	8.43	**0.001**
6	M_2 wear orientation	3.72	**0.034**	4.38	**0.044**	0.11	0.697	5.37	**0.013**
7	M_1–M_2	4.06	**0.026**	3.33	0.077	1.46	0.256	4.69	**0.040**
8	C crown height	0.31	0.695	0.34	0.714	0.55	0.588	9.46	**0.005**
9	C wear	2.09	0.156	0.42	0.665	1.04	0.318	22.51	**0.000**
10	M^1 buccal wear	4.38	**0.022**	1.66	0.185	0.81	0.529	27.27	**0.000**
11	M^1 lingual wear	5.81	**0.002**	5.44	**0.026**	1.72	0.230	37.80	**0.000**
12	M^1 wear orientation	2.31	0.109	2.45	0.124	4.92	**0.011**	0.69	0.410
13	M^2 buccal wear	2.51	0.152	1.44	0.235	1.69	0.248	41.26	**0.000**
14	M^2 lingual wear	5.29	**0.008**	10.76	**0.002**	4.27	**0.019**	41.96	**0.000**
15	M^2 wear orientation	4.52	**0.018**	1.45	0.040	0.53	0.592	6.30	**0.020**
16	M^1–M^2	3.27	**0.046**	0.01	0.993	0.47	0.623	1.33	0.255
17	C crown height	0.39	0.687	2.68	0.112	8.62	**0.007**	21.33	**0.000**
18	C wear	1.32	0.167	0.36	0.700	2.66	0.140	7.11	**0.012**

[1] Significance is set at $P < 0.05$; significant probabilities are boldfaced. Crown height of canine was measured to nearest tenth of a millimeter.

traits were analyzed by treating the rank of their scores as if they were equal-interval variables.

In order to investigate the pattern of differences, mean standardized residuals of wear scores from age were plotted by group. Interactions between site and sex groupings were tested for significance in the GLM. A significant sex by site interaction would be present if the effect of sex is not independent from the second grouping variable, site. In other words, an interaction is present when a line connecting one group, e.g., males when plotted by site, does not have the same profile as one that connects females.

Fisher's exact test. Fisher's exact test was used to evaluate frequency differences among sites for different health indicators. This test was appropriate, because sample sizes are small. The two-tailed test computes how likely is it to obtain cell frequencies as uneven as or worse than the ones that were observed. This probability is computed exactly by considering all possible tables that can be constructed based on the marginal frequencies.

RESULTS

Dental macrowear, intensity, and pattern

Only 3 of 5 samples were analyzed for dental wear. The Beiliu sample was omitted because the majority of teeth were worn past the cementoenamel junction due to old age (see Table 1). Since the age assessment of the commingled skeletons from Western Zhao sample was based predominantly on a single indicator, i.e., the obliteration of cranial sutures, it could not be compared to other samples for dental wear. The three samples analyzed included the Jiangzhai and Shijia samples, which correspond to the two subsequent phases of Yangshao culture, and the Kangjia sample, which represents the Longshan.

The comparison of dental wear indicators by the analysis of covariance among sites and among sexes is summarized in Table 3. All absolute wear scores (1, 2, 4, 5, 10, 11, 13, and 14) on molars and crown heights of canines (8 and 17) exhibited significant covariance with age, with $P < 0.01$. Wear orientations of the molars and wear differences between the first and second molars on the mandible displayed a smaller covariation with age than the absolute wear scores but the covariance was still significant, with $P < 0.05$. The only two wear indicators that did not show significant covariance with age were wear orientation on M^1 and wear difference between M^1 and M^2.

Four out of 18 wear scores demonstrated significant sex differences ($P < 0.05$). These included lingual wear scores for M^1 and M^2, and wear orientations for M_1 and M_2. In all these cases, female crowns wore more slowly with age than did the crowns of males. In addition, upper canine crown height and wear orientation on M^1 showed a significant interaction of site by sex.

Significant differences among the three sites were found for 10 wear scores (Table 3). Among them, the largest differences were observed for lingual wear on M^1 and M^2 ($P < 0.01$). Smaller but still significant differences were found for buccal wear on M^1 and M_1, lingual wear on M_1, wear orientations on M_1, M_2 and M^2, and the wear difference between the first and second molars on both the mandible and maxilla ($P < 0.05$).

To examine the pattern of observed differences among sites, wear indicators were plotted by time (Figs. 3–5). Since most of the wear scores showed significant association with age (Table 3), we regressed all macrowear indicators to the age score and used the standardized residuals for the among-site comparisons. The plots of age-adjusted stan-

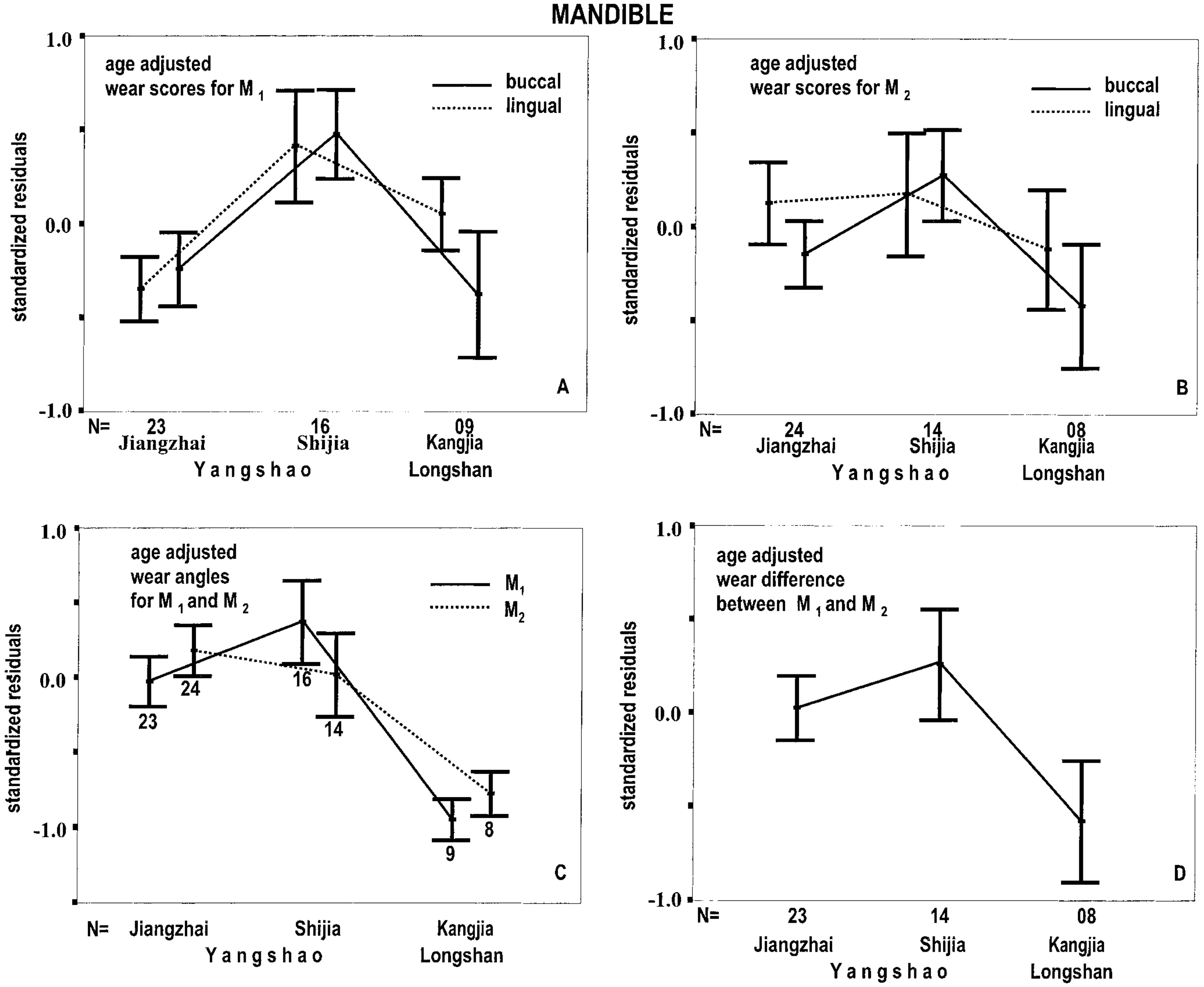

Fig. 3. Rates of occlusal dental wear for the lower molars, expressed as age-adjusted mean standardized residuals from the wear scores by Scott (1979a). Error bars are equal to two standard errors.

dardized residuals for occlusal macrowear (Figs. 3–5) showed a similar difference pattern among sites for all wear indicators, including those that did not reach the level of significance in the analysis of variance. For the majority of indicators, the highest rate of wear was found for the Shijia sample of Yangshao (Figs. 3A,B, 4A,B). The Shijia sample also exhibited the fastest rate of wear angle development (Figs. 3C, 4C) and the largest differences between wear on the first and second molars (Figs. 3D, 4D). The earlier Jiangzhai site overlapped with the later Kangjia site for the majority of wear scores. The exceptions were wear orientations on the lower molars and wear difference between M_1 and M_2. For these traits, the later Kangjia site had a significantly lower rate of development (Fig. 3C,D).

Lingual surface attrition of maxillary anterior teeth (LSAMAT)

Dentitions from the Jiangzhai site were noted for lingual surface attrition of the maxillary anterior teeth (LSAMAT) (Fig. 6). This wear pattern was expressed as large wear facets on the lingual surface of the upper incisors and canines slightly above the cementoenamel junction. No corresponding wear on anterior mandibular teeth was found. Observed characteristics correspond to the description of LSAMAT by Turner and Machado (1983). The pattern occurred only on dental sets lacking carious lesions. It occurred in adult individuals of both sexes.

Bony responses to masticatory stress: exostosis on maxilla and mandible, and osteoarthritis at TMJ

Among bony responses to stress, both buccal exostosis and osteoarthritis at TMJ differed significantly among archaeological sites but did not covary with adult age (Table 4). Expression of torus mandibularis did change with age. Despite absence of the trait after Yangshao, comparison did not show a statistically significant difference among sites, perhaps because of the rarity of the torus mandibularis.

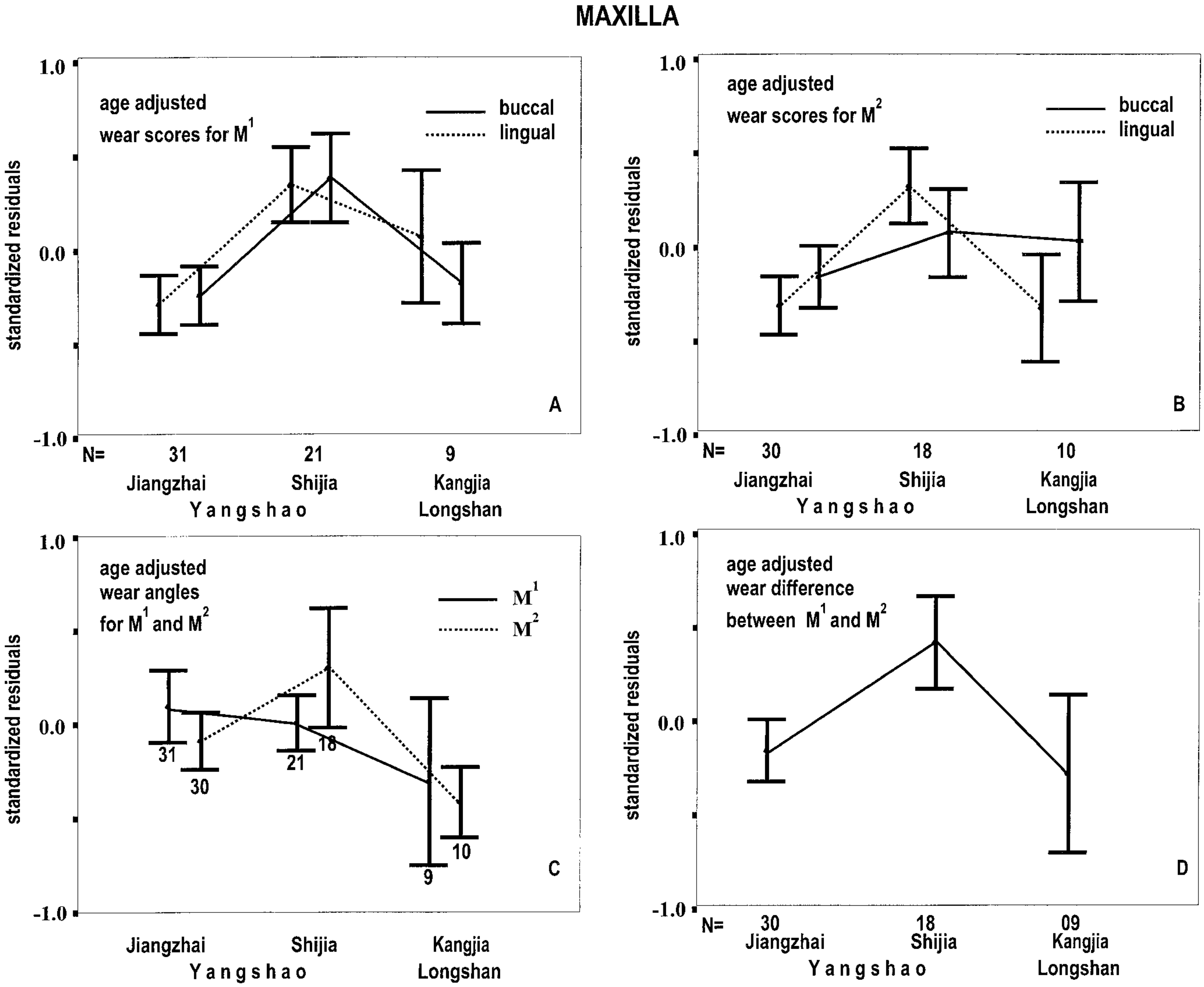

Fig. 4. Rates of occlusal dental wear for the upper molars, expressed as age-adjusted mean standardized residuals from the wear scores by Scott (1979a). Error bars are equal to two standard errors.

The Shijia site has the highest frequency of exostosis formations on the mandible and maxilla (Fig. 7), with alveolar bone formations observed in 54.3%, and tori in 26.5%, of the specimens. The Shijia sample had the second highest frequency of osteoarthritis at TMJ (51.5%). No exostosis formations were observed at the Kangjia site of Longshan or in the sample from the later time period of Western Zhao.

The occurrence of TMJ disorder was slightly higher in Kangjia and Western Zhao samples then in the Jiangzhai of Yangshao (22.2% and 21.7% vs. 14.3%, respectively). In the other two Yangshao sites, Beiliu and Shijia, TMJ disorder occurred more than twice as frequently as it did in samples from the later time periods.

Caries, calculus, and antemortem tooth loss

Significant covarience with age was observed for only one oral health indicator: antemortem tooth loss (Table 5). Significant differences among sites

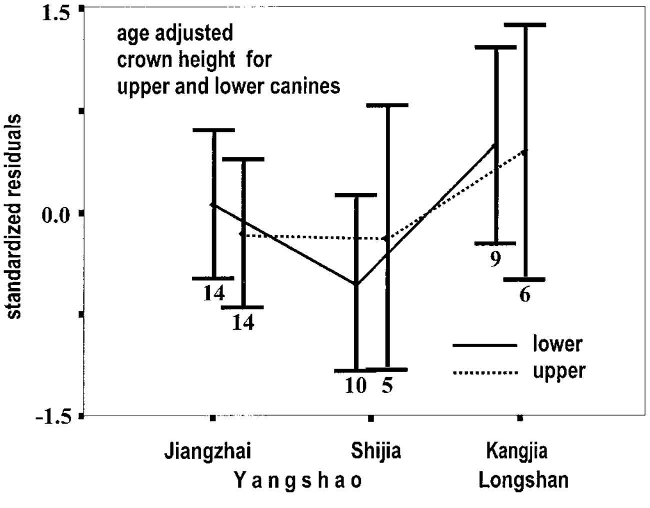

Fig. 5. Rates of occlusal dental wear for the upper and lower canines, expressed as age-adjusted mean standardized residuals from crown height. Error bars are equal to two standard errors.

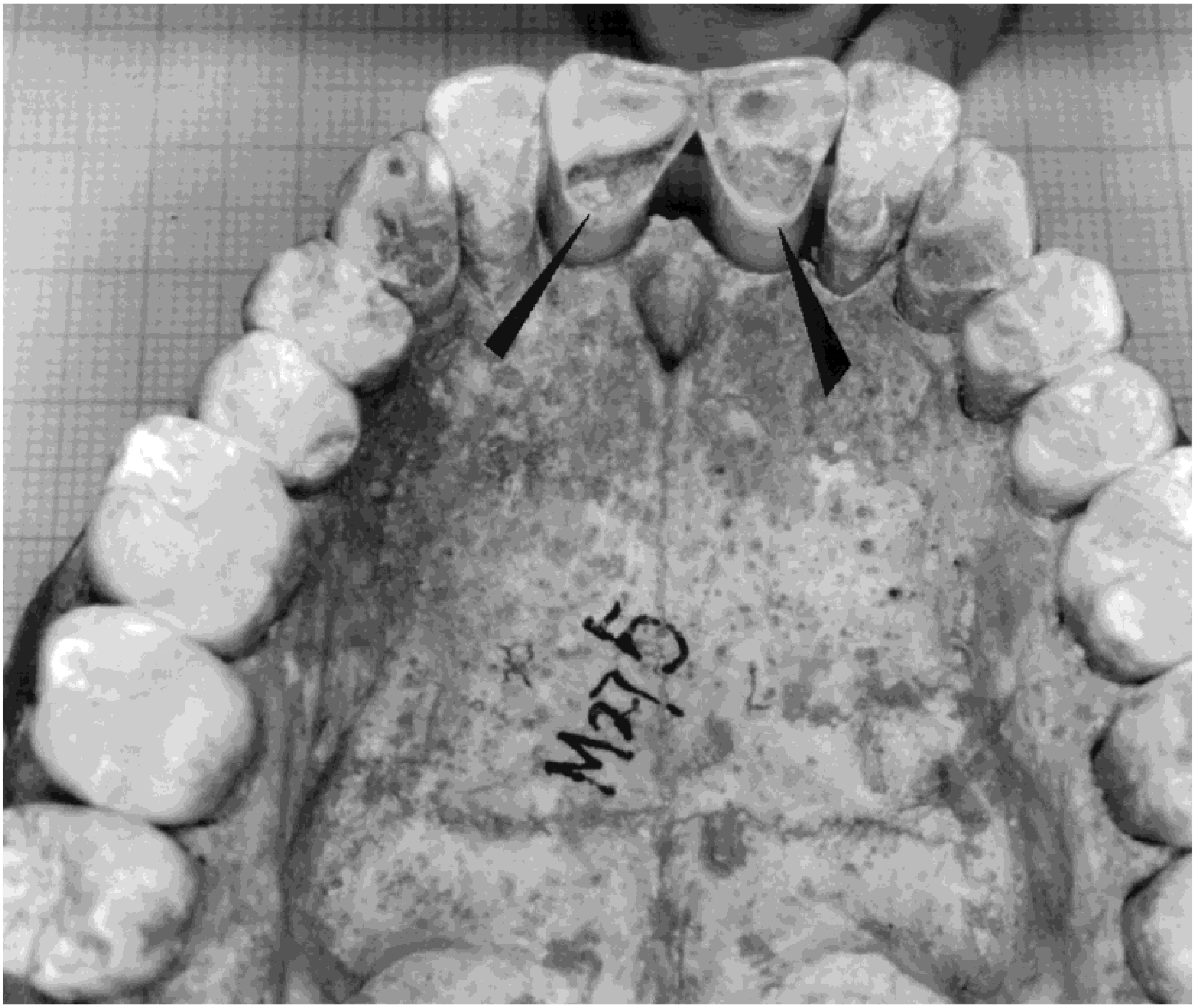

Fig. 6. Example of lingual surface attrition on maxillary anterior teeth from the Jiangzhai site of Yangshao. Arrowheads point at wear facets on the lingual surface of upper incisors.

TABLE 4. Exostosis on mandible and maxilla and osteoarthritis at temporomandibular joint (TMJ) as masticatory stress indicators: two-way analysis of variance for general linear model, with age as covariate and site and sex as grouping factors[1]

	Site		Sex		Site * sex		Age (covariate)	
Dependent variables	F (3 df)	*P*	F (1 df)	*P*	F (3 df)	*P*	F (1 df)	*P*
Buccal exostoses	3.56	**0.018**	2.60	0.111	1.01	0.390	1.25	0.26
Torus mandibularis	1.98	0.126	0.01	0.976	0.63	0.596	5.05	**0.03**
Osteoarthritis at TMJ	5.54	**0.002**	7.89	**0.007**	1.80	0.156	1.55	0.28

[1] Significance is set at $P < 0.05$; significant probabilities are boldfaced.

were found for the frequency of carious adults, including the frequency of adults with anterior and posterior caries, and the frequency of adults who experienced antemortem tooth loss ($P < 0.05$). Carious lesions were very rare during both phases of Yangshao (Fig. 8A). They were never observed on the anterior teeth in samples predating Longshan (Fig. 8B). Teeth affiliated with the later Kangjia site demonstrated higher frequencies of carious lesions both anteriorly and posteriorly than did teeth from Yangshao samples. The number of teeth lost before death was also greater in the Kangjia site of Longshan than was the case for individuals from the Jiangzhai and Shijia sites of Yangshao (Fig. 8C). The early Beiliu sample with its frequent tooth loss seems to be an exception among Yangshao samples, probably a consequence of the very advanced age of all individuals. In addition, antemortem tooth loss showed a significant site by sex interaction (Table 5). Specifically, in the early Yangshao sites of Beiliu

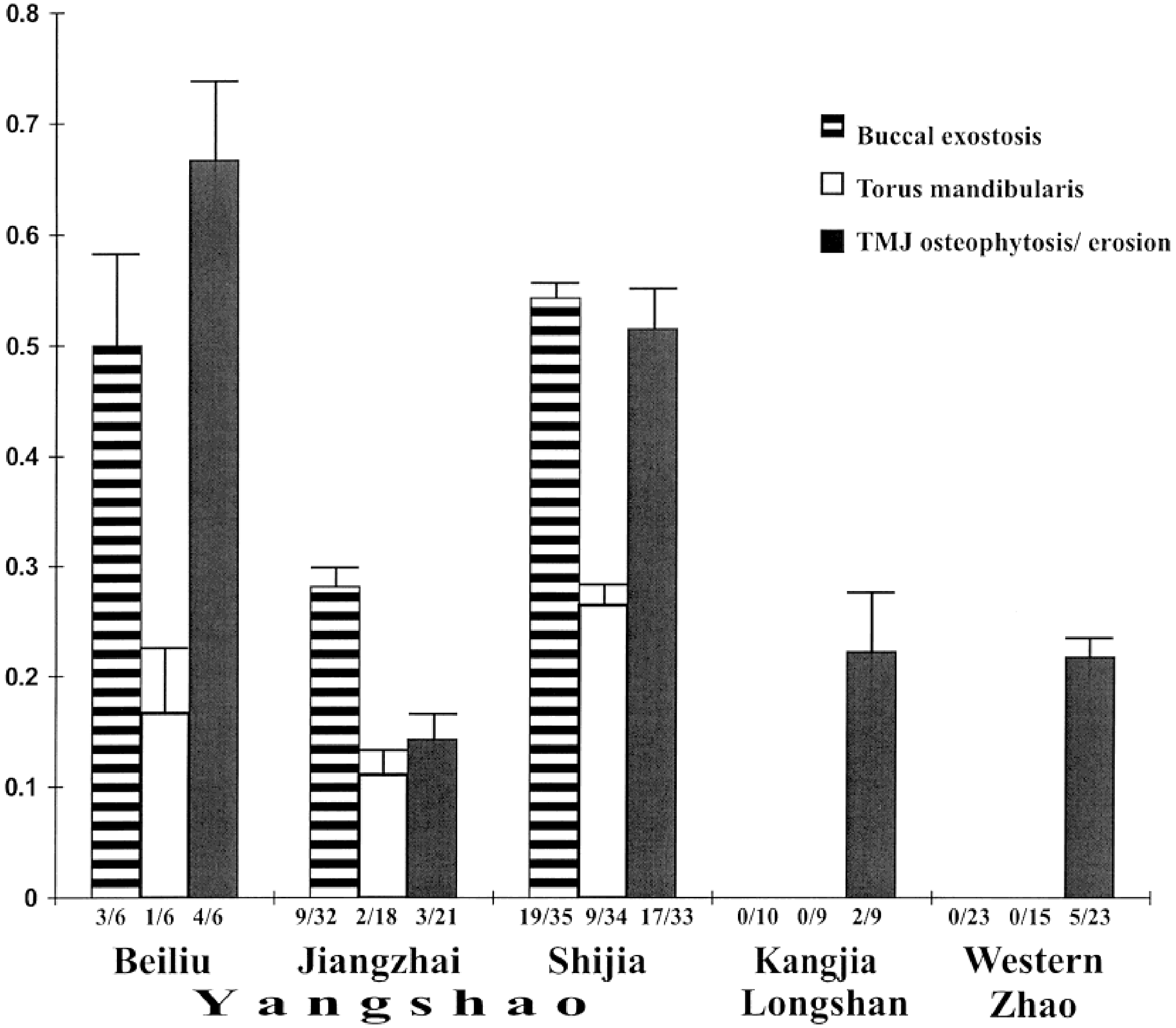

Fig. 7. Frequencies of masticatory stress indicators: torus mandibularis, buccal exostosis on maxilla, and osteoarthritis at temporomandibular joint. Error bars are equal to one standard error.

TABLE 5. Oral health indicators by individual: two-way analysis of variance for general linear model, with age as covariate and site and sex as grouping factors[1]

	Site		Sex		Site ∗ sex		Age (covariate)	
Dependent variables	F (3 df)	*P*	F (1 df)	*P*	F (3 df)	*P*	F (1 df)	*P*
Total caries	7.18	**0.001**	0.00	0.978	0.39	0.762	0.10	0.749
Posterior caries	8.33	**0.000**	0.04	0.840	0.21	0.893	0.21	0.646
Anterior caries	3.24	**0.034**	0.04	0.836	0.04	0.989	0.03	0.874
Teeth lost antemortem	13.57	**0.000**	4.19	**0.046**	8.38	**0.000**	6.32	**0.015**
Posterior teeth lost antemortem	6.15	**0.001**	2.05	0.157	2.99	**0.039**	5.22	**0.026**
Anterior teeth lost antemortem	0.99	0.404	0.01	0.936	2.60	0.060	0.38	0.541
Calculus total	2.29	0.113	6.89	**0.012**	1.53	0.228	0.59	0.444

[1] Significance is set at $P < 0.05$; significant probabilities are boldfaced.

and Jiangzhai, antemortem tooth loss was more frequent among males, while in the Longshan site of Kangjia it became more frequent among females (Fig. 8C).

Frequency of calculus deposits differed significantly between sexes but not among sites. In all sites, calculus was more common among males. The difference between sexes was especially large in the

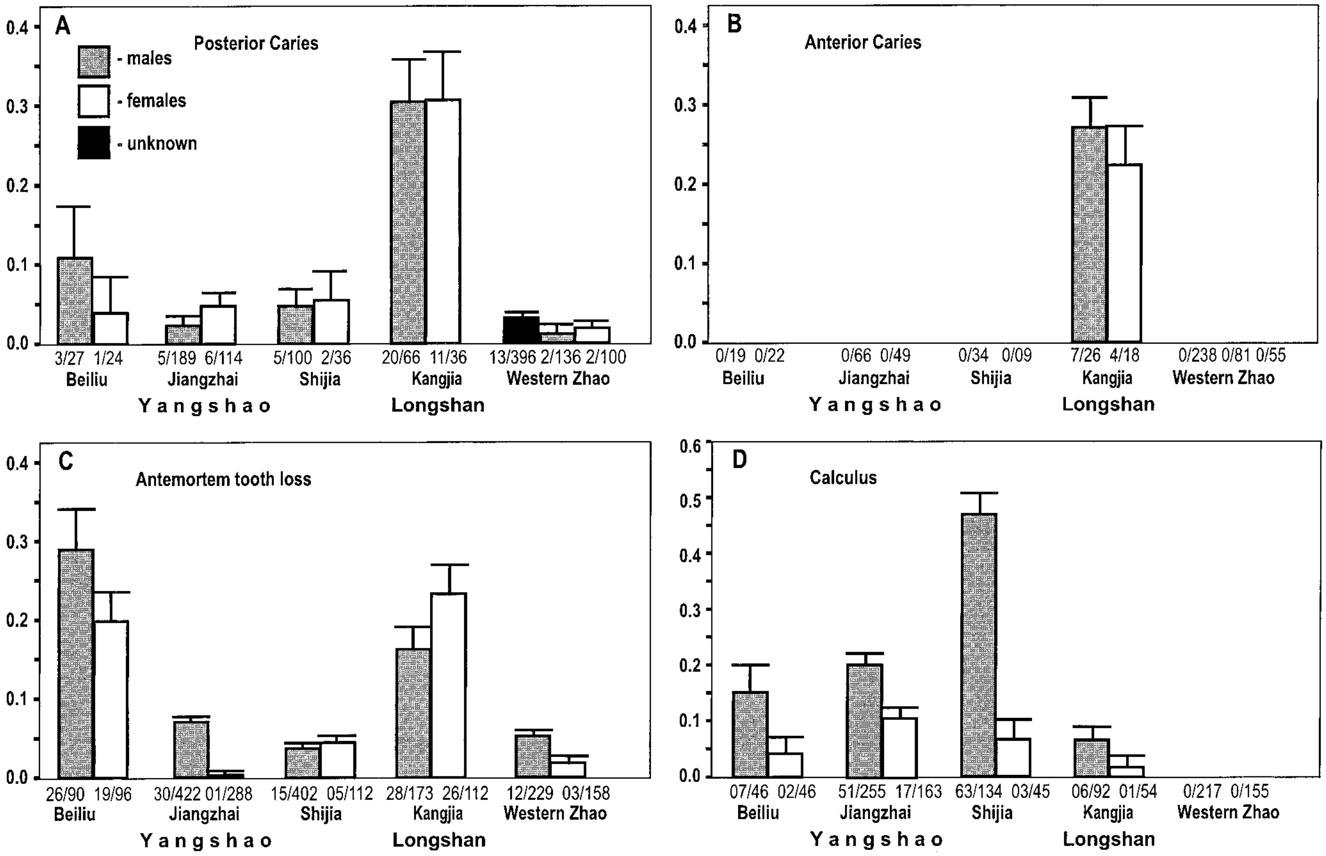

Fig. 8. Distribution of oral health indicators by site and sex. Error bars are equal to one standard error. A, caries on molars and premolars; B, caries on canines and incisors; C, teeth lost antemortem; D, calculus incidence.

TABLE 6. Community health indicators: two-way analysis of variance for general linear model, with age as covariate and site and sex as grouping factors[1]

Dependent variables	Site			Sex		Site * sex			Age (covariate)	
	F	df	*P*	F (1 df)	*P*	F	df	*P*	F (1 df)	*P*
LEH	1.60	2	0.223	0.25	0.621	**6.71**	2	0.005	0.85	0.365
Porotic hyperostosis	6.29	3	**0.001**	3.73	**0.028**	0.58	3	0.628	0.00	0.982
Cribra orbitalia	5.15	3	**0.003**	0.67	0.512	0.66	3	0.582	1.50	0.229
Z-scores	5.02	3	**0.004**	47.17	**0.000**	0.33	3	0.802	1.02	0.318

[1] Significance is set at $P < 0.05$; significant probabilities are boldfaced. Beiliu site was not included in analysis of LEH, because of extreme wear of anterior teeth.

late Yangshao sample of Shijia, where in males calculus was observed on 47.1% of teeth, while in females only 6.7% of teeth had calculus (Fig. 8D). Calculus deposits were mild in most analyzed dentitions. Moderate calculus was found only on dentitions affiliated with the Yangshao culture. At the Shijia site, moderate calculus was uniquely associated with males (28.7% of teeth with calculus), while at the Jiangzhai site, it was evenly distributed between males and females (27.8% and 30.0%, respectively). Not a single case of severe calculus, one with more than two thirds of the crown covered, was noted.

The frequencies of oral health indicators, including samples from the later Western Zhao period (see Fig. 8A–D), display a temporal trend. The high frequency of carious lesions and antemortem tooth loss observed at the Kangjia site of Longshan did not continue into the subsequent dynastic period.

Community health indicators

The results of GLM analysis of health indicators among adults are summarized in Table 6. None of these indicators showed significant covariance with age, implying that the four health indicators we studied had little impact on age-specific mortality during adulthood.

Significant differences among sites were found for all analyzed health indicators. For linear enamel hypoplasia, a strong site by sex interaction term was obtained ($F = 6.71, P < 0.01$). Thus, in the Jiangzhai site of Yangshao, LEH was almost four time as frequent in female teeth than in male ones. In the later Kangjia site of Longshan, the observed pattern was

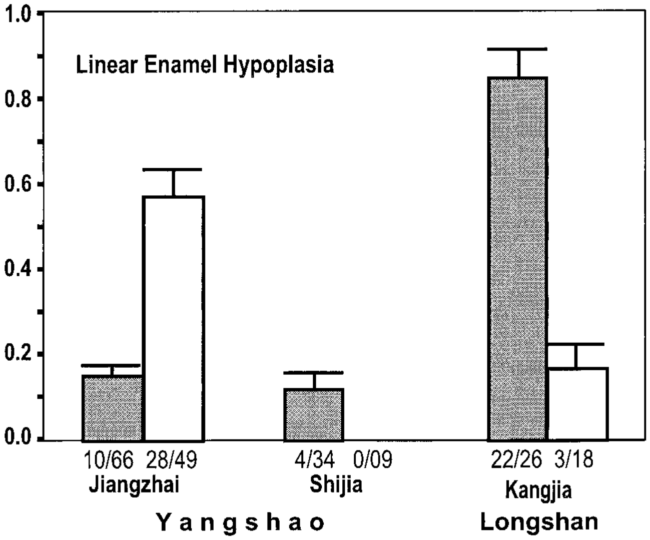

Fig. 9. Distribution of linear enamel hypoplasia by site and sex. Error bars are equal to one standard error.

reversed, and the frequency of LEH in male teeth was five times higher than in female teeth (Fig. 9).

For PH, CO, and the Z-scores of long bone lengths, there were no significant site by sex interactions; among-site comparisons yielded significant F criteria, all with $P < 0.01$ (Table 6). Both PH and CO had significantly higher frequencies and greater severity in the Kangjia sample (Fig. 10 A,B). Only one case of moderate porotic hyperostosis on the cranial vault was observed among 73 skulls of the pooled Yangshao sample, while 3 out of 9 Kangjia Longshan skulls had moderate porotic hyperostosis (Fig. 10A). Cribra orbitalia was generally rare among Yangshao skulls, occuring only in 6 out of 70 skulls. At the Kangjia site, 4 out of 9 skulls were noted with this condition (Fig. 10B). Significant differences between sexes were observed for PH but not CO. Males exhibited PH with slightly greater frequency than females in all analyzed samples.

No subadult skulls were available from the Kangjia site. Nine skulls of children ages 2–9 years, with an average age of 5.5 years, and four skulls of adolescents, ages 11–15, were well-preserved and suitable for study from the Jiangzhai and the Shijia sites. None of these skulls had any sign of porosity in the cranial vault, while cribra orbitalia was observed in two children and one adolescent. Notably, all three cribra orbitalia cases among children were mild, limited to simple porosity without pore coalescence.

Average limb-bone Z-scores were used as the proxy for achieved stature. Based on mean Z-scores, adults of both sexes were probably taller at the three Yangshao sites than were adults from the Kangjia site of Longshan and the Western Zhao sample (Fig. 11, Table 6). The difference was especially strong between males from the Shijia site of Yangshao and the Kangjia site of Longshan. Shijia males exhibited the highest mean Z-score of 0.86 ± 0.26 SE, and

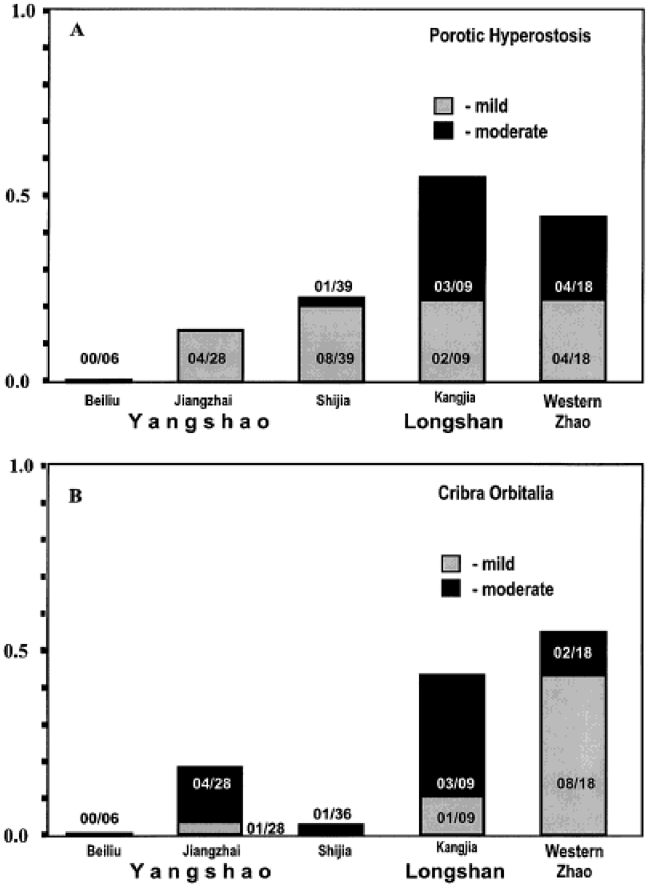

Fig. 10. Frequencies of porotic hyperostosis (**A**) and cribra orbitalia (**B**) by degree of severity.

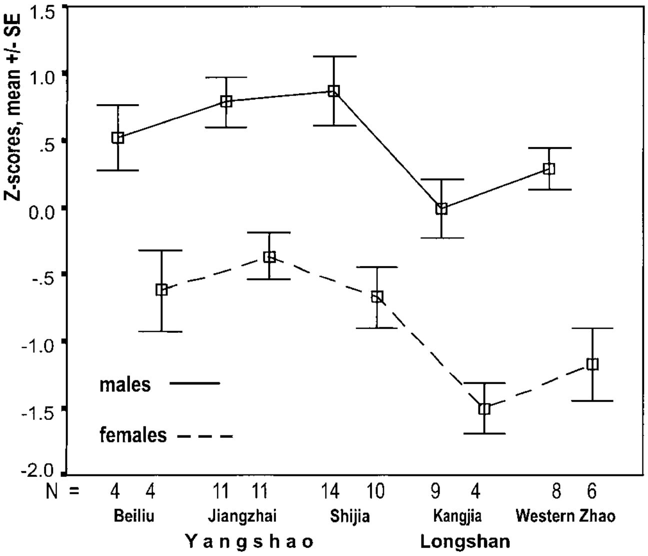

Fig. 11. Variation of long bone length, expressed as average Z-scores among sites. Error bars are equal to two standard errors.

Kangjia males, the lowest one, with a mean of −0.001 ± 0.22 SE. Jiangzhai and Beiliu males had a mean Z-score close to that of Shijia males (0.78 ± 0.18 and 0.52 ± 0.24 SE, respectively). The mean Z-score of Western Zhao males was only slightly

TABLE 7. Frequencies of affected individuals (f) in the Kangjia site of Longshan in comparison with those in the three Yangshao sites and Fisher's exact probability (P)[1]

	Yangshao sites										
	Longshan: Kangjia		Beiliu			Jiangzhai			Shijia		
	f	(N)	f	(N)	*P*	f	(N)	*P*	f	(N)	*P*
Caries anterior	0.30	(10)	0.00	(7)	0.200	0.00	(25)	**0.010**	0.00	(22)	**0.014**
Caries posterior	0.62	(13)	0.29	(7)	0.350	0.10	(30)	**0.001**	0.21	(28)	**0.017**
Calculus	0.23	(13)	0.43	(7)	0.613	0.53	(30)	0.098	0.46	(28)	0.187
Antemortem tooth loss	0.77	(13)	1.0	(7)	0.521	0.13	(30)	**0.000**	0.21	(28)	**0.001**
Linear enamel hypoplasia	0.80	(10)				0.44	(25)	0.071	0.09	(22)	**0.000**
Porotic hyperostosis total	0.56	(9)	0.00	(6)	**0.044**	0.14	(28)	**0.23**	0.23	(39)	0.099
Moderate porotic hyperostosis	0.33	(9)	0.00	(6)	0.229	0.00	(28)	**0.012**	0.02	(39)	**0.018**
Cribra orbitalia total	0.44	(9)	0.00	(6)	0.103	0.18	(28)	0.178	0.03	(35)	**0.004**
Moderate cribra orbitalia	0.33	(9)	0.00	(6)	0.229	0.14	(28)	0.327	0.03	(35)	**0.021**

[1] Significance is set at $P < 0.05$; significant probabilities are boldfaced.

higher than that of Kangjia males (0.29 ± 0.16 SE). Female samples generally repeated the male pattern of among-site variation, with females from the three Yangshao sites being taller than those from the later time periods. Jiangzhai females were the tallest (−0.37 ± 0.17 SE), and Beiliu and Shijia females only slightly shorter (−0.62 ± 0.30 and −0.67 0177 0.22 SE, respectively). Kangjia and Western Zhao females were significantly shorter (−1.5 ± 0.19 and −1.17 ± 0.27 SE, respectively).

The unusually high ratio of between- to within-sex variance for Z-scores ($F = 47.17$, $P < 0.001$) may indicate a surprisingly pronounced sexual dimorphism in stature. However, since 17 out of 74 individuals lacked ossa coxarum and sex had to be estimated by cranial and available postcranial elements, it is possible that sex assessment was affected by limb-bone size that artificially inflated sexual dimorphism.

Because the size of the Longshan sample was small, and because Longshan-Yangshao comparison is crucial for our hypothesis of profound health changes during the time of transition, we provide a more critical test of the differences between the Longshan and Yangshao samples. In GLM analyses, we treated ranked measurements as if they were equal-interval, continuously distributed variables. Here we use Fisher's exact test to compute the exact probability that the distribution of affected to nonaffected individuals is as uneven as or more uneven than that observed for comparisons of each Yangshao site with Longshan (Table 7).

Table 7 shows that despite the small sample size of the Longshan sample, it is highly unlikely that it was drawn from a population with the same frequencies of pathology indicators as the Yangshao samples. For instance, 7 out of 9 health indicators yielded significant differences between the Shijia site of Yangshao and the Kangjia site of Longshan with $P < 0.05$, three of them with $P < 0.01$. The probability that the Shijia and Kangjia populations had the same frequencies of LEH was 0.0002. Five out of 9 health indicators differed significantly between the Jiangzhai and Kangjia sites. Even with the very small size of the Beiliu sample, with only six complete crania, its PH frequency comparison with Kangjia resulted in a significant difference, with $P = 0.044$. Therefore, differences in health indicators are very marked between the Yangshao and Longshan cultures.

DISCUSSION

Dental wear and bony degeneration as the indicators of masticatory stress

All parts of the masticatory apparatus (dental crowns, temporal-mandibular joint, and alveoli) are involved in a life-long degeneration process associated with masticatory load. This process is multifactorial and can vary, for instance, with the degree of antemortem tooth loss, type of occlusion, elemental composition of food, integrity of apatite crystals in the tooth enamel (Scott and Turner, 1988). However, for comparisons among populations, food consistency (e.g., its composition, culinary practices, or amount of abrasive nonfood particles) and extramasticatory activity performed on a daily basis are assumed to be the most salient factors affecting the degeneration of the masticatory apparatus.

The extreme age dependency of this degeneration process complicates interpopulation comparisons, since even when two populations have a similar average age at death, their precise age composition can be rather different. Most efforts to overcome this obstacle have been made in dental macrowear studies, as in the studies of wear score or crown height differences between molars with different timing of eruption (Murphy, 1959; Lavelle, 1970; Lunt, 1978; Richards, 1984; Scott, 1979b; Benfer and Edwards, 1991), wear angle estimates (Smith, 1984), regression of wear facet size on chronological age (Hinton, 1982), and factor analysis of wear scores (Kaifu, 1999).

In the present study, wear scores were estimated following the system of Scott (1979a), where the occlusal surface of the molar is divided into four quadrants, which receive independent scores based on the development of wear facets and degree of dentine exposure (Table 2). Besides the absolute wear scores, we used indicators that were suggested as age-independent, such as wear differences between the first and second molars (Benfer and Edwards, 1991). We used wear orientation, the difference between total wear scores on buccal and lingual cusps, as a proxy for occlusal wear angles. These angles are known to change with different subsistence practices (Smith, 1984).

Interpretation of wear differences among the Yangshao and Longshan samples. The greatest difference between the teeth from the two Yangshao sites and the Longshan site was expressed in the wear angles, which developed more slowly at the Kangjia site (Figs. 3C, 4C). This could be due to particularly slow wear on the directly occluding cusps, i.e., buccal on lower molars and lingual on the upper ones (Figs. 3A,B, 4B). These cusps are usually the first to be removed by wear, so that the occlusal plane of lower molars is usually tilted buccally and that of the upper, lingually. With a slower rate of wear, the development of tilt of the occlusal plane is delayed. For example, Figure 3A shows that while both lingual and buccal wear was slower at the Kangjia sample than at the Shijia sample, it was buccal wear that slowed the most. Therefore, the low occlusal angles of Longshan molars are paradoxically due to slower and not faster wear, and should not be confused with the rapid flat wear of hunter-gatherers due to greater lateral excursion of mandible during heavy chewing (Smith, 1984).

The difference between the wear on M_1 and M_2 also sets the Kangjia site of Longshan apart from the Yangshao sites (Fig. 3D). This difference is primarily established by the amount of wear during the 6-year interval between the first and the second molar eruption. Thus, it can serve as an estimate of wear rate from early childhood diet (Scott, 1979b; Benfer and Edwards, 1991). Some slight positive association with age observed for the M_1-M_2 difference (Table 3) suggests that once the wear of the first molar had reached a certain stage, e.g., full dentine exposure, it progressed more rapidly, which amplified the difference between the first and second molars. Apparently at the Kangjia site, the childhood wear of teeth was minimal, so that the first and second molars remained at essentially the same low wear stage into adulthood. Taken together with the slowly developing wear angles, the slow rate of childhood wear implies a stronger dependence on soft, processed agricultural food, such as cooked cereals, particularly during childhood and early adolescence.

Absolute values for age-adjusted wear scores did not show a substantial difference between the Yangshao and Longshan samples, with the Jiangzhai and Kangjia sites overlapping. The greatest difference was observed between Shijia and the other two sites (Fig 4A–D), with the former exhibiting the highest rate of wear. The analysis of occlusal wear among Japanese samples (Kaifu, 1999) revealed that culinary practices, rather than staple changes, resulted in posterior wear reduction due to softer food and blander consistency. It is probable that the wear on anterior dentition is more sensitive to the dietary shift of the hunter-gather/agriculture transition. In our study, posterior rather than anterior wear, represented by the canine, showed differences among sites (Fig. 5). Therefore, we conclude that the reduction in posterior tooth wear at the Kangjia site is likely attributed to changes in food-processing techniques.

Interpretation of lingual surface attrition of maxillary anterior teeth on Yangshao dentitions. The special pattern of dental wear observed on the lingual surfaces of upper incisors and canines of skulls from the Jiangzhai site of Yangshao is known as lingual surface attrition of maxillary anterior teeth (LSAMAT) (Fig. 6). A similar pattern was reported for prehistoric populations from Colorado, the US Virgin Islands, Brazil,and Panama, and for the historic Senegalese (Turner and Machado, 1983; Irish and Turner, 1987, 1997; Larsen et al., 1998). These populations had highly abrasive diets, rich in carbohydrates such as sugar cane or manioc, as suggested by high frequencies of carious lesions. Thus, LSAMAT was interpreted as the consequence of continuous peeling of hard and sugary plant tissue with the anterior teeth (Turner and Machado, 1983; Larsen et al., 1998). In the case of the Chinese Neolithic, the situation is atypical: LSAMAT was present in the Jiangzhai sample, where the frequency of carious teeth was low. Dental sets exhibiting LSAMAT completely lacked caries (Figs. 6, 8A,B).

The observed pattern could emerge from pulling flexible material along the occlusal surface of the teeth, by pressing a cord or a sinew to the lingual surface of the incisors during weaving or basket-making. However, in this case one would expect to find a large wear facet between canine and premolar, corresponding to the cord exit. Since no such wear was observed, the weaving hypothesis seems implausible. Preparation of fibers from nonsugary plants, as was documented ethnographically (see Larsen et al., 1998), is a more likely explanation.

Exostosis on mandible and maxilla, a trait with a controversial etiology. Localized bone formation on the maxilla and mandible, or exostosis, was interpreted as an indicator of masticatory stress. Although the etiology of these traits remains unclear (reviewed in Seah, 1995), different forms of exostosis, such as torus mandibularis, torus palatinus, and buccal exostosis on the maxilla, seem to share causative factors of stress and therefore tend to co-occur (Jainkittivong and Langlais, 2000). The relationship of these bone formations to masticatory stress has been shown in clinical (Kerdpon and Sirirungrojying, 1999; Sirirungrojying and Kerdpon, 1999) and bioarchaeological (Halffman et al., 1992; Scott et al., 1991) studies. The latter investigations found that maxillary exostoses increased in size and frequency with the shift from a soft agriculture/animal husbandry-based diet to a more rough, wild game-based one. Within our sample, exostosis might be expected to vary with age, because of the accumulation of stress over the life of individuals. Positive association with age has been shown in several studies (Halffman, et al., 1992; Jiankittivong and Langlais, 2000). In our study, the development of torus mandibularis also showed a significant increase with age (Table 4).

Some genetic basis for development of exostosis has been proposed, based on interpopulation differences and family studies (Nary et al., 1977; Gorsky et al., 1998). It is most likely that exostosis is weakly heritable (the genetic variation of torus mandibularis was estimated to be approximately 30% from total phenotypic variation), with an expression threshold that might be exceeded with intense and recurring masticatory stress (Eggen and Natving, 1991; Eggen, 1992).

Both types of exostoses, torus mandibularis and buccal exostoses on the maxilla, were the most frequent at the Shijia site of Yangshao (Fig. 6), where more than one-half of individuals exhibited buccal exostosis. At Shijia, increased masticatory stress was also implied by the high rates of occlusal wear (Figs. 3–5). Closely paralleling the alveolar border, buccal exostoses could be a compensatory response to a periodontal disease (Aufderheide et al., 1998, p. 401–402). Loss of interproximal contact between the teeth due to extreme wear and mechanical damage in Shijia individuals, as well as a high degree of calculus accretion irritating the gum line (Fig. 8E), could be additional factors enhancing buccal exostosis. Torus mandibularis was less frequent than buccal exostosis in all samples. Both types of exostosis were lacking at the Kangjia site of Longshan and in the Western Zhao sample.

Archaeological evidence points to in situ development of Longshan from Yangshao in Shaanxi province (An, 1980), so large genetic change due to population replacement seems unlikely. Still, some genetic differences between the Yangshao and Longshan populations are possible due to minor migrations or genetic drift at the time of climatic adversities. If we accept the interpretation of exostosis as a weakly heritable threshold trait, transition to the softer, more processed food as well as genetic differences from possible population replacement between Yangshao and the later populations of Shaanxi province could be responsible for the difference in exostosis frequencies among sites. In any case, the fact that the distribution of exostosis so closely follows the pattern of occlusal macrowear among the sites implies a major role for masticatory stress in initiating the development of exostosis.

Degenerative process at TMJ and its relation to amounts of masticatory stress. The degeneration of TMJ expressed in osteophytosis and erosion of joint surfaces is another indicator associated with masticatory overloads resulting from heavy chewing as well as from using teeth as tools (Sheridan et al., 1991; Merbs, 1983). In our samples, the frequency of osteoarthritis at TMJ varies from 15% to over 50%, figures that lie within the range reported for Australian aborigines and that generally exceed the 4.5–33% frequency range for contemporary European and African populations (Webb, 1995, p. 177–179). High frequency of this pathology in Shijia was accompanied by an increased frequency of buccal exostosis and torus mandibularis. The co-occurrence of TMJ pathology with exostosis formations was demonstrated clinically (Sirirungrojying and Kerdpon, 1999). Being degenerative processes, TMJ osteophytosis and erosion might be expected to increase with age. However, their covariance with age in our pooled Neolithic sample was not significant (Table 4). In fact, Sheridan et al. (1991) found that deterioration of TMJ is more strongly associated with posterior tooth loss and corresponding mechanical loads on this joint than with age. So it may be that the frequent loss of posterior teeth in the Longshan site of Kangjia was responsible for the elevated frequency of TMJ osteoarthritis. In the Beiliu sample, both the high frequency of antemortem tooth loss and the advanced age of the individuals probably contributed to the elevated frequency of TMJ pathology.

The frequencies of TMJ disorder were distributed somewhat differently than those of exostosis among sites. The Longshan and Western Zhao samples, which did not exhibit any exostosis formations, had higher frequencies of TMJ disorders than did the Jiangzhai sample of Yangshao, where 28.1% of skulls had buccal exostosis. Thus, the two traits bear complementary rather than equivalent information regarding masticatory stress. Presumably Longshan and Western Zhao individuals never reached the threshold of stress sufficient for expression of the exostosis.

Summarizing the findings on dental wear and bony responses to masticatory stress, we note that significant dietary changes probably occurred between the earlier and later phases of the Yangshao culture in Shaanxi province. These changes increased masticatory stress and overall occlusal wear during the Shijia phase. Either heavier reliance on wild food sources or increased dependence on coarsely ground millet containing nonfood particles could have led to increased chewing stress during this time. During the subsequent Longshan period, daily chewing loads probably decreased, and remained low during the following Western Zhao dynastic period. These changes cannot be explained solely by an increasing reliance on millet. The proportion of millet in the diet of Shijia and Jiangzhai people was already high based on stable isotope analysis (Pechenkina and Ambrose, unpublished findings). The change in grinding and cooking practices of millet, greater reliance on fattier domestic rather than wild animals for the meat fraction of food, or a different subadult diet are all possible causes of observed changes. Extension of cooking time is likely during Longshan, in light of improved pottery. These dietary adjustments were associated with declining health during Longshan.

Oral health

Caries. Carious lesions have a complicated etiology and are affected by a variety of factors, including food composition, salivary contents, presence of dietary carbohydrates, oral hygiene, genetic predisposition, enamel defects, mineral composition of drinking water, and oral bacterial flora, to name but a few (Rowe, 1982; Ettinger, 1999; Marsh, 1999). Varying amounts of carbohydrates processed in the oral cavity is the most common explanation of caries frequencies in prehistory (Larsen et al., 1991; Sledzik and Moor-Janssen, 1991).

All Yangshao sites had relatively low caries frequencies (Fig. 7A,B), with values that fall within the upper half of the range for hunter-gatherers and the lower half for populations with mixed economies as defined by Turner (1979). The exceptions for the Yangshao series are the females from Shijia and Beiliu, whose caries frequencies are slightly higher than those expressed by populations with mixed subsistence. No cases of anterior caries were observed in Yangshao sites, while they were frequent in the Longshan series. Caries frequency in the Longshan-period Kangjia sample falls within the upper half of the range of populations practicing agriculture (29.3% of teeth for males, and 27.8% for females). Frequency of anterior caries at this site is almost as high as that of posterior caries (26.9% vs. 30.3% for males, and 22.2% vs. 30.5% for females).

Interestingly, the high frequency of caries observed in the Kangjia sample (over 25%) seems to be atypical for Northern China in later prehistory. For example, Turner (1979) reported 2.2% of teeth with one or more caries among an An-Yang sample from the Shang Dynasty. Another population, from the end of Shang Dynasty (3400–3100 BP), had 2.9–4.0% of carious teeth (Sakashita et al., 1997). Similarly, we found only 3.3% of posterior and no anterior caries in 634 teeth from the Xicun site of Western Zhao, in the Dynastic period following Longshan. Since all these populations are thought to rely on millet agriculture as a chief staple (Chang, 1986), it is obvious that millet alone cannot be blamed for the poor oral health at the Kangjia site. It is possible that inadequate mineral composition of food such as processed cereal could have resulted in poor enamel calcification and enamel defects that allowed caries formation. For the Kangjia sample, inadequate enamel mineralization is suggested by a high frequency of enamel hypoplasia (Fig. 9). Indeed, the role of enamel defects as a predisposing factor for caries has been supported by clinical studies (Infante and Gillespie, 1977; Li et al., 1996).

Antemortem tooth loss. Analysis of variance documented the age-dependence of antemortem tooth loss (Table 5). Age-related tooth loss in Yangshao individuals was probably a consequence of the mechanical damage at the gum line produced from high masticatory stress, since the caries frequency was very law (Scott and Turner, 1988). The extensive tooth loss observed in the Beiliu sample (Fig. 8C) appears unusual in the Yangshao period, and can be explained by the very advanced age of the individuals (see Table 1).

Antemortem tooth loss (Fig. 8C) generally repeats the pattern of variation among sites and between sexes of carious lesions on posterior teeth for the samples other than Beiliu. The lowest frequency of teeth lost antemortem occurred in the Shijia sample of Late Yangshao, and the second highest, in the Kangjia sample of Longshan. The Shijia sample of Yangshao exhibited the highest rate of occlusal wear. It seems likely that this rapid wear helped to prevent the development of large carious lesions and reduced the number of teeth lost to caries. Thus, large caries can be suggested as the leading contributor to the among-site variation in antemortem tooth loss.

Calculus accretion. Dental calculus is a mineralized plaque that results from the deposition of calcium and phosphates, resulting from interactions between the oral microbial plaque flora and the components of saliva (Wong, 1998). Due to the multiplicity of factors participating in calculus formation as well as the unpredictability of postmortem loss, there seems to be little agreement on the interpretation of calculus occurrence in prehistoric samples. On the one hand, food with a low abrasive quality, which is typical for most agriculturists, does not remove plaque formations and, therefore, can favor the development of calculus (Turner, 1979). On the other hand, protein intake increases the urea concentration in the blood and consequently the alkalinity of all bodily fluids, including saliva. Since plaque is more likely to mineralize in an alkaline solution, a positive association between a high meat diet and calculus accretion is expected (Hilson, 1979; Wong, 1998).

Consequently, a diet based on soft animal products, such as processed meat of domestic animals, milk products, and poultry, is expected to be favorable for calculus formation. Increase in calculus frequency was found for the shift from foraging to herding with the Mesolithic to Neolithic transition in the Ukrainian steppe (Lillie, 1996). Frequent calculus deposits (88%) were reported for the Yugoslavian Mesolithic, where a meat-based diet prevailed (y' Edynak, 1989). The shift from a fishing-based economy to agropastoralism in the Arabian Gulf led to an increase in calculus (Littleton and Frohlick, 1993), possibly due to less abrasive food.

Although other oral health indicators in our study varied mostly by site, the variation in calculus frequencies was primarily by sex (Table 5). Calculus was observed more frequently on male than on female teeth in the three Yangshao sites and one Longshan site. The difference is particularly well-expressed at the Shijia site (Fig. 8D). Prevalence of calculus among males is often reported in bioarchaeological studies and sometimes attributed to more frequent access to animal products by males (y' Edynak, 1989). The radiocarbon date obtained from the Shijia site places it at the end of Yangshao existence and coincides with the onset of periodic cold climatic episodes. A shift to more hunting and fishing could have occurred in an attempt to compensate for poor harvests. Thus, the large difference in calculus frequencies between males and females from the Shijia site could be due to greater male involvement in hunting or herding activities.

The complete absence of calculus for Western Zhao sample is surprising and we have no explanation, although it might be conjectured that there was a high postdepositional loss in Xicun site materials.

Changes in community health at the Yangshao-Longshan transition

Stress indicators. The health indicators examined here measure different aspects of childhood health. Linear enamel hypoplasia (LEH) reflects some temporary metabolic stress during tooth formation. The condition must be severe enough to depress the ameloblastic secretion, resulting in a band of abnormal enamel (Osborn, 1973). Insults from the introduction of solid food, inadequate diet during weaning and early childhood, severe infectious diseases, and episodes of malnourishment during tooth crown formation are among the factors thought to cause LEH (Corruccini et al., 1985; Goodman et al., 1987; Lanphear, 1990; Blakey et al., 1994). Unlike LEH, porotic hyperostosis and cribra orbitalia are caused by a chronic rather than acute condition, and are indirect markers of anemia. An anemic condition can develop in response to a prolonged energy deficiency in combination with inadequate mineral composition of food (Ulijaszek, 1991) or chronic parasitic loads (Stuart-Macadam, 1992). Whether chronic or acute, LEH-, PH-, and CO-causing conditions diminish health, and might reduce a child's life expectancy (Rose et al., 1978; Duray, 1996; Stodder, 1997). Therefore, the assessment of community health on the bases of nonspecific indicators in a mortuary sample is complicated by uncertain morbidity/mortality relationships among the subgroups, so that the observed profile of pathology indicator in a skeletal collection could be paradoxical (Wood et al., 1992). Anemia increases the likelihood of death during childhood, and its indicators (PH and CO) are often seen in subadult skeletons (Mittler and Van Gerven, 1994; Milner and Smith, 1990). Consequently, an increase of PH and CO on adult crania over time could signify an overall improvement in children's survival. Thus, Wright and Chew (1998) suggested that a higher occurrence of porotic lesions among adult Maya in prehistory than today was due to a lower childhood mortality in prehistory, one that allowed for the survival of anemic children. If it was a difference in early childhood mortality that caused the among-site variation in PH and CO in the Chinese case, then the sites with a lower occurrence of porotic lesions among adults, namely those from the Yangshao period, would be expected to have a higher frequency of porotic lesions among children. Contrary to this expectation, the pooled sample of subadults from the Yangshao period demonstrated only mild porotic hyperostosis, with a frequency barely exceeding that of adults. Relatively low occurrence of PH and CO among Yangshao children does not support the hypothesis that severe anemia was a dominating contributor to childhood mortality during that time, nor did childhood anemia predispose adults to an early death, as the correlation between PH and CO and age at death for adults was not significant.

Stature. Increased reliance on maize, rice, barley, and wheat agriculture led to a decline of adult stature in many prehistoric societies, but not universally (Larsen, 1995; Angel, 1984; Goodman et al., 1984; Kennedy, 1984a; Meiklejohn et al., 1984; Jackes et al., 1997). Thus, the decline of stature during the Longshan and later Dynastic period is not surprising in the context of proposed agricultural intensification. A broad variety of environmental factors, including those causing LEH and PH, and genetic predisposition could account for the reduced adult limb bone length observed for Longshan and the following Western Zhao (Fig. 11). Excessive stress during growth is suggested for the shortest people that comprise the Longshan sample, who displayed the highest LEH, PH, and CO frequencies in our study (Table 7). The co-occurrence of LEH with growth delays, reduced long bone length, and different body proportions has been demonstrated (Cook, 1984; Goodman et al., 1991; Buzhilova and Mednikova, 2001; Boldsen, 1998). The fact that the largest decline in stature was associated with the highest frequency of LEH in the Kangjia site supports the role of shared factors in LEH formation and stature reduction. Frequent growth disruptions during early childhood of Kangjia males, recorded by frequent LEH, could be responsible for the diminished adult stature.

It is interesting that during the Shijia phase of Yangshao culture, sexual dimorphism in stature increased. Indeed, while the Shijia males are the tallest among our samples, judging by limb bone length, the females from that site are shorter than females from Jiangzhai. These sex differences are associated with higher calculus accretion in male dentitions from the Shijia site, and can be tentatively interpreted as due to males having access to higher quality foods, especially animal protein, during the later phase of Yangshao culture. Masticatory stress had increased towards the end of Yangshao with climatic instability, but overall health, as judged by our nonspecific indicators of stress, did not begin to decline until sometime later.

Taken together, the increase in CO and PH frequencies and severity, the decline of adult stature, the somewhat elevated frequency of LEH, and the dramatic increase in frequency of carious lesions and antemortem tooth loss during the Longshan period support an interpretation that community health declined, probably due to settlement overcrowding (Liu, 1996a). In conjunction with declining sanitation, the increase in anemia could be viewed as a physiological response to increased parasitic load, since withholding iron from the blood inhibits the infection process by preventing the successful survival and reproduction of the parasite in the body (Stuart-Macadam, 1992).

Greater reliance on millet and, particularly, overuse of processed millet in the diet of young children, and extended time of food boiling, could be contributing factors to the observed decline in health in the later Longshan period. Generally high in iron for a cereal, millet, like most of other cereals, loses iron through cooking (Drake, 1989; Cisse et al., 1998). In addition, lower meat intake, as suggested by reduced calculus deposits in the Longshan sample, may have contributed to the observed increase in anemia.

The fifth millennium BP was a crucial point in the cultural development of the Old World. A number of cultural changes parallel to those seen in Northern China took place in India and the Middle East. Similar to the Neolithic revolution about 8000 BP (Flannery, 1969), these changes coincided with a period of climatic instability. The Indus Valley witnessed the rapid rise of Harappan civilization, whose preurban phase is contemporary with the Yangshao to Longshan transition (Possehl, 1990). The frequency of PH in Harappan mortuary samples was higher than evidenced in our Yangshao samples but lower than in Longshan and Western Zhao, varying from 18% at Mohenjo-Daro to 6.9% at Harappa (Kennedy, 1984b; Lovell, 1997).

With respect to population growth and community health, the Yangshao-Longshan transition pattern resembles the health decline that occurred during the Woodland to Mississippian transition (circa AD 1000) in the New World, with greater maize dependence in the Mississippian (Buikstra, 1984; Buikstra et al., 1986; Rose et al., 1978). However, in the North Chinese case, the precise role of specialization on a single staple for observed population dynamics is less clear. Yangshao people from the Jiangzhai and Shijia sites were already consuming large amounts of millet, as suggested by stable isotope analysis (Pechenkina and Ambrose, unpublished findings). Exactly what kind of subsistence and cultural changes allowed the base population to expand the caloric base circa 5000 BP and trigger the population growth associated with the rise of Longshan is a question that requires further analyses of paleodiet.

CONCLUSIONS

Based on the skeletal analysis of Yangshao and Longshan materials from Shaanxi province, it is proposed that the decline of Yangshao culture during the fifth millennium BP was associated with marked changes in subsistence practices. Dietary changes led to an overall increase in occlusal wear and masticatory stress in late Yangshao. The dietary differences between sexes most likely increased during this time, as can be inferred from the greater stature difference between males and females and elevated calculus occurrence observed on male dentitions. The subsistence changes were probably triggered in the first place by climatic oscillations during the terminal phase of Yangshao culture.

Serious deterioration of community health is not evident until the Longshan culture, when a marked decline in stature and an increase in the prevalence of anemia were found for both sexes. Overcrowding and a decline in sanitation in the larger Longshan settlements must have contributed to a deterioration of health. Poor community health persisted into the subsequent Dynastic period of Western Zhao.

Given the small size of our Longshan sample, it is uncertain whether the same pattern of dietary and health changes will serve as a model for all populations of Northern China. Different scenarios are possible in other environmental settings. Further research is necessary before this important shift in Chinese prehistory is well-understood.

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