

Paleolithic polygons: Voronoi tesserae and settlement hierarchies in Cantabrian Spain *

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Sometimes, the application of an unusual analytical technique to a body of commonplace data produces information as interesting as it was unexpected. This paper discusses suggestive patterns made by drawing Thiessen polygons (also called «Voronoi tesserae») around Paleolithic sites in the autonomous political region of Cantabrian Spain, where prehistoric investigations have been especially intense over the last few decades. The simple geometric patterns resulting from this purely mathematical procedure suggest that sites used during each of four periods fall into previously unrecognized hierarchical arrangements, that generally agree with informed evaluations of the «importance» of their assemblages, but that have no straightforward explanation in the purely environmental terms that are the prehistorian's conventional fallback.

Settlement studies are of the greatest interest to Paleolithic prehistorians and other archeologists. Yet despite the immense amount of data that have been gathered from Paleolithic sites during more than a century and a half of explorations, we can still not reconstruct the settlement systems corresponding to any Paleolithic complex anywhere. We have begun to recognize the characteristic signatures of some of recurrent «tasks» undertaken during individual Paleolithic occupations of a site, but site classification has scarcely proceeded beyond the obvious distinction between open air and cave sites, the differentiation of quarry/workshop sites from «butchering» sites, and of both from a heterogeneous category of other sites that probably includes some «base camps» and others that are almost certainly functionally specialized for

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sets of actividades whose signatures have not yet been determined. It is our fond hope that, by means of careful excavation (in fact, *only* by that means) we may eventually assemble the data needed to evaluate changing site functions, so that we may see how contemporary occupations fit into their proper position in a network or interrelationships, and identify the part each played in the larger settlement systems of the Paleolithic. But as yet, that is only a hope.

Our excavations already show us that some stratigraphic sequences are much longer and some occupation levels immensely richer in contents than others. We usually explain such differences in terms both vague and conjectural. The unverified postulate that all Old Stone Age societies must have been «simple and egalitarian», with little specialization of statuses, has generally been extended to the sites as well, and the idea that (roughly) contemporary sites might actually occupy positions in a graded settlement hierarchy, (a possibility commonly entertained by those who study the archeology of later and presumable more complex societies), is infrequently considered in literature about the Old Stone Age. In cultural studies, Thiessen polygons are part of the analytical battery of geographers and others who analyze relationships of centers to satellites, in settlement hierarchies. As such, their use would usually be considered out of place in Paleolithic prehistory. If others have applied this procedure to Paleolithic data (and I presume someone must have) I am ignorant of the fact.

The work that follows is a rough outline —a preliminary heuristic sketch for further exploration, rather than a finished study. It maps Voronoi polygons about sites from four major Paleolithic phases in Cantabria, Spain. The area considered is no a natural region but the autonomous political region of Cantabria. This arbitrary selection was made for convenience and can of course be challenged, since there are sites in both Asturias and the Basque provinces that would have added other polygons to the eastern and western Periphery of the studied area. However, it is justifiable. The omitted sites are far enough from the peripheral Cantabrian sites that their addition would alter my results minimally.

I realize that there are other possible objections to my choice of area and sample, but I do not believe that they invalidate this research. The northern boundary of the mapped area falls in the sea off Cantabria's coast. Since there are no known underwater sites, those on the immediate coast might be expected to be bounded by fewer neighbors than are ones further inland, but this theoretical objection is actually of little practical importance, since «coastal» sites prove to have relatively numerous neighbors, during at least some periods. The southern boundary of the mapped area coincides with the highest mountains in Cantabria. During the Paleolithic, human occupation was essentially absent above

about 600 meters. Bounding the study area here seems eminently reasonable, since the high uplands, extending in a wide east-west band along Cantabria's southern border, were evidently an important barrier to habitation throughout the Paleolithic. Of course, there probably are as yet undetected sites within the land area included in the study. But undetected sites should be scattered more or less at random over the landscape; there is no reason to think that they would be concentrated in any particular area at the expense of others. Exploration of Cantabria has been relatively thorough and uniform. Sites have been sought assiduously by local amateurs, professional archeologists, and expert speleologists, so there is no reason to assume that any part of the study region has been less thoroughly surveyed than any other. It is true that most known sites are in caves. But Cantabrian bedrock is mostly limestone, and caves are ubiquitous. Underrepresented sites are thus likely to be open-air sites buried deep below the surface. There has been a good deal of capital construction—roads, railroads, tunnels, and extensive building—and much quarrying. From all evidence to date, open air sites must have been very rare compared to sites in caves. There is no reason to believe that any part of the region is disproportionately rich in buried open sites, and the very few of these that are known were probably mostly quite small and have been extensively disturbed. The near-absence of open-air sites in our sample is a fact no one can remedy at present; the only way to proceed is to work with what we do have.

The next step of may exercise was to determine how to divide the Paleolithic universe in Cantabria into manageable and meaningful units. Acheulian localities with any guarantee of integrity are too few to be interesting. The earliest phase of regional occupation that is both reasonably distinctive and has enough sites for useful comparison is the Mousterian, if facies differences are disregarded. All the Mousterian sites are in caves, except Unquera. Early Upper Paleolithic sites with Chatelperronian or Upper Perigordian tools are not common in Cantabria, but there are several with Aurignacian occupations: combining them into «Early Upper Paleolithic» sites produces a second unit. There are enough well documented Solutrean and Magdalenian sites so that each complex could be considered separately, although it was not possible to subdivide either group further. I excluded from consideration all surface collection, all mixed and dubious sites—those where older collections have been lost or are not sufficiently diagnostic, and those recently tested sites that so far have produced inadequate samples for attribution—despite the fact that they appear on some published lists. I may possibly have excluded some sites that should have been included, but I don't think I have omitted any important site or included any dubious case. Where two or more

Table 1
Site adjacencies in descending order

Mousterian	Early U. P.	Solutrean	Magdalenian
<i>First Order</i>			
Castillo (6)	Castillo (6) Morin (6)	Castillo (7)	Castillo (7) Altamira (7)
<i>Second Order</i>			
Pendo (4) Morin (4) Cobalejos (4) Busta (4) Ruso (4)	Pendo (4)	Morin (6)	Pendo (6) Morin (6) Juyo (6) Camargo (6)
<i>Third Order</i>			
Cudón (3)	Cudón (3) Altamira (3) Salitre (3) Rascaño (3) Camargo (3) Otero (3)	Pendo (5) Altamira (5) Salitre (5) Carranceja (5)	Fuente (5) Pila (5) Salitre (5) Carranceja (5) Cobalejos (5) Otero (5) Cobrantes (5)
<i>Fourth Order</i>			
Hornos (2) Fuente (2)	Hornos (2)	Cobalejos (4) Camargo (4) Fuente (4) Bona (4) Haza/Mirón (4)	Rejo/Cabras (4) Cualventi (4) Busta (4) Rascano (4) Truchiro (4)
<i>Fifth (and Lower) Order</i>			
Unquera (1)		Cualventi (3) Hornos (3) Ruso (3) Mirón (2) Chufin (2)	Chora (3) Hornos (3) Loreto (3) Cuco (3) Peñajorao (3) Valle (2) Hermida (1)

sites are so close together that their plotted positions would coincide at this scale (the four sites in the Castillo hill, or the two sites of Rascaño and la Bona, for example) only the largest or principal site was plotted.

Sites mapped for each of the four «periods» compared are listed in Table 1. For the Mousterian and the Earlier Upper Paleolithic, there are the sites each. Sixteen Solutrean sites and twenty-five Magdalenian sites are identified. Several sites appear on more than one list—a few are on all. More detail on sites and occupation contents is available in the exce-

llent summaries by González Morales and González Sainz (1986) and Straus (1992).

The approximate position of each site was determined by scaling in two dimensions (elevation was not included) from site maps with scales of about 800,000 to 1 (8 km to the cm) published by González Morales and González Sainz (1986). Distances were scaled to the nearest mm (about 800 meters) only. Since my aims in this exercise were purely exploratory, I saw no need for greater precision at this point. There are practical problems in determining precise site location. Many sites are not located with any accuracy on existing topographic maps, and the approximate positions of latitude and longitude published for some sites may use either the Greenwich or the Madrid meridian without specifying; a few sites cannot now be located closer than a few tens of meters in any case, since they have been destroyed by quarrying. The results of this preliminary study indicate potential enough to warrant a greater investment in accurate site location, and I intend soon to locate each site as precisely as possible on the ground, using a global positioning indicator. For the present, largely heuristic purpose, the scaled relative locations used here are adequate.

I did not include topographic detail on the plots I used. The sites are at relatively low elevations, and movement between them is not obstructed by intervening barriers due to the presence of high mountains, irregularities in coastline, or impassable bodies of water. Nor do streams seem to have been magnets for human occupation. This may be due to the fact that much drainage is subterranean. Some sites (e. g., Castillo) are located along rivers or permanent streams, but many are not (e. g., Morín, el Juyo, Altamira) and there is no evident tendency for settlement to follow the course of waterways at any period.

From plots of scaled relative positions, Voronoi tessellations (Thiessen diagrams) were generated for the set of sites for each period. In this procedure, polygons are drawn around each site so that any point within a site's surrounding polygon is closer to that site than to any other. Such boundaries have proved analytically useful in such fields as geography, ecology, psychology and other social sciences, as well as in civilizational archaeology. In archeological application, evaluations of distributions about «central places» have principally been employed in studies of the areas, or the numbers of minor settlements, that might have been linked to different political or economic centers in the past (see, for example, Haggett 1966: 115-152; Hodder and Orton 1976: 51-63; Renfrew and Level 1979; Orton 1980: 188-194).

In the days before electronic computers were generally available, the corner points of linear boundaries could be determined by geometric construction or calculation, but the process became laborious if the number of centers was at all large, and plotting errors crept in. Nowadays, anyone with a good desktop computer and the right software can produce the diagrams with accuracy and ease. The SYGRAPH program incorporated in the statistical package SYSTAT has what is probably still the best Voronoi module, and was the program used here. In my opinion, a major defect of the program is that the total area included in a plot varies as do the maximum twodimensional coordinates of the sites it contains. It is so difficult to rescale the plots to compensate that I have not done so. Consequently, even though the maps are about the same size, a site that appears on more than one map will not occupy the same position on each, and distances between identical sites will seem to vary on different maps, as the scale of the area included on the maps differs. Since I am interested in relative positions only, these «defects» are irrelevant, however annoying.

Figures 1.1 through 1.4 show the resulting diagrams. While other aspects of the patterns might be analyzed, a few are especially interesting.

The first is the way in which polygon size varies in each of the four phases. In general, median polygon size decreases through time, as one might expect from the fact that site numbers in the study area generally increase from phase to phase. The exception is the change from smaller median polygon size for Mousterian sites compared to the larger Early Upper Paleolithic polygons—and in this case, site numbers are equal.

Increasing site densities are often assumed to correlate with increasing population density, but interpretation is actually more complicated. The phases do not represent equal time periods—the Mousterian plot covers a much longer temporal range than do any of the others, duration being shortest for the Solutrean, somewhat longer for the Magdalenian, and much longer still for the Early Upper Paleolithic. The possibility that seasonal or otherwise specialized sites were more abundant during some phases than during others is an additional complication; in fact, some Magdalenian levels at Rascaño and El Juyo are known to have been the loci of quite specialized extractive activities. The comparison thus has no straightforward implications for population studies.

All other things equal, one might suggest that polygon size may have some relationship to the size of exploited territories or «site catchment areas» about each site. But, especially for the earlier phases, there is simply no way to reconstruct the prehistoric landscape in sufficient detail to check this suggestion. If anything, there seems to be little or no rela-

tionship between the size of any given polygon and the probable abundance or variety of resources that were most likely available therein. The increase in median polygon size from Mousterian to Early Upper Paleolithic seems to mean that in the latter phase sites were more regularly spaced over the exploited landscape; this interpretation must be qualified, however, since the occupations I excluded as dubious or mixed include some that had questionably been assigned to the Earlier Upper Paleolithic.

It is nevertheless a fact that sites on the Solutrean and Magdalenian diagrams show a greater tendency to clump together than is true for earlier phases. That might suggest an increasing tendency to locate all sites in especially rich areas. Rascaño and El Juyo suggest that more probably later sites, specialized in the extraction of a limited set of resources, were located in areas where those resources were at least seasonally especially abundant: sites for coastal exploitation near the richest rías or rocky shores, specialization on alpine mammals in upland sites. If that is correct, sites should have been becoming increasingly interdependent over the region, as settlement location became part of increasingly focused extractive strategies and subsistence systems that must have involved growing networks of intraregional (seasonal?) transport or exchange. But even if this scenario is correct, it will not explain the locations of many sites, nor the sizes of the polygons around them.

Other intriguing information comes, not from the size or location of the individual polygons, but the number of adjacent polygons each contacts. The number of neighboring sites whose areas directly contact the area about a central site, is often called the «contact number» by Haggett (1965-51) and other geographers. I prefer the term «adjacency» (from graph theory) to that of contact number. A site's area is «1-adjacent» when it abuts only one other polygon, «2-adjacent» when it is bounded by just two others, and so on. Adjacency thus quantified can be treated as a set of integers that can be evaluated or combined mathematically: sums, means, and medians can be calculated from them as from any other integers. Adjacency differs from site to site within a period, and average adjacency varies from period to period. This provides a means of scaling sites and settlement systems: the sites from any phase may be arranged in a hierarchical order from greatest adjacency to least. The resulting order is surprisingly suggestive (Table 1). In fact, the ranked site list is one of the most interesting results of this essay.

Adjacency for ten Mousterian sites ranges from 1 to 6, with mean 3.4, median and mode each being 4.0. For ten Earlier Upper Paleolithic sites, adjacency ranges from 2 to 6, while the mean rises very slightly to 3.6, but median and mode drop to 3.0. The sixteen Solutrean sites range from 2 to

7, mean being 4.13, median and mode each being 4.0. For 25 Magdalenian sites, adjacency ranges from 1 to 7, and the mean is 4.4, median and mode each being 5. Fisher's exact probability tests detect significant difference (at the 0.05 level) between adjacency patterns in the Mousterian, Early Upper Paleolithic, and Later Paleolithic (Solutrean + Magdalenian) phases, whether the distribution of sites is considered by order in the list, or by adjacency number. No significant difference appears between these values when the Solutrean and Magdalenian plots are compared.

The Early Upper Paleolithic pattern is like the Mousterian pattern in more ways than it is like the later Upper Paleolithic. Nevertheless, it is well individualized, and its difference from the Mousterian pattern is quite real. After the Early Upper Paleolithic, there is a significant jump in both maximum and average adjacency, with a further rise in the Magdalenian. Were one or even a few other sites added to the plots for any period, these global contrasts would probably be little changed.

A larger proportion of sites falls into first and second order ranks during the Mousterian than is the case in other phases, while there is a disproportionate concentration of third order sites during the Earlier Upper Paleolithic. Interestingly, sites of first and second order are separated by an «adjacency gap» during both the Mousterian and Early Upper Paleolithic phases: first order sites are 6-adjacent, while second-order sites are 4-adjacent, and there are no 5-adjacent sites. Despite that fact, during the Solutrean and Magdalenian, sites of any order always have adjacencies at least one degree higher than Mousterian or Early Upper Paleolithic sites of the same order. As we shall see, that is an important finding of this exercise.

What, if anything, might these mathematical patterns have to do with cultural adaptations.

Unless virtually all the sites of the period are now drowned offshore, the Acheulian occupation of Cantabria seems to have been at best ephemeral and discontinuous. Only during the Mousterian, and probably relatively late at that, do people seem to have established a firm foothold in the region. It is relevant that faunal evidence shows that Cantabrian Mousterian peoples made little use of either maritime or alpine resources, so not surprisingly, except for surface scatters of artifacts (some of which are usually but doubtfully attributed to open-air Acheulian occupations), sites were not located either very near the coasts or in the highlands.

One might imagine that pioneering settlement of the relatively unfamiliar Cantabrian lowlands proceeded with the spread of many more or less independent small settlements, maintaining only sporadic contact

with a very few larger, more populous local centers. «Peripheral» sites on expanding frontiers have few neighbors. More adjacent «centers» might be the sites settled earliest, or those especially favored, either from the standpoint of availability of resources or ease of communication with other regions. The Castillo complex is unusual: it included two (perhaps three) closely neighboring Mousterian sites, Castillo and La Flecha, at about the same elevation on the sides of a single hill; otherwise, Mousterian sites do not «clump» closely together. These relatively elevated caves were ideal locations for game-spotting over an unusually large expanse of the broad Pas valley and adjacent lowlands. But Cantabria was (and is) an especially well endowed natural region, and neither well-excavated assemblages nor the best paleoenvironmental reconstructions suggest that there was much variability in the kinds or quantity of resources easily accessible from the settlements. Even where controlled excavations provide evidence for the local performance of specialized activities (as at Morín), about the same range of resources was involved as is the case for other, seemingly more «general-purpose» occupations. It seems likely that most sites were relatively self-sufficient, and engaged in about the same range of subsistence-related activities.

The Early Upper Paleolithic pattern seems from the archeological evidence a continuation of the Mousterian. Faunal assemblages suggest that a greater variety of resources were familiar and consistently exploited, but that in other respects, the approach to subsistence remained one of broad-spectrum, generalized or opportunistic resource exploitation. Most sites continued to be relatively small, and the number of «occupants» was limited where there is evidence for such a calculation. The principal breaks with Mousterian patterns are the presence of two equally adjacent centers —contiguous to each other— and the drop in modal adjacency. Multiplication of first-order centers may reflect an incipient regional differentiation, with shorter distances from low-order sites to the center in each region. Even though one of the two centers is much closer to the coast than the other, which is near the uplands, there is no indication of differential use of environmental potential —shellfish or alpine creatures are not especially abundant in either. The drop in median and modal adjacency, indicating more uniform site spacing through the utilized lowland zone, was perhaps coupled with a general equalization of the number of functions served by most sites. The picture is consonant with the interpretation that a majority of sites of the time were occupied by groups of about the same size, exploiting very similar sets of resources, and mostly doing so in similar ways and for similar reasons, without much functional differentiation between them.

The Castillo «clump» had dissolved, and only Castillo itself was utilized: perhaps central places had become less tolerant of very close neighbors than they formerly were. There is only one second-order site, suggesting a widened «gap» in functional diversity between centers and other sites. However, once more, the nature of site functions is not self-evidently only economic, or just subsistence-related.

The Solutrean phase lasted for a much shorter time than the earlier Upper Paleolithic. Despite this fact, Solutrean sites are over half again as abundant as they were earlier. Some (but not all) of this increase almost certainly reflects increased population density; on the other hand, some certainly reflects increased site specialization. Beginning in the Solutrean, there is a marked growth of the tendency for sites to occur in localized clumps. This may be due to the introduction of strategies of settlement location that preferred sites where some small set of productive resources was locally very abundant. The range of utilized resources had been broadened substantially, to include a greater representation of shellfish and fur-bearing carnivores. But instead of these being part of a continuing generalized, more-or-less opportunistic pattern of broad-spectrum exploitation, they augmented a pattern, best documented in Asturias by Straus, Clark, and other colleagues, that seems to have been shifting to the selective, concentrated exploitation of a limited number of particularly productive resources, such as herds of red deer.

As site numbers increase, the average area of site polygons inevitably decreases. During the Later Upper Paleolithic (especially the Magdalenian), many polygons are quite small. While it is impossible to prove a relationship between polygon size, an artificial geometric construct, and the size of territories actually exploited from each site, it would be very strange if no such relationship existed. When polygon size decrease correlates with growing site specialization, we should find a corresponding general increase of site packing, especially about local centers, as ease of movement of goods or personnel between sites becomes more important. That is exactly what happens, from the Solutrean on.

During the later Upper Paleolithic, maximum adjacency rose to 7, and even in the Solutrean, sites that are only of fourth-order are 4-adjacent—as well connected as second-order sites in earlier phases. During the Magdalenian, average adjacency increased still further and there was a real explosion of second order (6-adjacent) sites. The growth in numbers of many-adjacent (5+) sites in the later Upper Paleolithic, and the higher adjacency of lower-order sites, compared to the Early Upper Paleolithic and Mousterian, suggests that regular or sustained contact between sites of any order—not just peripheral sites and their centers—had become

increasingly important to settlement strategies. At the same time, the decrease in average polygon size indirectly suggests that extractive efficiency had increased, either by the introduction of new technological means for production, processing, storage, and distribution, or by improvements in the organization of social units responsible for these processes. In this case, both seem to be involved. Size standardization is evident in Solutrean leaf-shaped pieces, and new kinds of tools abound, including (in the Magdalenian) an abundance of cheaply made, interchangeable tool edges (backed bladelets and microliths). But more efficient organization, including greater functional specialization of occupations, was at least as important a part of the picture. We know from Altamira and Juyo that specialization of occupations had grown, on both economic and non-economic fronts. Alpine animals were then quite commonly hunted where they dwell, and shellfish collection produced true shell-middens in some coastal sites. Concentrated exploitation of locally abundant and productive resources, such as limpets at Juyo and Altamira, red deer herds at Juyo, or ibex at Rascaño, had evolved to become, in a real sense, the periodic «harvesting» of renewable wild foods.

Magdalenian sites often had multiple alternative (sequential) functions: at El Juyo, red deer were harvested when they were abundant; then, perhaps as the deer herds replenished themselves, limpets and winkles were harvested on the coast; evidence from one occupation at el Juyo puts its «functional mode» (FREEMAN 1977) in the past cultural system well outside the range of ordinary economic activities. Some occupation functions probably had a seasonal component, while other specialized activities might have been undertaken on a periodic but non-seasonal basis, others were only quasi-periodic, and still others were highly irregular.

When site dispersal over a given landscape is uneven, rather than regular, as site numbers and density increase, it is mathematically inevitable that average and maximum adjacency must rise. What is not inevitable — in fact it is surprising — is the fact that at each period, the sites with greatest adjacency are the sites with the archeologically most productive («richest») contemporary occupations. Here, one sees most clearly the connection between our mathematical exercise and past cultural «fact».

During the Mousterian phase, there is only one first-order site complex, whose adjacency is 6: the caves of Castillo. Mousterian levels at Castillo itself are the richest in all of Cantabria. Mousterian Level Beta at that site produced over 3100 retouched tools, and Level Alpha over 2800. No other Mousterian occupation level has produced anything like such quantities of material. There were no 5-adjacent sites, but fifty percent of Mousterian sites were 4-adjacent, placing them in the second order.

They include el Pendo, Morín, and all the caves with substantial or multi-level Mousterian occupations.

In the Earlier Upper Paleolithic data set, Castillo is once more a first order site, but it is joined by another 6-adjacent cave, Cueva Morín. With nine levels (one Chatelperronian, three Archaic Aurignacian, three evolved Aurignacian and two Perigordian), including structures and burials, Morín is arguably as rich and important an Early Upper Paleolithic site as any but Castillo, edging out even the long and impressive sequence at el Pendo, though the latter certainly comes close. And el Pendo does follow closely in adjacency and order.

Castillo is again the only first order (now 7-adjacent) Solutrean site in the Cantabrian autonomous region. No other Solutrean site in the region—not even Altamira—comes near it in archeological importance. The fact that Altamira is placed in a rank lower than Morín (I would have guessed it would rank at least as high) is the only respect—the single case—in which my subjective estimate of site «importance» failed to agree with position of the site in the adjacency hierarchy. I suspect that the Voronoi diagram is at fault. (The discovery of one or two new Solutrean sites to the South or southwest of Altamira would eliminate this disagreement).

During the Magdalenian, Castillo continues to be a topranked site, as one would expect from the size and richness of collections from the old excavations. Altamira has become its equal, and that is not surprising. Regardless of the small size of the collection from the early excavations that can be attributed with certainty to the Magdalenian, work in the 1980's shows that this deep level in the Altamira «Cocina» must have been as incredibly rich as it was areally extensive. New dates on engraved shoulder-blades from Altamira previously considered to be Solutrean place them instead in the range of the Magdalenian, and indicate once again how severe the problem of confused stratigraphy and level mixture is for those materials found in the early 1900's. Despite its long, rich Magdalenian sequence, El Juyo is a small site with evidently limited, specialized functions, and its lower placement does not surprise me. La Pila is another case that might rank somewhat higher, but as yet there is too little published information from that interesting site to justify formulating any confident expectation.

In general, the agreement between ranked adjacency values from Voronoi polygon constructions and informed archeological assessments of site importance is truly impressive. What could possibly be the reasons for such substantial coincidence between a prehistorian's evaluations of the relative archeological importance of Paleolithic occupation sites, on the one hand, and an abstract, purely mathematical construct

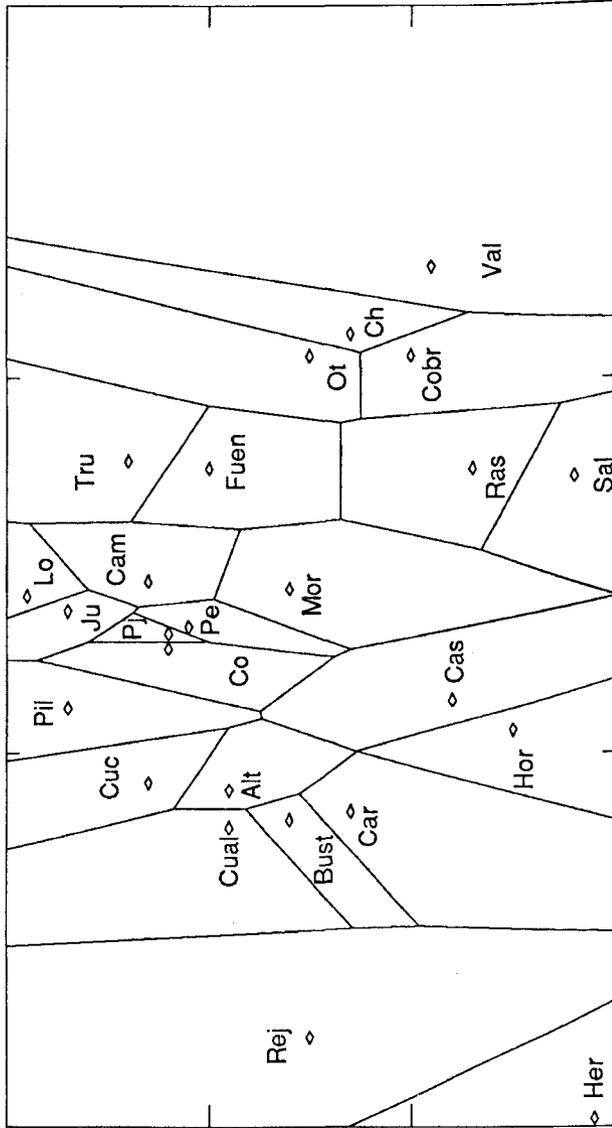
that uses only site latitude and longitude to draw geometric figures about the sites; on the other? I have suggested above that economic behavior and the increasing functional specialization of sites through time are partial explanations of the Voronoi tessellations. But, however useful and interesting, they tell only one part of the story—that part having to do with average sizes, numbers, and changes through time. They can not by themselves explain why a particular site occupies a particular position in the adjacency hierarchy.

One might suggest an explanation in strictly socioeconomic terms: that as exploitation of the diverse resources of different habitats in an area became more efficient, there was an accompanying need to rigidify hierarchical principles of organization in order to ensure the redistribution of desirable goods that were not found uniformly throughout the region. As we have seen, in later phases of Cantabrian occupation some sites had access to and extracted goods not available elsewhere—ibex in the uplands, mollusks on the coasts—but the evidence suggests that this is only a partial explanation.

Caves suitable for occupation are abundantly represented throughout Cantabria, but few are high in the adjacency ranking or archeologically important—some apparently ideal sites were not used at all during the Paleolithic, and others have occupations only during one or a few Paleolithic phases. Of these lower-ranking sites, many are positioned where raw materials for tool manufacture and resources for subsistence were as easily accessible as they were at Morín or Altamira. It is possible, even probable, that the continual privileged position of the Castillo complex is partly due to the particular geographic position of its caves, on one of the best routes leading from the Cantabrian coast over a high pass (the Puerto del Escudo) to the Spanish Meseta. But neither geographic position, nor topography, nor favorable environmental setting, alone or in combination, is enough to account for the high adjacency of Morín, Altamira, or the other high-ranking sites. These cases seem to me to call for other explanations.

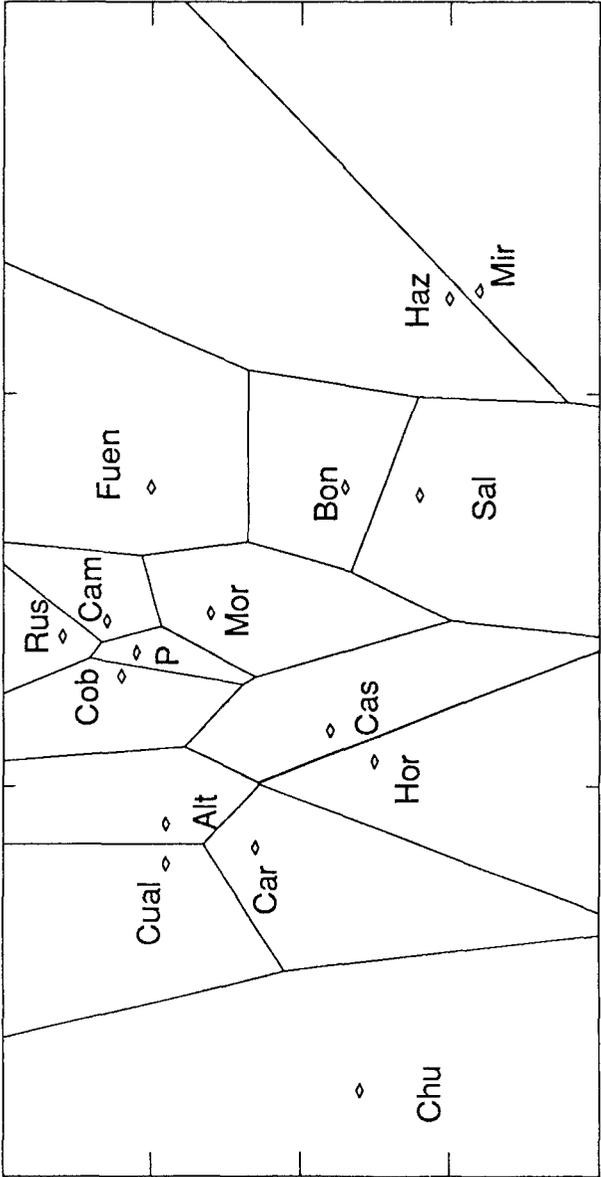
It is quite possible that adjacency correlates more directly with importance: that a site is rich and intensively occupied simply because it is surrounded by many other sites. The converse may of course be true: important sites may be magnets that attract other settlements. In either case, access to, or ease for movement of, consumable goods may be less important than accessibility to services or other kinds of resources—people of special status (e.g., arbitrators, chiefs, curers or other ritual practitioners, prospective marriage partners), essential information (e.g., traditional lore, customary law, technical instruction/training in tool manufacture, fighting, or performance), ritual activities (e.g., collective ini-

MAGDALENIAN



LONG

SOLUTREAN



LONG

tiations, world-renewal rites), or sacred places and ritual paraphernalia (e.g., shrines and their contents, ancestral homes, and perhaps even the painted caves themselves). There is of course no reason why economic exchanges, feasts, etc., could not accompany such transactions without being their central focus.

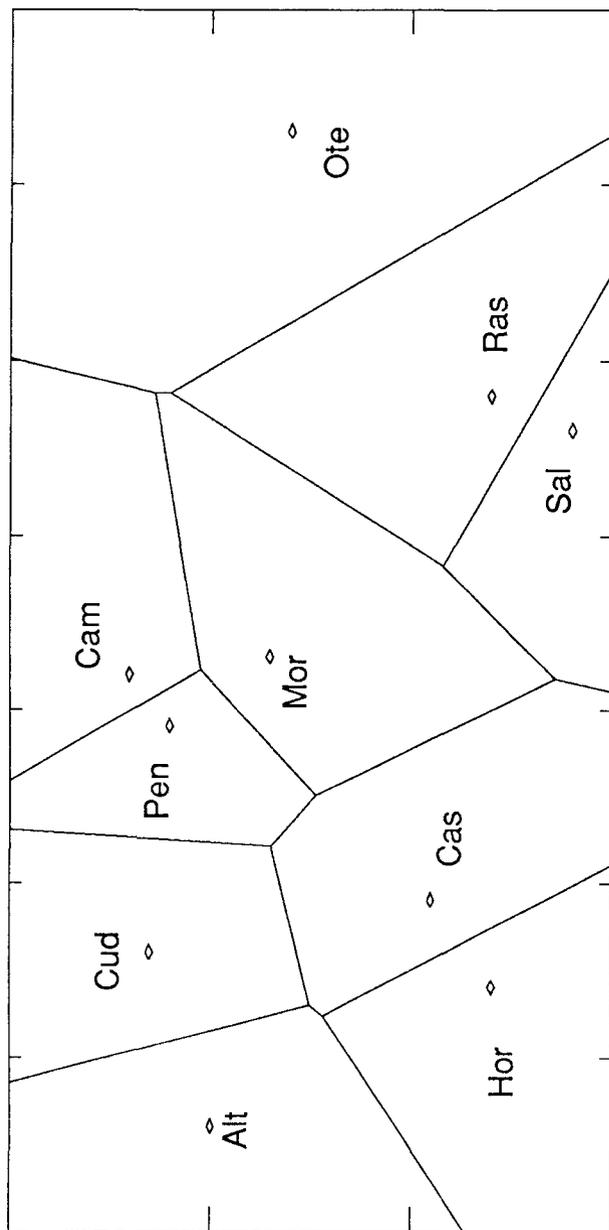
Some years ago, Margaret Conkey wrote a fundamental paper on stylistic elements in Magdalenian bone artifacts (CONKEY 1980). On the basis of a comparison of the broad range of decorative elements on bone tools from Altamira with the more limited ranges found at other sites, Conkey suggested that the Magdalenian system of subsistence and settlement shifted between sites occupied by separate, small and ordinarily independent groups, each with its proper, unlimited stylistic repertoire, and focal sites, with a range of bone decoration encompassing most motifs, where those small units periodically united into maximal social aggregates. These «aggregation sites» would have the loci of a number of functions including, perhaps, economic exchange, the performance of seasonal ceremonies, the rites of initiation, and so on. Despite the suggestive nature of her work, there has been little new evidence to evaluate her suggestions. The Voronoi tessellations are evidence that tends to reinforce her conclusions. If she is right, Castillo probably played a role comparable to that of Altamira during the Magdalenian.

As Barbara Bender (1981) pointed out, societies adapt not just to ensure population survival, but to ensure social reproduction. Increased productivity, she suggested, is correlated with social intensification. While there may be exceptions, the Cantabrian record certainly seems to exemplify her conclusions. It indicates increasing productivity, culminating in the wild-harvesting adaptations of the later Upper Paleolithic. The Voronoi diagrams suggest the growing hierarchization of structures of alliance that should be as much cause as concomitant of economic intensification.

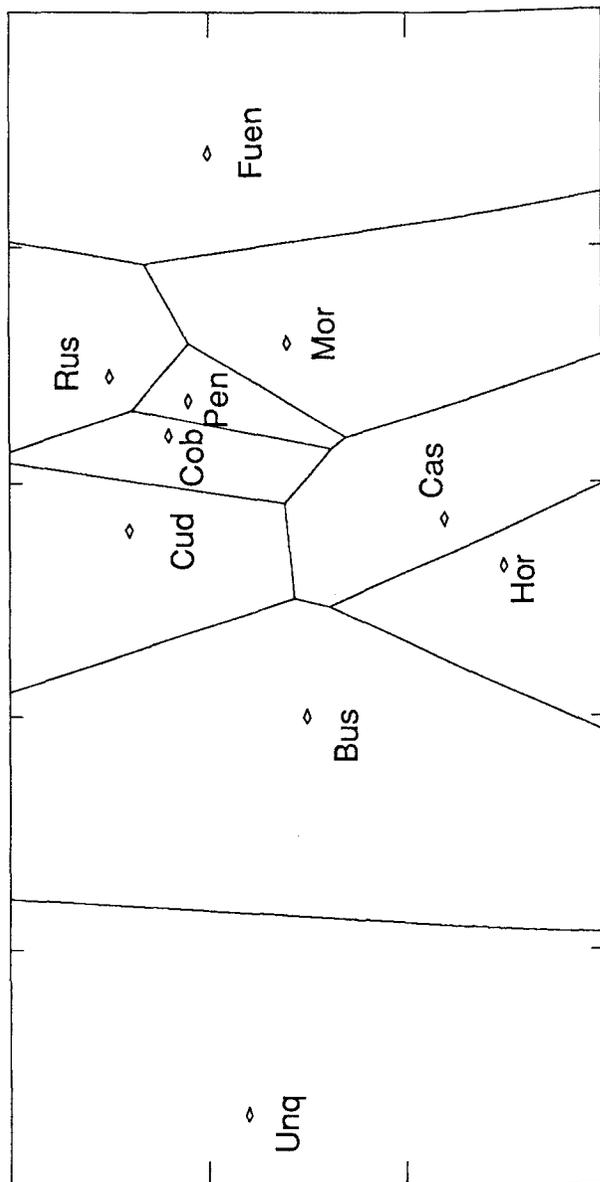
I cannot claim to have explained to my own complete satisfaction the coincidence between adjacency hierarchies calculated from the Voronoi polygons, on the one hand, and archeological evaluations of site importance, on the other. But it seems certain that such a coincidence does exist, and that other factors than the strictly economic ones that are our usual recourse may be required for its explanation.

Two potential practical applications of this exercise to fieldwork come immediately to mind. Archeological survey, surface collection and limited stratigraphic testing in a small and largely unexplored region produce maps of sites with materials from different phases of occupation. Where survey is thorough, the construction of Voronoi tesserae from survey maps may give hints of the structure of land use and possible hie-

EARLY UPPER PALEO



MOUSTERIAN



LONG

rarchical relationships between sites even before any excavation is planned. The polygons could potentially help plan excavation strategies, indicating which sites might be of especial interest due to their central (or their peripheral) location. Alternatively, when Voronoi tesserae are plotted for a relatively well explored region, such as Cantabria, and archaeologically important sites have lower rank or adjacency than seems reasonable (Solutrean Altamira is a case in point), it may be advisable to search harder for sites in immediately adjacent areas.

Despite the fact that these are preliminary results, they suggest that the plotting of Voronoi polygons, and the construction of adjacency hierarchies for sites, are useful exercises even in Paleolithic studies, and may point the way to further investigations that will lead to a clearer understanding of the organization of prehistoric settlement systems.

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