sions × ozone yield) for Cumberland by that for Johnsonville. Any unreacted NO_x (about 20% in the 12 July case) remaining in the Cumberland plume at local sunset could continue ozone production upon sunrise the next day. That remaining 20%, having been diluted overnight, should produce ozone more efficiently, just as in the dilute Johnsonville plume. Assuming an efficiency of 7 the next day for this unreacted NO_x, including it in the calculation for the Cumberland plume increases its estimated total efficiency by 50% to 3 molecules of ozone per NO_x emitted, still lower than Johnsonville by a factor of 2. Any nighttime oxidation of unreacted NO_x via processes involving the nitrate radical would act to minimize this increase.

19. These findings additionally imply a strong dependence of ozone production rate and yield on the dilution induced by natural meteorological processes after emission. Given that these factors can change drastically in relatively short amounts of time, we should expect a range of ozone rates and yields from a single point source emitting NO_x at a constant rate. Meteorological changes may affect multiple parameters influencing ozone photochemistry (e.g., a cloud deck that attenuates actinic fluxes may also reduce the surface heating that drives vertical mixing of plume constituents in the boundary layer).
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Dating Caral, a Preceramic Site in the Supe Valley on the Central Coast of Peru

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Radiocarbon dates from the site of Caral in the Supe Valley of Peru indicate that monumental corporate architecture, urban settlement, and irrigation agriculture began in the Americas by 4090 years before the present (2627 calibrated years B.C.) to 3640 years before the present (1977 calibrated years B.C.). Caral is located 23 kilometers inland from the Pacific coast and contains a central zone of monumental, residential, and nonresidential architecture covering an area of 65 hectares. Caral is one of 18 large preceramic sites in the Supe Valley.

The Late Archaic or Cotton Preceramic Period from ~5000 to 3750 years before the present (yr B.P.) was a time of substantial cultural change and the emergence of the first complex societies in the Americas. Here, we present radiocarbon dates from the site of Caral in the Supe Valley.

The Supe Valley, ~200 km north of Lima, was a focal point for early cultural development on the coast of Peru (Fig. 1). The Valley stretches ~90 km from the Pacific coastline to the sharply rising slopes of the Andes. There are, at present, 70 km^2 under cultivation and an average stream flow of 48,000,000 m^3 per year.

Supe has been perhaps best known in the archaeological literature as the location of the large coastal site of Aspero (Fig. 1). This site was first recorded in 1905 (*1*), and initial excavations at the site were carried out in 1941 (*2*). The site was revisited in the 1970s (*3*), when artificially constructed platform mounds were recognized for the first time. Further work at the site in the 1970s (*4, 5*) yielded dates of 3000 to 2400 calibrated years B.C. (Cal B.C.), which belong to the Preceramic Period in Peruvian prehistory. Aspero is distinctive in having an economy based primarily on maritime resources rather than on agriculture and domesticated plants. The site has been central to ongoing discussions of the maritime foundations of Andean civilization (*6, 7*).

A number of other large sites inland in the Supe Valley also have monumental architecture and lack surface ceramics (*8–10*). These include Caral (*11*) and 17 additional sites in the valley with extensive preceramic occupations. Caral (Fig. 2) is one of the largest and the most formally laid out of the major preceramic sites in the Supe Valley. It is located 23 km inland from the coast on a terrace 25 m above the floodplain of the Supe River on the south side of the valley (*12, 13*).

The central zone of Caral with monumental architecture covers an area of just over 65 ha, with the NW-SE axis measuring 1045 m and the NE-SW axis measuring 620 m (Figs. 3 and 4). This central zone includes six large platform mounds, numerous smaller platform mounds, two sunken circular plazas, an array of residential architecture, and various complexes of platforms and buildings. The largest of the platform mounds, the Piramide Mayor, measures 160 m by 150 m and is 18 m high. Testing within this platform mound indicates that, although there was much remodeling of the surface structures, the mound itself was constructed principally in two massive construction phases. The other five mounds range down in size to the smallest, which is ~60 m by 45 m and 10 m high. These other mounds appear to have been constructed in one or two major phases. All construction employed cut stone retaining walls with a combination of river cobbles and cut stone rubble fill. The fill material was transported to the mound in shicra bags [an open mesh bag made of reeds (*14*)], which were filled with stones and then placed inside the retaining walls, bag and all. The outer retaining walls were carefully faced and covered with multiple layers of colored plaster.

Secondary smaller mound alignments extend 1000 m to the northwest and 500 m to the southeast from the site center. These areas have not been tested, and at present, their chronological placement is uncertain. Details of these occupations are unclear because of much later ceramic-bearing architecture near these secondary mound extensions. In aerial photographs (Fig. 2), however, these long mound complexes appear to be integral parts of the original preceramic site. About 300 m to the southwest of the central mound complex at Caral is another sunken circular plaza and platform complex (which retains the name "Chupacigarro") (visible at the bottom center of Fig. 2). Its architecture covers an additional 23 ha. There is surface trash and residential architecture in between the central mound zone of Caral and the complex of Chupacigarro.

Excavations at Caral have revealed considerable diversity in residential architecture. Each of the six large mounds is associated with a large formally arranged residential complex. Each room complex covers an area of between 450 and 800 m^2, with carefully constructed and heavily plastered walls of cut stone. Domestic trash indicates that these rooms were residential in nature. A second kind of residential architecture is found in Sector A, covering an area of 5500 m^2 (Fig. 3). Rooms in this area are smaller and had walls built of wood poles, cane, and mud. This area shows extensive evidence of remodeling and sequential occupation, and construction of low platforms made of river cobbles in the later stages. Similar residential complexes are found in other parts of the site,

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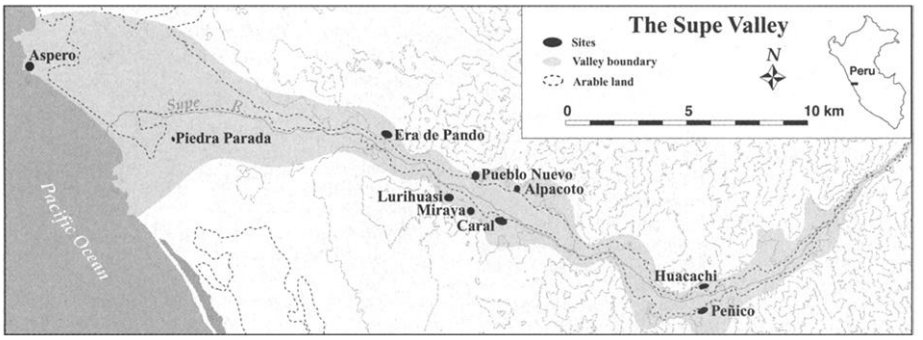

Fig. 1. Map of the Supe Valley. The locations of the 10 largest sites are indicated.

though those tested in other areas appear to have smaller rooms. Much of the architecture in Sector A is quite similar to the contemporary quincha construction still used in parts of the Supe Valley.

In addition to the platform mounds and residential architecture, there are a variety of architectural features that had some kind of ceremonial or administrative function at Caral. The two sunken circular plazas within the central zone of Caral and the one at Chupacigarro immediately to the west are all part of a widespread Andean architectural and ceremonial tradition (*15–17*). There are 15 other preceramic sites with sunken circular plazas in the Supe Valley, more than anywhere else in the

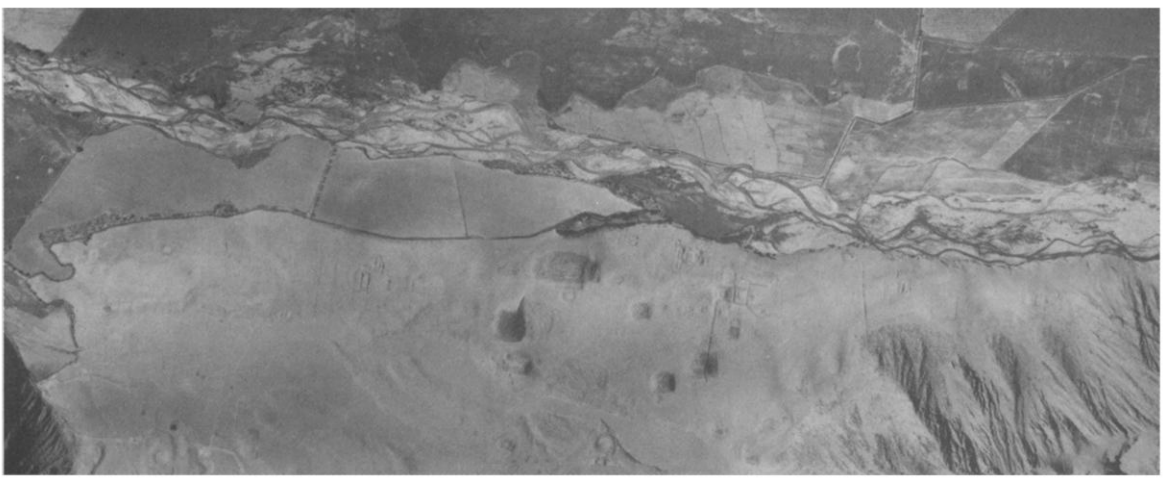

Fig. 2. Aerial photograph of Caral and adjoining farmland. The dark line at the upper edge of the site is the location of the present irrigation canal.

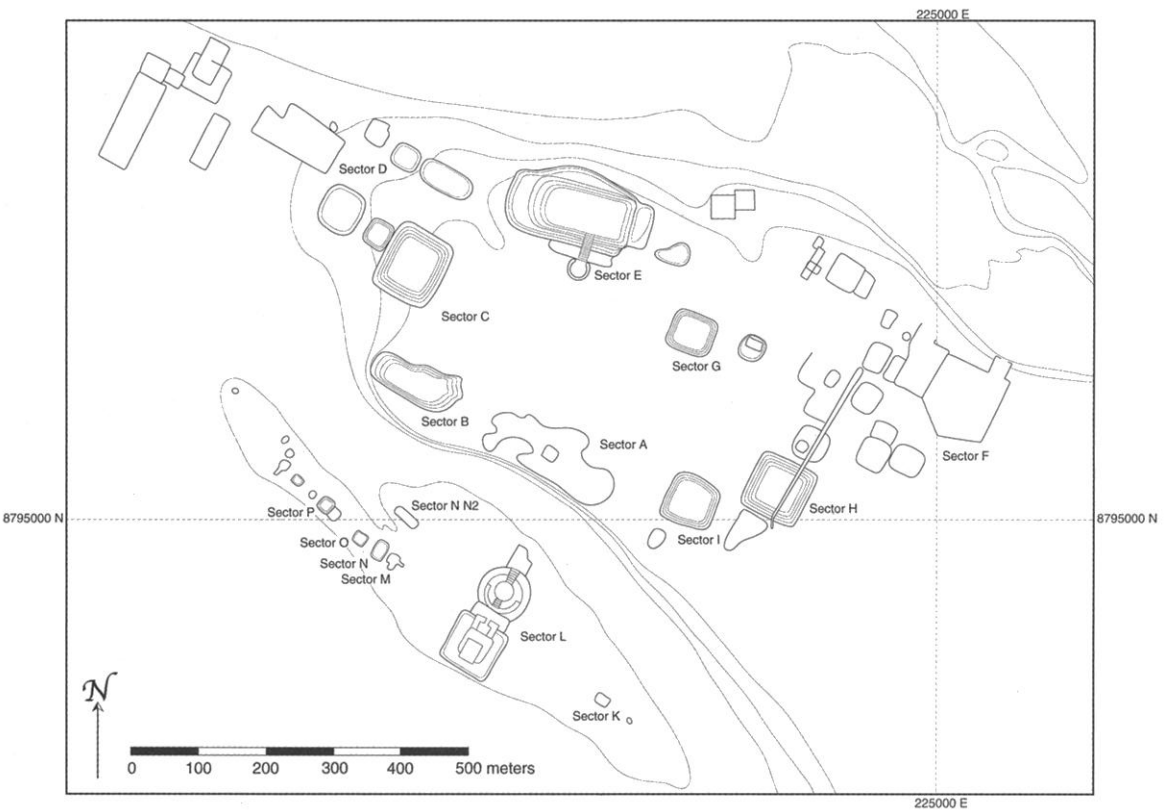

Fig. 3. Map of the central zone of Caral, Supe Valley, Peru.

Andes. Many other architectural complexes are found at Caral, including low platforms, hearths, terraces, and enclosures. The paucity of cultural material in these features makes it difficult to determine their function, other than to conclude that they were nonresidential.

Plant and animal remains are relatively abundant at the site. As in any of the dry desert valleys of the Peruvian coast, the inland location of Caral indicates that the site was dependent on irrigation agriculture. Although floodplain agriculture is possible in small areas farther downstream, there is no arable floodplain land within several kilometers of Caral. On the basis of local topography and geomorphology, it seems highly likely that a contemporary canal just below the site is in the same location as the original prehistoric canal (dark line at the upper edge of the site in Fig. 2).

Ethnobotanical remains recovered from the site confirm the inference of irrigation-based agriculture. Domesticated plants recovered include squash (*Cucurbita* sp.), beans (*Phaseolus vulgaris*), lucuma (*Lucuma obovata*), guava (*Psidium guajava*), pacay (*Inga feuillei*), camote (*Ipomoea batatas*), and cotton (*Gossypium barbadense*), among others (*12, 18–20*). Corn (*Zea mays*) is absent. Animal remains are almost exclusively marine, including quantities of clams (*Mesodesma donacium*) and mussels (*Choromytilus chorus* and *Aulacomya ater*) and an abundance of anchovies (*Engraulis ringens*) and sardines (*Sardinops sagax*). The subsistence economy at Caral was thus a mix of plants grown in irrigated fields within the Supe Valley and marine resources from the Pacific Ocean, 23 km to the west.

A set of new radiocarbon dates taken from a range of site proveniences at Caral (Table 1) (*21*) now allows for a much more accurate chronological placement of Caral and the Supe Valley in Andean prehistory. Most of the samples dated were fibers from plants with a relatively short (i.e., 1 year) life-span, thus eliminating potential problems associated with "old" wood in a desert environment. The uncalibrated dates for Caral range between 4090 ± 90 and 3640 ± 50 yr B.P (Table 1). When calibrated, these dates place the occupation of Caral in a 600-year span between 2627 and 2020 Cal B.C. (Fig. 5) (*22*).

The inland location of Caral is important for this time period. Along the entire Peruvian coast, the only sites yet recorded from the third millennium B.C. are all marine-based coastal villages (e.g., El Paraiso, Bandurria, Huaca Prieta, Rio Seco, Alto Salaverry, Culebras, Huaynuna, and Tortugas) (*23*). The move inland into the middle reaches of the Supe Valley thus appears to have been historically one of the first transitions from marine foraging to agriculture on the coast and to irrigation-based agriculture in Peru.

At 65 ha in the central zone alone, Caral is the largest recorded site in the Andes, with uncalibrated radiocarbon dates extending back earlier than 4000 yr B.P. Sites with similar early dates in the highlands, such as Galgada or Kotosh, are <10 ha in area (*24, 25*). Elsewhere along the coast, sites with dates before 4000 yr B.P. run from 12 ha at Aspero at the mouth of the Supe Valley, to 8 ha at Salinas de Chao (*26*), 4 to 5 ha at Bandurria (*27*), and <2 ha at Alto Salaverry (*28*). El Paraiso in the Chillon Valley south of Supe is of a similar size, but its radiocarbon dates range from 3790 to 3020 yr B.P. and only overlap with the latest dates at Caral (*29, 30*).

Paralleling the large scale of the site itself is the scale of monumental architecture at Caral. The smallest of the six major platform mounds at Caral, at 60 m by 45 m by 10 m, is as large as any other single third millennium edifice in the Andes. The largest of the mounds is the Piramide Mayor, at 160 m by 150 m by 18 m, with a total

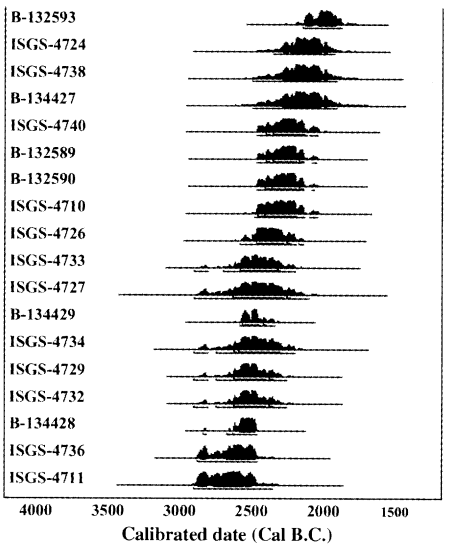

Fig. 5. Calibrated date ranges for all radiocarbon dates from Caral, arranged chronologically by uncalibrated radiocarbon dates before present. The numbers in the left column represent the laboratory identification numbers of the samples (B, Beta Analytic; ISGS, Illinois State Geological Survey). For each sample, the upper horizontal line refers to the 2δ calibrated age ranges, and the lower horizontal line refers to the 1δ age ranges. The vertical lines indicate the relative area under the probability distribution at possible intersection points with established calibration curves derived from tree-ring dates.

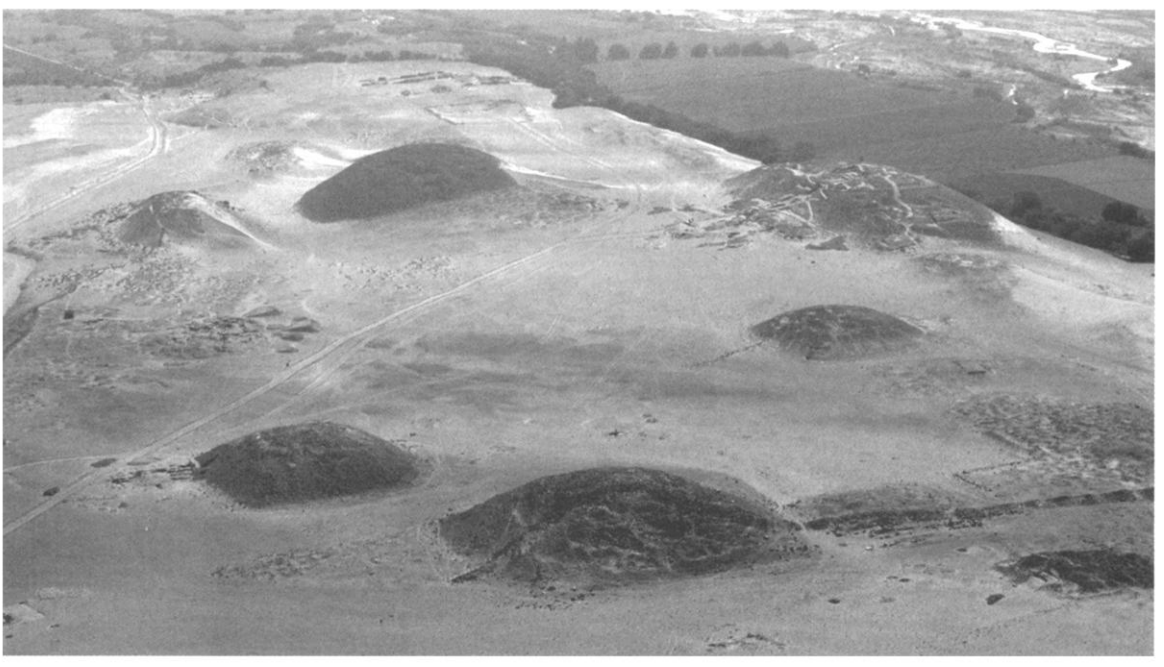

Fig. 4. Overview of the upper section of the central zone with a concentration of large platform mounds at Caral. The Piramide Mayor is at the upper right-hand side of the photo.

Table 1. Radiocarbon dates for Caral, Supe Valley, Peru. Beta, Beta Analytic; ISGS, Illinois State Geological Survey.

Laboratory number	$^{12}C/^{13}C$ corrected age (yr B.P.)	Weighted average midpoints (Cal B.C.)	Provenience
Beta-132593	3640 ± 50	2020	Construction fill of atrium on top of Piramide Mayor, Caral
ISGS-4724	3730 ± 70	2187	Construction fill of atrium on top of Piramide Mayor, Caral
Beta-134427	3740 ± 90	2170	Offering inside room on top of Piramide Mayor, Caral
ISGS-4738	3740 ± 80	2170	Floor construction center of stratified trash, rear of Sector N, Caral
ISGS-4740	3810 ± 70	2215	Upper level stratified trash, rear of Sector N, Caral
Beta-132589	3820 ± 60	2280	Upper level stratified trash, Sector A, Caral
Beta-132590	3830 ± 60	2395	Structure 1, Unit VII-2-I, Level 7, Chupacigarro
ISGS-4710	3840 ± 70	2237	Wall construction around sunken circular plaza in front of Piramide Mayor, Caral
SGS-4726	3900 ± 70	2407	Platform construction in front of Sector C, Caral
ISGS-4727	3960 ± 110	2470	Stratum under the platform in front of Sector C, Caral
ISGS-4733	3960 ± 80	2470	Lower level stratified trash, Sector A, Caral
ISGS-4734	3970 ± 90	2450	Lower floor on top of wall around sunken circular platform, Sector L, Caral
Beta-134429	3970 ± 40	2450	Lowest level (7) stratified trash, in rear of Sector N, Caral
ISGS-4729	3990 ± 70	2490	Floor contact residential architecture, Sector A, Caral
ISGS-4732	3990 ± 70	2490	Upper level stratified trash, Sector A, Caral
Beta-134428	4020 ± 40	2560	Upper level (3) stratified trash, rear of Sector N, Caral
ISGS-4736	4060 ± 70	2580	Lowest level stratified trash, rear of Sector N, Caral
ISGS-4711	4090 ± 90	2627	Stratum under sunken circular plaza in front of Piramide Mayor, Caral

volume of ~200,000 m^3. There are other sites with mounds and uncalibrated radiocarbon dates before 4000 yr B.P., but in all cases, the communal architecture is much smaller in scale or represents gradual accretion over hundreds of years (*6, 24*). The exceptional size of the platform mounds and the number of mounds at Caral provide an indication of the strength and extent of centralized decision-making in the prehistoric social system.

Caral also appears to mark the initiation of an architectural complex that combines the platform mound and associated sunken circular plaza. This ceremonial complex is common in the archaeological record of Peru for several thousand years. Three of the dates reported here are associated with construction of these complexes: one at Chupacigarro at 2415 Cal B.C. (3930 yr B.P.) and two at the two complexes at Caral dating to 2290 Cal B.C. (3840 yr B.P.) and 2470 Cal B.C. (3970 yr B.P.). Elsewhere in Peru, the earliest recorded examples of these complexes do not appear until ~1970 Cal B.C. (*17, 31*).

In addition to Caral and Aspero, 16 other substantial preceramic sites have been recorded in the Supe Valley to date. Eight of these [Piedra Parada, Era de Pando, Lurihuasi, Pueblo Nuevo, Miraya, Alpacoto, Huacachi, and Peñico (Fig. 1)] are enormous complexes of communal and residential architecture. All eight are >30 ha in area, and all have large-scale corporate architecture. Six of these eight, as well as six smaller preceramic sites, have sunken circular plaza and platform complexes. In view of the abundance of such sunken circular plazas in the Supe Valley, it seems likely that this ancient Andean pattern originated here.

Caral, Lurihuasi, and Miraya on the south side of the river and Pueblo Nuevo and Alpacoto on the north are all within an area of <10 km^2. It cannot be determined at this time whether all of these sites were occupied at the same time. A single radiocarbon date for Lurihuasi, 2580 Cal B.C. (4060 ± 140 yr B.P.) (*10*), suggests that at least one of the sites was contemporaneous with Caral. It is likely that all of these sites were occupied before the introduction of ceramics on the coast at 1800 Cal B.C. The Supe Valley was thus the locus of some of the earliest population concentrations and corporate architecture in South America. The results of the excavations at Caral, the radiocarbon dates, and the initial survey information on the other preceramic sites in the Valley will now allow for a broader consideration of the role of the production and exchange of maritime and agricultural resources in the development of complex societies in the Americas.

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11. At the time Kosok (*8*) visited the site, it was informally known by the name Chupacigarro Grande, after a local hacienda. However, this name was actually applied to four different sites in the area, designated Chupacigarro Grande (West and East), Centro, and Chico, and the common name was a source of confusion. The main site, Chupacigarro Grande (East), has now been renamed "Caral" after the local contemporary community. Chupacigarro Grande (West) retains the name Chupacigarro, Chico has been renamed Lurihuasi, and Centro is now Miraya.
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