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AI-accelerated Nazca survey nearly doubles the number of known figurative geoglyphs and sheds light on their purpose

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It took nearly a century to discover a total of 430 figurative Nazca geoglyphs, which offer significant insights into the ancient cultures at the Nazca Pampa. Here, we report the deployment of an AI system to the entire Nazca region, a UNESCO World Heritage site, leading to the discovery of 303 new figurative geoglyphs within only 6 mo of field survey, nearly doubling the number of known figurative geoglyphs. Even with limited training examples, the developed AI approach is demonstrated to be effective in detecting the smaller relief-type geoglyphs, which unlike the giant line-type geoglyphs are very difficult to discern. The improved account of figurative geoglyphs enables us to analyze their motifs and distribution across the Nazca Pampa. We find that relief-type geoglyphs depict mainly human motifs or motifs of things modified by humans, such as domesticated animals and decapitated heads (81.6%). They are typically located within viewing distance (on average 43 m) of ancient trails that crisscross the Nazca Pampa and were most likely built and viewed at the individual or small-group level. On the other hand, the giant line-type figurative geoglyphs mainly depict wild animals (64%). They are found an average of 34 m from the elaborate linear/trapezoidal network of geoglyphs, which suggests that they were probably built and used on a community level for ritual activities.

Nasca | geoglyphs | machine learning | archaeology | remote sensing

Significance

This paper demonstrates how AI accelerates discoveries in archaeology, even in a region as well known as the United Nations Educational, Scientific and Cultural Organization (UNESCO) World Heritage site of Nazca. Our vastly improved account of relief-type figurative geoglyphs reveals that they differ from line-type figurative geoglyphs beyond their style and size. The line type and relief type also differ in the motifs they depict, their distribution, and their relation to the meshwork of winding trails and the ceremonial network of linear/trapezoidal geoglyphs. Taken together, this makes a compelling case for different nature and purposes of relief-type and line-type figurative geoglyphs: the former sharing information about human activities with individuals or small groups and the latter built and used by the community for ceremonial purposes.

Geoglyphs are motifs created on the ground by manipulating surface stones or gravel and are found throughout the Nazca Pampa. They provide archaeologists with a unique window into the cultures and beliefs of the ancient people who started to use them at least 2000 y ago. Located 50 km inland from the south coast of Peru, on a desert tableland about 500 m above sea level, these geoglyphs have persisted for millennia because they were constructed in an area not easily affected by flooding and not suitable for agriculture. They were rediscovered in the early 20th century (1, 2).

Fig. 1 summarizes and classifies the types of geoglyphs and walking routes found on the Nazca Pampa. Geoglyphs are divided into geometric and figurative. Each of these types can be further divided into stylistic subtypes (*SI Appendix, Geoglyph Construction*). For example, the several-kilometer-long Nazca lines are part of the linear style of geometric geoglyphs, whereas the giant trapezoids are part of the areal style of geometric geoglyphs (3). Known figurative geoglyphs depict humanoids, animals (bird, monkey, fox, spider, lizard, killer whale, whale, fish, feline, and camelid), plants (flower, seaweed, rhizome, and tree), and tools (needle, loom, pin, fan, and musical instrument) (4–10). Figurative geoglyphs were also built in two distinct styles, the line-type and the relief-type style. Line-type figurative geoglyphs are large, with an average length of 90 m (11). Our field survey, in which we have walked near the geoglyphs for ground truthing, has revealed that there are 50 examples of this type of geoglyphs, of which 64% depict wild animals. On the other hand, 380 relief-type figurative geoglyphs are known to exist on the Nazca Pampa and surrounding areas. Relief-type geoglyphs are on average only 9 m in size, and they often depict humanoids and domesticated animals, more specifically llamas. However, since a comprehensive survey of them is lacking, it is uncertain whether this trend can be confirmed.

Previous Studies on the Purpose of Geoglyph Construction. As to the purpose of the geoglyph construction, there are at least five distinct, if not totally unrelated, hypotheses (12). These are i) calendar and astronomy, ii) geometry, iii) agriculture and irrigation, iv) movement or communication, including walking, running, and dancing, and v) artistic expression. The predominant opinion is that linear geoglyphs "were an integral part of the Nasca sacred space" (13). Many lines radiate or converge from the center (12). Some of the lines are associated with pilgrimage routes to and from Cahuachi, with the socioreligious

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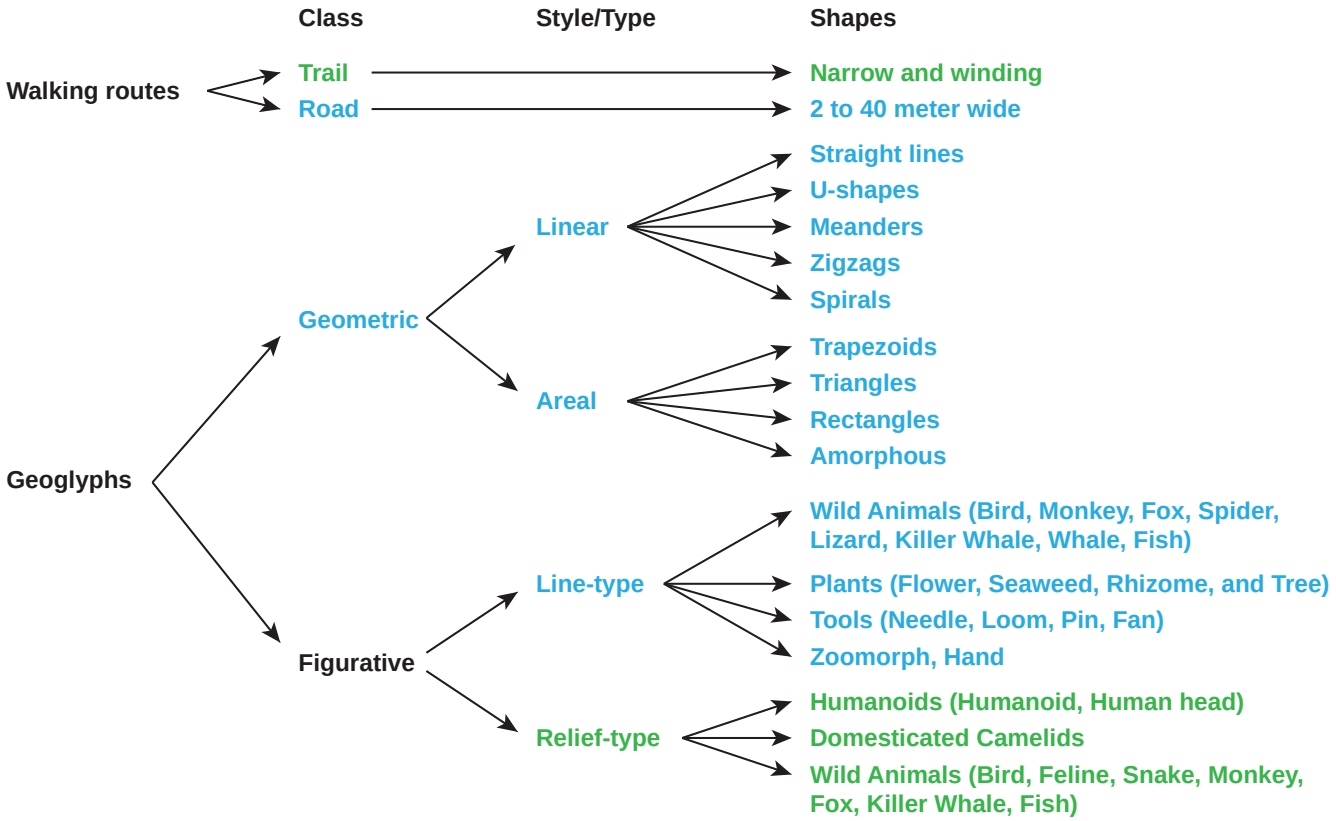

Fig. 1. Classification of geoglyphs and walking routes found on the Nazca Pampa. Walking routes are divided into winding trails and formal roads, while geoglyphs are divided into geometric and figurative. The geometric geoglyphs can further be divided into linear and areal, whereas the figurative geoglyphs can be divided into those produced in the line-type style and those in the relief-type style. This classification follows the one proposed by Lambers (3). With the help of AI, we were able to detect many new relief-type figurative geoglyphs. The improved inventory clarifies that line-type figurative geoglyphs are associated with the network of geometric geoglyphs and major roads (blue), whereas the relief-type figurative geoglyphs are associated with informal walking trails (green).

territory of particular social groups (13), and/or with subterranean water sources (14). Similarly, in the Chincha Valley on the south coast of Peru, a number of paired line segments not only marked the setting sun of the June solstice but also were part of a trade route (15, 16). In the case of line-type figurative geoglyphs, the calendar and astronomy hypothesis has attracted attention. It has been claimed that the line-type geoglyphs of animals correspond to the constellations. However, since these constellations are not mentioned ethnohistorically and ethnographically, this hypothesis has been criticized as being based on a Western view of the constellations (12, 17). Relief-type geoglyphs may have been created for viewing. The evidence for this is that this type of geoglyph tends to be distributed on the slopes of hills so that it can be seen from a distance (3, 18).

Hypotheses on the Distribution of Figurative Geoglyphs. One of the authors of this paper (Sakai) proposed the working hypothesis that line-type figurative geoglyphs are distributed along the linear/trapezoidal network stretching from the Ingenio River Valley to the Nazca River Valley (*SI Appendix, Giant Linear/Trapezoidal Network*) (11). However, this hypothesis has not been fully tested. On the other hand, a working hypothesis has been proposed that relief-type figurative geoglyphs are distributed along trails, imprinted onto the Nazca Pampa by people walking repeatedly (11, 19). These trails are winding and entangled, forming a meshwork (20) with no obvious starting or ending point. Prior to the current work, we were unable to obtain sufficient data to verify this hypothesis because the vastness of the Nasca Pampa prevented us from using the high-resolution aerial photographs to identify the distribution of relief-type geoglyphs.

Dating of Nazca Geoglyphs. Pottery sherds that are distributed on and near some geometric and figurative geoglyphs allow determining the approximate period when each of the geoglyphs was used. Previous field surveys suggest that the use of geoglyphs in the Nazca Pampa began by at least the 1st century BCE during the Initial Nasca period (100 BCE to 50 CE) and continued until the 15th century CE during the Ica period (11, 19, 21–23). Based on iconographic similarities between geoglyphs and pottery design, line-type figurative geoglyphs were probably made during the Nasca period (100 BCE to 650 CE) (12, 24). Pottery from the Early Nasca period (50 to 300 CE) was found at line-type geoglyphs such as "whale" and "monkey" (11, 12). Therefore, some line-type figurative geoglyphs were already used during this period. Relief-type figurative geoglyphs are thought to be associated with the Initial Nasca period or earlier, based on their iconographic features and production techniques (2, 25, 26).

Previous Field Surveys. Field surveys aided by aerial photography began in the 1940s and uncovered 112 figurative geoglyphs at the Nazca Pampa and surrounding areas (4–10). These consisted of 39 line-type and 73 relief-type geoglyphs. However, these studies did not cover the entire Nazca Pampa. In 2004 high-resolution satellite imagery (61 cm per pixel) was introduced to survey the distribution of geoglyphs (11). By 2020 we added high-resolution aerial photographs (10 cm per pixel) of the entire Nazca Pampa, and partial coverage by drone (less than 10 cm per pixel) to the field survey (27). As a result, a total of 318 new figurative geoglyphs were discovered from 2004 to 2020. These consisted of 11 line-type and 307 relief-type geoglyphs.

A comprehensive survey of relief-type figurative geoglyphs has not been attempted because the Nazca Pampa and surrounding area of interest stretches over 629 km^2. After nearly 2,000 y of exposure to the elements, these geoglyphs have poor visibility, and experts need to inspect high-resolution aerial imagery with the naked eye to identify candidates for field surveys. The current way of searching for these difficult-to-detect features is highly inefficient and impractical for a comprehensive survey. An AI-based distribution survey could revolutionize the search for relief-type geoglyphs on the Nazca Pampa.

Geoglyph Detection Assisted by AI. The success of deep learning has not only transformed language models (28) but also computer vision (29, 30), making it practical to automatically detect buildings, vehicles, or land-cover types in remotely sensed images. Even in the field of archaeology, where the objects of interest are faint, partially obstructed, or even buried under the soil, this form of AI has successfully been applied (31–34). Recently, two of the authors presenting this work identified 4 new Nazca geoglyphs using a then state-of-the-art object detection algorithm (27). It was highlighted that small, cropped images were key for the algorithm to be applied successfully, but a comprehensive survey was not attempted.

Results

In this paper, we present a comprehensive AI-assisted survey of the entire Nazca Pampa and surrounding desert area, which vastly improves the account of figurative geoglyphs and allows us to explain the different purposes of the line-type and relief-type figurative geoglyphs. This AI model focuses on relief-type geoglyphs that are small and difficult to identify since the distribution of the large line-type figurative geoglyphs is known from previous (manual) aerial studies that do not necessarily require inspection of high-resolution images. The AI-assisted method is much more scalable, as evidenced by the number of new geoglyphs it has identified: It has assisted in detecting 303 new figurative relief-type geoglyphs, almost doubling the amount of known relief-type geoglyphs (Fig. 2 and *SI Appendix*, Fig. S1).

The main challenge for the AI to overcome was detecting rare geoglyphs with poor contrast and limited training examples. Convolutional neural nets are typically trained on tens of thousands of images per class, while in the case of Nazca geoglyphs, we only had a few hundred known geoglyphs to train with. Our two most important AI strategies were to utilize an AI model (35) pretrained on natural photographs (36) and only fine-tune it on the relief-type geoglyphs. This requires fewer training examples than training a model from the ground up. Second, instead of employing an object detection algorithm that returns rectangular bounding boxes for the detected geoglyphs (27), we developed a gridded classification model that returns a continuous geoglyph probability map at 5 m resolution. This allowed us to transform each training geoglyph into small, cropped pieces that are shown to the model as multiple training examples. Technical details of our AI solution including other (minor) machine-learning strategies that often improve AI models are described in *SI Appendix*, *Details of the Artificial Neural Network*.

An example of our modeled geoglyph probability map is shown in Fig. 3*A*. It is postprocessed using a simple algorithm to generate geoglyph candidate outlines (*SI Appendix*, *Postprocessing of the Modeled Probability Map*). Resulting imagery (as in Fig. 3*B*) and corresponding geolocations are easily screened for their potential to be a genuine Nazca geoglyph by archaeologists on our team. As a result, the AI-model candidates were categorized into those with high potential for authenticity versus those with low potential for authenticity. The 1,309 candidates with high potential were further sorted into three ranks (Fig. 3*C*). A total of 1,200 labor hours were spent screening the AI-model geoglyph candidate photos. We processed an average of 36 AI-model suggestions to find one promising candidate. This represents a game changer in terms of required labor: It allows focus to shift to valuable, targeted fieldwork on the Nazca Pampa.

The field survey of the promising geoglyph candidates from September 2022 until February 2023 was conducted on foot for ground truthing under the permission of the Peruvian Ministry of Culture. It required 1,440 labor hours and resulted in 303 newly confirmed figurative geoglyphs. Fig. 4 shows the spatial distribution of the newly discovered as well as the previously

Fig. 2. Fifteen of a total of 303 newly discovered relief-type figurative geoglyphs from the AI-assisted survey. Drone images taken during the field survey that confirmed the geoglyphs as authentic. The scale bars are 5 m. Outlines have been added as a guide to the eye. Versions of the images without the outlines and archaeological interpretations of the relief can be found in *SI Appendix*, Fig. S1. The figurative geoglyphs depict humanoids, head, domesticated animal (camelid), killer whales, birds, feline, ceremonial scene, and human/animal interaction.

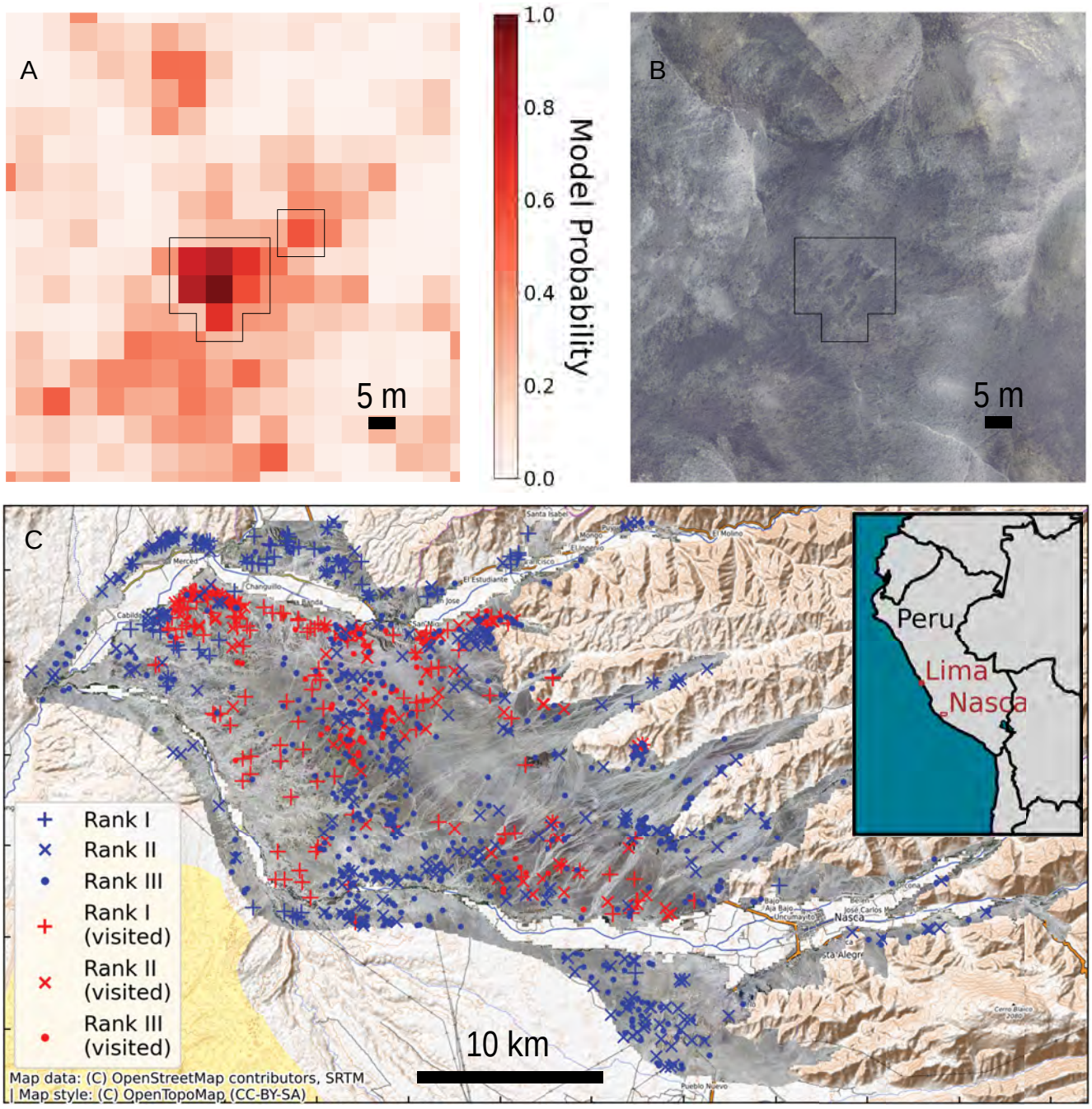

Fig. 3. Modeling and screening Nazca geoglyphs. (*A*) Closeup of the geoglyph probability map predicted by the model classifier. The outlines denote areas with probability above $P = 0.55$ (see *SI Appendix* for choice of P and N below). (*B*) AI candidate boxes on top of the corresponding high-resolution aerial image after dropping boxes composed of less than N = 2 image patches. We visually examined the 47,410 AI candidate boxes and assigned 1,309 high-potential candidates to 3 ranks, where Rank I (III) is the most (least) likely. (*C*) Map of examined AI-model candidates as a function of rank (see the legend). Candidate locations are the result of the combination of AI system and human screening and represent a fertile ground for exploration in field surveys. The 341 locations visited during the 6-mo 2022/23 field survey are highlighted in red. *Inset*: Location of the Nazca study area within present-day Peru.

known geoglyphs. In addition, 42 new geometric geoglyphs were discovered, which are presented under *SI Appendix*, *Newly Discovered Geometric Geoglyphs*, Fig. S5, and Table S3. All were documented by our team using drone-based imagery during the field survey. Correspondingly, the combined effort of researchers screening AI suggestions and surveying the resulting sites on the ground resulted in an effort of 2,640 labor hours.

Of the 303 newly discovered figurative geoglyphs, 178 were individually suggested by the AI and 125 were not individually AI-suggested (*SI Appendix*, Table S2, method c2). The most common situation of these additional finds occurred when an entirely new group of geoglyphs was discovered. (We assign geoglyphs within 50 m of each other to a group). Relief-type geoglyphs are often found in groups, such as a scene of humanoid figures, a scene of animals, or a scene of humanoids and human heads. Sometimes the AI flagged one or a few of these, but not all of them. This was the case in 23 out of 40 new AI-discovered groups with more than one geoglyph. *SI Appendix*, Fig. S4 exemplifies four newly discovered geoglyph groups and their relation to the AI model geoglyph candidate boxes. Geoglyphs that overlap with the AI model candidate boxes are individually AI-suggested and shown in green. We may account entire groups of geoglyphs as AI discovered if the AI led the researchers to at least one of them (*SI Appendix*, Table S2, method c1). Thus, of the 125 not individually AI-suggested

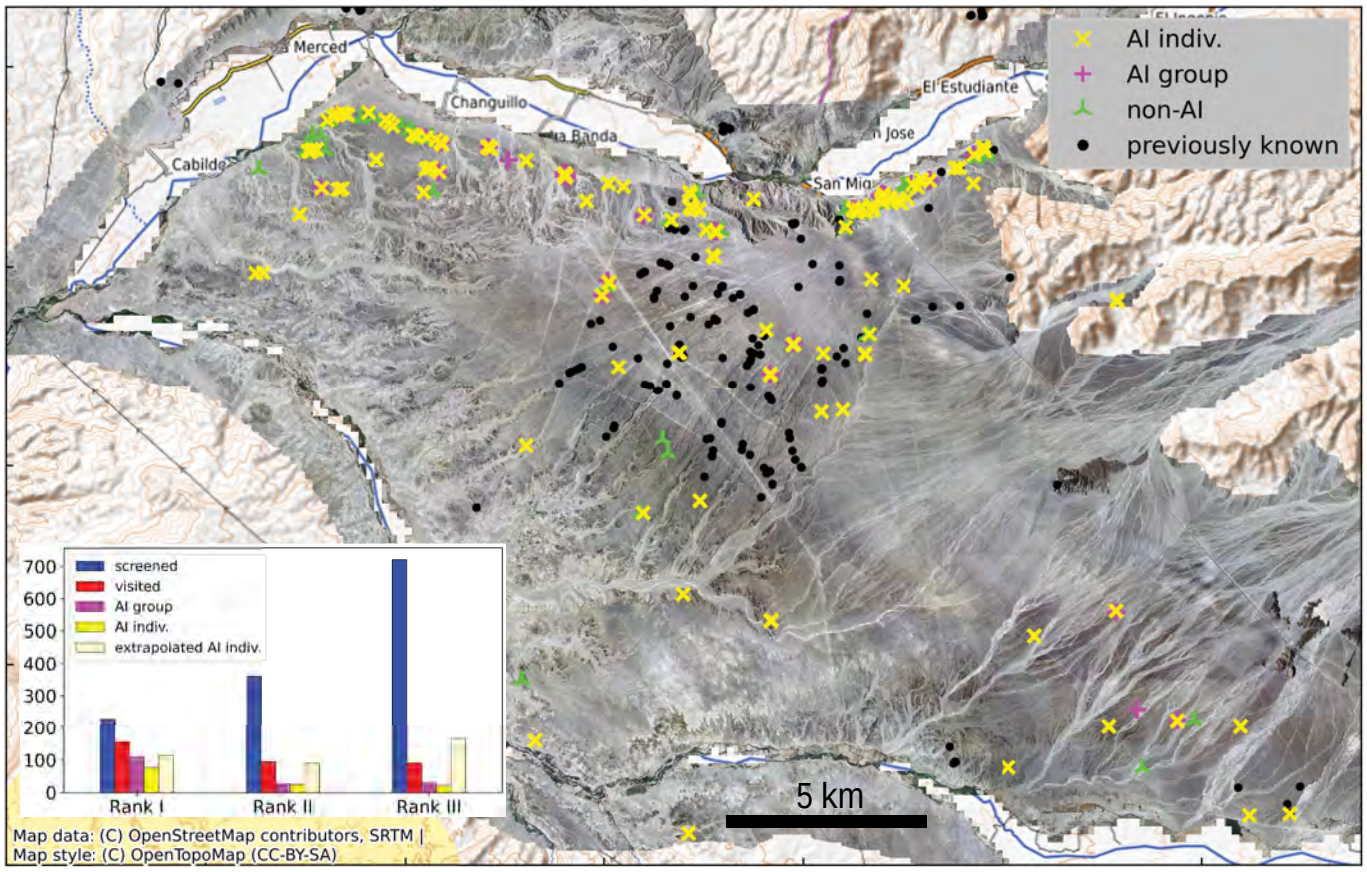

Fig. 4. Field survey confirms 303 new relief-type figurative Nazca geoglyphs. Map of 303 newly confirmed and 380 previously known (black) figurative relief-type geoglyphs. Newly confirmed geoglyphs are individually AI predicted (yellow), part of an AI-predicted geoglyph group (rose), or identified in the field survey without AI predicting that location (green). *Inset*: Histogram of ranked AI candidates (blue), visited AI candidates (red), new geoglyphs in AI groups (rose), individually confirmed AI geoglyphs (yellow), and extrapolated new geoglyphs (light yellow) as a function of rank. The extrapolation is based on the success rate within the three ranks (*SI Appendix*, Table S2).

geoglyphs, 66 were found as part of an AI-discovered group. The remaining 59 were found during the field survey without any help from AI or during screening outside of the AI-suggested boxes.

Nine hundred sixty-eight of the promising candidates could not be surveyed during the 2022/23 fieldwork. The distribution of the individually confirmed figurative geoglyphs over the 3 ranks is shown in *SI Appendix*, Table S2 and in the *Inset* to Fig. 4. Most of the Rank I geoglyphs have already been visited, while Rank II and Rank III candidates require more work. Applying success rates to all the candidate geoglyphs in each group, it can be pointed out that an additional 37 of the first rank, 66 of the second rank, and 145 of the third rank are likely to be authentic. Based on the above estimate, one may expect at least 248 additional AI-proposed figurative geoglyphs to be discovered from the Nazca Pampa upon completion of future field surveys. This estimate excludes additional finds in geoglyph groups and "non-AI" finds during the survey.

As a result of integrating the newly discovered 303 geoglyphs into the already known figurative geoglyphs, we found that there is a significant difference between the 50 large line-type geoglyphs and the 683 small relief-type geoglyphs in what is depicted (Fig. 5). Line-type geoglyphs predominantly depict wildlife-related motifs (e.g., wild animals and plants). Most relief-type geoglyphs (81.6%) depict human motifs or motifs of things modified by humans (33.8% humanoids, 32.9% decapitated heads, and 14.9% domesticated camelids). These do not appear in the line-type figurative geoglyphs at all. Decapitated heads are sometimes depicted alone, while humanoids are repeatedly depicted with decapitated heads and together with domesticated camelids. Examples of both are shown as *Insets* to Fig. 5. Wild animals, which dominate the line-type geoglyphs, represent only 6.9% (47 geoglyphs) of the relief-type geoglyphs. These include bird, cat, snake, monkey, fox, killer whale, and fish.

The distribution of relief-type figurative geoglyphs in relation to the winding meshwork of ancient trails is shown in Fig. 6*A*. Similarly, the distribution of line-type figurative geoglyphs in relation to the linear/trapezoidal network used during the Early Nasca Period, when the Cahuachi Temple was at its apogee as a ceremonial center (37), is shown in Fig. 6*B*. Note that the Early Nasca setting of this network of linear and trapezoidal geoglyphs was determined by the pottery sherds distributed on this network. The *Insets* to Fig. 6 show histograms of distances between relief-type figurative geoglyph groups and trails as well as those between line-type figurative geoglyphs and the linear/trapezoidal network. Average distances between relief-type geoglyph groups and the nearest trail are 43 m. Average distances between line-type geoglyphs and the nearest line/trapezoid are 34 m.

All individual geoglyphs that do not form geoglyph groups have been found to be visible from the trails. On the other hand, not all the geoglyphs that form groups are necessarily visible from trails: One or a few geoglyphs may be visible, while the others become visible only after walking to the first ones. Note that due to an only partially mapped trail meshwork, we set a cutoff of 500 m and remove all geoglyphs from the analysis that are not within 500 m of trails. Our findings support two hypotheses about the figurative geoglyph associations: Relief-type figurative geoglyphs are associated with the meshwork of trails beginning in the Initial Nasca Period since pottery from this period and later is distributed

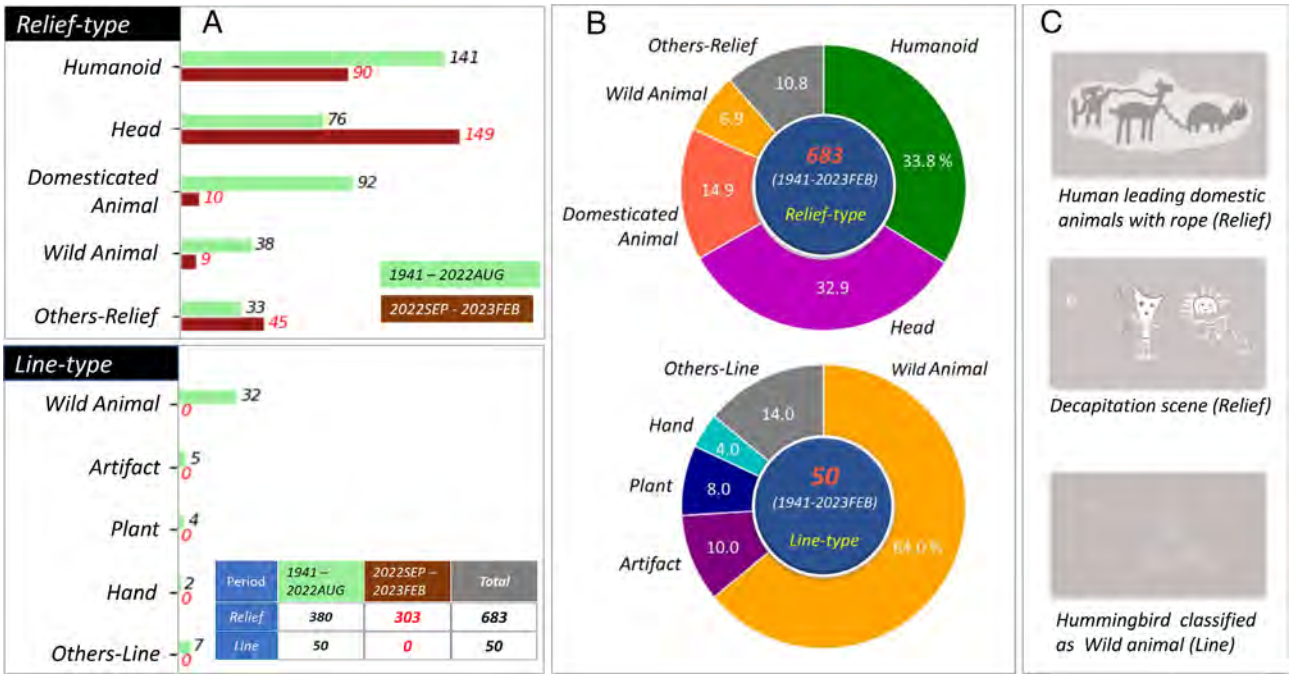

Fig. 5. Figurative geoglyphs identified in and around the Nazca Pampa, classified by their type (line-type and relief-type) and motifs. (*A*) Histogram of previously known and newly discovered figurative geoglyphs. The 303 newly detected geoglyphs during the present study are shown in brown. (*B*) Comparison of the motifs between relief-type and line-type geoglyphs. Most relief-type geoglyphs depict Humanoids, Decapitated Heads, and Domesticated Animals, while most line-type geoglyphs depict Wild Animals. (*C*) Drawings showing three different colors that appeared on the desert surface as a result of moving the stones to make the relief-type and line-type geoglyphs. White: stones removed; dark brown: piled stones; light brown: original surface.

there. Line-type figurative geoglyphs are associated with the network of lines/trapezoids of the Early Nasca period.

Discussion

The rate of discovery of new figurative Nazca geoglyphs has been historically on the order of 1.5 a y (from 1940s to 2000s). It has accelerated due to the availability of remotely sensed high-resolution imagery to 18.7/y from 2004 to 2020. Our current work represents another 16-fold acceleration (303 new figurative geoglyphs during the 2022/23 season of field work) using big geospatial data technologies and data mining with the aid of AI. Thus, AI may be at the brink of ushering in a revolution in archaeological discoveries like the revolution aerial imaging has had on the field.

Nazca geoglyphs are part of the human cultural heritage, and they are protected by the UNESCO and the Peruvian Ministry of Culture. Accidental or malicious destruction of geoglyphs has been occurring in the past. Climate change poses new threats to Nazca geoglyphs today, amplifying extreme weather events and potentially triggering more devastating flash floods in desert areas. We hope that efforts like ours to accelerate geoglyph identification and documentation with the help of AI may lead to better strategies to mitigate damage and manage cultural resources in desert environments (38).

Aided by the newly discovered Nazca geoglyphs, surveyed across the entire Nazca Pampa, we can make some well-informed conclusions and inferences. The differences in motifs of line-type and relief-type geoglyphs may reflect different activities practiced at the two types of figurative geoglyphs. Line-type figurative geoglyphs are distributed along the straight-line and trapezoidal geoglyph network used during the Early Nasca Period. Since they are on average only 34 m apart from lines and trapezoids, it is highly likely that the people of that period visited the line-type figurative geoglyphs on foot from the lines and trapezoids. Therefore, the line-type figurative geoglyphs along lines and trapezoids can be regarded as part of this network.

About 10 narrow entrances/exits to the network exist in the Ingenio River Valley at the northern end of the Nazca Pampa adjacent to which trapezoids and line-type figurative geoglyphs are concentrated. In the Nazca River Valley, on the other hand, line-type geoglyphs are distributed near only two major (more than 40 m wide) entrances/exits. One is located near the Cahuachi Temple on the opposite bank of the Nazca River. The other is near the confluence of two rivers (Tierras Blancas River and Aja River), where the Nazca River originates, and seems to be the equivalent of "tinkuy," an indigenous Quechua concept meaning a socially and supernaturally charged place where two opposing forces converge (17). Thus, it is likely that the Cahuachi Temple and the confluence of rivers in the Nazca River Valley were the intended destinations. This indicates that the network was mainly designed for groups from the Ingenio River Valley to make pilgrimages to the Cahuachi Temple and the confluence of rivers in the Nazca River Valley.

The line-type figurative geoglyphs are huge, with an average length of 90 m. It is highly probable that rituals were performed on the giant line-type geoglyphs at the beginning and/or the end of the pilgrimage across the Nazca Pampa. It is reasonable to regard the trapezoidal geoglyphs, around which about half of the line-type figurative geoglyphs are distributed, as ritual squares directly related to the line-type geoglyphs. There are about 10 such squares, ranging in length from 300 to 950 m, around which 24 line-type geoglyphs have been identified. Since the main motifs of the line-type geoglyphs are wild animals, it is probable that ceremonial activities related to these animals were performed during pilgrimages. Since not only the line-type figurative geoglyphs but also the straight-line network shows a certain level of standardization, they can be regarded as planned public architecture. It is reasonable to assume that they were established and used by the communities of the Ingenio River Valley.

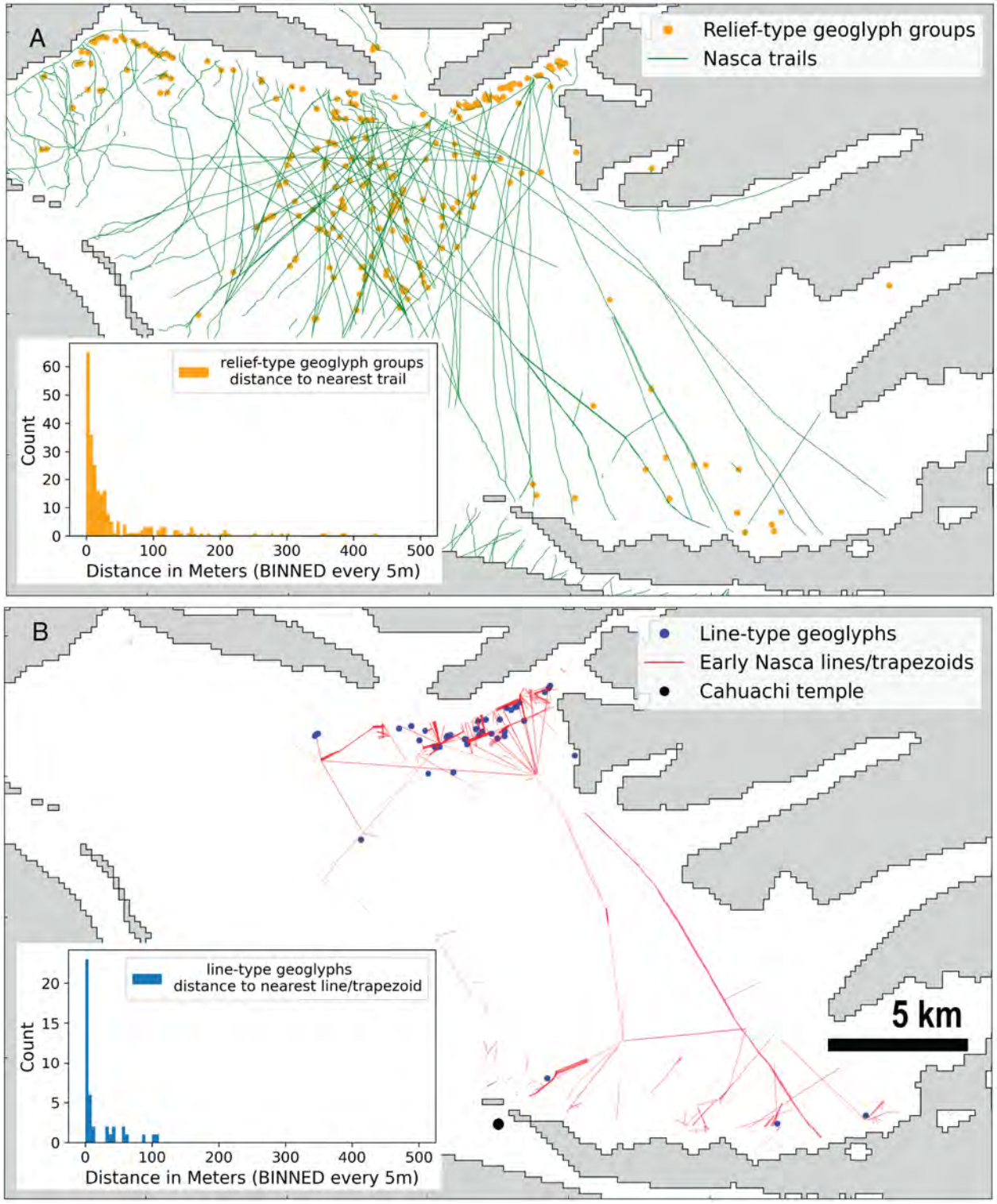

Fig. 6. Figurative geoglyphs and their associations. (*A*) Relief-type figurative geoglyphs are associated with the informal network of winding trails. *Inset*: Histogram of the distance between relief-type figurative geoglyph groups and the nearest Nazca trail. (*B*) Line-type figurative geoglyphs are associated with the formal network of linear/trapezoidal geoglyphs. *Inset*: Histogram of the distance between line-type figurative geoglyphs and the nearest Nazca line/trapezoid.

Informal trails that crisscross the Nazca Pampa differ greatly from the formal network of straight lines and trapezoids. They are a tangled meshwork that intertwine and intersect with each other. The trails are not the product of public architecture based on a systematic plan but are traces imprinted by people walking repeatedly, with no clear beginning or end point. It is highly likely that they were created and used by repetitive actions of individuals or small groups, rather than at the community level.

Relief-type figurative geoglyphs were constructed at an average distance of 43 m from the trails, either individually or as a combination of geoglyphs depicting some scene. They are thought to originate from the Initial Nasca period or earlier (3, 25, 26). The field survey confirmed that relief-type geoglyphs or geoglyph scenes could be recognized from the trails. Thus, the relief-type geoglyphs were objects to be viewed while walking along the trails. The main motifs of the relief-type geoglyphs were humans,

livestock, and human sacrifice, all of which depict scenes with humans or things modified by humans. Repeatedly observing relief-type geoglyphs from the trails probably facilitated sharing information about human activities related to these scenes.

In this paper, we have confirmed a difference in the purpose of line-type and relief-type figurative geoglyphs by relating them to the linear/trapezoidal network and trails and analyzing differences in the distribution of their motifs. This does not preclude the possibility that the Nazca geoglyphs may also have functioned at another level (12).

Materials and Methods

Workflow. The flowchart in *SI Appendix*, Fig. S2 summarizes our accelerated archaeological discovery workflow from the data curation over the AI model, the creation of geoglyph candidate outlines, the archaeologist's screening and field suvey of AI candidates, to the downstream task of analyzing the geoglyph spatial distribution and visibility.

Data Preparation for the Artificial Neural Network Model. Orthorectified RGB imagery (red, green, and blue channels), acquired by aircraft at 10 cm effective resolution, is rasterized, mosaicked, and fused by the IBM geospatial platform PAIRS (39). PAIRS provides fast random access to the curated data cube for machine learning, training of AI models, and spatiotemporal analytics workflows in general. A land classification mask (40) limits the prediction area to a relevant 629 km^2 of Nazca Pampa and surrounding barren land where agricultural land or urban scenes get excluded. RGB channels are individually sharpened by applying the PIL SHARPEN ImageFilter (41) twice.

Our AI model consumes true color ortho images of 112 × 112 pixels. These cover about 11 × 11 square meters each and are cropped from the continuous georeferenced data cube curated. Individual image crops are normalized using mean = [0.485, 0.456, 0.406] and std = [0.229, 0.224, 0.225] (ImageNet standard). For inference, we sampled the entire Nazca Pampa and its surrounding using a moving window with a step size of approximately 5 m so that neighboring crops overlap by 3 m.

The training/verification images were selected from 406 relief-type figurative geoglyphs, of which 380 are distributed in and around the Nazca Pampa and the rest in the Palpa area. Positive training/validation images are informed by 401 of these relief-type geoglyph outlines of which 368 are randomly picked for training and 33 for validation. Negative training labels are sampled from the immediate surroundings of the geoglyphs.

To leverage the limited number of known relief-type geoglyphs, and to render the training robust, data augmentation is paramount (42). Hand-labeled outlines of known geoglyphs serve to pick 10 random crops from within each of the known geoglyphs. These are also randomly rotated, horizontally flipped, and color jittered. Similarly, 25 negative training images are randomly cropped from the area surrounding each known geoglyph. We set the ratio of positive to negative training images to 10:25 for a reasonable balance between precision and recall (*SI Appendix*).

Data, Materials, and Software Availability. All non-restricted data used in this paper is included in the manuscript. The precise location data of the geoglyphs that were used for training the AI model is available in reports on previous NASCA surveys (43–45). We don't have permission to make this data accessible in a public database, but legitimate users may request it from the Peruvian Ministry of Culture. Data created by us on the geoglyphs are available upon request to Masato Sakai: sakai@human.kj.yamagata-u.ac.jp, if permission is granted by the Peruvian Ministry of Culture and other organizations. Software used in this article is available from the following public GitHub repositories (46, 47).

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