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5. Documentation of the Palpa geoglyphs

In this section, the investigation of the Palpa geoglyphs within the framework of SLSA's Nasca-Palpa Project is described in detail. The different steps of data acquisition and processing are outlined, and the applied archaeological and photogrammetric methods are explained.

Before fieldwork in Palpa started, a review of potentially suitable aerial photographs was undertaken in order to determine if existing imagery could be used for the planned photogrammetric documentation of the geoglyphs. As for most other coastal valleys, vertical aerial photographs of the Palpa area had been taken in previous decades by Peruvian governmental agencies. Images available prior to the start of the project are listed in table 3.

Of these images, only the series taken in 1944 (1:5,000) and in 1970 (1:10,000) were acquired from the SAN office in Lima since the scale of the other series would not have given enough detail to map the geoglyphs. No information on the camera used in either of the two flights was available. The 1944 images which covered only the central part of Cresta de Sacramento could not be oriented satisfactorily, most likely because there was a lack of camera calibration data (Fischer/Künstle 1999). They could therefore not be analyzed stereoscopically. The 1970 images could be oriented but were partially damaged and their scale did not give enough detail. Thus, it was decided to base the work in Palpa on a new series of images to be taken within the framework of the Nasca-Palpa Project. These images were especially designed to meet the requirements of a 3D documentation of the geoglyphs.

In order to deliver the desired results, the application of photogrammetry to record the Palpa geoglyphs required close cooperation between geomatic engineers and archaeologists. While the former provided the technological expertise and carried out the technical aspects of the work, the latter contributed the archaeological expertise and conducted the actual recording of the geoglyphs. A combined workflow was devised that integrated both archaeological and photogrammetric procedures in or-

der to get from the real-world geoglyphs to digital records of them. The steps of the workflow, shown in figure 8, are described in detail below. As the flowchart clearly indicates, the different steps of the workflow were highly interwoven so that the sequential description given in the following can characterize it only inadequately³⁴.

5.1 FLIGHT PLANNING

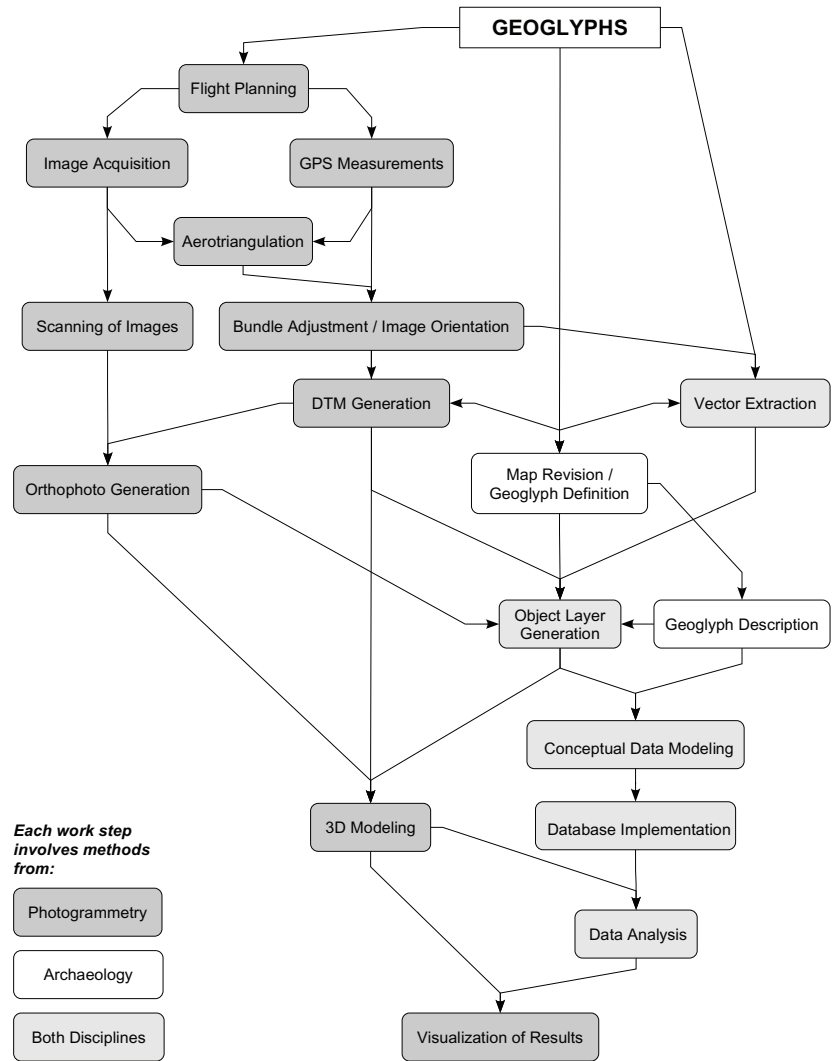
In the course of the project, two roughly rectangular areas or blocks were defined over the Palpa area where aerial images were to be taken (fig. 9). Both rectangles were laid out to include the areas with geoglyphs on the ridges and plateaus along the valleys. The smaller block covered Cresta de Sacramento, a low ridge northwest of Palpa between Río Grande and Río Palpa that was the main focus of the archaeological investigations in the first field season in 1997³⁵. The flight was planned so as to yield vertical aerial images at a scale of 1:5,000, organized in parallel strips with a 60% overlap in both directions in order to allow full stereo-processing.

The original plan was to take color photographs, but when the 1997 flight over Sacramento did not deliver results good enough for our purposes, it was decided to commission a second flight one year later in order to take black-and-white photographs of the same area using the same flight characteristics. By the time the second flight was to be carried out it had become clear that the *pampas* of San Ignacio and Llipata to the southeast of Palpa were also to be included in the archaeological project. Thus, a second area to be photographed was defined

³⁴ The following description does not coincide in all technical details with previous, preliminary reports. Where differences occur, information given in the present study should be regarded as definite.

³⁵ Grün/Brossard 1998; Grün 1999; Reindel et al. 1999.

Fig. 8. Workflow of geoglyph documentation, analysis, and visualization that combines photogrammetric and archaeological methods.



YEAR	AGENCY	NOMINAL SCALE	AREA COVERED	REMARK
1944	SAN	1:5,000	Sacramento, San Ignacio	only partial coverage
1944	SAN	1:12,000	Sacramento	scale probably 1:15,000
1955	IGN	1:60,000	whole Palpa area	
1970	SAN	1:10,000	whole Palpa area	
1986	IGN	1:70,000 1:80,000	whole Palpa area	
1992 to 2002	IGN	1:30,000 1:60,000 1:80,000	whole Palpa area	

Table 3. Aerial imagery of the Palpa area available from Peruvian governmental agencies (based on review of SAN archive, Lima, and IGN website: www.ignperu.gob.pe, accessed May 2004).

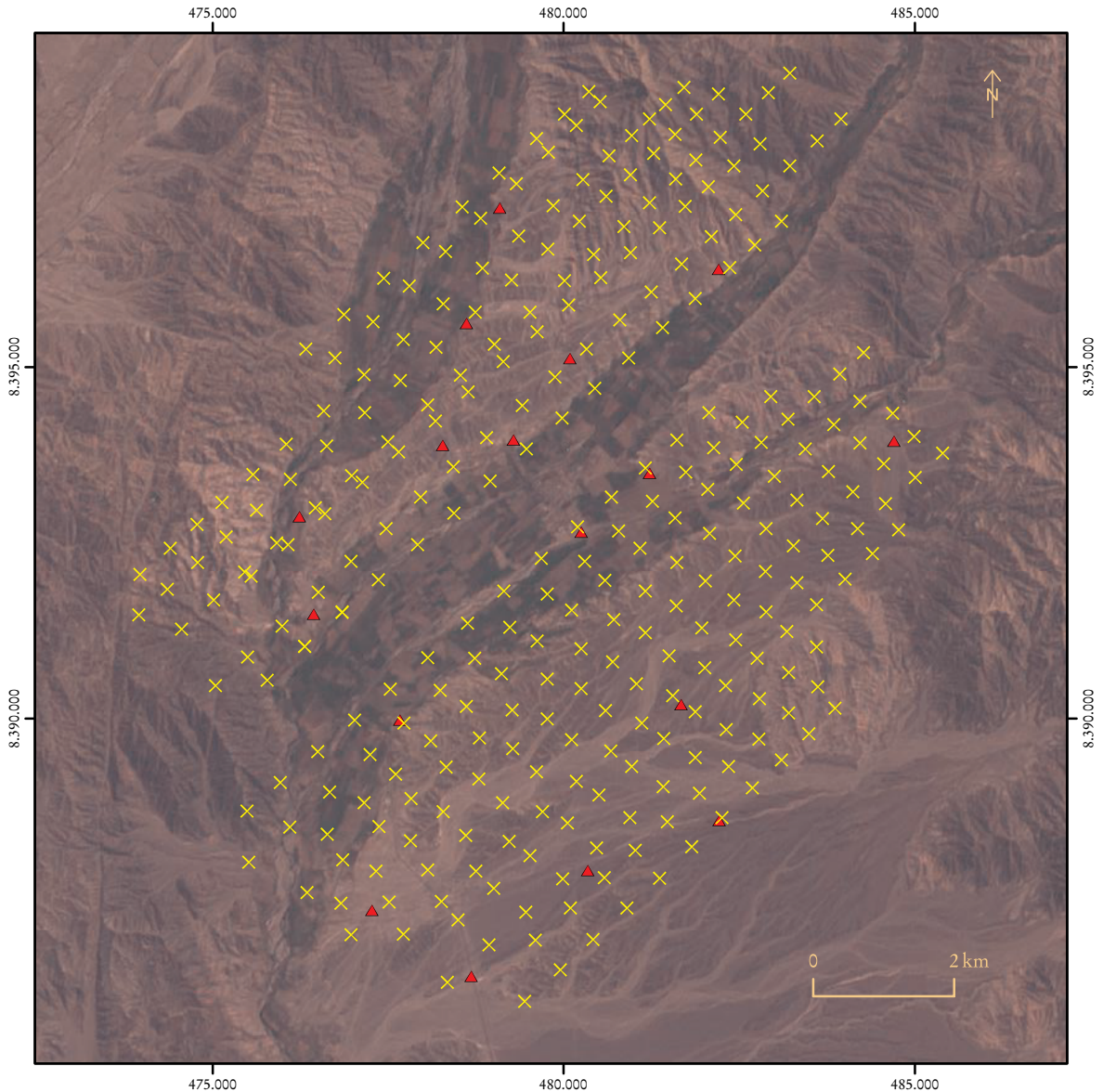


Fig. 9. Landsat 5 TM image of the Palpa area with projective centers of 1998 black-and-white aerial images (yellow crosses) and ground control points (red triangles).

over that area that was to be covered during the same flight. For each flight the flying height was defined according to the desired image scale, and the positions of the intended projective centers were marked on a topographic map. This data was then passed on to Horizons Inc.³⁶, Rapid City, SD in the United States and they carried out the actual flights.

³⁶ See company website at www.horizonsinc.com (accessed August 22, 2005).

5.2 IMAGE ACQUISITION

On May 1, 1997, the first photogrammetric flight was performed over Cresta de Sacramento. The flying height was approximately 750 m above ground. Using a calibrated Zeiss RMK A15/23 aerial camera with a focal length of 152.994 mm, 212 color photos were taken along eight parallel strips. After the flight the images turned out to be partially scratched and blotchy. Furthermore, their color was not ideal for identification of the geoglyphs, and an intensity falloff was visible towards the image edges.

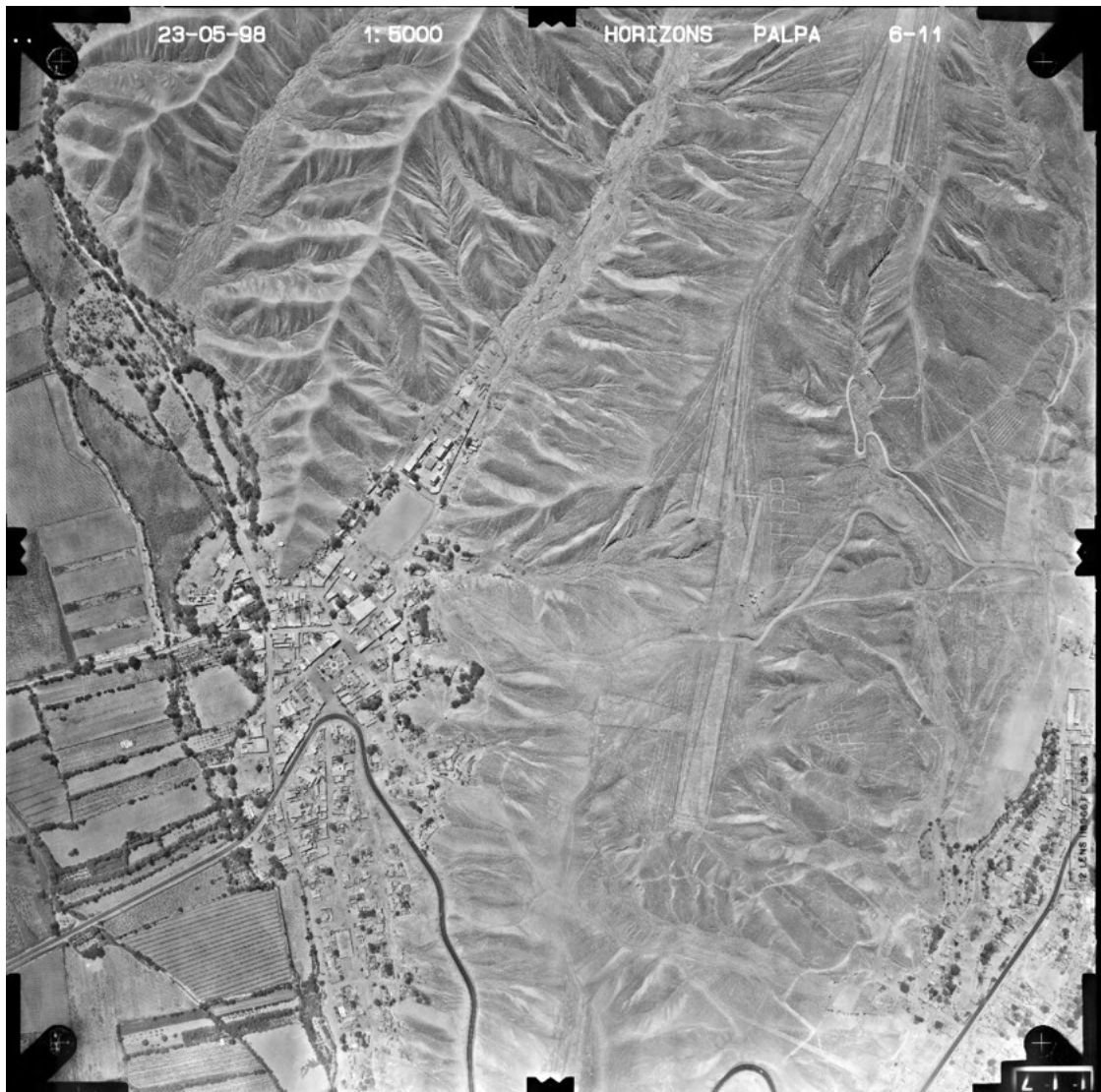


Fig. 10. Black-and-white vertical aerial image of the central part of Cresta de Sacramento (left: Río Grande).

Therefore, a second photo flight was undertaken the following year by the same company.

On May 23, 1998, 169 images along eight strips were taken over Cresta de Sacramento, this time in black-and-white (fig. 10). During the same flight the second area over the *pampas* of San Ignacio and Llipata was also covered. It comprised the area southeast of Palpa approximately 4.5 km into the desert from Río Viscas. Two hundred and fifteen images along eleven strips were taken over the second area with the same characteristics as the images of the first block³⁷. Since Cerro Carapo, to the northeast of

³⁷ Along with the acquisition of the Palpa images, another series of aerial images was taken over the Nasca *pampa*. These images have a nominal scale of 1:10,000 due to the larger area covered and were taken in 1997 (439 color images) and 1998 (401 black-and-white images), respectively. The Nasca images have not been analyzed during the first phase of the Nasca-Palpa Project, in which all efforts were focused on the Palpa region. Only some images of the northern edge of the Nasca *pampa* have been used by the Nazca Project of HTW Dresden (Teichert/Richter 2001, 2003). In the framework of the second phase of the Nasca-Palpa Project, the Nasca image series is now being analyzed at IGP in order to map the Nasca geoglyphs as well. That work will be reported on in a later study. See Sauerbier (2004) for some preliminary results.

Palpa between Río Palpa and Río Viscas, had also to be included in the photographed area, the first strips of the second block also covered a good part of the floodplain and the town of Palpa (fig. 9). Thus, although not intended at the beginning, the photos of both photographed areas actually overlapped slightly in the central part of the flown area (approximately 20% decreasing in northeasterly direction) which was very advantageous during analysis since it allowed the merger of the two areas into one (Sauerbier/Lambers 2003).

All in all the black-and-white aerial images taken in 1998 covered a roughly rectangular, southwest to northeast oriented area of approximately 89 km² around the town of Palpa (frontispiece, supplements 1, 2). The average image scale that was intended to be 1:5,000 turned out to be approximately 1:7,000 which was still sufficient for our purposes. Unlike the color photographs, the contrast of the black-and-white images allowed the detection of even narrow lines, and the image quality was generally good. Thus, it was decided to use the 1998 images for analysis.

5.3 GPS MEASUREMENTS

In order to obtain control data to orient the images spatially, GPS was used in two different modes. In 1997, when the area over Cresta de Sacramento was flown for the first time nine signalized ground control points were evenly distributed over the terrain whose position had been determined with differential GPS³⁸. Furthermore, kinematic GPS measurements were performed onboard the plane that could serve as approximations for the positioning of the projective centers (fig. 9). In 1998 when both areas were flown, kinematic GPS could not be used, and the signalized points in the Sacramento area were no longer available. The latter problem could be solved by performing a joint bundle adjustment of both the 1997 color images and the 1998 black-and-white images of the first area (see below). In the second area over San Ignacio and Llipata, however, no ground control points had been prepared. Therefore, in 1999 nine natural points – *i. e.* points clearly discernible in the aerial images without having been marked on the ground – were measured in the San Ignacio block again using differential GPS (Grün et al. 2000a; Grün/Beutner 2001). That way, solid GPS control data for both areas was available for image orientation.

All GPS coordinates were transformed into UTM zone 18 S projection which is the basis for the IGN topographical maps of the area. It should be noted here that during fieldwork a horizontal shift of several hundred meters was detected between the UTM coordinates obtained by GPS measurements and those taken from available maps. This was because the topographic maps used during the first field seasons (scale: 1:50,000 and 1:100,000, respectively) referred to the Provisional South American Datum 1956 (PSD 56) based on International Ellipsoid 1924. In the GPS measurements the World Geodetic System 1984 (WGS 84) provided both ellipsoid and datum. A later comparison showed that current versions of the same IGN maps refer to WGS 84 also, so that the shift between GPS coordinates and map coordinates is now eliminated.

5.4 AEROTRIANGULATION

The first step in image processing was the orientation of images relative to each other. For this purpose five to ten tie points clearly identifiable in the overlapping area of two adjoining images had to be measured. Image matching is today usually performed in an automated mode. However, the Palpa aerial images show largely the desert surface which is very homogeneous in texture and provides little contrast. As several tests showed, matching algorithms implemented on different commercial systems failed to produce acceptable results due to this lack of texture (Grün et al. 2000b; cp. Sauerbier 2004 for up-to-date results). Thus, the measurement of tie points had to be done manually on the analytical plotters available at IGP (Wild AC3 and S9). In the Sacramento flight area not only tie points to link images within the black-and-white series had to be measured, but also tie points to link the black-and-white images to the color images in which the signalized ground control points were visible. Two hundred and eleven images (134 black-and-white and 77 color images) were triangulated in the Sacramento block. In the San Ignacio flight area tie points and natural ground control points were measured within the black-and-white image series. Here, 168 out of 215 images were triangulated. The lower number of images used for triangulation as compared to the existing images is due to the fact that on the

³⁸ Grün/Brossard 1998; Grün et al. 2000a; Grün/Lambers 2003.

Block	Images Used	Control Points	Kinematic GPS	σ_0	Ground Accuracy
Sacramento	134 b/w and 77 color	8 signalized	yes	13.3 μm	9.3 cm
San Ignacio	168 b/w	9 natural	no	9.5 μm	6.7 cm

Table 4. Triangulation characteristics of the two image blocks over the Palpa area.

margins of the flight zones mountainous areas without geoglyphs were omitted for the sake of efficiency.

5.5 BUNDLE ADJUSTMENT AND IMAGE ORIENTATION

Once all images had been tied together via tie points and linked to the ground control points, a joint bundle adjustment for each area was performed using BUN which is in-house software developed at IGP. The orientation of each image with respect to each other image and UTM coordinates for each image point were calculated. As a result, all images were provided with orientations relative to each other and absolute in the UTM zone 18 S coordinate system. Table 4 summarizes the triangulation characteristics of both areas.

The achieved ground accuracy was good enough for the intended purpose. As a result of the bundle adjustment oriented images were obtained that could then be used in pairs of two neighboring, overlapping images (also called stereopairs or models) for 3D measurements.

5.6 DIGITAL TERRAIN MODEL GENERATION

As a prerequisite for the intended geoglyph study, a highly accurate digital terrain model (DTM, a geometric model of the topography) was needed before the recording of archaeological objects could start. The matching problems described above meant that automatic DTM generation was not feasible. Therefore, the measurements were undertaken again on analytical plotters. The manual measurement offered the advantage that a very good DTM, describing the actual terrain, could be measured while automated measurements would have led to a digital surface model (DSM) that would have described the surface including buildings, trees, etc. with lower accuracy.

The terrain was measured in the stereopairs, and 72 models from the Sacramento area and 94 models from the San Ignacio area were used for

these measurements. Points were obtained along parallel profiles that had a distance of 20 m from each other. Along these profiles the distances between measured points depended on terrain shape. In flat areas, less points were measured than in mountainous terrain. Special attention was paid to zones with geoglyphs. In addition to profiles, breaklines were measured along abrupt changes in the terrain in order to map the terrain more accurately. Unlike the profiles, the breaklines were measured as continuous vectors, whereas points measured along profiles were treated as isolated points not connected to each other. In the first iteration, only the actual terrain surface was measured. Later on, points measured during vector extraction were added in order to enhance point density especially in areas with geoglyphs. All in all approximately 1.4 million points were measured in an area of roughly 89 km² giving an average density of 1.6 points/100 m².

Based on this data a regular grid DTM was calculated with a grid spacing of 2 m. This was done in two iterations: firstly, a preliminary DTM was generated based on the corresponding measurements alone. After the revision of the resulting maps in the field the digital dataset was corrected, so that the final DTM could be produced (fig. 11). The DTM was generated using DTMZ which is another in-house software that performs Delauney triangulation and bicubic finite element interpolation. Neighboring points were connected by edges of triangles resulting in an approximation of the actual shape of the terrain surface. The breaklines were not bridged in the triangulation process to ensure that abrupt changes in the terrain were reproduced correctly in the DTM. Originally, two separate DTMs were generated that corresponded to the two original image areas over Sacramento and San Ignacio. Since the DTMs overlapped slightly, they could later on be merged into a single, continuous DTM. The file size is approximately 480 MB in ASCII xyz-format. The wire-frame model can be used as a base for 3D modeling. Various byproducts such as shaded reliefs or contour maps can be derived from the wire-frame model.

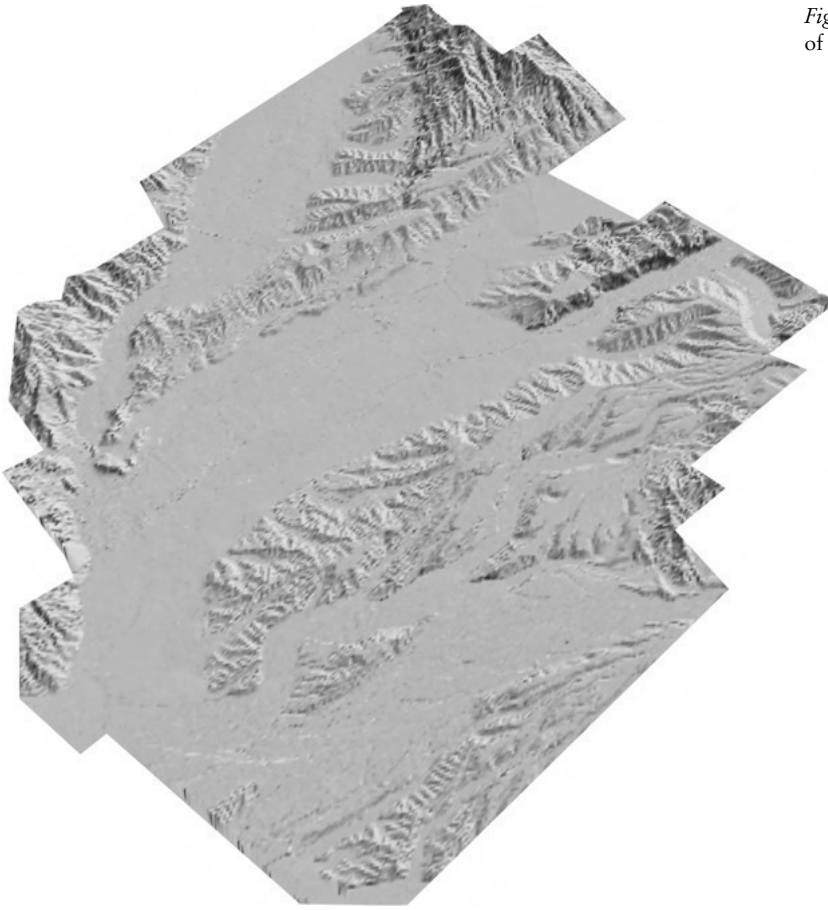


Fig. 11. Digital terrain model (DTM) of the study area as shaded relief.

5.7 SCANNING OF IMAGES

Along with the analysis of the stereopairs, the analog images acquired during the photo flight were scanned at high resolution in order to produce an easily accessible photographic record of all geoglyphs and to generate an orthoimage as texture for the DTM. To enable the latter the scanning had to be done on calibrated photogrammetric scanners that allowed high resolution scans with high geometric fidelity. The images of the Sacramento area were scanned at a resolution of $21\ \mu\text{m}$ pixelsize using an Agfa Horizon image scanner at IGP (fig. 10). The images of the San Ignacio area were scanned at the same resolution on a Zeiss SKAI scanner at the Swiss Federal Office of Topography (Swiss-topo, Wabern). The ground resolution is 15 cm, which ensured that even the most narrow lines were still visible. Like the DTM measurements, images on the margins of the flight areas that showed only mountainous areas were omitted for the sake of efficiency. The images were stored in TIFF format with an overall file size of about 2.15 GB.

5.8 ORTHOPHOTO GENERATION

The scanned images could be oriented based on the bundle adjustment. With the DTM as geometric reference they were combined into an orthomosaic using Socet Set on the Leica/Helava digital photogrammetric workstation (DPW) 770. The mosaic contains the rectified scanned images, *i. e.* images corrected so as to omit relief displacements caused by the central perspective of the original images, with smooth transitions between adjacent images. The result is a complete picture of the whole area covered by aerial images with each pixel provided with coordinates (supplements 3, 4). Like the DTM, the orthophoto was initially generated in two parts corresponding to the two original areas photographed. Later, when all necessary data had become available a complete orthophoto was generated that covered the whole area of investigation. According to different requirements several orthomosaics with a resolution ranging from 25 cm to 2 m pixel size were generated.

5.9 VECTOR EXTRACTION

Once the DTM had been generated, the actual feature extraction, *i. e.* the 3D mapping of the geoglyphs, could begin. This was done once again on analytical plotters using the XMAP software by Aviosoft. In each oriented stereopair, outlines of visible geoglyphs were marked with 3D vectors that could be digitally stored. Only actually preserved borders and borders that could be reasonably assumed to have once existed based on circumstantial evidence were mapped. Like the DTM, after a first iteration the vector data was revised in the field and then corrected and complemented in a second iteration. That way, 33,243 3D vectors, corresponding to roughly 1,500 geoglyphs, were produced.

As these numbers show, a peculiarity of this dataset is that in virtually no instance a given vector represents the entire outline of a single geoglyph; rather, it usually shows only a small part of its border (Sauerbier/Lambers 2004). This is due to the state of preservation of the geoglyphs: Many borders are interrupted where erosion had washed them away or where geoglyphs had been partially covered by other geoglyphs or footpaths. Furthermore, many geoglyphs do not have clearly defined borders on all their sides even if they are well preserved. For example, many trapezoids have an open narrow end without a clear margin. Thus, the result of the vector extraction was a huge number of unconnected 3D vectors. Based on this data, a vector layer was generated that could be exported into DXF format for further processing. The file size of the vector layer is about 20 MB.

In a separate step, all modern man-made elements visible in the stereopairs were also mapped in order to allow easier orientation. This was done in a generalizing way since the focus of the project was on the geoglyphs. The outlines of modern buildings, roads, etc. were marked and stored in a separate dataset. This dataset needed not to be revised in the field since all modern elements were clearly visible in the stereopairs, and did not constitute the focus of our investigation. The DXF file containing the modern elements has a size of about 9 MB.

5.10 MAP REVISION AND GEOGLYPH DEFINITION

As indicated above, maps resulting from image analysis were revised in the field in order to improve their quality. The digital datasets were

then revised accordingly. Map revision was accomplished during the field seasons. Due to the photogrammetric mapping, prior to archaeological fieldwork it was already fairly clear what to expect in the field. Reliable, though preliminary maps were available such that no surveying work had to be undertaken. Rather, in contrast to previous projects, the limited available time during fieldwork could be dedicated to the actual archaeological recording of the geoglyphs.

The first of three seasons of archaeological fieldwork was started in 2000. The fieldwork lasted eight months all in all. Out of the approximately 1,500 geoglyphs that had been mapped with photogrammetric means, all 639 geoglyphs located on Cresta de Sacramento, Cerro Carapo, and the area around La Muña on the right bank of Río Grande were recorded³⁹. These are the geoglyphs considered in the present study (supplement 5b). Due to time constraints, only a small fraction of the San Ignacio and Llipata geoglyphs (226 geoglyphs at five sites) could furthermore be recorded which is why their overall number cannot be given here. The map could be corrected for some of the additional sites in the area of densest concentration of geoglyphs on the first plateau above the Viscas Valley. The remaining majority of geoglyphs of San Ignacio and Llipata, however, were mapped by photogrammetric means alone (supplement 2). Although this procedure was not as reliable as the combined one employed on Cresta de Sacramento and Cerro Carapo, the San Ignacio and Llipata geoglyph maps can still be considered comparatively reliable. The geoglyphs in that area are generally better preserved, and their mapping was undertaken when experiences from earlier field seasons allowed geoglyph shape to be reliably identified in the aerial images.

Fieldwork required the making of paper maps based on digital data. In order to produce them different datasets were combined. Contour lines with an equidistance of 10 m were derived from the DTM and shown as background of the geoglyph outlines. Furthermore, modern elements were added to allow easier orientation in

³⁹ Geoglyphs 1 – 646, out of which numbers 246, 285, 362, 374, 420, 461 and 511 were not assigned to geoglyphs due to technical reasons. Different geoglyph numbers given in preliminary reports are due to geoglyph renumbering in the course of analysis, during which several geoglyphs originally recorded separately in the field were combined and others omitted (see geoglyph database on DVD).

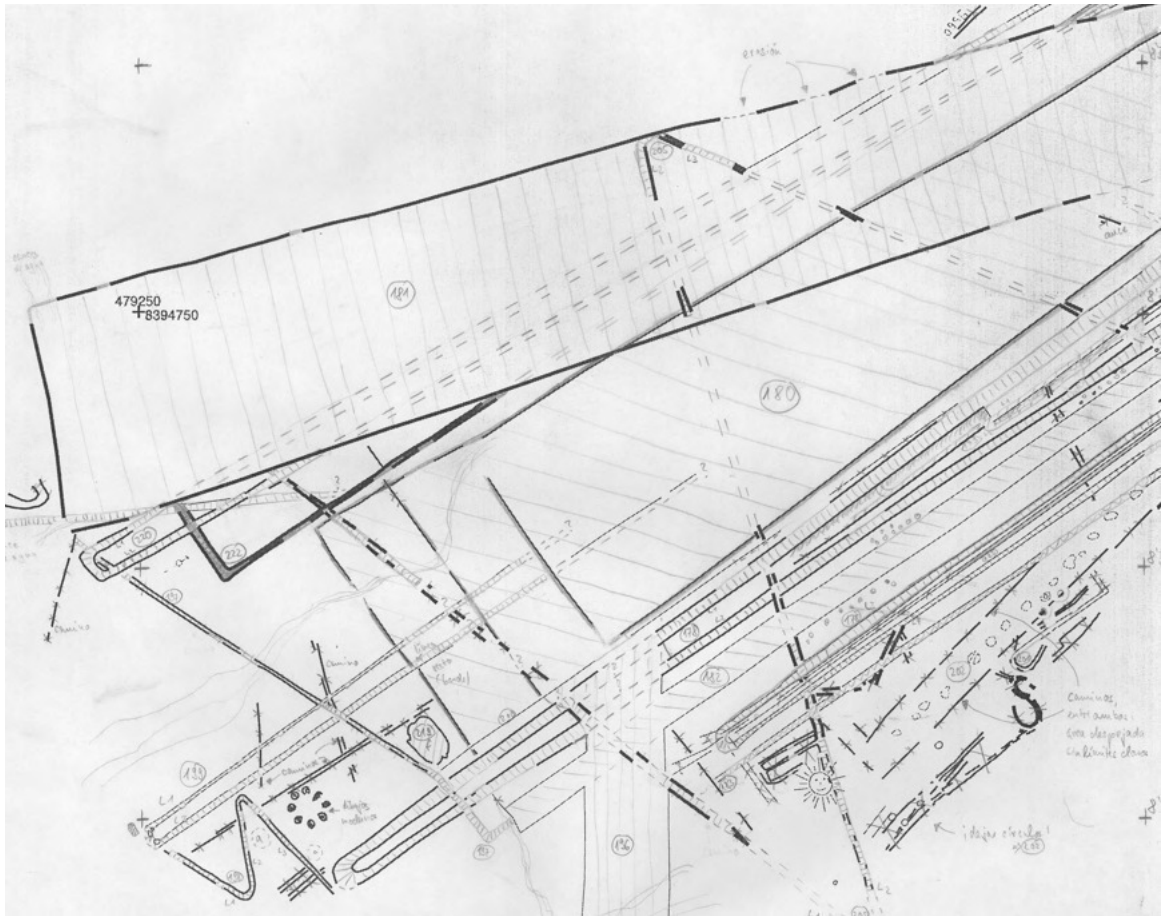


Fig. 12. Preliminary map of the southwestern portion of site PV67A-47 corrected during fieldwork.

the field. The datasets were combined in ArcView 3.2 and complemented with a coordinate frame. Using the layout tool, paper maps in A3 format could easily be laid out and printed in any desired scale.

The fieldwork allowed the detection of some minor errors in the DTM, but the main focus was on the revision of the vector dataset. Maps at scales ranging from 1:1,000 to 1:100 were taken into the field. Each geoglyph was located with the aid of these maps. Since the maps showed only disconnected sections of borders, vectors belonging together as part of a single geoglyph had first to be determined. Once the context was established, each geoglyph was assigned a consecutive code number or ID that allowed its unambiguous identification. This number was marked in pencil on the paper maps.

Each geoglyph was then walked over in order to determine if the mapping was correct. Although many details had been visible in the stereopairs during the mapping process, there

was still more to be seen on the ground. Badly preserved parts of geoglyphs like eroded edges, sections covered by other geoglyphs or modern features and geoglyphs on sandy terrain were usually better discernible on the ground. Furthermore, footpaths and erosion gullies erroneously identified as geoglyphs in the photos could be distinguished from actual geoglyphs in the field. Thus, additional information was obtained that could be used to improve the quality and reliability of the maps. The maps were revised accordingly, and corrections were marked on them in pencil (fig. 12).

Once the paper maps had been revised they were taken back to the laboratory. During a second review of the stereopairs on an analytical plotter, incorrect 3D vectors were deleted and missing 3D vectors added. Although these sections of geoglyphs had not been detected during the first review of the stereopairs, they could, in most cases, easily be discerned in the images once it was clear from observations made in the field what was to be looked for. The quality of

the 3D recording could that way be enhanced considerably. The revision of maps provided a good starting point for the geoglyph description described in the following section. On the *pampas* of San Ignacio and Llipata the revision of the preliminary maps constituted the main activity since only a small number of the geoglyphs were recorded archaeologically because of time constraints.

5.11 GEOGLYPH DESCRIPTION

The description of each mapped and defined geoglyph absorbed most of the time during fieldwork. The geoglyph ID was marked on a feature sheet. Each geoglyph was described in detail on such a sheet with standardized categories that helped to register all geoglyphs in a comparable way. The categories included were: Description of the geoglyph itself, its surroundings, orientation, size, shape, stratigraphy, associated cultural remains, state of preservation, etc. Of course, not all categories applied in all cases. If necessary, textual descriptions were complemented by sketches. The feature sheet was designed so as to structure the data as far as possible to allow its import into a database and query analysis. However, the category “general description” also allowed a comprehensive textual description of the geoglyph in cases where the structured categories could not cover all aspects. Once the geoglyphs had been recorded in the field, the descriptive data was fed into a preliminary MS Access 2000 database which allowed easy data management during fieldwork⁴⁰. Each record followed the structure of the feature sheets. For some categories, predefined pop-down menus allowed only a limited selection of values. Thus, the data format was as standardized as possible.

During recording, finds on or close to geoglyphs were surveyed, recorded, and classified. Typical archaeological finds consisted of potsherds, while lithics, textiles, and bones constituted a considerably smaller part of the whole repertoire. General remarks on the nature, composition, cultural affiliation, and location of the finds on each geoglyph were noted on the feature sheet. Unfortunately it was not possible to systematically sample the cultural materials. The available time and manpower was too limited to pursue such an approach, and the permits issued by INC differed for each field season, so that fieldwork had to be carried out under different legal conditions. For example, in

the first field season in 2000 it was not permitted to collect finds, so that they could only be briefly described. Fortunately, even for geoglyphs recorded during that field season limited samples were available since they had been recorded before at the site level in the course of the site survey of 1997 when the INC permit had included the right to collect finds (Reindel et al. 1999). However, during the site survey the focus had been on datable materials, so fineware ceramics are overrepresented in that sample. In the second and third field season we were permitted to collect finds, but did so only to a limited degree due to time constraints. However, we tried to collect samples from the most important geoglyphs that were representative not only with respect to the fineware ceramics, but also to undecorated pots.

The extensive fieldwork to document the Palpa geoglyphs was dedicated exclusively to describing the geoglyphs in detail. No measurements had to be undertaken. The same is true for photos since the aerial images already constitute a complete photographic record of all geoglyphs. Thus, only a few photos were taken in the field in order to show ground views of types of different geoglyphs.

5.12 OBJECT LAYER GENERATION

After the revision of geoglyph vectors, the vectors represented only the preserved borders of the geoglyphs, and borders that could reasonably be assumed to have once existed based on circumstantial evidence, but not the geoglyphs themselves. Thus the next step was to digitally combine vectors marking the outline of each of the geoglyphs defined during fieldwork into a closed polygon that represented the most likely original shape of that geoglyph, as far as it could be reconstructed on the basis of photos

⁴⁰ Since a good part of the data was obtained and processed by Spanish speaking team members, and Spanish was the working language during field seasons, all records were kept in that language. José Palomino (Los Molinos) and Alejandra Figueroa (Lima) entered most of the data. The whole database was then revised by Alejandra Figueroa to correct language errors, and by the author, to correct content errors. After fieldwork, the corrected datasets were integrated into the definitive Oracle database along with additional data (see sections 5.14 and 5.15). An extract of this data complemented by additional information obtained during data analysis is available on the DVD that accompanies this study.

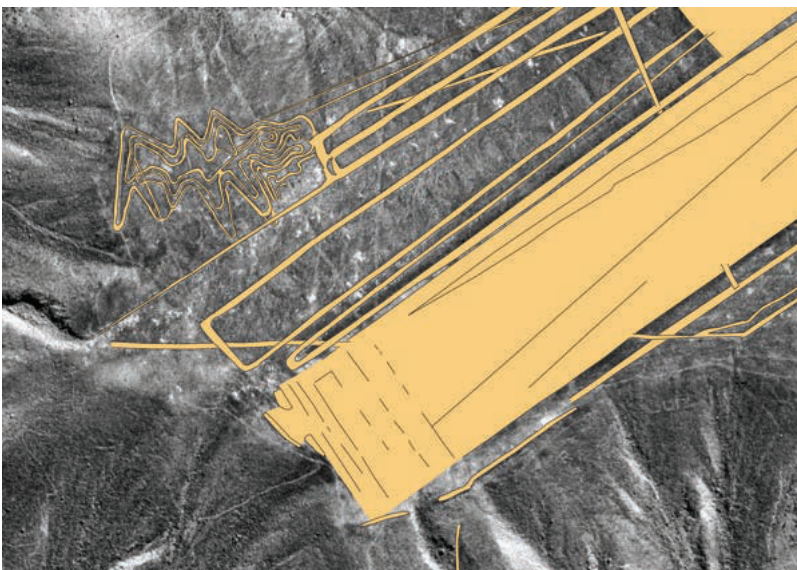
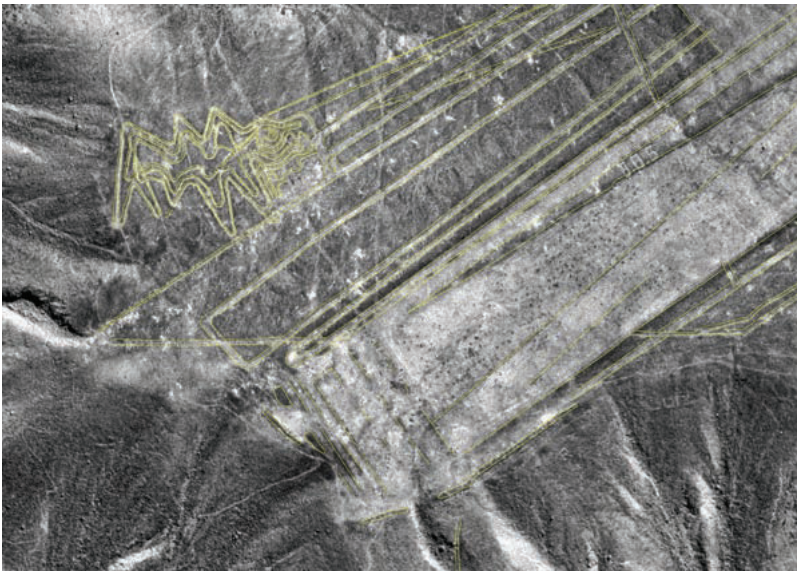
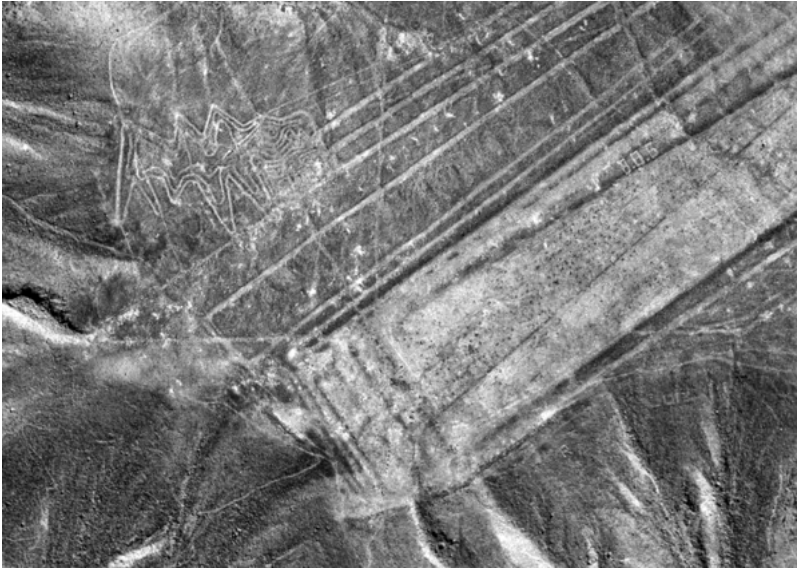


Fig. 13. Photogrammetric geoglyph mapping: Geoglyphs as visible in aerial images (top), vectors marking geoglyph outlines (center), polygons representing geoglyphs as defined from vectors (bottom).

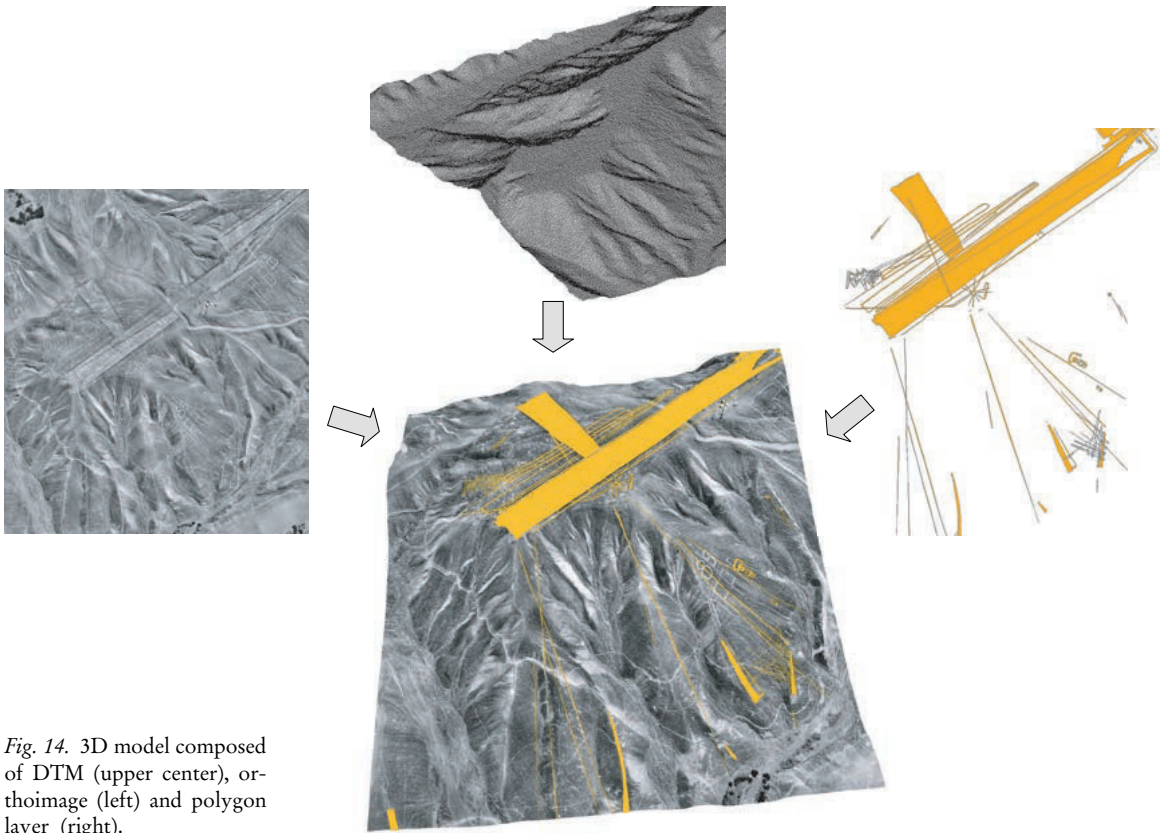


Fig. 14. 3D model composed of DTM (upper center), orthoimage (left) and polygon layer (right).

and field data. The goal was to generate digital 3D objects that represented the geoglyphs and could therefore be linked with the corresponding description.

In a first step it was tried to convert the vectors into polygons in ArcView 3.2 (Sauerbier/Lambers 2004). However, this procedure did not yield satisfactory results. The task could better be accomplished in ArcMap, a module of ArcGIS 8.3. Here, the revised vector layer was displayed with a high resolution orthoimage in the background. Based on what was visible in the orthoimage and what was known about the geoglyphs from fieldwork, existing vectors were connected and complemented in such a way that the most likely original outline of the geoglyph was marked by a continuous line. Using the topology tools available in ArcMap, polygons could then be automatically generated from these polylines. The resulting polygons, however, still did not represent specific geoglyphs for the following reasons:

- During automatic calculation, all possible polygons were calculated, *i. e.* not only those pertaining to actual geoglyphs, but also unaltered areas completely surrounded by geoglyphs

- In all cases where geoglyphs overlapped, each polygon represented only a part of a given geoglyph or, in other words, each geoglyph consisted of several (often many) polygons
- For the same reason, some polygons pertained to several geoglyphs at the same time. Where one geoglyph crossed another one, the overlapping area corresponded to both geoglyphs.

In order to define which polygon pertained to which geoglyph, each polygon was assigned the corresponding geoglyph IDs adopted from the feature sheets. This part of the work had to be done manually. Where geoglyphs overlapped the corresponding polygons were assigned two (or even more) geoglyph numbers. Finally, all redundant polygons, *i. e.* polygons not belonging to any geoglyph, could be automatically deleted. The result was a data layer with polygons clearly identifiable as pertaining to specific geoglyphs (fig. 13).

The process of object definition was accomplished in ArcMap. The 3D vector layer in DXF format was converted into a 2D shapefile. The newly generated polygons were stored in a separate 2D shapefile (file size: 2 MB). By intersecting them with the DTM, the height

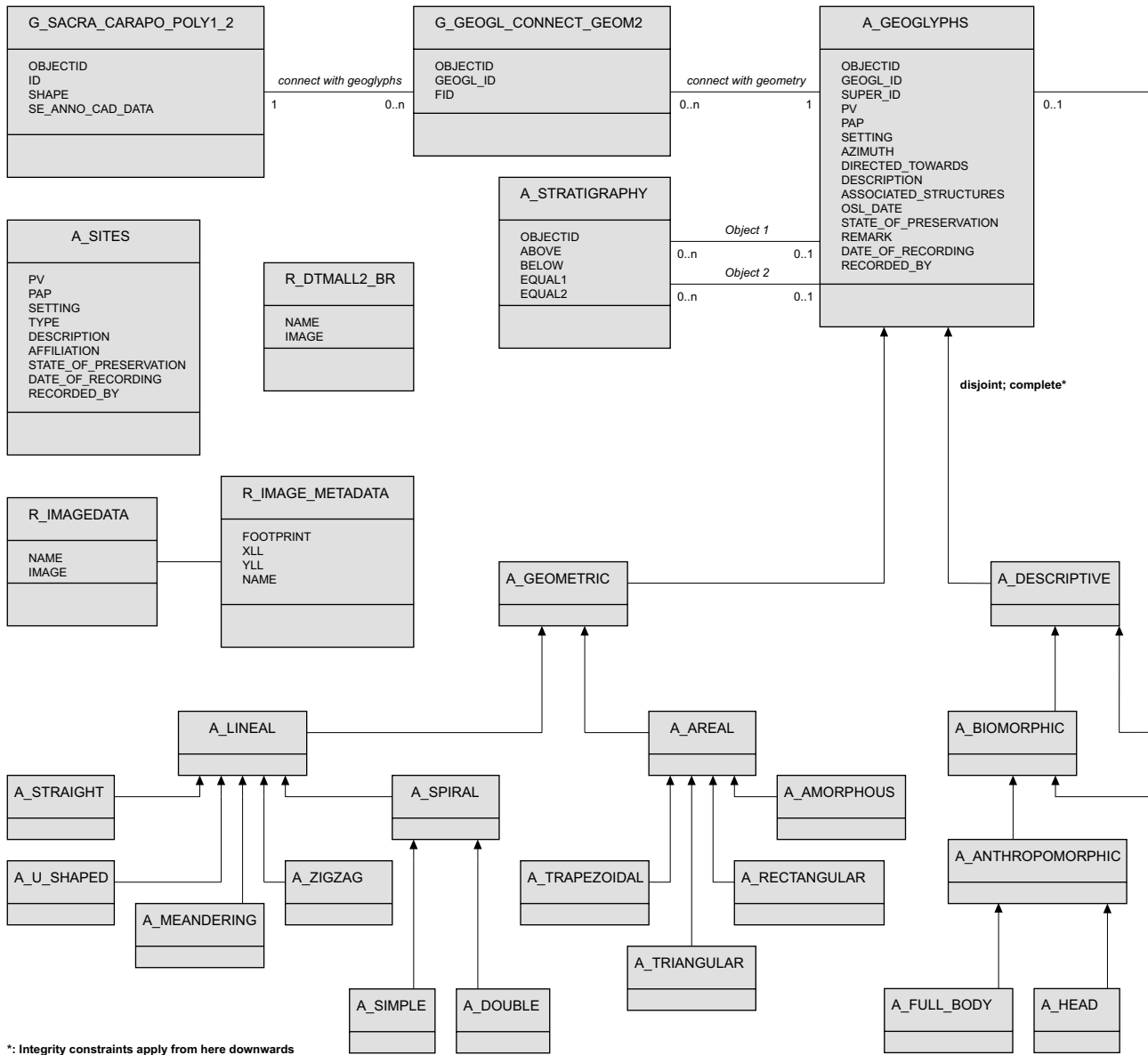


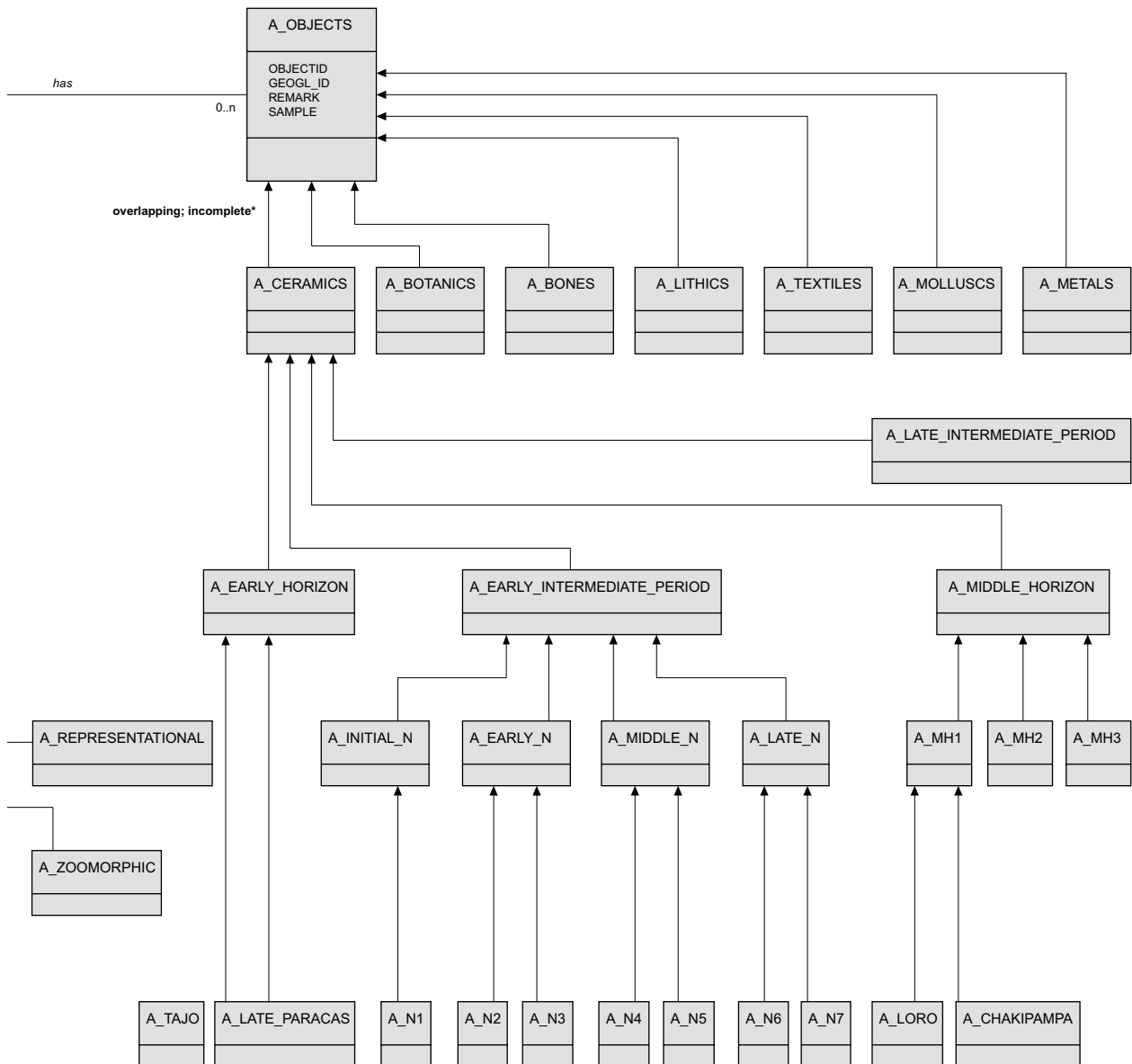
Fig. 15. UML class diagram of the conceptual data model.

dimension was added to the polygons. Since vectors and polygons are stored in different layers, the geoglyphs can be visualized (on maps or on-screen) in such a way that the provenience of the data is always transparent. The areal polygons, depicted for example as shaded in gray, represent the most likely original shape of the geoglyphs based on aerial images and field data. The lineal vectors displayed for example as black lines on the shaded polygons represent the preserved or assumed border sections of the geoglyphs, *i. e.* the actual information on which the reconstructed geoglyphs are based (maps 1–13).

5.13 3D MODELING

One aim of the documentation of the Palpa geoglyphs was to produce a highly accurate and detailed virtual 3D model of the geoglyphs and their environment that would allow navigation through it in real-time, and in which each geoglyph would be shown as a 3D object. Four different elements were used to generate the 3D model:

- The DTM showing the topography of the area around Palpa



- The orthomosaic as photorealistic texture showing the environment
- The vector layer showing the preserved outlines of the geoglyphs, and/or
- The polygon layer showing the most likely original shape of the geoglyphs.

The actual modeling process was accomplished using different commercial systems (*e. g.* ERDAS Imagine Virtual GIS 8.4, SkylineSoft Terra Explorer 3.0, *cp.* section 5.17). The 3D model integrating the different layers (fig. 14) constitutes a complete, digital documentation not only of the geoglyphs, but also of their environment as of 1998 when the aerial images were taken.

5.14 CONCEPTUAL DATA MODELING

Once the revised geoglyph descriptions and the object data layer representing the most likely original shape of the geoglyphs had become available, the first analytical step was the elaboration of a descriptive typology based on all recorded geoglyphs of Cresta de Sacramento, Cerro Carapo, and the area around La Muña. Formal criteria, described in detail in section 6.1.1, were used to sort geoglyphs sharing common attributes into hierarchical categories. In the process, it became clear that several geoglyphs originally defined separately in the field

were single geoglyphs. Therefore while assigning each geoglyph to a type, they were renumbered at the same time with a super ID (as opposed to the original geoglyph ID).

Descriptive data that resulted from archaeological recording of geoglyphs in the field had initially been stored in a preliminary, relational MS Access 2000 database. The final objective, however, was a more complex, object-relational database in which all data available for a given geoglyph – *i. e.* not only its textual description, but also its 3D geometry, images etc. – should be accessible via its super ID. This hybrid database was thought of as the central data storage and management facility for all later work. Such a storage and management system should allow data editing and retrieval from different platforms using standard procedures like structured query language (SQL), and its structure had to be flexible enough so as to allow the incorporation of additional data resulting from analyses of the original data. The database was furthermore to serve as core of the intended GIS. Due to its versatile capabilities it was decided to use an Oracle 9i database management system (DBMS).

In order to ensure a careful structuring of the database beforehand, a conceptual data model was developed using the object-oriented unified modeling language (UML⁴¹) (Lambers/Sauerbier 2003). The object-oriented approach allowed all available data to be structured in such a way that the real-world situation was reproduced in a simplified but accurate data model. Different types of data, *e. g.* spatial, textual, or image data, could be integrated into the model. The commercial software program Rational Rose 2002 was used for conceptual data modeling since it allowed data to be graphically structured on-screen. Furthermore, the resulting class diagram could then be directly converted into the logical Oracle database. In the following, the principle elements of the class diagram of the Palpa geoglyphs as shown in figure 15 are briefly described.

The core of the class diagram is the supertype A_GEOGLYPHS around which all information is structured. The central part of the class box features a series of attributes potentially shared by all geoglyphs. All subtypes inherit these attributes yet may have additional ones. The lower part of the box usually contains methods associated with an object that could likewise be inherited. In our case, this option was not used. Each geoglyph is represented by a series of polygons stored as Oracle spatial data objects

(SDO), here represented by the class G_SACRA_CARAPPO_POLY1_2. The link between geoglyphs and polygons is established by the class G_GEOGL_CONNECT_GEOM2 that connects both classes via the attributes GEOGL_ID, identifying a geoglyph as primary key, and FID, identifying a polygon as primary key, respectively. The cardinalities “1” and “0..n” describe the fact that one polygon may be part of more than one geoglyph. Each geoglyph may furthermore have a stratigraphic relationship with other geoglyphs, which is described by the class A_STRATIGRAPHY, the options being above, below, equal1 (equal) and equal2 (contemporaneous). The cardinalities are “0..1” on the A_GEOGLYPHS side, since not all geoglyphs are stratigraphically related to others, and “0..n” on the A_STRATIGRAPHY side, since a geoglyph may be superimposed by 0 up to n others.

The actual manifestations of the geoglyphs are represented by subtypes corresponding to the types defined in the descriptive typology (see section 6.1). Since the geoglyph typology is hierarchical in nature, it could easily be modeled in UML. Each geoglyph can be assigned to a subclass within this typological structure, so that the integrity constraints “dis-joint; complete” can be established.

Each geoglyph may have finds associated with it that are represented here by the class A_OBJECTS. While this class contains attributes applicable for all kinds of finds, the different find categories are again modeled as subtypes with their own attributes. The chronological classification of the geoglyphs is modeled as related to the find subtype A_CERAMICS since in fact only objects from this find category can be stylistically assigned to a time period. The subtypes representing chronological phases are hierarchically structured similar to the geoglyph typology. However, since datable ceramics were not found on all geoglyphs, whereas on others ceramics from different time periods were present, the integrity constraints are less strict (“overlapping; incomplete”).

Further data not directly related to single geoglyphs but nevertheless stored in the database and used for analysis are here shown as unconnected classes. A_SITES contains data on all prehispanic settlements, cemeteries, and other sites obtained during the regional settlement

⁴¹ UML™ by the Object Management Group, see UML resource page at www.uml.org (accessed July 9, 2004).

pattern survey. R_DTMALL2_BR represents the DTM with a mesh size of 2 m, whereas the class R_IMAGE_DATA stands for orthoimages which are stored in Oracle raster format in the database. While metadata for the DTM is automatically generated during the import process, for photogrammetrically processed image data metadata like the attributes listed in R_IMAGE_METADATA has to be acquired separately.

Thus, the conceptual data model developed using UML proved to be an efficient way to ensure a useful data structure as well as data integrity. It is furthermore a helpful tool to visualize relationships and interdependencies between different kinds of data.

5.15 DATABASE IMPLEMENTATION

The conceptual data model was converted into a logical database using an object-relational Oracle 9i DBMS that should also serve as the basis of the intended GIS. Since ArcGIS 8.3 was chosen as the GIS tool, the link to the database could be established using ArcSDE, ESRI's server application that allows ArcGIS to be connected to different DBMS. The object-oriented data structure based on the conceptual data model was implemented in an object-relational tablespace using SQL data definition language (DDL). The archaeological data was then stored into the defined tables by first importing the MS Access tables into Oracle 9i, and then distributing the attribute data into the table structure. Similarly, tables containing additional data like super ID, type, etc. were integrated into the database. For the import of geometric data ArcGIS toolbox was used to generate Oracle spatial data objects from the 2D polygon shapefile as well as DTM (2.5D) and images in Oracle raster format. To establish the predefined relations between geometric and archaeological data, as well as for visual error checking, scripts were developed in Visual Basic for Applications (VBA) that allowed convenient data editing via the graphical user interface of ArcGIS.

5.16 DATA ANALYSIS

The first analytical step had already been accomplished in the process of data modeling. This involved the elaboration of a descriptive typology that allowed an initial sorting and easy

handling of the geoglyphs, and served as basis for their definitive numbering. Once the structured data was accessible in the Oracle DBMS it could then be analyzed in different ways:

- Using scripts developed in Visual Basic, additional information on the geoglyphs was generated from their geometry, *e. g.* by calculating their surface area and orientation. The results were stored in the database.
- Using SQL, the database was queried for specific information. That way, quantitative data on the distribution of geoglyph types and datable ceramics on geoglyphs became available and could be graphically displayed in charts (figs. 26, 28, 32).
- Using tools for spatial analysis available in ArcGIS 8.3, geoglyph data and terrain data were related and analyzed. Distribution maps of geoglyphs and contemporaneous sites were produced for different time periods in order to study the development of geoglyph sites on a regional scale through time (supplement 5 to 10). Analyzing the topography of the terrain in which the geoglyphs are located, their accessibility, visibility, and orientation were investigated and displayed on maps.

The specific analyses as well as their archaeological results are described in detail in section 6.

5.17 VISUALIZATION OF RESULTS

The visualization of results was the final step in the workflow as illustrated in figure 8. It comprised the visualization of the 3D model composed of the layers mentioned above and the illustration of results of analyses. The virtual 3D model of the Palpa region has been visualized in different ways completely or in parts: Virtual 3D views (either static or dynamic), 2D paper maps, and finally a physical 3D model. Furthermore, 3D views and paper maps were used to show results of data queries and other analyses.

The most advantageous way of visualizing a 3D model is the generation of virtual, on-screen views of it. A virtual 3D model allows the review of every given part of the study region on-screen, *i. e.* in the office during analysis. A major constraint is the amount of data to be processed. In the case of the Palpa model, due to the large amount of photo texture about 2.7 GB of data had to be visualized. The aim was to achieve this on a standard PC platform.

To generate synthetic still views of subsets of the 3D model in high resolution, ERDAS



Fig. 16. Virtual view of the central part of Cresta de Sacramento generated using ERDAS Imagine Virtual GIS 8.4.



Fig. 17. Virtual view of site PV67A-22 generated using ERDAS Imagine Virtual GIS 8.4.

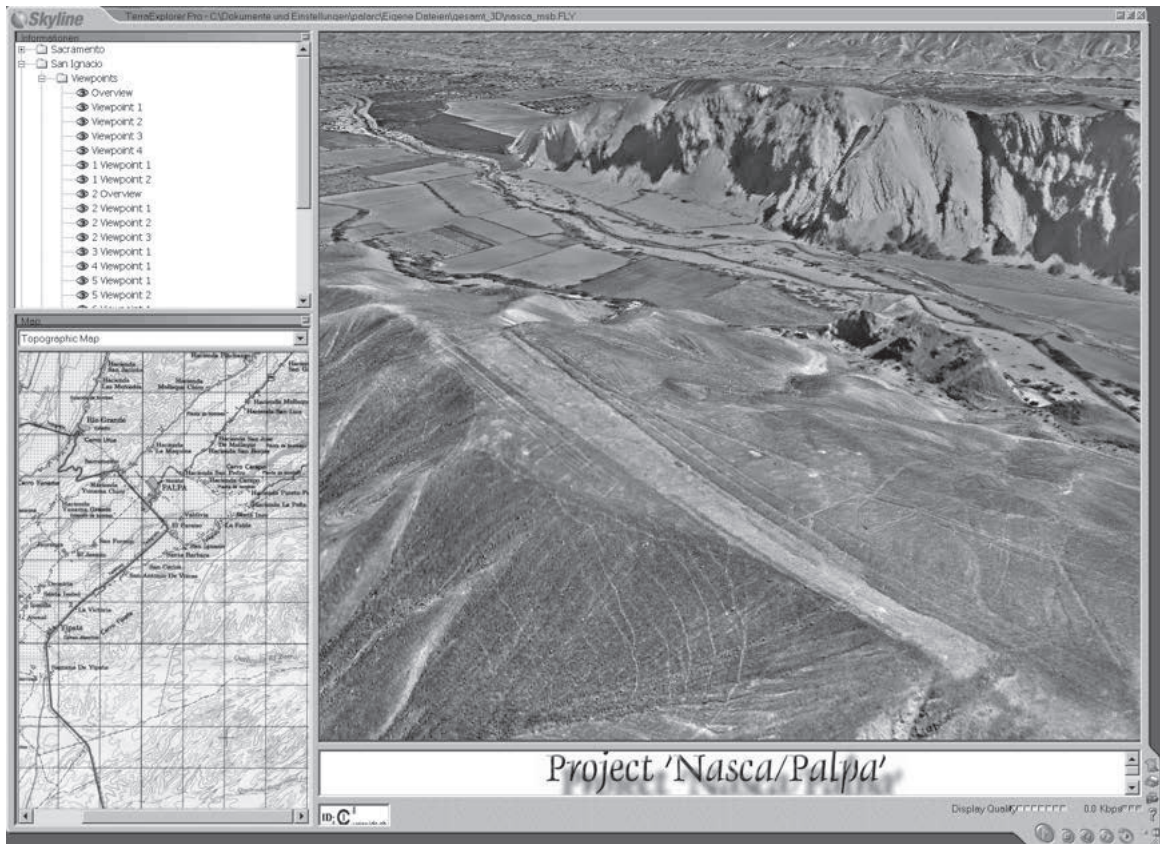


Fig. 18. Terra Explorer user interface with a virtual view of Cerro Carapo as seen from east (upper right), predefined viewpoints (upper left), topographic map indicating location of viewer (lower left), and project website (lower right).

Imagine Virtual GIS 8.4 by Leica Geosystems was mainly employed (figs. 16, 17). This software yields good quality results for photo texturing. The integration of vector and polygon layers is possible, but there can be problems. If they are integrated as 3D data, they do not coincide exactly with the interpolated DTM surface which is why some sections of lines or areas might disappear. If they are integrated as 2D data and mapped onto the DTM surface, they are dissolved into the pixel structure of the textured surface. While polygons are displayed in acceptable quality this way, thin lines are usually blurred. Therefore, most synthetic views produced for the Palpa area contain the DTM and photo texture only. Furthermore, the capabilities of ERDAS Imagine Virtual GIS 8.4 to process large datasets are rather limited. On the other hand, it allows the generation of short fly-throughs and offers some basic GIS functions such as viewshed analysis.

In order to visualize the Palpa 3D model in its entirety in real-time, *i. e.* allowing interactive navigation through the model, high-end visual-

ization software with Level-of-Detail capability (LoD) was needed. LoD means that in every frame of an image sequence only the foreground portion (*i. e.* close to the viewpoint) is shown at highest resolution, while the background is displayed at lower resolution. That way the amount of computations necessary to render each frame is reduced considerably. A prerequisite for such an approach is the generation of data pyramids (vector and raster data) based on the input data. For the Palpa model, commercial software with LoD capability was used for real-time visualization.

In Terra Explorer 3.0 by SkylineSoft⁴² (fig. 18) the hybrid input data (2.15 GB of photo texture plus DTM, vector, and polygon data) was compressed to a single file of roughly 600 MB. The model can be edited by the user, and additional data (predefined 3D objects, tabular data etc.) may be integrated. The user interface allows the lateral incorporation of further elements, like

⁴² See www.skylinesoft.com (accessed May 13, 2004).

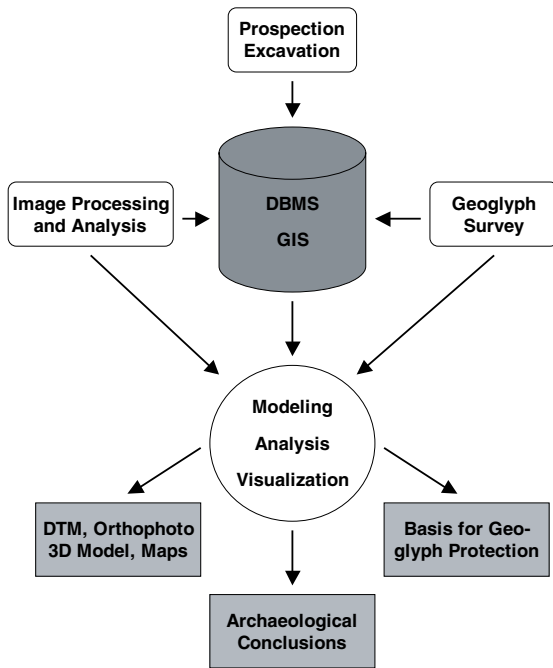


Fig. 19. Project design.

overview maps or the project website. Free navigation through the 3D model is possible via keyboard or joystick control. Fixed viewpoints can be defined and automatically approached, *e. g.* over certain geoglyphs. Flights through the model can be interactively defined and recorded to an export file, *e. g.* in AVI format. An example of a video produced this way is given on the DVD that accompanies this study. It features a virtual flight over the entire area around Palpa covered by the 3D model.

A problem concerning the Palpa model was that image resolution was not as good as input data would allow, and in recorded flights the limits of the area shown in highest resolution were clearly visible against areas displayed in lower resolution. Another major disadvantage was that objects from the vector layer were either blurred or not correctly mapped onto the surface due to the same issue described above for the ERDAS software. On the other hand, an advantage of Terra Explorer is that it allows the integration of self-defined objects into the model, *e. g.* in the Palpa case virtual posts like those found in excavations (see appendix 9.2.2). All in all, the Skyline software is a good tool for interactively exploring the photorealistic 3D model, but with certain limitations. A viewer without editing functionality is freely available for download from the provider website, so that

the model can easily be distributed to interested persons. The pros and cons of the Skyline software have been discussed in more detail elsewhere (Sauerbier, Lambers 2003).

Another way to visualize the 3D model is the generation of 2D paper maps derived from 3D data. Although maps clearly do not tap the full potential of the available data, the fact that reliable maps of the Palpa geoglyphs can be easily generated is a major step forward in Nasca archaeology. The Palpa data is available in digital form and organized in layers with different content. This allowed free data scaling and the combining of different layers. While geoglyph layers (polygons and vectors) and the layer containing modern elements (roads, buildings, etc.) can be shown largely unaltered on a map, the DTM may be replaced by a contour line layer derived from it (supplements 1, 2). The orthophoto layer may also be integrated into the map design (supplements 3, 4). Both ArcView and ArcMap offer user-friendly tools for easy map production. The combined layers were laid out on a map and complemented with coordinate frames, legends, scale bars, etc. Not only entire datasets, but also selections based on queries were generated using predefined map templates in order to ensure comparable results. That way only geoglyphs of a certain type or time period could be automatically selected to be shown on the map. Labels, charts, symbols, etc. were then added to explain the illustration. For printout, files were exported to standard raster or vector file formats like EPS, TIFF, etc. While maps used during fieldwork were produced in ArcView, all maps in the present study have been generated in ArcMap.

A less common way of visualizing the 3D model was the production of a physical model. For the newly established local archaeological museum in Palpa, a 3D model of Cresta de Sacramento was made using modern casting facilities of the General Command of Mapping, Ankara, Turkey⁴³. First, a mold was produced using an ASCII file containing the DTM data. In this mold a plastic model (scale 1:4,000, vertical exaggeration 1.5) was then cast. The high resolution photo texture derived from a Geo-TIFF file was automatically applied to the model surface during the casting process. Due

⁴³ Prof. Orhan Altan, head of the Division of Photogrammetry of the Faculty of Civil Engineering at Istanbul Technical University, is warmly thanked for his help in this matter.

to the length of Cresta de Sacramento two separate blocks had to be cast which could then be joined to form the complete model. Once the molds had been created further casts could easily be produced. It is hoped that the Sacramento model now on display in a showcase in the entrance hall of the Palpa museum will become a major attraction.

All in all, different ways of visualizing the 3D model proved fruitful for different purposes. The production of 2D maps was important for fieldwork, but also for illustration of results and in the new Palpa museum where the physical model is a further attraction. On-screen visualizations of the virtual model were not only used as tool for presentation, but also for research since a detailed reconstruction of the study region was constantly available during analysis.

5.18 SUMMARY: DOCUMENTATION OF THE PALPA GEOGLYPHS

The combination of archaeological fieldwork and analysis with photogrammetric and GIS techniques of data capture, processing, modeling, and visualization allowed for the first time the establishment of a comprehensive, digital database containing hybrid data on a large

sample of geoglyphs. Products generated during the process include:

- DTMs of the Palpa area with up to 2 m mesh size
- Orthomosaics of the same area with a highest resolution of 25 cm on the ground
- A hybrid database linking geometric representations of the geoglyphs with descriptive, structured attributes
- A virtual, interactive 3D model of the Palpa region and the geoglyphs
- Geoglyph maps at different scales and with different content.

Figure 19 summarizes the project design including input data, data processing and analysis, and output results. It shows the integration and interdependence of archaeological and geomatic methods, and the central role of the database and GIS for the joint management and analysis of both kinds of resulting data. The available data on the Palpa geoglyphs resulting from this integrated approach is of unprecedented scope and detail in the context of Nasca archaeology. Analysis as described in the following section is an important qualitative step forward in geoglyph research. Furthermore, the digital archive of the Palpa geoglyphs can now serve as starting point for their protection and long-term preservation⁴⁴.

⁴⁴ After the conclusion of the present study, the Palpa geoglyph map was put at the disposal of INC Lima. It is planned to use the map to define in close cooperation with UNESCO an extension of the existing protected geoglyph zone on the Nasca *pampa* in order to include the Palpa geoglyphs.