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The Nasca and Palpa geoglyphs: geophysical and geochemical data

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Abstract The Nasca geoglyphs in the stone desert in southern Peru are part of our world cultural heritage. These remarkable drawings have roused the interest of scientists from different disciplines. Here we report the results of integrated geophysical, petrophysical, mineralogical, and geochemical investigations of the geoglyphs at six test sites in the stone desert around Nasca and Palpa. The geomagnetic measurements revealed clear indications of subsurface structures that differ from the visible surface geoglyphs. The high-resolution geoelectrical images show unexpected resistivity anomalies underneath the geoglyphs down to a depth of about 2 m. Remarkable structures were revealed in both vertical and lateral directions. No evidence was found of geochemical or mineralogical alterations of the natural geogenic materials (desert pavement environment versus geoglyphs). Neither salts nor other mineral materials were used by the Nasca people to alter or prepare the surfaces of geoglyphs. This supports the hypothesis that the Nasca people simply removed stone material down to the natural hard pan horizon to create the geoglyphs.

Keywords Nasca lines · Geophysical investigation · Geochemical investigation

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Introduction

Many of the geoglyphs (drawings on the ground) of the desert districts of Nasca and Palpa in Peru are more than 2,000 years old. Since 1994, they have been under the United Nations Educational, Scientific and Cultural Organization (UNESCO) human heritage protection. Located in the arid coastal plain, these unique lines and figures cover an area of about 450 km^2. They depict living creatures, stylized plants, and fantasy beings, as well as geometric figures several kilometres long. These depictions are generally associated with the Nasca culture, which flourished between 200 B.C. and 600 A.D. Because of their quantity, origin, size and extent, these artefacts are among archaeology's greatest enigmas (Carpio 2005). The features of interest in the stone desert include geometrical or figurative lines (líneas), stone lines (unearthed soil material along the lines and trapezoids) and trapezoids of different shapes, up to several metres wide.

The geoglyphs are located in an area 400–450 km to the southeast of the Peruvian capital of Lima in the region between the towns of Palpa and Nasca. The climate is dry with less than 50 mm of rain per year (Eitel et al. 2004), sometimes only 2.4–5.1 mm per year (Montoya et al. 1994). This permanent drought preserves the geoglyphs over extended periods of time. In general, the two desert districts of Nasca and Palpa differ in respect to their morphology and geology. The geoglyphs around Palpa are exposed on the top of huge east–west trending quaternary gravel ridges, the so called pediment in the foot zone of the Andes. Those around Nasca are located in the wide flat Holocene alluvial plains (Montoya et al. 1994).

Despite the fame of the Nasca geoglyphs, decades of investigations and a huge number of publications — some of them propagating myths or nonverified hypotheses — it is surprising that rather limited geoscientific information and reliable data exist (Aveni 1990; Eitel et al. 2004, 2005; Cavatrunci et al. 2005). The extensive mapping and geodetic work of Maria Reiche (Reiche 1989), or later studies by Lambers (2006), as well as geomorphological studies supported by dating methods (Unkel et al. 2007), have provided valuable results in several fields of geoscience. Geophysical methods have been integrated in projects that aim at reconstructing the history of the Nasca culture and analysis of the complex interaction between environmental changes and cultural development (Reindel and Grün 2006; Faßbinder and Hecht 2004; Hecht and Faßbinder 2006; Faßbinder 2006).

Our project[1] is the first to follow an interdisciplinary geoscientific approach integrating geophysical, petrophysical, mineralogical and geochemical studies at six different test sites in both the Nasca and Palpa districts (Fig. 1).

The main objectives of this paper are comparison of the different types of geoglyphs from the two districts of Nasca and Palpa on the basis of their chemical and mineralogical composition or physical properties. The methodical study aimed to identify promising geoscientific field and laboratory methods for further investigations of the geoglyphs.

Materials and methodology

The selection of test sites was based on aerial images and satellite data (IKONOS and Quickbird). Three representative test sites, which include lines, trapezoids, stone line material and undisturbed desert pavement, were chosen in each of the Nasca and Palpa districts (Fig. 1). The origin and selection of samples and the methods used in the course of the geophysical, petrophysical, mineralogical and geochemical investigations are provided.

Geophysical investigations

A geomagnetic mapping was performed at all test sites with vertical gradient measurements of the total magnetic field. As high resolution is needed to detect the archaeological structures, a caesium-magnetometer (G-858 by Geometrics) was used. A rectangular area with a line distance of 0.5 m was marked. Additionally, the magnetic susceptibility of the desert surface was mapped (SM-20 by GF Instruments). As the coastal desert in southern Peru is one of the driest places on Earth, it was to be expected that resistivity measurements with a galvanic coupling to the ground would be challenging. A resistivity meter four-point light µC (by LGM, Germany) was used that enables reliable measurements by injecting extraordinarily small currents. The current strength was selected to obtain an optimal reading of the voltage signal in the interval between 1 and 10 mV. In most cases, a current of 10 µA was sufficient. A half-Wenner configuration was chosen because of several advantages for resistivity profiling (Hennig et al. 2005; Peschel 1967). The measurement profiles were generally directed orthogonal to the orientation of the geoglyph structures.

Petrophysical investigations

Physical soil parameters of test sites N1, P2 and N3 were measured in the field (see Table 1). For data acquisition of dry and wet density, as well as moisture content, the Troxler Model 3440 gauge was used. Measurements were made stepwise from −0.2 m upwards every 0.05 m along 50 vertical profiles over structures of lines and trapezoids.

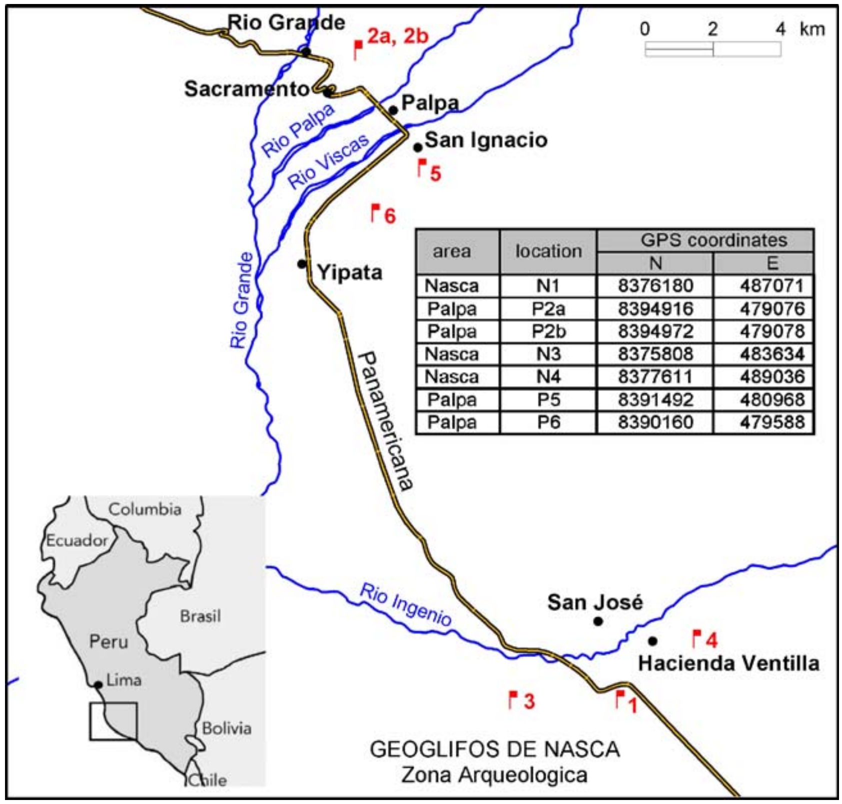
Grain density, magnetic susceptibility and water content were determined in the laboratory using 106 soil samples from all test sites. Eleven additional samples of different types of hard rocks (granite, andesite, gabbro, tuff) were collected at Nasca test site N4 (Hacienda Ventilla) for further laboratory investigation.

Mineralogical investigations

Another 25 samples, including material from desert pavement, trapezoids and lines, were selected for a detailed mineralogical investigation. The unprocessed dry samples were used for phase analysis and the determination of grain forms and size to interpret the source and transport modes of the material. Following drying, grinding and homogenisation, XRD-analyses were made to determine the mineralogical composition, including clay minerals. Polished carbon-coated thin sections were used for cathode luminescence investigations that reveal internal structures, e.g. mineral growth anomalies, and permit identification of the source rock material of the mineral grains. One sample was investigated in more detail after sputtering by scanning electrode microscopy with an EDX-detector and a cathode luminescence detector to characterise the amorphous phase that was detected in XRD analysis (Table 1).

[1] The project "Geoscientific investigation of the geoglyphs of Nasca" was initiated and supported by the University of Applied Sciences in Dresden, Germany, in close collaboration with Peruvian institutions.

Fig. 1 Area of investigation



Geochemical investigations

A total of 260 surface soil samples were collected from the sites to facilitate a direct comparison with the results of the geophysical and petrophysical investigations. A hand-held energy-dispersive X-ray fluorescence spectrometer (Niton XLt 898 Y) was used in the field to prescreen meaningful material without any sample preparation and to reduce sample transport. To verify the field data and to quantify lighter elements, eight selected samples of the sample set were analysed using a wavelength-dispersive XRF in the laboratory (Philips PW 2400) (Table 1).

Results

Geophysical investigations

Geomagnetic survey The resulting geomagnetic map (Fig. 2) revealed many subsurface features that were different from the visible surface structures. Additionally, clear indications for lines and trapezoids could be detected, except for the north–south trending structures that run parallel to the outer magnetic field and thus become invisible in the geomagnetic map. A modelling study verified this phenomenon.

Table 1 Number of samples and methodology

	Number of samples	Methodology
Geochemistry (field)	260	• X-Ray Fluorescence Spectrometer (ED-XRF; XLt 898 Y by NITON LLC)
Geochemistry (lab)	8	• Wavelength-dispersive XRF (Philips WD-XRF PW 2400)
	1	• Jeol JSM 6400, EDX-detector (Noran)
		• Cathode luminescence detector (Oxford Mono CL)
Mineralogy	25	• Phase analyses (Jenalab polarisation microscope and “Axiovision” software)
		• XRD-analyses (Seifert XRD 3000 TT and Seifert/Freiberger Präzisionsmechanik URD 6)
		• Cathode luminescence (HC1-LM with a hot cathode)
Petrophysics (field)	50	• Vertical profiles each with four measurements of dry and wet density
		• Moisture content (Troxler Model 3440)
Petrophysics (lab)	115	• Water content, grain density (Ultrapycnometer 1000, Quantachrome)
		• Magnetic susceptibility (Kappabridge KLY-2)

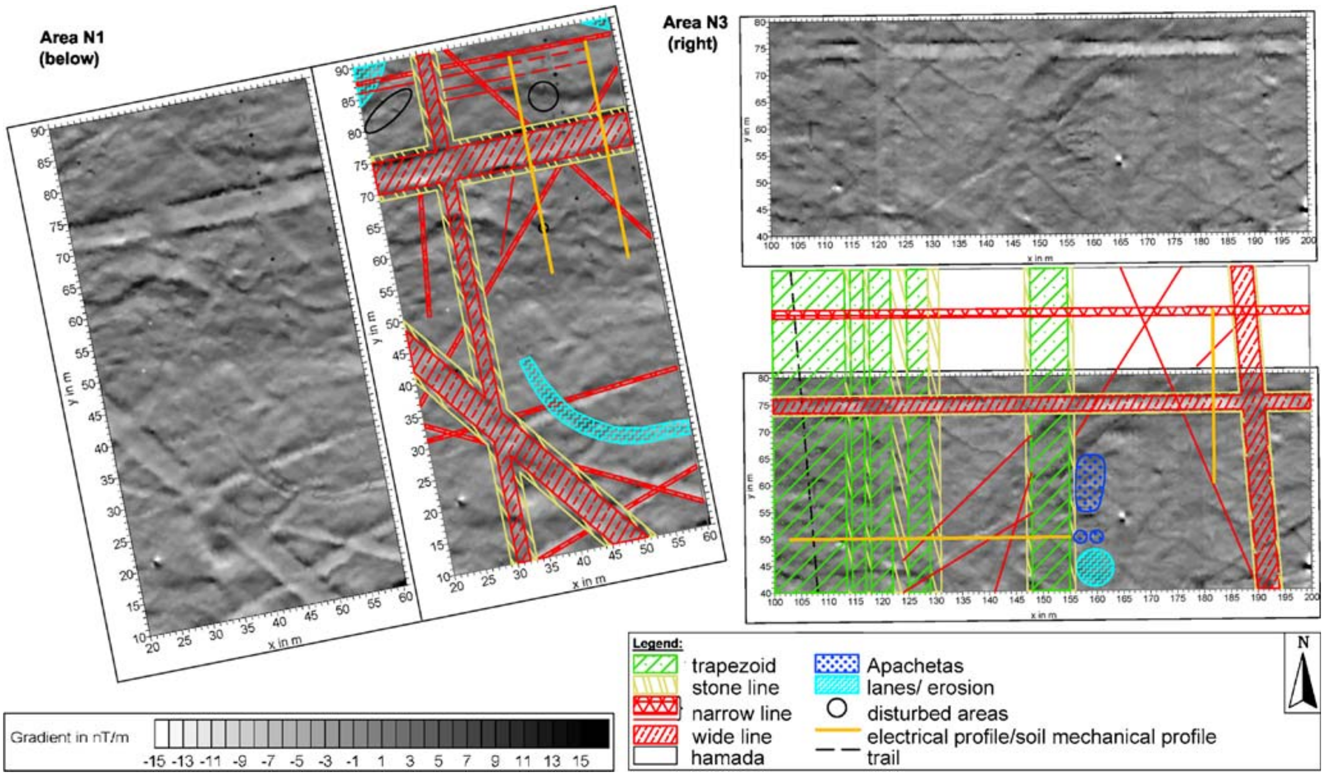


Fig. 2 Magnetic gradient maps of test sites N1 and N3

The most prominent elements on the map are the east–west trending line at N3 and a southeast–northwest directed line at N1 (Fig. 2). These lines, approximately 3 m wide and visible on the desert floor, form part of the system of geoglyphs that was drawn by the Nasca people. A remarkable network of structures differing from the visible surface features becomes evident in the magnetic map at site N3. These more or less linear elements are diagonally aligned to the visible lines. It is not clear whether the origin of the measured physical anomalies is related to sedimentary or anthropogenic (archaeological) structures. Further investigations are necessary to clarify the source of these linear structure patterns. Faßbinder (2006) reports the detection of similar structures in geomagnetic maps in the Palpa district.

Electrical imaging As a laboratory experiment using an additional soil sample taken at site N4 has shown that an increase of 2% water content causes a decrease in resistivity by a factor of 0.03, it becomes obvious that the resistivity images reflect to a large extent the distribution of soil water. The geoelectrical depth sections indicate unexpected resistivity anomalies under the geoglyphs down to a depth of about 2 m (Fig. 3). By removing the dark stones of the desert pavement along the lines, the Nasca people disturbed the natural soil protection against evaporation. On such uncovered places, evaporation increased compared with the undisturbed areas of the original stone desert. It is likely that the soil beneath the lines will be even dryer. Consequently, we expected that the lines should be characterised in the electrical sections by higher resistivity values.

At the two test sites N3 in the Pampa del Calendario and P6 in the Pampa del Cerro Llipata, the electrical profiles cross several visible structures and lines (Fig. 3). At test site N3, the 30-m-long profile crossed the wide line at y=75 m, the dominant structure in the magnetic map (Fig. 2), and another smaller line further to the north. At test site P6, the 25-m-long profile was directed over a so-called zigzag line at the south-eastern border of a large trapezoid. Figure 3a and c show for both sites the resulting pseudosection that averaged the half-Wenner forward and backward reading. The final model shown in Fig. 3b and d was generated with the 2-D inversion programme AC2DSIRT (Kampke 1999). At test site N3, the electrical image marks a remarkable resistivity anomaly at the location of the line (y=75 m), which is centred at a greater depth and does not reach the surface. Thus, it remains questionable whether it is related to the line or any geological structure. The narrower line at y=91 m can be clearly delineated as a surface anomaly. The geoelectrical depth-section at test site P6 (Fig. 3d) reveals a highly resistive anomaly near the north-eastern end of the profile at x=23.5–26 m. Though no visible surface structures were observed at this location, the anomaly

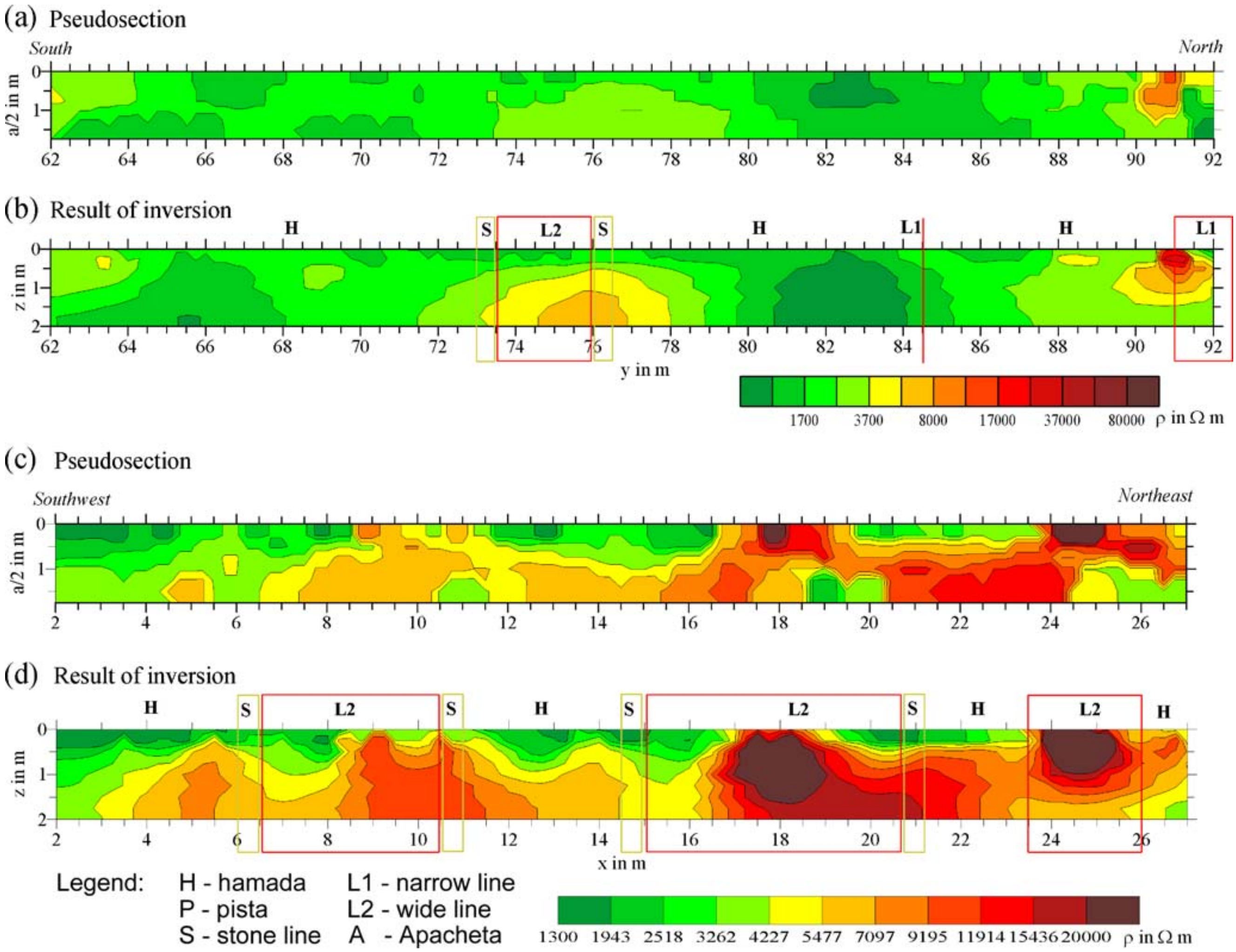


Fig. 3 Geoelectrical resistivity profiles: **a** Resistivity pseudosection at test site N3. **b** Result of inversion at test site N3. **c** Resistivity pseudosection at test site P6. **d** Result of inversion at test site P6

corresponds to an old line documented on earlier aerial photographs. Further resistive structures correspond to the visible zigzag lines at x=6.5–10.5 m and x=15–20.5 m.

Petrophysical investigations

The field investigations of selected profiles reveal no remarkable differences of wet and dry density or water content between desert pavement, trapezoids and narrow lines (Fig. 4). Only weak tendencies could be observed. The narrow lines are characterised by slightly increased values of dry and wet density close to the surface. It can be regarded as an indication of ascendent water transport of highly soluble constituents (salts, gypsum, anhydrite), as discussed above, and their precipitation during evaporation. An alternative explanation could be the higher mechanical compaction caused by people walking on it.

The water content of the trapezoids in the upper subsoil is slightly lower compared with the values at a depth of 10 cm. Here, the highest water content was measured at approximately 4% (Fig. 4). Considering the wide scatter in all data, further investigations should confirm the observed effects, which are possibly affected by the daily variations in temperature. The petrophysical parameters of comparative laboratory investigations show no relevant differences between the soil samples from both the Palpa and Nasca districts. The grain density varies between 2,530 and 2,730 kg m^{-3}, with an average of 2,650 kg m^{-3}. The laboratory values of mass normalised magnetic susceptibility fall in a range between 270 and 1650 10^{-8} m^3 kg^{-1}, with the average value of 570 10^{-8} m^3 kg^{-1} being closer to the lower limit. The hard rock samples cover a broader range, including diamagnetic (negative susceptibility) and paramagnetic behaviour with susceptibility values of up to 3240 10^{-8} m^3 kg^{-1}, reflecting the large diversity of surface rocks.

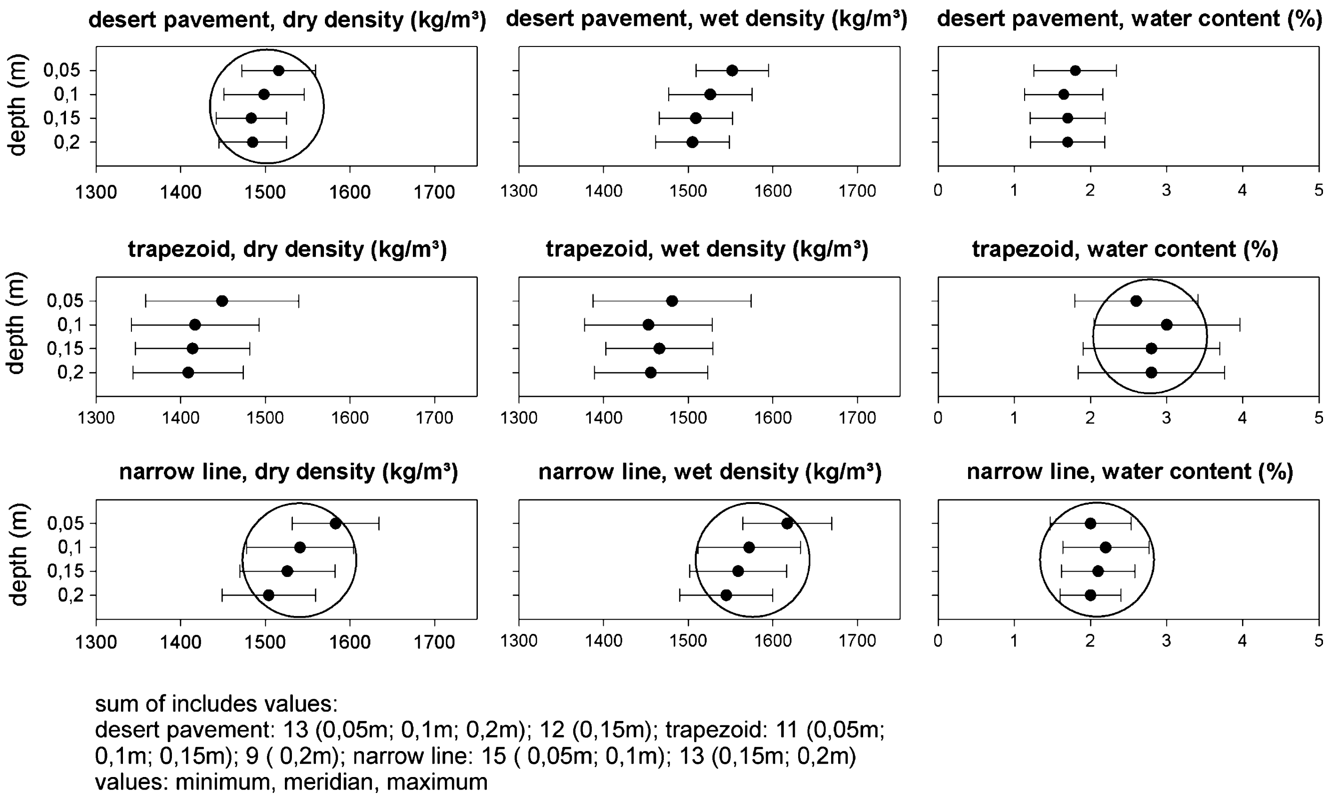


Fig. 4 Vertical distribution of density and water content

It can be assumed that the original water content has not been preserved during sample transport and storage for more than 4 weeks. But the values determined in the laboratory varied between 0.3% and 2.9%, corresponding to the range measured in the field. The parameters of laboratory measurements show a similar scatter as in the field data in Fig. 4. Consequently, the average values determined for samples originating from the desert pavement, lines, trapezoids and stone walls show only a restricted statistical relevance. But it is interesting to note that both field an laboratory measurements observe the lowest water content and the highest grain density at the lines.

Mineralogical investigations

All materials from both districts consist — with varying proportions — of the mineral phases quartz, smectite, feldspars (orthoclase and plagioclase) and muscovite as major, as well as gypsum, anhydrite, calcite, chlorite, hornblende, hematite and apatite as minor or trace compounds. All these minerals are related to bedrock material in the vicinity and immediate environment of the Nasca and Palpa plateau, quartzites of the Yura group, andesites of the Complejo Bella Unión group and granodiorites. Near the geoglyphs around Palpa, a white, fine-grained sediment layer was mapped, embedded in the sediments of the quaternary gravel ridges. Local villagers have used this material up until today to mark places or areas. A detailed scanning electron microscopy (SEM) investigation of the volcanic components revealed a fine-grained volcanic tephra of probably dacitic composition with some 74 vol-% glass shards. The phenocryst assemblage includes — in decreasing order — plagioclase (andesine), sanidine, quartz and accessory hornblende with traces of biotite. It is important to note that two profiles at 10 cm depth reveal an enrichment of gypsum (and anhydrite) at a lower layer, pointing to a sulphatic horizon as a result of ascending seepage water. No relevant differences between the Nasca and Palpa districts or between the different structures (desert pavement, trapezoids, lines, stone lines) could be identified.

Geochemical investigations

The hand-held X-ray fluorescence spectrometer (ED-XRF) delivered data that allows characterisation of the investigated material and a rather quick determination of the order of magnitude of element (or oxide) concentrations. These data were compared with the results of Wavelength-Dispersive X-Ray Fluorescence investigation to get the following quantitative information (Table 2).

No relevant differences occurred between the samples from Palpa and Nasca. The major elements of the sediments represent the typical range of felsic via intermediate to

Table 2 Chemical composition of the Nasca and Palpa sediments [X-ray fluorescence spectrometer (ED-XRF) data] selected oxides in wt-%, trace elements in mg kg^{-1}

Geoglyph/ area		Fe_2O_3	1σ	MnO	1σ	CaO	1σ	K_2O	1σ	TiO_2	1σ	As	1σ	Cu	1σ	Pb	1σ	Rb	1σ
Line	Nasca	6.0	1.2	0.11	0.02	3.6	0.4	2.1	0.2	0.80	0.20	10	3	30	11	15	4	80	7
	Palpa	5.3	0.8	0.09	0.01	4.1	1.1	2.3	0.2	0.73	0.13	15	4	33	8	15	4	94	25
Trapezoid	Nasca	5.7	0.8	0.09	0.02	4.5	1.7	2.2	0.2	0.67	0.07	12	2	27	6	14	2	87	7
	Palpa	5.2	0.4	0.09	0.01	4.9	1.4	2.2	0.2	0.67	0.07	14	4	30	8	15	5	89	9
Stone wall	Nasca	5.7	0.9	0.11	0.02	4.2	0.7	2.2	0.1	0.73	0.13	14	3	31	8	15	4	82	5
	Palpa	5.3	0.3	0.09	0.01	3.9	0.7	2.3	0.2	0.80	0.07	14	4	34	6	14	4	93	27
Desert pavement	Nasca	5.9	1.5	0.11	0.03	4.1	0.8	2.2	0.2	0.8	0.2	12	4	34	10	14	4	84	5
	Palpa	5.5	0.5	0.09	0.01	4.3	1.0	2.4	0.2	0.8	0.07	14	4	29	4	14	4	91	21
loess data from desert loess (Gallet et al. 1998; Schnetger 1992)		4–6		0.1–0.3		3–11		2		0.7–1.1		No data		14±6		13±4		81±12	
upper continental crust data after Reimann and de Caritat (1998)		4.7		0.07		4.2		3.4		0.5		1.5–2		14–25		17–20		110	

mafic rocks from the upper continental crust which is fully compatible with the geological situation. The material reflects the geogenic variance in the areas of the weathered material, which originated and was transported from the Andes to the lower coastal regions. Some slightly increased trace element concentrations such as arsenic and copper (compared with global background values, Table 2) are in equilibrium with the geological history of the area, including hydrothermal activity: copper, arsenic, silver, gold and subordinated lead are the dominant metals in local ore (Montoya et al. 1994).

Discussion and conclusions

The combination of geomagnetic and geoelectrical methods yields valuable information on the structure of geoglyphs. Hidden structures in the shallow underground were easily detected. The lines and trapezoids on the surface became visible in the geomagnetic gradient survey. However, it should be noted that structures trending in a north−south direction, parallel to the outer magnetic field, cannot be recognised by the magnetic method. Despite the dry surface conditions and the high transfer resistance, the electrical imaging method yielded good results in the desert areas of the geoglyphs. Remarkable subsurface structures could be detected at a depth of up to 2 m. Consequently, the electrical survey can be regarded as a promising tool for the investigation of the shallow subsurface in desert areas.

The geological environment of Palpa and Nasca is characterised by the Andean volcanic, intrusive and sedimentary rock assembly. Most importantly, no relevant geochemical, mineralogical or petrophysical differences occur between the geoglyph features and their desert pavement environment. This confirms that the Nasca people simply removed stone material to the hard pan horizon to create their geoglyphs. Neither salts nor other mineral material were used to alter or prepare the surfaces of geoglyphs.

To identify the unknown detected structures below the surface subsequent investigations should combine geo-electrical, petrophysical and geochemical measurements along vertical profiles. The verification of density differences over depth profiles at several locations would require an extended data base. The method of in situ determination of physical soil properties can be regarded as a reliable tool for practical work in desert areas.

Conclusions for a durable conservation of the lines and areas can only be drawn reliably once the chemical and physical processes at and in the vicinity of the geoglyphs are understood correctly. The approach to combine geophysical, petrophysical, mineralogical and geochemical methods has proven successful to extend the knowledge of these processes.

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