New Technologies for Archaeology

Multidisciplinary Investigations in Palpa and Nasca, Peru

With 223 Figures and 30 Tables
Preface

In 2002 the multidisciplinary research project “Nasca: development and adaptation of archaeometric techniques for the investigation of cultural history” (Nasca: Entwicklung und Adaption archäometrischer Techniken zur Erforschung der Kulturgeschichte) started, funded by the German Federal Ministry of Education and Research (Bundesministerium für Bildung und Forschung, BMBF) in its priority program “New scientific methods and technologies for the humanities” (Neue Naturwissenschaftliche Methoden und Technologien für die Geisteswissenschaften, NTG). This new project continued and in a certain way fulfilled a lasting goal of the ministry to integrate different branches of scientific activities and to foster the transfer of expertise gained in natural sciences to the humanities and vice versa. Archaeometry, by definition the application of scientific methods in archaeological investigation, has been a major focus of the priority program since its beginnings in 1989.

After funding numerous fruitful research projects that developed new archaeometric techniques mostly in bilateral cooperation, an even greater outcome was expected from a more multifaceted approach with the participation of various scientific disciplines around a well-defined, archaeological research topic. Furthermore, it was intended to establish a project outside the traditional research areas in central Europe or the Mediterranean. It was the great merit of the person formerly in charge of the BMBF priority program, Dr. Edgar Pusch, to develop these far-reaching perspectives and we are extremely grateful that after a rigorous screening our project among other interesting ones was selected for funding.

Our project was in a favourable situation because it met precisely the requirements defined by the BMBF, having developed a challenging research design centered on the puzzling problem of the Nasca lines in the desert of southern coastal Peru. The initial archaeological steps were financed by the Swiss-Liechtenstein Foundation for Archaeological Research Abroad (SLSA) and we are not only grateful for this support of the archaeological activities, but even more for this unique opportunity to develop a key project which in many ways became exemplary and trend-setting for future research activities. We also received very valuable financial support from the Japan Maria Reiche Fund, which enabled us to build a little museum in the center of Palpa where we can now present the results of our scientific work to the public.
We were always supported and assisted in the organization and management of the project by the project-executing institution at the Research Center Jülich, especially its representatives, Dr. Hans-Joachim Krebs and Dr. Sabine Gerhard. It was their idea to organize not only meetings and workshops in Germany, but also a field conference directly in the research area, in Palpa, where the base camp of our field campaigns was located. Five days of very intensive talks and discussions and the following excursion with about 70 participants of the field conference, among them the project members, Peruvian partners and colleagues, and international specialists from many different countries, reflected very well the special spirit of this project group: the concentration of knowledge in an interdisciplinary project in direct contact with the areas of research yielded an exceedingly high output of scientific results in an excellent working atmosphere.

At this point we as the coordinators and at the same time the editors of this volume, which constitutes the final report of our research project, would like to thank all our German, Swiss, Peruvian, and other international colleagues for their dedicated work in this very productive cooperative effort to develop new methods and technologies for archaeological investigation and to advance the knowledge of the ancient South American cultures.

In Peru we always received optimal support from the authorities and the cooperating institutions. We are indebted to the National Institute for Cultural Heritage (Instituto Nacional de Cultura, INC) for always handling the permits for our archaeological investigations in a nonbureaucratic and effective manner, and we especially thank the former director of the INC, Dr. Luis Guillermo Lumbreras, for his steady support of and interest in our project. We also thank our direct partners at the regional department of the INC, Rubén García and Susana Arce, for their very friendly and effective cooperation.

The realization of the high goals of our project, sometimes resulting in a very tight working schedule, would not have been possible without the support of the German embassy, which not only aided at the administrative level, but also enabled the logistics; exchanging research equipment and samples for the analyses in laboratories in Germany were crucial for the success of this project. We are especially grateful to the ambassador Dr. Roland Kliesow and the attaché for cultural affairs, Jens Urban, for their support and sincere interest as well as their visits to Palpa and participation in public activities of the project in Lima and Palpa.

Our special thanks go to our Peruvian colleagues and friends in Nasca and Palpa, for their hospitality and for their patience while introducing us to their fascinating world and showing us the enigmas of their pre-Hispanic history. Without their knowledge and careful observations, but also the ability to assimilate quickly new skills and at the same time to adapt to the sometimes seemingly strange behavior of the “gringos” who populated the Palpa valleys for a short time every year, they contributed a great deal to the success of the project. Our host for several years at the Fundo Jauranga, merits special mention: Don Oscar Tijero, who not only followed our research activities
with special interest, but also transmitted to us his fascination for the local history and motivated some of the most successful archaeological activities of the project.

In summary, after five years of intense research activities with a multitude of scientific results, new insights into Andean history, the development of new technologies for archaeology being useful also in other regions of the world, countless publications in different disciplines, public presentations and documentaries on radio and television, the people of Palpa will be astonished when they realize that the slogan they coined many years ago for their little forgotten desert town, turns out to be quite accurate: *Palpa es más de lo que te imaginás* (Palpa is more than you can imagine).

Bonn and Heidelberg
August 2008

Markus Reindel
Günther Wagner
# Contents

1 **Introduction – New Methods and Technologies of Natural Sciences for Archaeological Investigations in Nasca and Palpa, Peru**  
Markus Reindel and Günther A. Wagner  

## Part I Geoarchaeology

2 **Man and Environment in the Eastern Atacama Desert (Southern Peru): Holocene Climate Changes and Their Impact on Pre-Columbian Cultures**  
Bernhard Eitel and Bertil Mächtle  

3 **Built on Sand: Climatic Oscillation and Water Harvesting During the Late Intermediate Period**  
Bertil Mächtle, Bernhard Eitel, Gerd Schukraft and Katharina Ross  

## Part II Geophysics

4 **Beneath the Desert Soil – Archaeological Prospecting with a Caesium Magnetometer**  
Jörg W. E. Fassbinder and Tomasz H. Gorka  

5 **Quantum Detection Meets Archaeology – Magnetic Prospection with SQUIDs, Highly Sensitive and Fast**  
Sven Linzen, VolkmarSchultze, AndreasChwala, TimSchüler, MarcoSchulz, RonnyStolz and Hans-GeorgMeyer  

6 **Viewing the Subsurface in 3D: Sediment Tomography for (Geo-)Archaeological Prospection in Palpa, Southern Peru**  
Stefan Hecht
<table>
<thead>
<tr>
<th>Chapter</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>The Field of Sherds: Reconstructing Geomagnetic Field Variations from Peruvian Potsherds</td>
<td>103</td>
</tr>
<tr>
<td></td>
<td>Florian Stark, Roman Leonhardt, Jörg W.E. Fassbinder and Markus Reindel</td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>Part III</strong> Bioarchaeology</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>From Hunters to Regional Lords: Funerary Practices in Palpa, Peru</td>
<td>119</td>
</tr>
<tr>
<td></td>
<td>Johny Isla Cuadrado</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Talking Bones: Bioarchaeological Analysis of Individuals from Palpa</td>
<td>141</td>
</tr>
<tr>
<td></td>
<td>Elsa Tomasto Cagigao</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Who Were the Nasca? Population Dynamics in Pre-Columbian Southern Peru Revealed by Ancient DNA Analyses</td>
<td>159</td>
</tr>
<tr>
<td></td>
<td>Lars Fehren-Schmitz, Susanne Hummel and Bernd Herrmann</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Peter Horn, Stefan Hölzls, Susanne Rummel, Göran Åberg, Solveig Schiegl, Daniela Biermann, Ulrich Struck and Andreas Rossmann</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>The Nasca and Their Dear Creatures – Molecular Genetic Analysis of Pre-Columbian Camelid Bones and Textiles</td>
<td>193</td>
</tr>
<tr>
<td></td>
<td>Rebecca Renneberg, Susanne Hummel and Bernd Herrmann</td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>Part IV</strong> Archaeochronometry</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>Of Layers and Sherds: A Context-Based Relative Chronology of the Nasca Style Pottery from Palpa</td>
<td>207</td>
</tr>
<tr>
<td></td>
<td>Niels Hecht</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>The Clock in the Corn Cob: On the Development of a Chronology of the Paracas and Nasca Period Based on Radiocarbon Dating</td>
<td>231</td>
</tr>
<tr>
<td></td>
<td>Ingmar Unkel and Bernd Kromer</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>Cold Light from the Sediments of a Hot Desert: How Luminescence Dating Sheds Light on the Landscape Development of the Northeastern Atacama</td>
<td>245</td>
</tr>
<tr>
<td></td>
<td>Annette Kadereit, Steffen Greilich, Clemens Woda and Günther A. Wagner</td>
<td></td>
</tr>
<tr>
<td>Chapter</td>
<td>Title</td>
<td>Page</td>
</tr>
<tr>
<td>---------</td>
<td>-----------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>16</td>
<td>Light Thrown on History – The Dating of Stone Surfaces at the Geoglyphs of Palpa Using Optically Stimulated Luminescence</td>
<td>271</td>
</tr>
<tr>
<td></td>
<td>Steffen Greilich and Günther A. Wagner</td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>Part V Geomatics</strong></td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>Virtual Archaeology – New Methods of Image-Based 3D Modeling</td>
<td>287</td>
</tr>
<tr>
<td></td>
<td>Armin Gruen</td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>Virtual Flight Over the Nasca Lines – Automated Generation of a Photorealistically Textured 3D Model of the Pampa de Nasca</td>
<td>307</td>
</tr>
<tr>
<td></td>
<td>Martin Sauerbier</td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>Context Matters: GIS-Based Spatial Analysis of the Nasca Geoglyphs of Palpa</td>
<td>321</td>
</tr>
<tr>
<td></td>
<td>Karsten Lambers and Martin Sauerbier</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>A Model Helicopter Over Pinchango Alto – Comparison of Terrestrial Laser Scanning and Aerial Photogrammetry</td>
<td>339</td>
</tr>
<tr>
<td></td>
<td>Henri Eisenbeiss</td>
<td></td>
</tr>
<tr>
<td>21</td>
<td>Perspectives and Contrasts: Documentation and Interpretation of the Petroglyphs of Chichictara, Using Terrestrial Laser Scanning and Image-Based 3D Modeling</td>
<td>359</td>
</tr>
<tr>
<td></td>
<td>Peter Fux, Martin Sauerbier, Thomas Kersten, Maren Lindstaedt and Henri Eisenbeiss</td>
<td></td>
</tr>
<tr>
<td>22</td>
<td>Pottery Plotted by Laser – 3D Acquisition for Documentation and Analysis of Symmetry of Ancient Ceramics</td>
<td>379</td>
</tr>
<tr>
<td></td>
<td>Hubert Mara</td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>Part VI Archaeometallurgy</strong></td>
<td></td>
</tr>
<tr>
<td>23</td>
<td>Gold in Southern Peru? Perspectives of Research into Mining Archaeology</td>
<td>393</td>
</tr>
<tr>
<td></td>
<td>Thomas Stöllner</td>
<td></td>
</tr>
<tr>
<td>24</td>
<td>Fingerprints in Gold</td>
<td>409</td>
</tr>
<tr>
<td></td>
<td>Sandra Schlosser, Robert Kovacs, Ernst Pernicka, Detlef Günther and Michael Tellenbach</td>
<td></td>
</tr>
</tbody>
</table>
Contributors

Göran Åberg Bavarian State Collection for Palaeontology and Geology, Munich, Richard-Wagner Straße 10, 80333 Munich, Germany, goranelin@hotmail.com

Daniela Biermann Obere Beutau 79, 73728 Esslingen, Germany, Daniela. biermann@t-online.de

Andreas Chwala Institute of Photonic Technology e.V., POB 100239, 07702 Jena, Germany, andreas.chwala@ipht-jena.de

Henri Eisenbeiss ETH Zurich, Institute of Geodesy and Photogrammetry, ETH Hönggerberg HIL D 43.2, 8093 Zurich, Switzerland, henri.eisenbeiss@geod.baug.ethz.ch

Bernhard Eitel Institute of Geography, University of Heidelberg, Im Neuenheimer Feld 348, 69120 Heidelberg, Germany, bernhard.eitel@geog.uni-heidelberg.de

Jörg W.E. Fassbinder Bavarian State Department for Monuments and Sites, Archaeological Prospection, Hofgraben 4, 80539 Munich, Germany, joerg.fassbinder@BLFD.Bayern.de

Lars Fehren-Schmitz Johann Friedrich Blumenbach Institute of Zoology and Anthropology, Historical Anthropology and Humanecology, Georg-August-University Goettingen, Bürgerstraße 50, 37073 Göttlingen, Germany, lfehren@gwdg.de

Peter Fux Museum Rietberg Zürich, Gablerstrasse 15, 8002 Zürich, Switzerland, peter.fux@zuerich.ch

Tomasz H. Gorka Bavarian State Department for Monuments and Sites, Archaeological Prospection, Hofgraben 4, 80539 Munich, Germany, gorka@geophysik.uni-muenchen.de

Steffen Greilich Radiation Research Department, Risø National Laboratory for Sustainable Energy, Technical University of Denmark, Frederiksborgvej 399, 4000 Roskilde, Denmark, Steffen.Greilich@risoe.dk
Contributors

Armin Grün ETH Zurich, Institute of Geodesy and Photogrammetry, ETH Hönggerberg HIL D 43.2, 8093 Zurich, Switzerland, agruen@geod.baug.ethz.ch

Detlef Günther ETH Zurich, Department of Chemistry and Applied Biosciences, Laboratory of Inorganic Chemistry, HCI G 113, Wolfgang-Pauli-Straße 10, 8093 Zurich, Switzerland, detlef.guenther@inorg.chem.ethz.ch

Niels Hecht, M. A. German Archaeological Institute (DAI), Commission for Archaeology of Non-European Cultures (KAAK), Bonn, Dürenstraße 35–37, 53173 Bonn, Germany, nihecht@web.de

Stefan Hecht Institute of Geography, University of Heidelberg, Im Neuenheimer Feld 348, 69120 Heidelberg, Germany, stefan.hecht@geog.uni-heidelberg.de

Bernd Herrmann Johann Friedrich Blumenbach Institute of Zoology and Anthropology, Historical Anthropology and Humanecology, Georg-August-University Göttingen, Bürgerstraße 50, 37073 Göttingen, Germany, bherrmann@gwdg.de

Stefan Hölzl Bavarian State Collection for Palaeontology and Geology, Munich, Richard-Wagner Straße 10, 80333 München, Germany, s.h@lmu.de

Peter Horn Bavarian State Collection for Palaeontology and Geology, Munich, Richard-Wagner Straße 10, 80333 München, Germany, p.horn@lrz.uni-muenchen.de

Susanne Hummel Johann Friedrich Blumenbach Institute of Zoology and Anthropology, Historical Anthropology and Humanecology, Georg-August-University Göttingen, Bürgerstraße 50, 37073 Göttingen, Germany, shummel1@gwdg.de

Johny Isla Cuadrado Instituto Andino de Estudios Arqueológicos (INDEA), Lima, Av. Mariátegui 155, Dpt. 111, Jesús María, Lima 11, Perú, isla-nasca@amauta.rcp.net.pe

Annette Kadereit Luminescence Laboratory, Institute of Geography, University of Heidelberg, Im Neuenheimer Feld 348, 69120 Heidelberg, Germany, annette.kadereit@geog.uni-heidelberg.de

Thomas Kersten HafenCity University (HCU) Hamburg, Department Geomatics, Hebebrandstraße 1, 22297 Hamburg, Germany, thomas.kersten@hcu-hamburg.de

Robert Kovacs ETH Zurich, Department of Chemistry and Applied Biosciences, Laboratory of Inorganic Chemistry, HCI G 141, Wolfgang-Pauli-Straße 10, 8093 Zurich, Switzerland, robert.kovacs@inorg.chem.ethz.ch

Bernd Kromer Forschungsstelle Radiometrie der Heidelberger Akademie der Wissenschaften, c/o Institut für Umweltphysik, Heidelberg, Im Neuenheimer Feld 229, 69120 Heidelberg, Germany, bernd.kromer@iup.uni-heidelberg.de
Karsten Lambers  University of Konstanz, Zukunftskolleg, Department of Computer Science, P.O. Box 697, 78457 Konstanz, Germany, karsten.lambers@uni-konstanz.de

Roman Leonhardt  Department of Applied Geoscience and Geophysics Chair of Geophysics, University of Leoben, Peter-Tunner-Straße 25–27, 8700 Leoben, Austria, roman.leonhardt@mu-leoben.at

Maren Lindstaedt  HafenCity University (HCU) Hamburg, Department Geomatics, Hebebrandstraße 1, 22297 Hamburg, Germany, maren.lindstaedt@hcu-hamburg.de

Sven Linzen  Institute of Photonic Technology e.V., POB 100239, 07702 Jena, Germany, sven.linzen@ipht-jena.de

Bertil Mächtle  Institute of Geography, University of Heidelberg, Im Neuenheimer Feld 348, 69120 Heidelberg, Germany, bertil.maechtle@geog.uni-heidelberg.de

Hubert Mara  Vienna University of Technology, Institute of Computer Aided Automation, Pattern Recognition and Image Processing Group, Favoritenstrasse 9/183-2, 1040 Vienna, Austria, mara@prip.tuwien.ac.at

Hans-Georg Meyer  Institute of Photonic Technology e.V., POB 100239, 07702 Jena, Germany, hans-georg.meyer@ipht-jena.de

Ernst Pernicka  Curt-Engelhorn-Zentrum Archæometrie (CEZA) Mannheim, An-Institut der Universität Tübingen, D6, 3, 68159 Mannheim, Germany, ernst.pernicka@cez-archaeometrie.de; Eberhard-Karls-Universität Tübingen, Institut für Ur- und Frühgeschichte und Archäologie des Mittelalters, Abteilung für Jüngere Urgeschichte und Frühgeschichte, Schloss Hohentübingen, 72070 Tübingen, Germany, ernst.pernicka@uni-tuebingen.de

Markus Reindel  German Archaeological Institute (DAI), Commission for Archaeology of Non-European Cultures (KAAK), Dürenstraße 35–37, 53173 Bonn, Germany, reindel@kaak.dainst.de

Rebecca Renneberg  Graduate School Human Development in Landscape, Universitätsklinikum Schleswig-Holstein, Arnold-Heller-Straße 3, 24105 Kiel, Germany, rrenneberg@ghsdl.uni-kiel.de

Katharina Ross  Institute of Geography, University of Heidelberg, Im Neuenheimer Feld 348, 69120 Heidelberg, Germany, ninaross@gmx.de

Andreas Rossmann  Isolab GmbH Laboratorium für Stabil-Isotopenanalytik, Woelkstraße 9/1, 85301 Schweitenkirchen, Germany, isolab_gmbh@t-online.de

Susanne Rummel  Bavarian State Collection for Palaeontology and Geology, Munich, Richard-Wagner Straße 10, 80333 München, Germany, susanne.rummel@iaag.geo.uni-muenchen.de
Martin Sauerbier ETH Zurich, Institute of Geodesy and Photogrammetry, ETH Hönggerberg HIL D 43.2, 8093 Zurich, Switzerland, martin.sauerbier@geod.baug.ethz.ch

Solveig Schiegl Institut für Ur- und Frühgeschichte und Archäologie des Mittelalters, Abteilung Ältere Urgeschichte und Quartärökologie, Schloss Hohentübingen, Burgsteig 11, 72070 Tübingen, Germany, solveig.schiegl@uni-tuebingen.de

Sandra Schlosser Curt-Engelhorn-Zentrum Archaeometrie (CEZA) Mannheim, An-Institut der Universität Tübingen, D6, 3, 68159 Mannheim, Germany, sandra.schlosser@cez-archaeometrie.de

Tim Schüler Thüringisches Landesamt für Denkmalpflege und Archäologie, Humboldtsstraße 11, 99423 Weimar, Germany, SchuelerT@tlda.thueringen.de

Gerd Schukraft Institute of Geography, University of Heidelberg, Im Neuenheimer Feld 348, 69120 Heidelberg, Germany, gerd.schukraft@geog.uni-heidelberg.de

Volkmar Schultze Institute of Photonic Technology e.V., POB 100239, 07702 Jena, Germany, volkmar.schultze@ipht-jena.de

Marco Schulz Institute of Photonic Technology e.V., POB 100239, 07702 Jena, Germany, marco.schulz@ipht-jena.de

Florian Stark Department für Geo- und Umweltwissenschaften, Bereich Geophysik, Ludwig-Maximilians-Universität, München, Theresienstraße 41, 80333 Munich, Germany, stark@geophysik.uni-muenchen.de

Thomas Stöllner Deutsches Bergbau-Museum Bochum, Forschungsstelle Archäologie und Materialwissenschaften, Fachbereich Montanarchäologie, Herner Straße 45, 44787 Bochum, Germany, thomas.stoellner@bergbaumuseum.de; Fakultät für Geschichtswissenschaften, Institut für Archäologische Wissenschaften, Lehrstuhl für Ur- und Frühgeschichte, Universitätsstraße 150, 44780 Bochum, Germany, thomas.stoellner@ruhr-uni-bochum.de

Ronny Stolz Institute of Photonic Technology e.V., POB 100239, 07702 Jena, Germany, ronny.stolz@ipht-jena.de

Ulrich Struck Berlin Museum of Natural History, Invalidenstraße 43, 10115 Berlin, Germany, ulrich.struck@museum.hu-berlin.de

Michael Tellenbach Reiss-Engelhorn-Museen Mannheim, C5, Zeughaus, 68159 Mannheim, Germany, michael.tellenbach@mannheim.de

Elsa Tomasto Cagigao Pontificia Universidad Católica del Perú (PUCP), Departamento de Humanidades, Av. Universitaria cdra. 18, San Miguel, Lima 32, Perú, etomast@pucp.edu.pe
Ingmar Unkel  Department of Physics, Nuclear Physics, Lund University, Professorsgatan 1, 22100 Lund, Sweden, ingmar.unkel@geol.lu.se

Günter A. Wagner  Institute of Geography, University of Heidelberg, Im Neuenheimer Feld 348, 69120 Heidelberg, Germany, g.wagner@mpi-hd.mpg.de

Clemens Woda  Helmholtz Center Munich, German Research Center for Environmental Health, Institute of Radiation Protection, Ingolstädter Landstraße 1, 85764 Neuherberg, Germany, clemens.woda@helmholtz-muenchen.de
Chapter 1
Introduction – New Methods and Technologies of Natural Sciences for Archaeological Investigations in Nasca and Palpa, Peru

Markus Reindel and Günther A. Wagner

1.1 Natural Sciences in Archaeology

Applications of natural sciences in archaeology have actually a long tradition. In particular the chemical composition of metal artefacts was sporadically used for more than two hundred years, mainly for the purpose of material classification. One of the earliest examples is the quantitative analysis of Roman coins in 1799 by Martin Heinrich Klaproth in Berlin, a chemist who is better known as the discoverer of the element uranium. Based on the material composition of dominant remains, the Danish archaeologist Christian Jürgensen Thomsen formally introduced in the 1820s the three-age system of prehistoric archaeology into three consecutive time periods: the Stone Age, the Bronze Age, and the Iron Age.

Especially during the second half of the twentieth century, natural scientific approaches in archaeology experienced a nearly explosive increase. It became obvious that, when trying to reconstruct the past as comprehensively as possible, the archaeologist needs to take into consideration all sources of relevant information including those which are hidden to the naked eye, being the foremost tool of an archaeologist’s perception, and which are only revealed by scientific studies. Terms such as ‘science-based archaeology’ or simply ‘archaeometry’ are used for this new discipline. Originally coined in 1958 as the title for a journal (M. Aitken, in Olin, 1982, p. 142) and subsequently also used for an international symposium, ‘archaeometry’ was increasingly adapted within the past few decades for this field of research. It is acknowledged in the meantime by most archaeologists as an indispensable and integral part of archaeology.
1.2 Archaeometry

In our understanding ‘archaeometry’ designates the development and application of natural scientific methods and concepts in order to contribute to the solution of cultural–historical questions (Wagner, 2007). In this multidisciplinary, most extensive scope, archaeometry is the interface between the natural and the cultural–historical sciences. Archaeometry is both archaeology by ultimate aim (αρχαιολογία), but natural science by approach (μετρητικό). In this broad definition all disciplines of natural sciences that may contribute to archaeology are included, that is, not only physics, chemistry, and mathematics, but also the biological sciences, anthropology, geological sciences, astronomy, and remote sensing. Inasmuch as all of these disciplines describe natural phenomena quantitatively they readily identify themselves with the μετρητικό aspect of archaeometry.

As part of cultural history, which generally is concerned with the behaviour of past man, archaeology is the study of the material remains of man’s past with the aim to get broad insights into ancient human cultures, specifically their tools, techniques, economy, works of art, language, ideas, beliefs, customs, and so on. In achieving this goal, natural sciences enter archaeology twofold: first, by their application to inorganic artifacts (e.g., chemical analysis of ceramics) as well as biomaterials (e.g., isotopic studies of bones). Second, natural objects and phenomena as such are of archaeological importance for reconstructing the former environmental situation, such as landscape and climate. Because the natural environment sustains culture, the understanding of the interaction between nature and culture requests combined efforts of both the cultural–historical as well as the natural sciences, and thus the archaeo-environment is a subject of archaeometry.

Archaeometric projects should focus on relevant archaeological questions (e.g., prehistoric chronology), to which one tries to contribute by gaining primary data with an appropriate method (e.g., ¹⁴C), followed by scientific evaluation (e.g., reliability and meaning of the age value) and ultimately by archaeological interpretation (e.g., chronological significance). In other words, at first an archaeological question needs to be transformed into a natural scientific one, and then the scientific result needs to be translated back into an archaeological one. Archaeological topics, for which commonly archaeometric support is demanded, comprise mainly the identification, manufacture, and provenance of material remains, as well as the geophysical prospection, dating, and archaeo-environment of whole sites.

The occasionally raised dispute of whether archaeometry is research in its own or service to archaeology, is needless in such cooperation. There are cases where an archaeological problem triggers the development of a new technology, and other cases where an available technology stimulates the archaeologist towards fresh questions. An intensive and sustained interchange between natural scientists generating the data and those interpreting them
archaeologically obviously is required. The archaeologist should be familiar with the archaeometric possibilities to define accessible aims, and the natural scientist must understand the archaeological problems in order to optimize his or her efforts towards their solution.

1.3 Archaeometry in South America

Archaeometry is a quite recent discipline in American archaeology. The majority of archaeological investigations in South America is concentrated in the Andean region where the research area of the Nasca–Palpa project is located. Therefore the following overview of archaeometric approaches in South American archaeology focuses on this western part of the subcontinent and, of course, cannot be comprehensive. Rather it highlights the most important publications in an exemplary fashion.

One of the foremost interest and most traditional issues in archaeometry is chronometry. Right from the beginning of numeric dating with physical methods after the discovery of the radiocarbon ($^{14}$C) method by W.F. Libby, the American archaeologist J. Bird introduced this new method in Andean archaeology (Bird 1951). Radiocarbon dating is now the most widely used method for numeric dating and is an integral part of all major archaeological projects. The chronological placement of some of the most important cultures in South America such as the Valdivia culture relies mainly on radiocarbon dating (Marcos 1988). A large number of radiocarbon dates of the Central Andean area have been published by Ziolkowski et al. (1994), although many of these dates are lacking a detailed description of the archaeological context of the samples.

Other physical dating methods have been used only in very isolated cases in South America. Thermoluminescence (TL) dating for ceramics has been applied in coastal Ecuador (Reindel 2007; Alvarez 1995). Optically stimulated luminescence (OSL) was tested for the dating of the Nasca lines, actually in the same area where the Nasca–Palpa project later took place (Rink and Bartoll 2005). Obsidian hydration was applied soon after its discovery to date the early cultures of Ecuador (Evans and Meggers 1960). But until today this method could not be established as a reliable dating tool in South America, due to the problems of temperature and moisture changes over time, which heavily affect the dating results. However, recently good results have been achieved for dating obsidian objects in the extremely dry environment of the Nasca region on the south coast of Peru (Eerkens et al. 2008). Another product of volcanic activity, the deposition of tephra layers, which reach far into the coastal areas and can be correlated with datable eruptions of well-studied volcanoes of the cordilleras, has been successfully applied in Ecuador for dating and studying the impact of environmental change on pre-Columbian societies (Mothes 1998).

The analysis of inorganic materials is another original field of archaeometry. Recently the exact knowledge of the composition of minerals and metals is used
especially for provenance studies. The investigations of metal and ceramic production, led by I. Shimada on the north coast of Peru, may serve as an example of one of the most diversified long-term projects aimed at the reconstruction of pre-Hispanic procurement of raw materials and craft production (Shimada and Wagner 2007).

The chemical and mineralogical characteristics of ceramics, which are the most numerous findings by archaeologists, are investigated by thin sections, x-ray spectrometry, and neutron activation analysis (NAA). The available techniques have been applied in the last few years to trace the production centres and the distribution of ceramics in the Nasca region (Vaughn and Neff 2004; Vaughn et al. 2006; Vaughn and Gijseghem 2007). Mössbauer spectrometry was used to determine details of the production process of ceramics (Wagner et al. 2003b). With the development of laser ablation and inductively coupled plasma-mass spectrometry (LA-ICP-MS) it is now possible to analyze the mineralogical composition of ceramics and their decoration using only minimal amounts of sample material and thus nearly without destruction (Dussubieux et al. 2007; Vaughn et al. 2005).

In sharp contrast to the Old World, metal production played a minor role in South American cultures, except for the extensive use of gold ornaments in some regions such as Colombia and northern Peru. A representative overview of metal weapons and tools is given by Mayer (1986, 1992, 1994, 1998). The metallurgy has been studied especially in the Central Andean area (Root 1949; Lechtman 1979; Lechtman and Macfarlane 2005). Nondestructive techniques have been applied to analyze the composition of metals and to test by this means the authenticity of museum objects (Rovira 1990). Important advances in the study of copper and bronze production have been achieved on the north coast of Peru (Epstein and Shimada 1983; Merkel et al. 1994). Neutron activation analysis has also been applied to trace the provenance of metal objects (Gordus et al. 1996; Chapdelaine et al. 2001).

Inasmuch as the cordilleras of the Andes are active volcanic regions, obsidian is available in many places and has been used throughout the entire history of human occupation of South America. The study of obsidian artefacts, raw material sources, and trade routes has thus become a fruitful field of archaeological investigation. Glascock (2002) gives a summary of the obsidian provenance research in the Americas. Ecuador is one of the main regions where detailed studies on obsidian production and exchange among the pre-Hispanic cultures have been carried out (Burger et al. 1994; Bellot-Gurlet et al. 2008). And again, the central Andean area has produced the largest number of publications on this topic (Glascock et al. 2007; Burger et al. 2000, 2006). The Quispisisa obsidian source in the Peruvian department of Ayacucho is of special importance for our project because according to the available studies it was the major source for obsidian of the Nasca–Palpa region (Burger and Glascock 2000; Vaughn and Glascock 2005). Obsidian sources have been investigated also farther to the south, in Argentina and Chile (e.g., Giesso et al. 2008).
Anthropological studies have made great progress in South America since the establishment of systematic long-term projects, especially following the discovery of the royal tombs of Sipan and the related investigations of the Moche culture of the north coast of Peru. Traditional anthropological research has been carried out by Verano on different sites in the Andes (Verano 1997a,b, 2003, 2005). The discovery of mummies in regions with optimum conservation conditions, like the Chachapoyas region on the eastern slope of the Peruvian Andes as well as the extremely arid environment of the Atacama desert, fostered the establishment of a research cluster led by the Peruvian anthropologist Guillén (Guillén 2002, Guillén et al. 2004). Another focus of anthropological studies was the interdisciplinary projects of the Tiwanaku and the Wari cultures (Blom et al. 2003; Tung 2007). These studies were complemented by the most recent developments in anthropology, namely palaeogenetic studies. The few available pioneering publications in this field (Lewis et al. 2005, 2007; Shimada et al. 2006; Shinoda et al. 2006) are far away from giving a comprehensive picture of human population history, but they open a window to a fascinating field of future research being enlarged by the contribution of Fehren-Schmitz et al. in this volume.

Another new archaeometric analytical tool, which has been successfully applied in anthropological as well as in palaeobiological and palaeoecological studies, are stable isotopes. Examples of the Andean area illustrate the wide use of isotope studies for archaeology. Strontium isotopes have been used to investigate seasonality and the palaeodiet of the Chiribaya polity in southern Peru (Knudson et al. 2007; Knudson and Buikstra 2007). Isotope studies have also contributed to the history of maize in South America, which played an important role in the rise of Andean civilizations (Gil et al. 2006; Tykot 2006).

Palaeoecological studies always played an important role in the investigation of the early stages of South American populations. In the context of the general discussion of climate change and its influence on human societies, palaeoecological and especially palaeoclimatological studies have been intensified in the last years. Except for a few publications about the Amazon lowlands dealing with the influence of palaeoclimate on human development (e.g., Araujo et al. 2005) most studies are centered on the cordilleras of the Andes and Pacific coast of South America (e.g., Weng et al. 2006). Clearly, the most discussed topic is the El Niño phenomenon, which has far-reaching implications for human development on the central Andean coast. Studies have focussed on the early periods (Sandweiss 2003; Sandweiss et al. 2004; Keefer et al. 2003) as well as late periods where El Niño events are assumed to have had a major impact on pre-Hispanic societies (e.g. Satterlee et al. 2000). These studies are complemented by geoarchaeological investigations of long-term climate change influencing the occupation of the extreme south coast of Peru in the early periods (Lavallée et al. 1999; Usselmann et al. 1999). Later periods have been studied recently in the Titicaca region (Stanish 2003; Calaway 2005). Similar studies are available from the southern part of South America (Latorre et al. 2003; Iriarte 2006; Maldonado and Villagran 2002).
Geophysical prospection is far behind recent developments especially in Europe, where in the last decades the geophysical survey has become an integral part of most archaeological projects. In South America, geophysical techniques have been applied in major interdisciplinary projects. Magnetometry, conductivity, and resistivity surveys were pioneered in a project on the Amazonas delta in Brazil (Roosevelt 1991, 2007). The same techniques were employed in geophysical surveys in the Peruvian and Bolivian highlands, in Tiahuanaco and Pucara, for the detection of stone architecture (Williams et al. 2007; Klarich 2008). Successful magnetometry, electromagnetometry, and resistivity surveys have been applied also in the investigation of monumental architecture in the Casma valley of northern Peru (Fuchs et al. 2006). Another single study, using GPR, electrical, and electromagnetic methods, has been reported from northwestern Argentina (Martino et al. 2006; Osella et al. 2005).

Similar to geophysical prospection methods, remote sensing, which is widely used and in continuous development in Europe, is only beginning to be applied in South American archaeology (Baltsavias et al. 2006). Photogrammetric methods have been employed to map a limited area of the geoglyphs of the Pampa de Nasca in southern Peru (Hawkins 1974). In the same area a project of the Technical University of Dresden is developing a geographic information system using photogrammetric and satellite data (Teichert and Richter 2001; Richter 2007). Satellite data are also beginning to be used for the monitoring of cultural heritage sites as in the case of Machu Picchu (Hernandez 2006). But the systematic use of satellite and other remote sensing data for archaeological prospection and field research, as it is being realized in pilot projects in the Maya area in Mesoamerica (Saturno et al. 2007), still remains a challenging task for the future of South American archaeology.

Archaeobotanic studies have also advanced in the last few years through new analytical methods, giving fresh insights especially in early processes of plant domestication in South America. The archaeobotanists Pearsall and Piperno have greatly advanced traditional systematic studies of botanical remains as well as the use of new technologies (Pearsall 2000, 2004; Piperno and Pearsall 1998). Starch grain analysis allows for the identification of minimal plant remains in archaeological contexts even under humid conditions, opening new ways for the reconstruction of tropical agriculture and plant domestication (Chandler-Ezell et al. 2006; Perry et al. 2007). Phytoliths, the mineralized remains of certain plant components, are also very useful for the reconstruction of the plant inventory in humid environments or even in burnt contexts. In the last years sample databases for South America have been built up and were used in archaeological studies (Piperno 2006, 2008).

Also in contrast to the Old World, where the domestication of animals played a crucial role in the process of sedentarization and the rise of complex societies, the use of domestic animals played a minor role in South America. The only major animals in the Andes used for transport, but also as an important source of meat and wool, were the camelids. A comprehensive
overview of camelid studies can be found in Mengoni et al. (2001). The other relevant publications for the study of the domestication and use of camelids in South America are mentioned in the contribution by Renneberg et al. (this volume) on palaeogenetic studies of camelids.

1.4 Archaeology of the South Coast of Peru

Because of the lack of any known writing system in pre-Columbian times, archaeology is the only means for the reconstruction of cultural history in South America. Archaeological investigation from its beginning has paid special attention to the central Andean area because this region was the homeland of the most developed culture in South America at the arrival of the Europeans in the sixteenth century, the Inka culture, and because it was one of the few regions in the world where complex societies emerged about five thousand years ago. In recent years great advances have been achieved in the understanding of the mechanisms for the rise of early complex societies in the central Andes, in part as a result of the interdisciplinary cooperation between archaeology and natural sciences.

The earliest findings in the central Andean area date to the beginning of the Holocene. The Archaic period, which ends about 2000 BC, is still poorly known. Recent investigations have shown that the origins of early complex societies must be dated to the fourth millennium BC. This timeframe almost equals the chronological placement of the early urban societies in the Old World. With the recent findings of early monumental architecture and other spectacular discoveries, such as the royal tombs and beautifully decorated temple buildings on the north coast of Peru, the central Andean area occupies a prominent place in worldwide archaeological research.

Archaeological research began in Peru at the end of the nineteenth century with the work of Max Uhle. He recognized cultural styles that allowed the comparison of cultural developments based on stylistically similar artifacts, namely the Inka and Tiahuanaco style. He also identified regional styles that represented independent cultural developments. After the first investigations at the central and north coast of Peru, Uhle carried out archaeological excavations in the Ica valley on the south coast of Peru. There he discovered remains of the Nasca culture which previously had been studied merely in museum collections. Uhle recognized the Nasca-style as representing a regional development and considered it the earliest culture of this region.

Some years later Julio C. Tello discovered at the Paracas peninsula the remains of an even earlier culture. This Paracas culture was contemporaneous with the Chavin culture, represented by another horizon style which Tello had discovered before at Chavin de Huantar and in the Casma valley in northern Peru. This chronological system of horizon and regional cultures in the 1950s and 1960s was further developed by J.H. Rowe and his team. He based his work
on collections from the Ica valley where he intended to develop a master sequence for the cultures of the central Andean area. Hence the south coast of Peru has considerable importance for the systematic study of the central Andean cultures. However, in the years after 1960 the focus of archaeological investigation shifted to the central coast and highlands where a great number of early monumental sites pointed to the place of origin of complex societies in the Andes.

In archaeological terms the south coast of Peru is considered the part between the Cañete valley to the north down to the Acari valley in the south. In contrast to the rich alluvial fans of the central and northern valleys, the agricultural lands of the south coast are limited and offer fewer resources for the development of an agriculturally based economy. This is reflected by the lack of major complexes of monumental architecture on the south coast, which is a characteristic of the pre-Hispanic societies farther to the north. However, for the strategy of archaeological research, especially of settlement patterns, this has the advantage that the valleys of the south coast represent well-defined and clearly delimited settlement territories. This is especially true in the Nasca region where the research area of the Nasca–Palpa project is located.

The Nasca region is defined by the ten tributaries of the Río Grande de Nasca (Fig. 1.1) which is the only river that reaches the Pacific Ocean after crossing the coastal cordillera, which is a particular geomorphologic feature of this part of the Peruvian coast. The most famous archaeological culture of this region is the Nasca culture (200 BC–600 AD) which is characterized by polychrome painted vessels that can be found in many museums all over the world. On the other hand, the Nasca culture became famous for the geoglyphs that cover large areas of the desert plateaus between the fertile river valleys.

The largest site of the Nasca culture is Cahuachi in the Nasca valley. Despite long-term archaeological investigations it is not clear whether this site represents the central place of a political entity or a center for religious pilgrimage. Until the start of the Nasca–Palpa project, few data were available to answer this question. Archaeological research centered mostly on the esthetically attractive artefacts and the enigmatic geoglyphs of the Nasca culture. Settlement pattern studies and the investigation of the cultural and ecological context seemed to be of minor importance. The Paracas culture (800–200 BC), which preceded the Nasca culture, was poorly investigated. Only one single site of the Initial period (1500–800 BC) and one of the Middle Archaic period (approx. 4000 BC), respectively, had been studied. The same was true for later periods, the Middle Horizon (600–1000 AD), the Late Intermediate period (1000–1400 AD), and the Inka period (1400–1532 AD).

Therefore the Nasca valleys and especially the northern tributaries around the actual town of Palpa presented ideal conditions for the study of settlement patterns and cultural development of pre-Hispanic societies in a specific region:
1.5 Conception of the Nasca–Palpa Project

Inasmuch as archaeometry is largely based on scientific and technological expertise, the rapid progress of natural sciences carries a great potential that needs steadily to be taken advantage of for archaeology. The German Federal Ministry for Education and Research (Bundesministerium für Bildung und Forschung, BMBF) realized this potential and established in 1989 the research funding program ‘Neue naturwissenschaftliche Methoden und Technologien in den Geisteswissenschaften’ (new natural scientific methods and technologies in the humanities). The emphasis of the program lay originally on the adoption of new methods from natural sciences and their specific technological development for the benefit of humanity. In the course of the program it was recognized that a most effective means was combining various promising techniques around a central and important archaeological issue. In this manner not only the dialogue with archaeology but also among the different scientific disciplines could be enhanced. This concept stood in 2002 at the start of the Nasca–Palpa project Entwicklung und Adaption archäometrischer Techniken zur Erforschung der Kulturgeschichte (development and adaption of archaeometric techniques for the investigation of cultural history).

In the Palpa region, in the northern part of the Nasca drainage, the conditions for the establishment of such a multidisciplinary research program were excellent. Since 1997 archaeological investigations had been carried out with the financial support of the Swiss-Liechtenstein Foundation for Archaeological Research Abroad (SLSA), centered on the geoglyphs of the Nasca culture. In many cases research questions emerged that could not be solved with archaeological methods alone. It became clear, for example, that climate and landscape changes must have had considerable influence on the settlement patterns. The task of the documentation of the geoglyphs, which extended over hundreds and thousands of meters, as well as the topographic survey of the numerous extended settlements and landscape features could not be achieved with traditional methods of terrestrial surveying.
The lack of a reliable chronology based on numerical data was a major task in the context of the reconstruction of local settlement history. The complex population history could not be investigated with the analysis of settlement patterns and anthropological studies alone.

Imported raw materials, such as obsidian from the highlands or seashells from the Pacific Ocean, show clearly that the societies in the research area maintained complex trade relations which constituted an important base of their economy. The provenance and the processing of raw materials could only be investigated with adequate methods of archaeometric analysis. Especially interesting is the investigation of luxury goods such as gold and other precious objects.

Finally, it became clear that the systematic management of the rich data of the different kinds produced by the multidisciplinary project were a great challenge for the archaeologists, but at the same time held a great potential for analytical methods available today through geographic information systems (GIS).

In principle, a broad spectrum of archaeometric methods was on hand for this program. Our conception was to employ the different disciplines in a way that they would complement and interchange with each other in order to achieve quantitative as well as qualitative novel insights into the complex prehistory of southern Peru. This implied, of course, also new technological developments according to specific conditions in this near-equator region.

The pre-Columbian cultures in the desert belt of southern Peru were exposed to a harsh climatic environment. This requires a detailed knowledge of the climatic conditions and their effects on landscape and vegetation, hitherto unknown for this region. Therefore, geoarchaeological studies seemed to be of foremost importance for detecting climate changes and understanding their impact on pre-Columbian cultures at the edge of the Atacama desert in southern Peru.

The localization and extension of archaeological structures beneath the soil without digging was achieved by geomagnetic prospection and sediment tomography, whereby the problem of nearly surface-parallel geomagnetic field-lines presented a methodological challenge.

The biogenic remains, well preserved under the arid conditions of the Palpa region, initiated their bioarchaeological analysis and molecular-anthropological examinations. In particular, isotopic studies revealed the subsistence strategy and the migration patterns of humans.

Of crucial importance in prehistory is archaeochronometry. The achievement of a solid, highly resolving chronology of the Paracas and Nasca periods, based on radiocarbon, has implications far beyond our study area. Luminescence dating of the sediments sheds light on the landscape development. The successful dating of stone surfaces at the geoglyphs using luminescence is one of the new technologies.

Also new is the development and application of geomatics with its three-dimensional photorealistic modelling of the landscape, the GIS-based
Fig. 1.2 Chronological table containing the archaeological and the physical dating results of the Nasca–Palpa project. (After Unkel 2006)
modelling and spatial analysis of the geoglyphs of Palpa and Nasca, as well as the documentation and interpretation of prehistoric petroglyphs with laser scanning, photogrammetry, and satellite imagery.

Finally, archaeometallurgy and archaeoceramology employ geological and geochemical methods to identify the sources and to investigate the working of metals and ceramics. Thus, trading patterns and the technological skills of the Paracas and Nasca periods may be revealed.

The nuclear area of the Nasca–Palpa project was the valleys of the rivers Grande, Palpa, and Viscas of the Palpa province, in the northern part of the Nasca drainage. A systematic archaeological survey was carried out in the area between the confluence of the rivers Grande and Ingenio, up to the upper courses of the rivers at an elevation of about 2000 m. The research area thus comprises mainly the footzone of the Andes. For comparative reasons some sites of the neighbouring valley Santa Cruz, in the catchment areas of the valleys and in the lower course of the Rio Grande valley were studied (Fig. 1.1). Especially the radius of the geoarchaeological investigations goes far beyond the nuclear research area.

About 800 sites are registered in the database, 450 of which are settlements dating to different periods of pre-Hispanic history. In the course of the surveys the sites were dated according to the published chronological models. For a more detailed chronological placement, test excavations were carried out at many places. Furthermore, for nearly every major chronological period a large-scale excavation was designed in order to document the characteristics of each epoch in well-defined archaeological contexts. The most important sites mentioned in the contributions to this volume are marked on the map of Fig. 1.1.

In the course of the project and during the process of analysis of the findings the chronology was refined. Cooperation with the chronometric project especially yielded a great number of archaeological as well as geomorphological dates. As a result, the Palpa region now holds probably the most detailed chronology of landscape and cultural history in South America. The chronological table with its archaeological and physical numeric ages for the research area of the Nasca–Palpa project is represented in Fig. 1.2.
Part I
Geoarchaeology
Chapter 2
Man and Environment in the Eastern Atacama Desert (Southern Peru): Holocene Climate Changes and Their Impact on Pre-Columbian Cultures

Bernhard Eitel and Bertil Mächtle

Abstract  Geoarchaeological evidence for Holocene palaeoclimates in the eastern Atacama desert is compiled to reconstruct the palaeoenvironmental history in the Andean foreland. In contrast to earlier assumptions that El Niño events controlled the environment of pre-Columbian people in the Ica–Nazca region, major hydrological changes, triggered by oscillations of the summer monsoon in the western Andes, concurred with cultural changes. Loess deposits, phytoliths, and snail shells indicate that during the early and middle Holocene the eastern Atacama desert was a grassland until the third millennium BC. With the aridisation hunter–gatherer people concentrated on favourable sites along the river oases, which were flooded seasonally by reliable rains in the western Andes. During the rise of the Paracas culture the increasing population density went hand in hand with the formation of more complex societies. After ~200 BC the Nasca displaced the Paracas culture. Approximately four centuries later the aridisation of the region accelerated and the Nasca settlements shifted eastwards into the valleys of the Andean footzone. With even more reduced summer rains in the western Andes, the river oases dried up. Finally, shortly after 600 AD, the Nasca culture collapsed. A new hydrological oscillation took place after ~1100 AD. Monsoonal rains reached the Andean foreland again and narrowed the desert to ~40 km. During the following Late Intermediate Period (LIP), pre-Columbian people re-occupied the eastern Atacama desert until the sixteenth century AD. The Little Ice Age, with its coldest temperatures between the seventeenth and nineteenth centuries AD, was a very dry period in the study area, so that LIP settlements were abandoned and desert conditions reappeared lasting until today.

B. Eitel (*)
Institute of Geography, University of Heidelberg, Im Neuenheimer Feld 348, 69120 Heidelberg, Germany
e-mail: bernhard.eitel@geog.uni-heidelberg.de