# Workshop on the Role of Mineral Aerosols in Quaternary Climate Cycles – Models and Data

## 8-11 October 2000
## Jena, Germany

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# Table of Contents

# Introduction

Mineral dust aerosols play an important role in the global climate system, by mediating physical and biogeochemical exchanges among the atmosphere, land and ocean. As the net effect of these processes is still unknown, climate modelling studies are underway to assess the forcing effect of dust on the current climate. Records of dust accumulation from ice cores, marine sediments and loess deposits clearly demonstrate that glacial periods were considerably dustier than interglacial periods throughout the Quaternary. The high concentrations of atmospheric dust during the glacial period make it an excellent test of our ability to model the processes that determine fluxes, concentrations, and interactive effects of dust in the atmosphere. Observational datasets are crucial for quantifying changes in potential dust source areas, as well as identifying the magnitude and extent of dust deposition during past climate periods. The Dust Indicators and Records from Terrestrial and MArine Palaeoenvironments (DIRTMAP) Database has been established to serve both the earth science and modelling communities (see http://www.bgc-jena.mpg.de/bgc_prentice/). This dataset currently contains dust fluxes from ice cores, marine sediments, and loess deposits for the last 130,000 years. There is a need to expand this dataset in order to more comprehensively document the changes in dust accumulation in terrestrial environments, within the context of providing evaluation datasets for earth system model simulations of the role of dust in global climate change.

The aims of the workshop on the "Role of Mineral Aerosols in Quaternary Climate Cycles – Models and Data" were

- *to improve the terrestrial data coverage within the DIRTMAP database by involving representatives from key regions to co-ordinate the data synthesis process, and*
- *to facilitate interaction between the dust modelling and data collection communities.*

This three-day international workshop involved people from both the terrestrial data community and the dust modelling community. The workshop was structured as a series of eleven sessions designed to address three main themes: (1) What information is still required to advance the field, and what are the 'burning questions' that need to be addressed by both models and data? and (2) what processes still need to be understood and how can terrestrial dust data be used to address these questions (with a particular focus on regional modelling studies)? (3) What information should be included in the DIRTMAP database, to make it most useful to address both model validation and data community issues?

These eleven sessions were composed of brief overview talks, discussions, and practical 'working sessions.' The overview talks reviewed (a) the field of dust cycle modelling, (b) creative approaches to extracting information about dust from the geologic record, and (c) key issues for particular regions. Discussion sessions addressed the important issues and information required for regional data synthesis, the types of information required in the data base to allow proper evaluation of the techniques and methods used to date loess deposits, as well as possible scientific questions and advances to be addressed by regional modelling studies. Working sessions allowed participants to interrogate the DIRTMAP database and make suggestions about how to improve its format. Each session was assigned a 'rapporteur' who was responsible for summarising the main points, unifying themes, and important questions arising from each session.

This report summarises the meeting. Section 1 includes brief summaries of the information about loess deposits and aeolian research, written by representatives of each of the key, including Alaska, Australia, China, Midcontinental USA, Siberia, and South America. Section 2 includes the reports of the rapporteurs, summarising the main ideas discussed in the remaining sessions. The final rapporteur report on the Closing Session summarises the conclusions of the workshop, and outlined the concrete goals and plans for future workshops, reports, publications, and collaborations.

## Acknowledgements:
This workshop was supported by funds from the Max Planck Society, INQUA and IGBP PAGES. Technical assistance with this report was provided by S. Schott.

## Cover Photo:

The Palouse loess deposits of eastern Washington, USA were formed in the early Holocene. Today these hills are used extensively for wheat farming. This photo was taken from Steptoe Butte, on the field tour as part of the Dust Aerosols, Loess Soils, and Global Change Conference (October 1998, Seattle, Washington, USA).

# Workshop Agenda

## *8 October (Sunday):*

**9:30:** **Session 1: Interaction of Mineral Aerosols and Climate**
**Chair: Dan Muhs; Rapporteur: Ann Wintle**
1. Ina Tegen –Modelling dust in the climate system
2. Dale Gillette – Dust sources and emissions: Observations and modelling
3. Sandy Harrison – The role of dust in past climate changes

**11:00-11:15:** **Coffee/Tea**

**11:15:** **Session 2. Geologic Record of Dust**
**Chair: Ann Wintle; Rapporteur: De Anne Pinney**
1. Karen Kohfeld – DIRTMAP: the geologic record of dust
2. Zhou Weijian – The Chinese Loess Record of Long-term Climate Change
3. Katrine Krogh Andersen – Ice core records of dust
4. Ian Smalley: Mapping loess and dust, from Keilhack to Kohfeld

**13:00–14:00:** **Lunch**

**14:00** **Session 3. Regional Presentations**
**Chair: Liping Zhou**
1. Alaska/Beringia –Jim Begét
2. Mid-Continental USA – Dan Muhs
3. South America – Marcello Zárate

**Coffee/Tea**

4. Australia – Grant McTainsh
5. Siberia – Jiri Chlachula
6. China – Karen Kohfeld

**Discussion**

## *9 October (Monday): Morning*

**9:30** **Session 4: Discussion: Structuring Regional Loess Data Syntheses**
**Chair: Sandy P. Harrison; Rapporteur: Marcelo Zárate**

**Issues for Regional Data Synthesis Discussion Session**
This session will allow a free-ranging discussion of the issues that need to be resolved in order to make compatible regional syntheses of data that will be directly useful for comparison with model output. The issues could include, e.g.: What data needs to be included in the global loess database? What data is readily available? What problems exist and how can they be overcome? What should the initial main foci of the regional synthesis be? What types of estimates/measurements are required? What is required to make the data comparable to models? What co-ordination is required? How do we standardise dating control/reliability of interpretation?

**Coffee/Tea**

**Impromptu presentation:** Modelling of dust deflation from source regions using loess thickness and particle size information - Dale Gillette

**Session 5: Demonstration of DIRTMAP database and Chinese Database**
**Gerhard Boenisch**

How do we go from regional syntheses to a regional database to DIRTMAP? During this session will demonstrate the DIRTMAP computer database and also the Chinese regional synthesis database. Participants will be able to interrogate the databases themselves during the session. PCs will also be available throughout the meeting to enable participants to continue working with either database.

**13:00-14:00:** **Lunch**

## *9 October (Monday): Afternoon*

**14:15:** **Session 6. Parallel Sessions:**

**Working Session: Regional Synthesis (Main Seminar Room):**
The aim of this working session is to design the forms for reporting on regional data. We will need to determine the minimum necessary site data required, and how to input other kinds of data. We will begin working with prototype forms used for the Chinese regional compilation. As a way of investigating what kinds of problems are likely to be encountered, we ask participants to bring information on key sites from regions with which they are familiar so we can try inputting these data during the session. Data inputted during the meeting can serve as the core of the subsequent regional data synthesis.

**Impromptu Discussion: Dating Control (Main Seminar Room):** What information is required in the database in order to evaluate chronological data?

**Discussion: Modelling of Dust Processes on Regional Scales (5th Floor Seminar Room) Discussion Leader: Ina Tegen; Rapporteur: Dale Gillette**
Unlike ice core and marine records, loess provides a proxy for dust emissions and deposition at a regional scale. Regional modelling both of climate and dust processes is much less well developed than global modelling. The aim of this discussion session is to determine what progress could be made in this area, and how regional models might be used to investigate loess-related problems.

## *10 October (Tuesday):*

**9:30** **Session 7: Creative Approaches to Improving Interpretations of the Dust Record Chair: Paul Hesse; Rapporteur: Katrine Krogh Andersen**

1. Ed Derbyshire: Using micromorphological analysis to interpret the loess record
2. Liping Zhou: Chronology and the dust record
3. Ana Unruh: Using provenance studies to interpret the loess record
4. Dan Muhs: Aeolian records from lake sediments in Alaska
5. Helen Roberts: Using luminescence dating to detect initiation of agricultural practices on the Chinese Loess Plateau

**13:00-14:00** **Lunch**

**14:00-15:00** **Session 8: Working Session: Regional Synthesis**
Continued work on regional synthesis, including examination of modified tables, of global maps of key sites already identified and continued input of data/testing of regional database set-up.

**Session 9: Rapporteur Working Session**
Preparation of 1-2 page summaries (to be included in Meeting Report) of sessions by rapporteurs, with assistance from other participants as required. Modifications of regional data synthesis summaries should also be made at this time, so that they can be included in the report.

**15:00** **Session 10: Plenary Rapporteur Reports**
Session 1: Ann Wintle
Session 2: De Anne Pinney
Session 4: Marcelo Zárate
Session 6: Dale Gillette
Session 7: Katrine Krogh Andersen

## *11 October (Wednesday):*

**9:30 Session 11: Closing Session**
**Co-Chairs: Karen E. Kohfeld and Sandy P. Harrison**

1. Practical Organisation of the regional syntheses and completion thereof:
   Priorities
   Timeframe
2. Future Directions
   Recommendations for collaborative work
   New Projects
   New Focus for Another Meeting
3. Summary Report

**Meeting Will Close by Lunchtime.**

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# Section 1: Regional Reports:

## 1. The Alaskan Loess Record of Quaternary Climate Change

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Loess deposits in central Alaska comprise a valuable record of past climatic changes at high latitudes. Variations of environmental magnetism and sedimentology of high latitude loess deposits through time can be used to produce proxy climate records. Geochronological data indicate the timing and pattern of responses to local variations in wind intensity, storminess, and pedogenesis in eastern Beringia resemble the pattern of global climate change during the Quaternary reconstructed from studies of marine and ice core records.

Loess sequences at two sites Alaska go back more than 2.1 million years, indicating loess deposition began in the very latest Tertiary and continued through all of the Quaternary. One interesting aspect of the Alaskan loess record is that loess deposition did not stop or locally even slow during interglacial periods. Extensive glacier cover and large, glacier-fed river systems have evidently produced loess virtually continuously, so that thick deposits of both glacial and interglacial loess can be found. Loess deposits are typically thickest near major glacier-fed rivers and thin with distance away. Sequences more than 100 m thick are known in several areas.

Much new work is being done to refine the age of specific horizons and sequences within thick loess deposits. The age of palaeoclimatic fluctuations, permafrost and fossil permafrost features, volcanic ash horizons, buried forest layers and palaeosols, and other features of the eastern Beringian loess record can be directly determined using a variety of Quaternary dating methods. In addition to radiocarbon dating and thermoluminescence dating, the presence of numerous volcanic ash layers in the loess allows the fission-track method and the Ar/Ar dating method to be applied. The tephras themselves can also be used as dating and correlation tools, as identical ash layers can be traced between widely separated loess deposits.

In some cases it may also be possible to date loess by correlation with orbitally tuned global proxy climate records. Variations in the primary sedimentological and geophysical properties of Beringian loess reflect climatic regimes and their effects on surface processes at the time of deposition, and can be used to create continuous proxy climate curves analogous to those obtained from ice sheets or deep-sea sediments. Magnetic susceptibility profiling has proven especially useful. Proxy climate data sets from high latitude loess provide semi-continuous records of late Quaternary climate history. The pattern of climate change across Beringia as recorded in loess appears very similar to global palaeoclimatic histories and retrodictions of high latitude insolation, although questions still remain about the precise age of past climate events and climatic transitions.

Alaskan loess deposits, which in some cases have remained frozen for tens of thousands of years after deposition, contain uniquely well preserved plant fossils that reflect the palaeoecology of past environments. Entire trees dating to the last interglacial are locally preserved, as well as bone, insect, pollen and other sorts of palaeoecologic records. In rare cases frozen animal tissue and even entire carcasses of mammoth, bison, etc. are preserved.

Much current work is being done on deposits correlated with the last interglacial (i.e. MIS stage 5). These deposits are typically associated with the Old Crow tephra, and more accurate and precise dating of the Old Crow and other tephras, and careful stratigraphic studies of their position in the loess, is a high priority for future palaeoclimatic studies of loess in Beringia. Both the fission-track and thermoluminescence dates available at present are consistent with an age for the Old Crow tephra of about 140,000 ± 10,000 yr BP. The Old Crow occurs in the lower part of the last interglacial Eva Creek Forest Bed at Gold Hill and in a similar position in newly discovered site on the Yukon River, and so can potentially be used to constrain the timing of the last interglaciation. Unfortunately, the dating resolution cannot at this time rule out correlation with either warming in the Devils Hole record from Nevada at ca. 150,000 yr BP or with increases in Milankovitch insolation and the orbitally tuned date assigned to Termination II in the marine record at ca. 125,000 yr BP.

Records of Pleistocene glaciation and other independent proxy climate records in Alaska, such as those from lakes and ice caps, can be directly correlated with the loess record using tephrochronology. The tephrochronological dating suggests that at least the last several major glaciations in eastern Beringia were in phase with major cold period recorded in the Alaskan loess record, as well as with the periods of glaciation and global cooling designated as marine isotope stages 2, 4, and 6 in the deep-sea record.

Much less work has been done on Alaskan loess sites than those in China or Europe. Alaskan loess deposits provide a useful addition to geologic records of past climates preserved in loess found elsewhere on earth.

## 2. Australian Dust: Processes, Sediments, and Contributions to Soils

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**Aims of the Paper**

1. To summarise the state of knowledge of:
   - Present day dust processes, including: source areas, transport paths, sediment concentrations and deposition rates
   - Dust contributions to soils and ocean deposits
2. To examine some key issues associated with the study of dust contributions to soils and ocean deposits in the Australian region.

**Dust processes**

There are two general dust paths in the Australian region, to the southeast and the northwest, mainly associated with easterly moving frontal systems within the zonal westerly winds in the south and easterly trade winds in the north. The southeast dust path has received the most research attention, and studies of individual dust storms reveal complexity in dust trajectories. Meteorological records of present day dust storm occurrence show that most activity centres upon the Lake Eyre Basin and the western sector of the Murray-Darling Basin. The main dust source areas of the southeast dust path are in the southwest sectors of Queensland and New South Wales, and dust concentrations and deposition rates generally decrease to the east, downwind. Dust plumes pass out over the Tasman Sea and have been reported over New Zealand on at least 19 occasions (McGowan pers.comm).

**Dust Contributions to Soils**

Evidence of dust contributions to soils is strongest in the south east of the continent. The shortage of evidence in the northwest may reflect the relatively limited research attention in this region, but the existence of a downwind environmental gradient from arid to humid in the southeast, provides a more favourable setting for the stabilisation of dust deposits and loess soil formation.

There are at least four regions of dust mantled soils in southeast Australia:

**1. Adelaide region:** Highly calcareous loess deposits in this region identified by Crocker (1946), Ward (1966) and over a larger area by Firman (1969), were thought to have their source in the exposed continental shelf to the west of Adelaide during several glacial low sea level phases. However a study of stable isotopes within soil carbonates over this region (Quade et al., 1995) showed that while nearly all the calcium was derived from a marine source, nearly all the carbon was meteoric in origin (not marine) and derived from plant growth introducing carbon into the soil.

**2. Mallee-Western NSW region:** Calcareous loess (or parna) was first identified in this region by Butler and Hutton (1956), mixed with dunesand in the Mallee area in the west (Churchward 1963) and becoming finer and purer to the east (Butler, 1956a,b) towards Wagga Wagga (Beattie, 1970, 1972). Three of these highly aggregated dust layers have been identified. Butler and Churchward (1983) propose that the Mallee dunefield area is both, a deposition zone of dust from the Adelaide region and the source area of the parna on the Riverine Plain.

**3. Central Australian region:** The widespread gypseous loess deposit in the lower Lake Eyre Basin identified by Jessup (1960) is best preserved on the flat surfaces of tablelands there and in western NSW and Queensland and the proposed source is the gypsum-rich salt lakes of the Lake

Eyre Basin. The gypseous loess is overlain by two calcareous deposits with similar characteristics to parna on the Riverine Plain.

**4. Eastern NSW/Queensland region:** A new wave of studies has extended the distribution of dust mantled soils to eastern NSW and southeast Queensland. Townsend (1997), Campbell, (1999) and Peterson (1999) identified dust mantles in the Bathurst-Blayney area of NSW. Possible aeolian mantles have also been identified in the area between Wagga Wagga and Canberra (Scott et al., 1998). Ward and McTainsh, (1999) and Cattle et al., (2000) have identified a dust component in black earths of the Narrabri area. Manning and McTainsh, (in progress), have made field identifications of dust mantles in the St George area of southern Queensland, linking up with the much earlier evidence of Hubble and Isbell (1958). The dust components of these soils are often mixed with local materials and do not form recognisable layers. The source areas of these deposits may be the alluvial floodplains of the Darling R in western NSW and the Channel Country in western Queensland, which are current dust source areas.

### Dust Contributions to Ocean Deposits

**Tasman Sea Deposits:** Studies of dust deposits in the Tasman Sea (Hesse 1994) provide further evidence of the extent of dust deposition within the southeast dust path, timing of this deposition and the wind conditions during the last glacial maximum (Hesse and McTainsh, 1999). New records of aluminium flux to Tasman Sea sediments (Kawahata, 2000) support the earlier work, including much greater fluxes south of 30°S and strong glacial age peaks of dust flux. Ikehara et al. (2000) recently published a record of terrestrial biomarker deposition to the Southern Ocean, south of Tasmania. The inferred Australian source supports modelling of contemporary dust transport paths which bring Australian dust south and east (McGowan et al, 2000).

**Indian Ocean deposits:** There are less data available from the Indian Ocean adjacent to northwestern Australia, however unpublished results (Hesse) show a restricted dust path with dust fluxes comparable to the Tasman Sea and strong glacial peaks in marine isotope stages 2 and 6.

### Issues arising from studies of dust contributions to soils and ocean deposits

#### 1. Rudimentary knowledge of dust deposition and soil formation in Australia

Knowledge of loess soils in Australia remains at a rudimentary level. Despite >50years of study in eastern Australia, dust deposition is not a widely accepted soil forming process. In the western half of the continent, with the exception of studies by Bettenay (1962) and Brimhall et al. (1988), the evidence has not been well researched.

#### 2. Loess terminology: parna, aeolian clay, dust mantle or loess?

Australian soil scientists have tended to isolate themselves from the international loess world by emphasising the differences, rather than the similarities, between their loess soils and overseas examples. With the notable exception of the first study (Crocker, 1946), there has been a strong tendency to avoid of the use of the term loess, favouring instead, such local names as parna (< biblio >) and lakulangite (Jessup, 1960). Even when more generic terms were used, unconventional variants were chosen; for example, aeolian clays (Butler, 1974) or loessic clays (Dare-Edwards, 1983). As a result of this Australian soil scientists have not played a significant a role in international loess debates, such as the desert loess debate.

#### 3. Too much reliance upon "typical" soil characteristics.

Progress in advancing knowledge of loess soils in Australia has been limited by too great a reliance upon "typical" diagnostic loess characteristics; an approach probably inherited from peri-glacial loess research. It is only recently that the dynamism and complexity of desert-marginal environments been recognised and allowance has been made for loesses in different regions to have different characteristics, reflecting differences in source areas, transport distances and wind systems.

## 4. Models of Dust Entrainment and Transport from Australia

LGM dust entrainment from Australia modelled by Joussaume (1989) predicted dust source areas which bear little relation to known modern dust source areas (McTainsh and Pitblado, 1987) and appear to be overly influenced by wind conditions, while surface conditions (either soils or vegetation cover) were not modelled. Reader et al. (1999) modelled both dust sources from Australia and dust deposition in the Australian region and attempted to use palaeodata to constrain the model results, although the Australian dust record was not used. The model did not describe soil or surface conditions. Compared with the palaeodata (Hesse, 1994) the LGM increase in dust deposition appears to be too great. Reader et al. (1999) refer to the Et model of McTainsh et al. (1996) for support of the LGM/modern ratio of dust flux of 1.6. The Et model used the LGM palaeoclimate estimates of Wasson (1987) as input data to describe the frequency of dust storms in the LGM climate. These estimates assumed greater wind strength during the LGM, which later palaeodata (Hesse and McTainsh, 1999) and modelling (Wyrwoll et al., 2000) reveal may not be appropriate.

Mahowald et al. (1999) coupled LGM simulation output from a GCM run with BIOME model simulation of surface conditions and a model of dust entrainment and deposition. Modelled dust source areas compare well with geomorphic evidence and modern observations. The model also performs well in predicting dust deposition patterns over the Pacific and Indian Oceans however fluxes are too high, compared with the palaeodata, and the northwest dust plume appears to be too strong compared with the south east dust path (Hesse, unpublished results). Many of these models of dust processes rely on input temperature, precipitation or ground condition data derived either from palaeodata or GCMs. Recent palaeoclimatic studies, and work in progress, have the ability to substantially improve the performance of these models over Australia.

Improved models of dust entrainment, such as that of Shao et al., (1994, 1996) and Lu and Shao (1999), calibrated against broadscale and long term data on dust storm occurrence (McTainsh and Tews, 1998) may improve the simulation of dust fluxes on an annual or seasonal scale. Also, models of individual dust events (Shao and Leslie, 1997) calibrated with event-based field dust data (e.g. Nickling et al. 1999), dust plume trajectories (e.g. McGowan et al. 2000) and remotely sensed data (e.g.TOMS) can assist climate modelling.

## 5. Novel techniques for the identification of aeolian deposits

Several novel techniques have been used recently to identify aeolian dust deposits in eastern Australia. Gatehouse (pers. comm. 1999) has used SHRIMP U/Pb dating of zircons to distinguish aeolian material from its substrate, based on age histograms. A new technique has been investigated by Campbell (1999) and Cattle (pers. comm. 2000), following the work of Dickson and Scott (1998), to develop a signature of aeolian deposits from airborne gamma ray survey data which may be used to map dust mantles over various lithologies. Thorium content appears to be diagnostic in some areas (Campbell 1999) although some basaltic lithologies share the same thorium value, and potassium is diagnostic in others (Cattle (pers. comm. 2000). At present, scatter in the data is large and so far mapping has had mixed success, but the technique offers good potential as a mapping tool.

## References

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# 3. Late Quaternary Aeolian Deposition on the Chinese Loess Plateau

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## Introduction

The Chinese Loess Plateau (CLP) contains a 7-million-year record of aeolian deposition (Ding et al., 1999), covers an area of approximately 440,000 km$^2$, and has interbedded loess and palaeosol deposits ranging from 100 to 300 m in thickness. Its extensive nature makes it one of the most well studied regions in dust literature. Dust from the Chinese Loess Plateau and surrounding Asian deserts has been suggested as a probable source of dust transported long distances to the Pacific Ocean (e.g. Hovan et al., 1991) and to Greenland Ice Cores (Biscaye et al., 1997; Svensson et al., 2000). Thus, it provides an excellent test case of the use of aeolian data in terrestrial settings as a validation tool for earth system model simulations of the dust cycle. Sun et al., (2000) represents the most extensive compilation of data on loess accumulation from the CLP. This study compiled information from 98 sites in China, including information about stratigraphy, magnetic susceptibility, grain size, and age information, with the goal of constructing age models and mass accumulation rates for the last 150,000 years.

## Methods

Estimates of mass accumulation rate require information about accumulation rates AR (based on age models for each section), sediment bulk density BD, and the fraction $f$ of the sediment considered to be aeolian:

$$\text{MAR (g/m}^2\text{/yr)} = \text{AR (m/yr)} \quad \text{BD (g/m}^3\text{)} \quad f$$

The sections were examined to eliminate sites with contamination from reworked loess, colluvium, cultivation, and other influences. At the remaining sites, the aeolian fraction was assumed to be 1. Bulk density estimates were only available at two sites. For all other locations a constant value of 1.48 g/cm$^3$ (Liu, 1966) was assumed.

Two different categories of age models can be used on the CLP:

(1) those based on commonly-used correlation techniques between the marine isotope stratigraphy (Martinson et al., 1987) and magnetic susceptibility and pedostratigraphy

(2) independent "absolute" age dating techniques such as radiocarbon (calibrated to calendar years) and luminescence dating.

Although the Chinese Loess Plateau is a well-studied region, there are only very few sites with comprehensive, independent radiocarbon or luminescence dates. Only 12 of the 98 sites had enough luminescence dates to generate a mass accumulation rate estimate. Only 16 sites had enough information to estimate mass accumulation rates based on calibrated radiocarbon dates. In many cases, the appropriate documentation required to evaluate these dates was lacking. Thus, many of the age models in China are dependent on correlation techniques, which rely on assumptions of direct synchroneity between soil formation, magnetic susceptibility, and changes in global ice volume. Furthermore, both correlation techniques should effectively reinforce the canonical view that high accumulation is characteristic of glacial periods and low accumulation of interglacial periods. Interestingly, majority of magnetic susceptibility records is poorly correlated ($R^2$ < 0.5) with the marine isotope stratigraphy, suggesting that the usefulness of these correlation techniques for age models to determine aeolian accumulation rates is limited.

Of 355 mass accumulation rate estimates made on 77 sites, only 43 estimates could be made based on luminescence and radiocarbon chronologies.

Because the majority of the age models were based on correlation techniques, aeolian accumulation rates were averaged for the marine isotope stages (Stage 1 = 1-12 kyr BP; Stage 2 = 12-24 kyr BP; Stage 3 = 24-59 kyr BP; Stage 4 = 59-74 kyr BP; Stage 5 = 74-130 kyr BP).

**Results and Interpretation**

If one examines the average values of aeolian accumulation rates based on all data, Stage 2 MARs are the highest and are on average 4.9 times greater than Stage 5 (109 g/m$^2$/yr), and 3.5 times greater than Stage 1 accumulation rates. Accumulation rates are in general highest in the northwest region of the Plateau and are lowest in the southeast region. This pattern is robust for all five marine isotope stages. This observation is consistent with previous studies suggesting that the dust from the CLP is derived from the regions to the northwest of the CLP (see e.g. Derbyshire et al., 1998). Furthermore the largest glacial-interglacial changes were seen in the southeast portion of the CLP.

One notable observation is that the average aeolian accumulation rates for Stage 1 are consistently higher than those estimated for Marine Isotope Stage 5, the last interglacial period. In fact the MARs for Stage 1 (256 g/m$^2$/yr) are quite similar to the estimates for the interstadial Marine Isotope Stage 3 (222 g/m$^2$/yr). Several factors could result in the differences between Stages 1 and 5:

- **The difference in orbital parameters between the two different time periods**. Indeed the incoming solar radiation calculated from orbital parameters for Stages 1 and 5 are such that one might reasonably expect Stage 5 to be both warmer and wetter when compared with Stage 1. However, it is surprising to note the similarities in accumulation rates between Stage 1 and the interstadial Stage 3. This similarity would not be expected to be due to similarities in climate conditions during these two time periods. Thus one might expect another cause for this difference

- **The long history of human activity on the CLP**. A second plausible explanation is that the aeolian accumulation rates have been inflated by the effects of human activity and agriculture on and surrounding the CLP. Evidence suggests that agricultural activity may have extended back as far as 5-6000 years ago. Although this compilation has attempted to eliminate sites where cultivation layers are present at the tops of the section, assessing the broader, regional impacts of human activity on dust deflation and deposition is not easy to evaluate within the scope of this study.

- **A bias in the dating methods for the different time periods**. The average accumulation rates depend considerably on the type of dating method used. For example, the average MAR for the CLP for Stage 1 ranges from 149 g/m$^2$/yr (using magnetic susceptibility) to 548 g/m$^2$/yr (using radiocarbon dating). For Stage 2, the regionally averaged MAR ranges from 318 g/m$^2$/yr (magnetic susceptibility) to 745 g/m$^2$/yr (pedostratigraphy). The Stage 2/Stage 1 MAR ratio varies from 0.9 to 7.0, depending on which dating technique was used to define the stage boundaries. The estimates for earlier intervals in the loess records are mostly based on correlation methods (i.e. pedostratigraphy or MS) which are tuned to the marine isotope stratigraphy, and therefore tend to enhance glacial-interglacial differences in accumulation, when compared with radiometric dating methods used in Stages 1 and 2. Furthermore, the sites having either radiocarbon or luminescence dates do not represent a random-sampling of the data set. Sixty percent of the sites with radiocarbon- or luminescence-based Stage 1 MARs are loess terraces, but only 35% of the sites for which it is possible to derive Stage 1 MARs are loess terraces. Thus, if aeolian MARs from loess terraces are different from the MARs generated on other types of loess our radiocarbon- and luminescence-based MAR estimates will be biased.

- **A bias in the time period over which the dust accumulation rates are averaged.** It is possible that the duration of Stage 1 (12 kyr) is not sufficient to capture the full range of interglacial conditions (and hence interglacial variability in dust deposition rates) when compared with Stage 5 (56 kyr). There is insufficient dating control to examine millennial-scale variability in Stage 5. However, the 10 records with sufficient age control for Stage 1 show high rates of accumulation between ca 12-8 kyr BP, with minimum dust accumulation rates between 6 and 3 kyr BP. The changes in dust accumulation rates are significant, varying from an average value of 764 $g/m^2/yr$ at 9 kyr BP to 478 $g/m^2/yr$ at 4 kyr BP. Since aeolian accumulation rates have varied by almost a factor of 2 just within Stage 1, it is possible that the differing estimates obtained for Stages 1 and 5 could be influenced by differences in the length of the sampling period involved.

The geomorphological setting of the sites also had a significant impact on the accumulation rate estimate. The regionally averaged MAR for Stages 2 and 4 are 3 times greater at loess terrace sites than MARs from other sites. The average accumulation rate based on non-terrace sites is 286 $g/m^2/yr$ for Stage 2 and 300 $g/m^2/yr$ for Stage 4, compared with estimates of respectively 1062 and 935 $g/m^2/yr$ for terrace sites. Rates estimated from terrace sites were twice that of MARs from non-terrace sites for Stage 1. Glacial-interglacial ratios (Stage 2/Stage 1, Stage 2/Stage 5) were also significantly amplified in the loess terrace sites. The Stage 2/1 and Stage 2/5 ratios for terrace sites (5.6 and 8.0, respectively) are approximately twice as large as those for non-terrace sites (2.6 and 4.3, respectively). Terrace sites occur close to local riverine sources of dust. It is not therefore surprising that the rates of dust accumulation are significantly higher during all Stages and very much higher during glacial periods. However, these results indicate a further possible source of bias in the estimates of glacial-interglacial changes in dust accumulation rates. When loess terrace sites are removed from the data set, the spatial pattern of high accumulation in the northwest and lower accumulation in the southeast becomes even clearer. This further suggests that the terrace sites, which show considerable inter-site variability, are most likely dominated by local effects.

## Conclusions

Analyses of available data from the CLP thus show some interesting and potentially diagnostic patterns in both time and space. Dust deposition is enhanced during the extreme conditions of the glacial periods, with glacial-interglacial ratios ranging from 3.5-5 for the Stage 2/1 and Stage 2/5, when all of the data are averaged for the entire region. Furthermore, even the relatively small changes in climate towards interstadial conditions during Stage 3 were sufficient to reduce dust deposition rates towards interglacial levels

**However, the fact that the patterns are significantly affected by geomorphological setting and by the specific method used to erect chronologies means that the data require careful screening before they could be used for model evaluation.** There are insufficient sites with independent and well-resolved chronologies to be able to construct detailed records of the spatial patterns of changes in aeolian MAR for specific time windows (shorter than individual marine isotope stages). Thus, although the CLP represents perhaps the best-studied loess region in the world, there is still much work to be done to quantify changes in the aeolian mass accumulation rates, and an urgent need to develop better and more complete chronologies.

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# 4. A Brief Summary of Midcontinental North American Loess

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Loess of late Quaternary age is abundant in the central part of North America, found mainly in a broad, 1500 km-long east-west belt in the states of Ohio, Indiana, Illinois, Iowa, Nebraska and Colorado and a narrow, 1500-km north-south belt extending from Wisconsin to Louisiana. Loess is the most important parent material for agricultural soils in the United States.

Loesses deposited prior to the last glacial period are known to exist in the entire region. The oldest of these that is dated is the Loveland Loess, which, based on direct TL dating of the loess itself, is about 120,000 to 160,000 years old, and apparently correlates with the penultimate glaciation, or oxygen isotope stage 6. A well morphologically well expressed palaeosol called the Sangamon soil is developed in this loess and apparently dates to the last interglacial period, equivalent to oxygen isotope stage 5 (or the Eemian interglacial in European terminology) and probably also part of stage 4. The youngest pre-last-glacial loess, found east of the Mississippi River, is called the Roxana Silt, and dates to sometime in the interval between ~50,000 and ~30,000 yr BP, based on radiocarbon and TL methods, equivalent to some or all of isotope stage 3. An equivalent unit called the Gilman Canyon Formation is found west of the Mississippi River.

Most studies over the past 50 years have focused on loess of the last glacial period, referred to as the Peoria Loess. It is a massive silt loam that is as thick as 50 m in parts of western Nebraska, as thick as 40 m in western Iowa (east of the Missouri River), and as thick as 20 m to the east of the Mississippi River in Illinois. Despite the appearance of a continuous blanket over the mid-continent region, Peoria Loess composition is not spatially uniform. East of the Mississippi River, carbonate content of loess is higher, reflected in higher abundances of CaO and MgO. West of the Mississippi River, particularly in Nebraska and Colorado, loess is lower in carbonates, but higher in K-bearing minerals and plagioclase, reflected in higher $K_2O$ and $Na_2O$ contents. Clay mineral content is also higher in loess of the western part of the region, reflected in higher $Al_2O_3$ and $Fe_2O_3$ contents.

Peoria Loess composition at a given site also varies as a function of age/depth. For example, a thick loess section in western Iowa has low carbonate content in its lower 10 m, probably reflecting syndepositional leaching during slow loess accumulation. The 10-m above this zone have carbonates, but relatively low fine silt and clay contents, reflected in relatively low $Al_2O_3$ and $Fe_2O_3$ contents. The uppermost 20 m of the section are also calcareous, but much higher in clay and fine silt, reflected also in relatively high $Al_2O_3$ and $Fe_2O_3$ contents. The changes in particle size in this section are interpreted to reflect a shift from an exclusively local source (the Missouri River) to a local source augmented by far-travelled, fine-grained loess derived from western sources. Although there have been few studies of this detail, they indicate that a simple picture of a spatially and temporally uniform sediment blanket is probably not realistic for the region.

Radiocarbon ages of Peoria Loess show that loess deposition, while occurring broadly within the last glacial period, did not take place at the same time everywhere. Maximum-limiting radiocarbon ages (of organic matter in a soil formed in the uppermost Roxana Silt and the Gilman Canyon Formation) are as old as 30,000 to 34,000 years in some places and as young as 20,000 to 22,000 years in other places. Minimum-limiting ages are much more difficult to obtain and are based mainly on snails found in the upper parts of the loess in areas east of the Mississippi River and on organic matter in a soil that separates Peoria Loess from an overlying Holocene loess farther west. These minimum-limiting ages range from about 10,000 to 12,000 years. Rare occurrences of charcoal or spruce needles in the lower and middle parts of Peoria Loess yield radiocarbon ages of 12,000 to 20,000 years. Limited TL analyses of Peoria Loess have mostly yielded ages of about 17,000 to 24,0000 calendar years BP.

Numerous studies, dating back to the 1940s, have shown that Peoria Loess shows considerable variability in particle size away from river valleys that were major outwash-bearing valley trains from the Laurentide ice sheet during the last glacial period. With increasing distance east of the Missouri, Mississippi, Wabash and Ohio Rivers, Peoria Loess is thinner, lower in sand and coarse silt, higher in fine silt and clay, and lower in carbonates. Decreasing thickness reflects a decreasing supply of sediment away from a source whereas the increase in fine particles reflects the winnowing of coarse particles away from that source. The decrease in carbonate content reflects syndepositional weathering away from the source where sedimentation rates are lower.

Despite the obvious link to glacial outwash sources in Indiana, Illinois, Wisconsin, and Iowa, loess found to the west of these states, in Nebraska, Kansas, and Colorado, seems to be unrelated to sediment derived from the Laurentide ice sheet. Drainages adjacent to loess in this part of the region (the Great Plains) have headwaters that were not fed by meltwaters of the ice sheet during the last glaciation. Although meltwaters from much small glaciers in the Rocky Mountains fed Great Plains rivers during the last glaciation, it is unlikely that this was the major supply of silt to the region; Rocky Mountain glaciers were relatively small, but loess in Nebraska is as thick as 50 m. Isotopic studies (Pb isotopes in feldspars and U-Pb ages of zircons) have shown that loess in eastern Colorado is partly derived from a non-glacial source and loess in Nebraska is mostly derived from the same non-glacial source. This previously unsuspected parent sediment is volcaniclastic siltstone of the Tertiary White River Formation, which is exposed over large areas of the central Great Plains, to the north and northwest of the loess belt.

There are at least five major issues regarding Peoria Loess, all-important to climate modelling efforts, that need to be addressed in future studies. (1) It is not known why Peoria Loess is so much thicker than all pre-Peoria loesses, including those that date to major glaciations, such as the Loveland Loess of the penultimate glaciation. (2) It is not known how much of Peoria Loess in glacial terrain is not glaciogenic, but derived from far-travelled nonglacial sources now confirmed to exist in the central Great Plains. Continued isotopic studies of different size fractions could possibly answer this question. (3) Because mainly bracketing radiocarbon ages are the age control on Peoria Loess, it is not known what the variability in sedimentation rate within the last glacial period might have been, i.e., did sedimentation occur mainly in the early part of the last glacial period, at the last glacial maximum or during deglacial time. Detailed, high-precision OSL dating could answer this question. (4) The spatial trends in loess thickness, particle size, and carbonate content, as well as isotopic identification of non-glacial loess sources in central Great Plains, all indicate that last-glacial palaeowinds were likely from the west or northwest. This observation is in conflict with most AGCM results, which show dominantly northerly or northeasterly winds due to the presence of a strong glacial anticyclone over the Laurentide ice sheet. Studies of modern loess deposition in periglacial regions could possibly address this question if seasonally variable winds are responsible for the difference between the observed and modelled palaeowinds. (5) The identification of non-glacial loess sources in the Great Plains region is in conflict with simulation of last-glacial dust sources, using a linked AGCM-biome-biogeochemical model. The amount of dust/loess generated from this source far exceeds that recorded by other source areas of North America (Alaska, southwestern USA, Mexico) that were simulated by this model.

# 5. Loess-Palaeosol Records in Siberia

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## General Background

Loess and loess-like deposits in Siberia are distributed mainly in the southern part of the territory (between 50º and 59º N latitude and 66º and 97º E longitude), covering a broad geographical area ca 1500 km wide (from north to south) of about 800,000 $km^2$ between the Ob and Angara River basins north of the Altay and Sayan Mountains. They represent a continuation of the Eurasian loess belt spanning from Western Europe across the Russian Plains to the north-central China Loess Plateau. The Siberian loess ranges in thickness from a few metres in the Angara River valley and the Lake Baykal area in the east to up to 40 m in the Yenisei River valley in the southern Central Siberia, and reaching up to 150 m on the Priobie loess plateau in the west. The loess sections are locally intercalated with other aeolian, alluvial, and colluvial deposits (sands, silts, and clays), and interstratified with variably developed palaeosols, documenting a complex nature of the Pleistocene environments.

The Siberian loess record spans throughout the Quaternary Period, yet it is locally rather fragmentary or completely absent for the earlier stages (mainly preserved on the Ob Plateau and in the Kuzbass Basin in the western and central part of the territory, respectively). The most complete and nearly continuous sections date to the Late Pleistocene (the Yenisei area). The present climate is strongly continental with cold and dry winters with little snow cover, and warm to hot summers with mean annual temperature of –0.5 to –2 ºC.

## Current studies

The Siberian loess has been studied in detail during the last several years following the previous field investigations and chronostratigraphic interpretations made by Russian colleagues (e.g., Zykina et al., 1981). The principle Late Quaternary chronological system follows the scheme subdividing the Late Pleistocene into four climatic stages (the Kazantsevo Interglacial, the Zyryanka Glacial, the Karga Interstadial and the Sartan Glaciation), corresponding to Oxygen Isotope Stage (OIS) 5-2.

The major focus of the present studies is 1) the stratigraphy of long-term subaerial records in south-western Siberia (Zykina, 1999), 2) the high-resolution Late Pleistocene climatic records and related palaeoenvironmental evolution of landscape and biota (Chlachula et al., 1997, 1998), and 3) a chronological refinement of the loess archives for the last 130 ka by TL and OSL dating in central southern Siberia (Frechen and Yamskikh, 1999).

A particular attention is paid to the loess deposits in the upper Yenisey River valley, comprising the most complete record to date in this part of northern Eurasia for the last two glacial-interglacial cycles (Chlachula, 1999). A total of 32 pedogenic horizons from the OIS 7-1 time interval have been previously recognised in the area (Chlachula et al., 1997). The local loess mineralogy is characterised by quartz (54-72%) and feldspar (10-23%), calcite (4-7%) chlorite (3-6%), biotite (2-3%) and other minerals. The mineralogical composition and the fresh surface morphology of the fine silt fraction indicate a local provenance of the sediment, although most of loess in southern Siberia is assumed to have been derived from the ice-sheet from the north.

## Study methods and approaches

The present complex investigations are aimed at specifying the nature and rate of loess sedimentation and the subsequent pedogenic modification and to reconstruct environmental conditions prior to, during, and after formation of the fossil soils. The principal study aspects used as indicators of the past climatic change in the fossil palaeosol horizons are the TOC and

CaCO3 content; grain size and mineralogy of the sedimentary matrix; fossil periglacial features (solifluction, cryoturbation, frost wedge casts); and magnetic susceptibility.

Particular attention has been paid to magnetic susceptibility, low-frequency (LF) and frequency-dependent (FD%), as this has proven to be a reliable indicator of the past climatic change in the larger study area (Chlachula et al., 1997, 1998; Chlachula, 1999). The relationship between the climatic change and magnetic susceptibility fluctuation is clearly evident, with the LF susceptibility maxima corresponding to the intervals of the most intensive loess deposition and the minima correlating with the most developed chernozemic palaeosols. An intense wind activity leading to accumulation of greater quantities of larger ferrimagnetic (mainly magnetite) grains is believed to account for the magnetic susceptibility increase during cold (stadial) intervals (Chlachula et al., 1998). A similar pattern has been observed in loess in southwestern Siberia (the Ob Plateau). The total magnetic susceptibility capacity of palaeosol horizons is clearly not a function of weathering intensity and time, as in Europe or China, but depends a priori upon the quantity and quality of primary magnetic minerals within the unaltered parent material inherited from original geological sources. Magnetic susceptibility, coupled with other palaeoclimatic proxy data, has proven to be a very sensitive indicator of the past climate change in the broader area.

**Late Pleistocene loess-palaeosol records**

A series of high resolution loess-palaeosol sections has been investigated in the Ob, Yenisei and Angara River basins as a part of the 1500 km W-E continental transect project in 1997-1999, with a principal focus on the last interglacial (OIS 5, sensu lato). The results show patterned climatic variations and uniformity of natural environments across the south Siberian territory during the Late Pleistocene (Chlachula and Kemp, in prep). The key Late Quaternary records from the Northern Minusinsk Basin in the southern Krasnoyarsk region (Kurtak sections 29 and 33) and the southern Priobie loess plateau north of the Altay Mountains (Biysk and Iskitim sections) provide evidence for a strongly fluctuating climatic change in this part of Eurasia during the Late Quaternary. Magnetic susceptibility (low frequency and FD%) records, with maximum deviation amplitudes between 130 and 10 ka BP, together with other palaeoenvironmental proxy data (grain size, %CaCO3 and %organic carbon variations) show a globally diagnostic trend for the last glacial-interglacial cycle.

The last interglacial (sensu lato) includes several warm as well a very cold stages (correlated with OIS 5e-5a). A strongly continental warm climate culminating around the peak of the last interglacial (OIS 5e) is followed by a gradual shift to more humid and cooler conditions during the subsequent interstadial stages (OIS 5c and 5a). The cold substage 5d is documented by up to 1.5 m deep frost wedge casts dissecting the OIS 5e chernozem (TL dated to 125 ka), indicating a dramatic decrease of temperature and humidity, and establishment of a cold tundra environment. This evidence corroborates with the data from the Lake Baykal (Karabanov et al., 1998) suggesting an intense glaciation in Siberia during the last interglacial. Following this time interval, the climate in southern Siberia became more pronounced with very cold and dry stadials during the last glacial stages (OIS 4 and 2) interspersed with moderate mid-last glacial (OIS 3) interstadials.

**Past climate change and natural environments**

The past climatic variations are well monitored in the stratigraphic loess record indicating a similarity of natural environments in the steppe-parkland zone across southern Siberia. The initial pedogenic alteration of parent material is expressed by incipient gleying in a cold, humid environment within a seasonally waterlogged setting and a cold periglacial tundra. A progressive leaching of calcium carbonate from the loessic substratum accompanied by organic matter accumulation reflects a gradual increase of summer temperatures and surface stability that contributed both to prolonged weathering processes and formation of brown (forest-tundra) soils, and, under warmer conditions, of chernozemic (parkland-steppe) soils. An analogous pattern is documented in the Late Pleistocene loess sections in western Siberia (Zykina, 1999), with reactivated soil formation processes during surface stabilisation under warmer conditions and subsequent solifluction and cryoturbation due to climatic cooling and increased humidity.

**Summary and conclusion**

With respect to the mid-continental geographical location with largely reduced atmospheric effects of the world's oceans, the Siberian loess – palaeosol records are of major importance for mapping the Quaternary climatic and environmental change in central Eurasia and the principle mechanisms behind the process. Due to the pronounced climatic continentality and geographical isolation between the Central Asian mountain systems in the south and the Arctic Ocean in the north, the Siberian loesses provide an excellent source of high-resolution palaeoclimate proxy data of regional, as well as global, significance. Particularly the Late Pleistocene (OIS 5-2) loess archives have a key relevance for establishment of the close correlation framework between the European, Central Asian and Chinese loess-palaeosol records within the major W-E continental transect, and represent a significant source of proxy data for reconstruction of past climates and climate change in the Northern Hemisphere.

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# 6. Loess from South America

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### Distribution and age

The distribution of loess in southern South America covers most of the Chaco-Pampean plain of Argentina (Bolivia and Paraguay) and small areas of the western mountain environments. Loess was also reported in neighbouring areas of Uruguay and southern Brazil. Teruggi (1957) mapped the distribution of loessoid sediments (reworked loess and loess-like sediments), indicating that secondary loess was even more abundant than primary loess. Still the distinction between primary and secondary loess constitutes a major topic of discussion.

The beginning of the loessoid sedimentation cycle has been related to a phase of Andean orogeny that resulted in the elevation of the Andes Cordillera in the late Miocene (*circa* 10 Ma) which acted as a barrier to moisture laden Pacific winds. This initiated "the desertification of Patagonia caused by the rain shadow while precocious Pampas environments probably came into prominence at about this time" (Patterson and Pascual, 1972 in Marshall et al., 1983). The late Tertiary deposits as well as the Quaternary loess material, are mainly composed of volcaniclastic fine sandy silts, mostly modified by pedogenesis and reworked by aqueous transport agents. The scarcity of primary aeolian facies is attributed to their low preservation potential in the sedimentary record.

Stratigraphically, although the late Cainozoic loessoid complex was grouped under several different names, Pampean Formation (and informally Pampean sediments) is the most commonly used as a collective term including both Tertiary and Quaternary deposits. The two most important type sections are the Mar del Plata sea-cliffs and the Paraná river bankfulls. The classical concepts on the origin of Argentine loess are mostly based on the grain size and mineralogical analysis of samples from the Mar del Plata type section (Teruggi, 1957). Later, this study was extrapolated to the rest of the Chaco-pampean plains, resulting in an oversimplified model of the Argentine loess record.

### The regional loess record

During the last twenty years a renewed interest on the Quaternary, brought about several studies on palaeomagnetism, sedimentology, vertebrate palaeontology, palaeopedology, palynology and stratigraphy in different areas of the Pampas (Mar del Plata, northern Buenos Aires, south central Santa Fé, west central Córdoba) and NW Argentina (Tucumán). Although significant results were obtained the timing and climatic significance of the loess record is still difficult to interpret and correlate within the region because of the different methodological approaches followed and the lack of integration between the studies.

The Mar del Plata-Miramar type section (38º 10´S, 57º 40´ W) consists of loess-like sediments reworked by fluvial streams and slopewash while primary loess facies are minor sedimentary components. The late Pliocene to Late Pleistocene-Holocene record is continuously exposed with a thickness of 20-30 mts along 35 km of sea-cliffs. The sedimentation was discontinuous including important hiatuses. Lithostratigraphic, pedostratigraphic, biostratigraphic (vertebrate palaeontology) and magnetostratigraphic studies were performed. Pedogenesis deeply modified the deposits with faunal activity (both invertebrates and vertebrates) playing a significant role in the reorganisation of the original material. The age control is mostly based on vertebrate assemblages (land-mammal ages, stage-ages) (Tonni et al., 1992) and magnetostratigraphy (Orgeira and Valencio, 1984, Ruocco 1989, Orgeira, 1988). Numerical ages were recently obtained (Schultz et al., 1998). This section is particularly important to study the Pliocene-early Pleistocene interval consisting of a 20-m thick sequence of loess- (loessoid)-palaeosols.

In the Mar del Plata-Bahia Blanca area (38º´S- 38º 30´S; 58º 60º W) several studies on grain size, mineralogy, $^{14}C$ (among others, Zárate and Blasi, 1993; Bidart, 1996) and palynology (Prieto, 1996) were conducted on the late Pleistocene-Holocene record (sandy loess, loessial sands).

The northern Pampas of Buenos Aires (33º 45´S- 36ºS; 56ºW - 59º 30´W) is a type area of the Pampean Formation where classical studies on the stratigraphy and palaeontology of the Pampean loess were performed (Ameghino, 1889, González Bonorino, 1965). Since 1985, several sections have been the focus of analysis on palaeopedology (Teruggi and Imbellone, 1987, Imbellone and Teruggi, 1993; Zárate et al., submitted), palaeomagnetic studies (Bobbio et al. 1986, Nabel et al. 1999, Bidegain, 1998), environmental magnetism (Orgeira et al., 1998, Nabel et al., 1999), geochemical analysis (Gallet et al., 1998; Morrás, 1999) and vertebrate palaeontology (Tonni et al., 1999). General information on the grain size, mineralogical composition and chemical composition (carbonate, organic matter) is available. Following general models, loess was attributed to arid conditions and palaeosols to more humid and warmer conditions (Tonni et al., 1999). The age control is based on magnetostratigraphy and vertebrate palaeontology. Still, the correlation with deep-sea cores is not possible.

South central Santa Fé (32º 30´S- 33ºS; 59º 45´W - 61º 45´W) and also the eastern part of Córdoba (30ºS -32ºS; 62ºW -64ºW) were intensely studied by Martín Iriondo and collaborators (among others, Iriondo, 1997, 1999; Iriondo and García, 1993; Kröhling and Iriondo 1999; Kröhling 1999a) who carried out geomorphological, stratigraphic and sedimentological analysis (grain size and mineralogical composition, geochemical analysis). The chronological control was based on TL dates. These authors correlated the sequence of loess-palaeosols with the isotope stages of the last glaciation and the climatic oscillations of the Holocene. During *Isotope stage3* aeolian silty fine sands (Carcarañá Formation) were deposited with a palaeosol developed in its uppermost part. This unit is unconformably overlain by aeolian silty deposits (Tezanos Pintos Formation) attributed to the late Glacial Maximum-early Holocene. Its uppermost part was modified by soil development (Hypsithermal soil) which was truncated in the late Holocene *and buried by the deposition of the San Guillermo Formation between 3.5 and 1.4 ka BP. And arid period probably occurred during the Little Ice Age.*

The surroundings of Córdoba city (31º 10´S-32º 06´S; 64ºW - 64º 13´W) and the area of Rio Cuarto (33ºS-34ºS; 63ºW- 65ºW) were mainly studied by soil scientists (Sanabria et al., 1999; Karlsson et al., 1999). Information on the grain size and the mineral composition of the sediments along with the general stratigraphy and main geomorphological domains of the area is available (Cantú, 1992, Carignano, 1999). The age control is based on few TL dates.

In mountain areas of northwestern Argentina (Tafí del Valle, Tucumán), Sayago (1995) and Zinck and Sayago (1999) studied a loess-paleosol section (La Mesada, 26º 57´ 15´´S; 65º 45´30´´W), 42 m thick, containing 28 palaeosols interbedded with 26 loess layers. Radiocarbon dating yielded ages of 17,580 BP at 5.2 m to 27,660 BP at the bottom of the section. Following Sayago this loess record is part of the neotropical loess that extends between 20º S and 30º S corresponding to the present day subtropical area of the Chaco plain and the western mountain environments. Grain size and general mineralogical and chemical analysis (carbonate content, organic matter) were carried out; the age control is based on $^{14}C$ dates on vertebrate bones.

**South American dust and Antarctic ice-core dust**

Following Grousset et al. (1992) the isotopic results ( $^{87}Sr/^{86}Sr$, $^{143}Nd/^{144}Nd$, Nd(o)) obtained from 4 samples located in the southeastern part of Buenos Aires province in Argentina (38°S 59' W, 37.5°S 57° W), an area situated within the southern Pampas, confirmed a South American origin for the LGM dusts found at Dome C in East Antarctica. These samples were reported as coming from Patagonia, a region presently situated more than 400-km southwestward. Later, Basile et al. (1997) based on these same sort of isotopic analyses, reconfirmed the southern South American provenance of the dust deposited at both Vostok and Dome C during the glacial stages 2, 4 and 6. The study included the analysis of previous samples as well as three others from Tierra del Fuego and seven samples of sediments from the Argentine continental shelf between the Rio de la Plata (35.67° S 56.57° W) and a marine core at 54.17° S 64.97° W. For convenience, the authors used the term Patagonia to refer to the whole southern South America desert/arid/semiarid continental area east of the Andes (Basile et al.1997, p.583) which in this broad sense would also include the Chaco-pampean plains where the loess record of southern South America are found. (In relation to this, no significant loess records are reported from Patagonia). However, the environmental conditions of the Chaco-pampean plain during the glacial stages were not strictly Patagonian. Patagonia and the Chaco-pampean plain show very distinct geomorphological, climatic and biogeographic characteristics to be considered as a rather uniform region.

**Final remarks**

Several aspects of the classical and well- known model of Argentine loess needs to be reconsidered in the light of the new information coming from these different areas of the Chaco-pampean plain and the NW mountain environment.

- The distribution of primary loess is more restricted than reworked or secondary loess.
- The late Cainozoic record is mostly composed of reworked facies of loess deposits modified by pedogenesis.
- The southern Pampean plain (south of 34°S) is mostly covered by aeolian sands (The Pampean Sand Sea of Iriondo) while silty aeolian sediments (typical loess) are mainly distributed in the northern Pampas (north of 32° S), Iriondo (1999).
- The aeolian sediments show a grain size trend decreasing from sands in the west and southwest to more silty and clayey silty sediments in the northeast and east. The area between Mar del Plata and Bahia Blanca is covered by proximal facies of aeolian deposits, with sandy loess, loessial sands, sand mantles and sand dunes systems closer to the source areas, the floodplains of the Colorado and Negro River in northern Patagonia.
- In the southern Pampas the bulk of the aeolian material was transported by fluvial streams (Colorado, Negro in northern Patagonia) to the east and later deflated and deposited in the southern Pampas. The role of fluvial transport must be checked in the northern Pampas and the Chaco region.
- Loess mineralogy clearly demonstrates heterogeneity of loess composition with three main source areas: the Andes Cordillera, the central Pampean ranges of Córdoba and San Luis provinces (igneous and metamorphic rocks) and the Paraná river basin (Precambrian igneous and metamorphic rocks, Mesozoic volcanic rocks). The relative contribution of these source areas differs across the region (Morrás, 1999, Kröhling 1999b, Blasi et al., submitted).
- Volcanic ashfalls which permanently contributed to the Chaco-Pampean loess record are derived from the volcanic activity of two different volcanic provinces (Mendoza-Neuquén, south of 38º S) and the Puna (north of 28º S).
- The chronology of the loess deposits, still poorly known, is based on few TL dates and $^{14}C$ dates for the late Pleistocene and Holocene aeolian record. Magnetostratigraphy in conjunction with fossil vertebrate assemblages have been used to calibrate Pliocene and early Pleistocene and middle Pleistocene sequences assuming continuous sedimentary records, although numerous hiatuses are present throughout the successions.
- Palaeosol identification and recognition due to soil welding is a very common problem in the pampean successions. Usually palaeosols are interpreted as truncated profiles from which the A horizon has been stripped away by erosion. Micromorphological fabric of A horizons have been recognised in some sections (Pliocene and Middle to late Pleistocene)

indicating a soil surface accreted by aeolian deposition (Kemp & Zárate, 2000, Zárate et al. 2000, submitted).

- Geochemical studies are scarce and based on the analysis of very few samples coming from two areas of the Pampas. The isotopic composition is only known from less than 5 samples with no detailed stratigraphic setting.

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# Section 2: Rapporteur reports

## Presentations: Interaction of Mineral Aerosols and Climate

Rapporteur: Ann Wintle; Presenters: Ina Tegen, Dale Gillette, Sandy Harrison

### Modelling dust in the climate system (Ina Tegen)

The most understood impact of dust is its direct radiative forcing, where the dust particle parameters of extinction efficiency, scattering albedo and asymmetry parameter can be related to optical depth, scattering, and backscatter of incoming solar radiation. These parameters are wavelength dependent, and dependent upon particle size and mineralogy. These variations in optical properties were ignored in the early climate models. (For example in one early model from the Goddard Institute for Space Studies, Saharan dust was used as the only type of particle.) More data on dust mineralogy based on global surface maps would be useful to determine the true nature of dust optical properties.

To predict climate response, dust was treated as an interactive tracer in a general circulation model. So far, results are only available for fixed sea surface temperatures as boundary conditions, and fixed optical properties of dust. To obtain more realistic estimates of climate response to dust forcing, fully-coupled atmosphere-ocean earth system models need to be integrated with dust as interactive tracers having varying optical properties. So far, models have included a range of surface-related data such as surface texture, vegetation distribution, and changes in soil moisture and surface wind speed and directions. Recently, new ground conditions were added, such as "potential lake" distributions. Of particular interest for this workshop is the on-going improvement in modelling dust sources, transport and distribution, using transport models such as TM3. These result in identification of dust sinks where modern and palaeo-dust records can be used for verification.

Modelling of modern conditions can be compared with TOMS absorption data, and comparisons of predicted dust deposition rates with sediment trap data.

### Dust sources and emissions: observations and modelling (Dale Gillette)

The results of a regional scale study on the Arabian Peninsula were given in the time frame of the last few decades. Dust production was related to wind speed data and disturbance of the soil by movement of vehicles through the desert during the Gulf War. For the data model the wind speeds and directions were taken from the European Centre for Medium Range Weather Forecasting. Dust production was related to sand grain impact.

The model used the threshold wind velocity, the friction velocity, and a source area potential parameter. The friction velocity, U, can be obtained from the aerodynamic roughness height, $Z_o$. The calibration data were obtained from SW USA, with playa data being obtained from the Mojave Desert. This led to a discussion of the nature of lakes as sources, especially consideration of the contrast of dust emissions from places such as Owens and Rogers Lakes. The source area potential parameter was obtained from modern measurements.

Satellite data, photos, and a limited number of soil samples were used to relate emission parameters to geomorphic maps. Seven different types of geomorphic inputs were identified, and each was assigned values of roughness height, $Z_o$, and source potential parameter, Z, thus permitting U to be obtained from the calibration curve.

The model was integrated to predict the atmospheric concentration of fine particles in the atmosphere. The values obtained were compared with the measured PM10 concentration obtained at five ground locations and were also compared with TOMS data on optical thickness.

**The role of dust in past climate changes (Sandy Harrison)**

Dust is captured and stored in a number of natural archives, particularly loess, ocean sediments, and ice cores. One key time period is the Last Glacial Maximum. Several potential causes of increased dust deposition have been suggested; these include wind intensities, reduced intensity of the hydrological cycle and enlarged source areas.

Simple models simulating dust deposition failed to match the data obtained for the ice core records in Greenland at the LGM. A more recent modelling approach links models of climate and vegetation and thus allows source areas to be identified and used in the model. This approach enabled the dust flux today and at the glacial maximum to be calculated and compared with the values provided by a database such as DIRTMAP. One outcome is that regional differences appear. While the global dust loading was 2.5 times higher at the LGM than today, the dust flux at the LGM was about 20 times higher than today in the polar regions alone. The simulation also suggested that Alaska was a likely source area.

Changes in dust flux can be verified by looking at the dust accumulation recorded in polar regions. However, it is currently assumed, on the basis of a limited number of isotope studies, that the Greenland dust originated in Asia. However, other possible source areas need to be considered. This would require further provenance studies e.g. using geochemical or isotopic signatures. This was also considered to be a useful approach for Antarctica, particularly as there was some dispute as to the exact source material used for dust related to the Patagonian loess.

The most recent simulation has used the predicted dust distribution for the LGM, taking account of the amount of dust, the particle size distribution and the dust mineralogy to estimate the impact of higher dust loadings on the climate. This simulation also takes into account modelled cloud distribution and changes in seasonal albedo.

According to these simulations, dust had an impact on tropical climates as large as that caused by the lowering of $CO_2$ at the LGM. There is scope for further refining the information on mineral composition, with modelling considering the grain distribution to be a simple mix of quartz and hematite (external mixing) or for all grains to be considered as quartz grains coated with hematite. This would affect the scattering properties quite differently. Considering the strong albedo of the ice sheets, dust forcing at high latitudes had little effect.

## Presentations: Geologic Record of Dust

Chair: Ann Wintle; Presenters: Karen Kohfeld, Zhou Weijian, Katrine Krogh Anderson, Ian Smalley; Rapporteur: De Anne Pinney

The geologic record of dust is an important tool to help analyse the mechanisms and timing of global climate change in the past. It is clear that airborne dust and climate change are interrelated and have feedback effects on each other: climate affects wind and potential sources of dust, which in turn affects the dust record; and dust affects radiative forcing, atmospheric chemistry and biogeochemistry, and thus climate. We know that there are large glacial-interglacial changes in dust deposition, with different characteristics of deposition depending on location with respect to source emphasising that spatial patterns of deposits need to be considered.

The geologic record of dust is preserved in ice cores, marine sediment cores and, in the terrestrial environment, loess deposits. Research on polar ice cores illustrates the kinds of valuable data that have been recovered from these records. Long-term changes in the dust record can be compared to $\delta D$ and $\delta^{18}O$, which are indicators of temperature, and scientists can thus track changing dust characteristics in relation to changes in climate. For the past 100,000 years (Greenland) and 400,000 years (Antarctica) it has clearly been shown that dust deposition on the ice caps is a sensitive climate indicator, displaying significantly increased values during periods of cold climate. The relationship between the isotopic temperature indicators and the dust deposition is however not linear, and dust levels may change very abruptly, with significant changes taking place within a few decades or less. In Greenland the annual ice accumulation is relatively high and the upper, uncompressed layers of the ice display annual variations for many parameters, such as dust, isotopic composition, electrical conductivity and many chemical impurities. The annual signal in the isotopic records diffuses relatively fast and it is only well-conserved for a few hundred years. The annual signal of e.g. dust may by careful analysis be identified well within the last glacial period.

Calcium in ice cores mostly derives from aeolian dust, and the calcium signal is often used as dust proxy. It should however be noticed, that the relationship between dust and calcium content of the dust is not constant with time, and that these variations are not yet fully understood. In the same way the particle size distribution of dust particles found in ice cores changes with climate, and it seems that colder climate conditions may in general be associated with relatively fewer large particles, and thereby narrower size distributions of the particles deposited on the ice caps. At this point research into polar ice core dust provenance utilising mineralogy, isotopic data, and rare earth elements (REE) has indicated that the most likely source area for Greenland dust is Asia, and that most Antarctic dust probably has a Patagonian source, possibly from the exposed continental shelf. There is a critical need for more baseline data on the materials characteristics of potential dust source areas around the world.

One of the best-studied terrestrial dust records is that of the Chinese Loess Plateau, where loess deposits over 280 m thick have been accumulating for more than six million years. The magnetic susceptibility of the loess shows no apparent correlation to climate prior to 6 mya, with an increasing trend of correlation in younger deposits as well as higher frequencies of fluctuation. The relative proportion of coarse quartz grains in the deposits has also been correlated to temperature by comparison with $\delta^{18}O$ curves; this is believed to reflect increasing aridity and/or wind strength during the winter monsoon, with particularly great increases in the abundance of large quartz grains seen by 2.6 mya. The last interglacial shows extremely high frequency variability in the quartz grain size record that may be related to instability of the climate.

The Dust Indicators and Records of Terrestrial and MArine Palaeoenvironments (DIRTMAP) database has been designed to record diverse classes of dust data, including: aeolian accumulation rates; provenance indicators, including clay minerals, radioactive isotopes, heavy minerals, and trace metals; grain size; chronological data; and documentation, including such information as site location and references. Although individual loess sites may be dust sources, areas of dust transport, dust depositional sinks, or a combination of these, scientists are able to use the following equation to calculate general mass accumulation rates (MAR) that are critical to dust modelling efforts:

$$MAR_{eol} = AR * f_{eol} * DBD$$

Where: $MAR_{eol}$ = mass accumulation rate in $g/m^2/yr$
AR = accumulation rate in m/yr
$f_{eol}$ = aeolian fraction
and DBD = dry bulk density in $g/m^3$

For marine sediments the equation is solved using: AR as derived from $\delta^{18}O$ stratigraphy and radiocarbon dates; $f_{eol}$ as the fraction that remains after calcium carbonate, opal, organic carbon, and authigenic materials are removed; and DBD as found directly, by using salinity models, or by correlation with calcium carbonate and opal. For ice cores the equation is solved using: AR as found from ice flow models, layer counting, and stratigraphic correlation; and $f_{eol}$ and DBD as found using the dust concentration in the ice. Mass accumulation rates for loess deposits are calculated using: AR as found from thermoluminescence, radiocarbon dates, correlation of magnetic susceptibility, and pedostratigraphy; $f_{eol}$ equal to “1”; and DBD equal to 1.65 $g/cm^3$. Age control is a critical factor in all these calculations, emphasising the need for better dating of dust deposits.

MAR’s calculated using the DIRTMAP data in its current state show a number of significant features. The expected late Holocene peak of airborne dust from Africa and Saudi Arabia is seen, as well as a smaller peak from Asia. The last glacial maximum (LGM) shows an additional dust peak from North America. Comparison of dust patterns from the LGM with those of the Holocene show an overall increase in MAR’s during the LGM, with greater increases over the poles, the Indian Ocean into the Pacific Ocean, and in Australia. These results highlight the necessity to acquire more and better data, especially in the form of reliable dates, measured dry bulk densities, grain size distributions, and indicators of the aeolian component within a deposit. Another critical need is better mapping of the distribution and thickness of loess deposits. This is not only to document the deposits themselves, but also to relate dust to potential source areas and to help distinguish local, regional, and global influx of material at a given site.

# Presentations: Creative Approaches to Improving Interpretations of the Dust Record

Chair: Paul Hesse; Rapporteur: Katrine Krogh Andersen

## Chronologies of the dust record

Chronologies may be achieved with different methods that can generally be split into two types: Relative and absolute dating.

*Relative dating* implies stratigraphic comparison of a measured record with a known climate history, such as the $\delta^{18}$O-record from deep-sea cores. Records obtained from a loess deposit may include measurements of palaeomagnetic features, grain sizes, magnetic susceptibility, and micromorphological analyses. Problems with these dating method may include uncertainties as to the exact interpretation of a measured parameter (and the possibly different interpretation for a different site), the understanding of the connection between different measurements, and the dependency on e.g. the size distribution of the sample.

*Absolute dating* implies methods such as luminescence measurements or radiocarbon dating. Theses measurements are generally applicable for certain age ranges, and the error bars may be dependent on e.g. the age of the sample and the used technique.

There is an over-reliance on relative dating methods for constructing loess chronologies. This prevents these records from being used to investigate leads and lags between different climate forcings. A community-wide effort to improve the quality and number of absolute dates on loess sections should be an urgent priority.

## Micromorphology

Micromorphological measurements are potentially very fruitful for high-resolution records. Features such as gypsum crystals, crusts and cryogenic fabrics may be preserved in the sediments and they may reveal information on specific processes during loess formation. This may serve as an independent method for evaluating climatic changes, it gives a potential for deciding on good depths for absolute dating, and it may serve as a data quality control of particle size versus magnetic susceptibility.

## Mineralogical and isotopic provenance studies

Measurements of the mineralogical and isotopic composition of different samples may serve as a strong method for source determination. Several different isotopic ratios may be used for the distinction of different source areas, e.g. the $^{147}$Sm/$^{144}$Nd ratio may serve for large-scale distinctions, whereas lead isotope ratios have a potential for small-scale discrimination. However the isotopic composition of a sample may be grain size dependant, and changes in isotopic composition do not necessarily go in hand with changes in magnetic susceptibility. It is thus necessary to understand the meaning of these different changes. In combination with more PSA measurements, higher resolution measurements and a mathematical “unmix” of the source signals, provenance studies may serve for tracing of atmospheric changes, determination of climatic changes in source and deposition areas, and monitoring changing aeolian inputs to the oceans.

## Lake records

Lake sediments are potentially very useful records of aeolian input. Pollen preserved in the records supplies information on the vegetation and they may serve for radiocarbon dating. Whenever a clear distinction between the minerogenic input derived from the catchment (e.g.

via rivers) and the direct aeolian input is possible, lakes are potentially “optimal dust traps”. These conditions apply to marr lakes in basaltic terrains.

**Monitoring anthropogenic changes**

With the example of a Chinese loess record it was shown that loess records have a potential to record anthropogenic influences and changes in land use practices. This requires a high accumulation site with the potential of high resolution dating of the record.

**Thorium measurements**

Thorium may serve as a tracer of aeolian dust in (1) landscapes with thin mantles of loess and (2) possibly in profiles with additions of non-aeolian material. The thorium value of surface soils will also record post-depositional erosion dependent on landscape position, such as slope and curvature.

## Discussion: Structuring Regional Loess Data Synthesis

Rapporteur: Marcelo Zárate

The general goal is to use terrestrial (loess) records as an archive of information to fill the gaps represented by the continents in order to validate earth system model simulations of dust. The purpose of the session was to discuss issues that need to be resolved in order to make compatible regional synthesis of data. The test case selected for the data synthesis discussion was the Chinese Loess Plateau (CLP), mainly because of the large number of sites studied. The time interval of interest was the Late Wisconsin.

The CLP database was the case study to illustrate how the information was qualified and used. An important issue of discussion was the significance of large regions, which give fairly coarse resolution, and the importance of golden spike sites that can be different from the regional patterns.

**Site documentation:**

The discussion of the stratigraphic and dating information tables used for the database focused mainly on the methods applied to develop age models. Magnetic susceptibility (MS), geomorphological setting, vegetation cover (roughness) and dating techniques were particularly considered as sources of uncertainty in the calculations of mass accumulation rate (MAR). The lack of information on bulk density was considered a major problem. A value of 1.48 g/cm$^3$ was used at all sites except 2, for which there were measured values.

In the CLP, site correlation is based upon the MS record. The question was how the correlation works in relation to the stratigraphy. From a broad-scale perspective, MS has different meanings in different regions with the relative strengths of MS in glacials and interglacials being opposite between Alaska, Siberia, Argentina and the CLP. Another aspect was if MS represents a depositional or postdepositional signal, being valid if there is synchronicity. Closely related to MS is the particle size parameter which is fairly reliable as it was illustrated by the Alaska loess record where both are indicators. Another potential correlation problem is that the recording of the B/M boundary differs between loess and deep-sea cores. Also, some sedimentation may occur during soil forming intervals. Finally, pedostratigraphy and MS are too inter-related leading to circular arguments. The recommendation was to use both particle-size and MS. It was suggested that the best sites (with the most complete available information) in every region be used. However, there may be sites that provide some specific information on a particular aspect of interest that may also be included in the database.

The geomorphological setting was illustrated with the differences obtained in the calculation of MAR between terrace and non-terrace sites in the CLP. However, there may be potential problems also in non-terrace sites depending on the landscape position (upslope, midslope, footslope) which may cause variations in the thickness of aeolian material accumulated and hence in the calculation of MAR. The landscape position is also critical in providing information on local or regional sources of dust. The recommendation was to add in the database information on the landscape position of the selected sites.

The vegetation cover may influence the dust deposition in an area. A good example to illustrate the effect of vegetation is the Alaska record where during glacial times the conditions led to poor trapping of dust. In order to consider this aspect, it was recommended that a roughness index be included in the modelling.

# Discussion: Regional Synthesis and Dating Control

Rapporteur: Marcelo Zárate and Antje Voelker

The criteria used to evaluate dates yielded by luminescence and radiocarbon were considered. The main difficulty is that usually the information needed for the database is not given by the authors. It is necessary to classify the quality of data and propose a quality control scheme. A standard dating table was agreed upon including 10 field areas (site, depth, lab, lab #, material dated, technique, age, sd, reference, comment). It was also suggested that in the case of luminescence dating, palaeodose was entered, as, if it were included in the reference, all other data would be included to permit scrutiny of the date. For technique, radiocarbon by AMS or beta counting would be listed. For luminescence the options would be OSL, IRSL or TL. Both a list of techniques and material dated were made.

The dating techniques were grouped into two categories, correlation methods (tephrochronology, marine isotope stratigraphy (MIS), correlation to MIS (pedostratigraphy +MS), palaeomagnetism, AAR, biostratigraphy) and calibrated methods which yield numerical ages (fission track, luminescence, $^{14}C$, U-series, Ar/Ar, ESR, varve chronology, layer counting, ice-flow model).

The material for radiocarbon dating was divided into terrestrial (macrofossil, charcoal, shells, tooth enamel, bone (purified collagen), bone (bulk bone), bulk organic matter, humin, humic acid, pedogenic carbonate) and marine (planktonic or benthic foraminifera, mixed foraminifera, shells, bulk carbonate, bulk organic fraction). Dating by luminescence required mineral type to be given, e.g. quartz or feldspar or mixed mineral.

Evaluating radiocarbon dates, up to 20 $^{14}C$ kyr BP, the program CALIB 4 (Stuiver et al. 1998) is a reliable tool to calibrate terrestrial and marine radiocarbon ages. Beyond this age range there are (will be) several data sets available (Voelker et al. 1998, 2000; Kitagawa and van der Plicht 1998, 2000; Schramm et al. 2000; Beck et al. submitted; Hughen et al. 2000) that allow one to calibrate radiocarbon ages up to 40-45 $^{14}C$ kyr BP. Although some discrepancies exist between the different calibration data sets and no "formula" for calibration beyond 20 $^{14}C$ kyr BP is so far available, a first estimation of a calendar age is still possible. The application of the available calibration data and any future calibration curve could be used back to 40 $^{14}C$ kyr BP as this age is well within the dating range of most laboratories. The previous criterion of rejection of samples with 1 s.d. $\geq$ 2000 years was not considered useful.

The data from Lake Suigetsu (Kitagawa and van der Plicht 1998, 2000) should only be used up to 21 $^{14}C$ kyr BP ($\approx$ 25 calendar kyr BP), because in the older part the data totally disagree with the other high-resolution data sets, most probably due to an imprecise varve chronology of Lake Suigetsu (Kitagawa and van der Plicht 1998; Voelker et al. 2000). Between 13 and 21 $^{14}C$ kyr BP the high-resolution data from Lake Suigetsu is even more precise than CALIB 4.

For luminescence dating there is a greater problem of how to handle dates already in the geological literature. If the dating laboratory gave nothing other than a date with a standard error, then there is no means of checking the quality of the date. Although a 130,000-yr upper age limit had been proposed, discussion suggested that it was not applicable in all cases.
Criteria for other techniques will be left until dates have been entered into the database.

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## Discussion: Modelling of Dust Processes on Regional Scales

Discussion Group led by Ina Tegen; Rapporteur: Dale Gillette

The discussion focussed on how regional scale models could be used to supplement global scale modelling of dust emissions. Meso-scale models are needed to verify larger scale data. The mesoscale models will also be used to find details that a global scale model could not capture. Interaction of a global model with a mesoscale model is a technique by which predictions may be obtained that would not have been found by the mesoscale model or the global scale model alone. Regional modelling can be used to develop new or approaches to modelling dust emissions that can then be applied in models.

The data have certain uncertainties along with the models. Models and data will be used to find the consequences of certain uncertainties in each. In fact modelling may suggest improvements in data taking that will benefit atmospheric science as a whole. We must improve the resolution and quality of the data in order to get better results.

Three regions were chosen for modelling based on unique problems and their importance to global dust production. The mesoscale models are meant to develop techniques for dust emissions that can later be added to global scale models. Good data and well-defined problems were thought to be available for the three regions. The three regions and the dominant emission mechanisms they represent are given:

| Region | Dust emission mechanisms |
|---|---|
| Australia | dune fields, dry lakes, and inland river systems |
| North America | glaciation (last glacial maximum) |
| China | deposition by flooding, subsequent wind erosion |

Australia has three major sources, dune fields, dry lakes, and inland river systems. In Australia, river systems renew the supply of material available for deflation. Simulation of the supply of sediment is a basic need for a high time resolution model in order to renew its dust sources. The western part of Australia is poor in dust sources compared to the eastern part. Eastern Australia has renewable dust sources although it is not a huge supplier of dust in the world compared to such places as China. For present day conditions we see the model will simulate depositions which will be compared to observations. Recycling of sediment has led to an overestimating of dust sources because the recycling is not accounted for in the models. It may well be that the mesoscale climate modelling will produce better winds and better weather verification. Data and models are in place so that a model of Australia is now possible.

Concerning the LGM, data resources are also available for Australia. Geomorphic mapping (for example, dune lands and river lands) can be made available for modelling.

North American dust production was at a maximum during the last glacial maximum (LGM). During that time vast blankets of loess were laid down by the wind and by inference, huge quantities of dust were made airborne. Glacial dust was transported from the glaciers by fluvial transport where it dried at mid-latitudes. Wind erosion of the loess transported it to locations downwind of the source areas. For North America, the data needed is palaeodata that would consider glaciation, fluvial movement, deposition, and wind data.

China is a region that produces a very large amount of desert loess. Sediment supply is the key to this problem. The Yellow River floods often, bringing large amounts of silt deposition to lowland areas nearby. These flat silt-rich areas are very vulnerable to wind erosion following the flooding. Massive salt weathering and tectonic processes are also responsible for dust emissions in China. A small glacial input during the LGM is also responsible for dust emissions in China. The climate of China is dry but its rivers have intermittent floods. Ocean cores obtained near China confirm the dust emission and transport models. The LGM loess results are not confirmed, however. China has a reservoir of silt in dune fields and palaeolake sediments that are presently being stripped. There is a version of MM5 (3D mesoscale climate model) that is tuned up for China. The amount of soil material going into Chinese loess production is large compared to that in America and other places. The most relevant mechanisms are annually fed sediment depositions in the desert flood plains of the western part of the Yellow River. There are 30-40 dust storms per year at the maximum dust storm location in China. There are no supply limitations in China.

**Needs for the modelling:**

We need to model the terrain and the atmospheric surface layer. One technique recommended by the group was the use of percentages of the surface that have a given roughness length and drag coefficient. The dust production from these areas seems to adequately simulate observed emissions. The effect on other moisture fluxes is not known for this approach, however. Also needed are grain size data in a profile and crusting of the surface. To get surface crusting only small amounts of rainfall (5mm) are required. Scaling up from mesoscale models to global models may use the proportions of the land's surface in definite land types.

# Discussion: Closing Session

Co-chairs: Karen E. Kohfeld and Sandy P. Harrison
Rapporteur: Karen E. Kohfeld

The purpose of this session was (a) to identify and summarise future directions for model development and the application of these developments of various problems concerning the dust cycle and climate change, and (b) to define complementary data collection and technique developments required to evaluate such simulations. Based on the conclusions of these discussions, our goal was to come up with some practical products that might result from this workshop.

**Future Directions for Complementary Model and Data Research**

## I. Model Development

### 1. Impact of land-surface conditions on the dust cycle

Several questions related to model development were discussed as being potentially important. These questions relate primarily to the impact of land-surface conditions on dust emissions, atmospheric dust properties, and deposition. In terms of the simulation of emissions, the following questions were identified as potentially important:

- What is the wind speed dependence of emission rates and how does it vary from region to region?
- How does one treat preferential sources (e.g. lakes and rivers) in models?
- What is the effect of vegetation phenology on dust emissions?
- How does one approach the problem of scaling winds in simulations of various temporal and spatial scales so as to simulate emissions appropriately?
- What are the hydrological controls on lakes and how will this affect the sediment types that might be deflated?

Changes of land surface conditions (specifically in potential source regions) could also affect the radiative properties of the dust:

- How do we properly simulate changes in modern and palaeo-mineralogy, and particle size of atmospheric dust?

Finally, the land-surface could affect the effectiveness of trapping dust at the surface:

- What is the impact of various vegetation types on surface roughness, and therefore dust deposition?

### 2. Palaeo-applications of models

Currently, most models of the dust cycle have simulated the dust under modern-day climates, with palaeo-simulations focussing primarily on the Last Glacial Maximum as a period with very high dust concentrations. Some obvious questions about the LGM include:

- What additional processes are required to simulate the LGM? And what processes should be the focus of continued research on the Last Glacial Maximum?
- What are the implications for LGM changes in dust concentrations on climate?
- Can we simulate other glacial periods, or are there other ”prizes” in dust research?

### 3. Mesoscale modelling (test-bed vs. application, interpretation)

The focus on this type of research would be to determine the role of various smaller scale processes on regional dust production, and how these processes might impact global dust production. The types of systems proposed included modelling of dune fields, dry lakes, inland river systems, glacial and periglacial dust production processes, and the effects of flooding and wind-erosion processes. The notion was that these regional scale models could supplement the global scale modelling already in progress. It was recognised that the importance of these smaller scale processes may vary from region to region. Thus, comparisons of these various regions may serve to understand and prioritise the importance processes in modelling studies.

Three specific regions (North America, Australia, and China) were suggested as potential target areas for regional dust model studies. The motivation for choosing these regions was (a) the type of process believed to control the dust emissions, (b) our past inability to model these regions, and/or (c) an abundance of data in these regions that will allow us to test the effectiveness of the modelling effort:

**II. Data questions and Techniques:**

The focus of the DIRTMAP project is not to push loess research per se or to develop new techniques, but rather to develop a validation data set that can be used for current and future simulations of the dust cycle. Nevertheless the database effort can be used for other purposes, to address key process-oriented questions in the field of dust research, and to encourage further development of additional techniques and data collection. Data collection and technique development must occur in parallel with modelling efforts and can serve both to validate existing model simulations as well as to shape the types of questions that model simulations of the dust cycle should be addressing.

**1. What are the dust transport pathways to the polar ice caps in both the Northern and Southern Hemispheres?**

This is an issue that still has not been modelled entirely successfully, based on available mineralogical and isotope provenance data, either for both the modern or the last glacial climate periods. Back trajectory analyses or climatological data could prove useful in analysing modern dust transport patterns. However, more extensive data compilations (mineralogical, shallow core transects, data from continental shelf areas in the Southern Hemisphere) would prove very useful in reconstructing past transport paths from potential source areas.

**2. What is actually emitted to the atmosphere?**

The spatial scale of global model studies is such that many of the smaller-scale processes involved in dust emission have until very recently been neglected. For example, dust emissions from periglacial sources, glacial runoff, and local riverbeds are not included in state-of-the-art simulations. It is in the interest of both the modelling and data collection community to assess how much dust is actually produced from very local sources. A second aspect of this problem concerns the empirical assessment of the initial mineralogy and particle size of dust from source regions, and how both of these characteristics might change with distance away from source regions. The mineralogy, iron content, and particle size of loess deposits could be measured and evaluated by using data from loess transects that track changes downwind of local source regions, in order to indirectly address the questions of what remains in the atmosphere. These data could easily be incorporated into the DIRTMAP database.

**3. What is the iron content of dust derived from different potential source regions, and how does this change on glacial-interglacial cycles?**

These questions are ultimately important for determining the radiative impact of dust from different source regions, as well as having a potential impact on both terrestrial and marine ecosystems. Yet the iron content of source regions is not well determined. Furthermore, recent studies have demonstrated that the radiative impact of iron in soil dust depends on the manner in which the iron is incorporated. For example, is the iron present as coatings, or is it locked in the mineral structure of the aerosol? Both aerosol measurements and quantification of materials present in loess sediments may help to address these questions.

**4. What is the impact of landscape position and surface roughness on deposition?**

Presentations about both the loess and lake records (particularly in Alaska and China) brought up the questions of the ability of different vegetation types and topographies to alter surface roughness, and ultimately to affect the ability of a land surface to capture dust. Palaeo-lake records could be utilised more in future, both as records of dust deposition and as records of changes in palaeovegetation and therefore the potential impact of vegetation on surface roughness and dust deposition rates. It was suggested that transects of lake records spanning gradients of vegetation type and distance from source region might be useful in addressing some of these issues.

**5. What data is appropriate and compatible for a model experiment? What is the intelligent way to select data for a model simulation?**

A unifying theme of this workshop is the importance of considering a comparable model and data scale to address a particular problem and the importance of careful selection of data so that it can address the scientific modelling issue at hand. While a detailed, well-dated site may provide information about long term changes at one site, a network of sites are required to capture changing spatial gradients that may appear in model simulations. Furthermore, spatial patterns observed in local scale data may not be observed in global scale model simulations.

## III. The structure and strategies of the DIRTMAP database:

The DIRTMAP data base structure is in the process of being modified based on a basic plan developed by Gerhard Boenisch (MPI-BGC-Jena), and the suggestions of workshop participants. The goal is to improve the accessibility and flexibility of the database for use with multiple applications. Suggestions included the standardisation of data input from multiple palaeo-environments, including diagnostic information such as landscape environment of deposition, and increasing the documentation of quality control, specifically for dating methods and age models. It was also recommended that an increased amount of grain size and mineralogical data be incorporated in the database, both for diagnostic and model validation purposes.

The previous structure of the DIRTMAP data base has been centred around the activities at the Max Planck Institute for Biogeochemistry in Jena, Germany, where efforts have focussed on modelling past climate periods, and validating these simulations with global palaeoenvironmental data bases. This work has been supported by umbrella organisations such as IGBP and INQUA, but the development and contributions of DIRTMAP have centred around activities in Jena.

At the Loessfest meeting 1999, it was proposed that regional co-ordinators should organise regional syntheses of loess data (e.g. for the regions represented at this meeting: N. America, S. America, Africa, Siberia, Australia, etc.). The DIRTMAP database in Jena would then serve as a base for co-ordination, standardisation of data input, and as a central archive. If this structure is followed there needs to be discussion of who participants will be, how this will be facilitated, what group synergies will exist, and the time frame over which these syntheses will be accomplished.

One way of facilitating this structure will be the production of regional synthesis review papers (see 'future publications' below), which include standardised data tables, site inventories for a particular region, standardised estimates of mass accumulation rates, and supporting data specific to regions.

## IV. Future Publications:

In order to bring the results of this workshop to a wider audience, the workshop participants agreed on the following publication strategy:

1. Workshop summary report (distributed to all participants; http://www.bgc-jena.mpg.de/bgc_prentice/).
2. Submission of summary to Loessletter and the PAGES Newsletter.

3. Summary article submitted to EOS (spearheaded by A. Unruh)
4. Quaternary Science Reviews Special Issue publication edited by Ed Derbyshire and co-ordinated by Sandy P. Harrison
   This special issue volume will contain review papers representing the first regional syntheses of the terrestrial (loess) information. Each publication will contain standardised tables and maps, including information about site locations, estimates of 'modern' and 'LGM' mass accumulation rates, site maps, and LGM and modern aeolian accumulation rate maps. The deadline for submissions the Special Issue is 12 April 2001 at 12:00 (GMT). The anticipated publication date will be early in 2002.

The following papers/regions were identified, with the following participants identified as co- and lead authors on each publication:

1. Review of Global Dust Modelling – Ina Tegen
2. Alaska – De Anne Pinney, Jim Begét, and Dan Muhs
3. Australia – Grant McTainsh, Paul Hesse
4. Central Asia – Liping Zhou
5. Central Europe – Liping Zhou
6. China – Karen Kohfeld, Weijian Zhou, Sandy Harrison
7. Siberia – Jiri Chlachula
8. South America – Marcelo Zárate
9. USA Mid-Continent – Dan Muhs, Helen Roberts
10. New Zealand – Dennis Eden, Andrew Hammond

5. A global review paper targeting the dust modelling community will summarise the information from the regional publications and provide target datasets for model validation.

**V. Future Workshops and Meetings:**

Given the success of the present workshop in promoting interactions between the modelling and data collection communities, and in outlining key tasks for the future, it would be useful to bring the community together again through follow-up workshops. Several possible workshops were identified as useful follow-up meetings:

1. **Modern Dust Validation Workshop, ~September 2001**, to be co-organised by Ina Tegen and Grant McTainsh. Topics of this workshop will include synthesising modern dust information measured using various techniques and formulating a global approach for validating modern simulations of the dust cycle. Types of data to be considered: satellite aerosol indices, photometer measurements, meteorological visibility data, atmospheric measurements, marine and land sediment trap data, historical records, as well as marine surface sediment measures. One aim of this workshop will be to improve the quality of the modern dust data in the DIRTMAP database.

2. **Palaeo-Data-Model Comparison Workshop, 2002**, tentatively, to be co-organised by Paul Hesse and Sandy P. Harrison. As this first workshop has focussed on the compilation of terrestrial data, this next workshop would be more comprehensive, broadening to cover information from the ice core, marine sediment, and terrestrial (loess and lake sediment) environments. This workshop would have an active data/model comparison component, where synthesised data would be compared with palaeo-simulations of the dust cycle that had already been completed.

3. **INQUA, Reno, Nevada, 2003**: A symposium entitled "Observations and modelling of the palaeodust cycle" has been accepted as part of the next INQUA Congress. This symposium, which is supported by the Loess Commission, will be chaired by Ina Tegen and Karen Kohfeld.