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New approaches to European loess: a stratigraphic and methodical review of the past decade

Review Article

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Abstract: This review paper intends to summarize the state of the art in loess research at the first international "Loessfest'99" conference and to outline progress in loess research during the past decade. The focus is on loess as a terrestrial archive of climatic and environmental change during the Quaternary. The review highlights remarkable new results from regional investigations into European loess, as well as the emergence of new methods and refinements of established techniques, focussing on stratigraphy, dating and palaeoenvironment. It is concluded that loess research during the past decade not only has developed rapidly to take an outstanding place in Quaternary sciences, but also promises exciting perspectives for the next decade, in particular when combined approaches are applied to benefit from the now comprehensive pool of established and new methods.

Keywords: Loess • Europe • dating • palaeoenvironment methods•

1. Introduction

The international „Loessfest 2009" in Novi Sad, Serbia, was a renewal of the international „Loessfest '99" held in Heidelberg and Bonn, Germany, in March, 2009, which placed itself in the tradition of the international symposium "Wind blown sediments in the Quaternary record" held at the University of London in January, 1994. The present contribution examines new developments during the past decade since "Loessfest'99", thereby disregarding research in geotechnical or applied aspects. This review will rather focus on loess as a terrestrial archive of climatic and environmental change. Of course, this review is inevitably influenced by personal viewpoints of the author and may thus, be somewhat one-sided in the focus on European loess. Newly emerging approaches to the study of loess, however, transcend regional boundaries, even if applications within this paper are on a local or regional scale. In order to outline progress in this field, the state of the art methodologies and thinking from "Loessfest'99" will be summarized first. From this, progress in loess research will then be examined under regional and methodological aspects. Although the author is primarily involved in chronostratigraphy of loess, the present review will encompass the broad scientific nature of recent loess research, including aspects of which the "loess community" may not be fully aware of.

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2. State of the art at "Loessfest'99"

Outcomes of the "Loessfest'99" were published in two special volumes, Earth Science Reviews vol. 54, 2001 (keynotes), edited by E. Derbyshire [1], and Quaternary International vol. 76/77, 2001, guest editor E. Derbyshire [2]. Beyond these volumes, many papers appeared in numerous peer-reviewed journals during the following years. The end of the 1990s saw the triumphal procession of the consistent Chinese loess stratigraphy in different ways: It was convincingly correlated to the marine isotope stratigraphy and did not stay constrained to the Chinese loess plateau but was increasingly adopted also in other parts of Asia. Furthermore, the outline of Chinese loess stratigraphy started to enter Europe – despite its fragmentary local stratigraphies - and to combine with Kukla's stratigraphic scheme [3].

Progress in Quaternary dating methods had led to increased applications in loess and loess-like sediments. This refers in particular to direct luminescence dating (with optical dating taking priority over thermoluminescence dating), indirect magnetic (environmental magnetism, palaeomagnetism) and chemical dating (amino acid geochronology). Together with increased and new applications of dating methods, however, their new emerging problems challenged further research and careful interpretation of apparent dating results.

Palaeobiological proxies, in particular molluscs, have had a long tradition in loess research but were now objected to innovative data processing and interpretations. Pollen analysis from loess-palaeosol sequences, normally not expected to yield stratigraphically meaningful results, proved a very helpful tool for palaeoenivronment reconstruction and climatic stratigraphy, at least in suited regions such as the Ukraine. Isotopic proxies from loess – radioactive isotopes such as ^{10}Be as well as stable isotopes including ^{13}C – emerged during the 1990s but systematic applications remained rather confined to individual key sections.

New sedimentological methods (mainly laser grain size analysis) and related provenance studies emerged. Grain size distribution indices based on high resolution granulometry promised to serve not only as a lithostratigraphic, but also as a chronostratigraphic tool, by correlation with continuous dated high resolution records such as ice cores and deep sea drillings.

As a result of improved and novel methods, refined stratigraphies, in particular of the last glacial cycle in loess, could be proposed. As a revolutionary approach, even equivalents of "Heinrich Layers" and D/O-cycles in high resolution loess sequences were suggested, thus elevating high resolution loess sequences to a unique terrestrial palaeoclimate and palaeocirculation record.

The state of the art at the turn of the millennium can be summarized by:

- Long loess-paleosol records were recognized as very valuable terrestrial paleoclimate archives.
- Equivalents of D/O-cycles and Heinrich layers in loess became apparent. But often such proposals were still speculative (mainly due to dating uncertainties).

Having established a wide range of science-based methods loess research could be seen to face the question as to whether it stood at the transition from fundamental to applied research. From a present-day point of view the answer could be yes and no. "Yes", because of:

- The application of newly emerged methods in numerous regional studies,
- More profund interregional correlations,
- The reconstruction of climate and environmental gradients on continents derived from loess-palaeosol records.

In short: it is evident that the success of a scientific discipline is witnessed by its application. But "no" because of:

- Ongoing refinement of methods,
- Development and testing of new methodologies.

The question cannot be answered unambiguously because continuous regional application, refinement and development of advanced methods characterizes loess research:

- 185 years after von Leonhard introduced the term "Loess" in geosciences literature [4],
- 48 years after foundation of INQUA Sub-Commission on European Loess Stratigraphy and 40 years after its upgrading to a full Loess Commission,
- 6 years after restructuring INQUA commissions and start of SACCOM (Commission on Stratigraphy and Chronology).

The vitality of loess research should, however, not primarily be illustrated by organisational aspects but rather by its scientific and methodological development. Some highlights of the past decade will therefore be mentioned briefly.

3. The past decade

Progress in loess research during the first decade of the present millennium can be evaluated through the division of the research into regional and methodological aspects as follows:

3.1. Regional

First of all, it may be emphasised that Chinese loess stratigraphy is now more or less accepted as a „standard" stratigraphy of the continental Quaternary. This does not argue against regional stratigraphies of glaciations and interglaciations, or stadials and interstadials of a given glaciation. Glacial stratigraphies are, however, intermittent and cannot comprise the entire Quaternary. The dating of glacial advances and retractions is still a major challenge for Quaternary sciences, and, thus, for correlation with marine isotope and loess stratigraphies. So far, the Chinese standard loess stratigraphy is the only complete terrestrial stratigraphy of the Quaternary. This fact is one important reason for maintenance (as system/period) and revision of the Quaternary starting at 2.6 Ma ago [5]. Besides this, it is now well established that the Chinese Loess Plateau (CLP) serves as an excellent archive of the East Asian Paleomonsoon and delivers most valuable data for reconstructing and understanding the sensitivity of the Asian monsoon, which is probably the most prominent atmospheric circulation system in the world's biggest continent.

Beyond the establishment of a complete terrestrial Quaternary stratigraphy, refined chronostratigraphies of the last glacial-interglacial cycle have been elaborated from many regions of the world. Whereas in oceanic parts of the loess belt, in particular in Western and Central Europe, refined loess stratigraphies have been known for up to four decades, within continental areas interstadial soils are often difficult to distinguish using visual field evidence and can only been identified by the use of advanced methods. Some examples will be shown later.

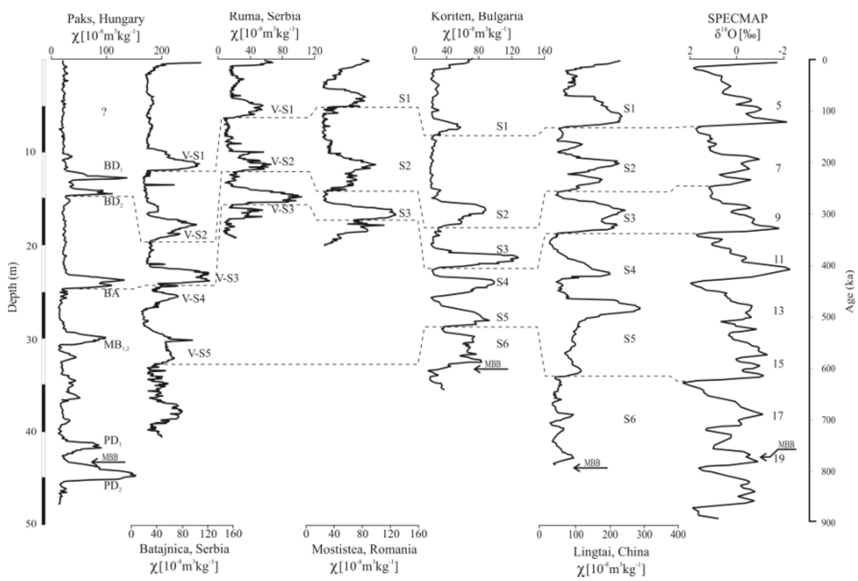

Figure 1. Suggested correlation of loess-palaeosol sequences from the Danube Basin in Hungary, Serbia, Romania and Bulgaria with the Chinese loess stratigraphy and the SPECMAP curve (from [9]).

Ongoing regional research attempts to adopt the Chinese stratigraphic scheme to the entire Eurasian loess belt. Nevertheless, some pending problems (e.g. [6] vs. [7]) persist because of different chronostratigraphic models. Enforced research in the Carpathian Basin has by now revealed plateau loess ranging back >1.000 ka with a consistent age model [8]. Missing regional links between China and Europe must not be concealed in this context, but a correlation of Middle and Upper Pleistocene loess-paleosol sequences in the Pannonian Basin and the Lower Danube Lowland (Romania, Bulgaria) based on magnetic susceptibility records, with the Chinese loess stratigraphy and the SPECMAP $\delta^{18}O$ record appears reasonable (Figure 1). It is striking that in the Pannonian Basin the last 3 interglacials were drier than previous ones, as is demonstrated for the Batajnica section in Serbia [9] (Figure 2).

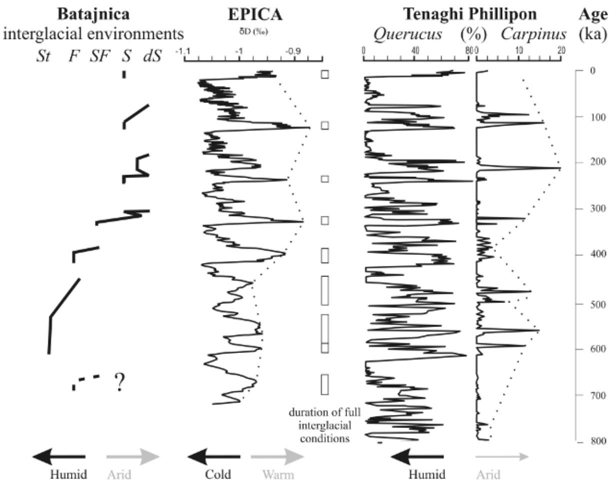

Figure 2. Humidity trends from Middle and Upper Pleistocene interglacials in the Batajnica section, Serbia, and suggested correlation with the EPICA ice core and the Tenaghi Phillipon pollen record (Greece) (from [9]).

Within Europe, despite its considerable climatic gradients, interregional correlation of Middle and Upper Pleistocene loess-paleosol sequences (based on magnetic susceptibility) and of the global ice volume curve (based on marine oxygen isotopes) reveals similar patterns [10]. This can be best demonstrated for MIS 7 (Figure 3). A further typical pattern becomes evident from paleosol S5 comprising MIS interglacial stages 13 and 15 [11]. In the sections studied S5 is more well developed than younger paleosols, even if the chronology of the Stary Kaydaki section (Ukraine) is still under debate.

Within the principally continental Pannonian Basin interstadial soils of the last glacial cycle are much more difficult to detect by field evidence than further to the West and to the North (Central and Western Europe [11]). Again, magnetic susceptibility turns out to be a valuable tool for a refined stratigraphy beyond field inspection, as was shown for the Surduk section (Serbia) including the weak interstadial "Surduk soil" [12]. At the same time for this section a rather detailed luminescence chronology of the last glacial-interglacial cycle is now available (Figure 4), allowing for higher resolution palaeoenvironmental interpretation and comparison with other well-dated records on a regional to hemispheric scale.

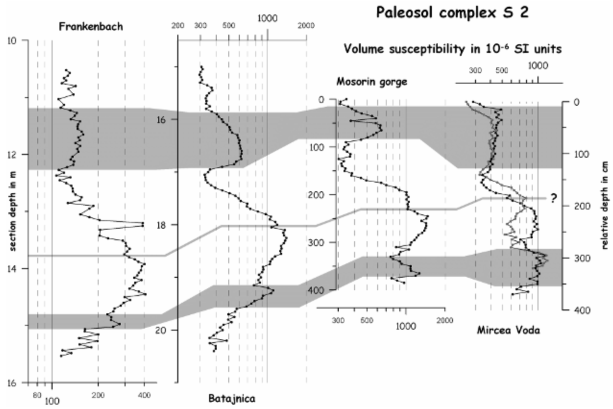

Figure 3. Characteristic pattern of magnetic susceptibility from MIS 7 pedocomlex (S2) through Central and Eastern Europe (from [10], adopted).

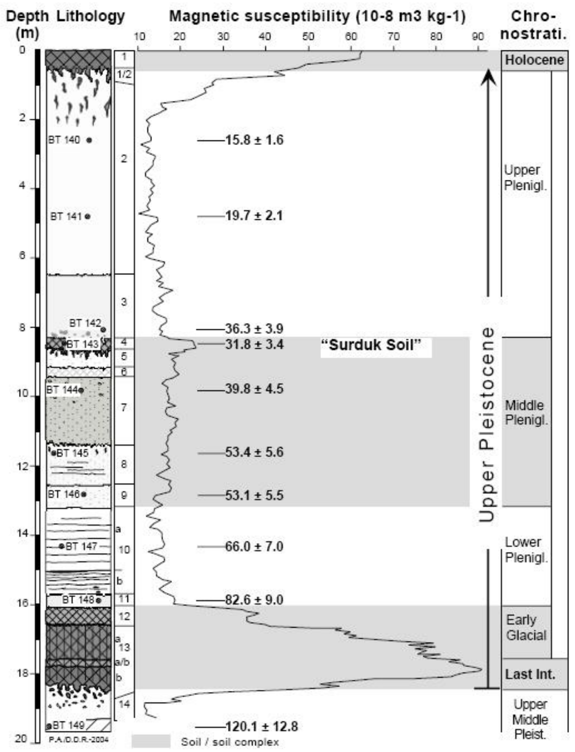

Figure 4. Last glacial-interglacial cycle in the Surduk section, Serbia, with luminescence dating results (from [12]).

New attempts are now underway to close the "gap" in Central Asia between Chinese and European loess records and fill in the missing links. An inter-profile correlation of loess-palaeosol sequences from Central Asia and China (Figure 5) was proposed [13] which however, needed sound geochronological support at that time. More recently the chronology of the penultimate glacial to Holocene part of the Remisowka section, SE Kazakhstan, was partly revised based on radiocarbon dating and aminostratigraphy, and the authors propose to include the major influence of the Asiatic polar front, in particular its long-term migration, seasonal duration, and permanency during the late Pleistocene in circulation models [14]. For the first time a tentative chronology of loess-paleosol sequences from north and northeast Iran, a region with extreme present day climate gradients, has been presented [15, 16], as well as the first geochronological data from Late Pleistocene to Holocene sediment-soil sequences in Southern Iran (hot desert), which are now recognized as desert margin loess or loess derivates [17]. Thus, in this part of Asia the strongly desirable link between "typical loess" and desert margin loess ("semi-desert loess") (see [18]) appears to be within sight. Recent studies in desert margin loess on Lanzarote (Canary Islands, Spain) was the first to achieve success in deciphering palaeoenvironmental information from such archives, but problems arose with undifferentiated application of methods now established for investigation of "typical" loess [19] (with further references).

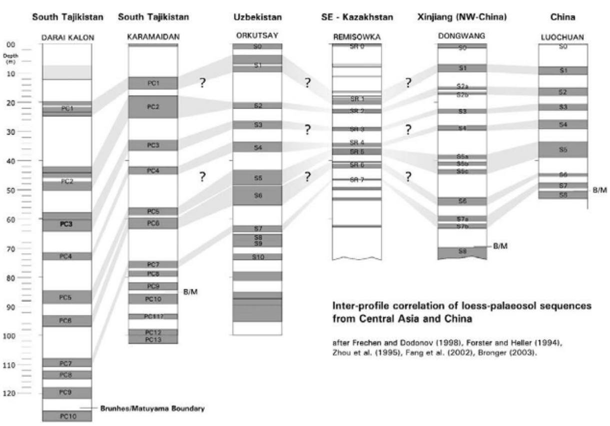

Figure 5. Tentative correlation of Asian loess palaeosol-sequences from Uzbekistan to the Chinese Loess Plateau (from [13]).

High resolution loess records from the last glacial cycle not only require high sedimentation rates, but also climatic oscillations strong enough to be well recorded in loess. As is noted since decades, these requirements are very well met in several parts of Western and Central Europe. Application of new methods have, nevertheless, yielded considerable progress in refined loess stratigraphy of these areas. As an example the Nussloch section south of Heidelberg, Germany, was first presented to an international community in 1989 [20]. Upper Pleniglacial loess here is exceptionally thick (Figure 6) and also Middle Pleniglacial loess and wind borne sand exhibit detailed stratification seldom known elsewhere. Both Upper and Middle Pleniglacial beds are interstratified with weak to moderate palaeosols (mainly tundra gleys, arctic browns and their transitions) (e.g., [21–23]). From the Middle and Lower Rhine area stacked profiles are presented [24, 25] which are correlated with marine isotope stages 11 to 1 with special attendance to MIS 5e to 1, the Greenland ice record, and the central European biostratigraphic (palynological) subdivision. As this stacked profile still lacks detailed physical dating the proposed correlation may still be regarded as somewhat tentative, nevertheless the stacked profile demonstrates a detailed and high resolution stratigraphy, which most probably reflects Greenland stadials and interstadials known as Dansgaard-Oeschger cycles.

Even higher time resolution from the last glacial inception, down to decennial scale, was achieved from the ELSA maar lakes archive [26, 27]. Although the warved lake sediments include components other than loess, decadal pulses of dust input can clearly be detected. Recently, a high resolution radiocarbon-dated stacked loess chronostratigraphy of Central Europe (circum-Carpathian area) was presented ranging from the Middle Pleniglacial to the Late Glacial [28], in which the authors believe to see interstadial soils on a millennial to centennial scale. For the past >24 ka (measured through ^{14}C dating) a correlation is established with the high resolution loess sections at Kurtak on the Jenissei River, Siberia. Correlation with the GISP2 record suggests that there are more interstadial soils than Greenland Interstadials in the same time period (Figure 7). Provided that all horizons addressed as paleosols can be proved as soils by (palaeo) pedologic methods unimagined perspectives for loess as highest resolution terrestrial archive of paleoenvironment may emerge.

It should be noted that Central European loess stratigraphy has often tried to adopt the morphostratigraphic subdivision of the Northern Alpine Foreland, despite its recently outlined inconsistencies (see [29]). For the northeastern Alpine Foreland the section at Wels-Aschet, Austria, exposing a loess-paleosol sequence including 5 fossil luvisols on top of a glaciofluvial gravel terrace attributed to the Günzian glaciation, presents a key section. Recent chronostratigraphic interpretations of the section [30, 31], however, yielded controversial results. Deviant from "counting from the top" and implying 100-ka cycles [30], application of IRSL dating [31] suggests some shorter cycles and, thus, a shorter chronology. This open

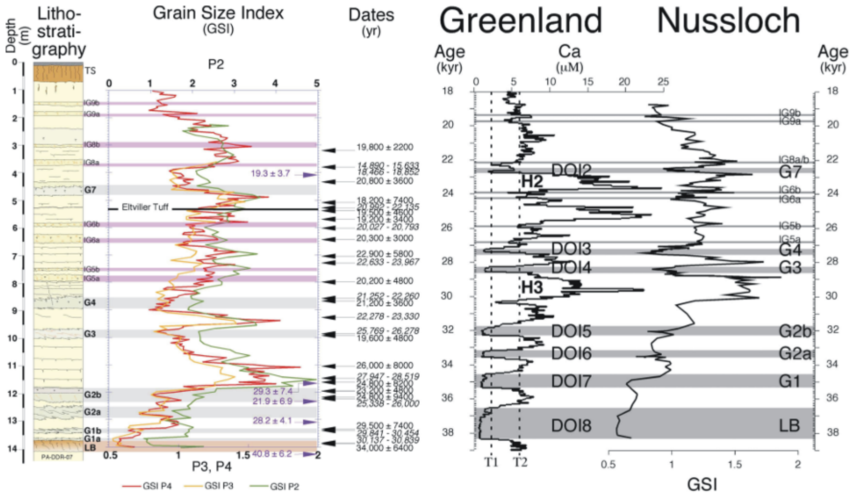

Figure 6. Refined stratigraphy of thick upper pleniglacial loess from the Nussloch site, Germany, showing grain size indices and geochronology (left) and correlation with dust record and Dansgaard/Oeschger cycles in Greenland ice (GRIP, right, from [21]).

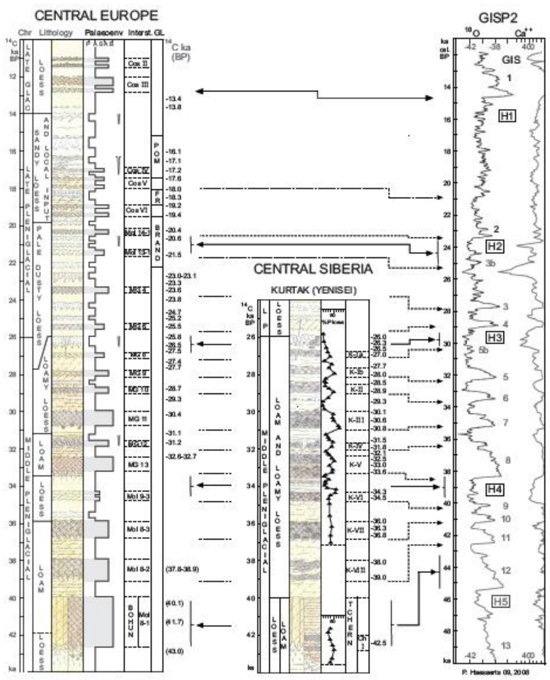

Figure 7. Refined loess stratigraphy of Middle und Upper Pleniglacial loess of Central Europe and central Siberia with radiocarbon chronology (not calibrated) and suggested correlation with the GISP 2 Greenland ice record (from [28], with kind permission of the authors).

question leads onto the discussion of methodological developments.

3.2. Methods

The past decade afforded considerable progress in methods of loess research, concerning both the advancement of previously existing methods and the emergence of new ones. The present review will focus on a few dating methods and on proxies for environmental reconstruction, which themselves can also be used for dating purposes via correlation with well-dated records.

A review of the advancement of dating methods cannot overlook luminescence dating, despite problems of upper age limits and age underestimates (see recent comprehensive reviews in [32–34]). One of the greatest innovations during the past decade has been the establishment of the "Single Aliquot-Regeneration" (SAR) protocol in OSL dating [35, 36], later also applied to K-rich feldspars [37]. The SAR protocol allows for higher precision in OSL age estimates but suffers from a rather low saturation dose limiting the dating range from loess to some 50 to 80 ka (depending on dose-rates). The much higher saturation dose of feldspars may enable IRSL dating for up to 200 or 300 ka (and possibly beyond) but so-called "anomalous fading", a phenomenon known for more than three decades but still not sufficiently understood, hampers the reliability of IRSL ages. Anomalous fading is detected as longer-term instability of laboratory-induced TL or IRSL signals beyond thermal instability of related electron traps, leading to age underestimates. At present, it appears that not all published IRSL ages are underestimated due to anomalous fading, but the extend of underestimates may depend on regional provenance (and, thus, geological history) of feldspars and/or from laboratory protocols (see, e.g., [31, 34]). As the solid state physics background of so called anomalous fading is still under debate, procedures to correct apparent ages for anomalous fading [38–40] have not yet convinced the entire luminescence dating community. The understanding of the physical reasons of "anomalous fading" and development of unambiguous protocols to circumvent connected age underestimates remains a priority task. An actual approach is "post-IR IRSL" dating [41]. The authors believe that meaningful ages up to ca. 300 ka can be obtained without correction for anomalous fading.

The discussion about anomalous fading has been brought forward through the development of radiofluorescence (RF; formerly called radioluminescence) dating of K-feldspars [42, 43]. It uses a near infrared emission (865 nm) which is a characteristic of potassium feldspar only. The dose-response curve of IRSL (as well as of TL and OSL), ideally, is an exponential saturation curve, where the IR emission dose-response curve of RF from K-feldspars, however, is described by an exponential decay curve. According to the model elaborated in [43] this difference is due to the fact that during TL, IRSL and OSL a photon of a certain wavelength is emitted by recombination of an electron evicted from its trap below the conduction band with a certain luminescence centre. During RF, by contrast, a photon is emitted by the trapping process itself. The fact that something like anomalous fading has not been observed in RF dating of K-feldspars not only challenges anomalous fading but also allows for dating sedimentation ages of K-feldspars using a SAR protocol up to a saturation dose of ca. 800-1000 Gy. For loess, assuming typical natural dose-rates, this corresponds to an upper dating limit of 200 to 300 ka. So far RF dating has only been applied to K-feldspar grains in the sand fraction. In the silt fraction it is much more difficult to separate K-feldspar grains from plagioclase grains. Thus, without separation, the IR-RF signal is "diluted" and too low using available measurement techniques. For this reason RF ages from loess have not been published so far. Nevertheless RF dating is eligible to open up new methods for dating loess back to at least ca. 300 ka.

The limited OSL saturation dose for quartz may be overcome by using Thermal Transfer OSL (TT-OSL) saturating at about 2500 Gy. As the TT-OSL consists of two components from which only the Recuperated OSL bears the signal to be used for sediment dating, the upcoming technique is now known as **T**hermal **T**ransfer-**OSL**/**Re**cuperated**OSL** (TT-OSL/ReOSL) [32, 44, 45]. At present it is too early to state that this new technique is in general suited to date loess-paleosol sequences back to the Matuyma/Brunhes geomagnetic reversal (780 ka), but further developments of this technique deserve attention, as does the orange-red TL emission (ca. 580 nm, RTL) from quartz. Although the RTL saturation dose from quartz grains extracted from Chinese loess, estimated to ca. 550 Gy [46], is by more than an order of magnitude lower than for heated quartz [47], further detailed studies into the dose response in the orange-red part of the spectrum appear promising. A disadvantage of RTL emissions from quartz is their limited bleachability by daylight. Residual doses of 100 Gy or more were found in Chinese loess samples [46]. It appears that the measured RTL signal consists of a minimum two components from which one component is not daylight-sensitive at all. Further research may, therefore, focus on more effective separation of bleachable and non-bleachable components comparable to recent observations of the bleachability of ESR signals from quartz [48].

Similar to RTL, the use of ESR for dating sediments has been hampered by a non-bleachable residual of a very similar percentage of the natural signal. Using cryo-ESR spectroscopy (at 105-110 K) several Ti-related absorption lines with different sensitivity to light were detected in quartz grains extracted from Australian dune sands [48]. More fundamental research is needed before reliable dating of aeolian sediments can be achieved. But as dose-response curves are not saturated at 1 500 Gy ESR dating using sedimentary quartz may emerge as an additional paleodosimetric dating method for older (Middle Pleistocene) loess.

Other dating methods based on natural radioactivity cannot directly date loess deposition itself. With radiocarbon dating – limited to ca. 50 ka – a careful checking of the context and the quality of the dated organic material is essential to obtain meaningful information on the age of sedimentation or soil formation [28]. Recent progress in refined chronostratigraphy of loess achieved by ^{14}C dating is, however, primarily based on refined sampling strategies of users, and on extension and refinement of calibration (e.g., http://www.calpal.de/). The extension of the calibration time scale to ca. 50 ka [49] or even 70 ka (Hulu Cave, China) relies on high resolution U-series ages and, thus, refinements of these dating methods have had some direct impact on loess research [50]. Otherwise, the use of U-series dating for loess research is somewhat restricted to the dating of imbedded or underlying travertine up to 300-350 ka (e.g., [51]). K/Ar or Ar/Ar dating of distal tephra layers in loess can, of course, only be applied if suitable non-weathered tephra layers are available, which is rare except in the vicinity of Quaternary volcanic fields. Tephrochronology may, however, establish correlations with distant eruptive centres by geochemical or isotopic fingerprinting. Tephra beds of the ca. 40 ka old "Campanian ignimbrite", e.g., originating from the Phlegrean Fields in Southern Italy, are widespread over Southern, South-eastern and Eastern Europe (see Figure 1 in [52]) and are well-correlated with the onset of the Heinrich Event 4 and the termination of the geomagnetic Laschamps Event [53]. In Palaeolithic archaeology the tephra is an excellent marker for the Middle to Upper Palaeolithic cultural transition in Europe [53, 54]. In Belgium the Lower Weichselian "Rocourt tephra", originating from the West Eifel Volcanic Field [55], serves as a loess stratigraphic marker, as does the Upper Weichselian "Eltville Tephra" [22, 23]. In the Danube Basin several distal tephra layers have been detected in loess (e.g., [9]) but exact provenance and age are not yet established. Reinforced tephrochronological studies may, however, make future correlations with well-dated eruptions likely.

This leads to dating loess through other methodologies. Among others, aminostratigraphy of loess-paleosol sequences has developed during the past two decades into a powerful tool. Due to complex thermal history of such sequences, amino acid racemization (AAR) measurements from molluscs fossilized in loess are not well-suited to calculate numerical ages, but allow for good correlation with dated standard sequences from the same or a very similar climate zone, taking into account lower-ranking differences in present-day mean annual temperatures. The Chinese and the European standard stratigraphies fulfil the requirements on a regional to continental scale. This aminostratigraphy has yielded convincing results from the Upper and Middle Pleistocene loess. New results from the Vojvodina region (Serbia) [7, 9, 56], from Hungary [51] and from Kazakhstan [14] were presented. Further data from Central and Eastern European as well as from Central Asian loess-palaeosol sequences are desirable in order to establish an aminostratigraphic frame throughout the Eurasian loess belt.

Palaeomagnetism has been recognized as a very important dating tool for loess-paleosol sequences for decades, but nevertheless refined techniques have evolved during the past decade (see recent review, [57]). In particular, the establishment and use of a global curve of the relative paleointensity of the earth's magnetic field, known as "GLOPIS" (Global Paleointensity Stack) has enabled high resolution measurements from of the last glacial loess to detect geomagnetic excursions such as the Mono Lake Event and the Laschamps event as time markers [57, 58].

Magnetic susceptibility and more complex rock and mineral magnetic parameters (enviromagnetism) must be distinguished from paleomagnetism. The rock magnetic parameters, which serve as proxies for various paleoenvironmental conditions, are suitable to provide a magnetic stratigraphy which can be correlated to independently dated climatic proxy records [57], as was demonstrated above including some recent stratigraphic impacts (as discussed in *Regional*).

The now widespread use of laser analyzers for high resolution grain size distribution has increased the value of this proxy considerably. Calculated ratios (grain size index GSI) of fine/medium sized grains, e.g., (20-50 μm)/<20 μm, not only can serve as a tool for high resolution correlation of various profiles within a large exposure [21], but also for interregional correlation or correlation with independently dated climate archives such as ice cores [23, 59]. Furthermore, grain size data from weak stadial-interstadial cycles (tundra gley doublets) in loess coupled with other proxies suggest detailed correlation with Dansgaard/Oeschger cycles in Greenland ice (Figure 8).

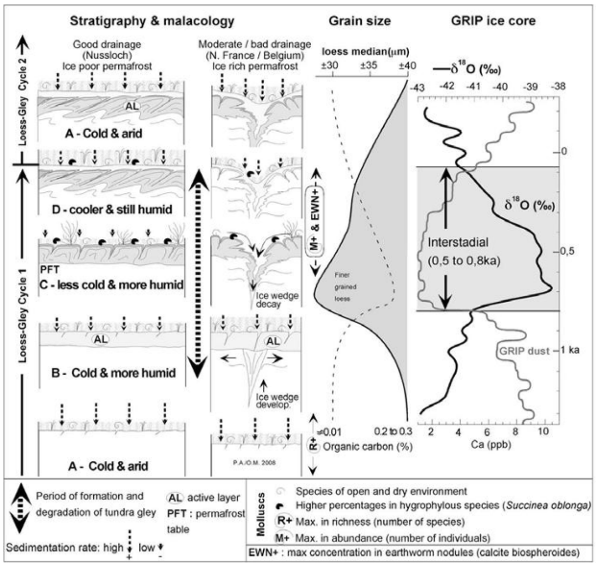

Figure 8. Model of a loess tundra-gley doublet in Pleniglacial loess developed during one Dansgaard/Oeschger cycle (from [23]).

Geochemical proxies, beyond their traditional use as indicators of weathering processes and soil formation (e.g., [60]), now also prove to be a tool for provenance studies of loess [61] (Figure 9). Isotope ratios are distinguished between stable isotope ratios and those containing at least one unstable isotope. Long-life unstable isotopes yield information on either weathering or soil formation intensity (see [62]), or provenance, or both. Unfortunately, very few data have been published from European loess during the past decade [63, 64] which therefore prevents sound provenance studies. $^{87}Sr/^{86}Sr$ isotope ratios of acid-leached residues from the Louchuan loess section, China, are consistently higher in paleosol than in loess residues [65]. The authors also deduce a general increase in deposition rates from 2.5 Ma to the present. Furthermore, in a more recent paper [66] the authors stated that Sr isotope ratios are controlled by their parent rocks, particle sizes and chemical weathering, whereas $^{143}Nd/^{144}Nd$ ratios are only related to their parent rocks. Thus, the Tarim Basin, deserts in the central and west parts of Inner Mongolia and the Tibetan Plateau are identified as the main sources of the Chinese Loess Plateau. Through the comparison of $^{87}Sr/^{86}Sr$ ratios of acid-soluble and acid-insoluble materials proxy indicators of Asian summer and winter monsoon are suggested. $^{3}He/^{4}He$ ratios on magnetic reversal boundaries of the loess-palaeosol sequence at Luochuan were analyzed as a proxy for interstellar dust particles mixed with terrigenous dust to various extents [67]. So far the database appears to be insufficient for further conclusions concerning chronostratigraphy or provenance. The discussed examples demonstrate, however, the great capability of such isotope methods in loess research. This may however, be limited due to man-power intensive and expensive laboratory procedures.

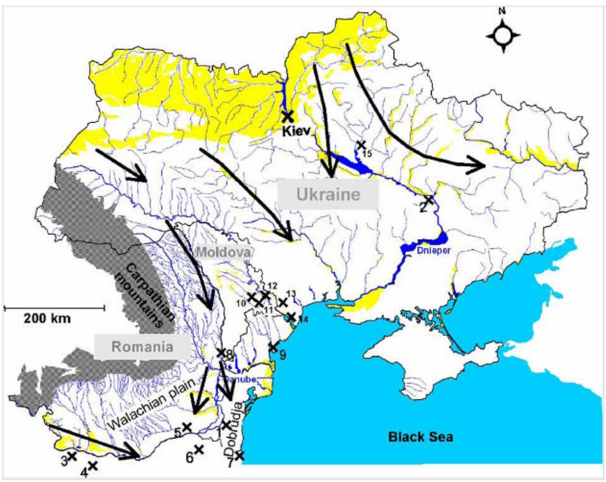

Figure 9. Provenance of loess in the Black Sea region, derived from geochemical parameters (from [61]).

Very exciting developments in the application of stable isotopes to loess research have appeared in the field of "molecular fossils". The lipid biomarker composition (*n*-alkanes) preserved in loess-paleosol sequences bears information on (local) vegetation cover of a given site at a given time. This still very young approach is developing rapidly and there is still debate about how to correctly read and interpret the stored molecular information. δD was measured from several *n*-alkanes (C_{27}, C_{29}, C_{31}) extracted from up to 130 ka old loess of the Xifeng section, Chinese Loess Plateau (CLP) [68]. The authors demonstrated a convincing similarity with the magnetic susceptibility record of the profile and concluded that the method supplies useful paleoclimatic and paleoenvironmental indicators. A "Lipid Index" was introduced as a paleovegetation and climate indicator, and compound specific (C_{31} n-alkanes) $\delta^{13}C$ values were used to estimate the C4 plant percentage in the Louchuan and Xunyi sections, CLP, for the past 170 ka [70]. In a similar study from a 40 ka loess section at Xifeng, CLP [70], the authors stated that $\delta^{13}C$ values of the TOC can be used to investigate vegetation history in semi-arid loess areas. $\delta^{13}C$ values of *n*-alkanes, however, were found as more precise recorders of *in situ* vegetation, whereas *n*-alkanes from leaf waxes are supposed to rather record regional vegetation. An optimized method for compound-specific stable carbon isotope ($\delta^{13}C$) analysis of *n*-alkanes was developed recently [71] and applied to European loss (Crvenka section, Serbia, spanning the last ca. 130 ka) [72]. End member modelling of long chained (C_{27-33}) odd *n*-alkane ratios suggests reconstruction of vegetation dynamics with some surprising results: grassland dominated at the end of the last interglacial and the beginning of the „V L1" loess deposition (MIS 4) as well as during the formation of the „V L1S1" interstadial palaeosol (MIS 3). Ever since, trees contributed varyingly to the soil organic matter even during the LGM [73]. This modelling result disagrees with existing ideas about vegetation history in Central to Eastern European loess landscapes, which may, however, be dominated by proxies (e.g., pollen) derived from too remote areas or non-representative archives. These first results are a significant challenge for loess research. A recent publication [74] on compound specific analysis of $\delta^{18}O$ from neutral sugars in soils, using an optimized protocol for GC-Py-IRMS measurements, has not yet been tested for paleosols but may be applicable in loess research as an additional climate proxy. There is an urgent need for further studies into the potential use of these new approaches.

4. Concluding remarks

The presented review reflects – as probably any review does – a personal perspective, and thus the conclusions will also reflect a personal viewpoint. Nevertheless the question of whether there is anything substantially new from (European) loess during the last decade is clear, and the answer is irrefutably yes. The present contribution, despite the incompleteness of the discussed examples, encourages the thought that there will be substantial further development in loess research in the next decade.
This review has shown:

- Loess research has taken its outstanding place in terrestrial Quaternary stratigraphy, paleoclimatology and palaeoenvironmental reconstruction.

- Other than marine or ice records, loess research is capable to unravel *on site* palaeoenvironmental history using a multiproxy approach. At the same time, the local or regional loess-palaeosol archives in many cases can be well correlated with global or hemispheric records based on direct or indirect dating. Loess-palaeosol archives are, thus, complementary to limnic records.

- Delivering proxy data on past local environmental conditions and circulation patterns (regionalization), high resolution investigations of loess archives allocate necessary inputs for atmospheric palaeocirculation models.

- Gaps between the regional "hot spots" of loess research are actually being successively closed, but much work is left for the future. Desert margin loess of lower latitudes is actually revisited and recognized as important archives for better understanding palaeoclimate and palaeoenvironment of continental lower latitudes and at the zonal interface of tropical and extratropical atmospheric circulation.

- Established methods in loess research have been continuously refined. The adoption of improved laser granulometric techniques has yielded new results not only for palaeoenvironmental reconstructions but also for stratigraphic correlations. In luminescence dating several attempts are actually tested to extend the range of reliable dating beyond 200 ka. Magnetic dating has achieved considerable progress in two ways: palaeomagnetism and environmental magnetism. Although radiocarbon dating is still impaired by ambiguous calibration results beyond MIS 2, highly sophisticated sampling and AMS measurement procedures have demonstrated its usefulness for high resolution comparative chronologies back to almost 50 ka.

- New challenging methods using stable isotopes have emerged and stand by for further testing and application. Results need to be compared and discussed in a multiproxy approach. The new methods should be regarded as a promising enrichment of the pool of methods available for multiproxy investigation.

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