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CORRELATIONS BETWEEN LOESSIC DEPOSITS OF THE EURASIAN AREA (GERMANY-AUSTRIA-CZECHIA-HUNGARY-RUSSIA-SIBERIA-CHINA) BASED ON THE TL STRATIGRAPHY METHOD

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INTRODUCTION

Correlations of loess sequences usually are based on the number of paleosols and the degree of the soil formation. However the degree of soil development is a direct function of time only if other soil-forming factors, such as local climate, slope,..., have been constant. Discontinuous loessic exposures also prevent inter-site correlations. As a result, and despite the increase of the absolute age determinations for loesses and paleosols, the stratigraphy of loess sequences still is debate (e.g. WINTLE, 1990; ZÖLLER *et al.*, 1994; OCHES & MCCOY, 1995).

The TL stratigraphy is a relative dating technique, without any attempt to estimate absolute ages. The TL stratigraphy is adapted to a rapid and comprehensive studies of loess chronology (BALESCU *et al.*, 1986a). This method gives results in a faster way than absolute TL age determination. It also permits analyses of a higher number of samples and hence a better control of both the chronological and regional coherence of the TL results.

The TL stratigraphy method provided stratigraphic correlations between loessic units of NW Europe and, in particular, a good chronological differentiation between Weichselian and Saalian loesses (BALESCU *et al.*, 1986a,b,c; 1988). In this paper, the TL stratigraphy method has been applied to loess sequences from a large area extending from Germany to China. The following 18 sequences have been extensively sampled: Ariendorf, Wallertheim (Germany); Willendorf, Grubgraben, Göttweig, Hollabrunn, Stillfried A and B, Stratzing (Austria); Dolni Vestonice (Czechia); Mende, Basaharc (Hungary); Zelezragorsk, Khotelievo, Lichvin (Russia); Tagi Djar (Tajikistan); Kurtac (Siberia) and Huangling (China). The TL stratigraphy mainly based on the TL study of quartz coarse grains (40-50 µm), has been established for the above mentioned sequences. Our relative TL dates show stratigraphic consistency both within the individual sequences and laterally. It shows that the TL stratigraphy method can be applied to correlate loess sequences from a very large geographic area. Our TL results lead to a clear discrimination between Weichselian loesses and older loesses, which is in good agreement with the stratigraphy mainly based on sedimentological features and absolute dates.

THE TL STRATIGRAPHY METHOD

Thermoluminescence (TL) is the light emission of crystals heated to a temperature below incandescence, after receiving a radiation dose.

Two types of TL are distinguished according the source of radiation:

- the natural thermoluminescence (NTL) results from the natural radiation due to the decay of the radioactive isotopes - ^{238}U, ^{235}U, ^{232}Th, and ^{40}K - in the sediment;

- the artificial radiation (ATL) results from an artificial irradiation of the materials, produced in laboratory.

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The details of the mechanism by which TL is produced in any given mineral are not well understood (AITKEN, 1992). In terms of a simple model, the radiation causes electrons to become dislodged from atoms within the crystal lattice of a mineral grain. The electrons rapidly become trapped at crystal defects, known as electron traps. In the laboratory, the heating of grains produces emission of photons due to the ejection of the electrons from these traps and their subsequent recombination at luminescence centres (Wintle, 1990). The main minerals that give rise to the TL signal from a bulk sample of loess are quartz and feldspars (Wintle, 1990). The emission of light against temperature is the glow curve which often shows several glow peaks (see Fig. 1).

The TL stratigraphy method, developped by Balescu (1988), is based on two relative dating parameters. The relative age determination using the quartz fraction is provided by the following MQ parameter (Balescu, 1988):

$$MQ = H5N/H5A$$

where:

- H5N is the natural TL intensity of the H5 peak (Fig. 1A)
- H5A is the artificial TL intensity of the H5 peak, obtained after a γ dose saturating the quartz sample.

The MQ parameter was successfully used to discriminate between Weichselian loesses (~20 ka) (MQ = ~0.5) and Saalian loesses (older than 120 ka) (MQ = ~1) of N.W. Europe (BALESCU *et al.*, 1986 b; BALESCU, 1988). However, this quartz technique did not allow any further stratigraphical discrimination since Saalian quartz was found to be close to saturation. That is the reason why Balescu (1988) defined the following MF parameter that provides a relative age of loessic deposition (Fig. 1B): $MF = ED/\beta$

where ED is the equivalent dose of feldspars and ß is the ß activity of the bulk sediment. The MF parameter provided relative TL age estimates that lead to a clear separation of the pre-Weichselian periods of NW european loess deposition in the time period 130-300 ka BP (BALESCU *et al.*, 1986c).

MATERIALS

Sampled loess sequences

The samples were taken from eighteen loessic sequences being dispersed from Germany to China (Table 1, Fig. 2). For each section, the loess samples were collected referring to the lithological descriptions of P. Haesaerts (1996). A large number of samples was taken in order to provide a statistical assessment of the results. The MQ parameter has been determined for most of these samples, except the Tajikistan sequence (TL measurements in progress).

Table 1: Studied loess sequences

Country	Local name	# samples
Germany	Ariendorf	38
	Wallertheim	5
Austria	Willendorf	22
	Göttweig	13
	Stratzing	33
	Hollabrunn	7
	Grubgraben	22
	Stillfried A	8
	Stillfried B	18
Czech Republic	Dolni Vestonice	19
Hungary	Mende	23
	Basaharc	22
Central Russia	Khotelievo/Lichvin	8
	Zelezragorsk	13
Tajikistan	Tagi Djar	36
Central Siberia	Kurtac	47
China	Huangling	32

Sample treatment

Samples were treated following the methodology described in Balescu (1988). The 40-50 µm grain size fraction was obtained by wet-sieving of the bulk sample. This fraction was treated with HCl (to remove carbonates) and with H_2O_2 (to remove the organic matter). Separation of quartz and K-feldspars was accomplished by centrifugation in a heavy liquid (d = 2.60). Quartz was treated with HF to remove residual feldspars, and a centrifugation in a heavy liquid (d = 2.72) was driven to eliminate white mica (in plentiful supply in some sequences). Feldspars were treated using the citrate-bicarbonate-dithionite method (Mehra and Jackson, 1960) to remove iron oxydes. In some cases, a magnetic separation was necessary to remove brown mica from the feldspar fraction.

TL measurements

The TL apparatus developped at the Mons laboratory has the following features:

- high sensitivity due to a photon-counting technique and an optical system (fluorite) of high quality calculated for this experimental device and the nature of the TL emission (detection system of low light emission, often characterizing the quartz TL intensity);

- a linear heating programme (linear slope: 1.5 °C/sec) connected with a micro-computer ;

- an interaction between the photon counter and the micro-computer for acquisition, processing and recording of TL data. In this way, mathematical computations from the glow curve are possible.

TL measurements were made using a EMI 60945 photomultiplier tube without filter. A very low quantity of the 40-50 µm fraction was used: 0.05 g. for quartz and 0.025 g. for feldspar. ATL and NTL intensity are expressed in counts/sec. The artificial TL was measured on quartz, previously exposed for 24 hours to UV irradiation and irradiated (^{60}Co) for a time corresponding to the saturation dose. For each loess sequence, the saturation dose was determined using the total bleach-regeneration method (Mejdahl, 1986). The saturation dose, expressed in hours of g irradiation, is ranging between 24 and 96 hrs according to the loess sequence (Fig. 3).

RESULTS

The artificial TL intensity of the H5 peak for saturated quartz depicts values (Fig. 3) that are related to the regional area of the studied sequences:

- in central Europe (including Ariendorf and Wallertheim, in Germany), the ATL intensity is ranging between ~15,000 and 45,000 counts/sec, except the Göttweig sequence for which the intensity is rather low (< 14,000 counts/sec);

- in central Russia, the ATL intensity is ~ 80,000 counts/sec;

- in central Asia (Siberia and China), the ATL intensity is ranging between 5,000 and 15,000 counts/sec.

The MQ parameter was determined for each sample of the studied sequences. The MQ values are averaged for the different lithological units recognized in the sequences (Figures 4 to 7). These figures also diplay variations of the NTL intensity of the F3 peak (cf. Fig. 1B) obtained on K-feldspar grains, according to the depth. These last results are not discussed here, only a brief comment is provided.

The Huangling sequence (China)

The variation of the MQ parameter is in relatively good agreement with the stratigraphic position of the studied samples. The mean MQ value discriminates between the different loessic sections of the sequence (Fig. 4A):

- MQ is ~ 0.6 for the L 1-1 loess and 0.87 for the L 1-3 loess. It must be observed that MQ reaches the value of 1 for the lowest sample of the L 1-3 loess;

- MQ is 1.2 for the L 2 loess, and all the samples are saturated (i.e. MQ ≥ 1). The mean MQ value doesn't discriminate between the L 2-1, L 2-2 and L 2-3 loesses;

- MQ is 1.53 for the L 4 loess, then clearly higher than the mean MQ value (1.2) for the L2 loess.

The Kurtac sequence (Central Siberia)

The variation of the MQ value also is in good agreement with the stratigraphic position of the studied samples (Fig. 4B), although some samples depict too higher or too lower MQ values. For example, two samples of the Bezgouzinski loess are characterized by an unexpected high MQ values (~0.9). On the other hand, some samples below the Kameneloc soil have a very low MQ value (0.47 and 0.62). These discrepancies could be explained by reworked loess.

In any way the mean MQ value, determined for each loessic unit of the sequence, vary according to their stratigraphy position:

- MQ is 0.7 for the Bezgouzinski loess;

- MQ is 0.9 for the Chaninski Loess;

- MQ is 1.12 (or 1.03, if low values are considered) for the loess section between the Kameneloc and the Vilmokovski soils ;

- MQ is 1.5 for the loess unit below the Vilmokovski paleosol.

The Zelezgragorsk, Khotelievo, and Lichvin sequences (Central Russia)

Three sequences from central Russia - Zelezgragorsk, Khotelievo, and Lichvin - have been sampled. The TL results for the composite sequence are shown figure 4C. The samples above the Mezin paleosol have MQ values ranging from 0.39 to 0.66. The four samples between the Mezin paleosol and the paleosol of the lower part of the sequence have a MQ value of ~ 1. The two studied samples of the lowest loessic part of the sequence have a MQ value of 1.14.

The Basaharc and Mende sequences (Hungary)

A mean MQ value of 0.71 characterizes the upper loess of the Basaharc sequence (Fig. 5A, B). Both for Basaharc and Mende loess, quartz below the MF paleosol is saturated (MQ = ~1). MQ values do not discriminate the loessic units older than the MF paleosol. Nevertheless, the MQ values are similar both for Basaharc and Mende samples, depicting a coherent regional correlation of these two sequences, based on the TL stratigraphy .

The Dolni Vestonice sequence (Czech Republic) (Fig. 5C)

The MQ value is relatively constant (~0.6) for the upper part of the Dolni Vestonice sequence. Samples below the PK II unit of the sequence have a MQ value progressively increasing until ~1. Loesses just below and just above the PK III paleosol are characterized by similar MQ values (~0.95).

The Stillfried A & B sequences (Austria)

The figure 6A presents TL results for a composite sequence grouping the two separate sequences of Stillfried (i.e. Stillfried A and B). The loess above the Stillfried B paleosol clearly is not saturated (mean MQ = 0.74). Below the Stillfried A paleosol, quartz are saturated and the mean MQ value is 1.01.

The Stratzing sequence (Austria) (Fig. 6B)

The first four samples of the upper part of the sequence have a relatively constant MQ value (0.65). With the depth, MQ increases, reaching a MQ value of ~1, just above the paleosol (here labelled 1). Below this paleosol, MQ shows large variations (0.88-1.26), but the mean MQ value is higher than 1.

The Göttweig sequence (Austria) (Fig. 6C)

The loess unit above the GÖ I paleosol is characterized by a MQ value of 0.62. The samples below GÖ I and below GÖ II have a MQ value higher than 1.

The Willendorf sequence (Austria)

The MQ value is rather constant and doesn't permit any discrimination between the B, C,and D lithological units (Fig. 7A). The mean MQ value for the sequence is 0.43.

The Grubgraben sequence (Austria)

The MQ value is rather constant all along the Grubgraben sequence (Fig. 7B). The mean MQ value for the sequence is 0.56.

The Hollabrunn sequence (Austria) (Fig. 7C)

The MQ values clearly discriminate between the loess unit above the paleosol (MQ = 0.60) and the loess below the paleosol (MQ = 0.88).

The Ariendorf sequence (Germany) (Fig. 7D)

The upper part of the LD III loess is characterized by a MQ value of 0.49. For the lower part of LDIII, surprisingly MQ is decreasing with the depth. The quartz is saturated only for samples below the ARI III paleosol.

DISCUSSION

Coherent TL stratigraphy based on China and Siberia sequences

The Huangling and the Kurtac sequences provide a good opportunity to establish a coherent TL stratigraphy. These sequences are long, recording the three or four last glacial/interglacial cycles. Moreover, the chrono-stratigraphy of the Chinese sequence is well-established (KUKLA *et al.*, 1988). The mean MQ values obtained for the different loessic generations of the two sequences are displayed in table 2, and compared to the MQ values obtained by Balescu (1988) for loess deposits in NW Europe..

Table 2: Mean MQ values of the Kurtac and Huangling sequences. Comparison with NW European loesses.

Huangling	MQ ± 1s	MQ ± 1s	Kurtac	NW Europe[1]
L 1-1	0.59 ± 0.05	0.70 ± 0.18	L 1-A (Bezgouzinski)	~ 0.5
L 1-2			Kurtac	
L 1-3	0.87 ± 0.15	0.90 ± 0.20	L 1-B (Chaninski)	
S 1			Kameneloc	
L 2-1				
L 2-2				
L 2-3	1.15 ± 0.15	1.12 ± 0.17	L 2	~1
L 2-4	1.33 ± 0.15			
L 2-5	1.16 ± 0.05			
S 2				
L 3		1.50 ± 0.18	L 3	
S 3				
L 4	1.53 ± 0.19			

1. Balescu *et al.*, 1986b.

The MQ values for the L 1-1 loess of both sequences are very similar, and relatively close to the MQ value (~0.5) obtained by Balescu *et al.* (1986b) for the upper Weichselian loess (< 20.000 ka BP) of the NW Europe. Table 2 also indicates that MQ clearly discriminates between the L 1-1 and L 1-3 loesses.

Loesses below S1 (i.e. older than the last interglacial soil) reached saturation (MQ > 1). This fact also was observed for the Saalian loesses of NW Europe (BALESCU *et al.*, 1986c; BALESCU, 1988). Moreover, the L2 loesses (L 2-3, L 2-4, L 2-5) are not differenciated by the MQ parameter, a result also highlighted by Balescu (1988).

It must be noted that some samples of the lower part of the L 1-3 loess are saturated (MQ ≥1) (see Fig. 4A, B), showing that the mean MQ values must be established from a high number of samples in order to avoid any confusion between the L 1-3 and L 2 loesses.

In any way, comparison of our TL results from China and Siberia with the Balescu's ones shows that the TL-stratigraphy method can be applied to loess deposits of a very large area.

Synthesis and regional correlations

According to the results obtained on China and Siberia sequences and on NW European sequences (BALESCU *et al.*, 1986b; BALESCU, 1988), the loessic sections with a mean MQ value ≥ 1 are considered older than the last interglacial soil. This is the case for the following loess units (table 3):

Table 3: Loess units older than the last interglacial soil.

Sequence	loess units
China (Huangling)	below the S1 paleosol
Siberia (Kurtac)	below the S1 paleosol
Central Russia	below the Mezin paleosol
Hungary (Mende & Basaharc)	below the MF paleosol
Austria (Stillfried)	below the Stillfried A paleosol
Austria (Göttweig)	below the GÖ I paleosol
Austria (Stratzing)	below the paleosol 1
Germany (Wallertheim)	below the paleosol 1

Based on the MQ values, regional correlations between the studied sequences are provided in figure 8. It can be observed that our quartz relative dates show consistency both within individual sections and laterally. However, there are two TL anomalies:

- at Dolni vestonice, loess below the PK III paleosol (see Fig. 5C) cannot be surely considered as older than the last interglacial, because of the two similar values obtained for loesses on both sides of the PK III paleosol;

- at Ariendorf, an uncertainty is also observed for the LD II and LD I loesses (see Fig. 7D). Their MQ values are abnormally too low compared to the MQ value of the lower part of the LD III loess. A systematic investigation of TL absolute dating also revealed major problems with the Ariendorf sequence (Frechen, 1992).

Loess of the last glacial period (Weichsel) are characterized by a mean MQ value less than 1. Moreover, MQ values clearly differentiate the L1-1 from the L1-3 loesses both for the China and the Siberia sequences. This is also observed for the following sequences - Dolni vestonice, Stratzing, Hollabrunn and Ariendorf- for which the MQ values of the last glacial loesses well discriminate between the upper loess (~0.6) and the lower loess (~0.9) (Fig. 8).

TL stratigraphy versus litho-stratigraphy

Table 4 display the Haesaerts's stratigraphy (1996) from which four major loess generations are recognized (labelled L1 to L4), and three sections (labelled a, b, c) are distinguished in the L1 loess.

The stratigraphic position of the last interglacial soil based on the TL method is in a good agreement with the stratigraphic schema proposed by Haesaerts, for most of the sequences (Table 4): Wallertheim, Göttweig, Stillfried, Stratzing, Basaharc, Mende, Zelezragorsk, Kurtac and Huangling. At Hollabrunn, however, according to the mean MQ values the paleosol of the sequence is considered as younger than the last interglacial soil. Two other discrepancies, in the Ariendorf and Dolni Vestonice sequences, have been previously discussed. Taking into account TL results of the Frechen's study (1992), we believe that low MQ values obtained for the L 2 loesses of Ariendorf can be considered as TL anomalies. At Dolni Vestonice, more investigations (i.e. more samples below PK III) are necessary to confirm low MQ values for loess below the PK III paleosol.

Loesses with a MQ value higher than 0.8 were considered as belonging to the L1-3 loess. Consequently a discrimination between L1-1 and L1-3 loesses has been proposed for the Ariendorf, Stratzing, Hollabrunn, Dolni

Vestonice, Kurtac and Huangling sequences (see Fig. 8). This discrimination is quite coherent with the Haesaerts's stratigraphy (Table 4).

However, compared to this litho-stratigraphy, the TL stratigraphy results show that the L1-c loesses of the Göttweig, Basaharc and Zelezragorsk sequences could be younger and then correlated to the L1-1 loesses (Table 4). It must be noted that, for these sequences, few samples younger than the S1 paleosol have been studied. Consequently, our results for these loessic sections must be confirmed by more sample analyses before any attempt to explain these discrepancies.

Schematic model for the MQ variations as a function of time

Thanks to numerous MQ values measured on individual samples of the different loess sequences, a schematic model of the evolution of the MQ value through depth is provided (Fig. 9):

- the L1-1 loess has a mean MQ value around 0.6, and the individual MQ values often is relatively constant through depth. This can be clearly observed for upper loess of the Dolni vestonice, Stillfried, Hollabrunn, Grubgraben, and Willendorf sequences;

- the L1-3 loess has a mean MQ value between 0.8 and 0.96, and the individuals MQ values progressively increase with depth, reaching 1 (or even more). This is observed in the Huangling, Kurtac , Dolni Vestonice , Stratzing, and Hollabrunn sequences.

- for loesses older than the last interglacial soil, mean MQ value is around 1, but shows large variations that are not always consistent with the increasing depth. This is observed at the Huangling, Kurtac , Mende and Basaharc, Göttweig, and Stratzing sites.

This schematic model highlights some general aspects to use the TL stratigraphy method:

- only a continuous sampling allows a clear discrimination between the L 1-1, L 1-3 and older loesses generations;

- as a consequence, calculation of the mean MQ value imply TL measurements from numerous samples. This statistical approach only can provide a consistent TL stratigraphy;

- based on the mean MQ value, distinction between loesses older than the L1 loess is rather difficult (if not impossible), because most of the quartz samples are saturated.

The MQ variation model is consistent with the schematic model of the relative F3N intensity variation (Fig. 9). This last model shows that the F3N intensity (that can be considered as a time-dependent factor) is increasing with depth, even for "old" loesses. It indicates that feldspar TL stratigraphy probably will provide promising results in order to discriminate between older loessic generations (> 130 ka BP).

CONCLUSIONS

1. TL stratigraphy using quartz coarse grains provided relative dates - the MQ parameter - of loessic deposits, that showed consistency both within the individual sequences and laterally.

2. The TL stratigraphy method allows a rapid chronological investigation that can provide coherent correlations between loess deposits within a very large area (from Germany to China).

3. Based on the MQ parameter, a clear discrimination between L1 loesses (Weichselian loess) and older loesses (*i.e.* >130,000 years) is obtained. Our results also show the possibility to differenciate between the two loessic generations (i.e. L1-1 and L1-3) of the last glacial period.

4. Most of these TL stratigraphy results are in a good agreement with the stratigraphy based on sedimentological investigations.

5. Preliminary results from feldspar TL show that the TL stratigraphy based on the MF parameter would provide discrimination between loesses generations older than 130,000 years.

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Table 4: Comparison between TL and "sedimentology" stratigraphy. The mean MQ values have been plotted in the table following the Haesaerts's stratigraphy. Arrows indicate changes of stratigraphic position according to TL results.

		China	Siberia	Russia	Hungary		Czechia	Austria						Germany	
		Huangling	Kurtac		Basaharc	Mende	Dolni V.	Göttweig	Stratzing	Hollabr.	Stillfried	Grubg.	Willend.	Wallerth.	Ariend.
L1	**a**	0.59	0.70	0.39			0.61		0.65	0.60	0.74	0.56	0.43		0.49
	b														
	c	0.87	0.90	0.62	0.71		0.96	0.62	0.95						0.81
S1															
L2		1.2	1.12	1.01	0.99	1	? 0.95	1.26	1.05	0.88	1.01			1	0.76 ?
S2															
L3			1.50	1.14	1.09	1		1.33							0.86 ?
S3															
L4		1.53				1.21									1.04

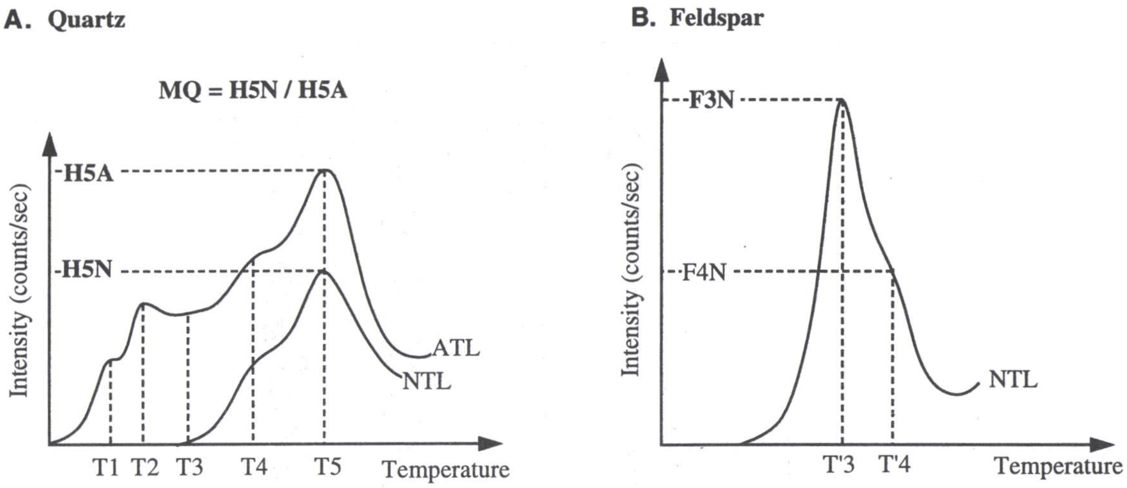

Figure 1: (A) Natural and artificial glow curves of quartz and MQ determination from intensity of the H5 peak. (B) Typical natural glow curve for feldspar.

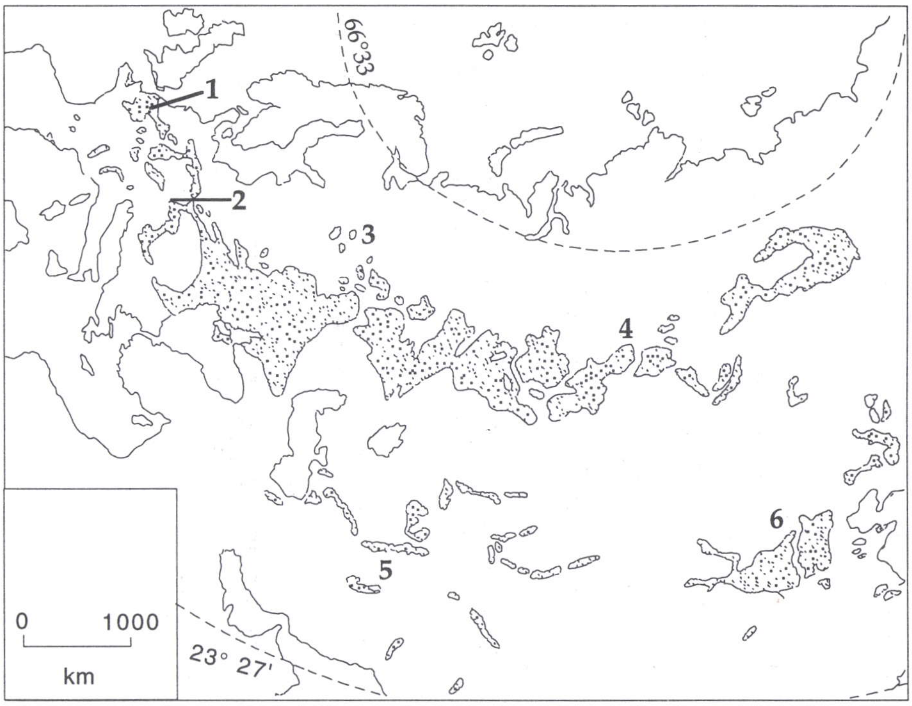

Figure 2. Loess deposits of Eurasia (modified from Billard, 1993). Regions referred to in this study: 1. NW Europe; 2. Central Europe; 3. Central Russia; 4. Central Siberia; 5. Tajikistan; 6. China.

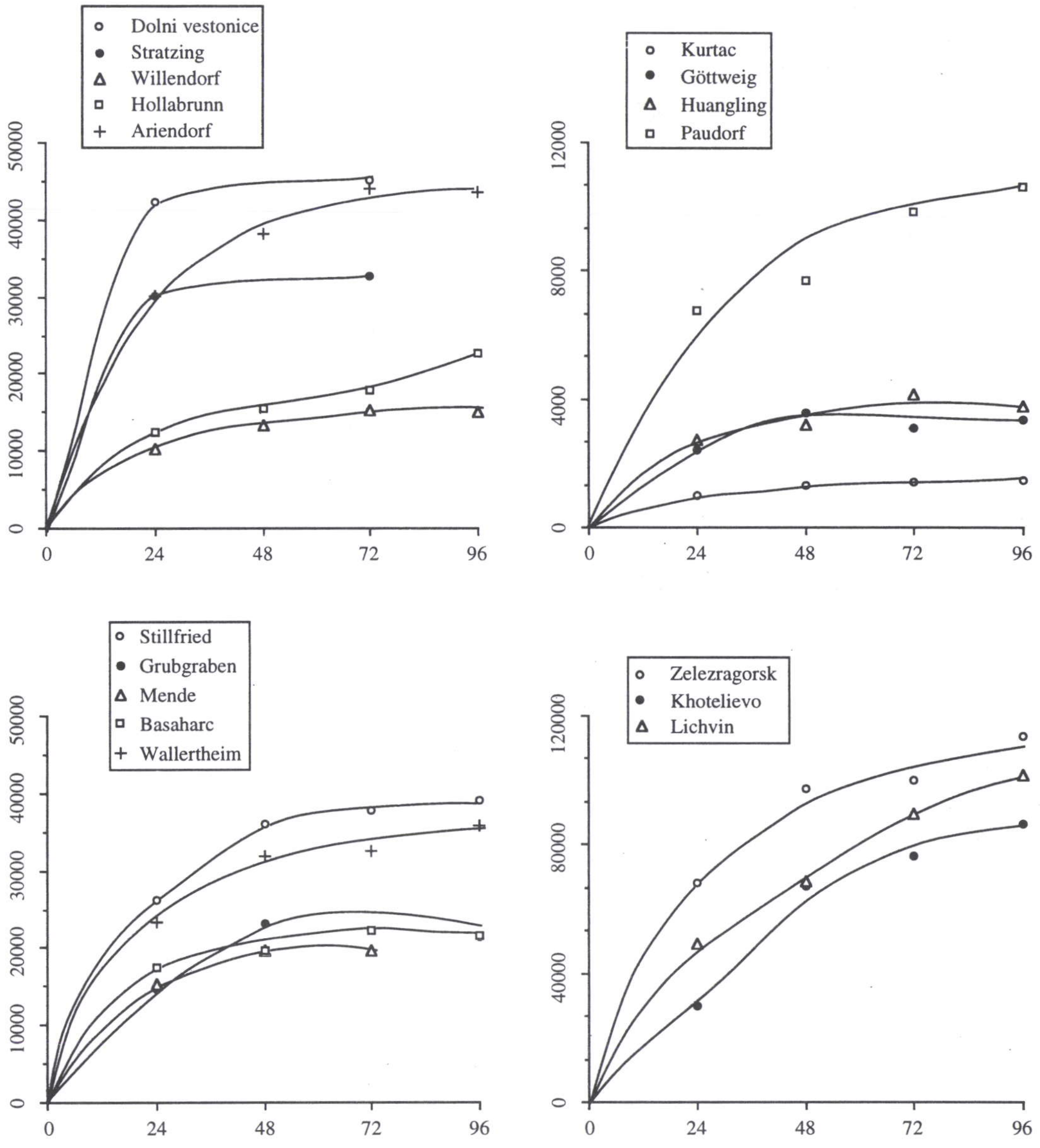

Figure 3. Saturation dose for quartz, using the total bleach-regeneration method. (hours of γ irradiation vs. H5A intensity).

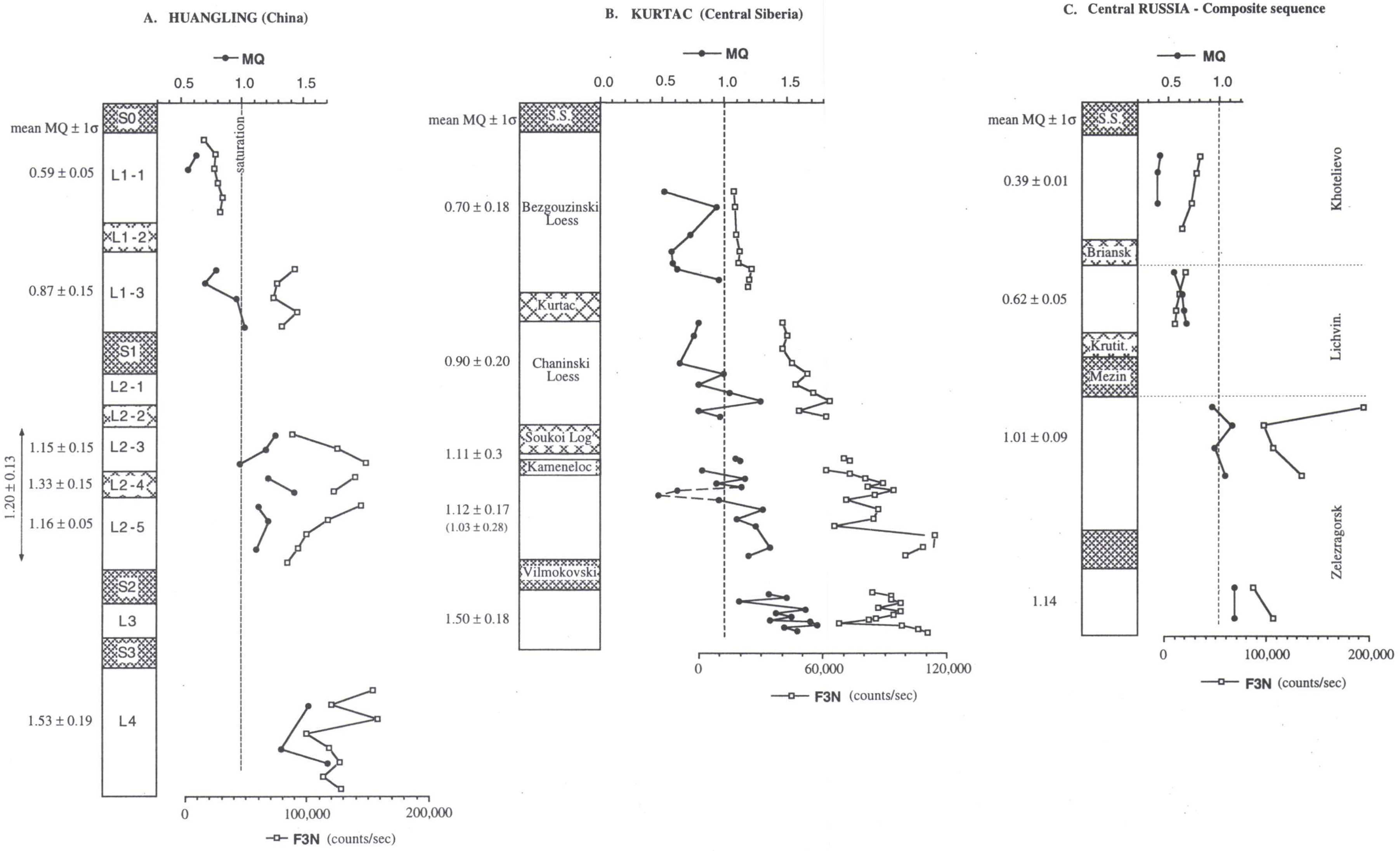

Figure 4. MQ values and intensities of the feldspar NTL as a function of depth for (A) Huangling, (B) Kurtac, and (C) Central Russian loess sections.

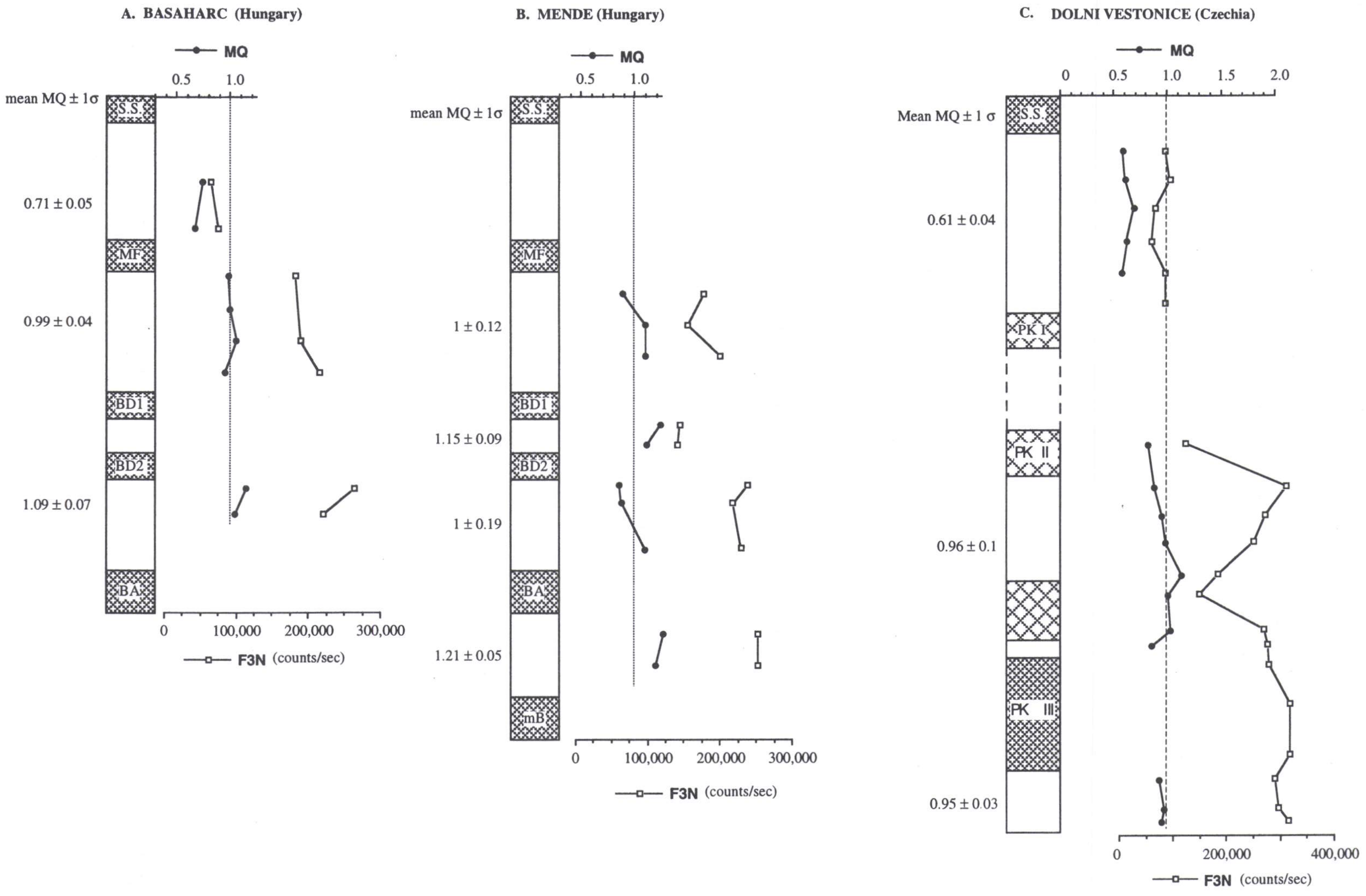

Figure 5. MQ values and intensities of the feldspar NTL as a function of depth for (A) Basaharc, (B) Mende, and (C) Dolni Vestonice loess sections.

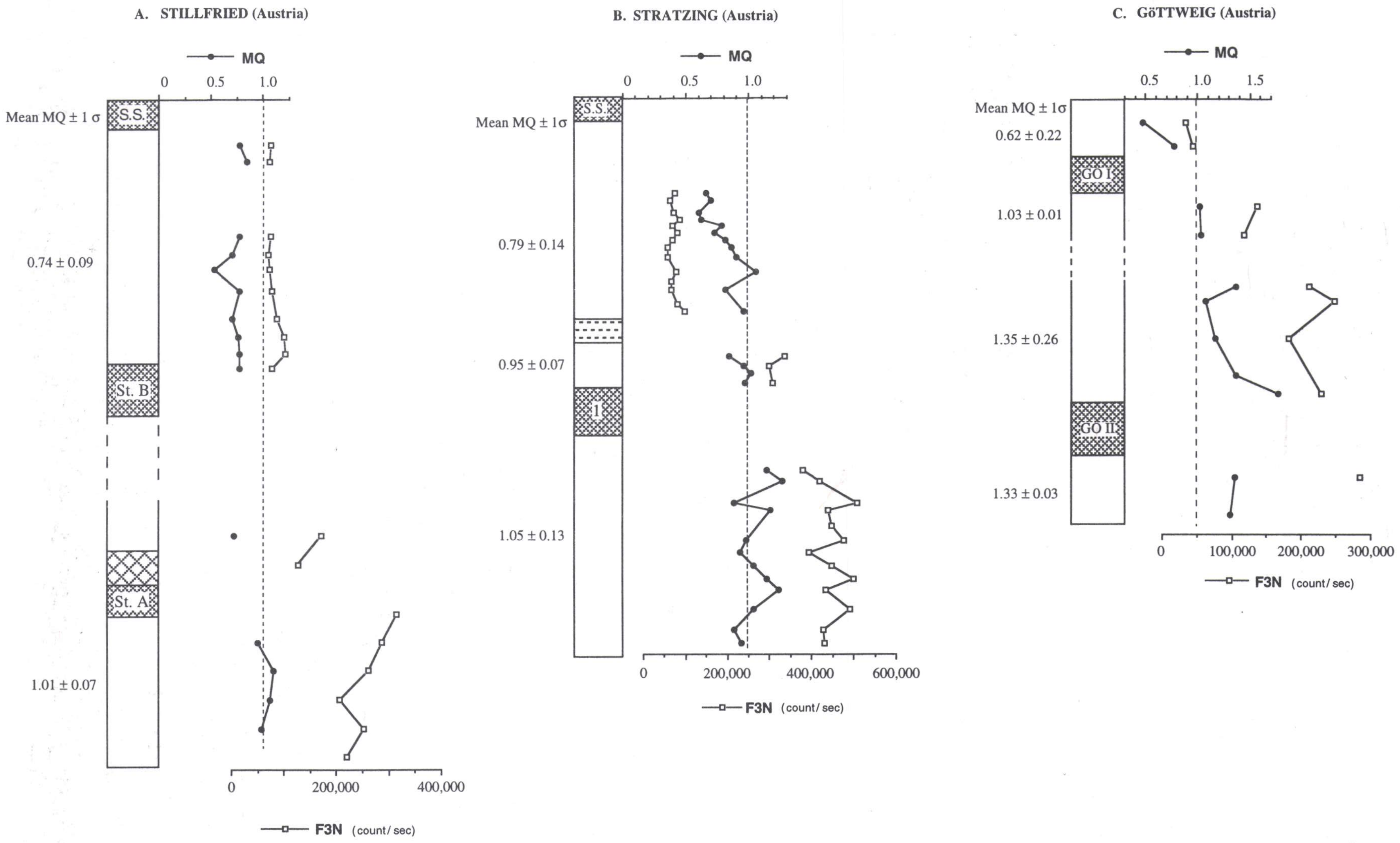

Figure 6. MQ values and intensities of the feldspar NTL as a function of depth for (A) Stillfried, (B) Stratzing, and (C) Göttweig loess sections.

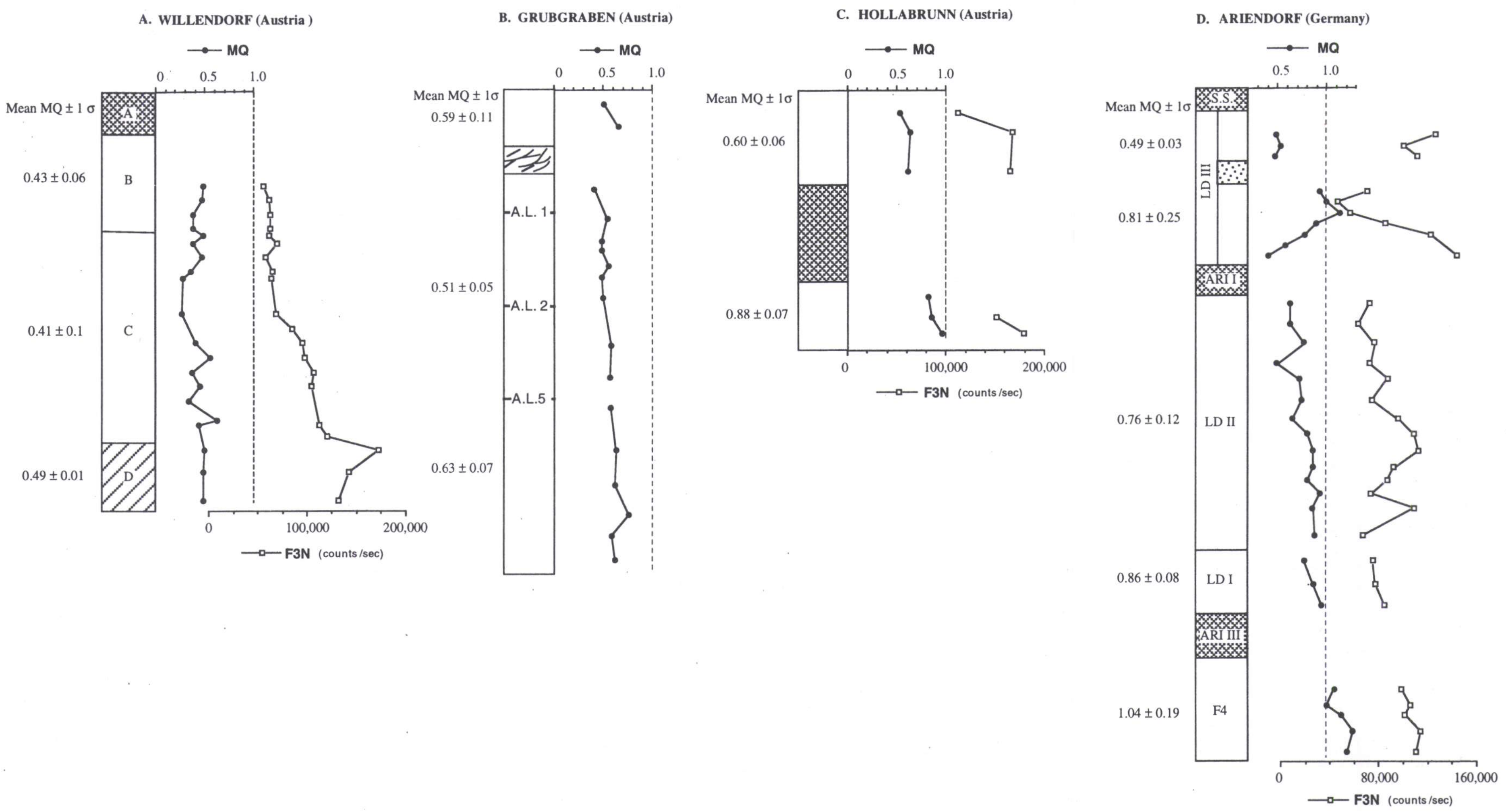

Figure 7. MQ values and intensities of the feldspar NTL as a function of depth for (A) Willendorf, (B) Grubgraben, (C) Hollabrunn, and (D) Ariendorf loess sections.

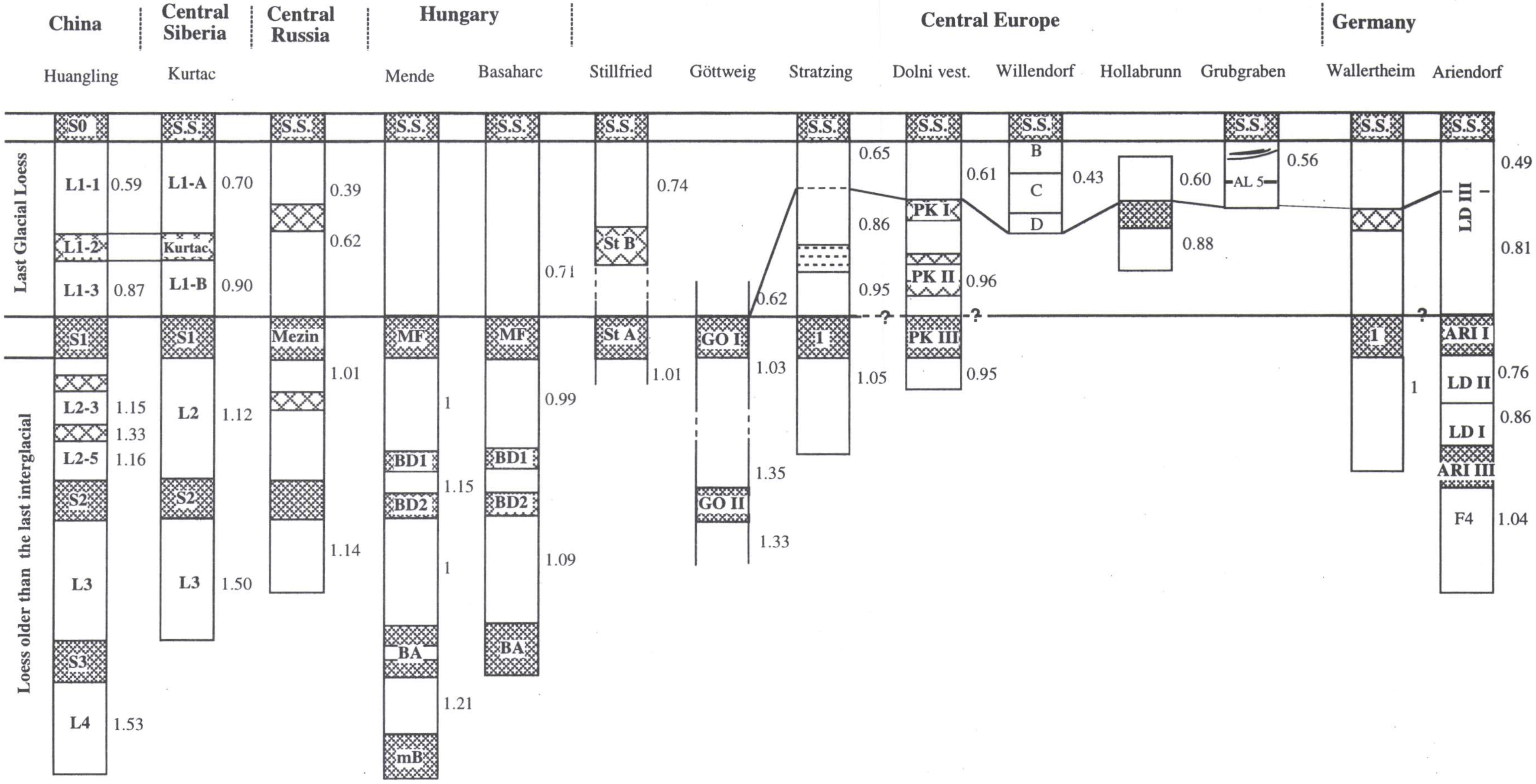

Figure 8. Correlations between loess sequences, based on the mean MQ values.

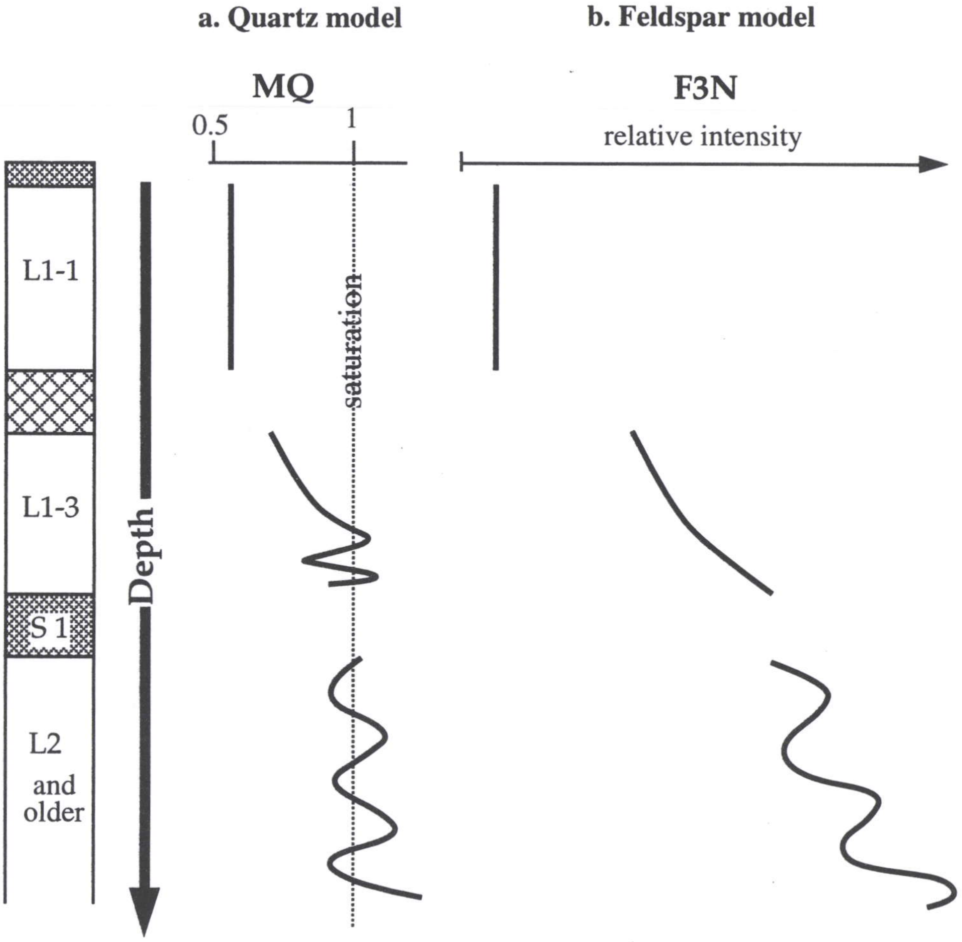

Figure 9. A schematic model for the variation of (a) the MQ value, and (b) the NTL feldspar intensity with depth.