J Paleolimnol (2007) 37:77–88
DOI 10.1007/s10933-006-9024-7

ORIGINAL PAPER

Luminescence geochronology for sediments from Lake El'gygytgyn, northeast Siberia, Russia: constraining the timing of paleoenvironmental events for the past 200 ka

**Steven L. Forman · James Pierson ·
Jeaneth Gómez · Julie Brigham-Grette ·
Norbert R. Nowaczyk · Martin Melles**

Received: 17 September 2003 / Accepted: 1 May 2006 / Published online: 12 December 2006

Abstract This study focused on the luminescence dating of sediments from Lake El'gygytgyn, a meteorite impact crater 100 km north of the Arctic Circle in northeast Siberia, formed 3.58 Ma ago. The sediment is principally eolian deposited in to a lake with nearly permanently ice. The fine-grained polymineral and quartz extracts taken from nine distinct levels from the upper 12.3 m of sediment core PG1351 were dated by infrared stimulated (IRSL) and green stimulated luminescence (GSL) using multiple aliquot additive dose procedures. The veracity of these ages is evaluated by comparing to an age model for the core derived from magnetic excursions and from correlation of variations of the magnetic susceptibility record to similar magnitude variations in $\delta\ ^{18}$O in the Greenland Ice core record. The IRSL ages from the upper 9 m of core correspond well with the independent age control for the past ca. 200 ka. However, sediments deeper in the core at 12.3 m with an inferred age of ca. 250 ka age yield a saturated IRSL response and therefore a non-finite OSL age. The youngest sediment dated from 0.70 m depth yielded the IRSL age of ca. 11.5 ka, older than the corresponding age of 9.3–8.8 ka, indicating a discrepancy in dating the youngest sediments in the upper 1 m of core. This study confirms the utility of IRSL by the multiple aliquot additive dose method to date sediments <200 ka old from eastern Siberia.

Keywords Luminescence dating · Arctic lake · Geochronology · Siberia

Introduction

A prerequisite to forward paleoenvironmental interpretations of lacustrine systems is the determination of an absolute chronology for individual

---

This is the *sixth* in a series of eleven papers published in this special issue dedicated to initial studies of El'gygytgyn Crater Lake and its catchment in NE Russia. Julie Brigham-Grette, Martin Melles, Pavel Minyuk were guest editors of this special issue.

S. L. Forman (✉) · J. Pierson · J. Gómez
Department of Earth and Environmental Sciences,
University of Illinois, 845 W. Taylor Street, Chicago,
Illinois 60607-7059, USA
e-mail: SLF@uic.edu

J. Brigham-Grette
Department of Geosciences, University of
Massachusetts, Morrill Science Center, 611 North
Pleasant Street, Amherst, MA 01003-9297, USA

N. R. Nowaczyk
GeoForschungs Zentrum Potsdam, Telegrafenberg
Section 3.3, D-14473 Potsdam, Germany

M. Melles
Institute of Geophysics and Geology, University of
Leipzig, Leipzig, Germany

lake sediment cores. An accurate chronology is essential for assessing causative links between proxy environmental indicators (e.g., diatoms, magnetic susceptibility) and broader climate drivers like changes in atmospheric chemistry, solar insolation, and ocean circulation. Advances in dosimetry-based geochronologic techniques in the past decade, such as optically stimulated luminescence (OSL) provide new capabilities for dating Quaternary sediments (e.g., Aitken 1998; Duller 2000, 2004; Forman et al. 2001; Murray and Wintle 2000; Stokes 1999). Luminescence geochronology has emerged as an important approach for deciphering paleoliminologic records because it is one of the few techniques that can be applied to a variety of aquatic settings, potentially dating environmental events spanning the past ca. 200 ka (e.g., Berger et al. 2004; Berger and Anderson 2000; Kaufman et al. 1996, 2001; Wolfe et al. 2000).

The focus of this study is evaluating the accuracy of optically stimulated luminescence to date sediments from Lake El'gygytgyn, a meteorite impact crater 100 km north of the Arctic Circle in northeast Siberia (Fig. 1), created ca. 3.58 Ma (Layer 2000). These analyses are part of a larger effort to study the hydrometeorology of the lake basin (Nolan et al. 2002; Nolan and Brigham-Grette 2007) and to extract paleoclimatic inferences from lake cores that span the past 300 ka (Brigham-Grette et al. 1998, 2001; Nowaczyk and Melles 2007). The present crater-lake has a diameter of 12 km and maximum depth of 175 m (Nolan et al. 2002). The surface of the lake at 495 m above sea level remains ice covered for ~9 months of the year with open water historically documented as early as mid-July and as late as mid-October (Nolan et al. 2002). The basin is surrounded by hills that rise to about 850–950 m asl along the west rim of the crater. Fifty streams drain into the lake and are nearly all <5 km long, limiting the catchment to the crater rim; the Enmyvaam River is the only outlet to the south. One source of sediment is through freezing of particles into the ice at the shore and with spring breakup this sediment is released in to the lake (Nolan et al. 2002). Silts and

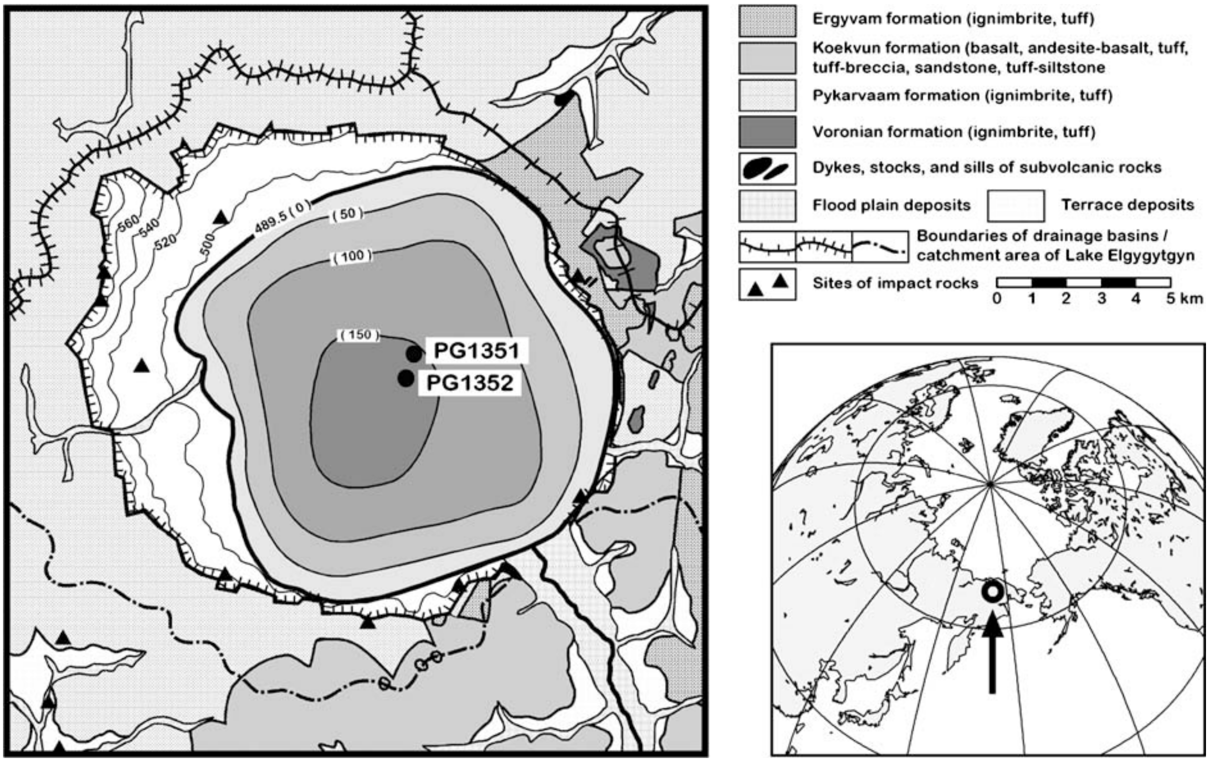

Fig. 1 Basic geologic map of El'gygytgyn impact structure (left) located in northeastern Siberia, Russia (right). (from Nowaczyk et al. 2002)

clays, presumably of eolian origin, accumulate on the surface of the ice and with melting are delivered to the lake bottom (Brigham-Grette et al. 1998, 2001). This fine-grained sediment is the target for luminescence analyses to evaluate the suitability of infrared stimulated luminescence (IRSL) for dating sediments deposited in the past ca. 200 ka.

Glacial geologic research clearly indicates that Lake El'gygytgyn and much of eastern Siberian Chukotka remained unglaciated during the Quaternary (Brigham-Grette et al. 2001, 2003; Gualtieri et al. 2000; 2003; Heiser and Roush 2001). Lake cores extracted from Lake El'gygytgyn confirm a non-glacial influence, consisting of non-laminated muds alternating with finely laminated grayish to greenish muds with little to no sand. Previous research concentrated on providing a geochronologic framework largely from biostatigraphic, magnetic susceptibility and rock magnetic properties for a 12.7 m-long core (PG1351) (Nowaczyk et al. 2002; Nowaczyk and Melles 2007). An age model for the past 300 ka for the core is based on identified time horizons, such as the Blake Event (115 ka), the base of the Eemian (130 ka) and Holocene (10 ka) pollen zones and tuning of the magnetic susceptibility series to highly similar variations in the oxygen isotope record of the Greenland Ice sheet (Fig. 2) (Nowaczyk et al. 2002; Nowaczyk and Melles 2007). The errors associated with this age model have yet to be calculated but probably do not exceed 10% (Nowaczyk pers. com., 2003). This age model provides a metric to evaluate the veracity of luminescence dating for 9 distinct levels from the upper 12.3 m of core PG1351.

Luminescence geochronology

Luminescence geochronology is based on the time-dependent dosimetric properties of silicate minerals, predominately feldspar and quartz (Aitken 1985, 1998). The technique has been used to date sediments usually <200 ka old that received prolonged sunlight exposure prior to deposition (e.g., Berger and Anderson 2000; Duller 2000; Forman and Pierson 2002). Exposing sediment to sunlight for hours (e.g., Godfrey-Smith et al. 1988) or heating to >300°C eliminates most of the previously acquired luminescence from mineral grains. After the sediment is buried and shielded from further light exposure ionizing radiation from the decay of naturally occurring radioisotopes of U, Th, and K produces free electrons which are subsequently trapped in crystallographic charge defects in silicate minerals. Excitation of these minerals by heat or light results in recombination of the stored charge that yields luminescence emissions. The intensity of the luminescence is calibrated in the laboratory to yield an equivalent dose (De), which is divided by an estimate of the radioactivity that the sample received during burial (dose rate, D_r) to render a luminescence age.

The OSL is reset to a low readily definable level by exposure of sediment to sunlight prior to deposition. In turn, optical dating techniques use light (e.g., infrared) to rapidly release electrons from light sensitive traps (e.g., 1.41 ev, Hütt et al. 1988) within the mineral lattice. A key advantage of OSL is the rapidity and the completeness of solar resetting of the signal compared to thermoluminescence. For example, the green OSL emission from quartz and potassium-feldspar grains are reset after exposure to sunlight for as little as 20 s and is similar to the reduction in the TL signal after a 20-h sunlight exposure (e.g., Godfrey-Smith et al. 1988), attesting to the broad utility of optical techniques for dating eolian sediments.

Eolian silts are common in eastern Siberia sourced from the many northward flowing rivers (e.g., Zander et al. 2003; Waters et al. 1999). Optically stimulated luminescence is most appropriate to date sediment from Lake El'gygytgyn because fine-grained silt particles (4–11 μm) are derived from nearby sources by eolian transportation and deposited on the lake ice and were surely exposed to unfiltered sunlight for >1 h prior to deposition in the lake. Light exposure is effective in eliminating most, if not all, of the inherited luminescence signal (Fig. 3) and thus, the luminescence signal reflects the time since burial of the silt grains. Once deposited, silt grains are shielded from further light exposure and subsequently acquire time-dependent luminescence properties with exposure to ionizing radiation.

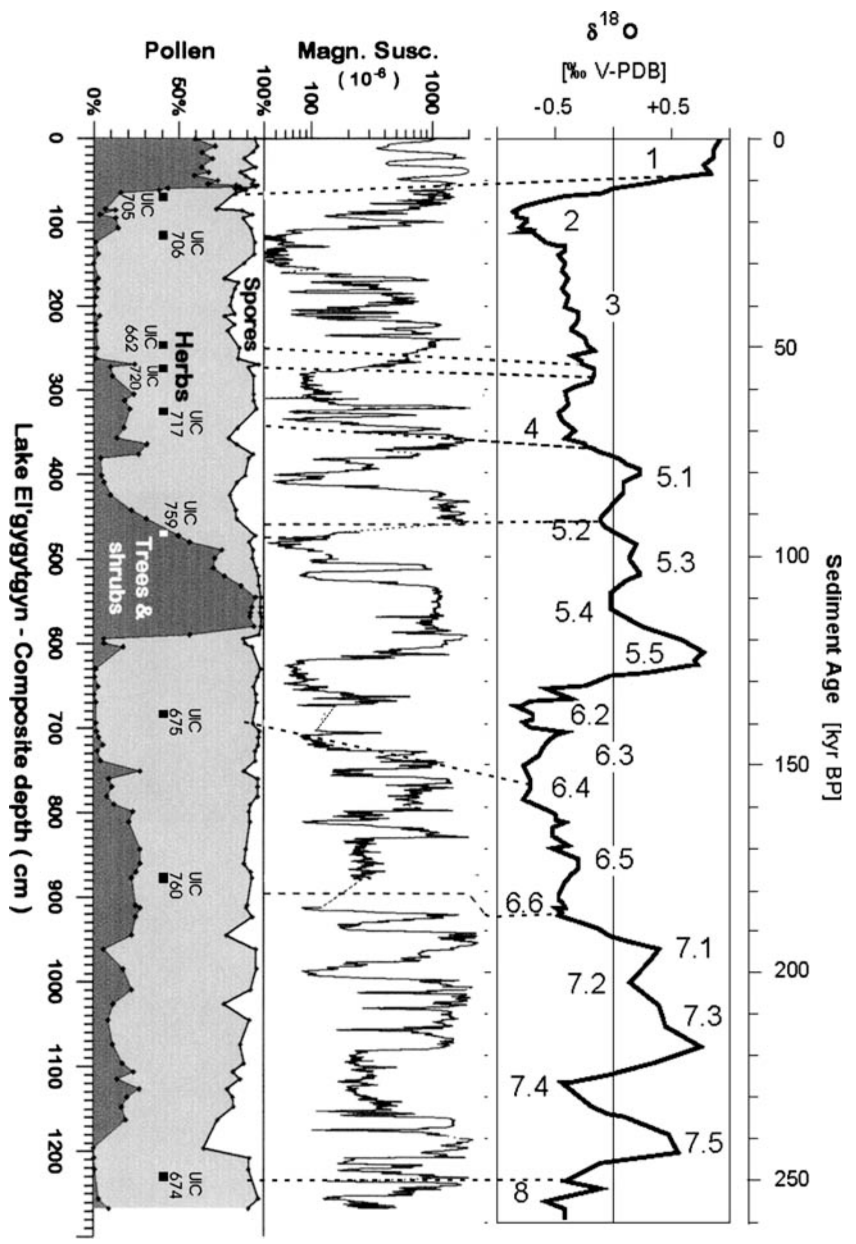

Fig. 2 Marine oxygen isotope records from ODP Site 677, equatorial Pacific and the GRIP ice core record versus time together with high-resolution record of magnetic susceptibility and simplified pollen diagram from Lake El'gygytgyn core PG1351. Location of infrared stimulated luminescence (IRSL) samples and laboratory numbers are shown in the pollen plot. Dashed lines show IRSL age ranges incorporating errors and sampling interval. (from Nowaczyk et al. 2002; Nowaczyk and Melles 2007)

Infrared-stimulated luminescence and green stimulated luminescence (GSL) ages are determined on the fine-grained (4–11 μm) polymineral and quartz fractions for nine and three levels from Lake El'gygytgyn core PG1351, respectively (Table 1). The fine-grained quartz fraction was isolated from three levels (UIC706, UIC759 and UIC675) by digestion in hydrofluosilicic acid saturated in respect to quartz, and thus preferentially dissolves non-quartz minerals (Berger et al. 1980). The low photon output (< ~8000 counts) and lack of response with infrared stimulations confirms the purity of the quartz separation. Multiple-aliquot additive-dose procedures (Singhvi et al. 1982) are used to generate IRSL and GSL ages because this approach has yielded finite and apparently accurate ages for loess and other fine grained deposits spanning the past ca. 150 ka (e.g., Berger et al. 2004; Forman 1999; Forman and Pierson 2002; Frechen and Yamskikh

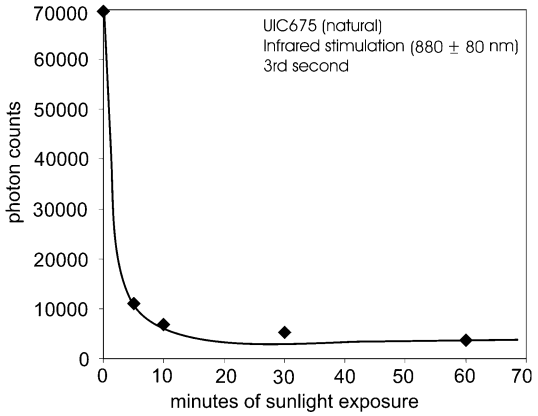

Fig. 3 Solar resetting of natural luminescence for a fine-grained polymineral extract (UIC675) with infrared excitation. This sample yielded infrared stimulated luminescence age of 159.5 ± 13.1 ka (Table 1). Luminescence is reduced to a low definable level after 5 min light exposure

1999; Frechen et al. 2001; Lang 1994; Richardson et al. 1997) and most recently for eastern Siberian loess (Zander et al. 2003), a sediment genetically related to that dated from Lake El'gygytgyn.

Optical stimulation of sediments was accomplished using an automated Daybreak 1100 reader with infrared emission (880 ± 80 nm) from a ring of 30 diodes (Spooner et al. 1990) and green emission (514 ± 40 nm) from a filtered halogen (100 W) light-source. The infrared diode array and green light source delivers approximately 17 mW/cm^2 and 7.4 mW/cm^2, respectively, to the sample. The resultant blue emissions were measured at elevated temperature (125°C) by a Thorn-EMI 9635 Q photomultiplier tube coupled with one 3-mm-thick Schott BG-39, and one 3-mm-thick Corning 7–59 glass filters that blocks >90% luminescence emitted below 390 nm and above 490 nm from the sediments. Blue-dominated emissions were chosen for measurement because previous studies indicate greater suitability as a chronometer than ultraviolet wavelengths (e.g., Balescu and Lamothe 1992, 1994; Berger et al. 1994; Lang and Wagner 1996; Rendell et al. 1995). The background count rate for measuring blue emissions was low (<80 counts/s), with a signal-to-noise ratio of >20. Samples were excited for 90 s, and the resulting IRSL or GSL signal was recorded in 1 s increments.

The IRSL and GSL ages were determined on the fine-grained (4–11 μm) corresponding polymineral and quartz fractions of sediments (Table 1). Prior to analysis aliquots for IRSL and GSL dating were preheated at 140°C for 10 h and 150°C for 1 h, respectively and then stored for 24 h. These preheats, similar to previous studies (e.g., Berger 2003; Kaufman et al. 1996, 2001; Frechen et al. 2001; Forman 1999; Forman and Pierson 2002; Nowaczyk et al. 2001; Ollerhead et al. 1994; Stokes 1992; Watanuki and Tsukamotto 2001), are effective in largely circumventing an unstable luminescence component (anomalous fading) (Wintle 1973) associated with laboratory irradiation and yield IRSL ages in agreement with independent chronologic control. Tests on luminescence signal stability were completed by comparing changes in IRSL emissions for an additive dose between 0.74 and 1.52 kGy after preheating at 140°C for 10 h and storage for 24 h; separate aliquots were measured immediately and after storage at 25°C for 31–47 days (Table 1). Stability of the laboratory dose-induced luminescence is indicated by the ratio of luminescence emission after storage divided by the immediate measurement; a ratio of 1.0 indicates stable luminescence. The stability ratio for the lacustrine sediments studied range between 0.92 and 0.99, which indicates little to no signal instability and the detected deviation from a ratio of 1.0 is within analytical resolution. There may be a small diminution of the additive dose signal by 5–10% for some samples but this is well within other associated dating errors. Another indication of IRSL stability is the age concordance to GSL measurements on the fine-grained quartz fraction (Table 1). Quartz luminescence is a magnitude lower than the corresponding polymineral infrared emissions and is known not to exhibit signal instability (Wintle 1973; Roberts et al. 1994). These observations indicate that the preheated feldspar grains do not display significant signal instability and may reflect an inherent property of the dated feldspars, rather than a response to the preheat (Spooner 1992; Spooner et al. 1990; Huntley and Lamothe 2001). There is no clear evidence for instability of the IRSL or systematic age underestimation, which obviates the need for

Table 1 Infrared stimulated luminescence (IRSL) and green stimulated luminescence (GSL) data and ages for the fine-grained (4–11 μm) polymineral and quartz fractions from core PG1351, Lake El'gygytgyn, northeast Siberia, Russia

Correlated core depth (cm)	Lab number[a]	Test dose (kGy)/days stored	Thermal[b] stability ratio	Equivalent dose (Gy)[c]	a Value[d]	U (ppm)[e]	Th (ppm)[e]	K_2O (%)[f]	Water (%)	Dose rate (Gy/ka)[g]	IRSL or GSL age (ka)	Correlative age (ka)[h]
66–70	UIC705	0.82/36	0.99 ± 0.02	36.62 ± 0.48	0.03 ± 0.01	3.42 ± 0.48	11.76 ± 1.46	3.01 ± 0.02	60 ± 3	3.19 ± 0.14	11.5 ± 0.8	8.8–9.3
116–120	UIC706	0.82/31	0.95 ± 0.03	54.42 ± 0.23	0.04 ± 0.01	2.68 ± 0.47	10.06 ± 1.28	3.03 ± 0.02	55 ± 5	3.12 ± 0.14	17.5 ± 1.3	17.1–17.9
116–120	UIC706g			63.01 ± 0.57	0.04 ± 0.01	2.68 ± 0.47	10.06 ± 1.28	3.03 ± 0.02	55 ± 5	3.12 ± 0.14	20.2 ± 1.6	17.1–17.9
244–247	UIC662	0.82/31	0.92 ± 0.04	153.43 ± 2.28	0.03 ± 0.01	3.31 ± 0.46	10.34 ± 1.14	2.96 ± 0.03	50 ± 5	3.18 ± 0.14	48.2 ± 3.9	54.5–55.3
271–275	UIC720	1.02/35	0.98 ± 0.02	193.16 ± 0.58	0.03 ± 0.01	3.43 ± 0.42	8.58 ± 1.02	2.83 ± 0.03	50 ± 5	3.06 ± 0.14	61.6 ± 4.3	58.8–59.4
321–327	UIC717	1.50/31	0.99 ± 0.01	222.44 ± 1.12	0.03 ± 0.01	3.60 ± 0.61	12.42 ± 1.68	3.32 ± 0.03	55 ± 5	3.59 ± 0.15	63.5 ± 4.5	72.3–73.7
459–474	UIC759	1.22/43	0.96 ± 0.02	382.13 ± 1.29	0.04 ± 0.01	3.57 ± 0.59	11.29 ± 1.64	2.98 ± 0.03	43 ± 2	3.67 ± 0.16	104.2 ± 7.5	103.9–110.7
459–474	UIC759g			302.93 ± 4.54	0.04 ± 0.01	3.57 ± 0.59	11.29 ± 1.64	2.98 ± 0.03	43 ± 2	3.67 ± 0.16	82.1 ± 5.9	103.9–110.7
678–693	UIC675	1.55/37	0.98 ± 0.03	573.41 ± 5.22	0.11 ± 0.01	3.04 ± 0.40	8.48 ± 1.01	2.72 ± 0.03	50 ± 5	3.59 ± 0.18	159.5 ± 13.1	152.7–155.7
678–693	UIC675a			483.81 ± 5.36	0.08 ± 0.01	3.04 ± 0.40	8.48 ± 1.01	2.72 ± 0.03	50 ± 5	3.59 ± 0.18	148.9 ± 11.1	152.7–155.7
678–693	UIC675g			>371.42 ± 4.30	0.08 ± 0.01	3.04 ± 0.40	8.48 ± 1.01	2.72 ± 0.03	50 ± 5	3.59 ± 0.18	>112.1 ± 8.8	152.7–155.7
878–895	UIC760	1.22/43	0.96 ± 0.03	565.46 ± 0.92	0.03 ± 0.01	2.42 ± 0.34	8.51 ± 0.86	2.00 ± 0.03	36 ± 5	2.39 ± 0.11	212.3 ± 16.1	185.8–187.2
1224–1232	UIC674	0.76/37	0.96 ± 0.03	441.84 ± 1.79	0.02 ± 0.01	3.42 ± 0.43	9.25 ± 1.26	2.38 ± 0.03	50 ± 5	2.71 ± 0.13	>162.5 ± 11.8	249.9–250.4

[a] "g" designates analyses of quartz fraction under green light excitation (514 ± 40 nm). All other samples are analyzed by infrared light (880 ± 80 nm); "a" indicates a duplicate analysis

[b] The stability of the laboratory beta-induced (Gy) luminescence signal was tested by comparing luminescence emissions immediately after preheating (10 h at 140°C) and with at least a 31 day storage. A thermal stability ratio between 0.99 and 0.92 indicates little or no signal instability, which is within analytical resolution

[c] The resultant blue emissions are detected with 3-mm-thick Schott BG-39, and one 3-mm-thick Corning 7–59 glass filters that blocks >90% luminescence emitted below 390 nm and above 490 nm in front of the photomultiplier tube. Errors for De determinations are determined using a non-linear least-squares routine, based upon the Levenburg–Marquardt method (Marquardt 1963; Press et al. 1986, pp. 521–528), in which inverse-variance weighted data are modeled by a saturating exponential function. Errors are generated for each De calculation in a variance-covariance matrix. The resulting uncertainties in De reflect dispersion in the data and random errors associated with modeling the dose response as a saturating exponential. The mean De and errors is evaluated from a range of individual De's for 2 to 90s since infrared exposure. Standard statistical data-weighting procedures are utilized to calculate an average De and associated errors (Bevington 1969; pp. 69–71, 119–131). All errors are at one sigma

[d] The measured alpha efficiency factor as defined by Aitken and Bowman (1975)

[e] U and Th ppm levels calculated from alpha count rate, assuming secular equilibrium. The ratio of bulk alpha count rate under sealed and unsealed counting conditions is >0.95 indicating little to none radon loss

[f] Percent K_2O determined by ICP-MS on a homogenized 5 g aliquot by Activation Laboratories LTD, Ontario, Canada

[g] Dose rate value includes a contribution from cosmic radiation of 0.10 ± 0.02 Gy/ka (Prescott and Hutton, 1994)

[h] Inferred ages from Nowaczyk and Melles (2007)

a correction factor (e.g., Mejdahl and Christensen 1994; Huntley and Lamothe 2001).

All samples were analyzed by the total-bleach method (Singhvi et al. 1982), with the solar-reset residual level measured on four aliquots of each sample. The luminescence of Lake El'gygytgyn sediments is rapidly reset with sunlight exposure with a >90% diminution of signal after 10 min light exposure (Fig. 3). The lowest solar reset level is obtained after exposure to 1 h of sunlight, which results in near-total resetting of the IRSL signal (Fig. 3). The rate of IRSL growth was evaluated by applying additive beta doses to the natural IRSL signal by a series of irradiations with a calibrated ^{90}Sr/^{90}Y source. The highest radiation dose added to the natural IRSL signal was at least five times the calculated De, which is usually sufficient for accurate extrapolation (Fig. 4). The natural and additive-dose data were fitted by a saturating exponential function (cf. Grűn 1996; Huntley et al. 1987) for emissions from the 2nd to 89th second of infrared excitation that encompasses over 95% of the measured IRSL signal and exhibits a pronounced plateau in De values (Fig. 4). However, De determinations are limited by the extent of growth of luminescence with additive dose; if there is little increase in the resultant luminescence the response is considered ''saturated'' (Mejdahl 1988). Similar to a previous effort (Forman and Pierson 2002)

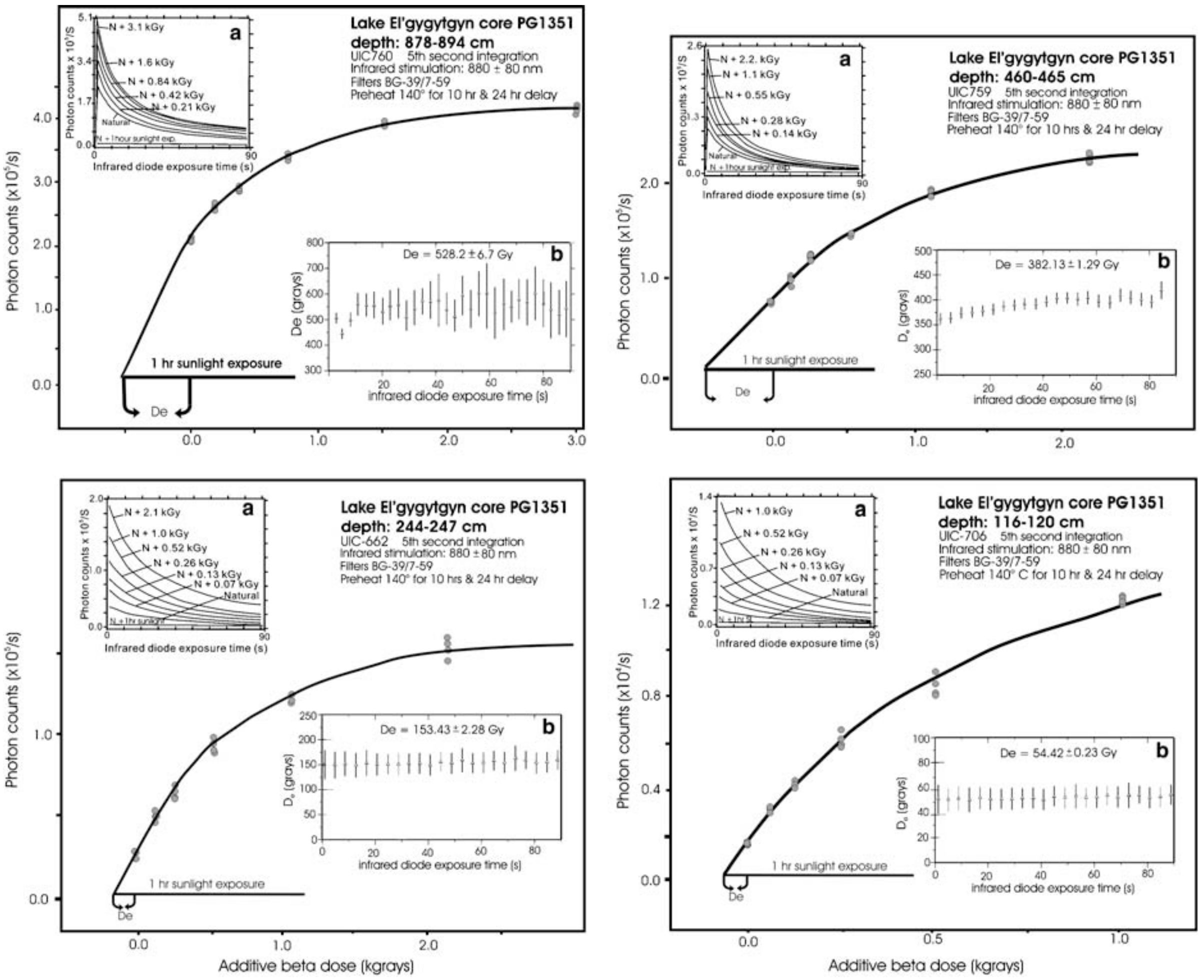

Fig. 4 Infrared stimulated luminescence (IRSL) additive β dose response for four different levels for core 1351 from Lake El'gygytgyn. Inset (**a**) show IRSL shine down curves for natural, solar reset and additive β dose treatments. Inset (**b**) show the equivalent does values for a range of infrared exposures times

we consider De's calculated with < 150% increase in luminescence emission with additive beta compared to the natural level (Fig. 4; UIC760) to provide insufficient differentiation in dose response to calculate a finite equivalent dose.

Dose rate measurements

A critical parameter for luminescence dating is the dose rate (D_r), which is an estimate of the exposure of the sediment to ionizing radiation during the burial period (Table 1). Most ionizing radiation in the sediment is from the decay of isotopes in the U and Th decay chains and ^{40}K. The U and Th content are determined by thick-source alpha counting, which assumes secular equilibrium in the decay series. The radioactive potassium component (^{40}K) is determined from the assayed K_2O content of the sediment by inductively coupled plasma-mass spectrometry by Activation Laboratory LTD, Ontario, Canada. A small cosmic ray component, 0.10 ± 0.01 Gy/ka, is included in the estimated dose rate following calculations of Prescott and Hutton (1994) which largely reflects attenuation by 175 m of water that overlies the core site. The alpha efficiency value (*a*-value; Aitken and Bowman 1975) is determined under infrared stimulation for multiple aliquots of the polymineral fraction and ranges from 0.03 to 0.11 (Table 1). The present moisture content (by weight) of core PG1351 is rather well known with analyses for water content by weight determined at nearly 2 cm intervals (Fig. 5), which serves as a basis for estimating the moisture content during the burial period. Moisture content is highest at ~70–80% in the uppermost 30 cm of the core reflecting limited compaction and with increasing overburden decreases to 30–40% at 800–900 cm depth. Moisture content used for age calculation is approximately 5% wetter than the measured values to reflect an earlier history of wetter conditions, of unknown duration and, possible loss of sediment pore water with core retrieval and extraction. This inferred added moisture content results in ages ~4% older than calculated for the original measured moisture content.

Discussion: assessing the accuracy of IRSL ages

An a priori assumption is that the magnetic/tuned timescale generated for core PG1351 is accurate and this certainty reflects the definition of known time markers (e.g., Blake Event 115 ka) and subsequent tuning against temperature proxies (δ^{18}O) from the Greenland ice cores (Nowaczyk et al. 2002; Nowaczyk and Melles 2007). This tuning of the Lake El'gygytgyn record is justified because both records primarily reflect changes in solar insolation, the principal driver in Quaternary

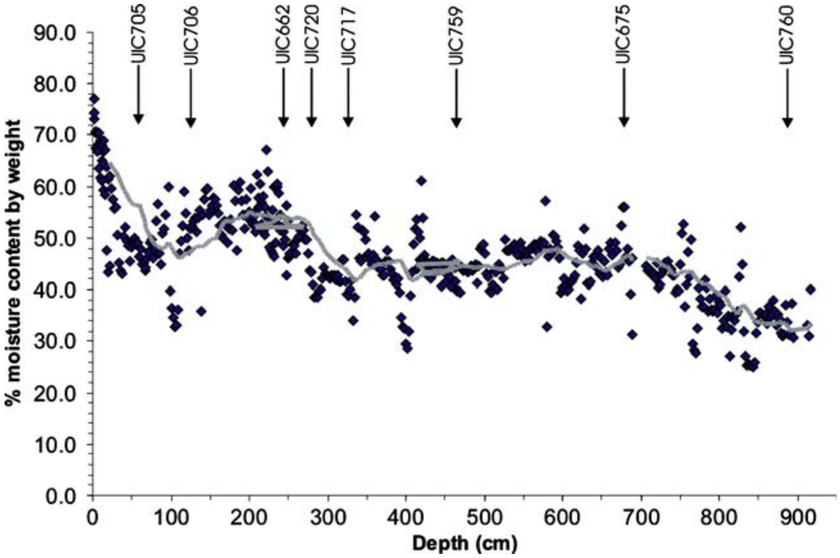

Fig. 5 Measure moisture content (by weight) of core 1351 from Lake El'gygytgyn

climate changes in high latitudes (e.g., Bradley 1990; Kutzbach et al. 1998). There are two possible sources of error with the core age model. The first is the age span for intervals (3–15 cm) of sediments that are dated by IRSL that reflect < 1000 years to ~5000 years (Table 1). The other source of error is associated with the tuning of the Lake El'gygytgyn time series to the Greenland ice core records, which remains unevaluated for potential leads and lags and may account for additional errors of ± 10%.

The oldest sediment dated by luminescence is from 1224 to 1232 cm depth (UIC674) with an inferred age of ca. 250 ka (Nowaczyk et al. 2002; Nowaczyk and Melles 2007). This sediment exhibits a rather modest response to additive β dose with < 100% in growth in IRSL emissions above the natural response which, is insufficient to interpolate an accurate equivalent dose. Thus, the IRSL age of >162.5 ± 11.8 ka (UIC674) (Table 1) is not finite or reliable because the response to additive beta dose is near saturation (Mejdahl 1988; Forman and Pierson 2002). Younger sediment from 878–895 cm depth (UIC760) with a correlated age of 185.8–187.2 ka (Nowaczyk and Melles 2007) showed an increase in IRSL emissions of ~160% above the natural luminescence, just sufficient to calculate an accurate equivalent dose. This analysis yielded an IRSL age of 212.3 ± 16.1 ka (UIC760) is concordant at 2 sigma with the correlated age of 185.8–187.2 ka (Nowaczyk and Melles 2007). The available analyses indicate that the upper limit for IRSL dating sediment from Lake El'gygytgyn is at least 150–200 ka, well within the inferred ages for sediments in the upper 700 cm of core PG1351 that were subsequently dated (Table 1).

An important chronostratigraphic marker is the first occurrence of Eemian pollen assemblage, at ca. 130 ka at 589 cm depth. Lake sediment above at 459–474 cm and below at 678–693 cm this marker were dated by IRSL (Table 1). The deepest sediment yielded the IRSL age of 159.5 ± 13.1 ka (UIC675) and a duplicate analysis gave an age of 148.9 ± 11.1 ka (UIC675a); both ages concordant with independent age control (152.7–155.7 ka) at one sigma (Table 1). These pre-Eemian sediments showed >150% rise in luminescence above the natural emission and a non-saturated response with additive β dose of >2 kGy, indicating a geochronologically sensitive response. A corresponding (UIC675g) fine-grained quartz extract showed less response to additive beta dose and yielded the minimum limiting age of >112.1 ± 8.8 ka. The sediment at 460 cm depth yielded an IRSL age of 104.2 ± 7.5 ka (UIC759) and GSL age of 82.1 ± 5.9 ka (UIC759g) on the fine-grain quartz extract, which overlap at two sigma. These ages are consistent with the post-Eemian pollen assemblage and a documented shift in magnetic intensity immediately below the dated sediments associated with the Blake Event, at ca. 115 ka (Nowaczyk et al. 2002).

Five levels in the upper 330 cm of core PG1351 are dated by IRSL spanning the past ca. 70 ka (Fig. 2, Table 1). Sediment from 321–327 cm and 271–275 cm yielded the respective IRSL ages of 63.5 ± 4.5 ka (UIC717) and 61.6 ± 4.3 ka (UIC720) which over lap at two and one sigma levels, respectively with correlative ages of 72.3–73.7 and 58.8–59.4 ka (Table 1). The IRSL ages on fine-grains from 244 to 247 cm and from 116 to 120 cm depth are 48.2 ± 3.9 ka (UIC662) and 17.5 ± 1.3 ka (UIC706), are in close agreement with correlative ages of 54.5–55.3 ka and 17.1–17.9 ka, respectively (Table 1). A quartz extract from the 116–120 cm level yield the age of 20.2 ± 1.6 ka (UIC706g), within one sigma of the corresponding IRSL age of 17.5 ± 1.3 ka (UIC706) (Table 1). The uppermost sediment dated from core PG1351 from 66 to 70 cm yielded IRSL age of 11.5 ± 0.8 ka (UIC705), which is somewhat older than the correlative age of 9.3–8.8 ka (Table 1). However, the modeled timescale for the upper 1 m of the core is problematic because of the lack of calibration points and loss of sediments with coring. Eight out of the nine levels in core PG1351 dated by IRSL overlap well within 2 sigma errors with the associated correlative age (Fig. 6).

The growth of luminescence with additive β dose in the laboratory shows distinguishable trends for the different age sediments dated from core PG1351 (Fig. 4). The luminescence emissions for the youngest lake sediment, 66–70 cm and 116–120 cm below the surface increased

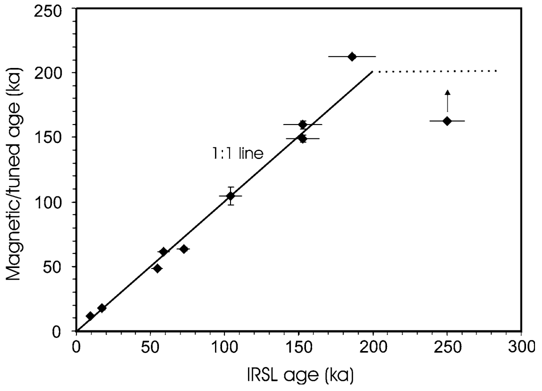

Fig. 6 Comparison between IRSL ages and corresponding ages determined from sediment magnetic data and tuning to other dated records (Nowaczyk and Melles 2007)

nearly at a linear rate up to an additive dose of approximately 0.26 Gy. Sediments from depths of 2–5 m show linear growth up to approximately 0.20 Gy. The oldest sediments dated below 678 cm do not exhibit linear response to additive dose but show instead saturation in luminescence emissions with an additive dose >1 kGy. This progressive non-linear luminescence response to laboratory irradiation down core PG1351 and clear saturated exponential luminescence response to additive β dose from the deepest sediments reflect a dynamic equilibrium between continuous electron trap occupation, associated with an infinite matrix dose and long term trap emptying (Mejdahl 1988). These competing processes for electron capture and trap emptying within the mineral lattice result in an upper age limit for IRSL dating by additive dose techniques for Lake El'gygytgyn sediments of ca. 200 ka.

Conclusion

1. Eight of the nine fine-grained polymineral extracts from the upper 9 m of sediment from Lake El'gygytgyn yield IRSL ages that correspond well with the magnetic/tuned timescale for the past ca. 200 ka (Nowaczyk and Melles 2007). Ages on fine-grained quartz extracts from three levels are consistent with corresponding IRSL ages and thus confirms the temporal sensitivity of the IRSL signal.
2. The uppermost sediment dated from core PG1351 from 66 to 70 cm yielded an IRSL age of 11.5 ± 0.8 ka (UIC705), which is older than the correlative age of 9.3–8.8 ka. This discrepancy highlights chronologic uncertainties for sediments deposited in the past ca. 15 ka, within the upper 1 m of retrieved sediments.
3. Sediment from 12.3 m depth yielded a rather modest response to additive β dose with $<100\%$ in growth in IRSL emissions above the natural and this response is insufficient to interpolate an accurate equivalent dose. Therefore, the corresponding IRSL age of >162.5 ± 11.8 ka (UIC674) is not finite or reliable because the response to additive beta dose is near saturation. IRSL is an effective geochronometer for light-exposed Arctic sediments for the past ca. 150–200 ka, consistent with previous results of Berger et al. (2004) and Zander et al. (2003). The apparent upper limit for effective dating largely reflects electron trap saturation effects, rather than signal instability documented for coarse grain feldspars (Huntley and Lamothe 2001).

Acknowledgements OSL analyses of sediments from Lake El'gygytgyn was supported by NSF award OPP-0012345 to J. Brigham-Grette. Review comments by F. Preusser and an anonymous reviewer are much appreciated.

References

Aitken MJ (1985) Thermoluminescence dating. Academic Press, New York, 359 pp

Aitken MJ (1998) An introduction to optical dating: the dating of quaternary sediments by the use of photon-stimulated luminescence. Oxford University Press, New York, 267 pp

Aitken MJ, Bowman SGE (1975) Thermoluminescent dating: assessment of alpha particle contribution. Archaeometry 17:132–138

Balescu S, Lamothe M (1992) The blue emissions of K-feldspar coarse grains and its potential for overcoming TL age underestimates. Quat Sci Rev 11:45–51

Balescu S, Lamothe M (1994) Comparison of TL and IRSL age estimates of feldspar coarse grains from waterlain sediments. Quat Sci Rev 13:437–444

Berger GW (2003) Luminescence chronology of late Pleistocene loess-paleosol and tephra sequences near Fairbanks, Alaska. Quat Res 60:70–83

Berger GW, Anderson PM (2000) Extending the geochronometry of arctic lake cores beyond the radiocarbon limit by using thermoluminescence. J Geophys Res 105(D12):15439–15455

Berger GW, Mulhern PJ, Huntley DJ (1980) Isolation of silt-sized quartz from sediments. Ancient TL 11:8–9

Berger G, Pillans BJ, Palmer AS (1994) Test of thermoluminescence dating of loess from New Zealand and Alaska. Quat Sci Rev 13:309–333

Berger GW, Melles M, Banerjee D, Murray AS, Raabs A (2004) Luminescence chronology of non-glacial sediments in Changeable Lake, Russian High Arctic, and implications for limited Eurasian ice-sheet extent during the LGM. J Quat Sci 19:513–523

Bevington PR (1969) Data reduction and error analysis for the physical sciences. McGraw-Hill, New York

Bradley RS (1990) Holocene paleoclimatology of the Queen Elizabeth Islands, Canadian High Arctic. Quat Sci Rev 9:365–384

Brigham-Grette J (2001) New perspectives on Beringian Quaternary paleogeography, stratigraphy, and glacial history. Quat Sci Rev 20:15–24

Brigham-Grette J, Gaultieri L, Glushkova OY, Hamilton TD, Mostoller D, Kotov A (2003) Chlorine-36 and C-14 chronology support a limited last glacial maximum across central Chukotka, northeastern Siberia, and no Beringian ice sheet. Quat Res 59:386–398

Brigham-Grette J, Cosby C, Apfelbaum MG, Nolan M (2001) The Lake El'gygytgyn sediment core—a 300 ka climate record of the terrestrial Arctic. Eos Trans AGU 82(47):F752

Brigham-Grette J, Glushkova O, Minyuk P, Melles M, Overduin PP, Nowaczyk N, Nolan M, Stone D, Layer P (1998) Preliminary lake coring results from El'gygytgyn Crater, Eastern Siberia. Eos Trans AGU 79(45):F477

Duller GAT (2000) Dating methods: geochronology and landscape evolution. Prog Phys Geog 24:111–116

Duller GAT (2004) Luminescence dating of Quaternary sediments: recent advances. J Quat Sci 19:183–192

Forman SL (1999) Infrared and red stimulated luminescence dating of late Quaternary near-shore sediments from Spitsbergen, Svalbard. Arctic, Antarctic, Alpine Res 31:34–49

Forman SL, Pierson J (2002) Late Pleistocene luminescence chronology of loess deposition in the Missouri and Mississippi river valleys, United States. Palaeogeog Palaeoclim Palaeoecol 186:25–46

Forman SL, Pierson J, Lepper K (2000) Luminescence Geochronology. In: Sowers JM, Noller JS and Lettis WR (eds) Quaternary geochronology: methods and applications. American Geophysical Union Reference Shelf 4; Washington, DC, pp 157–176

Frechen M, Yamskikh AF (1999) Upper Pleistocene loess stratigraphy in the southern Yenisei Siberia area. J Geol Soc 156:515–525

Frechen M, van Vliet-Lanoe B, van den Haute P (2001) The Upper Pleistocene loess record at Harmignies/Belgium—high resolution terrestrial archive of climate forcing. Palaeogeog Palaeoclim Palaeoecol 173:175–195

Gualtieri L, Glushkova O, Brigham-Grette J (2000) Evidence for restricted ice extent during the last glacial maximum in the Koryak Mountains of Chukotka, far eastern Russia. Geol Soc Amer Bull 112:1106–1118

Gaultieri L, Vartanyan S, Brigham-Grette J, Anderson PM (2003) Pleistocene raised marine deposits on Wrangel Island, northeast Siberia and implications for the presence of an East Siberian ice sheet. Quat Res 59:399–410

Godfrey-Smith DI, Huntley DJ, Chen W-H (1988) Optical dating studies of quartz and feldspar sediment extracts. Quat Sci Rev 7:373–380

Grün R (1996) Errors in dose assessment introduced by the use of the ‘‘linear part’’ of a saturating dose response curve. Rad Meas 26:297–302

Heiser P, Roush JJ (2001) Pleistocene glaciations in Chukotka, Russia: moraine mapping using satellite synthetic aperture radar (SAR) imagery. Quat Sci Rev 20:393–404

Huntley DJ, Lamothe M (2001) Ubiquity of anomalous fading in K-feldspars and the measurement and correction for it in optical dating. Can J Earth Sci 38:1093–1106

Huntley DJ, Berger GW, Bowman SGE (1987) Thermoluminescence response to alpha and beta irradiations, and age determinations when the dose response is non-linear. Nucl Trac Rad Eff 105:279–284

Hütt G, Jaek I, Tchonka J (1988) Optical Dating: K-feldspars optical response stimulation spectra. Quat Sci Rev 7:381–385

Kaufman DK, Forman SL, Lea PD, Wobus CW (1996) Age of pre-late Wisconsin glacial-estuarine sedimentation, Bristol Bay, Alaska. Quat Res 45:59–72

Kaufman DK, Manley WF, Forman SL, Layer PW (2001) The last interglacial to glacial transition, Togiak Bay, southwestern Alaska. Quat Res 55:190–202

Kutzbach JE, Gallimore R, Harrison S, Behling P, Selin R, Laarif F (1998) Climate and biome simulations for the past 21,000 years. Quat Sci Rev 17:473–506

Lang A (1994) Infrared stimulated luminescence dating of Holocene reworked silty sediments. Quat Sci Rev 13:525–528

Lang A, Wagner GA (1996) Infrared stimulated luminescence dating of archaeosediments. Archaeometry 38:129–141

Layer P (2000) Argon-40/Argon-39 age of the El'gygytgyn impact event, Chukotka, Russia. Meteorit Planet Sci 35:591–599

Marquardt DW (1963) An algorithm for least-squares estimation of non-linear parameters. J Soc Indust Appl Math 11:431–441

Mejdahl V (1988) The plateau method for dating partially bleached sediments by thermoluminescence. Quat Sci Rev 7:347–348

Mejdahl V, Christiansen HH (1994) Procedures used for luminescence dating of sediments. Boreas 13:403–406

Murray AS, Wintle AG (2000) Luminescence dating of quartz using an improved single-aliquot regenerative-dose protocol. Rad Meas 32:57–73

Nolan M, Brigham-Grette J (2007) Basic hydrology, limnology, and meteorology of modern Lake El'gygytgyn, Siberia. J Paleolimnol. DOI 10.1007/s10933-006-9020-y (this issue)

Nolan M, Liston G, Prokein P, Brigham-Grette J, Sharpton VL, Huntzinger R (2002) Analysis of lake ice dynamics and morphology on Lake El'gygytgyn, NE Siberia, using synthetic aperture radar (SAR) and Landsat. J Geophys Res-Atm 108:8162

Nowaczyk NR, Melles M (2007) A revised age model for core PG1351 from Lake El'gygytgyn, Chukotka, based on magnetic susceptibility variations correlated to northern hemisphere insolation variations. J Paleolimnol DOI 10.1007/s10933-006-9023-8 (this issue)

Nowaczyk NR, Minyuk P, Melles M, Brigham-Grette J, Glushkova O, Nolan M, Lozhkin AV, Stetsenko TV, Anderson P, Forman SL (2002) Magnetostratigraphic results from impact crater Lake El'gygytgyn, northeastern Siberia: A 300 kyr long high-resolution terrestrial paleoclimatic record from the Arctic. Geophys J Int 150:109–126

Ollerhead J, Huntley DJ, Berger GW (1994) Luminescence dating of sediments from Buctouche spit, New-Brunswick. Can J Ear Sci 31:523–531

Prescott JR, Hutton JT (1994) Cosmic ray contributions to dose rates for luminescence and ESR dating: large depths and long-term time variations. Rad Meas 23:497–500

Press WH, Flannery BP, Teukolsky SA, Vetterling WT (1986) Numerical recipes: the art of scientific computing. Cambridge University Press, Cambridge UK, 458 pp

Rendell HM, Townsend PD, Wood RA (1995) TL and IRSL emission-spectra of detrital feldspars—new experimental-data. Phys Stat Sol B 190:321–330

Richardson CA, McDonald EV, Busacca AJ (1997) Luminescence dating of loess from the northwest United States. Quat Sci Rev 16:403–415

Roberts RG, Spooner NA, Questiaux DG (1994) Paleodose underestimates caused by extended duration preheats in the optical dating of quartz. Rad Meas 23:647–653

Singhvi AK, Sharma YP, Agrawal DP (1982) Thermoluminescence dating of dune sands in Rajasthan, India. Nature 295:313–315

Spooner NA, Aitken MJ, Smith BW, Franks M, McElroy C (1990) Archaeological dating by infrared-stimulated luminescence using a diode array. Rad Protect Dos 34:83–86

Spooner NA (1992) Optical dating: preliminary results on the anomalous fading of luminescence from feldspars. Quat Sci Rev 11:139–146

Stokes S (1992) Optical dating of quartz from sediments. Quat Sci Rev 11:153–159

Stokes S (1999) Luminescence dating applications in geomorphological research. Geomorphology 29:153–171

Watanuki T, Tsukamoto S (2001) A comparison of GLSL, IRSL and TL dating methods using loess deposits from Japan and China. Quat Sci Rev 20:847–851

Waters MR, Forman SL, Pierson JM (1999) Late Quaternary geology and geochronology of Diring Yuriakh, an early paleolithic site in central Siberia. Quat Res 51:195–211

Wintle AG (1973) Anomalous fading of thermoluminescence in mineral samples. Nature 245:143–144

Wolfe AP, Frechette B, Richard PJH, Miller GH, Forman SL (2000) Paleoecology of a >90,000-year lacustrine sequence from Fog Lake, Baffin Island, Arctic Canada. Quat Sci Rev 19:1677–1699

Zander A, Frechen M, Zykina V, Boenigk W (2003) Luminescence chronology of the Upper Pleistocene loess record at Kurtak in Middle Siberia. Quat Sci Rev 22:999–1010